An Analysis of Noise Reduction in Variable Reluctance Motors Using Pulse Position Randomization

by

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Abstract

The design and implementation of a control system to introduce randomization into the control of a variable reluctance motor (VRM) is presented. The goal is to reduce noise generated by radial vibrations of the stator. Motor phase commutation angles are dithered by 1 or 2 mechanical degrees to investigate the effect of randomization on acoustic noise. VRM commutation points are varied using a uniform probability density function and a 4 state Markov chain among other methods. The theory of VRM and inverter operation and a derivation of the major source of acoustic noise are developed.

The experimental results show the effects of randomization. Uniform dithering and Markov chain dithering both tend to spread the noise spectrum, reducing peak noise components. No clear evidence is found to determine which is the optimum randomization scheme. The benefit of commutation angle randomization in reducing VRM loudness as perceived by humans is found to be questionable.

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Chapter 1

INTRODUCTION

The variable reluctance motor (VRM) is a versatile motor that has relatively few applications today. Its major disadvantage is that it is acoustically noisy, to the point where humans often require hearing protection in the vicinity of an operating VRM. This discomfort and potential for damage to an unprotected person's hearing have severely limited the use of VRM's. This thesis explores the use of different randomization schemes on VRM switching to reduce acoustic noise from VRM's.

1.1 Background

The VRM has many advantages over other types of motors. The most obvious advantage is its simpler construction, and thus lower cost. Dc motors and ac synchronous motors require windings on the rotor, along with a commutator or slip rings. The induction motor has either windings or conducting bars on the rotor. The VRM rotor simply consists of iron laminations, without windings or bars. Thus, the VRM rotor is the most robust rotor available. In addition to the rotor, the stator of a doubly salient VRM is relatively easy to construct, since the phase windings can be mounted separately in any sequence. Doubly salient means both the rotor and stator have salient poles. This arrangement produces the highest torque per frame size in VRM's.[1, 2]

The VRM has other advantages over induction motors (IM), the most widely used motors today. Moghbelli conducted an analysis of VRM and IM attributes, using 10 hp motors, and found that the VRM compared favorably[1]. The most notable VRM attribute was efficiency; VRM efficiency was found to be relatively constant for 75-100% of rated load, and generally higher than IM efficiency which varied with load. Thus, the VRM produced torque efficiently and economically at various speeds and loads. In addition, the VRM can give constant power over a range of speeds, which makes it very good for traction applications[3].

The major disadvantage of the VRM is acoustic noise. It is well documented that VRM's are noisy, but this writer could not find literature specifically directed at reducing the noise. Cameron determined that the vibrations that produce the most noise are radial vibrations of the stator induced by radial magnetic forces in the motor[4,5]. Another disadvantage of the motor is that it produces a pulsating torque compared to the smoother torque of other motors[1].

In addition to the actual motor, a power controller is required for proper operation of the VRM. The control circuitry must be complex enough to synchronize the power applied to the various phases with rotor position, to ensure a unidirectional torque. The controller must determine rotor position and provide power to the proper phase. The energy conversion takes place in the inverter circuitry. Other motors do not require such complex control systems for their power electronics.

Because the VRM requires a controller, the circuitry is already present to introduce randomization into the switching pattern. The nominal switching waveform is rotor position dependent, and randomization involves varying the rotor positions where power is applied to the stator phases. Cameron demonstrated that random perturbations of these positions reduced acoustic noise[4,5]. These random perturbations prevent coherent excitation of resonant frequencies of the stator at noisy motor speeds.

There has been some literature on reducing acoustic noise using power electronic inverters for motors other than VRMs. Handley demonstrated that a dithered pulse width modulation (PWM) strategy with a PWM chopper-controlled DC motor replaced tonal noise emission with wideband noise[6]. He found that the PWM generated noise was the dominant acoustic noise source in a variable speed drive, overshadowing the contributions of bearing, fan and motor noise. The spectra of the PWM drive noise depended on the probability density function (pdf) of the dither signal, and he chose a uniform pdf to eliminate tonals. Habetler also attempted noise reduction in sinusoidal PWM by using a randomly modulated carrier[7]. His randomization involved varying the slope of the triangle carrier used to generate the sinusoidal PWM. Again, the spectral content of the applied voltage was spread, producing acoustic noise that was more pleasing to the ear.

Characterization of the randomization of a standard switching pattern was investigated by Stanković[8]. He used different pdfs in his randomization schemes while maintaining the same average duty cycle to maintain the same average power.

His work provides a unified spectral analysis of switching patterns that have a random component introduced. He also investigated the use of Markov chains to better shape the power spectra. Applying randomization techniques to an inverter and associated VRM has an effect on acoustic noise, as shown in [4], [6], and [7]. Stanković's techniques represent a new approach to motor and power electronic converter quieting, and this thesis applies some of these techniques in an attempt to demonstrate an acoustic noise reduction in VRM's.

1.2 Thesis Outline

This thesis presents the operation, hardware design, software control system and randomization techniques necessary to understand and implement Stanković's theories. Chapter 2 describes the theory of operation and characteristics of VRMs in general, along with the specific characteristics of the experimental VRM used for this research. The equation for the major source of acoustic noise, radial vibrations is the stator, is derived using Maxwell stress tensor analysis.

Chapter 3 presents the control system. Hardware operation is described in basic terms, and the reader can refer to Appendix A for specific wiring. The major facets of the controller software are described, highlighting the features of the Motorola 68332 Microcontroller Unit (MCU). Some aspects of controller design are taken from [9]. The chapter ends with a discussion of fault tolerance in VRM's and their associated control systems.

Chapter 4 introduces the terminology and theory necessary for understanding the randomization schemes applied to the VRM. Stationary and non-stationary randomization are described, with an extended description of the ergodic Markov chain used in the experiments. A discussion of the considerations involved in choosing control signal timing is presented.

Chapter 5 presents the experimental results. First, the laboratory setup and measurement techniques are described. Then, the data is presented, showing the effect of randomization. Randomization is especially effective at a mechanical resonance of the VRM. Limitations of the research are also presented.

Chapter 6 draws conclusions about the benefits of randomization as applied to VRMs. The applicability of this research extends beyond VRMs, with applications to all power electronic motor drives.

Chapter 2

VRM AND INVERTER OPERATION

The basic elements necessary for VRM operation are the VRM itself, an inverter, and a controller. This chapter begins by describing the construction of the VRM used in the laboratory experiments, followed by a discussion of VRM operation using lumped-parameter electromechanical energy principles. The inverter used to drive the VRM is then explained by describing a single inverter phase as a simple switching circuit with two modes of operation. Sources of acoustic noise in the VRM are described in the third section, with discussions of the mechanics of VRM construction and the effect of the inverter drive on VRM noise generation. The controller is described in Chapter 3.

2.1 VRM Construction

A VRM is constructed with a ferrous rotor that has salient poles with no permanent magnets or electrical excitation. The sole source of excitation is windings on the stator. The stator can have either concentrated windings with salient poles or

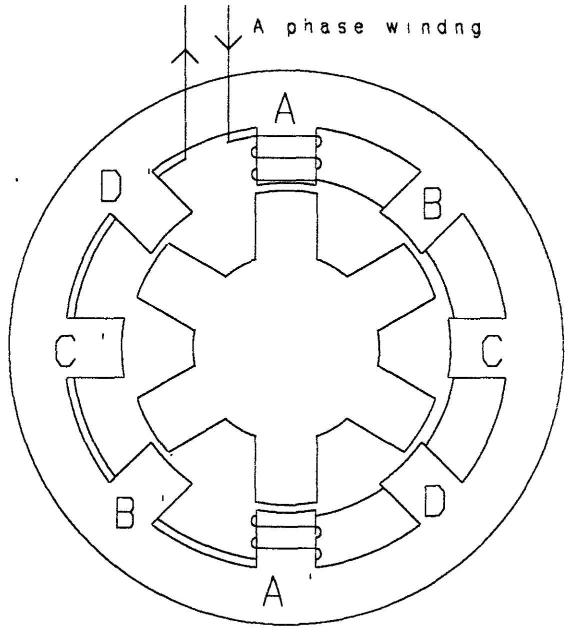

Figure 2.1 End view of the geometry of the 8/6 VRM. An example winding is shown.

distributed windings with no saliency, classifying a VRM as either doubly salient or singly salient.

The experimental 0.5-hp VRM was donated (but not manufactured) by General Electric Corporation to MIT for experimental work done by Derrick Cameron in 1989[4,5]. The stator consists of iron laminations with eight salient poles. Each pole subtends a 21° arc. The 24° of arc between poles contains the windings, with a space factor of approximately 0.8. Each pole has a concentrated copper winding, connected in series with the diametrically opposite pole's winding to form a phase. The connections are such that the fluxes are additive. The six rotor poles also consist of iron laminations. Each rotor pole subtends a 23° arc, with 37° between poles. Figure 2.1 shows an end view of the VRM.

The depth of the lamination stacks on the stator and rotor is 2 inches. The stator laminations are supported by two aluminum endbells. Holes bored in the endbells house precision thrust bearings at each end of the rotor, whose laminations are mounted on a steel shaft. For all analysis, the construction is assumed to be symmetric, with identical electrical and mechanical characteristics for each stator phase and for each rotor pole.

2.2 VRM Principles of Operation

Torque production in the VRM is the result of the tendency of rotor poles to align with stator poles to maximize the flux linkage (λ) when a magnetomotive force (mmf) is applied to the stator. Torque is produced by the tangential components of the resulting forces. The radial components of the forces cause radial deflections of the stator, which is the major source of acoustic noise in the experimental VRM[4,5]. The rest of this section describes the particulars of VRM torque production and acoustic noise.

2.2.1 VRM Dynamics

The general operation of a VRM is described by three equations:

$$\frac{d\lambda_n}{dt} = v_n - R_n i_n, \qquad n = 1, \ldots, N_p \tag{2.1}$$

$$\frac{d\theta}{dt} = \omega_r \tag{2.2}$$

$$J\frac{d\omega_r}{dt} = \tau_m - B_r\omega_r - \tau_f\frac{\omega_r}{|\omega_r|} - \tau_l \tag{2.3}$$

where λ_n, i_n, and v_n are the flux linkage, current, and applied voltage of the nth phase winding, R_n is stator phase winding resistance, θ is rotor position, ω_r is rotor speed, J is total rotor and load inertia, N_p is the number of phases, τ_m is magnetic torque, B_r and τ_f are coefficients of viscous and coulomb friction, and τ_l is load torque[4]. Flux linkage of the *n*th phase, λ_n, is related to the *n*th phase inductance L_n by

$$\lambda_n = L_n(\theta)i_n \tag{2.4}$$

There is no mutual inductance term in (2.4) because the low reluctance of the stator makes flux linkage with other windings negligible[2].

To determine τ_m produced by a phase, an energy/coenergy analysis is used. Conservation of power for a magnetic system is

$$\frac{dW}{dt} = i\frac{d\lambda}{dt} - \tau_m\frac{d\theta}{dt} \tag{2.5}$$

The energy conservation law gives

$$dW = i\,d\lambda - \tau_m\,d\theta \tag{2.6}$$

where W is energy. Coenergy (W') is defined by the equation

$$\lambda i = W' + W \tag{2.7}$$

which leads to the coenergy conservation law

$$dW' = \lambda di + \tau_m d\theta \tag{2.8}$$

By holding i constant for the integration, the equation for torque becomes

$$\tau_m(\theta) = \left.\frac{dW'}{d\theta}\right|_i = \frac{d}{d\theta}\left.\left[\int_0^i \lambda(i',\theta)di'\right]\right|_i \tag{2.9}$$

Substituting (2.4) into (2.9) and integrating yields the equation for torque from a single VRM phase

$$\tau_m(\theta) = \frac{1}{2}\, i^2 \,\frac{dL(\theta)}{d\theta} \tag{2.10}$$

Net torque of the VRM is just the sum of individual phase torques.

VRM torque depends on the magnitude of the current and the rate of change of inductance with position, and the VRM always tries to align the rotor to the position of maximum inductance. The sign of the rate of change of inductance determines the sign of the torque. To produce a unidirectional torque, the control system must ensure each stator phase is energized during the period of rising inductance, and de-energized during the period of falling inductance. This unidirectional torque can be produced in either direction, depending on the order of phase excitation, as long as each phase is energized during the period of rising inductance.

VRM torque depends on inductance, which is a function of angular position. From basic magnetics, the equation for inductance of a phase is

$$L = \frac{\mu_0 N^2 A_c}{2g} \tag{2.11}$$

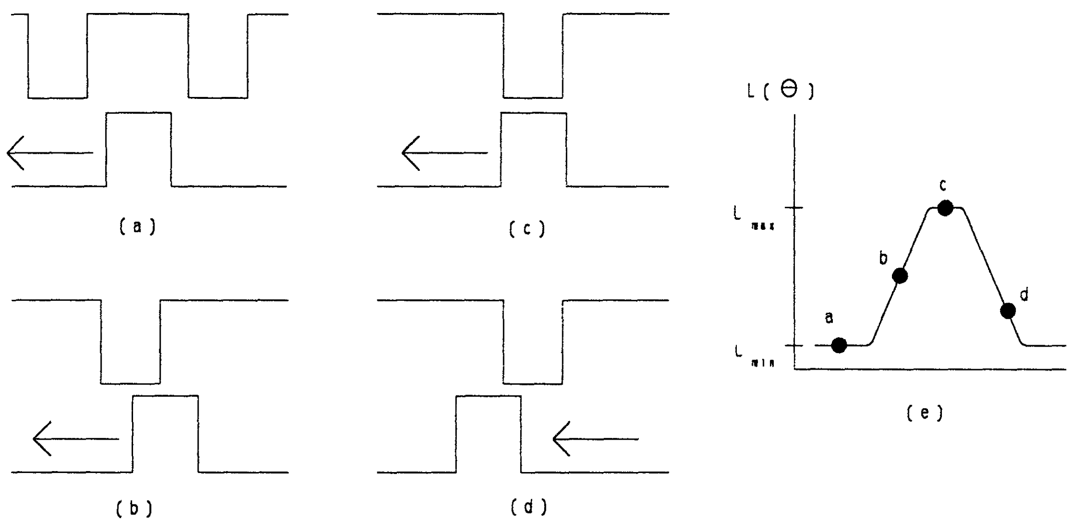

Figure 2.2 Idealized variation of phase inductance with rotor position. (a) Minimum inductance. (b) Inductance increasing linearly. (c) Maximum inductance. (d) Inductance decreasing linearly. (e) Inductance vs. position (not to scale).

where μ_0 is the permeability of free space, N is the number of turns, A_c is the cross sectional area of overlap between the stator pole and rotor pole, and g is the air gap length. When a stator pole and rotor pole are completely unaligned, g increases to an effective gap between the stator pole and the side of the nearest rotor pole, giving a small inductance. As the rotor turns, each phase's inductance can be in one of four conditions: (1) minimum when the poles are unaligned (L_{min}), as shown in Fig. 2.2(a); (2) increasing linearly when the poles' alignment is increasing, as shown in Fig. 2.2(b); (3) maximum when the poles are aligned (L_{max}) as in Fig. 2.2(c), and (4) decreasing linearly when the poles' alignment is decreasing, illustrated in Fig. 2.2(d).

2.2.2 VRM Practical Considerations

A VRM will not operate properly if connected directly to an ac or dc power

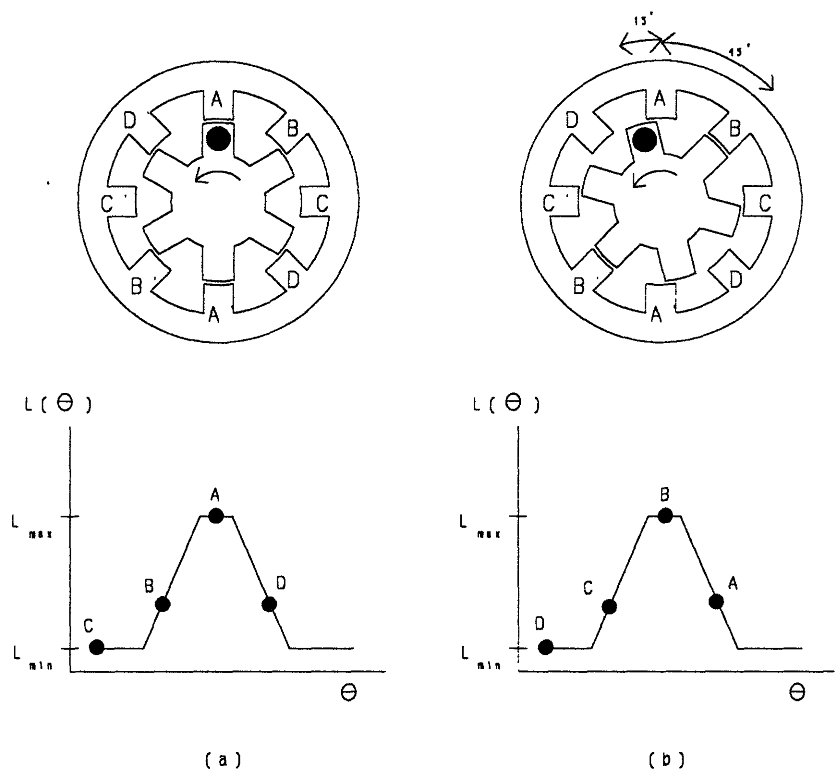

Figure 2.3 (a) Rotor position and inductance of the four phases with phase A aligned. (b) Rotor position and inductances for phase B aligned. The stator flux wave shifted 45° CW; the rotor turned 15° CCW.

source. Proper operation of a VRM requires a continuously active controller which energizes and de-energizes the stator phases at the proper rotor positions. Thus, a VRM requires a closed loop control system with position feedback to apply the stator mmf to each phase at the appropriate rotor position.

The direction of rotation of the VRM rotor is opposite to the direction of rotation of the stator phase excitation. If the stator phases are excited in a clockwise sequence, the rotor turns counterclockwise. Since the stator poles repeat every 45° and the rotor poles repeat every 60°, shifting from phase A to phase B forces the rotor to move only 15°. Figure 2.3 shows the phase inductance for all four phases with phase

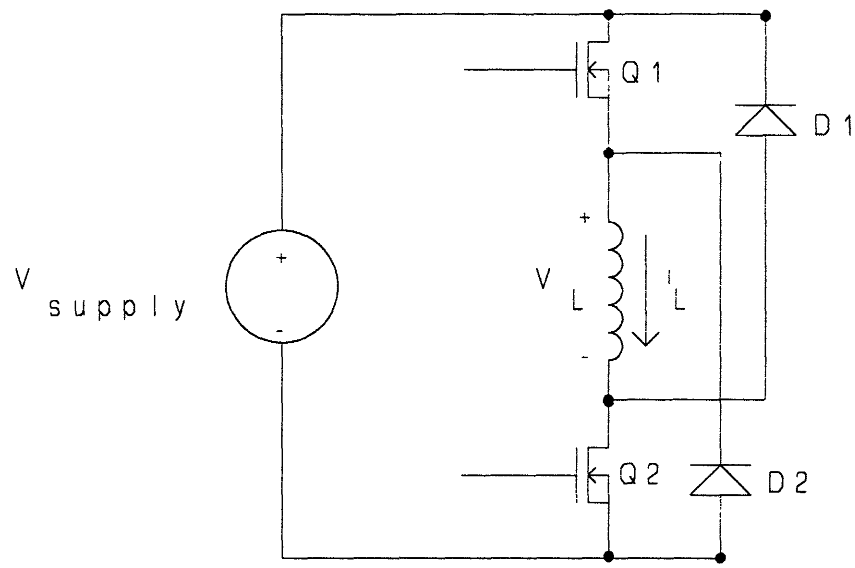

Figure 2.4 Simplified circuit for a single phase of the VRM inverter.

A aligned and then phase B aligned. For every complete revolution of the stator flux, the rotor turns only 1/3 revolution in the opposite direction.

2.3 VRM Inverter Operation

The VRM requires an inverter and control system to operate properly. VRM torque does not depend on current direction because of the i^2 term in (2.10). This allows the use of unidirectional current switches in the inverter. The basic inverter circuit for each phase consists of the phase winding, two field effect transistors (FET) with gate signals supplied by the controller, and two freewheeling diodes. Figure 2.4 shows a simplified circuit for one phase. Appendix A contains the wiring diagram for the inverter and all other circuitry. The inverter can be operated in two modes: normal and regenerative. This section describes the two modes of operation.

2.3.1 Normal Operation

The normal operating mode minimizes the amount of switching in the inverter. Switching accomplishes two functions: commutation between phases based on rotor position, and current chopping to maintain the desired phase current. The controller provides the current setpoint and on/off signals. The current setpoint defines a hysteresis band to maintain an average current at a user specified value. Refer to Fig. 2.4 for the following discussion of normal mode operation.

There are four possible states for the inverter:

State 1: Q1, Q2, D1, D2 off

State 2: Q1, Q2 on; D1, D2 off

State 3: Q2, D2 on; Q1, D1 off

State 4: D1, D2 on; Q1, Q2 off

Assume the initial condition is State 1 where all devices are off. At the proper position, the controller sends the ON signal, which forces State 2 by turning on Q1 and Q2. In State 2, $v_L = v_{supply}$ is applied across the phase winding, and i_L ramps up with the relationship

$$\frac{di_L}{dt} = \frac{v_L}{L} \tag{2.12}$$

At some point, i_L reaches the high current level defined by the hysteresis band. To prevent i_L from increasing indefinitely, the controller turns Q1 off, forcing D2 on, and the inverter enters State 3. The phase winding then begins discharging its magnetic energy by maintaining current flow through Q2 and D2. The discharge rate is again determined by (2.12), where the induced negative v_L is just the short circuit voltage drop across the two conducting devices, Q2 and D2. This small voltage drop allows current to ramp down slowly. When i_L reaches the low current level defined by the hysteresis band, the controller sends the inverter back to state 2 by turning on Q1. This current chop cycle repeats until the rotor reaches the off position, where the controller turns off Q1and Q2 and the inverter enters State 4. The phase winding discharges its magnetic energy by maintaining current flow, forcing D1 and D2 to turn on. The induced voltage across the phase winding is $v_L = -v_{supply}$, which allows i_L to rapidly ramp down to zero, at which point D1 and D2 turn off and the inverter returns to State 1.

The current chopping strategy used in the normal mode is called soft chopping, since only one of two transistors is switched to maintain current level. Q1 and D2 are called the "chop transistor" and "chop diode." Q2 and D1 are called the "commutation transistor" and "commutation diode" because they change state during commutation and not during current chopping. This distinction is arbitrary, because Q2 and D1 could do the chopping.

2.3.2 Regenerative Operation

The regenerative operating mode produces a higher switching frequency than the normal operating mode. Both FETs are switched together for chopping and commutation. Refer to Fig. 2.4 for the following discussion of the regenerative mode.

There are three expected states for the inverter:

State 1: Q1, Q2, D1, D2 off

State 2: Q1, Q2 on; D1, D2 off

State 3: D1, D2 on; Q1, Q2 off

Assume the initial condition is State 1 where all devices are off. As in the normal mode, Q1 and Q2 are turned on by the controller at the proper position to produce torque, and the inverter enters State 2. At the high current level, current chopping is accomplished by turning both Q1 and Q2 off, forcing the inverter to State 3. The negative voltage $-v_{supply}$ is across the phase winding, causing i_L to rapidly ramp down by the relationship in (2.12). At the lower current level, the controller turns on both FETs and sends the inverter back to State 2. The two states where one FET is on and the other is off are possible due to unequal circuit delays; these cases would cause a temporary condition like State 3 of the normal mode where the phase winding discharges through one FET and one diode until the other FET responds to its gate control signal. At the turn off point, the inverter is sent to State 3 where it remains until the phase winding has discharged completely. When there is zero current through the diodes, the inverter returns to State 1 to wait for the next ON signal from the controller.

The current chopping strategy used in the regenerative mode is called hard chopping. Chop frequency is higher than in the normal mode since i_L ramps down faster during chopping. The mode is called regenerative because the phase winding returns energy to the dc supply's capacitor during chopping.

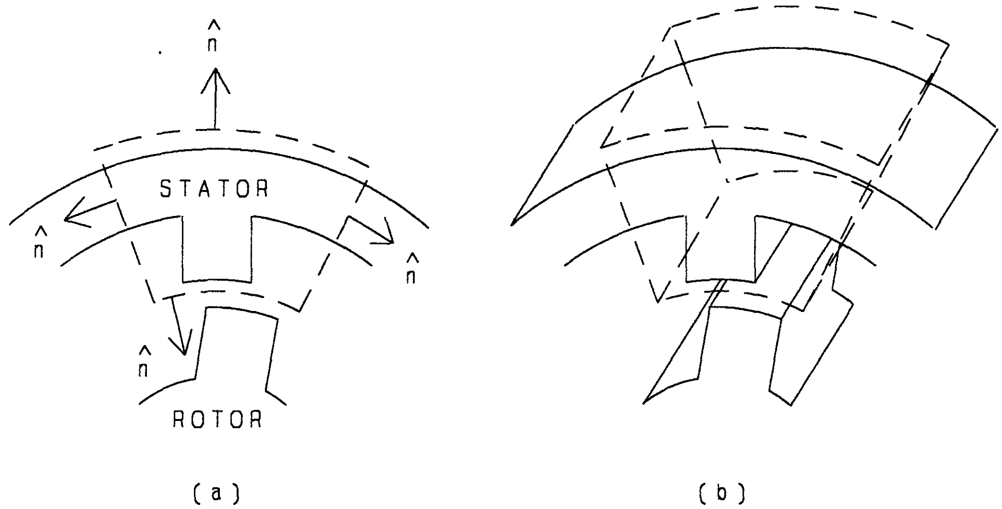

Figure 2.5 (a) 2D view of closed surface for calculating forces on the stator. Normal directions shown in radial and tangential directions. (b) 3D view of closed surface.

2.4 VRM Acoustic Noise

A VRM is a noisy motor[1,4,5,11]. Two basic factors contribute to this noise: the doubly salient construction of the rotor and stator, and the frequency components of the phase current.

2.4.1 VRM Noise Sources

A doubly salient VRM is noisy for a very simple reason: the strong pulsating radial magnetic forces cause frame distortions which are transmitted to the surroundings as acoustic noise. A singly salient VRM is less noisy, but also produces less torque.

Cameron's experimental work showed that radial vibrations of the stator are the dominant noise source in the VRM[4,5]. Maxwell stress tensor analysis can be used to determine the equation for the radial forces on the stator. Figure 2.5 shows the surface used for the integration. The closed surface surrounds a stator pole, and is conveniently chosen so that its surfaces are perpendicular to the longitudinal, radial and tangential directions. Some reasonable assumptions simplify the derivation. The flux in the air gap is radially directed, and uniform where the air gap is uniform. The flux is negligible where the poles are not aligned. Fringing effects are ignored, and the permeability, μ, of the stator and rotor is infinite compared to μ_0. This leaves a component of the magnetic field intensity H in the radial direction only, H_r.

The net force f on the surface in any direction m can be described by the equation

$$f_m = \iint_{closed\ surf} \mu_0 (H_m H_n - \frac{\delta_{mn}}{2} H_k H_k)\ \hat{n}\ d\vec{S} = \iiint_V F_m \hat{i}_m dV \quad (2.13)$$

where H is the magnetic field intensity, δ is the Kronecker delta, $\hat{i}_m$ is the unit vector in the m direction, $\hat{n}$ is the outward pointing normal, and F_m is the force density. Given the above assumptions, the only nonzero force is in the radial direction, and (2.13) simplifies to

$$f_r = \iint_{closed\ surf} \frac{\mu_0 H_r^2}{2} \hat{i}_r\ \hat{n}\ d\vec{S} \quad (2.14)$$

The normal vector $\hat{n}$ points toward the center and the unit vector $\hat{i}_r$ points away from the center, so the dot product produces -1. The surface integral reduces to the surface between the rotor and stator pole, with the area dS equal to $A_c(\theta)$ which is the cross sectional area of overlap between the stator and rotor poles.

The radial force can be related to circuit parameters by making the substitution

$$H_r = \frac{Ni}{2g} \tag{2.15}$$

where N is the total number of turns on the phase (including both poles), i is the current through the phase winding, and g is the air gap length between a stator and rotor pole. Substituting (2.15) into (2.14) yields the equation for the radial force on the stator pole

$$f_r = -\frac{\mu_0 A_c(\theta) N^2 i^2}{8g^2} \tag{2.16}$$

The result of (2.16) is that the stator poles are pulled toward the rotor when that phase is energized. Cameron's experimental results show that the net deflection is on the order of a micron for the experimental VRM used in this thesis. The modes of vibration also affect the acoustic noise. Three modes of mechanical resonance in the acoustic range exist for the experimental VRM: single ovalization at 2604 Hz, double ovalization at 9200 Hz, and a uniform expansion/contraction or breathing mode at 14200 Hz. Figure 2.6 shows the three modes.

2.4.2 Inverter Drive Contributions to VRM Acoustic Noise

The inverter control strategy used to drive the VRM also affects acoustic noise emissions. In broad terms, the frequency of the applied signal excites mechanical frequencies of the stator to produce noise. From (2.16), i^2 is a factor in determining the magnitude of the radial vibrations of the stator. Current is supplied to the VRM by the inverter, so the inverter must have an effect on stator vibrations and hence

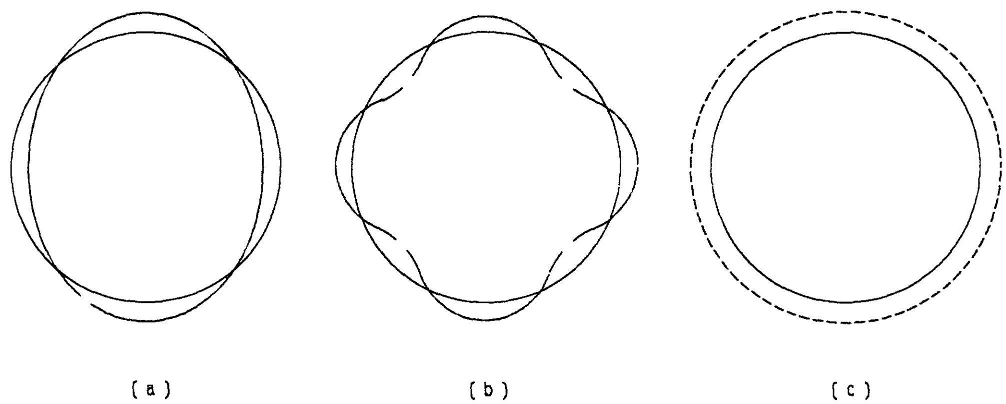

Figure 2.6 Stator vibration modes. Dashed lines show the deformations (not to scale). (a) Single ovalization of the stator. (b) Double ovalization of the stator. (c) Breathing mode of the stator.

acoustic noise. If the inverter coherently excites the stator's resonant frequency, the acoustic noise will be higher. The other variable is the sensitivity of the human ear; frequencies out of range of human hearing are not troublesome, while frequencies near the average ear's maximum sensitivity in the vicinity of 3kHz are of considerable concern.

The major contribution of the inverter drive to VRM acoustic noise comes from the current commutation frequency. For the 8/6 VRM, the fundamental frequency of each phase is 6 times the rotor speed. Each phase commutates on and off for each rotor pole passage, thus with 6 rotor poles a stator phase winding undergoes 6 current fundamental periods per revolution. The fundamental mechanical excitation of the VRM as a whole occurs at 24 times the rotor's rotational speed (6 poles x 4 phases). The use of unidirectional current switches gives double the excitation frequency of

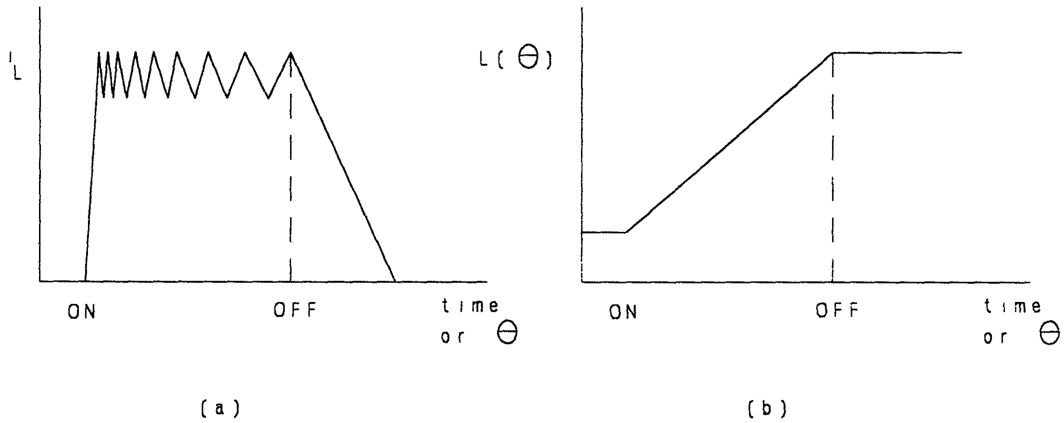

Figure 2.7 (a) Plot of current vs. time (position) during the time a phase is energized. The scale is exaggerated for clarity to show the decrease in frequency as inductance increases. (b) Plot of inductance vs. time during the same period.

bidirectional current switches.

Experiments on an 8/6 VRM have shown that, although the predominant noise peak always occurred in the same frequency band regardless of speed or load, lower levels of noise did occur at 24 times the speed. The predominant noise peak corresponds to a mechanical resonance of the stator. Additional noise components were observed at integer multiples of the fundamental pulse frequency[10].

Another contribution of the inverter drive to VRM acoustic noise is the current chop frequency. This frequency is significantly higher than the commutation frequency, with the regenerative mode producing a higher frequency than the normal mode. It must be noted that the current chop frequency is not a constant. From (2.12), the time derivative of i_L is inversely proportional to phase inductance for a given v_L. Since L is a function of position, and increases while the phase is energized and pulling the rotor pole into alignment, the instantanteous chop frequency decreases as pole overlap increases. Figure 2.7 illustrates the changing chop frequency with increasing inductance. If the switching frequency of the inverter during current chopping is in the audio range, as in the laboratory setup, then current chopping also contributes somewhat to acoustic noise.

Some research has attempted to quantify the contribution of an inverter to motor noise. In general, non-sinusoidal voltages applied to a motor's phase winding produce higher acoustic noise than sinusoidal voltages produce[12,13]. These non-sinusoidal voltages produce harmonics which excite different modes of stator distortion. Much of the research comes to the same conclusion: when a harmonic of a non-sinusoidal phase voltage coincides with a spectrum component of the electromagnetic noise produced by the motor at a natural frequency of the stator, a high noise level results[12,13,14]. Based on this research, the inverter drive plays an important role in determining motor acoustic noise.

The work in this thesis investigates acoustic noise generated from commutation of the stator phases. This noise is in the range of human hearing. At a rotor speed of 5000 rpm the fundamental frequency of the VRM is 24 times higher at 2 kHz. Several harmonics of the commutation frequency also fall within the range of human hearing. The contribution of current chopping and the inverter to acoustic noise is also a consideration, even though it is at a lower dB level than the commutation noise. Its frequency, which is a function of supply voltage, phase inductance, and chopping method, could possibly be more annoying to the human ear than commutation noise.

There is some evidence that soft chopping produces less acoustic noise than hard chopping. There is also some evidence that using voltage pulse width modulation (PWM) instead of current chopping produces quieter operation[11]. All experiments in this thesis were conducted using hard or soft current chopping.

There are many potential benefits of a reduction in a motor acoustic noise through randomization, and there is more research to be done. If a VRM or any other motor can operate quieter through changes in its control system, there is no need for an expensive mechanical redesign. Another solution to noise problems in use today is increasing inverter switching frequency, which increases switching power losses. This thesis demonstrates the effects of randomization of the commutation points on acoustic noise.

Chapter 3

CONTROLLER OPERATION

The controller for the VRM laboratory setup incorporates hardware and software to send the appropriate signals to the VRM inverter. The main element of the control system is the Motorola 68332 Microcontroller Unit (MCU). It performs real-time calculations to implement randomization schemes based on user input. The MCU and controller hardware provide ON and OFF signals to inverter FET gate circuits, thus controlling VRM phase currents and torque.

The necessity of position feedback and current chopping for proper VRM operation is described in Chapter 2. The control system for the VRM uses two feedback loops to accomplish these functions. A digital outer loop provides the commutation ON and OFF signals, while an analog inner loop regulates the phase currrents for the active phases. In the outer loop, MCU software determines the ON and OFF points for each stator phase using position feedback from the VRM via an optical shaft encoder. An IBM XT personal computer provides a user interface to the MCU. Figure 3.1 shows a block diagram of the major components of the VRM

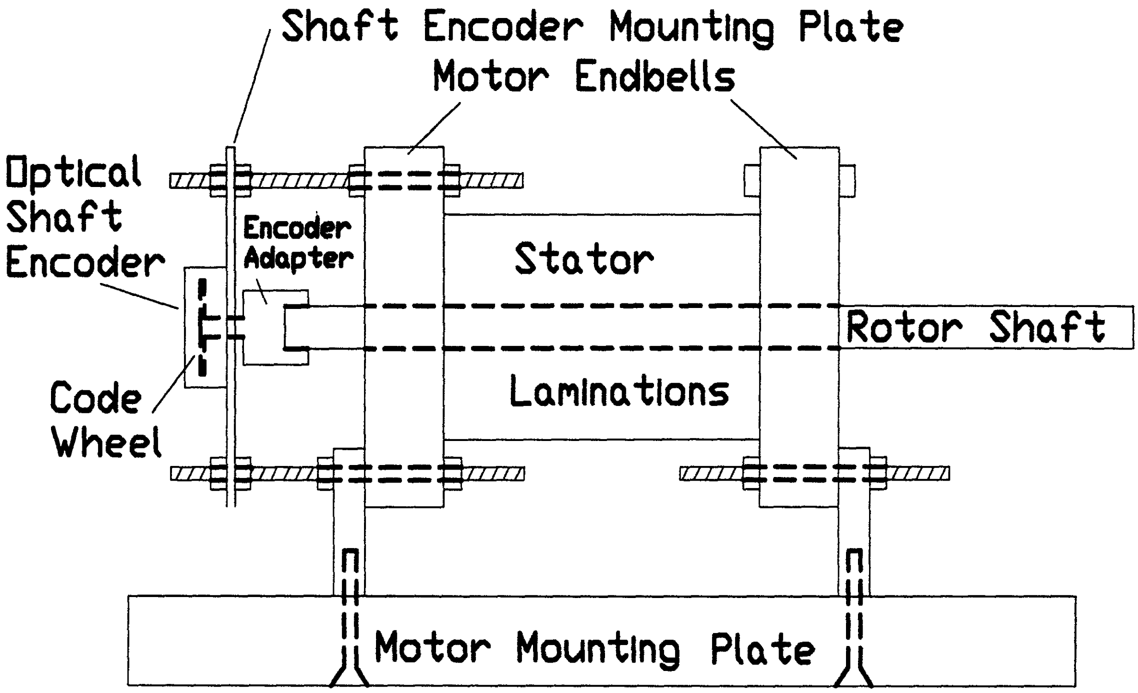

Figure 3.1 Block diagram of the VRM laboratory setup including inverter, control system and user interface.

laboratory setup. Appendix A contains circuit wiring diagrams. The rest of this chapter describes the elements that form the control system.

3.1 Optical Shaft Encoder

A Hewlett Packard HEDS-5000 optical shaft encoder provides the position feedback necessary to determine rotor position. The stationary body of the encoder is mounted on a plate which stands off 2 inches from one end of the VRM. A code wheel is mounted on the rotor shaft, and positioned inside the body of the shaft encoder. Figure 3.2 shows the mounting of the shaft encoder. The shaft encoder uses three light emitting diodes (LEDs). Collimated light from the LEDs passes through slots in the code wheel to photodiodes, which produce three output signals called channels A, B, and I. The LEDs and photodiodes for Channel A are offset from those for Channel B, while sharing the same slots, to produce square wave outputs in quadrature (phase difference of 90 degrees). Although it is possible to produce 800 pulses per revolution from the 200 mechanical slots in the code wheel by a logical XOR of channels A and B, only 200 pulses per revolution are used, as explained in Section 3.2.1.

The best angular resolution from the shaft encoder of 0.45 mechanical degrees per revolution was considered too low to allow a variety of randomization schemes.[1] Because the range of increasing inductance for each phase covers only 21 mechanical degrees, variations of ON and OFF points up to only 2 degrees were permitted.[2] The best shaft encoder resolution would allow only five possible states for a 2 degree variation. Code wheels with more slots were available, but a better solution was to use MCU features which provided a much greater resolution. Section 3.2.1 describes how the MCU further divides the position count to achieve high resolution. An MCU limitation only allows the use of one channel for position count. Channel A is not used, and Channel B gives a position count resolution of 1.8 mechanical degrees from the shaft encoder.

Channel I, the third output channel from the shaft encoder, is an index signal which produces a pulse only once per revolution. It uses slots at a different radius

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[1]360 deg/rev * 1 rev/800 slot

[2]Uniform variation of the ON point by only 2 degrees from the nominal ON point would reduce average torque by about 5% (1 degree/21 degrees) for a given current level. Chapter 4 describes this in more detail.

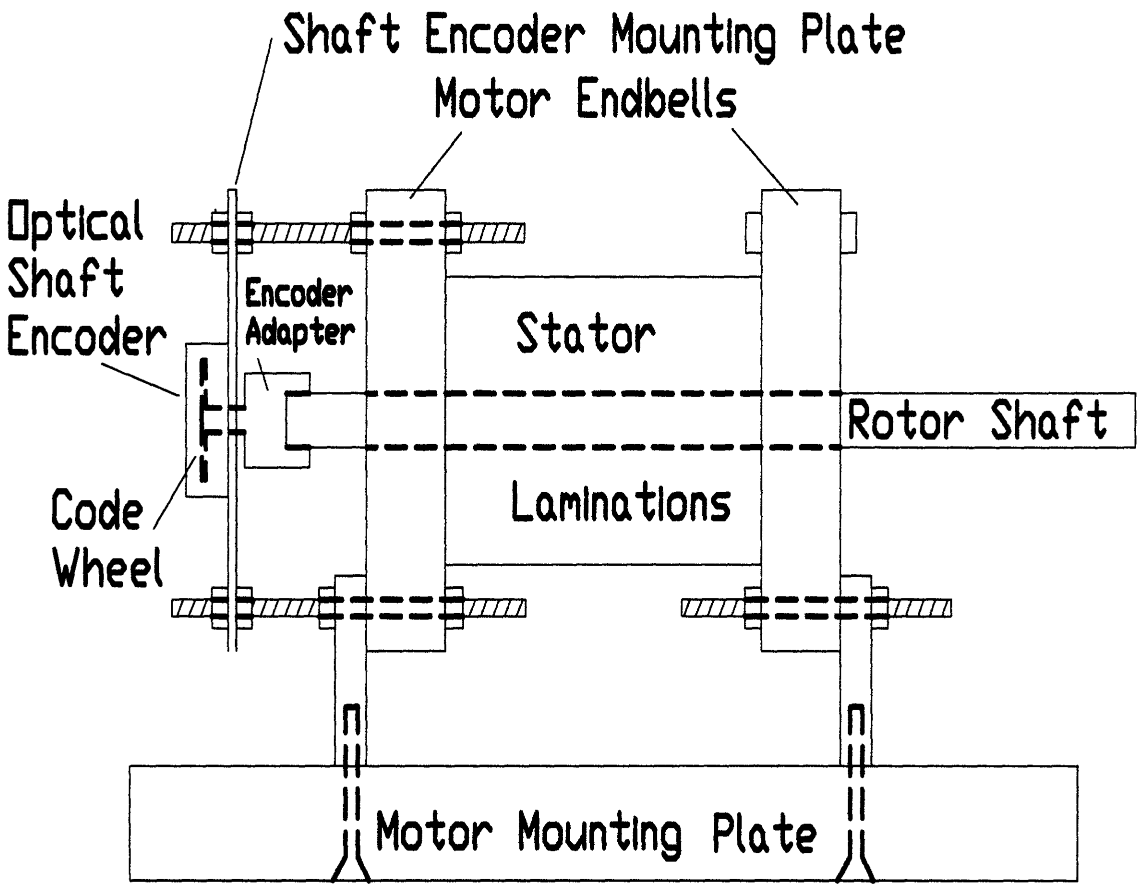

Figure 3.2 Side view of VRM showing shaft encoder mounting

than those for channels A and B. By resetting the cumulative pulse count from channel B to zero every time an index pulse is detected, correlation is achieved between rotor position and pulse count. The pulse counts corresponding to alignment of each rotor pole with each stator phase were determined using a separate circuit containing an up/down counter with a reset. The phases were energized one at a time, the rotor was moved to the six positions of maximum alignment for the phase, and the count recorded. The unaligned positions were determined from the aligned positions and motor geometry, because the unaligned positions are positions of unstable equilibrium.

3.2 Motorola 68332 Microcontroller Unit (MCU)

The MCU used in the laboratory setup is part of a promotional evaluation system developed by Motorola, the Motorola 68332EVS. It sits on a platform board that contains the MCU, one parallel and two serial RS-232 compatible input/output (I/O) ports, 32k x 16 bit random access memory (RAM), 64k x 16 bit erasable programmable read only memory (EPROM), and convenient pinout logic analyzer connections that fit standard connectors. The assembler and In Circuit Debugger (ICD) used in controller development were provided by P&E Microcomputer Systems, Inc., of Woburn, Massachusetts.

The MCU contains separate stand-alone modules which provide functions that facilitated design of the control software. These modules operate independently, simultaneously with the Central Processor Unit (CPU). Most of the MCU's modules were not used in the final design. The Serial Control Interface (SCI) allows communication between the MCU and IBM XT via an RS-232 connection using communication interface software contained in the ICD. The time-related requirement for randomizaton was fulfilled by using the Time Processor Unit (TPU). This module provides the phase commutation signals and is described in the next section. References [15]-[17] are reference manuals for the MCU.

3.2.1 Time Processor Unit Operation

The TPU contains 9 separate timing functions for control of external devices. These functions can be programmed on any of the 16 available TPU channels. Two functions of the TPU are used to produce the phase commutation signals. Channel 0 uses an input signal derived from the shaft encoder, and operates in the Period Measurement with Missing Transition Detection mode (PMM). This function mode allows measurement of the pulse period between normal, regularly occurring input transitions. Pulses from the shaft encoder provide the single input signal, with channel B and channel I signals logically NANDed to produce a regular pulse train with a missing transition once per revolution. This missing transition allows the TPU to determine its position every revolution and at startup. The TPU module is designed for angle-based engine control, and with appropriate software can be used to implement myriad randomization schemes.

The critical parameter for the TPU is the pulse period, which is 1/200th of a revolution. Each pulse period represents 1.8 mechanical degrees, with 199 pulse periods and one missing transition per revolution. The pulse period measurement is a 23 bit count of clock cycles between shaft encoder position pulses, stored in register TCR1. A separate register (TCR2) counts shaft encoder position pulses from 0 to 198, and resets whenever the missing transition is detected. The missing transition is detected by a delay between input pulses, with the delay trigger set in software to 1.5 pulse periods. The previous pulse period is always used for calculations, allowing the MCU to respond accurately to speed changes and speed ripples.

Eight TPU channels are used to produce the ON and OFF signals for the four stator phases. Channels 1 through 8 operate in the Position-Synchronized Pulse Generator (PSP) mode. Once initialized and synchronized to the input pulse sequence, the PSP function continually generates output pulses based on ANGLE and RATIO parameters. For each PSP channel, ANGLE is the position count corresponding to the ON (or OFF) point. The ANGLE register has only 8 bits, which makes 256 the maximum allowed number of pulses per revolution. For this reason, only 200 of the 800 possible pulses per revolution from the shaft encoder were used for position count.

Each PSP timing function uses a fractional multiply to resolve position down to a precise angle. RATIO holds the value for calculating a fraction of a pulse period for ON and OFF point angle resolution. When the count in TCR2 matches the position indicated by ANGLE, RATIO is used to determine when the channel should output a control signal pulse. The 8 bits in RATIO divide two pulse periods into 256 positions, using the previous pulse period measurement from TCR1. This fractional multiply increases resolution to 1/128 of 1.8 mechanical degrees, which is sufficient to implement randomization schemes. The PSP output pulses are sent to a flip-flop whose output controls phase commutation. The duration of the control signal output pulse from a PSP channel is one pulse period, and the signal is used to PRESET or CLEAR a D flip-flop. The flip-flop stores the phase's commutation state.

Each phase of the VRM is turned on and off six times per rotor revolution, as discussed in chapter 2. Thus, ANGLE and RATIO parameters for each phase's ON and OFF points are updated six times per revolution. Nominal ON and OFF points are stored in a table in the controller software. Randomization schemes are implemented on a real-time basis by adding to or subtracting from the nominal ON and OFF points for each phase, and placing the values in the ANGLE and RATIO registers while the phase is off.

3.2.2 Software Development

The software used in the control system was developed using the ICD, which allows parallel communication between the MCU and IBM XT for downloading programs and debugging. A separate serial communications cable allows user interface with the MCU by using the IBM XT as a dumb terminal. Appendix B contains a program listing of all MCU software.

The hardware features of the MCU TPU described in section 3.2.1 minimize the operations that the software has to perform. The MCU clock rate of 16.78 MHz is high enough that the 24 sets of calculations required for randomization of the ON and OFF points for all phases each revolution can be accomplished in real-time. Calculations for a phase's subsequent ON and OFF positions are conducted during the opposite phase's ON period. The calculations are initiated by TPU generated interrupts. Phases A and C are opposite, as are phases B and D. Randomization schemes and the timing sequence of the phases are described in chapter 4.

Software is used to allow user input to the MCU. In the initialization routine, the MCU prompts the user to select which pre-programmed randomization scheme to use. Choices are described in Chapter 4. The control software is designed such that the laboratory setup is a general test bed for applying randomizations schemes. Additional randomization schemes can be inserted with minimal effort.

3.3 Controller Hardware

Controller hardware consists of two separate circuit boards, which combine to send signals to the FET gate drivers on the inverter board. The MCU interface board's sole purpose is to provide electrical isolation between the MCU and other hardware. The inverter controller board is a modification of the current-mode controller hardware developed by Cameron[4]. Phases A and C share much of the same controller hardware, as do phases B and D, which reduces the amount of hardware required. This arrangement is possible since opposite phases are never on at the same time.

3.3.1 MCU Interface Board

The MCU interface board provides electrical isolation between the MCU and logic/analog circuitry on the Inverter Controller board. It uses Darlington optocouplers, which have a relatively fast response time of 40 nsec.

Signals that could be defined in software were eliminated in the late stages of design to minimize the number of optocouplers. In the initial design, an eight bit digital to analog converter allowed setting the current chop level through the user interface to the MCU. Electrical isolation would have required eleven optocouplers, and was not cost effective. The eight TPU channel signals are coupled from the MCU to the Inverter Controller, and the index signal and PMM signal are coupled from the Inverter Controller to the MCU.

3.3.2 Inverter Controller Board

The inverter controller board contains the shaft encoder connection to the VRM, current chopping and commutation hardware. It produces the gate control signals for the FET gate drivers. It uses a sampled hysteresis control scheme to control motor phase current. The feedback loop for current chopping is composed of analog hardware. Linear Hall effect sensors are used to detect motor phase currents. Opposite phases share Hall effect sensors and current chopping circuitry. Each hall effect output is a voltage level, which represents current level feedback from the VRM. Inverter mode is set to normal or regenerative with a toggle switch. The current chop setpoint is determined by a potentiometer.

Eight outputs from the MCU TPU channels configured for the PSP function are sent to the MCU interface board. These signals either preset or clear the flip-flop for the proper phase. The four outputs from these flip-flops are the phase commutation signals, where a logical 1 means ON and a logical 0 means OFF. These commutation signals are combined with the current chopping signals to control the FET gate drivers.

Current chopping is achieved by comparing the present current level to the setpoint. The output of the Hall effect sensor with zero current through it is nominally 6V. The current setpoint reference level is set to match the Hall effect sensor zero current output voltage using a potentiometer. Current chop level is set with a second potentiometer, with a voltage scale of 0.24 volts/amp to match the sensitivity of the Hall effect sensors. The current chop level is added to the current setpoint reference level to produce the voltage necessary to cause current chopping. Actual current level and inverted current setpoint signals are summed and sent via buffer stages to a flip-flop. At the current limit, the flip-flop input is pulled low, and the next inverter controller clock pulse places a logic 0 at the output to turn off the appropriate FETs.

As current falls, and Hall effect sensor voltage falls below the setpoint voltage, the Schmitt trigger output changes to set the flip-flop. The Schmitt trigger hysteresis band represents 0.2 amps. Flip-flop clock frequency is set to 30 kHz. Flip-flop output is logically combined with the mode and commutation signals to send the appropriate ON and OFF signals for each FET to the inverter board.

The Inverter Controller gives a FET an ON (OFF) signal when three conditions are met: (1) the commutation signal from the microprocessor indicates the phase should be on (off), (2) the current chop circuitry indicates the current is below (above) the setpoint, and (3) the mode control switch indicates the FET should be turned on (off).

3.3.3 Inverter Board

The inverter board contains the 4 phase inverter circuits described in section 2.3, gate drivers for the FETs, optocouplers for electrical isolation, and the Hall effect sensors. One IR2110 gate driver per phase provides gate signals to the low and high side FETs. Each gate driver has a floating power supply for the high side FET. The optocouplers between the Inverter Controller board and Inverter board give the VRM circuitry a third separate ground. Thus, power ground is separated from logic ground which is separated from MCU ground.

The IR2110 is very sensitive to inductance in its output circuit. In the initial layout of the inverter board, leads between the IR2110s and the FETs were too long and placed too much inductance in the gate signal path. When an IR2110 received an ON signal from the inverter controller board, it tried to produce a 15V gate signal.

This step change in voltage caused ringing, and the oscillation triggered an undervoltage lockout in the IR2110 which reset the gate signal to zero and turned off the FET. This problem was solved by four changes to the initial inverter design: 1) The inverter board was rewired and the IR2110s physically placed very close to the FETs to minimize lead inductance. 2) Gate resistors were added to damp LC oscillations during turn-on, with parallel diodes for quick turn-off. 3) Tantalum and ceramic disk capacitors in parallel were placed across the low and high side IR2110 power supplies for better high frequency response. These capacitors were physically placed very close to each IR2110. 4) Each high side voltage source was changed from a bootstrap capacitor to a transformer with rectifier.

3.4 Fault Tolerance

The fault tolerance of the VRM and its associated controller is considered high compared to that of other motor drives for a couple of reasons[11,18]. First, the power electronics for each phase are completely independent from the power electronics for all other phases. The VRM can still produce torque with a fault in one or more phases if the rotor's inertia allows the rotor to rotate through the position where the faulted phase or phases would be the only source of torque. Operation would be degraded because of an increase in torque ripple.

Inverter design plays a role in VRM fault tolerance. In ac inverters used in other motor drives, the high and low switches (FETs or some other device) are connected in series between the dc supply's low and high rails. A fault which shorts a switch also shorts the dc power supply when the other switch turns on. In the VRM's inverter, a shoot-through path does not exist with a switch failure because a stator phase lies between the switches. A short circuit fault in the high or low switch places dc supply voltage across the phase winding without affecting power to the other phases. Separate fuses for each phase ensure that the other phases can continue operation in the event of a short circuit fault in one phase, of one FET in the normal mode or both FETs in the regenerative mode.

Another reason for the VRM's high fault tolerance is the lack of rotor excitation. The rotor does not follow a rotating mmf that produces torque as in an ac motor. If there is a fault in one phase, the other phases continue to operate unaffected. Because the rotor has no field winding or permanent magnet, there is no generated voltage induced in a stator phase when it is open-circuited[11,18].

Chapter 4

RANDOMIZATION SCHEMES

The use of various randomized switching functions and their effects on power electronic converters and motor drives has been the topic of much recent research[6,7,8,19]. This thesis quantifies the effect of several different randomization schemes on the acoustic noise produced by an experimental VRM. A common framework for applying randomization schemes is presented in this chapter. Terminology and definitions provided in this chapter are used in Chapter 5 to describe the experimental results.

4.1 Commutation Points

The position feedback of the controller described in Chapter 3 provides the commutation signals at the ON and OFF points. When a phase is on, it produces unidirectional torque and its current is limited by the current chopping hardware. When a phase is off, it does not contribute to torque.

4.1.1 Nominal Timing Between Phases

In the 8/6 VRM used in the experiments, at least one phase is always energized

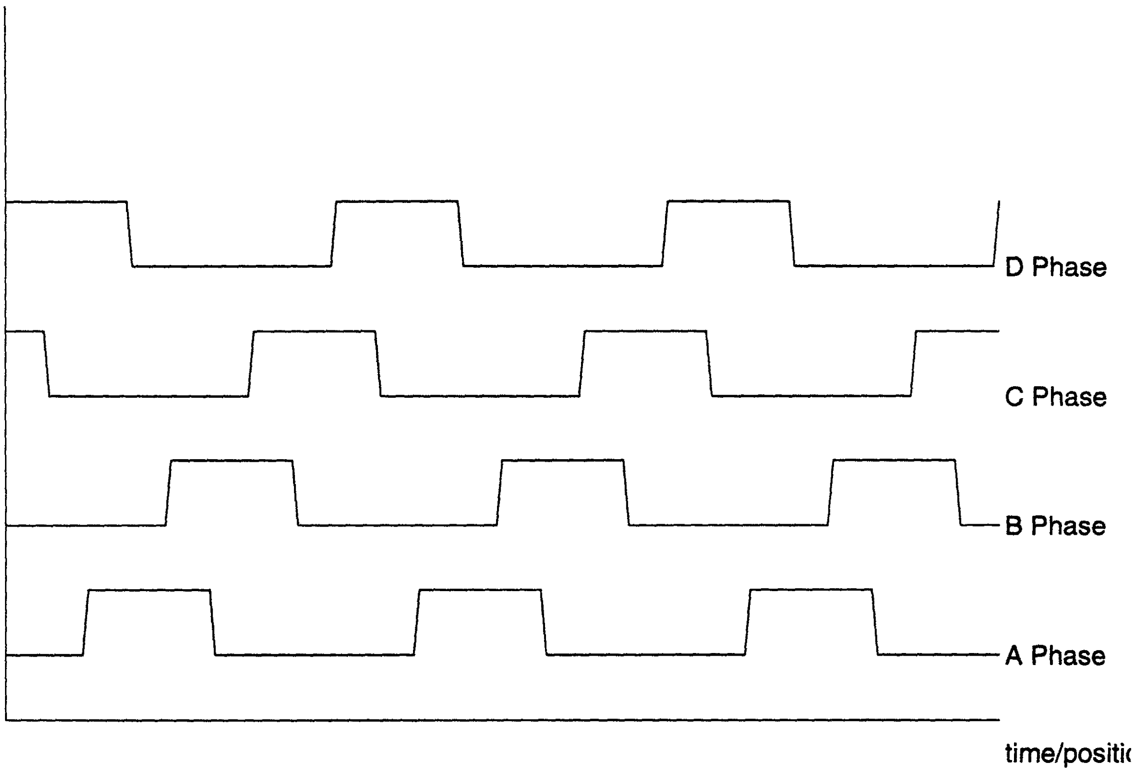

Figure 4.1 Nominal timing relationship between the control signals for the four phases.

while the VRM is operating. Two phases are energized at the same time during an overlap period. Only one phase is energized 60% of a revolution, and two phases are energized for the other 40% of a revolution. Figure 4.1 shows the nominal timing relationships between the four phases.

Note that phases A and C are opposite; only one of them is energized at a given time. Phases B and D are also opposite. Angular separation between the OFF point of one phase and the ON point of its opposite phase is nominally 9 mechanical degrees. This separation allows randomization of both ON and OFF points without energizing opposite phases at the same time. If dc supply voltage is relatively low and the current setpoint is relatively high, the discharge rate of a phase at the OFF point could be slow enough that opposite phases have non-zero current flow at the same time. This is undesirable for two reasons: 1) the phase turning off is producing negative torque, and 2) the shared Hall effect sensor could cause the on phase's current to chop at less than the current chop setpoint because of the addition of the current from the phase turning off.

4.1.2 Nominal ON and OFF Points

A simplified description of VRM operation is presented in Section 2.2. In Fig. 2.7, the nominal ON point is shown at the transition between the unaligned position and the region of increasing overlap of the stator and rotor poles. However, there are other considerations which give more desirable relative positions for the nominal ON and OFF points.

The nominal ON point has a significant effect on torque, but can have a small effect on acoustic noise. To understand this, suppose that phase A is off and all rotor poles are in the unaligned position with respect to phase A. Inductance for phase A is minimum per the discussion in Section 2.2. The major source of acoustic noise, as discussed in Section 2.4, is radial vibrations of the stator. The radial force which causes these vibrations, from (2.16), is inversely proportional to the square of the air gap length (g^2). Thus, when the phase A is not aligned with any rotor pole, energizing it would not produce any significant radial force. Phase A could be energized at any point while it is unaligned without contributing any significant acoustic noise.

Continuing with the phase A example, if phase A is turned on while it is in the unaligned position, its low inductance forces a high rate of current rise based on

(2.12). When a rotor pole begins overlapping phase A, current could already be chopping, which would allow maximum torque production per (2.10).

The case for the nominal OFF point is basically the opposite of the case for the ON point. Current through the phase when inductance is maximum (at the position of maximum alignment) does not contribute to torque. If current is still present when pole alignment starts decreasing from maximum, a negative torque is produced. Additionally, the larger inductance at maximum alignment gives a longer time constant (L/R), which could also contributes to phase current being present when alignment starts decreasing. This was observed during initial experiments with low voltage (30V), high current (4A) and no mechanical load on the VRM at approximately 1500 rpm. When the current chop level was decreased, with no change to voltage or controller operation, VRM speed increased.

Current through the phase at maximum alignment affects acoustic noise, because the radial force on the stator is at its maximum value. When the phase is turned off, the radial force decreases as current falls, which contributes to stator vibration. There is experimental evidence to support the conclusion that the OFF point transient produces more acoustic noise than the ON point transient or current chopping[20].

The optimum case for the ON point which gives maximum torque production and minimum acoustic noise is to have the ON point during the unaligned position, allowing current to begin chopping by the time inductance starts to rise as the poles begin aligning. Randomizing the ON point in the unaligned position has little effect on acoustic noise because of the small radial forces. Randomizing the ON point over a range of increasing alignment decreases the power delivered by the phases.

The optimum case for the OFF point is to turn the phase off while the stator pole is completely overlapped by the rotor pole, and early enough that phase current has enough time to decrease to zero before pole alignment starts to decrease. Randomizing the OFF point varies the spectral content of the stator vibrations, and the effects on acoustic noise are described in Chapter 5. For the reasons discussed above, most of the randomization schemes involve dithering the OFF point. References [11] and [21] further discuss these issues.

4.2 Randomization Terminology

A standard terminology is introduced here to allow comparisons between the different randomization schemes. The terminology used is taken from [8], [22] and [23]. All randomization schemes begin with the same information, the nominal ON and OFF points for each phase. How these ON and OFF points are changed during randomization defines the type of randomization.

4.2.1 Waveform Description

All the randomization schemes used in the experiments are periodic, with the period for each phase equal to 1/6 of the time per revolution. If one makes the simplifying assumption that torque ripple is negligible, the period is equal to the time between successive nominal ON (or OFF) points. The start of each period is referenced to an arbitrary point in the cycle such that the phase control signal's 0-1

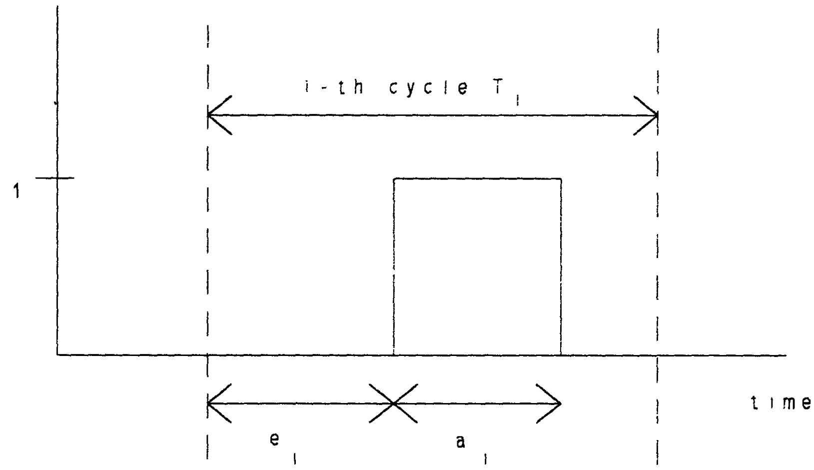

Figure 4.2 Classification of basic random switching terminology.

transition at the ON point and 1-0 transition at the OFF point are completed somewhere in the middle of the period.

Three parameters are necessary to describe the basic switching cycle. Figure 4.2 shows their temporal relationship during an arbitrary *i*-th cycle. Let T_i be the duration of the *i*-th cycle. The position of the ON point in the *i*-th cycle is given by e_i, and the on-time is given by a_i (the time between the ON and OFF points). This gives a duty ratio $d_i = a_i/T_i$. These definitions are rigorous for the phase control signals, but are only an approximation of the current waveform. Each control signal transition defines a phase commutation ON or OFF point, but does not show the current chopping that occurs between the ON and OFF points. Chopping is influenced by the hysteresis set in the controller hardware. Only the timing of the ON point and OFF point are well-defined, because the rise and fall times of current during commutation and chopping are variable. Randomization schemes tested in this thesis only alter the commutation points; the current chop hysteresis band is not changed.

In general, e_i, a_i, or T_i can be dithered, either individually or simultaneously. Randomization schemes in the experiments do not explicitly attempt to dither T_i, although dithering of T_i is unavoidable to some extent because of torque ripple in the operation of the VRM. Combinations of e_i, a_i, and T_i used in the experiments are described in the next paragraph.

The randomization schemes are described by the effect of dithering on e_i and a_i, ignoring the inevitable changes in T_i with torque/speed ripple. The titles with defined acronyms use standard terms in literature.

- Random pulse width modulation (PWM): e_i fixed, a_i changes.
- Random pulse position modulation (PPM): e_i changes, a_i fixed. The ON and OFF points are varied by the same amount.
- Random ON modulation: e_i varies, a_i varies such that $e_i + a_i$ is a constant and the OFF point occurs at the same point in each T_i. The opposite case for varying the OFF point is PWM.

PWM, PPM and random ON modulation are lumped under the heading pulse randomization, because a standard term to describe all possible combinations does not yet exist in the literature. Randomization is also classified by different categories, which are described in Section 4.2.2.

4.2.2 Categories of Randomization

The randomization schemes used in the experiments fall into two categories:

stationary and non-stationary. Stationary means two things in terms of probability: 1) the nominal ON-OFF pattern being dithered does not change from cycle to cycle, and 2) each new cycle is independent of the previous cycle. Thus, both the deterministic and probabilistic structures are constant in time. Using a fair coin (or any coin with fixed probabilities) to choose between two values for dithering is an example of a stationary randomization scheme.

All stationary schemes used in the experiments can be further classified as wide sense stationary (WSS), which gives two additional constraints: 1) the expected value of a variable x as a function of time t, $E\{x(t)\}$, is constant and 2) the autocorrelation depends only on $\tau = t_1 - t_2$. The autocorrelation $R(\tau)$ of a periodic switching waveform $x(t)$ is defined as

$$R(\tau) = \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} x(t)\, x(t+\tau)\, dt \qquad (4.1)$$

where T is the (nominal) switching period. Autocorrelation and power spectral density are a Fourier transform pair, and are measures of the coherence of the variable $x(t)$.

In schemes that are not WSS, a "time-averaged" autocorrelation and the corresponding average power spectrum are used[22]. In this thesis, some schemes are non-stationary, which means the outcome of the randomization event is influenced by the previous outcome or outcomes. Trials are dependent, and their outcome is biased by the history of previous outcomes. In all non-stationary randomization schemes tested, ergodic Markov chains are used.

A Markov chain changes the probability density function (pdf) of the randomization scheme for the next trial. An ergodic Markov chain is one where every possible state can be reached from every other state, and the chain is periodic. Markov chains can be understood by using a simple example. Consider the 4-state Markov chain used in the experiments for 1 degree of dither. There are only two possible outcomes from randomizing the nominal OFF point in the simple 4-state Markov chain randomization scheme. Either the OFF point is left as the nominal OFF point, representing a short commutation cycle, S, with no delay, or the OFF point can be delayed 1 degree from the nominal point, representing a long commutation cycle, L. The chain responds with the following switching policy taken from [8] and shown in Fig. 5.3:

- Either an L or S delay can be next, regardless of state history.
- The controller observes the last two delays, and if they are SL or LS, then either L or S is allowed for the next delay with probability 0.5.
- If the previous pair is LL, than a subsequent S delay receives a probability of 0.75 and another L delay has a probability of 0.25.
- If the previous pair is SS, then a subsequent L delay receives a probability of 0.75, and another S delay has a probability of 0.25.

The goal of using the Markov chain is to reduce the probability of coherently exciting a particular frequency with several sequential OFF pulses at the same delay.

4.3 Experimental Randomization Schemes

All randomization schemes for the experiments start with a uniformly

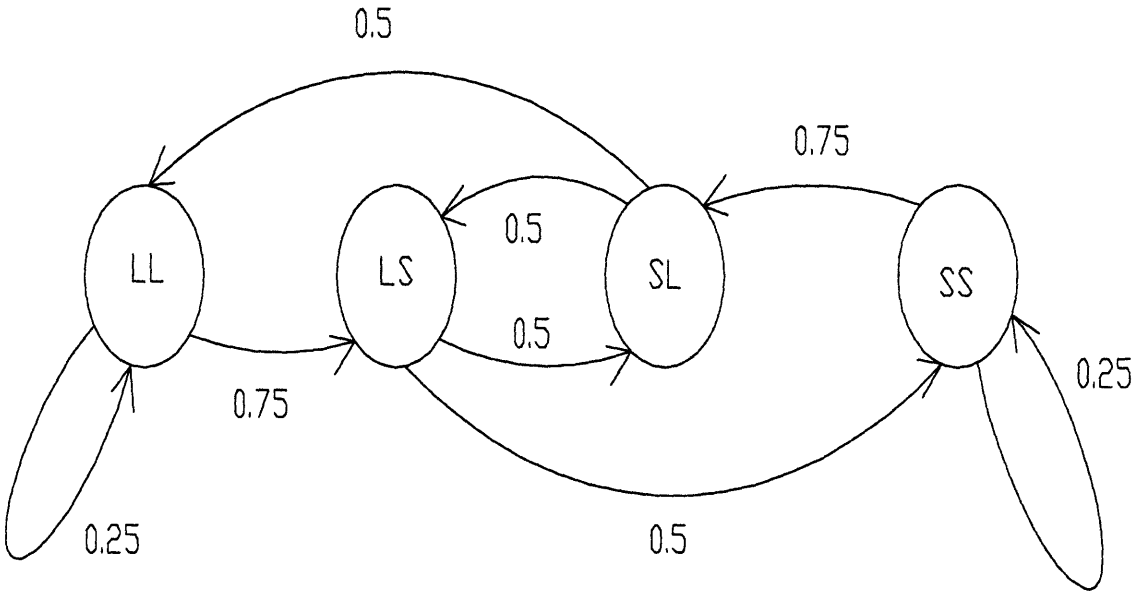

Figure 4.3 Four state Markov chain used in the experiments. Numbers represent the assigned probabilities for all possible state transitions.

distributed random 8 bit variable from the same random number generator. The 8 random bits are used to determine the magnitude of the change in mechanical position of the appropriate phase's ON and/or OFF points. In most cases the ON and/or OFF points are randomized for all phases, and in one case the points are randomized for only one phase.

4.3.1 Random Number Generation

The validity of the randomization schemes is a function of the quality of the random number generation. Computer generation of an infinite sequence of statistically independent random numbers is a contradiction in terms because an algorithm must be used. Given the algorithm, the next "random" number in a sequence is completely determined. However, it is quite possible to produce long sequences of pseudo-random numbers with a uniform distribution that passes basic statistical tests.

The random number generator used in the control system was first proposed by D. H. Lehmer in 1951, and is implemented in the controller subroutine GETRAND using the programming algorithm contained in [24]. This parametric multiplicative linear congruential algorithm produces essentially random unsigned 32 bit numbers. It is a full period random number generator, which means that it cycles through all 2^{32} possible combinations of bits before repeating.

The 32 random bits generated each iteration are divided into four different eight bit random numbers. In the uniform randomization schemes, these 8 bits are scaled according to the number of mechanical degrees of dithering and added to the RATIO parameter of the appropriate PSP channel (which is discussed in Section 3.2.1). In the simple Markov chain scheme, only 1 bit is necessary to determine if the next control pulse should be long or short. If the prior (2 state) Markov history is LL and the random bit indicates L should be the next commutation cycle, another trial is conducted which reduces the probability of another L signal from 0.5 to 0.25. With this simple algorithm, implementing the Markov chain is no more complicated than implementing a stationary randomization scheme.

4.3.2 Selection and Application of Randomization Schemes

The number of possible randomization schemes that can be applied is infinite. This thesis uses different randomization schemes, without *a priori* prediction of the results. Several factors were considered in choosing the randomization schemes. The major factor was the research carried out by A.M. Stanković in [8] and [19], which suggests the benefit of Markov-based random modulation. Also, the experience with uniform random modulation in Cameron's work suggests that this method should also be tested[4].

Stanković's work concentrates on power converters, and the use of a VRM introduces some interesting challenges in implementing randomization schemes. The position feedback is a function of speed, instantaneous speed is a function of torque ripple, and torque ripple is unavoidable in the experimental VRM. In this sense, there is always a small amount of randomization in the ON and OFF points even when using the nominal ON and OFF points.

All stationary schemes in the experiments used the uniform pdf of the random number generator. Gaussian and other distributions with allowed values over a wide (or infinite) range were not used because values outside a narrow limit (such as a standard deviation) would not have produced useful torque. The control signal would have been too short to produce much torque, or too long and negative torque would have been developed. Many other pdf's could possibly be used, but are not considered in this thesis.

The number of degrees of dithering is a tradeoff between the loss of torque with a shorter on period and the benefits of randomization in reducing acoustic noise. The maximum dither is 2 mechanical degrees, with $E\{x(t)\}$equal to 1 degree. Using the 21 degrees of the stator pole as a measure of the most torque that can be produced for a given current chopping level, and assuming worst case where randomization occurs during the region of increasing inductance, one can expect a reduction in power applied to the VRM of about 5%. This comes from the average loss of 1 out of 21 degrees of useful torque production per pole. To deliver the same average power to the load, chop current when using a randomization scheme would have to be increased with a corresponding increase in the magnitude of radial forces on the stator. The net result on acoustic noise depends on the spectral content of the vibrations and mechanical resonances of the stator.

The choice of starting point for dithering depends on several factors. For the ON point, the dithering takes place where the stator and rotor poles do not overlap. This minimizes the loss of torque when current is not at the chop level by the time inductance starts rising. The effectiveness of dithering the ON point in reducing noise is questionable.

The choice of starting point for dithering the OFF point is a major concern, because of the possibility of entering the negative torque region. The experimental VRM is inductance limited, with a relatively slow time constant at turn off. For this reason, the highest speed for the experimental VRM is achieved when the nominal OFF point and start point for OFF dithering are placed in the region of rising inductance.

In addition to using the different schemes defined in Section 4.2.1, the other randomization variable is the number of phases to which dithering is applied. Dithering was applied to either one or four phases. Using one phase is an attempt to quantify the acoustic effect of randomization while minimizing the variation in power delivered to the load.

Chapter 5

EXPERIMENTAL RESULTS

This chapter describes the results of the various randomization schemes on acoustic noise generated by the experimental VRM. Six randomization schemes, in addition to the nominal control system, were tested. For clarity, they are described in this chapter by the names of their subroutines in the control system, which are always of the form DITH#. The experimental setup is described first, along with various aspects of acoustic measurements and implementation of the randomization schemes, then the results are presented in Section 5.4.

5.1 Experimental Setup

A diagram of the experimental setup is shown in Fig. 5.1. Electrical connections to the controller and inverter are described in Chapter 3. Several pieces of equipment were used to collect data. A computer, two oscilloscopes, a current probe, and sound meter collected the data and verified proper controller operation.

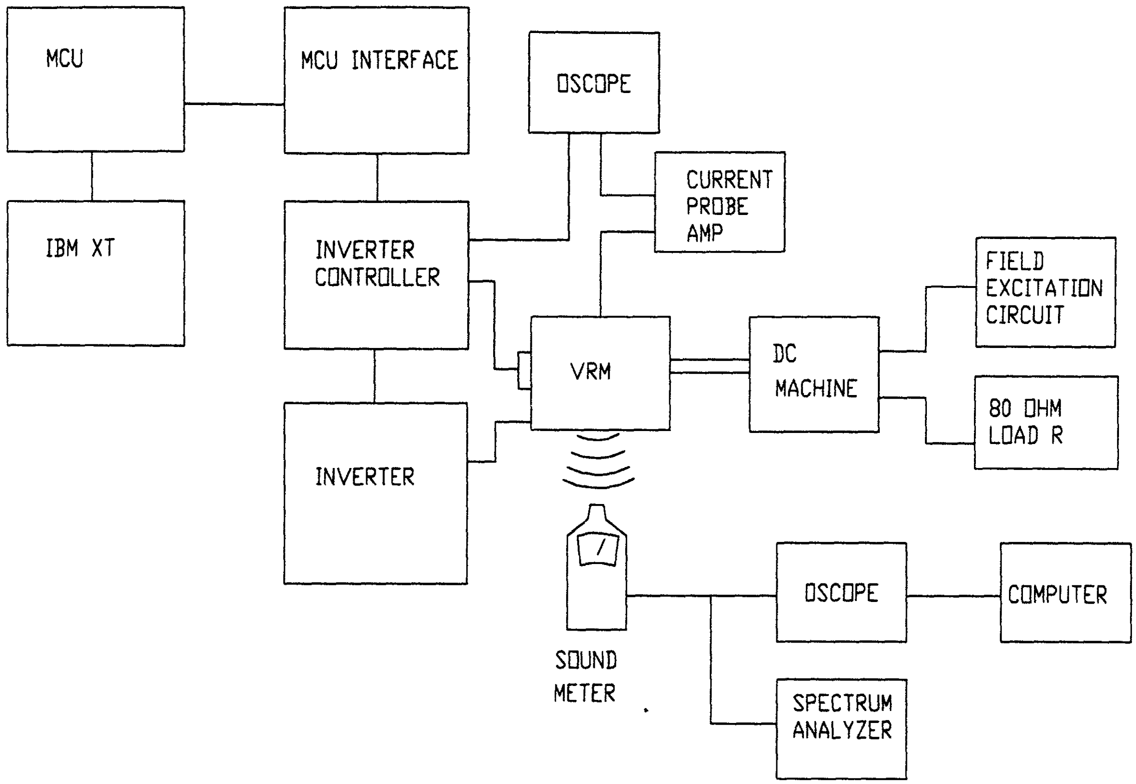

Figure 5.1 Block diagram of the laboratory setup, showing the VRM and load, control system components, and measuring equipment.

This equipment was in addition to the computer, microprocessor, and hardware of the controller.

Mechanical load for the VRM is provided by a DC compound machine connected to the VRM shaft with a rubber coupling and hose clamps to minimize noise transmission. DC generator armature load is held constant at 80Ω. VRM mechanical load is changed by varying excitation to a separately excited field winding in the DC machine with a variac and bridge rectifier.

5.1.1 Acoustic Noise Measurement

Noise measurements are made using a Realistic 33-2050 sound meter mounted on a tripod. A very important aspect of sound measurements is consistency, and within each series of experiments the relative positions the VRM and sound meter are held constant. The VRM and connected dc load machine are clamped to a table, separate from all other equipment, to minimize the possibility of secondary noise. The sound meter's tripod stands on the floor.

The sound meter provides two forms of output. The first is an analog meter movement, which provides an indication of average sound level, but cannot respond to instantaneous sound levels in the audio range. Sound pressure is measured in dB relative to the internationally accepted reference pressure,

$$p_{ref} = 2x10^{-5} \frac{N}{m^2} = 20 \ \mu Pa \tag{5.1}$$

The analog meter's scale is logarithmic, from -10 dB to +6 dB relative to the center point. Seven different center points are available on the sound meter, in increments of 10 dB from 60 to 120 dB. The sound meter is always placed at a distance from the VRM such that when the VRM runs without randomization, average relative dB level is zero. This allows measurements to be taken where the meter is most sensitive to sound variations without clipping peaks and minimums.

The second form of output is voltage proportional to instantaneous sound level. This output voltage is calibrated to noise level for each series of experiments by recording voltage at a known sound level (from the analog meter) and taking the average. A computer-generated tone with programmable frequency is used for this calibration. Sound meter output is sent to a digital storage oscilloscope, which samples 4000 points at time intervals of 20 µsec (50 kHz). This sampling rate is chosen from the available sampling rates on the oscilloscope because the frequencies of interest are in the audio range, which extends up to 20 kHz. The sampling rate of 50 kHz is the closest available choice to twice the Nyquist frequency. Sampled data is downloaded to a computer to allow data analysis.

Sound meter output voltage is calibrated by measuring several known sound levels with the sound meter, then correlating dB levels read on the analog meter with average sampled voltage from the oscilloscope. Fast response is selected (versus slow response) on the sound meter to allow detection of all audio frequency components of VRM noise, instead of relying on an average value.

Acoustic weighting is set to A-weighting, which has been standardized by the International Electrotechnical Commission[25]. The human ear does not hear all frequencies equally, and A-weighting adjusts sound meter frequency response to match an experimentally determined equal-loudness contour for the human ear.

5.1.2 Speed Measurements

Speed measurements are made by two methods. The output of the shaft encoder is periodic, and is used to derive the control signals for the VRM as discussed in Chapter 3. The INDEX pulse, once per revolution, provides a direct indication of speed. By capturing two consecutive INDEX pulses on an oscilloscope, speed can easily be determined. Phase control signals without randomization can also be used to determine frequency, because they occur at six times the rotation rate of the VRM.

The second method is not an exact measurement of speed, but is the method used to ensure that the VRM sees the same load. Output voltage from the dc machine is recorded for the case with no randomization, and used as a reference level. When randomization changes VRM speed, inverter dc supply voltage is changed until dc machine output voltage returns to the same level. Dc machine excitation is held constant throughout this process to ensure load torque is not affected. In general, when randomization provides a smaller average current (i.e. the same chop current for fewer mechanical degrees) to the VRM, inverter dc supply voltage must be increased to provide the same average power to the load.

5.1.3 Other Measurements

An oscilloscope and current probe are used to provide indication of proper controller operation. Current measurements show current chopping, and provide an indication of phase inductance because of the L/R time constant involved in changing VRM phase current. Circuit voltages are used for speed measurements, and to show timing relationships.

A measurement which is not taken is temperature. It is evident from touching the VRM that stator temperature increases during motor operation. Core loss is the major cause of the temperature rise, and is produced by two mechanisms: hysteresis and eddy currents. These losses are approximated by the relation

$$P_{core} \;\; \alpha \;\; f\, B^{(1.6-2.0)} \qquad (5.2)$$

where f is frequency in Hz and B is magnetic flux density in Wb[26]. From (5.2), current chopping frequency has a major effect on core loss. This core loss explains why VRM speed does not necessarily increase as inverter dc supply voltage is increased, because higher voltage gives a higher copy frequency. Conservation of energy shows that less power is delivered to the load as core loss increases

$$P_{out} = P_{in} + P_{losses} \tag{5.3}$$

where P_{losses} are governed by (5.2) in a VRM.

5.2 Comparing Randomization Schemes

Six separate randomization schemes are used in the experiments, plus DITH0 which has no randomization. DITH0 provides a baseline for comparing the different schemes. The biggest challenge in comparing the schemes is to hold some variable constant such that the comparisons are valid. The controller software produces a random displacement, within a user-specified bound of 1 or 2 degrees, which is added to a reference. Two different methods are used to determine the reference angle. Some experiments use the nominal ON and OFF points as references, and add the random angle to the nominal angle. Other experiments use a reference angle such that the expected value of the randomized angle equals the nominal angle. For example, given a uniform pdf and 1 degree of dither, the reference angle in the second method is 1/2 mechanical degree prior to the nominal angle, because the expected value $E\{x(t)\}$ is 1/2. This method is an attempt to maintain the same average torque without changing any other parameters. This method did not achieve its goal; experimental results using both methods show speed changes with different randomization schemes. The number of degrees of dithering is also variable. The choices are limited to one and two degrees as suggested by Cameron's research[4].

The method chosen for comparing randomization schemes is to compare dc machine output power. The separately excited field is held constant on the dc load machine, along with the armature's load resistor in each separate series of experiments. A multimeter on the output of the dc load machine measures average voltage, which is converted to power. If the voltage remains constant, average power and speed are also constant (all other factors being equal). Voltmeter readings are recorded for this comparison, along with frequency measurements from an oscilloscope.

5.3 The Experimental Randomization Schemes

The six different randomization schemes include four stationary and two non-stationary processes. DITH0, as discussed above, contains no randomization and uses the nominal ON and OFF points.

5.3.1 Stationary Randomization Schemes (DITH1, DITH2, DITH3, and DITH6)

The four stationary schemes use a uniform pdf to dither the ON and/or OFF points. DITH1 varies the ON point only, and DITH2 varies the OFF point only. DITH3 is a combination of DITH1 and DITH2; it independently varies the ON and OFF points. DITH1, DITH2, and DITH3 vary the respective ON and/or OFF points for all four phases. Each occurrence of a control pulse uses a randomized angle.

DITH6 operates only on phase A; the other three phases use the nominal ON and OFF points. DITH6 is an attempt to determine if the torque ripple and non-coherent vibrations generated from one phase are significant enough to reduce acoustic noise from all four phases.

5.3.2 Non-Stationary Randomization Schemes (DITH4, DITH5)

The two non-stationary schemes are versions of the 4-state Markov chain described in Section 4.2.2. Both dither only the OFF point. DITH4 uses the simple 4-state Markov chain with only two possible values for the OFF point. The short commutation cycle (S) uses the nominal OFF point, and the long commutation cycle (L) adds 1 or 2 degrees to the nominal OFF point based on user input.

DITH5 is a combination of uniform dithering and the simple Markov chain. The same decision process is used for S or L commutation, but an S OFF displacement from the nominal OFF commutation point can be any of 128 possible fractions from 0/128 to 127/128 of a half degree (for 1 degree of dither selected by the user) or full degree (for 2 degrees of dither). Similarly, an L OFF commutation point's displacement can be any point from 128/128 to 255/128 of a half or full degree past the nominal OFF point.

5.4 Results

The experimental results show that randomization does have an effect on acoustic noise. The data is in the form of output voltage from the sound meter. Data is collected and transferred to a computer as a series of 4000 voltage levels. These levels vary over wide range (over 1 volt) compared to the average voltage levels that correspond to dB levels on the analog meter (about 0.3 volts). Figure 5.2 shows the result of calibrating the meter, with the best-fit straight line used for voltage-dB correlation. Measured acoustic noise reduction for the various schemes is on the order

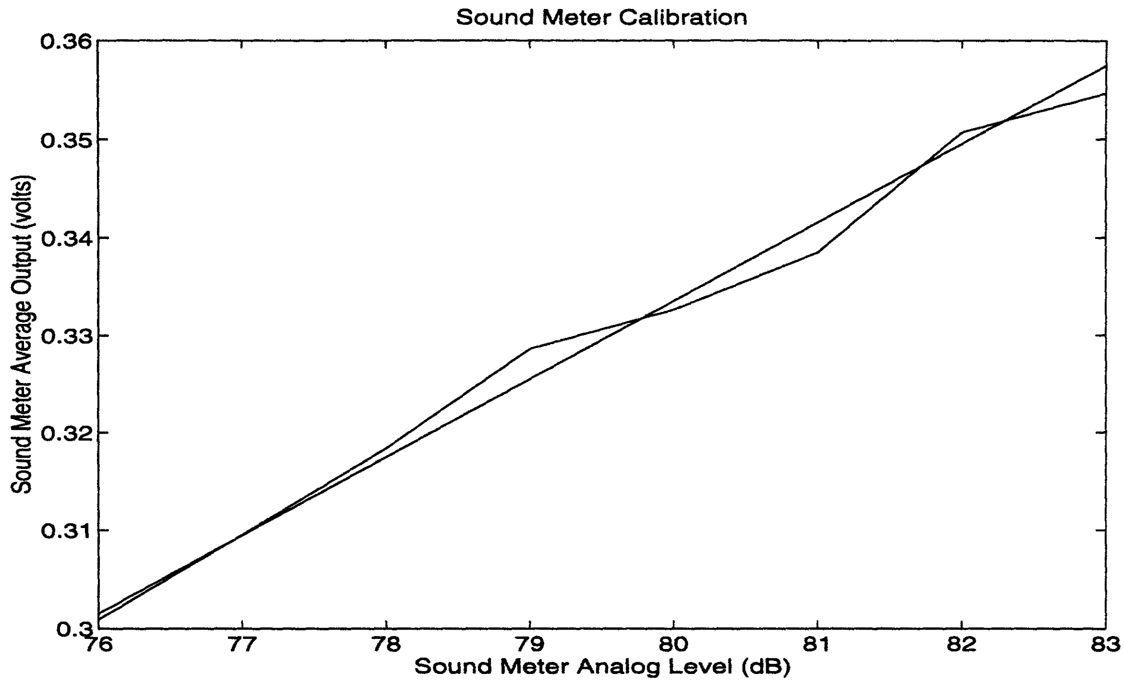

Figure 5.2 Sound meter average output voltage correlation to sound meter analog dB level.

of 1/2 to 1dB, obtained from averaging sound meter output voltage.

Instantaneous sound meter output voltages are analyzed using the Matlab computer program. A Fast Fourier Transform (FFT) of the data is used to provide spectral content of the meter's voltage. This instantaneous voltage does not correlate to dB levels on the meter because of the wide swings in voltage. Figure 5.3 shows an example of instantaneous output voltage and the result of the FFT analysis. The spectrum analysis shows a large peak near 1300Hz, which corresponds roughly to the fundamental mechanical excitation of the VRM as a whole, and is due to the contributions of the 4 phases and 6 poles per phase. The theory is discussed in Section 2.4.2. Measured frequency on an oscilloscope of consecutive ON signals for the same phase is about 46 Hz, which corresponds to an excitation frequency of 1100

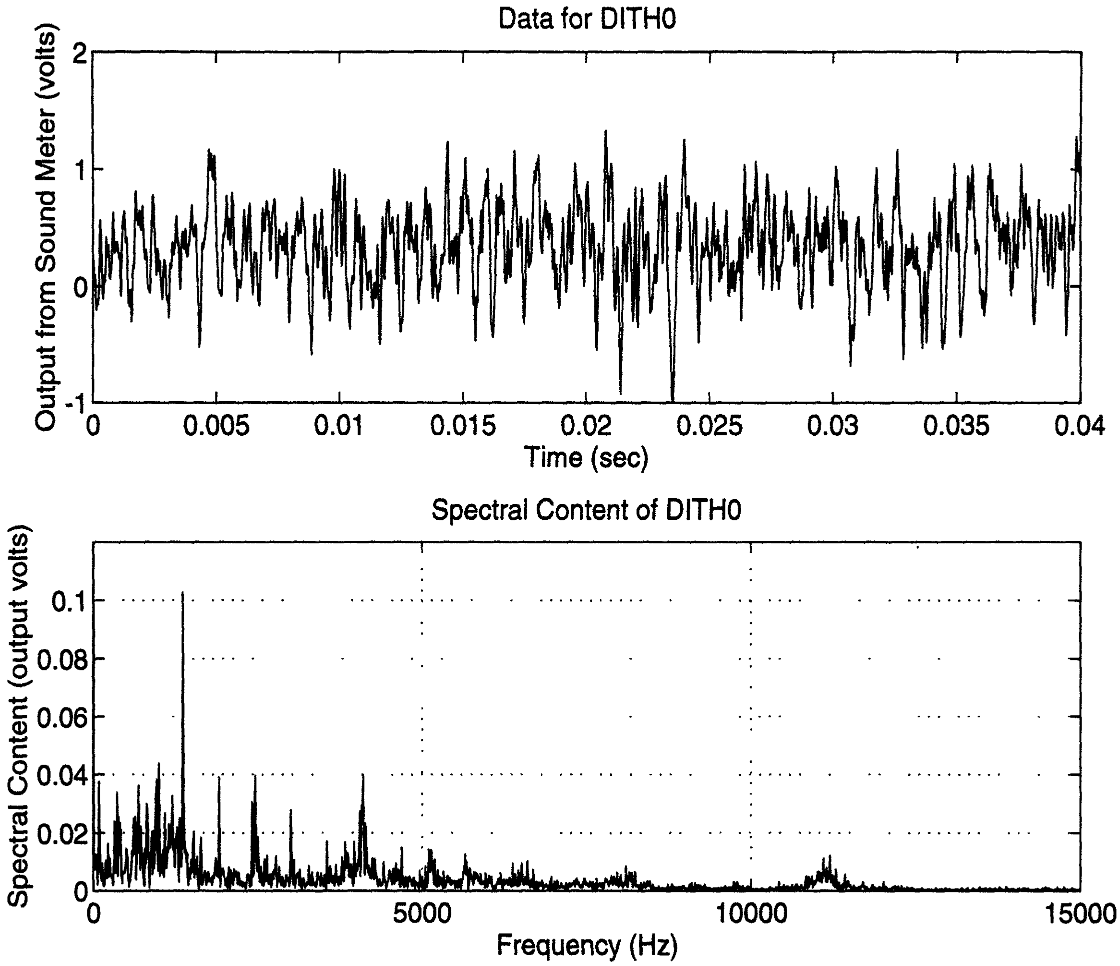

Figure 5.3 Raw data and spectral analysis, equal angle trials, dc supply = 30V, chop current = 1.96A, 2700 rpm, scheme DITH0 no dither.

Hz.. The disparity between actual and calculated VRM fundamental frequency is assumed to be due to speed ripple and inaccuracy in measuring frequency using cursors on the oscillocope. Speed ripple, as discussed in Section 5.1.2, could not be measured accurately. The ripple is discernable as variations in dc machine output voltage and fluctuations in sound perceived by the ear.

5.4.1 Trials

The most rigorous trials in the experiments are the equal angle trials. In these trials, the nominal ON point is changed such that the E{x(t)} for all randomization schemes is the same, where x(t) represents each commutation ON and OFF point. The software always adds dithering to the nominal point, thus the nominal point is changed for different amounts of dithering. Consider DITH0 with no dithering and DITH2 with OFF point uniform dithering. in the 1 degree of dither case, the nominal OFF point occurs 1/2 degree sooner in DITH2 than in DITH0.

Representative trials are presented in this thesis. Equal angle trials for all OFF point randomizations are compared. Fewer trials with ON dithering were conducted, as discussed in Chapter 4. Results for ON dithering (DITH1 and DITH3) come from initial trials, where the equal angle principle is not applied.

5.4.2 Spectral Plots

This section presents plots from equal angle OFF trials and initial ON trials. Comparison of the plots (which are all presented on the same scale) supports some generalizations. Dithering does have an effect on spectral content. Equal angle trials consistently show that the peak frequency component (other than the dc component) has a consistent drop from the no dither case. This tends to spread the frequency spectrum, and raise spectral density at other frequencies. In general, the equal angle trials show that the VRM operates at the same average speed, though with a larger ripple. Variation of dc load machine voltage output in equal angle trials with no separately excited field on the dc load machine is approximately 2 percent on the multimeter. Results from initial ON dither trials do not show a consistent trend. It is unclear whether this is due to the dithering or the significant differences in speed.

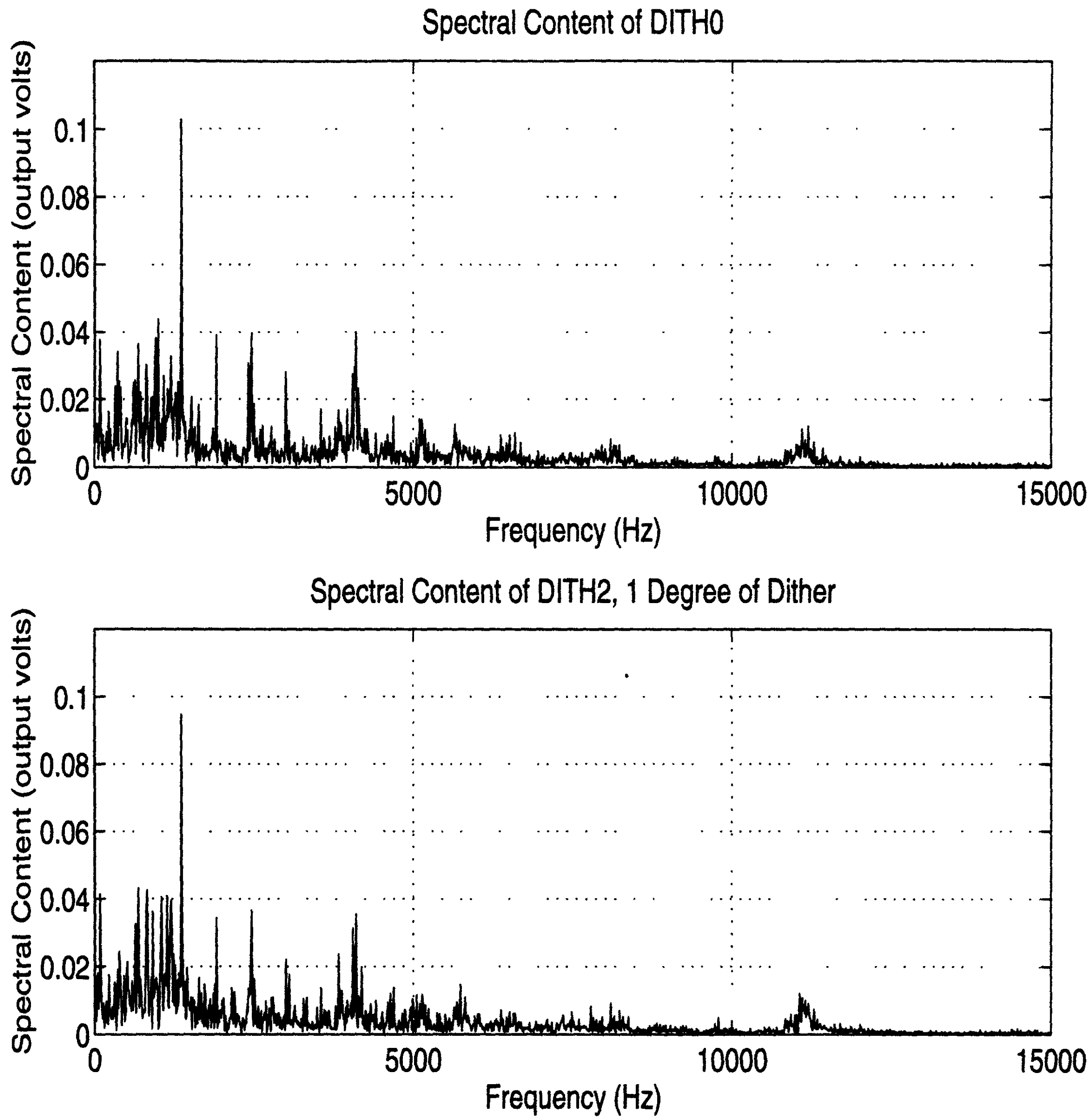

Figure 5.4 Comparison between equal angle trials at dc supply = 30V, chop current = 1.96A, 2700 rpm, scheme DITH0 no dither and scheme DITH2 with 1 degree of OFF dither.

Another significant variable in determining the randomization effectiveness is the choice of nominal ON and OFF points. In initial trials, the nominal points come from shaft encoder alignment and stationary calibration described in Section 3.1. Because of the effect of the large L/R time constant at the OFF point, these points were optimized experimentally. This optimization occurred after initial trials, which

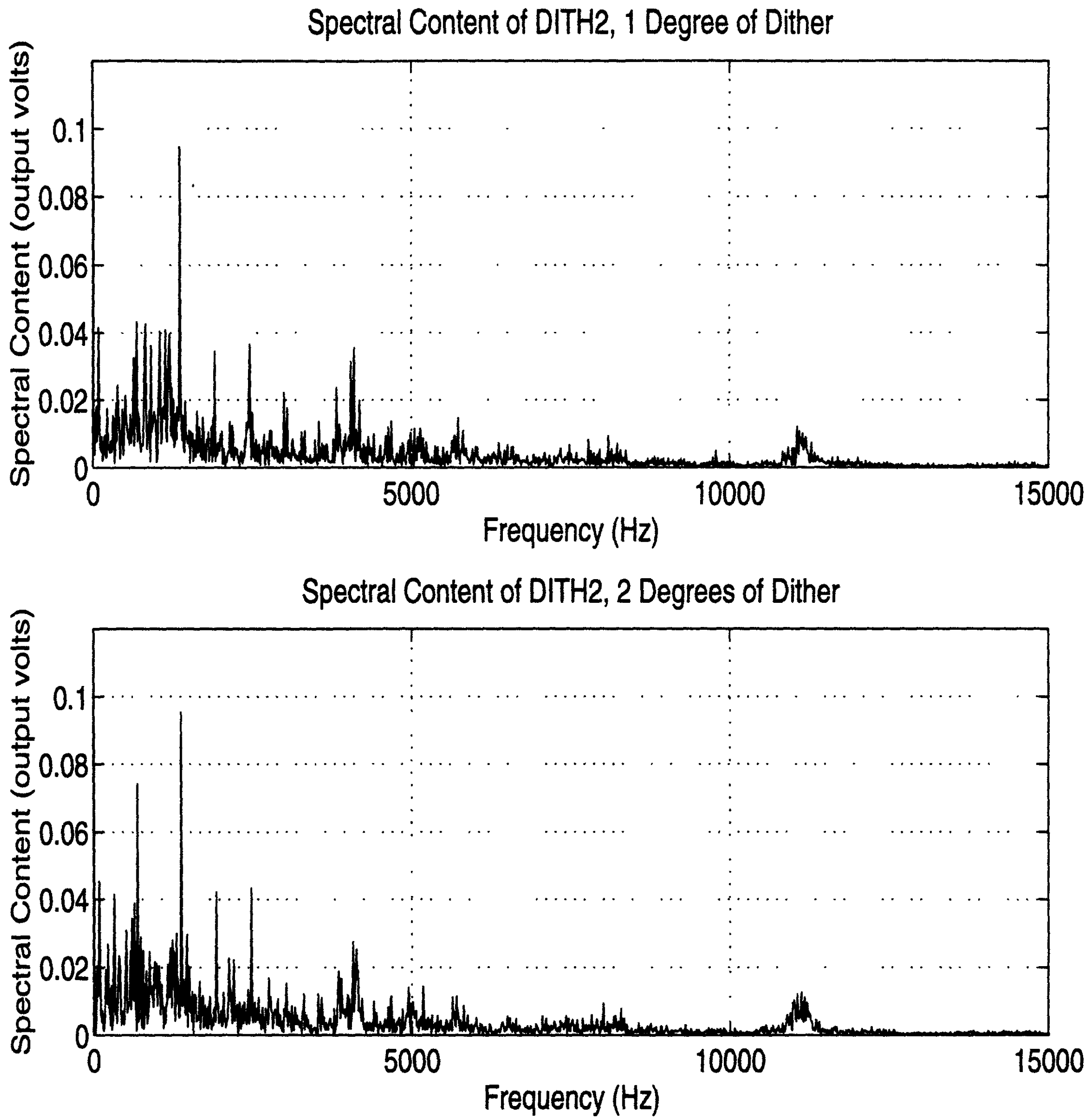

Figure 5.5 Comparison between equal angle trials at dc supply = 30V, chop current = 1.96A, 2700 rpm, scheme DITH2 with 1 degree and 2 degrees of OFF dither.

makes the ON dither results (during initial trials) questionable.

During optimization, the dc load machine field excitation is set to a constant value, and the nominal points are adjusted while variations in load power are observed. These changes are made dynamically with a subroutine in the controller software. By moving the position of the nominal ON and OFF points back almost 6 degrees,

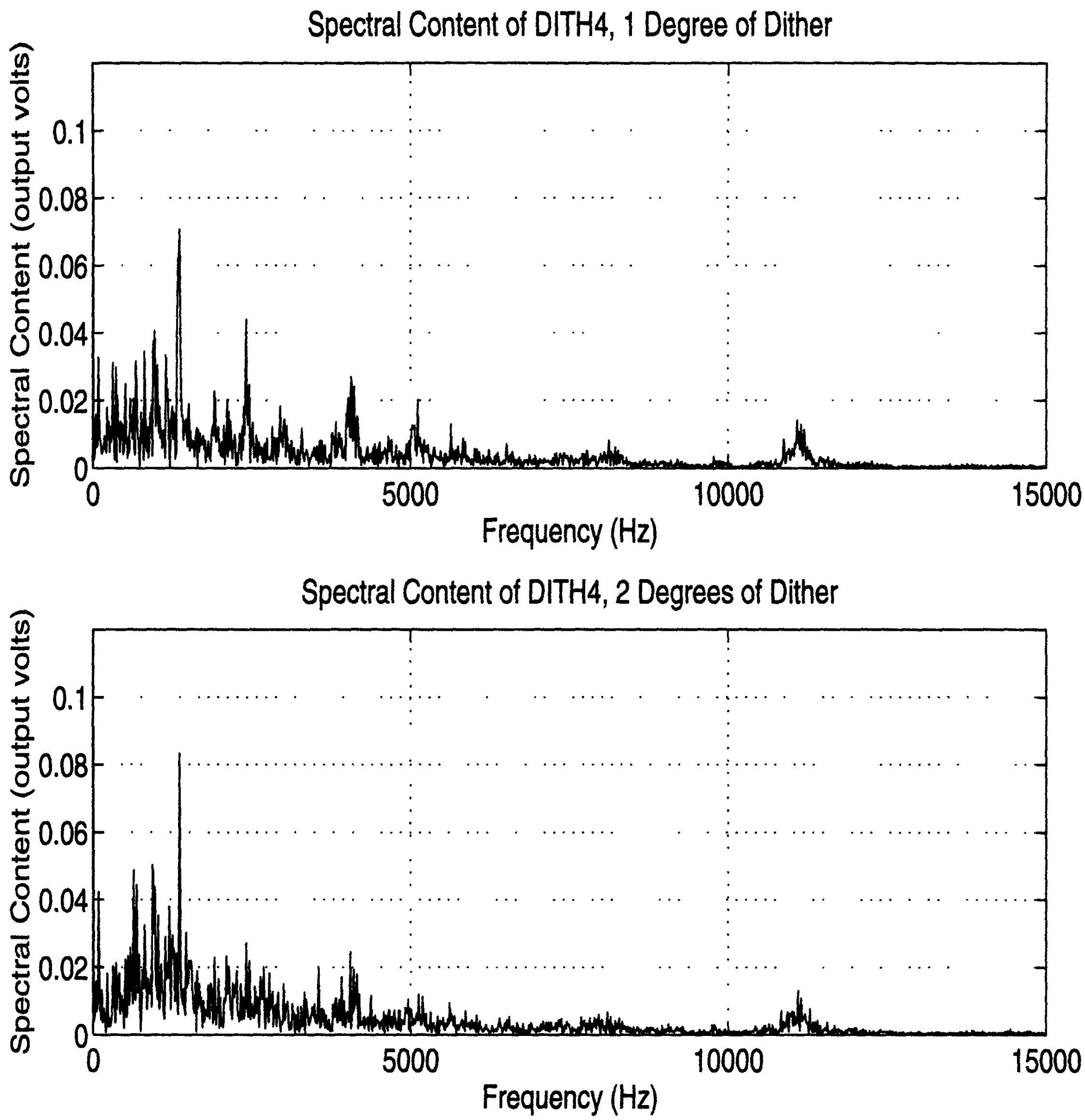

Figure 5.6 Comparison between equal angle trials at dc supply = 30V, chop current = 1.96A, 2700 rpm, scheme DITH4 with 1 degree and 2 degrees of OFF dither.

load voltage increased from 11.3V to 19.2 V (an increase in output power of 189%).

Supply voltage and current chop level were not changed during this optimization.

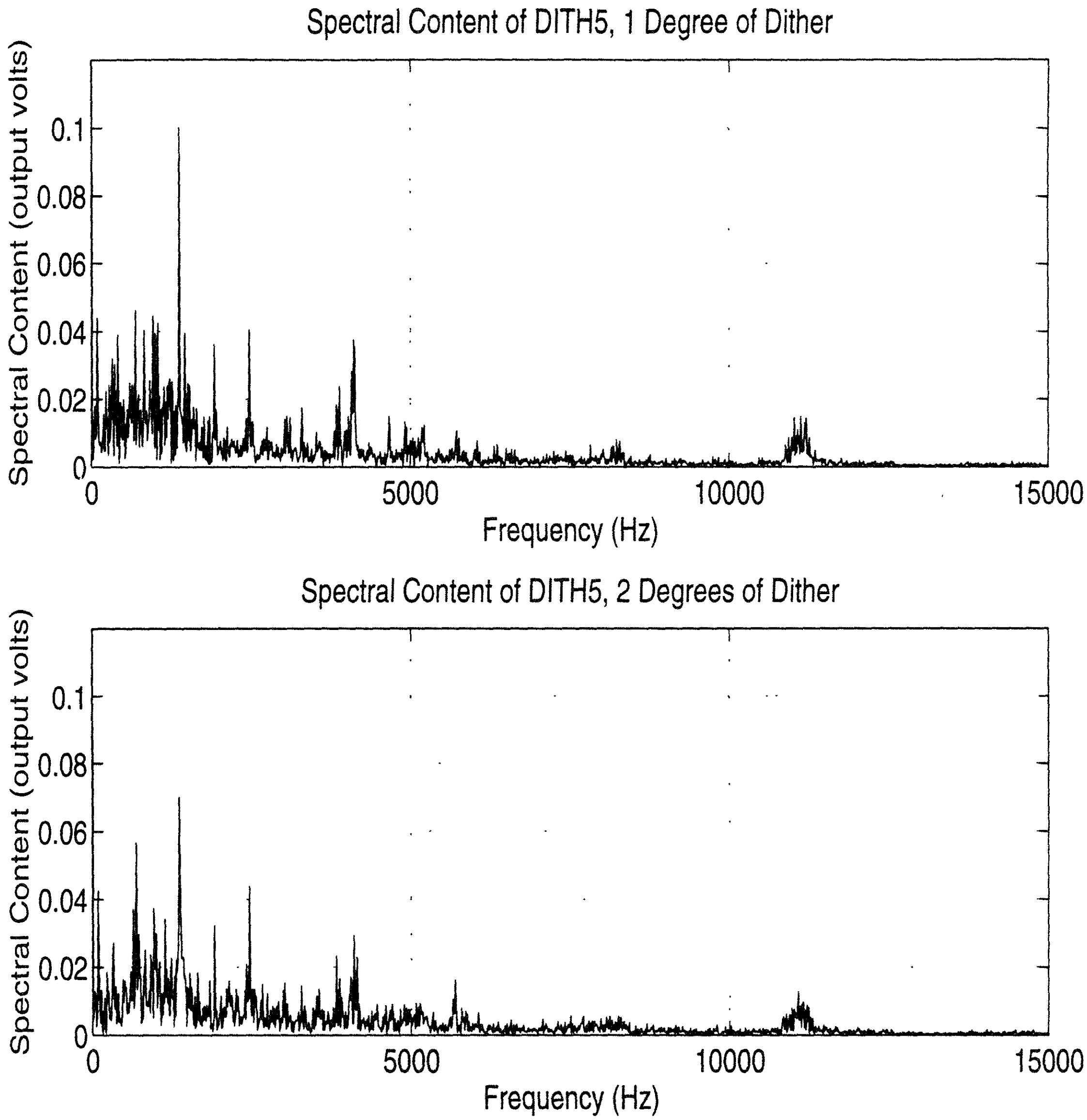

Figure 5.7 Comparison between equal angle trials at dc supply = 30V, chop current = 1.96A, 2700 rpm, scheme DITH5 with 1 degree and 2 degrees of OFF dither.

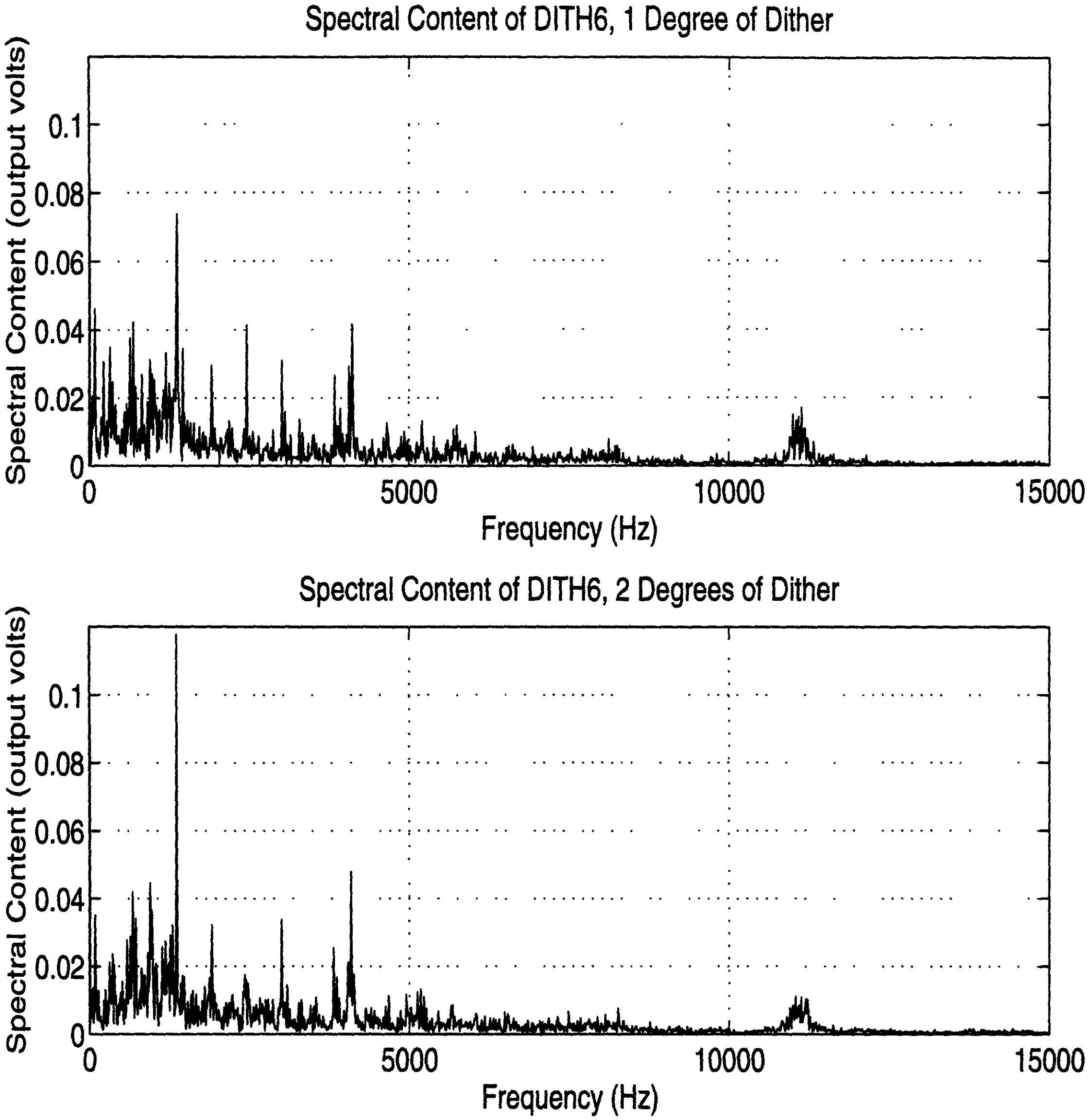

Figure 5.8 Comparison between equal angle trials at dc supply = 30V, chop current = 1.96A, 2700 rpm, scheme DITH6 with 1 degree and 2 degrees of OFF dither.

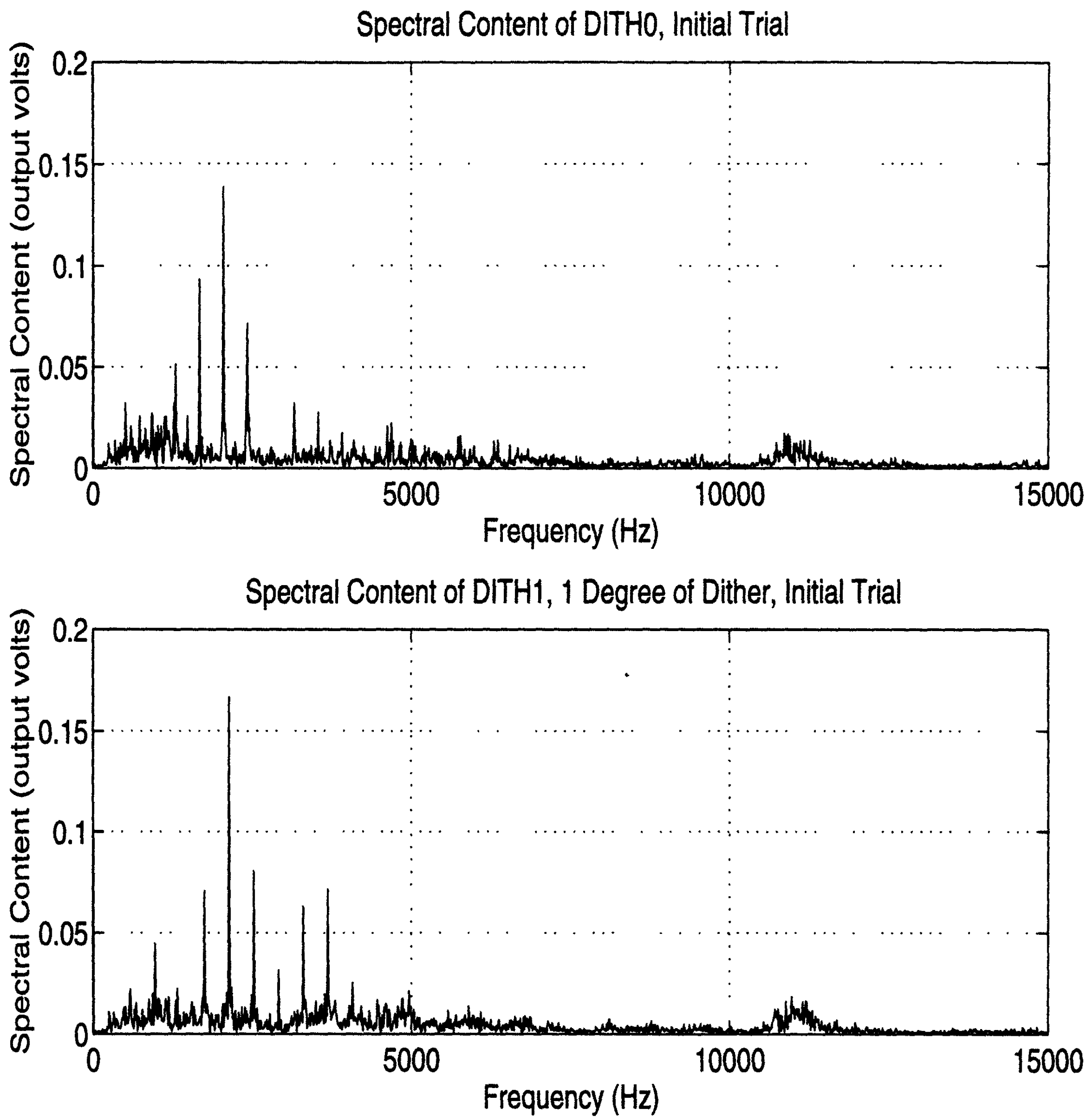

Figure 5.9 Comparison between initial trials without equal angles and before optimizing at dc supply = 30V, chop current = 2.35A, DITH0 no dither and DITH1 with 1 degree of ON dither. DITH0 speed = 1600 rpm, DITH1 speed = 1670 rpm.

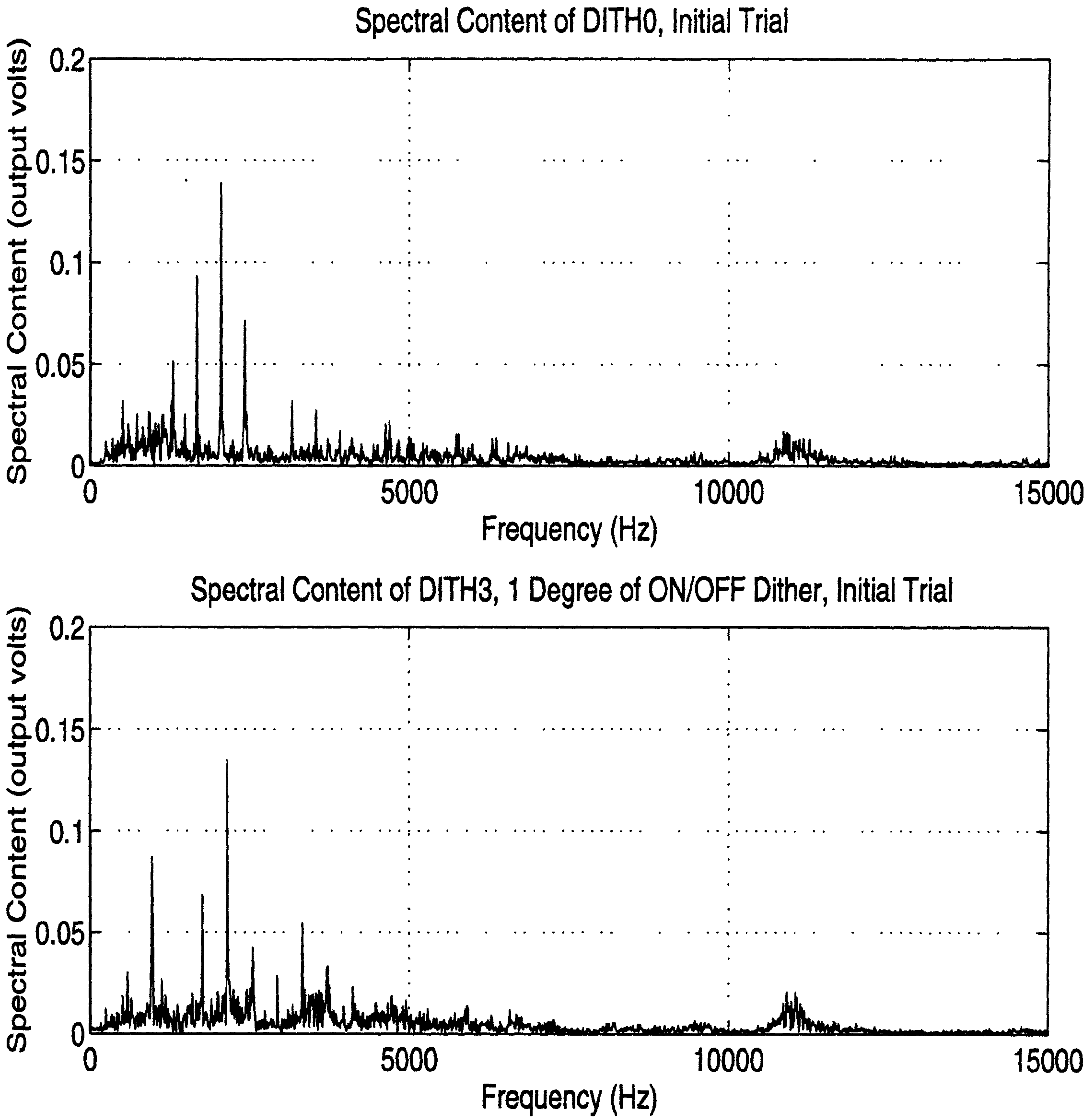

Figure 5.10 Comparison between initial trials without equal angles and before optimizing at dc supply = 30V, chop current = 2.35A, DITH0 no dither and DITH3 with 1 degree of ON/OFF dither. DITH0 speed = 1600 rpm, DITH3 speed = 1870 rpm.

5.4.3 Experimental Limitations

The operating points of most concern are mechanical resonances of the stator. The first mechanical resonance occurs at 3720 rpm based on research in [4]. This was confirmed using scheme DITH0. Unfortunately, at 3720 rpm, the overhead associated with real-time randomization calculations interferes with controller operation. There are two solutions to this problem. First, many subroutines can incorporated into one routine, eliminating the costly (in terms of time) subroutine calls and returns. While this solution would gain some speed, the problem could still remain at higher rpm within the VRM's operating envelope.

Another solution is to use the same software to produce a look-up table of randomization values. Even though this method would use a lot of memory, it would eliminate the timing limitation without forcing a restructuring of the subroutines. A final solution is to use hardware generated random values, using either counters or random bit generation chips (such as the National Semiconductor MM5437)[27].

Chapter 6

CONCLUSIONS

This thesis is successful in showing that randomization has an effect on acoustic noise. The reduction in acoustic noise is easily seen in a spectral analysis of noise generated the VRM. In terms of human hearing, the reduction achieved in non-resonant trials is less than 1 dB. Thus, although randomization affects the noise spectrum, these experiments do not show a significant human advantage.

There are advantages to spreading the noise spectrum. In applications where signature reduction is important, such as machinery noise on naval vessels, spreading the noise spectrum can help prevent identification of the vessel by signature. These advantages are not limited to VRMs; any machine which receives energy through power electronic devices can reap the benefits of a spread spectrum.

A significant area that is not covered in this research is the behavior of the VRM at a mechanical resonance. The software that determines the amount of dithering has too many instructions and subroutine calls. When the VRM is run at the first mechanical resonance, the program cannot complete calculations for one phase before it is time for the next phase's calculations.

6.1 Lessons Learned

Several problems during the design and initial test phase of this research have important lessons associated with them. The inductance-limited operation of the experimental VRM tended to minimize the time spent chopping current, and maximize the time for current changes at the commutation points. Randomization of the OFF points could not occur during the maximum aligned positions, because of the negative torque produced after the OFF signal. Depending on the optimum nominal OFF position, effectiveness of randomization could involve a tradeoff between the noise reduction and torque.

Noise generated by the inverter circuit is another concern. In the regenerative mode, the VRM returns energy to the power supply. Thus, during current chopping, there is a large rate of change of current (from positive to negative current chop level and vice versa) in the connections to the power supply. The induced magnetic and electric fields that result can cause noise problems. In this research, the optically isolated microcontroller's memory was affected by the aluminum plate the circuit was mounted on.

6.2 Suggestions for Future Research

The major area that still needs investigation is noise reduction at motor resonance points. This can be accomplished with the control system software and hardware designed and successfully used during this research. Modifications to the control system to decrease computational overhead are needed to achieve the desired high speed operation. Tightening the structure of the code is probably sufficient for achieving this. Other improvements would be to use other, less computationally demanding, methods for random number generation, such as lookup tables or hardware random bit generators. It is expected that the reduction in noise from randomization at resonance would exceed the slight noise reduction achieved at non-resonant speeds with OFF point dithering. An area related to VRM resonance is load resonance. The effect of randomization on the drive motor of a load at resonance could also be investigated. Investigations of these areas may yield much more significant results with the randomization techniques implemented in this thesis.

Signature reduction through the use of randomization is another area of potential research. Waterborne noise is still the primary method used by submarines for detecting other submarines. The noise spectrum emitted by a vessel can be used for positive identification. Randomization can be used to muddle machinery noise signatures, preventing a positive identification.

The effect of randomization on machine efficiency could be part of any one of these topics. Efficiency is not addressed in this thesis. A dynamic method for analyzing efficiency would be necessary, because of the rapidly changing motor torque.

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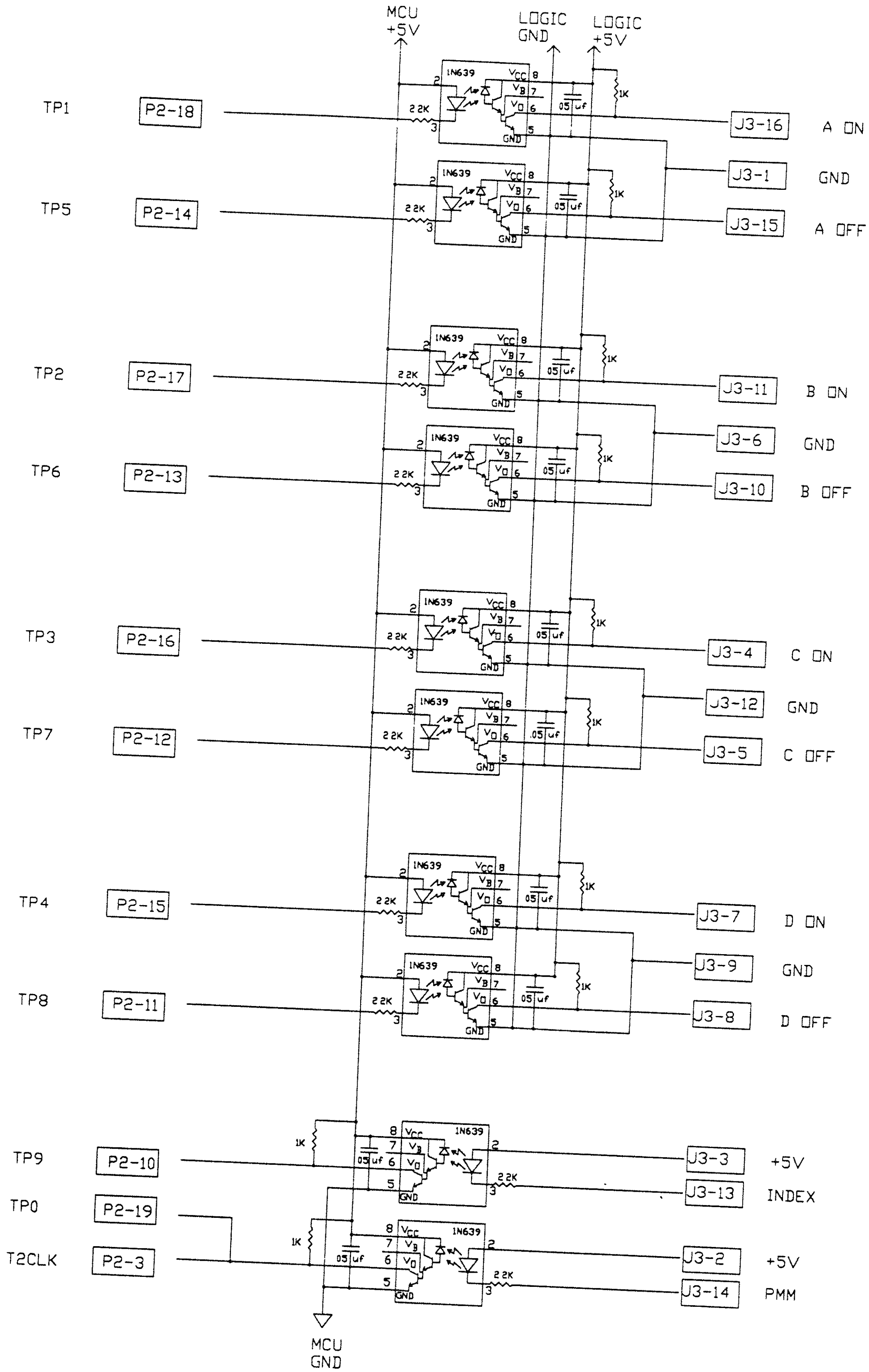
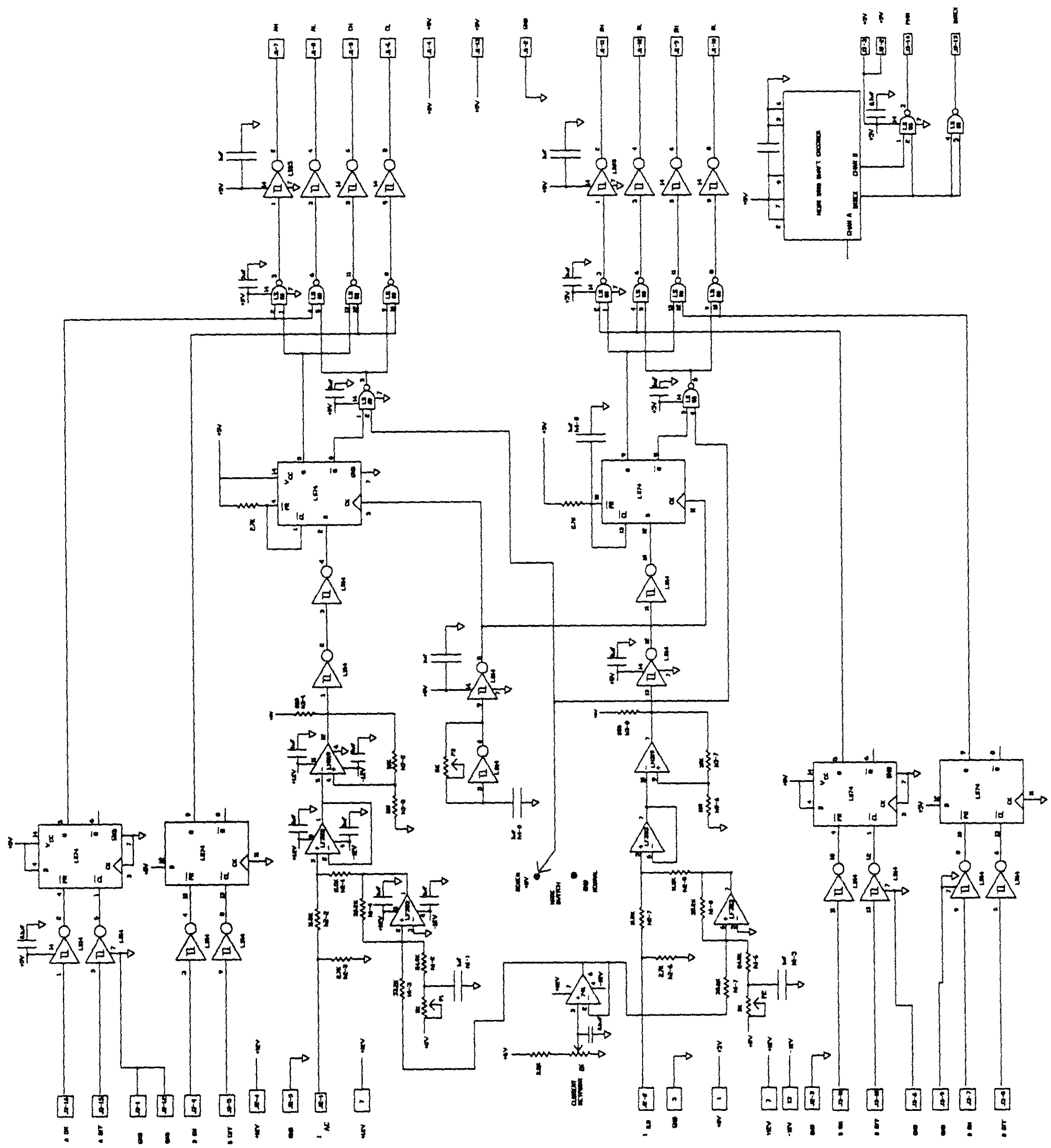
APPENDIX A

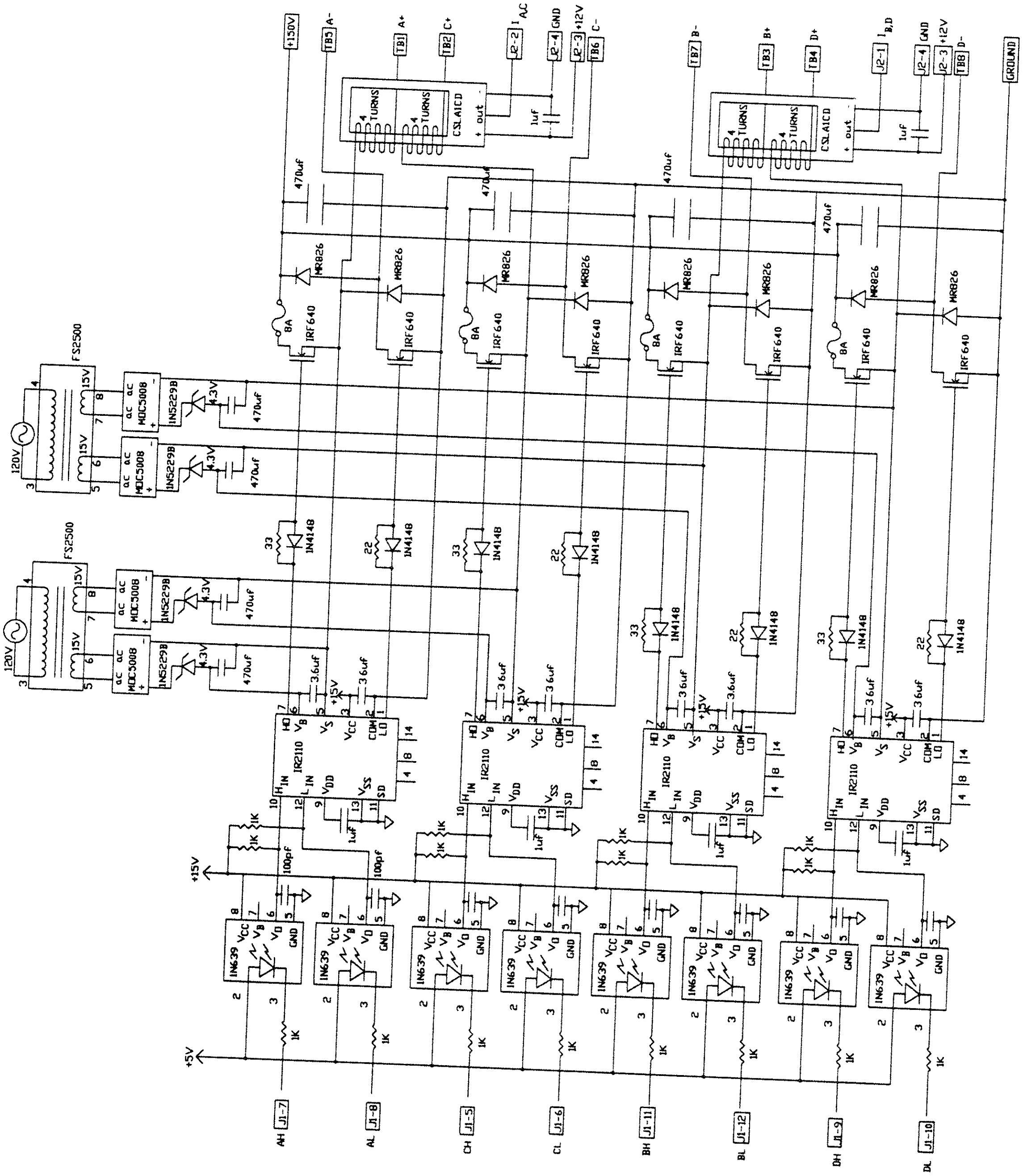
Schematic Diagrams



MCU Interface Board



Inverter Controller Board



Inverter Board

APPENDIX B

Controller Source Code

```
;Setup communications - define registers
CREG        EQU     $FFFA39         ;Test Submodule Control Reg
QMCR        EQU     $FFFC00         ;QSM Configuration Register
QILR        EQU     $FFFC04         ;QSM Interrupt Level Register
QIVR        EQU     $FFFC05         ;QSM interupt vector register
SCCR0       EQU     $FFFC08         ;SCI control register 0
SCCR1       EQU     $FFFC0A         ;SCI control register 1
SCSR        EQU     $FFFC0C         ;SCI status register
SCSRLOW     EQU     $FFFC0D         ;lower byte of SCSR
SCDR        EQU     $FFFC0F         ;SCI data reg (lower 8 bits)

;data and ASCII characters for serial interface
CR          EQU     13T             ;ASCII for carriage return
LF          EQU     10T             ;ASCII for line feed
BS          EQU     08T             ;ASCII for back space (to delete)
PROMPT      EQU     62T             ;ASCII for >
CHSIZ       EQU     06T             ;character buffer size

;External Bus Interface registers; disables all external interrupts
PEPAR       EQU     $FFFA17         ;Port E Pin Assignment Register
DDRE        EQU     $FFFA15         ;Port E Data Direction Register
PORTE       EQU     $FFFA11         ;Port E Data Register
PFPAR       EQU     $FFFA1F         ;Port F Pin Assignment Register
DDRF        EQU     $FFFA1D         ;Port F Data Direction Register
PORTF       EQU     $FFFA19         ;Port F Data Register

;TPU setup parameters
TMCR        EQU     $FFFE00         ;TPU Module Configuration Register
TICR        EQU     $FFFE08         ;TPU Interrupt Configuration Register
CIER        EQU     $FFFE0A         ;Channel Interrupt Enable Register
CFSR0       EQU     $FFFE0C         ;Channel Function Select Reg 0
CFSR1       EQU     $FFFE0E         ;Channel Function Select Reg 1
CFSR2       EQU     $FFFE10         ;Channel Function Select Reg 2
CFSR3       EQU     $FFFE12         ;Channel Function Select Reg 3
CISR        EQU     $FFFE20         ;Channel Interrupt Status Reg
HSQR0       EQU     $FFFE14         ;Host Sequence Register 0
HSQR1       EQU     $FFFE16         ;Host Sequence Register 1
HSRR0       EQU     $FFFE18         ;Host Service Request Register 0
HSRR1       EQU     $FFFE1A         ;Host Service Request Register 1
CPR0        EQU     $FFFE1C         ;Channel Priority Register 0
CPR1        EQU     $FFFE1E         ;Channel Priority Register 1
PMMCHCO     EQU     $FFFF00         ;PMM Chan 0 CHANNEL CONTROL
PMMMAX      EQU     $FFFF02         ;PMM Chan 0 MAX_MISSING NUM_TEETH
PMMRAT      EQU     $FFFF06         ;PMM Chan 0 RAT TCR_2_MAX
PSPPER1     EQU     $FFFF10         ;PSP Chan 1 PERIOD_ADDRESS
AONREG      EQU     $FFFF18         ;PSP Chan 1 Ratio 1, Angle 1
BONREG      EQU     $FFFF28         ;PSP Chan 2 Ratio 1, Angle 1
CONREG      EQU     $FFFF38         ;PSP Chan 3 Ratio 1, Angle 1
DONREG      EQU     $FFFF48         ;PSP Chan 4 Ratio 1, Angle 1
AOFFREG     EQU     $FFFF58         ;PSP Chan 5 Ratio 1, Angle 1
BOFFREG     EQU     $FFFF68         ;PSP Chan 6 Ratio 1, Angle 1
COFFREG     EQU     $FFFF78         ;PSP Chan 7 Ratio 1, Angle 1
DOFFREG     EQU     $FFFF88         ;PSP Chan 8 Ratio 1, Angle 1
PERIOD      EQU     $FFFF08         ;PSP Chan 0 PERIOD_HIGH_WORD

;Definitions for Random Number Calculations
a           equ     16807T          ; multiplier
m           equ     2147483647T     ; prime modulus
q           equ     127773T         ; m div a
r           equ     2836T           ; m mod a
SEED        EQU     530599108T      ; initial seed for random
BITS8       EQU     $0000FF00       ;mask to isolate 8 rand bits


            ORG     $0400
            JSR     CLRTPU          ;all motor phases off
            BCLR.B  #0,CREG.L       ;prevent test submodule reset
            MOVE.L  #00H,D0
            MOVEC   D0,VBR          ;initialize VBR
            MOVEA.L #STACK0,A7      ;initialize the stack pointer
```

```
;**********************************************************************
;The following INIT routines initialize the VRM program setup, entering
;default values and asking for changes.

;INITEBI initializes the EBI, disabling external interrupts and external
;data and address acknowledge lines (pins are floating, and spurious
;signals mess up the program)
INITEBI   MOVE.B     #00,PEPAR.L    ;assign PORT E pins 0,2,3 as I/O
          MOVE.B     #0FFH,DDRE.L   ;assign PORT E output pins
          MOVE.B     #00H,PFPAR.L  ;assign PORT F pins as I/O
          MOVE.B     #0FFH,DDRF.L  ;assign all PORT F pins as output

;INITCOM initializes the serial communications setup.
INITCOM   MOVE.W     #0087h,QMCR.L  ;supv access, int arbitration 7
          MOVE.B     #02H,QILR.L    ;use SCI, int pri 2, QSPI disabled
          MOVE.W     #55T,SCCR0.L   ;clock rate 9600 baud, @16.777 Mhz
          MOVE.W     #100CH,SCCR1.L ;9600,N par,8 data,1 stop,no int

;load interrupt vector addresses
          MOVEC      VBR,A2           ;load vector base register address
          MOVE.L     #AINT,($104,A2)  ;load channel 1 interrupt (A on)
          MOVE.L     #BINT,($108,A2)  ;load channel 2 interrupt (B on)
          MOVE.L     #CINT,($10C,A2)  ;load channel 3 interrupt (C on)
          MOVE.L     #DINT,($110,A2)  ;load channel 4 interrupt (D on)
          MOVE.L     #STRT,($124,A2)  ;load channel 9 interrupt (STRT)

;initialize PMM channel 0
          MOVE.W     #0004H,PMMCHCO.L    ;PMM, rise edge, use TCR1
          MOVE.W     #01C6H,PMMMAX.L     ;1 miss xsit to reset TCR2
          MOVE.W     #0C0C6H,PMMRAT.L    ;Missed tooth if 1.5 periods

;initialize PSP channels 1-8, transition channel 9
          MOVEA.L    #PSPPER1,A5      ;use as base reg for loading
          MOVE.W     #0A10H,(A5)      ;  all 8 PSP channels with
          MOVE.W     #0A10H,(10H,A5) ;  PMM chan 0 PERIOD_LOW_WORD
          MOVE.W     #0A10H,(20H,A5) ;  and force pin low if error
          MOVE.W     #0A10H,(30H,A5) ;  causes force mode. Force mode
          MOVE.W     #0A10H,(40H,A5) ;  occurs if pulse period ovflows
          MOVE.W     #0A10H,(50H,A5) ;  23 bits in chan 0.
          MOVE.W     #0A10H,(60H,A5)
          MOVE.W     #0A10H,(70H,A5)
          MOVE.W     #000FH,(80H,A5) ;chan 9 transition mode, input
          MOVEA.L    #AONREG,A5       ;use as base reg for loading
          ADDA.L     #1T,A5
          MOVE.W     #0020H,(A5)      ;  all 8 PSP channels with
          MOVE.W     #0020H,(10H,A5) ;  HIGH_TIME
          MOVE.W     #0020H,(20H,A5)
          MOVE.W     #0020H,(30H,A5)
          MOVE.W     #0020H,(40H,A5)
          MOVE.W     #0020H,(50H,A5)
          MOVE.W     #0020H,(60H,A5)
          MOVE.W     #0020H,(70H,A5)
          MOVE.W     #0020H,(80H,A5)
          MOVE.W     #0,ACNT          ;initialize to first entry in
          MOVE.W     #0,BCNT          ;  the ON and OFF tables for
          MOVE.W     #0,CCNT          ;  each phase
          MOVE.W     #0,DCNT
          MOVE.W     #0,AMEM          ;initialize first Markov pair
          MOVE.W     #0,BMEM          ;  to SS
          MOVE.W     #0,CMEM
          MOVE.W     #0,DMEM

;TPUSETUP initializes the random number generator, TPU setup registers
TPUSETUP  MOVE.L     #SEED,D7        ;seed the random no gen
          JSR        RANDOM          ;set up first random nos.
          MOVE.L     #4T,D4          ;init counter for random nos. left
          MOVE.W     #208EH,TMCR.L  ;divide by 64, hi pri interrupt
          MOVE.W     #0740H,TICR.L  ;non-maskable interrupts at vbr+64 (*4)
          MOVE.W     #0000H,CFSR0.L ;chan 1-8 PSP, chan 0 PMM, chan 9 DIO
          MOVE.W     #008CH,CFSR1.L
          MOVE.W     #0CCCCH,CFSR2.L
          MOVE.W     #0CCCBH,CFSR3.L

;show default inputs, ask for changes
INITPROG  MOVE.L     #WELCOME,A2
          JSR        SENDSTR         ;send welcome message
          MOVE.L     #DITH0,A3       ;default is no randomization
```

```
         JSR        ASUB            ;load initial ratio1/angle1 and
         JSR        BSUB            ;  ratio2/angle2 parameters
         JSR        CSUB            ;  for each phase
         JSR        DSUB
         JSR        SCHEME

;TPUFINAL only after all setup is done, and TPU is ready to go!
;Enables channels 9 and 0, so the VRM can be manually started.
;Gets PSP channels ready for enabling in STRT
TPUFINAL MOVE.W     #0001H,HSQR0.L  ;PSP angle-time mode
         MOVE.W     #5557H,HSQR1.L  ;PMM count mode
         MOVE.W     #000EH,HSRR0.L  ;init host serv 11 for DIO,
         MOVE.W     #0AAA9H,HSRR1.L ;  10 for PSP, 01 for PMM
         MOVE.W     #0200H,CIER.L   ;chan 9 interrupt enabled for STRT
         MOVE.W     CISR.L,D0       ;two steps to negate
         MOVE.W     #0,CISR.L       ;  int status flag
         MOVE.B     #1,FLAG9.L      ;flag to count # STRT interrupts
         MOVE.W     #000CH,CPR0.L   ;High priority for DIO for STRT
         MOVE.W     #0003H,CPR1.L   ;High priority for PMM always

;*********************************************************************
;ALLDAY is where the program sits, waiting for user input.  Timing signals
;for motor control are interrupt driven.  No interrupt is required for
;communications.
ALLDAY   MOVE.L     #CMD_SUM1,A2    ;give command summary
         JSR        SENDSTR
         CLR.L      D1
         JSR        ONECHAR         ;wait (forever) for user input,
         JSR        CRLF            ;then match for proper subroutine
         CMPI.B     #88T,D1         ;X?
         BEQ        EXIT
         CMPI.B     #120T,D1        ;x?
         BEQ        EXIT
         CMPI.B     #78T,D1         ;N?
         BEQ        NOMINAL
         CMPI.B     #110T,D1        ;n?
         BEQ        NOMINAL
         CMPI.B     #72T,D1         ;H?
         BEQ        HELP
         CMPI.B     #104T,D1        ;h?
         BEQ        HELP
         CMPI.B     #83T,D1         ;S?
         BEQ        SPEED
         CMPI.B     #115T,D1        ;s?
         BEQ        SPEED
         CMPI.B     #82T,D1         ;R?
         BEQ        RNDMIZE
         CMPI.B     #114T,D1        ;r?
         BEQ        RNDMIZE
BADCHAR  MOVE.L     #ERROR2,A2      ;not a valid character
         JSR        SENDSTR
         JMP        ALLDAY
NOMINAL  JSR        CHGNOM
         JMP        ALLDAY
EXIT     JSR        CLRTPU
         MOVE.L     #EXIT_MSG,A2
         JSR        SENDSTR
SITHERE  NOP
         JMP        SITHERE
HELP     MOVE.L     HELP_MSG,A2
         JSR        SENDSTR
         JMP        ALLDAY
SPEED    JSR        SPD
         JMP        ALLDAY
RNDMIZE  JSR        SCHEME
         JMP        ALLDAY

;*********************************************************************
;WAIT_IN is used during the initialization routine to wait for a
;2 digit input number.
;Returns the char in D1 after echoing back to monitor. To allow
;use of backspace to delete, waitin waits for a carriage return
;before returning to the initialization routine. Upon return, the 2
;ascii number digits are in D0.
WAIT_IN  MOVE.L     #CHBUF,A5       ;CHBUF is char buff (stack)
         CLR.L      D2              ;clr D2, ready to count digits
         CLR.L      D0              ;clr D0, ready to receive answer
```

```
WAIT1     BTST      #6T,SCSRLOW.L  ;is RDR full? check RDRF bit
          BEQ       WAIT1          ;RDRF = 0, Z = 1, no input yet
          MOVE.W    SCSR.L,D1      ;arm SCSR clearing mechanism
          MOVEQ.L   #0,D1          ;clear D1
          MOVE.B    SCDR.L,D1      ;ascii char in D1
          CMPI      #BS,D1         ;is char a backspace?
          BNE       WAIT2          ;if no, jump
          CMPI.B    #0,D2          ;beginning of buffer?
          BEQ       WAIT1          ;if yes, wait for next char
          JSR       SENDCHAR       ;echo backspace
          MOVE.B    -(A5),D1       ;pop char stack (delete char)
          SUBQ.B    #1T,D2
          JMP       WAIT1          ;wait for next char
WAIT2     CMPI      #CR,D1         ;is char a carriage ret?
          BNE       WAIT3          ;if no, jump
          JSR       CRLF           ;send CR,LF
          CMPI      #2,D2          ;have 2 digits been received?
          BNE       WAITONE        ;  if no - retain default value?
          MOVE.W    CHBUF.L,D0     ;  if yes - done receiving input
          JMP       WAITDONE
WAITONE   CMPI      #0,D2
          BNE       WAITERR        ;if equal, retain default value
WAITDONE  RTS
WAITERR   MOVE.L    #ERROR3,A2     ;send error msg for wrong digits
          JSR       SENDSTR
          JMP       WAIT_IN        ;try again
WAIT3     CMPI      #2,D2          ;more than 2 digits?
          BNE       WAIT4          ;not full, jump
          MOVE.L    #ERROR1,A2     ;full, get too long error msg
          JSR       SENDSTR        ;send error msg
          JMP       WAIT_IN        ;start over
WAIT4     CMPI      #48T,D1        ;test if valid number
          BGE       WAIT6          ;  ascii 48-57
WAIT5     MOVE.L    #ERROR2,A2     ;if invalid, send error msg
          JSR       SENDSTR
          JMP       WAIT1
WAIT6     CMPI      #57T,D1
          BGT       WAIT5
          JSR       SENDCHAR       ;echo character
          MOVE.B    D1,(A5)+       ;push char onto stack
          ADDI.B    #1,D2          ;update digit count
          JMP       WAIT1          ;wait for next char

;*******************************************************************
;ONECHAR waits for and receives one ascii serial comm
;character, placing it in D1
ONECHAR   BTST      #6T,SCSRLOW.L  ;is RDR full? check RDRF bit
          BEQ       ONECHAR        ;RDRF = 0, Z = 1, no input yet
          MOVE.B    SCDR.L,D1      ;ascii char in D1
          JSR       SENDCHAR       ;echo char to screen
          RTS

;*******************************************************************
;SENDSTR sends a string whose starting address is in A2. Strings end in 00.
SENDSTR   MOVE.B    (A2)+,D3       ;Get next char to send
          BNE       SENDSTR1       ;if not 00, good char, xmit
          RTS                      ;00 char is end of string
SENDSTR1  BTST.B    #7T,SCSRLOW.L  ;prev xmit done? check SCSR TC bit
          BEQ       SENDSTR1       ;TC = 0, Z = 1, xmit busy
          MOVE.B    D3,SCDR.L      ;send char to SCDR
          JMP       SENDSTR        ;send next char

;*******************************************************************
;SENDCHAR sends a single ascii char via serial comm.  The ascii char
;to send is in D1.
SENDCHAR  BTST.B    #7T,SCSRLOW.L  ;prev xmit done? check SCSR TC bit
          BEQ       SENDCHAR       ;TC = 0, Z = 1, xmit busy
          MOVE.B    D1,SCDR.L      ;send char to SCDR
          RTS

;*******************************************************************
;CRLF is a subroutine that sends a carriage return, line feed
CRLF      MOVE.B    #CR,D3
          JSR       SENDCHAR       ;send carriage return
          MOVE.B    #LF,D3
          JSR       SENDCHAR       ;send line feed
          RTS
```

```
;*********************************************************************
;SPD determines rotor speed in rpm, by scaling the pulse period from
;TPU channel 0. RPM =
;[16.777/4 Mcnts/sec * 60 sec/min] / [TCR1 cnts/period * 200 period/rev]
SPD      MOVE.L      PERIOD.L,D0      ;get latest TCR1 cnts
         MOVE.L      #1258275T,D1
         DIVU.L      D1,D0            ;answer in D0
;         JSR         HEX_ASCII
         RTS

;*********************************************************************
;ASC_DEC converts a 2 digit ascii number in D0 to BCD which it returns
;in D0 and hexadecimal which it returns in D1.  Validity of numbers
;was already checked in WAIT_IN
ASC_DEC  SUBI.W      #3030H,D0        ;convert 2 digits from ascii to dec
         MOVE.L      D0,D1            ; by subtracting 48
         ANDI.W      #0FF00H,D1       ;isolate tens digit
         ROR         #8,D1
         MULU.W      #10T,D1          ;multiply by 10
         MOVE.L      D0,D2            ;isolate ones digit
         ANDI.W      #0FFH,D2
         ADD.W       D2,D1            ;D1 holds hex version of number
         MOVE.L      D0,D2            ;move tens digit over 4 in D0
         ANDI.W      #0FH,D0
         ANDI.W      #0F00H,D2
         ROR         #4T,D2
         ADD.W       D2,D0            ;BCD version of current in 0
         RTS

;*********************************************************************
;ONEDIG retrieves a 1 digit num from the user interface, and returns it
;in hex in D1.
ONEDIG    CLR.L      D1
          JSR        ONECHAR         ;get single character
          JSR        CRLF
          CMPI.B     #48T,D1         ;is char a valid number?
          BLT        ONEERR
          CMPI.B     #57T,D1
          BGT        ONEERR
          SUBI.B     #48T,D1         ;convert to hex from ascii
          RTS                        ;done
ONEERR    MOVE.L     #ERROR2,A2      ;here if illegal char
          JSR        SENDSTR
          JMP        ONEDIG          ;try again

;*********************************************************************
;DEC_SEND takes a 2 digit BCD number in D1 and sends it to the screen
;in tenths, in the form #.#
DEC_SEND  MOVE.B     D1,DECSTOR.L    ;store BCD value
          ANDI.W     #00F0H,D1       ; isolate MS digit
          ROR        #04T,D1         ; put in lower 4 bits
          ADDI.B     #48T,D1         ; convert to ascii #
          JSR        SENDCHAR        ;send MS digit
          MOVE.L     #DECPT,A2     ;send decimal point
          JSR        SENDSTR
          MOVE.L     #0,D1           ; clear D1
          MOVE.B     DECSTOR.L,D1    ; load decimal value of cur
          ANDI.B     #0FH,D1         ; isolate LS digit
          ADDI.B     #48T,D1         ; convert to ascii #
          JSR        SENDCHAR        ;send LS digit
          RTS

;*********************************************************************
;SCHEME allows the user to change randomization schemes.  This subroutine
;must be changed if a new randomization scheme choice is added.
SCHEME    MOVE.L     #RANDMSG,A2     ;tell user current scheme
          JSR        SENDSTR
SCHEME0   CMPA.L     #DITH0,A3       ;is current scheme DITH0?
          BNE        SCHEME1
          MOVE.L     #RMSG0,A2
          JSR        SENDSTR
          JMP        CHGSCH
SCHEME1   CMPA.L     #DITH1,A3       ;is current scheme DITH1?
          BNE        SCHEME2
          MOVE.L     #RMSG1,A2
          JSR        SENDSTR
          JMP        CHGSCH
```

```
SCHEME2  CMPA.L   #DITH2,A3      ;is current scheme DITH2?
         BNE      SCHEME3
         MOVE.L   #RMSG2,A2
         JSR      SENDSTR
         JMP      CHGSCH
SCHEME3  CMPA.L   #DITH3,A3      ;is current scheme DITH3?
         BNE      SCHEME4
         MOVE.L   #RMSG3,A2
         JSR      SENDSTR
         JMP      CHGSCH
SCHEME4  CMPA.L   #DITH4,A3      ;is current scheme DITH4?
         BNE      SCHEME5
         MOVE.L   #RMSG4,A2
         JSR      SENDSTR
         JMP      CHGSCH
SCHEME5  CMPA.L   #DITH5,A3      ;is current scheme DITH5?
         BNE      SCHEME6
         MOVE.L   #RMSG5,A2
         JSR      SENDSTR
         JMP      CHGSCH
SCHEME6  CMPA.L   #DITH6,A3      ;is current scheme DITH6?
         BNE      CHGSCH         ;becomes SCHEME7 if added
         MOVE.L   #RMSG6,A2
         JSR      SENDSTR
         JMP      CHGSCH
CHGSCH   MOVE.L   #RANDMSG1,A2   ;change scheme?
         JSR      SENDSTR
         CLR.L    D1
         JSR      ONECHAR        ;wait for user input in D1
         CMPI.B   #CR,D1         ;is it CR?
         BNE      CHGSCH0        ;branch if yes, change scheme
         MOVE.L   #RANDMSG3,A2   ;no change, say so, then leave
         JSR      SENDSTR
         JMP      ENDSCHEM
CHGSCH0  MOVE.L   #RANDMSG2,A2   ;send new scheme message
         JSR      SENDSTR
         CMPI.B   #48T,D1        ;is it scheme 0?
         BNE      CHGSCH1        ;no, try 1
         MOVE.L   #RMSG0,A2
         JSR      SENDSTR
         MOVE.L   #DITH0,A3      ;globally load scheme 0 address
         JMP      ENDSCHEM
CHGSCH1  CMPI.B   #49T,D1        ;is it scheme 1?
         BNE      CHGSCH2        ;no, try 2
         MOVE.L   #RMSG1,A2
         JSR      SENDSTR
         JSR      ONDITH
         MOVE.L   #DITH1,A3      ;globally load scheme 1 address
         JMP      ENDSCHEM
CHGSCH2  CMPI.B   #50T,D1        ;is it scheme 2?
         BNE      CHGSCH3        ;no, try 3
         MOVE.L   #RMSG2,A2
         JSR      SENDSTR
         JSR      OFFDITH
         MOVE.L   #DITH2,A3      ;globally load scheme 2 address
         JMP      ENDSCHEM
CHGSCH3  CMPI.B   #51T,D1        ;is it scheme 3?
         BNE      CHGSCH4        ;no, try 4
         MOVE.L   #RMSG3,A2
         JSR      SENDSTR
         JSR      ONDITH         ;get degrees of ON dither
         JSR      OFFDITH        ;get degrees of OFF dither
         MOVE.L   #DITH3,A3      ;globally load scheme 3 address
         JMP      ENDSCHEM
CHGSCH4  CMPI.B   #52T,D1        ;is it scheme 4?
         BNE      CHGSCH5        ;no, try 5
         MOVE.L   #RMSG4,A2
         JSR      SENDSTR
         JSR      OFFDITH        ;get degrees of OFF dither
         MOVE.L   #DITH4,A3      ;globally load scheme 4 address
         JMP      ENDSCHEM
CHGSCH5  CMPI.B   #53T,D1        ;is it scheme 5?
         BNE      CHGSCH6        ;no, try 6
         MOVE.L   #RMSG5,A2
         JSR      SENDSTR
         JSR      OFFDITH        ;get degrees of OFF dither
         MOVE.L   #DITH5,A3      ;globally load scheme 5 address
```

```
         JMP       ENDSCHEM
CHGSCH6  CMPI.B    #54T,D1         ;is it scheme 6?
         BNE       ERRSCHEM        ;no, must be error
         MOVE.L    #RMSG6,A2
         JSR       SENDSTR
         JSR       OFFDITH         ;get degrees of OFF dither
         MOVE.L    #DITH6,A3       ;globally load scheme 6 address
         JMP       ENDSCHEM
ERRSCHEM MOVE.L    #ERROR5,A2      ;invalid scheme chosen
         JSR       SENDSTR
         JMP       CHGSCH
ENDSCHEM RTS

;*******************************************************************
;GETDITH asks for 1 digit for dithering, and the only acceptable values
;are 1 and 2.  Returns answer to the screen, and returns hex dither value
;in D1.
GETDITH  JSR       ONEDIG          ;get # degrees of dither
         CMPI.B    #0,D1           ;0 is unacceptable
         BNE       GETDITH2
DITHERR  MOVE.L    #ERROR2,A2
         JSR       SENDSTR
         JMP       GETDITH         ;try again for valid digit
GETDITH2 CMPI.B    #3,D1           ;>2 is unacceptable
         BLT       GETDITH3        ;OK digit (1 or 2)
         JMP       DITHERR
GETDITH3 MOVE.L    #CURINST1,A2    ;return # degrees to screen
         JSR       SENDSTR
         ADDI.B    #48T,D1
         JSR       SENDCHAR
         MOVE.L    #DEGNOW1,A2
         JSR       SENDSTR
         SUBI.B    #48T,D1         ;restore hex to D1
GETDITH4 RTS

;*******************************************************************
;ONDITH asks for degrees of ON dither, and places value in DITH1DEG
ONDITH   MOVE.L    #DITH1MSG,A2    ;ask for # degrees of ON dither
         JSR       SENDSTR
         JSR       GETDITH
         MOVE.L    D1,DITH1DEG.L   ;store # degrees of dither
         RTS

;*******************************************************************
;OFFDITH asks for degrees of OFF dither, and places value in DITH2DEG
OFFDITH  MOVE.L    #DITH2MSG,A2    ;ask for # degrees of OFF dither
         JSR       SENDSTR
         JSR       GETDITH
         MOVE.L    D1,DITH2DEG.L   ;store # degrees of dither
         RTS

;*******************************************************************
;STRT is executed twice, when the interrupt is enabled and when
;the motor is manually started. FLAG9 is used to discount the first
;interrupt, since enabling a DIO channel causes an interrupt. 2nd int
;is when the first index pulse is received.  This is the only time
;channel 9 is used.  It uses channel I from the shaft encoder
;as an input, and reacts to the first transit to produce the int
;which accesses this routine.  The interrupt processing activates PSP
;channels 1-8, and deactivates channel 9. Forces C phase to be
;energized first (function of shaft encoder code wheel alignment).
STRT     MOVE.W    CISR.L,D0       ;two steps to negate
         MOVE.W    #0,CISR.L       ;  int status flag
         CLR.L     D0
         MOVE.B    FLAG9.L,D0      ;check interrupt count
         BNE       NOTYET          ;if turn-on int, ignore
         MOVE.W    #001EH,CIER.L   ;chan 1,2,3,4 interrupts enabled
         MOVE.W    #0000H,CPR0.L   ;Hi pri CON, PMM
         MOVE.W    #00C3H,CPR1.L   ; No priority for others
         JMP       STRTEND         ;done with STRT interrupt
NOTYET   SUBI.B    #1,D0           ;update STRT int counter
         MOVE.B    D0,FLAG9.L
STRTEND  RTE

;*******************************************************************
;CLRTPU is called during initialization and during the stop/exit
;routine.  It places all 8 phase TPU channels in DIO mode, and clears
```

```
;all outputs to zero.  It also cycles the OFF signals to clear all
;the hardware latches that hold the control signals.  VRM HV DC supply
;to the inverter should not be energized until after this routine is called,
;to ensure that all phases are off.
CLRTPU    MOVE.W      #00H,CPR0.L     ;turn off all TPU channels
          MOVE.W      #00H,CPR1.L
          MOVE.W      #00H,CIER.L     ;disable all TPU interrupts
          MOVE.W      #0008H,CFSR1.L ;TPU channels 1-9 DIO
          MOVE.W      #8888H,CFSR2.L
          MOVE.W      #8880H,CFSR3.L
          MOVE.W      #0001H,HSRR0.L ;set hi output on OFF channels, low
          MOVE.W      #56A8H,HSRR1.L ; output on ON channels.
          MOVE.W      #0003H,CPR0.L  ;go, service 8 ON/OFF TPU channels
          MOVE.W      #0FD54H,CPR1.L
          JSR         CLRTPU1
          MOVE.W      #0002H,HSRR0.L ;set lo output on OFF channels
          MOVE.W      #0AAA8H,HSRR1.L
          JSR         CLRTPU1
          MOVE.W      #00H,CPR0.L     ;turn off all TPU channels
          MOVE.W      #00H,CPR1.L
          RTS

CLRTPU1   CLR.L       D0
          MOVE.W      HSRR0.L,D0      ;give TPU time to service all
          ADD.W       HSRR1.L,D0      ;  channels
          BNE         CLRTPU1         ;done yet?
          RTS

;**********************************************************************
;CHGNOM allows changing the nominal ON and OFF points from the
;values stores in PHASETAB which holds RATIO and ANGLE parameters
;for all 8 PSP channels. This adjustment may be necessary depending
;on the accuracy of the values calculated from the shaft encoder
;placement.  CHGNOM can also restore the nominal points.
CHGNOM    MOVE.L      #NOMMSG8,A2     ;restore nominal points?
          JSR         SENDSTR         ;ask
          JSR         MODECHG
          BEQ         CHGNOM1
          MOVEA.L     #AONNOM,A2      ;address of 1st nominal pt
          MOVEA.L     #AONTAB,A1      ;1st address of point table
          MOVE.L      #24T,D1         ;counter for 24 long words
NOMBACK   MOVE.L      (A2)+,(A1)+     ;restore nominal point
          SUBI.L      #1T,D1          ;update countdown
          BNE         NOMBACK
CHGNOM1   MOVE.L      #NOMMSG,A2      ;change modes?  ask
          JSR         SENDSTR
          JSR         MODECHG         ;get answer in D0
          BEQ         CHGEND          ;if no, done
ONQUEST   MOVE.L      #NOMMSG1,A2     ;change ON pts?
          JSR         SENDSTR         ;ask
          JSR         MODECHG         ;get answer
          BEQ         OFFQUEST        ;if no, change OFF pts?
ONANGQ    MOVE.L      #NOMMSG6,A2     ;adjust ON angle?
          JSR         SENDSTR         ;ask
          JSR         MODECHG         ;get answer
          BEQ         ONRAT           ;if no, adjust ON ratio?
          MOVE.L      #NOMMSG2,A2     ;subtract or add?
          JSR         SENDSTR         ;ask; y = add, n = sub
          JSR         MODECHG         ;get answer in D0
          BEQ         SUBON           ;n = subtract 1 from angle
ADDON     CLR.L       D1              ;set up counter
          MOVE.L      #AONTAB,A1      ;load address of ONTABS
          JSR         ADDPT           ; add 1 to ANGLE
          BRA         ONANGQ          ;change angle again?
SUBON     CLR.L       D1              ;set up counter
          MOVE.L      #AONTAB,A1      ;load address of ONTABS
          JSR         SUBPT           ; sub 1 from ANGLE
          BRA         ONANGQ          ;change angle again?
ONRAT     MOVE.L      #NOMMSG4,A2     ;change ON RATIO?
          JSR         SENDSTR         ;ask
          JSR         MODECHG         ;get answer in D0
          BEQ         OFFQUEST        ;if no, go to OFF pt questions
          MOVE.L      #AONTAB,A1      ;load address of ONTABS
          CLR.L       D1              ;set up counter
          JSR         ADDRAT
          BRA         ONRAT           ;another 1/4 degree?
OFFQUEST  MOVE.L      #NOMMSG3,A2     ;change OFF pts?
```

```
          JSR       SENDSTR        ;ask
          JSR       MODECHG        ;get answer
          BEQ       CHGEND         ;if no, done
OFFANGQ   MOVE.L    #NOMMSG7,A2    ;adjust OFF angle?
          JSR       SENDSTR        ;ask
          JSR       MODECHG        ;get answer
          BEQ       OFFRAT         ;if no, adjust OFF ratio?
          MOVE.L    #AOFFTAB,A1    ;load address of OFFTABS
          MOVE.L    #NOMMSG2,A2    ;subtract or add?
          JSR       SENDSTR        ;ask; y = add, n = sub
          JSR       MODECHG        ;get answer in D0
          BEQ       SUBOFF         ;n = subtract 1 from angle
ADDOFF    MOVE.L    #AOFFTAB,A1    ;load address of OFFTABS
          CLR.L     D1             ;set up counter
          JSR       ADDPT          ; add 1 to ANGLE
          BRA       OFFANGQ        ;change OFF ANGLE again?
SUBOFF    MOVE.L    #AOFFTAB,A1    ;load address of ONTABS
          CLR.L     D1             ;set up counter
          JSR       SUBPT          ; sub 1 from ANGLE
          BRA       OFFANGQ        ;change OFF ANGLE again?
OFFRAT    MOVE.L    #NOMMSG5,A2    ;change OFF RATIO?
          JSR       SENDSTR        ;ask
          JSR       MODECHG        ;get answer in D0
          BEQ       OFFQUEST       ;if no, go to OFF pt questions
          CLR.L     D1             ;set up counter
          MOVE.L    #AOFFTAB,A1    ;load address of ONTABS
          JSR       ADDRAT
          BRA       OFFRAT         ;another 1/4 degree?
CHGEND    RTS

;*********************************************************************
;ADDPT adds 1.8 mechanical degrees (1 angle) to the present
;nominal point
ADDPT     MOVE.W    (A1),D0        ;get ratio/angle
          ANDI.L    #0FFH,D0       ;isolate angle
          CMPI.B    #0C6,D0        ;is angle 198?
          BNE       ADDPT1         ;if angle isn't 198, no problem
          MOVE.W    (A1),D0        ;get ratio/angle
          CMPI.L    #8000,D0       ;if angle 198 and
          BGE       ADDZERO        ; big ratio (~ "199")
          BRA       ADDPT1         ; small ratio, can increase to "199"
ADDZERO   MOVE.W    (A1),D0        ;since angle is 198, ratio big,
          ANDI.L    #BITS8,D0     ; set ang to zero
          SUBI.L    #8000H,D0      ;decrement ratio by 1 angle
          MOVE.L    (A1),D3        ;get original point
          ADD.L     D3,D0          ;update point
          MOVE.L    D0,(A1)        ;place updated point in memory
          BRA       ADDPT2
ADDPT1    MOVE.W    (A1),D0        ;reload ratio/angle
          ADDI.B    #1T,D0         ;increase angle
          MOVE.W    D0,(A1)        ;place updated point in memory
ADDPT2    ADDA.L    #2T,A1
          ADDI.B    #1T,D1         ;increment counter
          CMPI.B    #24T,D1        ;cycled thru all 4 phase tables?
          BNE       ADDPT
ADDEND    RTS

;**************************f*****************************************
;SUBPT subtracts 1.8 mechanical degrees (1 angle) from the present
;nominal point
SUBPT     MOVE.W    (A1),D0        ;get ratio/angle
          ANDI.L    #0FFH,D0       ;isolate angle
          BNE       SUBPT1         ;if angle isn't 0, no problem
          ADDI.L    #198T,D0       ;load 198 (2 angles < 0)
          ADDI.L    #8000H,D0      ;increment ratio by 1 angle
          CLR.L     D3
          MOVE.W    (A1),D3        ;get original point (w/ 0 ang)
          ADD.L     D3,D0          ;update point
          MOVE.W    D0,(A1)        ;place updated point in memory
          BRA       SUBPT2
SUBPT1    MOVE.W    (A1),D0        ;reload ratio/angle
          SUBI.B    #1T,D0         ;decrease angle
          MOVE.W    D0,(A1)        ;place updated point in memory
SUBPT2    ADDA.L    #2T,A1
          ADDI.B    #1T,D1         ;increment counter
          CMPI.B    #24T,D1        ;cycled thru all 4 phase tables?
          BNE       SUBPT
```

```
SUBEND    RTS

;*********************************************************************
;ADDRAT adds 1/2 degree to the nominal point by adding to RATIO,
;incrementing ANGLE if necessary.  1/2 degree = ratio of 36.
ADDRAT    CLR.L      D0
          MOVE.W      (A1),D0        ;get ratio/angle
          ANDI.L      #0FFH,D0       ;isolate angle
          CMPI        #198T,D0       ;compare to max # teeth
          BNE         ANGPT1         ;if angle isn't 198, no problem
          MOVE.W      (A1),D0        ;reload ratio/angle
          CMPI.L      #0DC00,D0      ;if angle 198, ratio >= 220T?
          BLT         ANGPT1         ;if small ratio, go increase ratio
ANGZERO   MOVE.W      (A1),D0        ;get ratio/angle again
          SUBI.L      #6B00H,D0      ;decrement ratio by 1.5 deg (107T)
          ANDI.L      #0FF00,D0      ;make angle 0
          MOVE.W      D0,(A1)        ;place updated point in memory
          BRA         ANGPT2
ANGPT1    MOVE.W      (A1),D0        ;get ratio/angle again
          ADDI.L      #2400H,D0      ;ratio by 1/2 mechanical degree
          CMPI.L      #10000H,D0     ;test if ratio too big
          BLT         ANGPT3         ;if not too big
          SUBI.L      #8000H,D0      ;subtract 128 from ratio
          ADDI.B      #1H,D0         ;add 1 to angle
ANGPT3    MOVE.W      D0,(A1)        ;place updated point in memory
ANGPT2    ADDA.L      #2T,A1
          ADDI.B      #1T,D1         ;increment counter
          CMPI.B      #24T,D1        ;cycled thru all 4 phase tables?
          BNE         ADDRAT
ANGEND    RTS

;*********************************************************************
;PHASEINT is processing for the interrupt generated by the
;PHASEON signal.  PHASEINT calculates next ON and OFF points for C's
;opposite phase, phase A.  A3 always holds the address of the
;randomization scheme chosen by the user.  Since PSP generates
;two interrupts per evolution, after 1st, disable interrupt.
;Re-enable interrupt during opposite phase's interrupt.
AINT      JSR         TEMPIN          ;store regs
          MOVE.W      CISR.L,D0       ;two steps to negate
          MOVE.W      #0,CISR.L       ;  int status flag
          MOVE.W      #0004H,CIER.L   ;prevent 2nd A int, enable B int
          MOVE.W      #0003H,CPR0.L   ;Hi pri DOFF, BON, AON, PMM
          MOVE.W      #003FH,CPR1.L   ;No priority for others
          JSR         ASUB            ;allows init using ASUB
          JSR         TEMPOUT         ;restore regs
          MOVE.W      #8080H,HSRR1.L  ;immediate update of C points
AINT1     RTE
ASUB      MOVE.L      #CONTAB,A4      ;address of CONTAB
          MOVE.W      CCNT.L,D0       ;get placeholder in CxTAB
          JSR         GETONOFF        ;get ratios, angles (uses A4,D0)
          MOVE.W      D0,CCNT.L       ;store updated CCNT
          CLR.L       D1
          CLR.L       D2
          CLR.L       D3
          MOVE.W      CMEM.L,D3       ;in case Markov dither used
          JSR         (A3)            ;call proper randomization scheme
          MOVE.W      D3,CMEM.L       ;in cased Markov dither used
          MOVE.L      ON.W,CONREG.L   ;load C ON RATIO1/ANGLE1
          MOVE.L      OFF.W,COFFREG.L ;load C OFF RATIO1/ANGLE1 address
ASUB1     RTS

BINT      JSR         TEMPIN          ;store regs
          MOVE.W      CISR.L,D0       ;two steps to negate
          MOVE.W      #0,CISR.L       ;  int status flag
          MOVE.W      #0008H,CIER.L   ;prevent 2nd B int, enable C int
          MOVE.W      #0000H,CPR0.L   ;Hi pri AOFF, BON, CON, PMM
          MOVE.W      #0CF3H,CPR1.L   ;No priority for others
          JSR         BSUB            ;allow init using BSUB
          JSR         TEMPOUT         ;restore regs
          MOVE.W      #0002H,HSRR0.L  ;immediate update of D points
          MOVE.W      #0200H,HSRR1.L  ;immediate update of D points
BINT1     RTE
BSUB      MOVE.L      #DONTAB,A4      ;address of DONTAB
          MOVE.W      DCNT.L,D0       ;get placeholder in DxTAB
          JSR         GETONOFF        ;get ratios, angles (uses A4,D0)
          MOVE.W      D0,DCNT.L       ;store updated DCNT
```

```
          CLR.L     D1
          CLR.L     D2
          CLR.L     D3
          MOVE.W    DMEM.L,D3         ;in case Markov dither used
          JSR       (A3)              ;call proper randomization scheme
          MOVE.W    D3,DMEM.L         ;in case Markov dither used
          MOVE.L    ON.W,DONREG.L     ;load D ON RATIO1/ANGLE1
          MOVE.L    OFF.W,DOFFREG.L ;load D OFF RATIO1/ANGLE1 address
BSUB1     RTS

CINT      JSR       TEMPIN            ;store regs
          MOVE.W    CISR.L,D0         ;two steps to negate
          MOVE.W    #0,CISR.L         ;  int status flag
          MOVE.W    #0010H,CIER.L   ;prevent 2nd C int, enable D int
          MOVE.W    #33C3H,CPR1.L   ;Hi priority BOFF, CON, DON, PMM
          MOVE.B    #1,CFLAG          ;set flag for CINT for DITH6
          JSR       CSUB              ;allow init using CSUB
          MOVE.B    #0,CFLAG          ;clear CINT flag for DITH6
          JSR       TEMPOUT           ;restore regs
          MOVE.W    #0808H,HSRR1.L ;immediate update of A points
CINT1     RTE
CSUB      MOVE.L    #AONTAB,A4        ;address of AONTAB
          MOVE.W    ACNT.L,D0         ;get placeholder in AxTAB
          JSR       GETONOFF          ;get ratios, angles (uses A4,D0)
          MOVE.W    D0,ACNT.L         ;store updated ACNT
          CLR.L     D1
          CLR.L     D2
          CLR.L     D3
          MOVE.W    AMEM.L,D3         ;in case Markov dither used
          JSR       (A3)              ;call proper randomization scheme
          MOVE.W    D3,AMEM.L         ;in case Markov dither used
          MOVE.L    ON.W,AONREG.L     ;load A ON RATIO1/ANGLE1
          MOVE.L    OFF.W,AOFFREG.L ;load A OFF RATIO1/ANGLE1 address
CSUB1     RTS

DINT      JSR       TEMPIN            ;store regs
          MOVE.W    CISR.L,D0         ;two steps to negate
          MOVE.W    #0,CISR.L         ;  int status flag
          MOVE.W    #0002H,CIER.L   ;prevent 2nd D int, enable A int
          MOVE.W    #0C30FH,CPR1.L ;Hi priority AON,DON,COFF,PMM
          JSR       DSUB              ;allow init using DSUB
          JSR       TEMPOUT           ;restore regs
          MOVE.W    #2020H,HSRR1.L ;immediate update of B points
DINT1     RTE
DSUB      MOVE.L    #BONTAB,A4        ;address of BONTAB
          MOVE.W    BCNT.L,D0         ;get placeholder in BxTAB
          JSR       GETONOFF          ;get ratios, angles (uses A4,D0)
          MOVE.W    D0,BCNT.L         ;store updated BCNT
          CLR.L     D1
          CLR.L     D2
          CLR.L     D3
          MOVE.W    BMEM.L,D3         ;in case Markov dither used
          JSR       (A3)              ;call proper randomization scheme
          MOVE.W    D3,BMEM.L         ;in case Markov dither used
          MOVE.L    ON.W,BONREG.L     ;load B ON RATIO1/ANGLE1
          MOVE.L    OFF.W,BOFFREG.L ;load B OFF RATIO1/ANGLE1 address
DSUB1     RTS

;**********************************************************************
TEMPIN    MOVE.L    D0,TEMP0.L        ;store D0 value
          MOVE.L    D1,TEMP1.L        ;store D1 value
          MOVE.L    D2,TEMP2.L        ;store D2 value
          MOVE.L    D3,TEMP3.L        ;store D3 value
          RTS

TEMPOUT   MOVE.L    TEMP0.L,D0        ;restore D0 value
          MOVE.L    TEMP1.L,D1        ;restore D1 value
          MOVE.L    TEMP2.L,D2        ;restore D2 value
          MOVE.L    TEMP3.L,D3        ;restore D3 value
          RTS

;**********************************************************************
;GETONOFF gets the nominal ON and OFF values of ratio and angle from
;the appropriate phase's tables, given ONTAB in A4, and
;CNT in D0.  Updates CNT for next interrupt.  Generic for any phase.
;Based on order in memory, OFF values 48 words later than ON values.
GETONOFF  ADDA.L    D0,A4             ;to access proper ONTAB entry
```

```
         MOVE.W      (A4),ON.L       ;get ON ratio/angle
         MOVE.W      (48T,A4),OFF.L  ;get OFF ratio/ang
         ADDI.B      #2T,D0          ;update CNT (by 2 bytes)
         CMPI.B      #12T,D0         ;is it at end of table?
         BNE         GETEND
         MOVE.B      #0,D0
GETEND   RTS                         ;returns new CNT in D0

;*********************************************************************
;DITH0 is randomization scheme 0, no randomization.  Nominal ON
;and OFF points are used.
DITH0    RTS

;*********************************************************************
;DITH1 is randomization scheme 1, uniform distribution, dithering the
;ON point only by 1 or 2 degrees as selected by the user.  Scaling is
;used since pulse counts represent 1.8 degrees with the 200 slot
;code wheel.  See chapter 3.  The random number is 8 bits, 2 pulses,
;or up to 3.6 mechanical degrees. Mult by # deg, divide by 3.6 for
;proper scaling of ratio.  No dithering scheme exceeds 3.6 degrees
;of dithering, so masking with #BITS8 is valid.
DITH1    JSR         GETRAND          ;Put 8 random ratio bits in D5
         MULU.L      DITH1DEG.L,D5    ;multiply ratio by # deg
         MULU.L      #10T,D5          ;multiply by 10/36 to divide
         DIVU.L      #36T,D5          ;  by 3.6
         AND.L       #BITS8,D5        ;isolate ratio bits after math
         CLR.L       D1
         MOVE.W      (ON),D1
         JSR         RATANG           ;change ON point
         MOVE.W      D1,(ON)
         RTS

;*********************************************************************
;DITH2 is randomization scheme 2, uniform distribution, dithering the
;OFF point only by 1 or 2 degrees as selected by the user.  Scaling is
;used since pulse counts represent 1.8 degrees with the 200 slot
;code wheel.  See chapter 3.  The random number is 8 bits, 2 pulses,
;or up to 3.6 mechanical degrees. Mult by # deg, divide by 3.6 for
;proper scaling of ratio.  No dithering scheme exceeds 3.6 degrees
;of dithering, so masking with #BITS8 is valid.
DITH2    JSR         GETRAND          ;Put 8 random ratio bits in D5
         MULU.L      DITH2DEG.L,D5    ;multiply ratio by # deg
         MULU.L      #10T,D5          ;multiply by 10/36 to divide
         DIVU.L      #36T,D5          ;  by 3.6
         AND.L       #BITS8,D5        ;isolate ratio bits after math
         CLR.L       D1
         MOVE.W      (OFF),D1
         JSR         RATANG           ;change OFF point
         MOVE.W      D1,(OFF)
         RTS

;*********************************************************************
;DITH3 is randomization scheme 3, uniform distribution, dithering the
;ON and OFF points independently by only by 1 or 2 degrees
;as selected by the user.
DITH3    JSR         DITH1
         JSR         DITH2
         RTS

;*********************************************************************
;DITH4 is randomization scheme 4, 2 state MARKOV chain described in
;Chapter 4.  A short state gives the nominal OFF pt, a long state
;gives DITH2DEG degrees of delay of the nominal OFF pt.  RATIO of
;71 corresponds to 1 mechanical degree
DITH4    JSR         GETRAND           ;get random number
         JSR         S_OR_L            ;get state, look at history
         CMPI.B      #1,D2             ;D2 is 1 if 2nd trial nec
         BEQ         DITH4             ;do 2nd trial if 1st LLL or SSS
         CMPI.L      #0T,LSFLAG.L
         BEQ         DITH4END          ;if S, no dither
         MOVE.L      (DITH2DEG).L,D5   ;get degrees of dither
         MULU.L      #71T,D5           ;scale dither to #degrees
         ROL.L       #8T,D5            ;place in ratio bits
         MOVE.W      (OFF),D1
         JSR         RATANG            ;change OFF point
         MOVE.W      D1,(OFF)
DITH4END RTS
```

```
;*********************************************************************
;DITH5 is randomization scheme 5, which uses the same Markov scheme as
;DITH4 that is described in Chapter 4.  Instead of 2 discrete states,
;a uniform distribution is used where S represents 0 to half size, and
;L represents half to full size of the possible dithering value.  Only
;the OFF point is dithered.  Uses the same scaling as DITH1.
DITH5    JSR        GETRAND            ;get random number
         JSR        S_OR_L             ;get state, look at history
         CMPI.B     #1,D2              ;D2 is 1 if 2nd trial nec
         BEQ        DITH5              ;do 2nd trial if 1st LLL or SSS
         MULU.L     (DITH2DEG).L,D5    ;multiply ratio by # deg
         MULU.L     #10T,D5            ;multiply by 10/36 to divide
         DIVU.L     #36T,D5            ;  by 3.6
         AND.L      #BITS8,D5          ;isolate ratio bits after math
         CLR.L      D1
         MOVE.W     (OFF),D1
         JSR        RATANG             ;change OFF point
         MOVE.W     D1,(OFF)
         RTS

;*********************************************************************
;DITH6 is randomization scheme 6, which uniformly randomizes phase A
;only, using the method of DITH2.  Checks CFLAG to see if this is
;the CINT, which processes phase A.
DITH6    CMPI.B     #1,CFLAG
         BNE        DITH6END           ;don't dither unless phase A
         JSR        DITH2
DITH6END RTS


;*********************************************************************
;S_OR_L is a subroutine that determines if the present random number
;is short or long, by comparing msb of the number in D5 to 1
S_OR_L   BTST.L     #15T,D5
         BEQ        IS_S
IS_L     JSR        LONGP
         MOVE.B     #1T,LSFLAG.L
         BRA        SLEND
IS_S     JSR        SHORTP
         MOVE.B     #0T,LSFLAG.L
SLEND    RTS

;*********************************************************************
;LONGP is the subroutine that processes a long pulse in Markov
;schemes.  See Chapters 4, 5.
LONGP    CMPI.B     #00H,D3            ;get history state - SS?
         BEQ        S_L
         CMPI.B     #01H,D3            ;SL?
         BEQ        SL_L
         CMPI.B     #02H,D3            ;LS?
         BEQ        S_L
LL_L     CMPI.B     #1,D2              ;1st or 2nd trial?
         BEQ        LL_LOK             ;if 2nd trial, LLL is OK
         MOVE.B     #1,D2              ;set flag, allow 2nd trial
         BRA        LONGPEND
LL_LOK   CLR.L      D2                 ;no more trials
         BRA        LONGPEND           ;history remains unchanged
S_L      MOVE.W     #1T,D3             ;history becomes SL
         CLR.L      D2                 ;no more trials
         BRA        LONGPEND
SL_L     MOVE.W     #3T,D3             ;history becomes LL
         CLR.L      D2                 ;no more trials
LONGPEND RTS

;*********************************************************************
;SHORTP is the subroutine that processes a short pulse in Markov
;schemes.
SHORTP   CMPI.B     #00H,D3            ;get history state - SS?
         BEQ        SS_S
         CMPI.B     #01H,D3            ;SL?
         BEQ        L_S
         CMPI.B     #02H,D3            ;LS?
         BEQ        LS_S
L_S      MOVE.W     #2T,D3             ;prev SL or SS, next LS
         CLR.L      D2                 ;no more trials
         BRA        SHRTPEND
LS_S     MOVE.W     #0T,D3             ;next SS
```

```
        CLR.L      D2                 ;no more trials
        BRA        SHRTPEND
SS_S    CMPI.B     #1,D2              ;1st or second trial?
        BEQ        SS_SOK             ;if 2nd trial, SSS is OK
        MOVE.B     #1,D2              ;set flag, allow 2nd trial
        BRA        SHRTPEND
SS_SOK  CLR.L      D2                 ;no more trials, history SS
SHRTPEND RTS

;*********************************************************************
;RATANG is a subroutine which takes D5 as RAT, the change to a
;PSP RATIO1 parameter, and D1 as the RATIO/ANGLE values for
;the given ON or OFF point.  Bits 8-15 of D5 are the only bits that
;can be non-zero (i.e. a change in RATIO1).  Changes are always
;in the positive direction (added).  The change RAT is added
;to RATIO1, and ANGLE 1 is changed if necessary.  TPU latency
;problems are ignored.  The word is in the order RATIO1-ANGLE1.
RATANG  ADD.L      D5,D1             ;add the RATIO
RATANG1 CMPI.L     #10000H,D1        ;is there overflow?
        BLT        RATANG3           ; if no, done
        MOVE.L     D1,D0
        AND.L      #0FF,D0           ;isolate present angle
        CMPI.L     #198T,D0
        BNE        RATANG2           ;branch if 199 not an issue
        SUBI.L     #10000H,D1        ;from 198 to 0 is 2 angles
        ANDI.L     #01FF00H,D1       ;make angle 0
        BRA        RATANG1           ;more overflow?
RATANG2 ADDI.L     #1T,D1            ;add 1 to ang (won't exceed 199)
        SUBI.L     #8000H,D1         ;   sub 128 from ratio (1.8 deg)
        BRA        RATANG1           ;check for more overflow
RATANG3 RTS

;*********************************************************************
;GETRAND is a subroutine to get the next random number, which is left
;in D5.  Incorporates RANDOM.
;RANDOM program is a prototype for a pseudo-random number generation routine.
;  The RNG is based on the agorithm in "Random Number Generators: Good Ones
;  Are Hard to Find" by S. Park and K. Miller (Communications of the ACM,
;  Vol. 31, No. 10, pp.1192-1201, OCT 1988).  Specifically, it is modeled after
;  the integer version 2 of their code, which is designed to operate properly
;  with signed integers of max val 2^31-1.  The algorithm is a parametric
;  multiplicative linear congruential generator with multiplier 16807 and prime
;  modulus 2^31 - 1 (both base ten), proposed by D.H. Lehmer in 1952.  Code
;  written by D. J. Perreault, modified by M. C. Smoot
;8 random bits represent 2*1.8 degrees of ratio used in RATIO1 in PSP mode.
GETRAND   MOVE.L     D6,D5          ;D6 holds all random bits left
          AND.L      #BITS8,D5      ;d5 has 8 avail random bits
          SUBI.B     #1,D4          ;dec count of 8 bit seg avail
          BNE        GETRAND1       ;if new random no. unnec
Random:   MOVE.B     #4T,D4         ;# of sets of 8 rand bits avail counter
           divsl.l     #q,d6:d7          ; calc lo:hi (seed mod q:seed div q)
           muls.l      #a,d6             ; calc a*lo --> d6
           muls.l      #r,d7             ; calc r*hi --> d7
           sub.l       d7,d6             ; test = a*lo - r*hi --> d6
           bLE         rndskip1
           move.l      d6,d7             ; test >0, test --> seed
           bra         rndend
rndskip1:  move.l      #m,d7             ; test <=0, test + m --> seed
           add.l       d6,d7             ; d7 will have rand for next calc
           MOVE.l      D7,D6             ; D6 holds rand bits (expendable)
rndend:    JMP          GETRAND2
GETRAND1  ROR.L      #8T,D6         ;if old ok, shift next 8 bits to ready
GETRAND2  RTS

;*********************************************************************
;MODECHG waits for a 1 char input of Y (or y) for yes, ENTER (or
;N or n) for no.  If yes, returns a 1 in D0; if no, returns a 0 in D0.
MODECHG   JSR        ONECHAR        ;get one character
          JSR        CRLF
          CMPI.B     #CR,D1         ;check if Y or N was input
          BEQ        NOCHG
          CMPI.B     #78T,D1        ;N?
          BEQ        NOCHG
          CMPI.B     #110T,D1       ;n?
          BEQ        NOCHG
          CMPI.B     #89T,D1        ;Y?
          BEQ        YESCHG
```

```
         CMPI.B     #121T,D1        ;y?
         BEQ        YESCHG
         MOVE.L     #ERROR2,A2      ;invalid character
         JSR        SENDSTR
         JMP        MODECHG
YESCHG   MOVE.L     #1,D0
         RTS
NOCHG    MOVE.L     #0,D0
         RTS

;*******************************************************************
;phaseONNOM and phaseOFFNOM store the original nominal points,
;determined from experiments to be the optimum ON and OFF
;points.  These values never change.
;phaseONTAB and phaseOFFTAB store the present
;nominal values for phase ON and OFF points, dependent on code wheel
;position.  If code wheel is removed, these values must be reset.
;These are word values, to be loaded in RATIO1/ANGLE1 for the 8
;TPU PSP channels for each of the six rotor poles.
AONNOM   DW    $5CBC,$0616,$3137,$5C58,$067A,$319B
BONNOM   DW    $06C5,$311E,$5C3F,$0661,$3182,$5CA3
CONNOM   DW    $3105,$5C26,$0648,$3169,$5C8A,$06AC
DONNOM   DW    $5C0D,$062F,$3150,$5C71,$0693,$31B4
AOFFNOM  DW    $1500,$4021,$6B42,$1564,$4085,$6BA6
BOFFNOM  DW    $4008,$6B29,$154B,$406C,$6B8D,$15AF
COFFNOM  DW    $6B10,$1532,$4053,$6B74,$1596,$40B7
DOFFNOM  DW    $1519,$403A,$6B5B,$157D,$409E,$6BBF

AONTAB   DW    $5CBC,$0616,$3137,$5C58,$067A,$319B
BONTAB   DW    $06C5,$311E,$5C3F,$0661,$3182,$5CA3
CONTAB   DW    $3105,$5C26,$0648,$3169,$5C8A,$06AC
DONTAB   DW    $5C0D,$062F,$3150,$5C71,$0693,$31B4
AOFFTAB  DW    $1500,$4021,$6B42,$1564,$4085,$6BA6
BOFFTAB  DW    $4008,$6B29,$154B,$406C,$6B8D,$15AF
COFFTAB  DW    $6B10,$1532,$4053,$6B74,$1596,$40B7
DOFFTAB  DW    $1519,$403A,$6B5B,$157D,$409E,$6BBF

;*******************************************************************
;Data space definitions
CHBUF    DS          8T           ;character buffer for serial comm
CURDEC   DS          4T           ;chop cur dec val,2 digits,1/10amp
DECSTOR  DS          4T           ;temp storage for DEC_SEND
MODE     DS          4T           ;flag for storing inverter mode
STACK1   DS          2056T        ;set up supv stack space
STACK0   DS          4T           ;start of stack, load in A7
TEMP0    DS          4T           ;temp storage for D0
TEMP1    DS          4T           ;temp storage for D1
TEMP2    DS          4T           ;temp storage for D2
TEMP3    DS          4T           ;temp storage for D3
ON       DS          4T           ;temp storage for ON word for PSP
OFF      DS          4T           ;temp storage for OFF word for PSP
DITH1DEG DS          4T           ;Holds ON dither degrees
DITH2DEG DS          4T           ;Holds OFF dither degrees
ACNT     DS    4T                 ;placeholder for phase A tables
BCNT     DS    4T                 ;placeholder for phase B tables
CCNT     DS    4T                 ;placeholder for phase C tables
DCNT     DS    4T                 ;placeholder for phase D tables
FLAG9    DS    4T                 ;counter to use 2nd STRT interrupt
AMEM     DS    4T                 ;memory for AOFF Markov
BMEM     DS    4T                 ;memory for BOFF Markov
CMEM     DS    4T                 ;memory for COFF Markov
DMEM     DS    4T                 ;memory for DOFF Markov
LSFLAG   DS    4T                 ;1 for L, 0 for S in Markov
CFLAG    DS    4T                 ;set if CINT, cleared otherwise
;*******************************************************************
;Strings for messages to the PC monitor
CURINST1 DB   'YOU HAVE ENTERED ',00
DECPT    DB   '.',00
DEGNOW1  DB   ' DEGREES',CR,LF,00
ERROR1   DB   CR,'ERROR1 - TOO MANY CHARACTERS; RETYPE',CR,LF,PROMPT,00
ERROR2   DB   CR,'ERROR2 - ILLEGAL CHARACTER, RE-ENTER',CR,LF,PROMPT,00
ERROR3   DB   CR,'ERROR3 - TWO DIGITS ARE REQUIRED, START OVER',CR,LF,00
ERROR5   DB   CR,'ERROR5 - INVALID RANDOMIZATION SCHEME',CR,LF,00
WELCOME  DB   'WELCOME TO THE VRM MOTOR CONTROL PROGRAM',CR,LF,PROMPT,00
CMD_SUM  DB   'LIST OF USER OPTIONS:',CR,LF,LF
         DB   'C - CURRENT. SET THE CURRENT CHOPPING LEVEL    ',CR,LF
         DB   'D - DEGREES. SET DEGREES OF PERTURBATION OF ANGLE ',CR,LF
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         DB   'H - HELP. DISPLAYS THE COMMAND SUMMARY',CR,LF
         DB   'M - MODE. CHANGES THE INVERTER MODE   ',CR,LF
         DB   'S - SPEED. DISPLAYS SPEED IN RPM  ',CR,LF,CR,LF
         DB   'TO CHANGE PARAMETER, INPUT SINGLE LETTER FROM   ',CR,LF
         DB   'THE LIST ABOVE',CR,LF,PROMPT,00
CMD_SUM1 DB   'X-STOP  N-NOMINAL  M-MODE  R-RANDOMIZE       ',CR,LF
         DB   'CHOOSE FUNCTION BY ENTERING A SINGLE LETTER',CR,LF,PROMPT,00
HELP_MSG DB   'Choose user option by entering the letter   ',CR,LF
         DB   'which corresponds to your choice from the   ',CR,LF
         DB   'list provided. Then follow instructions.    ',CR,LF,00
NOMMSG   DB   'CHANGE THE NOMINAL ON OR OFF PTS?   ',CR,LF
         DB   'Y for yes, N or ENTER for no',CR,LF,PROMPT,00
NOMMSG1  DB   'CHANGE THE NOMINAL ON PT?   ',CR,LF
         DB   'Y for yes, N or ENTER for no',CR,LF,PROMPT,00
NOMMSG2  DB   'ADD OR SUBTRACT 1.8 DEG FROM NOM PT?',CR,LF
         DB   'Y for ADD, N or ENTER for SUBTRACT',CR,LF,PROMPT,00
NOMMSG3  DB   'CHANGE THE NOMINAL OFF PT?  ',CR,LF
         DB   'Y for yes, N or ENTER for no',CR,LF,PROMPT,00
NOMMSG4  DB   'REFINE THE NOMINAL ON ANG BY ADDING 1/2 DEG?   ',CR,LF
         DB   'Y for yes, N or ENTER for no',CR,LF,PROMPT,00
NOMMSG5  DB   'REFINE THE NOMINAL OFF ANG BY ADDING 1/2 DEG?  ',CR,LF
         DB   'Y for yes, N or ENTER for no',CR,LF,PROMPT,00
NOMMSG6  DB   'MAKE GROSS ADJUSTMENT TO ON ANGLE? ',CR,LF
         DB   'Y for yes, N or ENTER for no',CR,LF,PROMPT,00
NOMMSG7  DB   'MAKE GROSS ADJUSTMENT TO OFF ANGLE?',CR,LF
         DB   'Y for yes, N or ENTER for no',CR,LF,PROMPT,00
NOMMSG8  DB   'DO YOU WANT TO RESTORE ORIGINAL NOMINAL POINTS?',CR,LF
         DB   'Y for yes, N or ENTER for no',CR,LF,PROMPT,00
RANDMSG  DB   'CURRENT RANDOMIZATION SCHEME IS SCHEME ',00
RANDMSG1 DB   'CHANGE SCHEME? ENTER # (0 - 6) OR RETURN FOR NO',CR,LF,00
RANDMSG2 DB   'YOU HAVE CHOSEN SCHEME ',00
RANDMSG3 DB   'YOU HAVE CHOSEN TO KEEP THE SAME RANDOMIZATION SCHEME',CR,LF,00
RMSG0    DB   '0:  NO DITHERING',CR,LF,00
RMSG1    DB   '1:  UNIFORM DITH OF ON PT',CR,LF,00
RMSG2    DB   '2:  UNIFORM DITH OF OFF PT',CR,LF,00
RMSG3    DB   '3:  UNIFORM DITH OF ON AND OFF PTS',CR,LF,00
RMSG4    DB   '4:  TWO STATE MARKOV OF OFF PT',CR,LF,00
RMSG5    DB   '5:  MOD MARKOV, UNIFORM DIST IN A SHORT',CR,LF
         DB   '    OR LONG DELAY FOR OFF POINT',CR,LF,00
RMSG6    DB   '6:  UNIFORM DITH OF PHASE A OFF POINT (ONLY)',CR,LF,00
DITH1MSG DB   'ENTER # OF DEGREES OF ON DITHER (1 OR 2)',CR,LF,PROMPT,00
DITH2MSG DB   'ENTER # OF DEGREES OF OFF DITHER (1 OR 2)',CR,LF,PROMPT,00
EXIT_MSG DB   'PROGRAM STOPPED ... ALL PHASES OFF  ',CR,LF
         DB   'hit F1, type PC 400, then GO to restart',CR,LF,00
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