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recommend its acceptance:

Accepted for the Council:

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Comparison of Equivalent Three and Five Phase Brushless dc Motors: Evaluation of Torque Production for Inverter Failures in One Phase

A Thesis

Presented for the

Master of Science

Degree

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Brian Lain

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DEDICATION

This thesis is dedicated to my family, who have given me encouragement and support during this effort, and to my Lord and Savior, Jesus Christ.

Acknowledgments

I want to express my deep gratitude to all those who directly or indirectly helped me to complete this thesis. I want to thank my advisor Dr. J.S. Lawler for patiently guiding me through this study. I want to thank my committee members Dr. J.M. Bailey and Dr. F.W. Symonds, who have provided continued support and advice. I am also grateful to my fellow graduate assistants, Steve Daniel, Sassine Ghazi, John Parsley, Krishna Sadasivam, and John York.

Abstract

In this study the post-failure torque production of three-phase and five-phase brushless dc motors is compared for inverter single phase failures. Brushless dc motors are conventionally configured as three-phase motors, however a five-phase brushless dc motor can produce more torque after a single phase failure. To allow equitable comparison of these two systems an "equivalent" basis is established. The "equivalent" systems will be equal with respect to physical size, dc supply voltage, dc supply current, rated power, and rated torque.

After a failure in the inverter the three-phase and five-phase systems have different abilities to produce torque. Two types of failures were chosen to represent typical failures and to provide a basis to compare the post-failure torque production of the systems. Specifically the failures used for comparison are one transistor open and two transistors open in one leg of the inverter.

For nominal conditions the equivalent five-phase inverter requires a lower transistor current rating. It is found that the nominal equivalent five-phase inverter has a volt-ampere product that is five-sixths the value required of the equivalent three-phase system. After a failure of one or two transistors in one phase, currents of the five-phase system

exceed nominal values. An increased transistor current rating or a limiting of the phase currents is required for the five-phase system to operate safely.

Although the transistor currents exceed nominal values, the five-phase motor can develop full torque even after two transistors fail open in one phase of the inverter circuit. With increased transistor current ratings the five-phase motor can safely produce full torque even after a failure of one complete phase. The three-phase system can only produce 33.33% of the average nominal torque for one transistor failed open and only 66.67% of the average nominal torque for two transistors failed open in one phase.

If the transistor current rating of the five-phase inverter could not be increased then the five-phase system could be operated with the phase currents limited to the maximum allowed limit. The limiting of the phase currents would reduce the torque capability of the five-phase system. With the current limited the five-phase system could produce 80% and 60% of average nominal torque with one and two transistors failed open, respectively.

The post-failure starting torque capabilities of the equivalent three-phase and five-phase systems are significantly different. The three-phase system can only produce torque for two-thirds and one-third of the rotor positions for one and two transistors failed, respectively. Therefore, the three-phase motor can not start after a failure for many of the rotor positions. After a failure the five-phase system with the current limited can produce

at least 50% of rated torque for all rotor positions. The five-phase system with adequate transistor current ratings can produce full rated torque for all rotor positions after either one or two transistors have failed open in one leg of the inverter.

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List of Symbols

B	Flux Density
F	Force
f	Flux Density in the Air Gap
i	Current
l	Length
K_t	Torque Constant
K_v	Voltage Constant
N	Number of turns
P	Power
T	Torque
Vol	Volume
λ	Linked Flux
λ_m	Maximum Linked Flux
θ	Rotor Angle in Electrical Degrees
ω_r	Rotor Speed in Radians per Second

List of Abbreviations

emf	Electromotive Force
HP	Horse Power
KW	Kilo-Watts
PM	Permanent Magnet
RPM	Revolutions Per Minute

1. Introduction

Electrical motors are used in all kinds of consumer and industrial applications. They are used to drive and move anything from can-openers to robot arms on the space shuttle. Many of these applications use a brushless dc motor which offers the following advantages: high torque per machine weight, tight control of torque and speed, four quadrant operation, low rotor inertia, and full torque at start.

Brushless dc motors are conventionally configured as three-phase motor systems, typically operated with two phases active and one phase resting. However, McCleer, Bailey and Lawler have developed a five-phase brushless dc motor system (US Patent 5,394,321 "Quasi Square-wave Back EMF Permanent Magnet AC Machines with Five or More Phases"). This proposed system is star connected with an isolated neutral and has four of the five phases active at any time during normal operation. The five-phase motor is designed to have back emf flat top and square wave current widths of 144 electrical degrees.

This study is a broad stroke evaluation of the comparable torque production abilities of three and five phase systems following single phase failures. This study does not attempt

to evaluate the reason a system component failed, only what effect the failure will have on the torque production of the steady-state post-failure system.

The failures in a brushless dc motor system are most likely to occur in the inverter circuit. Multiple failures are possible, but this study is limited to failures that affect one phase only. The possible failures of a brushless dc motor system include shorted windings, shorted inverter components, open windings, and open inverter components. Of all the possible failures in one phase, only two are studied here. Specifically, the failures studied are one transistor open or both transistors open in one leg of the inverter circuit.

There are many different ways the two types of systems could be made "equivalent," but this study proposes a set of constraints to allow equitable comparison of the torque production abilities of the three and five phase motor systems. The three and five phase motors are different, but the equivalent systems will be equal with respect to physical size, dc supply voltage, dc supply current, rated power, and rated torque.

The five-phase system requires an inverter with ten transistors, while the three-phase system only requires six transistors. Typically the five-phase system is perceived as more expensive than the three-phase system because it requires more transistors. However, the equivalent five-phase system is not necessarily at a disadvantage since the transistor current rating will be one-half the transistor current rating of the equivalent three-phase inverter.

The analysis is supported by simulations of the equivalent three and five phase brushless dc motor systems. A simulation software, Simnon, was used to model the pulse width modulated (PWM) systems. In addition PSpice, an electrical circuit simulation software, was used to develop a step-drive model of the systems. Both transient, and steady state analysis of constant speed nominal conditions, and failed conditions were performed. The baseline motor for the simulations is a three-phase brushless dc motor system manufactured by Unique Mobility Inc. The motor system is rated at 42.9 HP/32 KW and a continuous torque of 154 Newton-meters (Nm) at a base speed of 2000 RPM.

An overview of brushless dc motor systems is presented in chapter 2. General information about brushless dc motor classification, construction, back emf production, torque production, and starting torque is reviewed in section 2.1. The operation of three-phase brushless dc motor systems, which includes back emf waveforms, inverter topology, commutation sequence, and torque production, is reviewed in section 2.2. The operation of five-phase brushless dc motor systems, including back emf waveforms, inverter topology, commutation sequence, and torque production, is clarified in section 2.3. The equivalent machines are defined and the differences and similarities of the two equivalent systems are presented in section 2.4. The failures most likely to occur are identified, and the reason for choosing the two failure types is clarified, in section 2.5.

Chapter 3, the primary analysis and evaluations of this study, compares the equivalent three and five phase systems. Section 3.1 evaluates the volt-ampere product of the inverters' transistors, and the total volt-ampere product for each inverter. The copper and conduction losses of the three and five phase systems are evaluated in section 3.2. The post-failure torque production ability of the three-phase and five-phase systems are evaluated in section 3.3 and 3.4, respectively. The post-failure torque production abilities of the five phase system with the maximum transistor current limited to the rated level is evaluated in section 3.5. The starting torque of the three and five phase systems are compared in section 3.6. The last chapter, four, presents the conclusions of the study.

2. Overview of Brushless dc Motors Systems

An overview of brushless dc motor systems is presented in chapter two. General information about brushless dc motor classification, construction, back emf production, torque production, and starting torque is reviewed in the first section. The operation of three-phase brushless dc motor systems which includes back emf waveforms, inverter topology, commutation sequence, and torque production is reviewed in the second section. The operation of five-phase brushless dc motor systems which includes back emf waveforms, inverter topology, commutation sequence, and torque production is clarified in the third section.

In order to compare the three-phase and five-phase systems an "equivalent " machine is proposed to directly compare the torque production ability of the three-phase and five-phase systems. The proposed equivalent machines are defined in section four. The machines are equivalent in that they are of equal; physical size, voltage supplied, current supplied, rated power, rated torque, and machine losses. It will be shown, in section four, that the equivalent five-phase machine has resistance per phase winding that is twice the resistance per phase winding of the three-phase equivalent machine. The difference in resistance dictates that the wire in the five-phase machine has a smaller diameter, and one-sixth less copper weight.

Finally an overview of the basic types of failures most likely to occur in a brushless dc motor system is given in section five. The two most probable types of failures are chosen as a basis for comparing the torque production abilities of the three-phase and five-phase systems.

2.1 Construction and Operation of Brushless dc Motors

The brushless dc motor has some of the basic characteristics of the conventional wire wound rotor dc motor, but is quite different in several other aspects. The brushless dc motor has a permanent magnet (PM) rotor and is electrically commutated. The brushless dc motor has full torque at zero speed, low rotor inertia, and tight control of torque and speed.

2.1.1 Classification

The brushless dc motor is classified as a permanent magnet synchronous ac machine since the supplied current is an alternating square wave[Hanselman]. Figure 2.1-1 shows how the brushless dc motor is classified relative to several other types of electrical motors, including its closest relative, the permanent magnet dc motor. Permanent magnet (PM) motors drives are basically synchronous motor drives in self-control mode [Kou]. The

armature supply frequency is changed in proportion to the rotor speed changes, so that the armature field always moves at the same speed as the rotor. The brushless dc motor has a commutation mechanism consisting of rotor-position detection and electrically controlled switching of the armature/stator supply.

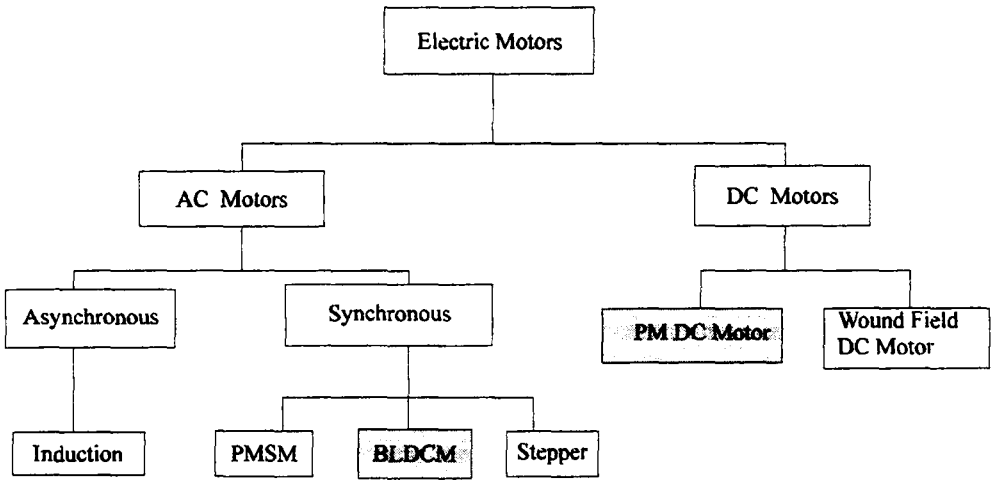


Figure 2.1-1 Classification of Electrical Motors

2.1.2 Construction

The structural configuration of the brushless dc motor is the inverse of the conventional dc machine. The armature is on the outside and the field is provided by permanent magnets on the rotor. A cross sectional view of the brushless dc motor is pictured in Figure 2.1-2, along with two other related motors, the permanent magnet dc motor , and the wound rotor dc motor.

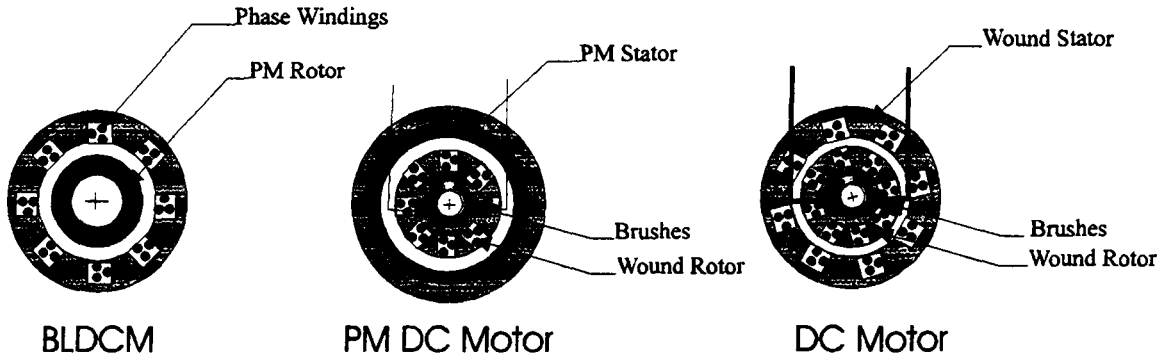


Figure 2.1-2 Cross Sectional View of Three Types of Motors

(Brushless dc Motor, Permanent Magnet dc Motor, dc Motor)

The brushless dc motor has multiple concentrated armature windings on the stator that are supplied by a switched electrical inverter circuit. The concentrated windings produce the characteristic trapezoidal back emf voltage waveform. Not to be confused with the brushless dc motor is the permanent magnet synchronous motor(PMSM). The permanent magnet synchronous motor has sinusoidally distributed windings and has sinusoidal back emf.

2.1.3 Permanent Magnets

Permanent magnetic material and the handling of permanent magnets represent a major cost item in the construction of brushless dc motors. The cost of using brushless dc motors has been falling over the past few years. The fall in cost is due to three factors ; improvements in motor control electronics, capital investments by manufacturers of brushless dc motors, and advances in magnet technology [Ellis]. The most radical

improvement in magnet technology is increased energy product. Today's neodymium-iron-boron (NdFeB) magnets have many times the energy product of ceramic(ferrite) magnets, as can be seen in Figure 2.1-3.

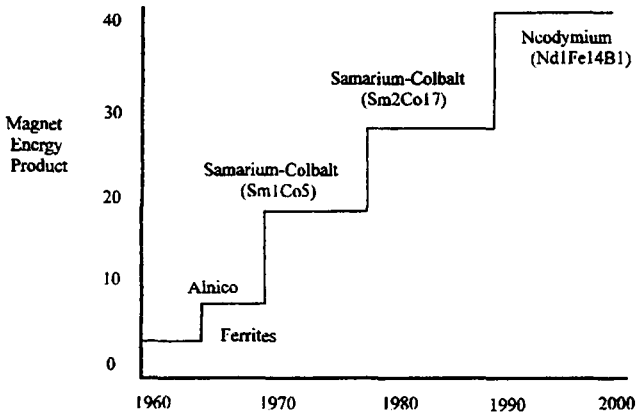


Figure 2.1-3 Magnet Energy Product vs. Time

Adapted from [Ellis]

Note that "magnet energy product" is a term used to evaluate different magnetic materials; broadly, materials with higher energy products can be used to produce stronger magnets. The higher the energy product the less magnetic material required for a given flux density in the air gap. NdFeB magnets can reduce motor cost by reducing the need for iron and copper, albeit while increasing the cost of magnetic material. The overall impact of smaller, lighter, more efficient motors often reduces system costs[Ellis].

2.1.4 Back emf

The back emf shape and magnitude is directly determined by the flux linkage waveform. The flux linkage is determined by the stator winding configuration, the type of magnets, the width of the magnets, the rotor position, and rotor speed. The period of the flux linkage waveform is equal to 2π electrical radians (360 electrical degrees), and is physically equal to twice the pole pitch. Therefore, one pole pitch is equal to π electrical radians[Hanselman, p70]. The period of the flux linkage waveform is defined as the electrical period of the motor. This study will refer to the position of the rotor in terms of electrical degrees, unless otherwise stated. The linked flux is dependent on the position of the rotor, as the poles pass the teeth of the stator. The back emf is dependent on the flux.

The back emf will be the voltage induced in the stator phase windings by the flux of the permanent magnets as the pole passes across the winding. The ideal flux is a square wave, but with fringing effects the actual flux will have rounded corners. The back emf then has the 'trapezoidal' shape, that is characteristic of the brushless dc motor. Figure 2.1-4 show the flux linkage waveforms that produce the trapezoidal back emf for the brushless dc motor.

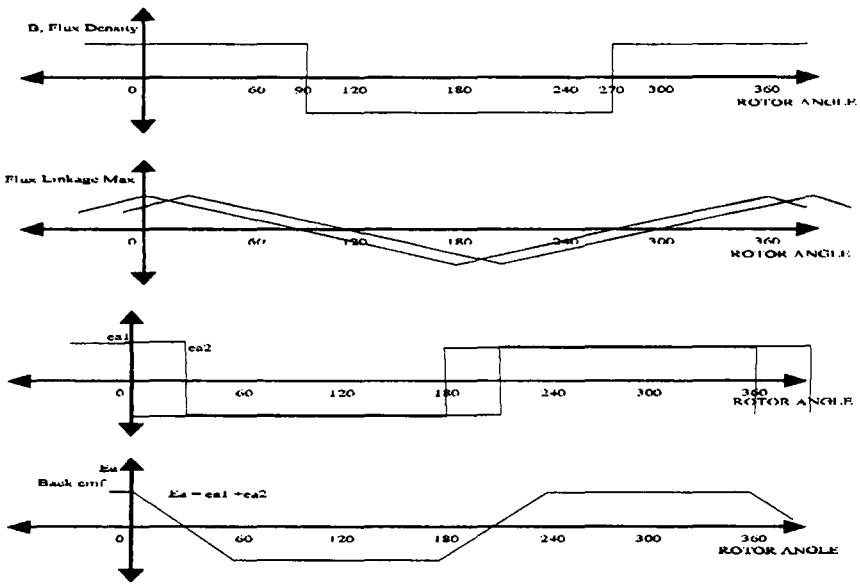


Figure 2.1-4 Back emf Waveform Produced by the Flux

The back emf is given by the product of velocity and the rate of change in flux linkage with respect to position [Hanselman, p72]. For a radial air gap machine with a full-pitch concentrated stator winding, the flux linkage with the phase winding varies linearly with rotor position , and is given by equation {2.1}.

$$\lambda(\theta) = \left(1 - \frac{2}{\pi}\theta\right)\lambda_m \qquad \{2.1\}$$

The maximum flux linkage (λ_m) may be written as the product of the number of turns (N_1), the airgap flux density(B_{mag}), the pole pitch (τ), and the stator length (l_s) [Nasar, p188].

$$\lambda_m = N_1 B_{mag}\, \tau\, l_s \qquad \{2.2\}$$

The voltage induced in a phase winding due to the flux linkage is defined by equation {2.3}.

$$E_a = -\frac{d\lambda}{dt} = -\frac{d\lambda}{d\theta}\frac{d\theta}{dt} = \frac{2}{\pi}\lambda_m \omega_r , \qquad \{2.3\}$$

where ω_r = rotor angular speed in electrical radians per second(ω_r = P*rotor speed, P = number of pole-pairs)

2.1.5 Torque Production

The brushless dc motor uses square wave currents synchronized with the flat top emf to produce flat top torque, as illustrated in Figure 2.1-5.

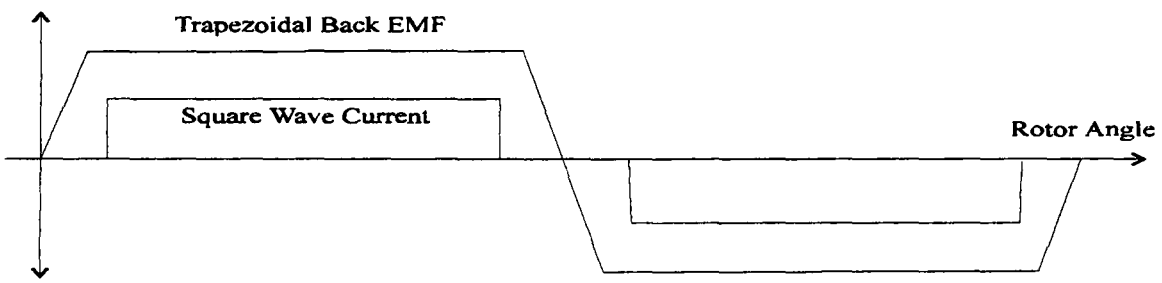


Figure 2.1-5 Trapezoidal Back EMF and Square Wave Current vs. Rotor Angle

The torque of the machine can be derived from the relationship of the force produced by the interaction of a magnetic field and a current (*i*) carrying wire. Force is developed

from a current-carrying wire of length (l), in a magnetic field. The permanent magnet rotor performs the function of providing the magnetic field density(B) for the BLI Law.

$$F = B * l * i \qquad \{2.4\}$$

The torque is directly proportional to the current. The shape of the current will determine the shape of the torque produced. Therefore to obtain flat torque, there must be flat current.

2.1.6 Starting Torque

The conventional model basis for simulations involve the calculations for torque from the relationship of equation {2.5}. In order to calculate torque at zero speed a different equation must be developed.

$$T_{DEV} = \frac{P_{DEV}}{\omega_{rotor}} \qquad \{2.5\}$$

The production of torque in a brushless dc motor is similar to the operation of a conventional brush dc motor. The basic relationships for torque, of the dc motor and the brushless dc motor, are the same except the brushless dc motor is a polyphase machine. The torque of the brushless dc motor is a summation of the torque components contributed from each winding. The value of torque is the product of a motor winding constant (k), the linked flux , and the current in the windings.

$$T_{DEV} = k * \Phi * I \qquad \{2.6\}$$

By grouping the linked flux and the winding constant into one constant term the relationship takes a more familiar form, as shown in equation {2.7}. The torque is proportional to the machine torque constant and the line current.

$$T_{MACH} = K_t * I \qquad \{2.7\}$$

The motor constant shown is the torque constant, but the values for the torque constant (K_t [Nm/Amp]) and the back emf constant (K_V [V/rad/Sec]) are the same values in the MKS system. The constants are the same because they originate from the same source. To simplify the following discussions, the back emf constant will be used in place of the torque constant. For the brushless dc motor the torque is the summation of all the torque components of the individual phase windings. The torque can be represented as the product of the voltage constant, the current, and the unit normalized shape of the airgap flux density (f_j).

$$T_{DEV} = K_V * \sum_{j}^{N} i_j(\theta) * f_j(\theta) \qquad \{2.8\}$$

The representation of the torque shown in equation {2.10}, can be used to calculate torque at zero speed, where f_j is the normalized unit shape of the flux density produced as a pole moves along the stator phase winding. The flux density is a function of the rotor angle.

$$T_{DEV} = K_V * (ia * fa(\theta) + ib * fb(\theta) + ic * fc(\theta) + id * fd(\theta) + ie * fe(\theta)), \qquad \{2.9\}$$

The torque produced is based on the shape of the flux density, and current as a function of rotor position. The flux density waveform shape as a function of rotor position is the same as the characteristic trapezoidal back emf shape. Using the flux shape per rotor position, the voltage constant, and the current in the windings, the torque can be calculated at zero speed.

The product of the voltage constant and the unit normalized flux density shape will be called the torque efficacy waveform. The torque efficacy waveform is illustrated in Figure 2.1-6. The torque is dependent on the position of the rotor with respect to the windings carrying current.

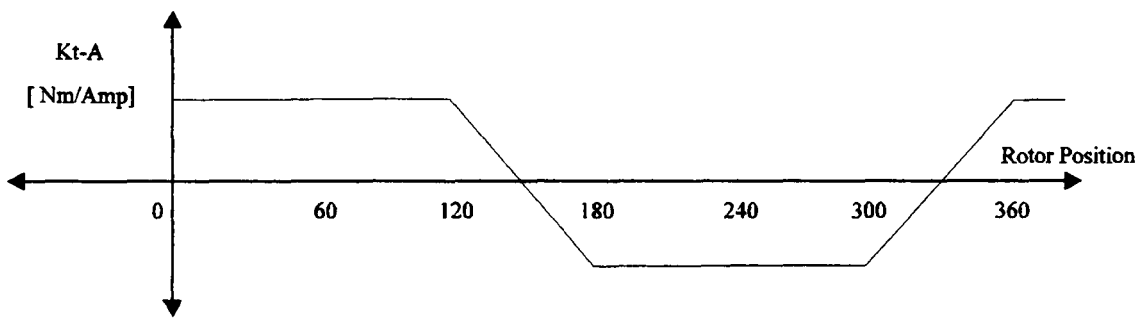


Figure 2.1-6 Torque Efficacy Waveform for One Phase of a Three-Phase Motor with 120 Degree Flat Top.

The torque efficacy waveforms are scaled in units of Newton-meters per ampere(Nm/A). The waveforms look familiar because they are the same shape as the back emf waveforms. Both the torque efficacy and the back emf waveforms originate from the airgap flux density waveforms. The ability to produce torque is illustrated as a torque efficacy

waveform, in order to emphasis that rated torque is available at zero speed. The torque efficacy is only dependent on rotor position, not on the speed.

2.2 Three-Phase Brushless dc Motor System

The three-phase brushless dc motor operation is typical of other three-phase systems, with commutations every 120 electrical degrees, and a balanced WYE winding configuration. The three-phase brushless dc motor is commonly used for a wide range of types and sizes of applications.

2.2.1 Back emf for the Three-Phase Motor

As described earlier in section 2.1, the back emf of the three-phase motor is developed from the flux of the magnetic poles as they pass across the windings in the stator. The back emf waveforms of the three-phase motor are shifted from each other by 120 electrical degrees, as shown in Figure 2.2-1. The magnitude of the back emf is directly proportional to the product of the voltage constant (Kv) and the speed of the rotor. The peak back emf voltage can be calculated as:

$$V_{EMF} = K_V * \omega_{rotor} \qquad \{2.10\}$$

The amplitude of the back emf for each phase is dependent on the rotor position, but during any specific state the value of the back emf can be considered constant. The back

emf peak voltage is dependent on the speed, but our analysis assumes the speed is constant. The value of the back emf will be the same for all the phases, and therefore the back emf can be represent as in equation {2.11}.

$$E_P = |V_{EMF}| \qquad \{2.11\}$$

The back emf waveforms' flat top width is dependent on the length of the magnets used on the rotor. Typically the rotor magnets are less than 180 degrees long, and produce a back emf flat top of between 150 to 120 degrees. The equivalent three-phase machine will have a back emf flat top of at least 120 electrical degrees.

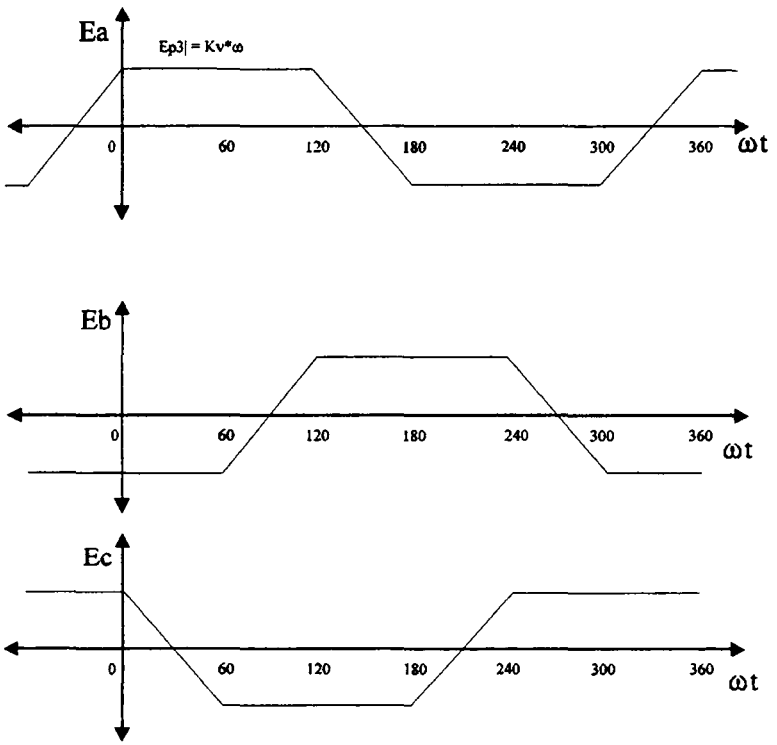


Figure 2.2-1 Back emf Wave Forms for the Three-Phase Motor

2.2.2 Inverter for the Three-Phase Motor

A voltage source inverter (VSI) circuit is used to commutate the winding currents. The inverter circuit for the three-phase motor system is shown in Figure 2.2-2. The three-phase system requires six transistors to control the three windings. The type of transistors that is typically used for medium to large (approx. 50 HP) motor systems is the insulated gate bipolar transistor (IGBT) [Takesuye]. A free-wheeling diode is placed in anti-parallel to the transistor to allow a path for the stored current to dissipate. The sequential switching of states can be performed with a simple step like drive.

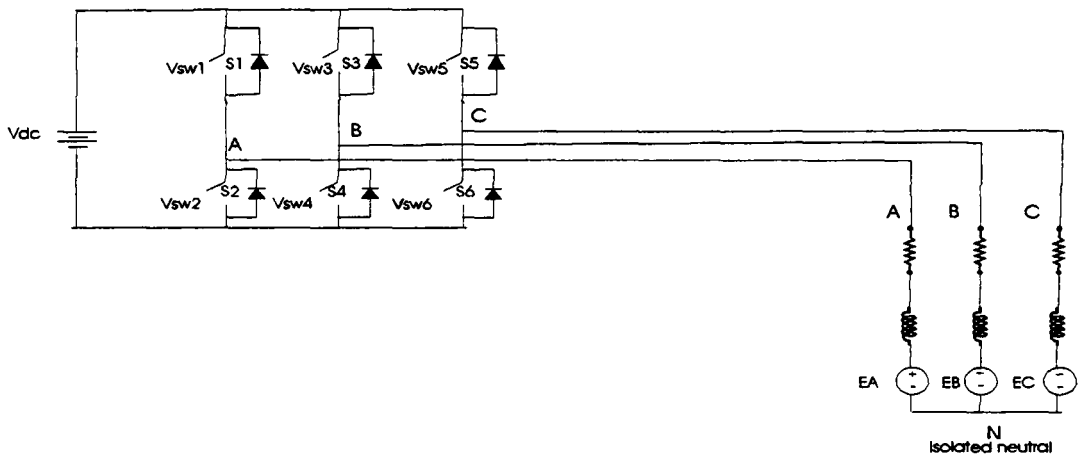


Figure 2.2-2 Six Step Voltage Source Inverter for Three-Phase Motor

Brushless dc motor systems require the speed and rotor position to be fed back to the controller, so that commutation of the windings can be synchronized with the rotor

position. The rotor speed/position can be measured by, tachometers, encoders, or resolvers.

The inverter can be controlled by a simple step drive, or can use pulse width modulation (PWM) to vary the dc voltage. The dc link voltage is chopped to reduce the average dc voltage. The ability to PWM the voltage source, allows a wider range of control over the motor than the use of simple stepping of the inverter. The PWM voltage waveform can be shaped to whatever average dc voltage is desired. Typically the inverter is a voltage source inverter, with constant link voltage. The transistors are pulse width modulated to control the currents.

2.2.3 Commutation Sequence for the Three-Phase Motor

The three-phase motor is commutated six times per cycle, and each commutation requires one transistor to turn-off and another transistor to turn-on. The steady state periods between commutations can be described as conduction states. During a conduction state the winding configuration is unchanged. The winding configuration during a conduction state can be represented by a circuit diagram of the active, and inactive windings, as shown in Figure 2.2-3.

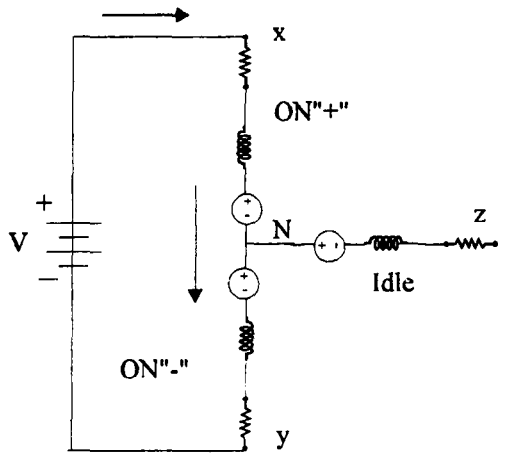


Figure 2.2-3 Conduction State Winding Configuration for Three-Phase Motor

The three-phase motor always has two windings active and one winding resting. At any particular time one active winding is carrying current in the positive referenced direction, and the other active winding is carrying current in the negative referenced direction. The general three-phase motor configuration illustrates the three-phase motor operation of two windings "ON" and one winding "OFF". The positive referenced winding is labeled "x", and the negative referenced winding is labeled "y", while the idle winding is labeled "z". Table 2.2-1 lists the winding configurations of the six conduction states. The states are dependent on the rotor position in electrical degrees. The general labels, "x", "y", "z", are referenced to the specific windings of the three-phase motor, "A","B", "C", for each conduction state.

Table 2.2-1 Three-Phase Winding Configurations per Conduction State

Conduction States	Rotor Position [degrees]	Windings x, ON "+"	y, ON " - "	z, Idle
1	0< ωt <60	A	B	C
2	60< ωt <120	A	C	B
3	120< ωt <180	B	C	A
4	180< ωt <240	B	A	C
5	240< ωt <300	C	A	B
6	300< ωt <360	C	B	A

The three-phase commutation sequence is also represented by Figure 2.2-4, where the overlapping of the transistor "ON" times is better illustrated. The letters designate the active phase windings. The letters with the over strike are the active negative referenced windings. Each conduction state is 60 electrical degrees in duration. The active winding is "ON", for four consecutive conduction states, which adds up to a duration of 120 electrical degrees.

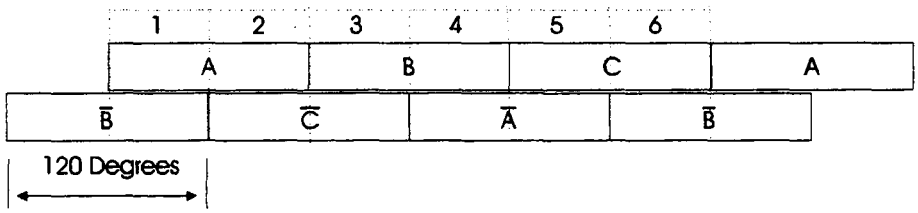


Figure 2.2-4 The Six Conduction States for the Three-Phase System

The winding currents are synchronized with the rotor position and the flat top of the back emf. A model of the three-phase motor system was developed and the system simulated.

The simulated three-phase system uses pulse width modulation (PWM) to varying the supply voltage, and to control the currents. A set of currents over one cycle for the simulated three-phase motor is shown in Figure 2.2-5. The simulated motor is a two pole machine, running at a constant speed of 2000 RPM. The small ripple produced by the PWM can be seen along the peak of each square wave.

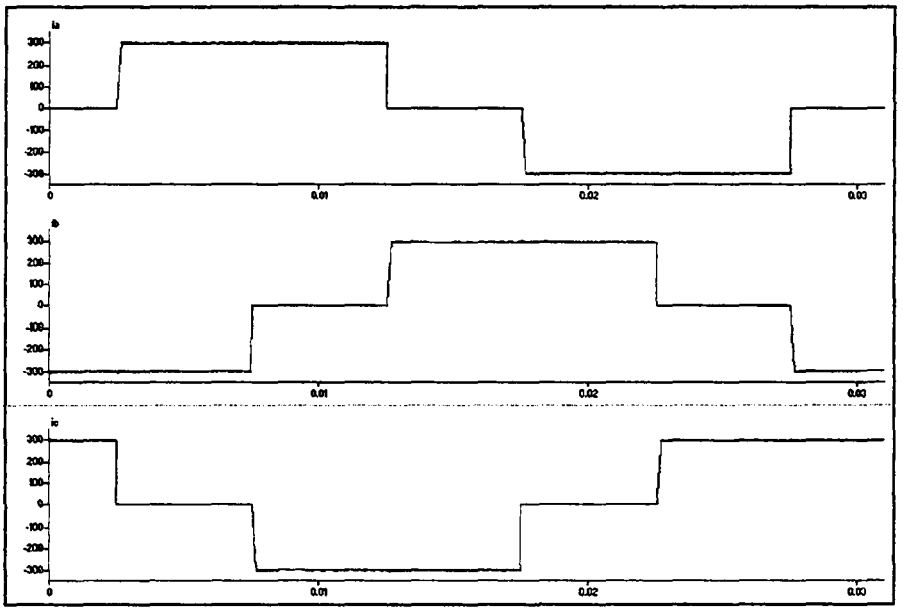


Figure 2.2-5 Phase Currents of Three-Phase Motor

2.2.4 Torque for a Three-Phase Motor

The torque of brushless dc motors is developed from the interaction of the current in the windings and the linked flux. The torque can be calculated as the sum of the products of the voltage constant and the current in each winding. The three-phase system has two windings active, and one winding resting. Therefore the torque of the three-phase system

is calculated as two times the product of the voltage constant and the phase current, as shown in equation {2.12}.

$$T_3 = 2 * Kv * i_{P3} \qquad \{2.12\}$$

The two comes from the two windings in series at any time. The torque is dependent on the position of the rotor with respect to the windings carrying current. A diagram of the ability to produce torque per phase as the rotor moves can be described by a torque efficacy waveform, as pictured in Figure 2.2-6 The torque efficacy waveforms are scaled in units of Newton-meters per ampere(Nm/A), and are dependent on the rotor position.

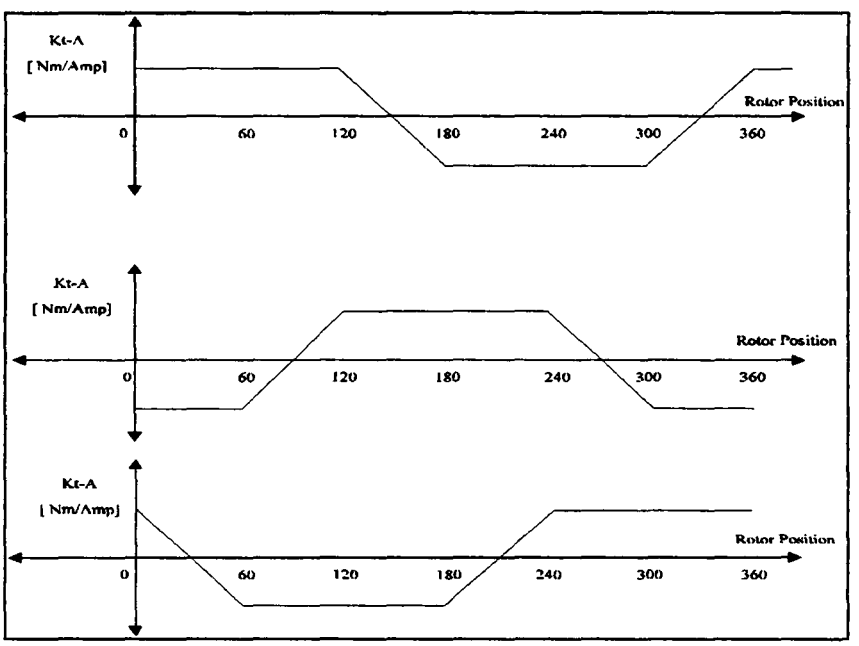


Figure 2.2-6 Torque Efficacy Waveforms for the Three-Phase Motor

The torque of the simulated three-phase motor is shown in Figure 2.2-7. The torque is shown for two cycles, and the twelve conduction states can be identified in the figure. The small ripple at the top is from the PWM of the supply voltage. The motor system is fed from a voltage source inverter, but is current controlled. The level of torque produced will depend on the amount of current in the windings. The simulations were performed for the system at base speed, maximum current, and torque conditions.

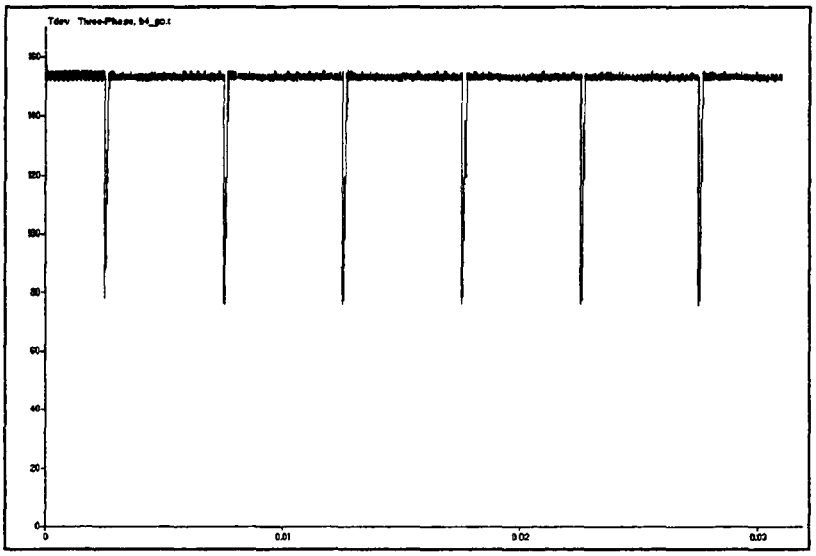


Figure 2.2-7 Torque of the Three-Phase Motor

2.3 Five-Phase Brushless dc Motor System

The five-phase motor has five windings on the stator rather than the conventional three windings. The five-phase motor operation is similar to the three-phase motor, but there are several significant differences. The five-phase motor always has four windings active

and one winding resting. The five-phase motor's windings are commutated ten times every electrical cycle.

2.3.1 Back emf for Five-Phase System

Back emf is the voltage induced in the windings by the flux of the rotor magnets. The shape and magnitude of the back emf will be dependent on the change in linked flux as a function of rotor position and rotor speed. The flat top of the back emf waveforms of the five-phase systems are 144 electrical degrees wide, and the waveforms are shifted from each other by 72 electrical degrees, as illustrated by Figure 2.3-1.

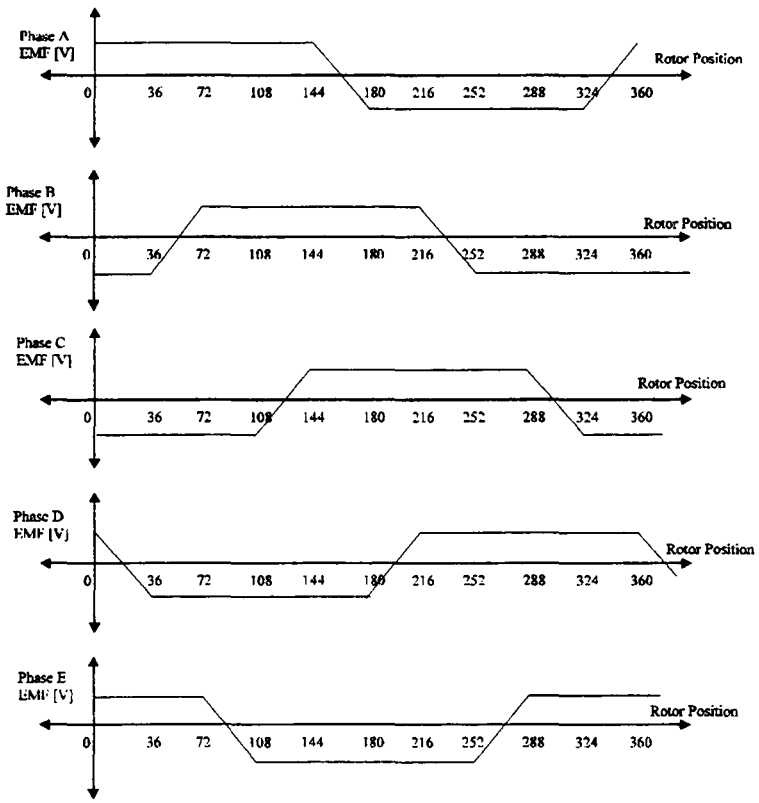


Figure 2.3-1 Five-Phase Back emf Waveforms

The currents in the five windings are synchronized with the flat top of the back emf waveforms to produce flat topped torque. The active phase windings will be "ON" only when the back emf is at a flat top value. The magnitude of the back emf is dependent on the speed of the rotor and the position of the rotor relative to the phase winding. For constant speed the magnitude of the back emf flat top will remain constant.

2.3.2 Inverter for Five-Phase System

The five-phase machine requires a ten step inverter with ten transistors, as shown in Figure 2.3-2. Each step is one of the conduction states. The five-phase system like the three-phase system requires that the speed and rotor position be fed back to the controller, so that the commutation of the windings are synchronized with the rotor position. The controller switches the transistors of a voltage source inverter (VSI) to commutate the windings.

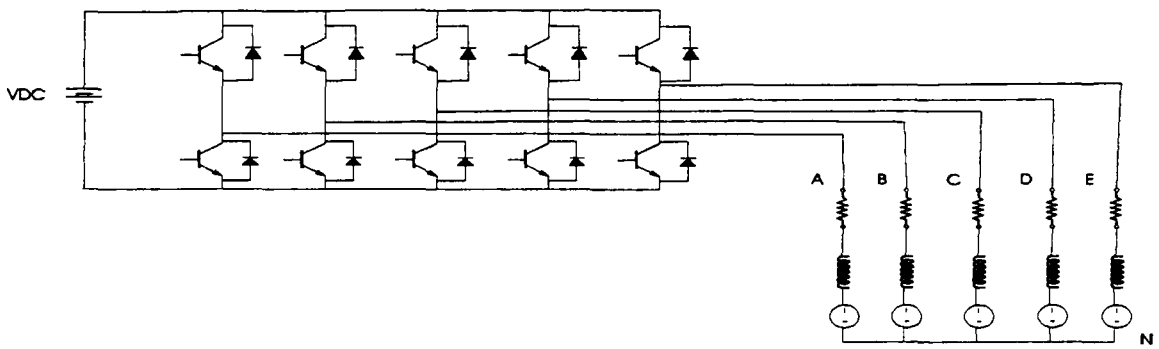


Figure 2.3-2 Ten Step Inverter Circuit

The inverter can be driven by simple step control, or can use pulse width modulation (PWM) to vary the supplied voltage. The ability to PWM the voltage source, allows a wider range of control over the motor than the use of simple stepping of the inverter. The dc link voltage is chopped to reduce the average dc voltage. The PWM voltage waveform can be shaped to whatever average dc voltage is desired. The simulated five-phase motor system is a current controlled pulse width modulated system.

2.3.3 Commutation Sequence for Five-Phase System

Figure 2.3-3shows a general winding configuration for one of the ten conduction states of the five-phase brushless dc motor. The phase windings are labeled with general labels, q,r,s,t,u. The specific windings for each of the ten states is listed in Table 2.3-1. There are always four windings "ON" and one winding "OFF" during each state. The fifth winding, "u , Idle", dissipates all of its' current and rests during the off-time. The next time the fifth phase is activated it will carry current in the opposite direction.

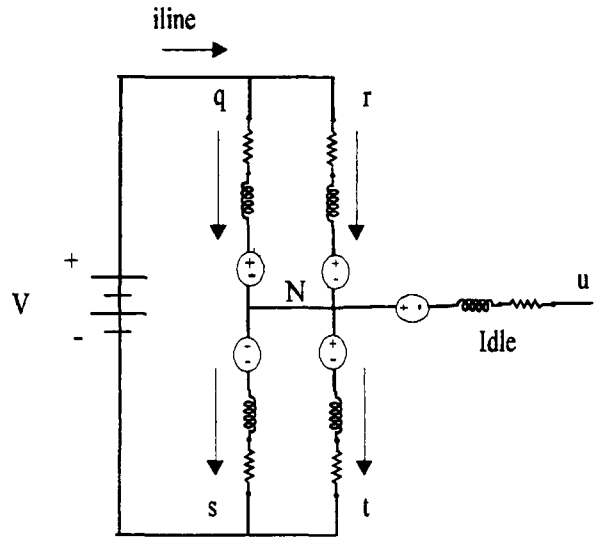


Figure 2.3-3 Conduction State Winding Configuration for Five-Phase Motor

Table 2.3-1 Conduction State Winding Configurations for the Five-Phase Motor

Conduction State	**Rotor Position [Electrical Degrees]**	**Winding Configurations for Five-Phase Motor**				
		q, ON"+"	**r, ON "+"**	**s, ON"-"**	**t, ON"-"**	**u, Idle**
1	0< ωt <36	A	E	B	C	D
2	36< ωt <72	A	E	D	C	B
3	72< ωt <108	A	B	D	C	E
4	108< ωt <144	A	B	D	E	C
5	144< ωt <180	C	B	D	E	A
6	180< ωt <216	C	B	A	E	D
7	216< ωt <252	C	D	A	E	B
8	252< ωt <288	C	D	A	B	E
9	288< ωt <324	E	D	A	B	C
10	324< ωt <360	E	D	C	B	A

The five-phase system conduction sequence is also represented in Figure 2.3-4. It is clear from the figure that the current pulses are 144 electrical degrees in width and over lap other transistor "ON" times. The conduction states are each 36 electrical degrees wide. Each winding is active for four consecutive states, which adds to 144 electrical degrees in duration.

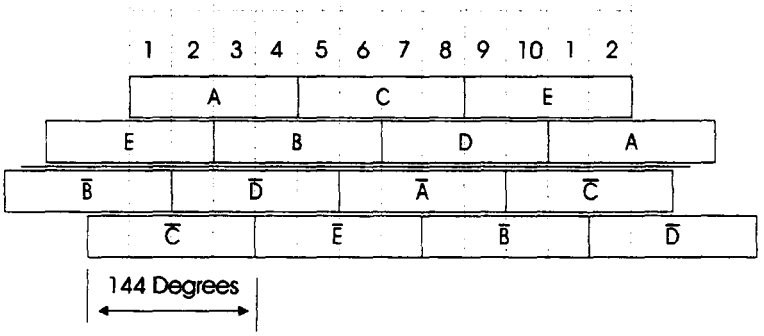


Figure 2.3-4 Ten Conduction States for Five-Phase System

A model of the equivalent five-phase system was developed to better illustrate the behavior of the brushless dc motor system. A set of phase currents for the five-phase motor are shown in Figure 2.3-5. The square wave currents illustrate the PWM of the supplied voltage to control the current of the windings.

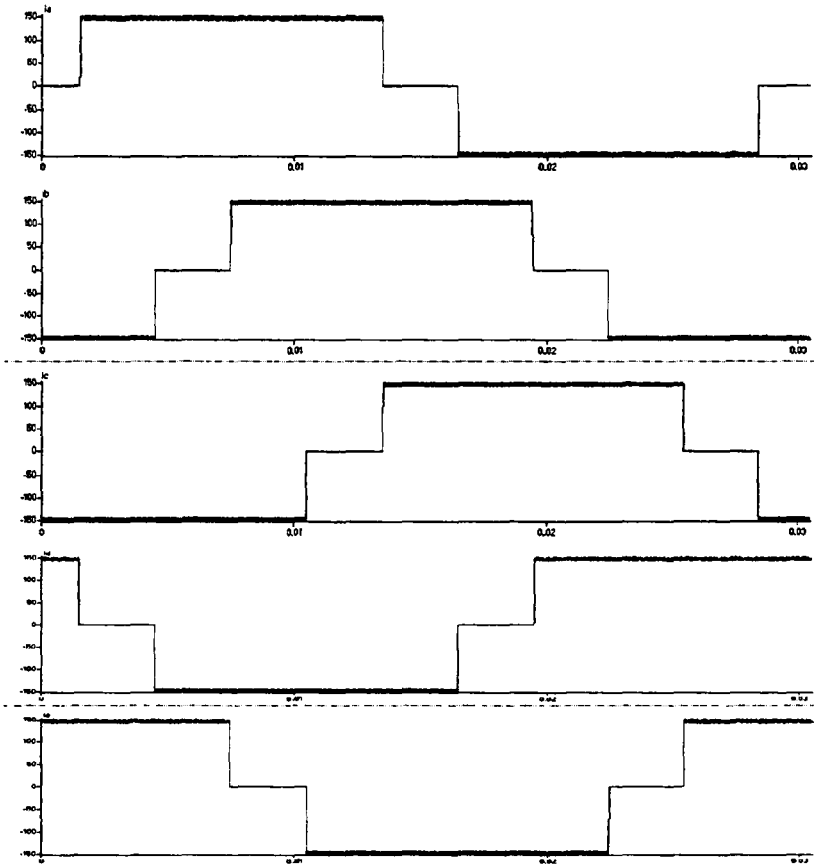


Figure 2.3-5 Phase Currents for Five-Phase Motor

2.3.4 Torque of the Five-Phase System

The torque developed by a brushless dc motor is dependent on the rotor position and magnitude of the current in the windings as the rotor passes the stator windings. Only when the flux of the magnets interact with the current is torque produced. The average torque of a five-phase motor can be calculated as the sum of the product of the voltage constant(Kv) and the value of current in the windings, as shown in equation {2.13}.Figure 2.3-6 shows the torque efficacy waveforms for the five-phase motor.

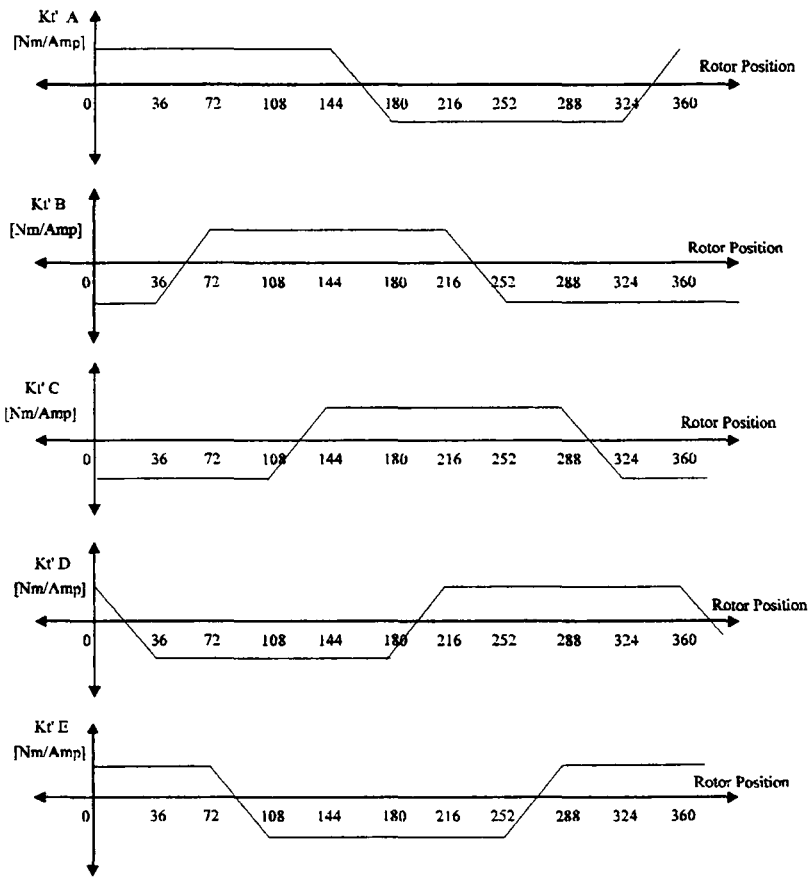


Figure 2.3-6 Torque Efficacy Wave Forms for Five-Phase Motor

The torque efficacy waveforms help to emphasize the dependency of torque on the rotor position. The torque developed is dependent on the linked flux and the current carried by windings. The torque efficacy waveforms look familiar because they have the same shape as the back emf waveforms. Both the torque efficacy waveforms and the back emf waveforms originate from the airgap flux density waveforms.

$$T_5 = 4 * Kv * i_{P5} \qquad \{2.13\}$$

The torque efficacy waveforms are scaled in units of Newton-meters per ampere (Nm/A). The torque is directly dependent on the current in the windings. The torque of the five-phase motor is illustrated in Figure 2.3-7. The torque is shown for two cycles, and the twenty conduction states can be identified.

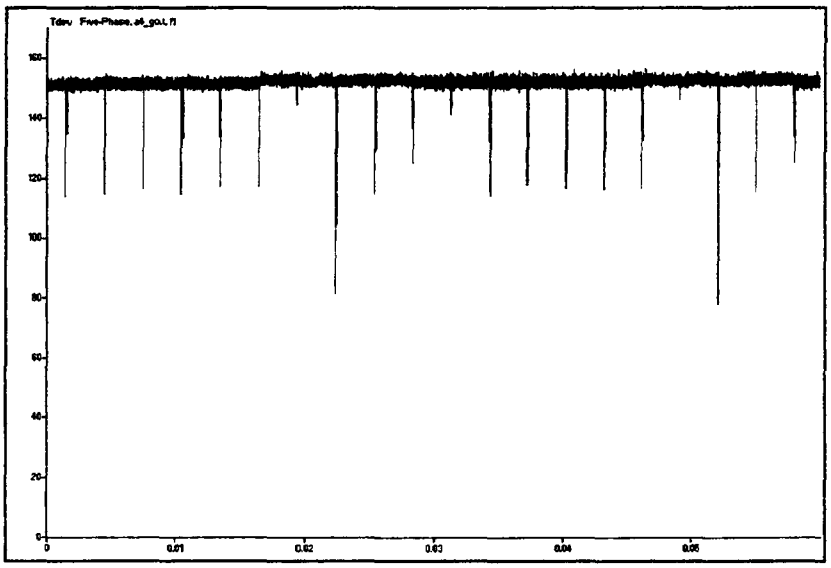


Figure 2.3-7 Torque of the Five-Phase Motor

2.4 Equivalent Machines

There are an many ways the two types of systems could be made "equivalent", but this study proposes a set of constraints to allow equitable comparison of the torque production abilities of the three-phase and five-phase motor systems. In order to compare the three-phase and five-phase motor systems fairly, a concept of equivalent machines is

presented. The three-phase motor and five-phase motor are different as explained in the earlier sections, but the equivalent machines would be equal with respect to physical size, and rated power. Equivalent machines would have rotors with equal diameters, and would have stators with equal inner and outer diameters. The five-phase equivalent machines would have more phase windings and therefore more slots per pole. The equivalent machines would be supplied by identical voltage sources, and have the same dc link current, rated power, base speed, and rated torque.

2.4.1 Back emf of Equivalent Machines

For the same load conditions the equivalent machines would draw the same dc link current and have the same dc supply voltages. The machines will have the same values of back emf for each phase winding, and the same voltage constants for each phase winding. Therefore the machines will have the same ability to link flux per phase winding, and the same number of turns for each phase windings. The equivalent machines would have the same number of turns per phase, the same voltage constants, and the same peak back emf. The relationships of the equivalent machines is defined by the equations, {2.14}, {2.15}, {2.16}.

$$n_{P5} = n_{P3} \qquad \{2.14\}$$

$$Kv_5 = Kv_3 \qquad \{2.15\}$$

$$Ep_5 = Ep_3 \qquad \{2.16\}$$

2.4.2 Winding Resistance of Equivalent Machines

For the equivalent machines to operate with identical supplies the resistance at the terminals of the machines must be the same. The machines will draw the same amount of line current, but the equivalent machines will have different conduction state winding configurations. The five-phase machine, with four windings always active, has an "H" winding configuration. For the line current of the equivalent machines to be the same, the resistance of the five-phase windings must be twice the resistance of the three-phase windings.

$$R_{P5} = 2 * R_{P3} \qquad \{2.17\}$$

With the constraint that the equivalent machine's individual windings have equal length, and twice the resistance, then the difference in wire diameters can be solved for. The resistance of a wire is proportional to the length and the resistivity, and is inversely proportional to the cross sectional area.

$$R_P = \frac{\rho * l}{\pi * r^2} \qquad \{2.18\}$$

The same type of copper wire, with the same resistivity, will be used in each machine. The number of turns per winding are the same, but the resistance per winding of the five-phase equivalent motor is to be twice the resistance of the three-phase windings. Therefore the diameter of the equivalent machines' wire will be different. The difference of the winding resistances is used to determine the ratio of the diameters.

$$\frac{\rho * l}{\pi * r_5^2} = 2 * \frac{\rho * l}{\pi * r_3^2} \quad \{2.19\}$$

The radius of the five-phase machine's wire is solved for with respect to the radius of the three-phase motor's wire. The five-phase motor's wire radius will be the square-root of one-half times the radius of the three-phase motor's wire.

$$r_5 = \sqrt{\frac{1}{2}} * r_3 \approx 0.707 * r_3 \quad \{2.20\}$$

The radius of the five-phase motor's wire is seven-tenths the radius of the three-phase wire.

2.4.3 Winding Volumes of Equivalent Machines

The equivalent machines have the same number of turns per phase, which means the lengths of the phase windings are the same. The difference in volume per winding will depend on the radii of the wire types. The volume of a wire is proportional to the length and the cross sectional area.

$$Vol_P = l_P * \pi * r^2 \quad \{2.21\}$$

The total volume of each machine will be the sum of the volumes per phase winding. The volume of the wire in the three-phase machine will be three times the volume per winding.

$$Vol_{MACH3} = 3 * l * \pi * r_3^2 \quad \{2.22\}$$

$$Vol_{MACH5} = 5 * l * \pi * r_5^2 \quad \{2.23\}$$

Using the relative wire radii, the ratio of wire volume per machine is determined. The copper wire volume of the five-phase equivalent machine is five-sixths the volume of the three-phase equivalent machine.

$$\frac{Vol_{MACH5}}{Vol_{MACH3}} = \frac{5*l*\pi*\frac{1}{2}*r_3^{\,2}}{3*l*\pi*r_3^{\,2}} = \frac{5}{6} \qquad \{2.24\}$$

The volume of wire for the five-phase equivalent machine is less than the volume of wire for the three-phase equivalent machine. The equivalent machines will have different volumes and different weights of copper wire.

So that the line current of the two machines will be the same, the phase winding resistance of the five-phase machine must be twice the resistance of the three-phase windings,. The machines will draw equal line currents, but the five-phase machine will have phase currents of one-half the value of the three-phase machine. The differences in resistance, with the same number of turns per phase, resulted in the five-phase wire diameter being about seven-tenths the diameter of the three-phase wire. The total wire volume of the five-phase machine will be five-sixths the volume of the three-phase machine.

2.4.4 Torque of Equivalent Machines

The torque capabilities, during the normal operation, of the equivalent three-phase system and equivalent five-phase system are equal. The torque is calculated as the product of the

number of the windings active, the voltage constant, and the current in the windings. The torque of the three-phase motor is twice the voltage constant time the current in the windings.

$$T_3 = 2 * Kv * ip_3 \qquad \{2.25\}$$

The five phase system has four phase windings carrying current at any specific time. The voltage constant for the five-phase system is the same as the three-phase motor's voltage constant, but the current in the windings is one-half the current in the three-phase windings.

$$T_5 = 4 * Kv \ * ip_5 = 4 * Kv \ * \left(\frac{1}{2}\right) * ip_3 \qquad \{2.26\}$$

The equivalent machines produce the same torque for the same supply voltages and the same line currents. The proposed equivalent machines, other than the five-phase machine being lighter weight, will be functionally the same. The proposed equivalent designs will provide an equitable basis for comparison of the five-phase and three-phase systems.

2.4.5 Cost of Equivalent Machines

The copper wire is typically priced by the pound. The more copper used the greater the cost. The five-phase equivalent machine will use five-sixths the copper of the three-phase equivalent machine. The cost of copper wire for an equivalent five-phase motor will be a 16.67% less than for a three-phase equivalent motor. For the rotors to be identical, the

magnet pitch needs to be long enough to accommodate the five-phase system's required 144 electrical degrees. The typical three-phase motor only uses square wave currents of 120 electrical degrees and therefore only require a back emf flat top of 120 electrical degrees. To have interchangeable rotors the three-phase motor would have back emf flat tops of 144 electrical degrees and a rotor with more magnet material than is necessary. The additional cost would be based on the price of the permanent magnet material. The overall cost of the brushless dc motor system will depend more on the electronics and controls, than on the motor. Typically there is a general rule of thumb that 70% of the cost of the brushless dc motor system is based on the cost of controls and electronics, and only 30% is the cost of the motor. It will be shown in section 3.1, that the cost of inverters for the equivalent machines, although they are different, will have similar costs. Therefore the overall cost of the equivalent systems will be very similar.

2.5 Failure Modes

Any kind of mechanical or electrical system will fail after it has been in use for an extended period of time. A failure in a brushless dc motor system will most likely occur in the electrical inverter circuit. Multiple failures are possible, but this study limits its' focus to failures in one phase only. The probability of two isolated failures occurring is very low, and is not addressed in this study. This study will assume that the inverter circuit uses insulated gate bipolar transistors (IGBT) for the electronic switching devices. The anti-

parallel diodes are assumed to be separate devices, but may be copackaged with a transistor. The most likely failures were chosen to best represent the possible failure conditions. All the possible failures are considered and the possible failure types narrowed to the two most likely types.

2.5.1 Shorted Windings

The equivalent systems for this study are use simple control systems, that do not include sophisticated remedial or corrective action. A short circuit of the phase windings would produce a complete system failure. A short circuit of the phase windings is not as likely to happen as many other types of failures. To simplify the evaluation a short circuit condition will not be included in the comparison of the two types of systems.

2.5.2 Inverter Short Circuit

A short circuit of any of the electronic components would lead to at least one opened electronic device. A short circuit of any electronic component will be assumed to lead to an opened device in the inverter. An open transistor, or diode will be considered in one of the following sections.

2.5.3 Open Phase Winding

An opened phase winding will eliminate that winding from the system, and should not lead to any other failures. If a phase winding of the motor opens, it will be the same as if two transistors in one leg opened. An open phase winding will be combined with the two transistors in one leg failure type.

2.5.4 One Transistor Open

A likely failure of the brushless dc motor system is an opened transistor in the inverter. The case of one transistor open assumes the free-wheeling diode is a discrete part, and is not part of the semiconductor transistor. For the one transistor open case, the phase winding for that inverter leg can only be active during half the normal conduction time. The failure of one transistor should not necessarily lead to more failures.

2.5.5 One Diode Open

The one diode open case assumes a discrete diode used for free-wheeling current. The diode's purpose is to allow a path for the inductor current to dissipate the energy stored in the inductor. A diode failed open will eliminate the dissipation path way for the energy stored in the inductive phase winding. The stored energy will be seen as a very large

change in voltage across two of the transistors. The voltage spike produced will be large (10 kVolts to 100 kVolts) and would be more than large enough to destroy at least one transistor. Therefore for this case at least one, and maybe two transistors in one leg are assumed to be failed open.

2.5.6 Two Transistors Open

As discussed above it maybe possible for two transistors to be destroyed when a diode fails. Many other conditions could lead to the failure of two transistors in one leg, such as a short in the inverter. The failure of two transistors would eliminate that leg of the inverter and would eliminate a complete winding of the motor from being controlled.

2.5.7 Two Failure Types for Comparison

The failures other than the shorted windings, lead to one of two basic failure types. The two failure types evaluated in this study will be one transistor open, and two transistors open in one leg. These two basic types of failures satisfactorily represent the most likely failures to occur and are adequate to fulfill the goals of this comparative study.

3. Comparison of Three-Phase and Five-Phase Systems

Chapter three contains the primary analysis of this study. In order to compare the three-phase and five-phase systems an "equivalent " machine is proposed to directly compare the torque production ability of the three-phase and five-phase systems. The machines are equivalent in that they are of equal physical size, voltage supplied, current supplied, rated power, and rated torque. In chapter three the equivalent systems are compared with respect to the inverter volt-ampere product, copper and conduction losses, post-failure torque production ability, torque production ability with the current limited, and starting torque of the equivalent systems.

3.1 Inverter Volt-Ampere Product

The most likely failure of a brushless dc motor system will occur in the inverter circuit. Power semiconductors are inherently susceptible to damage or destruction from over currents and over voltages. These conditions may cause immediate breakdown or progressively degrade the transistor so as to shorten its useful life. The most probable failure will be an open transistor. The reliability of transistors depends on the operation of a transistor within the rated device limits.

The five-phase system requires an inverter with ten transistors, while the three-phase system only requires six transistors. Typically the five-phase inverter is seen as a much larger cost for electronics than the three-phase inverter, because it requires more transistors. The five-phase inverter is not necessarily at a disadvantage since the transistor current rating will be one-half the transistor current rating of the three-phase inverter's.

During the "OFF" time the transistor will be required to block a voltage equal to the value of the supply voltage. The supply voltage is at least equivalent to twice the value of the back emf at rated speed. During the "ON" time the voltage across the transistor (V_{CE}, voltage from collector to emitter) is small, but the transistor will carry the full nominal current. The volt-ampere product is a figure of merit, and is calculated as the product of the maximum blocking voltage and the maximum transistor current. The volt-ampere product is an indicator of the size of the required transistor silicon substrate, and therefore an indicator of the cost of the inverter circuit.

The volt-ampere product of the three-phase transistors will be the product of the blocking voltage (twice the maximum back emf voltage) and the maximum phase current.

$$VA_{3SW} = I_{3P} * V_{Blocking} = I_{3P} * V_{Supply} = I_{3P} * 2 * E_{3P} \qquad \{3.1\}$$

The five-phase transistor's blocking voltage is the same, but the current is one-half the three-phase transistor current. The volt-ampere product required of the five-phase transistor is one-half the volt-ampere product of the three-phase transistors.

$$VA_{5SW} = \frac{1}{2} * I_{3P} * 2 * E_{3P} = \frac{1}{2} * VA_{3SW} \qquad \{3.2\}$$

The total volt-ampere product per inverter can be calculated and compared. The total volt-ampere product of the three-phase inverter is six times the volt-ampere product of the three-phase transistor rating.

$$VA_{3Total} = 6 * VA_{3SW} \qquad \{3.3\}$$

The total volt-ampere product of the equivalent five-phase inverter is ten times the rating per transistor. The current in the five-phase transistor will be one-half the current of the three-phase transistors, and the total inverter volt-ampere product is only five times the three-phase transistor volt-ampere product.

$$VA_{5Total} = 10 * VA_{5SW} = 10 * \frac{1}{2} * VA_{3SW} = 5 * VA_{3SW} \qquad \{3.4\}$$

To compare the volt-ampere product with respect to the three-phase, the ratio of inverter volt-ampere products is calculated. The total volt-ampere product of the five-phase inverter is five-sixths that of the three-phase inverter.

$$\frac{VA_{5TOTAL}}{VA_{3TOTAL}} = \frac{5 * VA_{3SW}}{6 * VA_{3SW}} = \frac{5}{6} \qquad \{3.5\}$$

What originally seemed to be a disadvantage for the five-phase inverter, may be an advantage. Depending on how the semiconductors are manufactured and packaged, the five-phase inverter's cost for electronics may be less than the three-phase inverter's cost. The volt-ampere products are summarized in Table 3.1-1. From the summary in Table 3.1-1, it is clear that even though the five-phase inverter requires more transistors, it is not at a disadvantage. In contrast to an intuitive assumption, the three-phase inverter requires a higher volt-ampere product than the equivalent five-phase inverter.

Table 3.1-1 Inverter Volt-Ampere Ratings for Equivalent Machines

Inverter Type	**Transistor Volt-Ampere Product Per Unit**	**Inverter Volt-Ampere Product Per Unit**	**Inverter Volt-Ampere Product Percentage**
Three-Phase Inverter	**1 pu**	**6 pu**	**100 %**
Five-Phase Inverter	**1/2 pu**	**5 pu**	**83.33 %**

3.2 Losses of Three-Phase and Five-Phase Equivalent Systems

Power losses in brushless dc motor systems come from at least two sources: power lost due to the resistance of the windings, and power lost in the transistors during conduction. The equivalent three-phase system and equivalent five-phase system are very similar, and that is supported by the copper and conduction losses. The following analysis compares

the conduction loss and the copper loss of equivalent three-phase and equivalent five-phase systems.

The equivalent three and five phase motors will be supplied from identical sources. The supply voltage and the line current for the three-phase and five-phase machines will be the same. The back emfs will be the same, which defines the machines to have the same number of turns per phase. Also the machines will have the same ability to link flux and the same voltage constant. The machines produce the same amount of torque for the same line current. The phase winding current of the three-phase system is the same as the line current. The phase winding current of the five-phase system is one-half the line current. The equivalent machines will be the same physical size, but the five-phase machine will have two extra slots per pole. The resistance of the five-phase windings will be one-half the resistance of the three-phase windings.

3.2.1 Copper Loss of Equivalent Machines

Power lost in the copper windings is proportional to the resistance and proportional to the square of the current. The three-phase motor has two windings carrying current at a time. The three-phase system's power lost in the copper windings is two times the square of the current times the resistance.

$$P_{CU3} = 2 * (ip_3)^2 * R_3 \qquad \{3.6\}$$

The five-phase systems has four windings active at any time, and the power lost due to the resistance will be four times the square of the phase current, times the winding resistance.

$$P_{CU5} = 4 * (ip_5)^2 * R_5 \qquad \{3.7\}$$

The equivalent five-phase system has one-half the winding current and twice the resistance per winding, of the equivalent three-phase system. The five-phase system has twice as many windings active, but the current is one-half the current of the three-phase windings.

$$P_{CU5} = 4 * \left(\frac{1}{2}\right)^2 * (ip_3)^2 * 2 * R_3 = 2 * (ip_3)^2 * R_3 \qquad \{3.8\}$$

The five-phase system's power lost in the copper is the same as the power lost in the three-phase system's copper.

3.2.2 Conduction Loss of Equivalent Machines

The power lost during the conduction of the transistor is the product of the current through the transistor and the voltage drop across the transistor. The transistor is in saturation during full conduction and the voltage drop is small, but the current is very large. The transistors in the three-phase-inverter and the five-phase inverters will have saturation voltages that can be considered equal.

The power lost during conduction of the transistor is the product of the saturation voltage and the transistor current. The three-phase system will have two transistors conducting at

any specific time. The conduction loss of the three-phase system will be two times the saturation voltage, times the transistor current.

$$P_{COND3} = 2 * Vce * ip_3 \qquad \{3.9\}$$

The five-phase inverter will have four transistors conducting at any specific time. The conduction loss is four times the product of the saturation voltage and the current through the transistors.

$$P_{COND5} = 4 * Vce * ip_5 \qquad \{3.10\}$$

The transistor current of the five-phase system is one-half the current in the three-phase system, while the transistor voltage drop is the same as the three-phase system's.

$$P_{COND5} = 4 * Vce * \frac{1}{2} * ip_3 = 2 * Vce * ip_3 \qquad \{3.11\}$$

The conduction loss of the five-phase system and the three-phase system is the same. The copper losses of the five-phase motor will be the same as the copper losses of the three-phase motor. The conduction losses of the five-phase inverter will be the same as the conduction losses of the three-phase inverter.

3.3 Post-Failure Torque of the Three-Phase System

The normal operation of the three-phase brushless dc motor has been discussed, but in this section the torque production of a three-phase system with one transistor failed open, and with two transistors failed open will be evaluated. The post failure operation of the three-

phase motor can be evaluated on the basis of the torque provided per conduction state. During each conduction state the active windings contribute to the total torque produced by the machine.

During the pre-failure operation all six of the conduction states are of the same winding configuration and contribute identical torque. After either of the two types of failures, the six conduction states are no longer identical. The failure of one transistor will affect two of the conduction states. A failure of two transistors will affect four of the conduction states. For the three-phase system each conduction state consists of two windings in series. If one of the windings is eliminated by an opened circuit in the inverter, then both of the windings are excluded from the torque production of the motor.

3.3.1 Torque for the Three-Phase System with One Transistor Open

There are two possible winding configurations for one transistor open , or two transistors open in one leg. In Figure 3.3-1 the two winding configurations are shown. Three-phase case #1 represents a fully functional state circuit with two phase windings in series. If a conduction state involves a failed transistor, then the circuit configuration will be three-phase case #2, where no current is carried by the windings, and no torque is developed.

If one transistor in the inverter fails as an open circuit, two of the conduction states will be affected. The failure of one transistor will open the series circuits of two of the conduction states, and eliminate those states from producing torque.

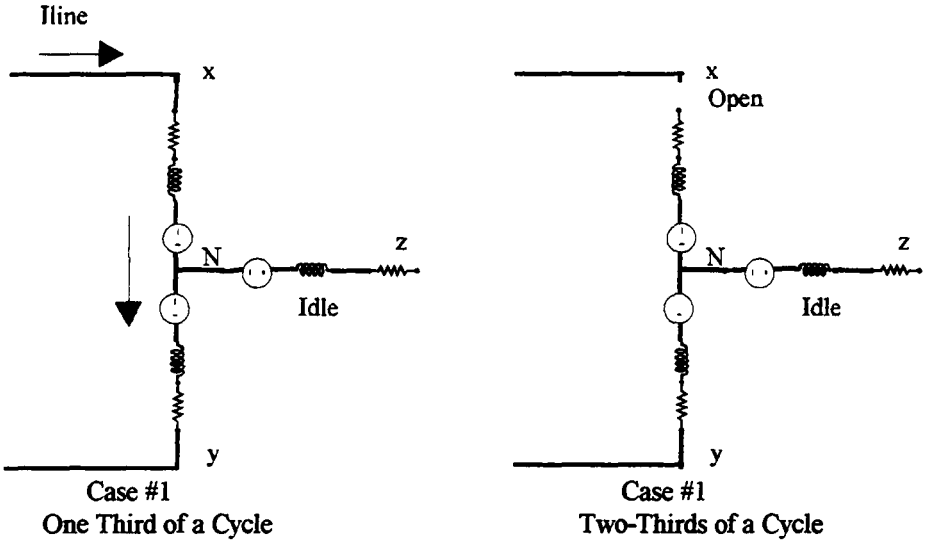


Figure 3.3-1 Winding Configurations for Three-Phase with One Transistor Open

With one transistor open the three-phase motor will not be able to produce torque for one-third of the cycle. The torque developed for one active conduction state is the sum of the torque components from the windings carrying current. The torque for one conduction state will be two times the voltage constant times the winding current.

$$T_{3DEV/PHASE} = K_{V3} * (i_A + i_B) = K_{V3} * 2 * I_{3FULL} = T_{3FULL} \qquad \{3.12\}$$

The average torque for one cycle will be the sum of the torque components from the active conduction states. If one transistor fails then only four of the six possible

conduction states are active. The average torque of the three-phase motor, with one transistor failed, will be two-thirds the nominal torque.

$$T_{3DEV/CYCLE} = \frac{4 * T_{3FULL}}{6} = \frac{2}{3} * T_{3FULL} \approx 0.6667 * T_{3FULL} \qquad \{3.13\}$$

The three-phase motor was modeled and simulated to produce back emf, winding current , and torque waveforms. The torque of the simulated three-phase system with one transistor failed is illustrated in Figure 3.3-2.

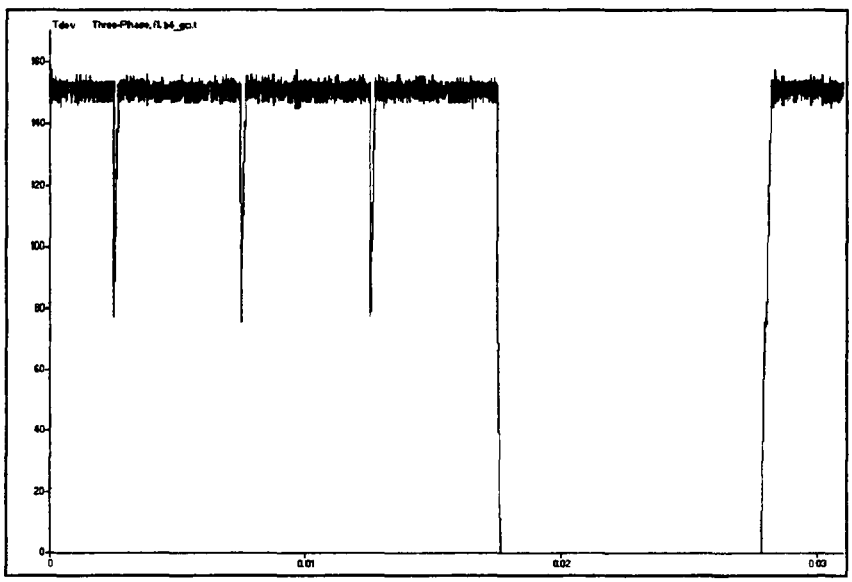


Figure 3.3-2 Torque for Three-Phase System with One Transistor Failed

The simulated system has a rated torque of 154 Nm, for a rated current of 300 Amps. The average torque is two-thirds of the nominal torque, but the torque is eliminated for one-third of the cycle.

3.3.2 Torque for the Three-Phase System with Two Transistors Open

Figure 3.3-3 shows the winding configurations for the three-phase motor when two transistors fail in one leg. The first configuration is case #1, where the full torque capability is available. The second, and third configurations both produce zero torque, and will be grouped together as case #2. The failure of two of the transistors in one leg of the inverter eliminates four of the six conduction states from contributing any torque. No torque will be produced for two-thirds of each cycle.

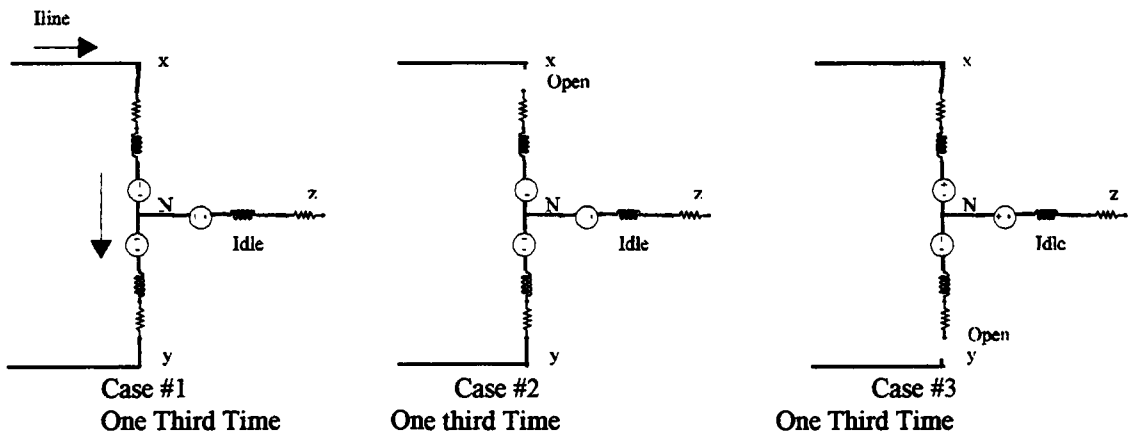


Figure 3.3-3 Winding Configurations for Three-Phase Motor with Two Transistors Open

If two transistors in the same leg are open then only two of the states are active. The average torque produced is calculated as the average of the active state torque-components. The average torque with two transistors failed is only one-third the nominal torque.

$$T_{3DEV/CYCLE} = \frac{2 * T_{3FULL}}{6} = \frac{1}{3} * T_{3FULL} \approx 0.3333 * T_{3FULL} \qquad \{3.14\}$$

The three-phase motor system was simulated to verify and support the analysis. The torque waveform of the three-phase system with two transistors failed is shown in Figure 3.3-4. The average torque after a failure of two transistors is one-third the nominal torque, but the torque is eliminated for two-thirds of the cycle.

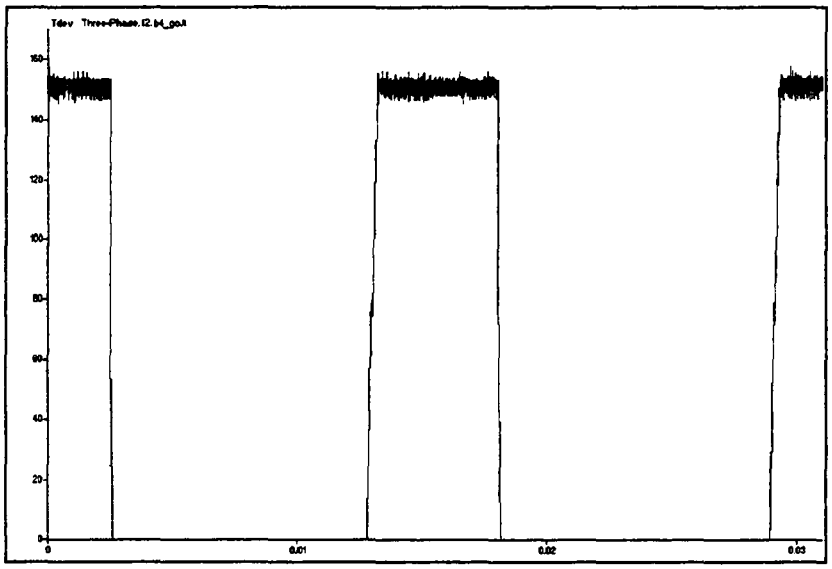
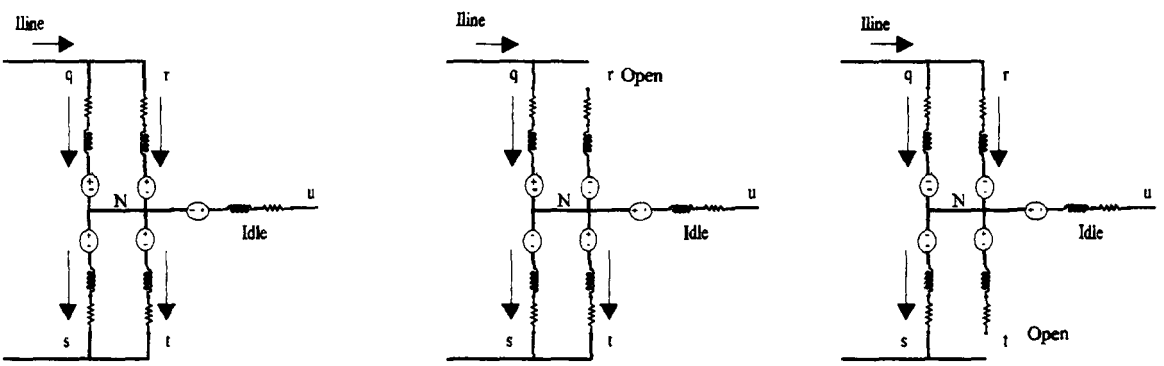


Figure 3.3-4 Torque of Three-Phase System with Two Transistors Open

If the motor is in motion when the failure occurs, depending on the amount of the load, the motor should be able to stay in motion, although the speed, and torque delivered will drop. At higher speeds the effective torque is the average torque, but the load will be subjected to discontinuous torque. The discontinuous torque waveforms, as shown in Figure 3.3-2, and Figure 3.3-4, may create a very bumpy speed profile depending on the inertia of the load.

3.4 Post-Failure Torque of the Five-Phase System

In this section the torque production of a five-phase motor with one transistor open and two transistors open in one leg is evaluated. The speed and load conditions are considered to be constant. With one or two transistors failed open, the circuit configuration during any of the ten conduction states will be of one of the three forms shown below. In terms of the torque produced for each state configuration, the second and third cases are duplicates. Case #2 and case #3 will be combined and the analysis will only consider case #1 and case #2.



Case #1 Case #2 Case #3

Figure 3.4-1 Five-Phase System State Configurations

The voltage is applied by a conventional ten transistor inverter. The phases are assumed to be balanced, with identical resistive, inductive and back emf elements. The amplitude of the back emf for each phase is dependent on the rotor position and speed, but during any specific state the value of the back emf can be considered constant.

The analysis of the torque is done per conduction state, in which the ten states for one cycle are added to get the torque per one cycle. For constant speed and load conditions the torque for one cycle will be the same for every cycle, and can therefore be considered the average torque.

3.4.1 Five-Phase Case #1: Fully Functional Winding Configuration

For case #1 the circuit configuration represents a fully functional winding circuit. Case #1 will produce the maximum torque for the given speed and current levels. This case will represent the basis of the comparison with the failed circuit configurations.

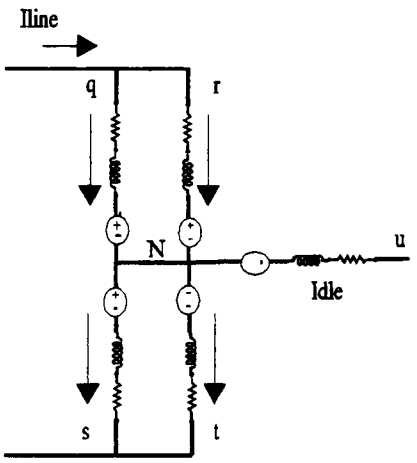


Figure 3.4-2 Five-Phase Fully Functional Conduction State Circuit

For the five-phase case #1 the winding current will be the same for all the phases. The value of the phase current will determine the value of the torque produced by any particular phase winding. The phase current of the fully functional configuration will be used to determine the amount of degradation of the failed configurations. The torque developed from the

case #1 configuration will be the sum of the torque components from each active phase winding. The torque developed by one phase winding is determined by the product of the back emf constant and the current in the phase windings.

$$T_{5DEV} = K_V * (i_A + i_B + i_C + i_D) \qquad \{3.15\}$$

The torque produced by the circuit of five-phase case #1 is the full torque that can be developed by a fully functional set of windings, and will be designated as T_{5FULL}.

3.4.2 Five-Phase Case #2: Failed Transistor Winding Configuration

Case #2 is the failed case, where one of the phases is no longer active. The elimination of the phase during this state could be from an open transistor, or an open winding. Figure 3.4-3 illustrates the case #2 winding configuration. For case #2 the conduction state circuit configuration is not symmetrical, and therefore the phase currents are not the same. The current in the top transistor will be the line current, and the current in the two lower transistors will be one-half the line current. In this winding configuration the current in one of the windings will be twice the value of the nominal winding currents. The other two active windings will have the nominal phase current.

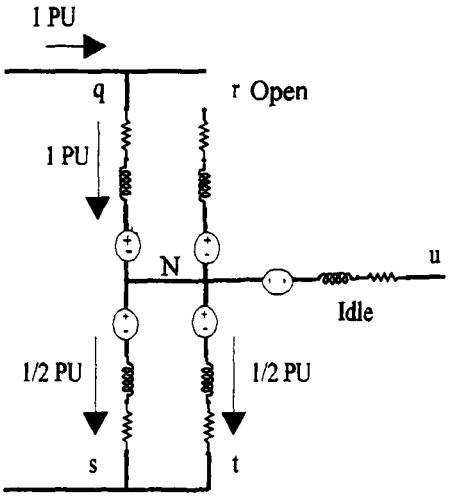


Figure 3.4-3 Failed Conduction State for Five-Phase Motor

The torque developed for this conduction state is the sum of the torque components from each winding. Each winding current contributes to the torque developed for this conduction state.

$$T_{DEV2} = K_V * \left(i_q + i_s + i_t\right) \qquad \{3.16\}$$

One of the currents is twice the nominal phase current, the other two currents are the nominal phase current.

$$T_{DEV2} = K_V * \left(i_{Line} + \frac{1}{2} * i_{Line} + \frac{1}{2} * i_{Line}\right) \qquad \{3.17\}$$

The total torque developed for the failed conduction state is the full nominal torque as shown in equation {3.18}.

$$T_{DEV2} = K_V * 2 * i_{5FULL} = T_{5FULL} \qquad \{3.18\}$$

The winding configuration of the failed state can provide full torque, but one of the transistors is carrying twice the nominal current. At rated line current and one transistor open the five-phase system will have two transistors carrying current that is twice the maximum nominal current. A motor does not usually operate at rated conditions, but during acceleration the maximum torque maybe required. A conservative design usually specifies a transistor current rating that is twice the required nominal value. With transistor ampere ratings that are twice the maximum phase current limit, the post-failure currents are just at the device limit.

The equivalent three and five phase systems were established such that the they are interchangeable at the dc supply terminals. The transistor currents of the equivalent five-phase system are one-half the transistor currents of the equivalent three-phase system. Because the transistor currents are lower, the volt-ampere rating of the equivalent five-phase inverter had a volt-ampere rating that was one-sixth lower than the equivalent three-phase inverter volt-ampere rating. If the volt-ampere rating of the five-phase inverter was increased by one-sixth, to the same level as the three-phase inverter, then the post-failure current levels would be within the design rating. To protect against additional failures the transistors should be specified for a device limit higher than twice the rated phase current.

With the assumption that the system can handle the increased current and does not have additional failures, the torque can be evaluated for the two failure types. If the inverter

can accommodate the increased currents then the torque produced for either one transistor open or two transistors open will be the full nominal torque, as will be shown.

3.4.3 Torque for the Five-Phase System with One Transistor Open

With one transistor open, four of the ten conduction states will be affected by the failure, the remaining six conduction states are unaffected. The affected states continue to contribute the full torque, but the current in two of the transistors is at twice the nominal phase current. The average torque for one cycle is calculated by summing the torque contributions from each state and dividing by the number of states in one cycle.

$$T_{DEV/CYCLE} = \frac{6 * T_{5FULL} + 4 * T_{5FULL}}{10} = \frac{10}{10} * T_{5FULL} \approx 100\% \qquad \{3.19\}$$

For one transistor open, the torque is still the full nominal torque. The torque from the simulated five-phase system is shown in Figure 3.4-4. For the simulated torque the inverter is assumed to continue operating without additional failures.

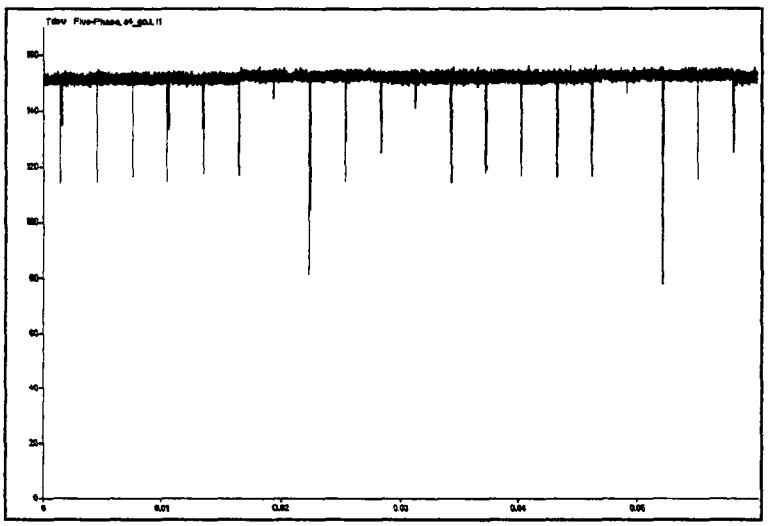


Figure 3.4-4 Torque for Five-Phase System One Transistor Open

3.4.4 Torque for the Five-Phase System with Two Transistors Open

If two transistors, in one leg of the inverter, fail then only two states are not affected (case #1) and eight states are affected(case #2). The failed states provide the full torque of a non-failed state. The average torque is the sum of the state torque contributions divided by the number of states in one cycle.

$$T_{DEV/CYCLE} = \frac{2 * T_{5FULL} + 8 * T_{5FULL}}{10} = T_{5FULL} \approx 100\% \qquad \{3.20\}$$

The average torque for the five-phase motor with two transistors open is 100 % of the nominal average torque. The simulated results help to illustrate the torque waveform for the failure of two transistors. Figure 3.4-5 shows the torque of the five-phase motor for two transistors failed. The failure of two transistors completely excludes one of the phase windings from producing torque.

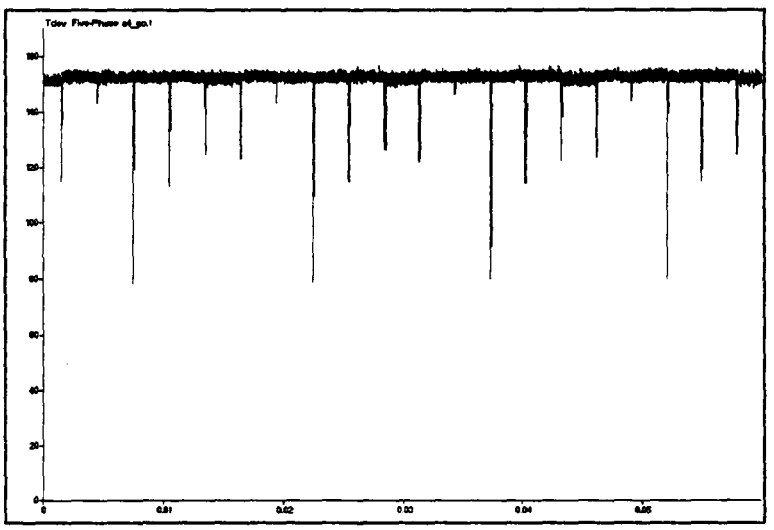


Figure 3.4-5 Five-Phase System , Two Transistors Open

3.5 Post-Failure Torque of the Five-Phase System with Limited Currents

The torque production ability of a five-phase system with the phase currents limited to the rated value is evaluated in this section. For the five-phase system with either one transistor open or two transistors open in one leg, the current will be twice the nominal

value in two and four transistor respectively. For rated line currents the device limits would be exceeded and additional transistors may fail. In order to ensure the transistor limits are not exceeded the phase currents could be limited to the maximum level. If the phase currents were limited from exceeding the value of the rated phase currents, the maximum torque capabilities would be reduced.

The phase currents would need to be measured in order to ensure they do not exceed the maximum value. The measured values would be used by the inverter's control system to limit the current of any specific winding at any time to the rated value or less. The ceiling or upper limit of the phase currents would reduce the torque capabilities of the five-phase system for the two types of failures.

The analysis will be divided into two cases as shown in Figure 3.5-1. Case #1 represents the conduction states where the nominal winding configuration is available, and the full value of torque is possible. Case #2 represents the conduction states where one of the four windings is eliminated because of a failed transistor in the inverter.

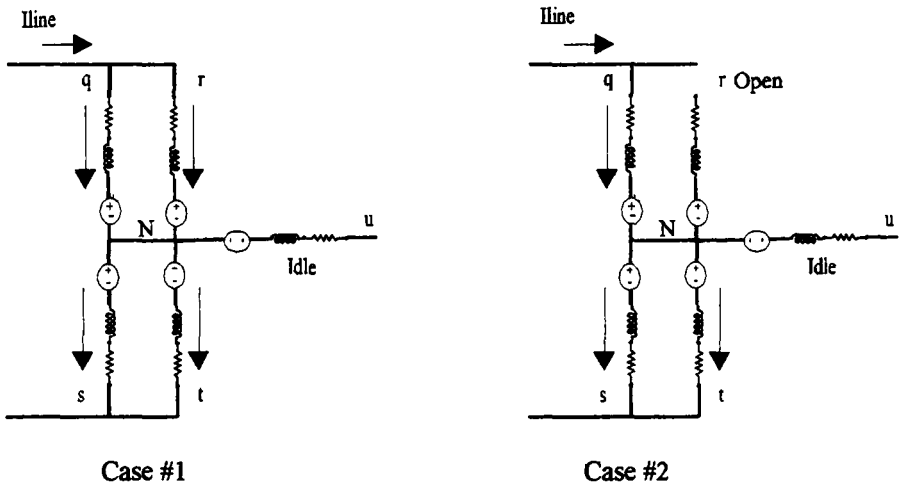


Figure 3.5-1 Five-Phase System State Configurations

The torque developed by the circuit of five-phase case #1 is four times the back emf constant times the phase current and will be designated as T_{5FULL}. For case #2 the conduction state circuit configuration is not symmetrical. The current in the top transistor will be the line current, and the current in the two lower transistors will be one-half the line current. If the all the phase currents are to be no greater than the maximum nominal phase current then the torque will as shown in equation {3.21}.

$$T_{DEV} = K_V * \left(\frac{1}{2} * i_{PU} + \frac{1}{4} * i_{PU} + \frac{1}{4} * i_{PU} \right) \qquad \{3.21\}$$

The total torque developed for the failed conduction state is one-half the nominal torque.

$$T_{DEV} = K_V * \frac{2}{2} * i_{PU} = \frac{1}{2} * [2 * Kv * i_{PU}] = \frac{1}{2} * T_{5FULL} \qquad \{3.22\}$$

The limiting of the phase currents reduced the torque capability of failure affected conduction states to one-half the full nominal value.

3.5.1 Currents Limited and One Transistor Open

With one transistor open, four of the ten conduction states will be affected by the failure, the remaining six conduction states are unaffected, and contribute the full value of torque. The simulations of the five-phase motor system support the analysis, as shown in Figure 3.5-2.

$$T_{DEV/CYCLE} = \frac{6 * T_{5FULL} + 4 * \frac{1}{2} * T_{5FULL}}{10} = \frac{8}{10} * T_{5FULL} \approx 0.80 * T_{5FULL} \qquad \{3.23\}$$

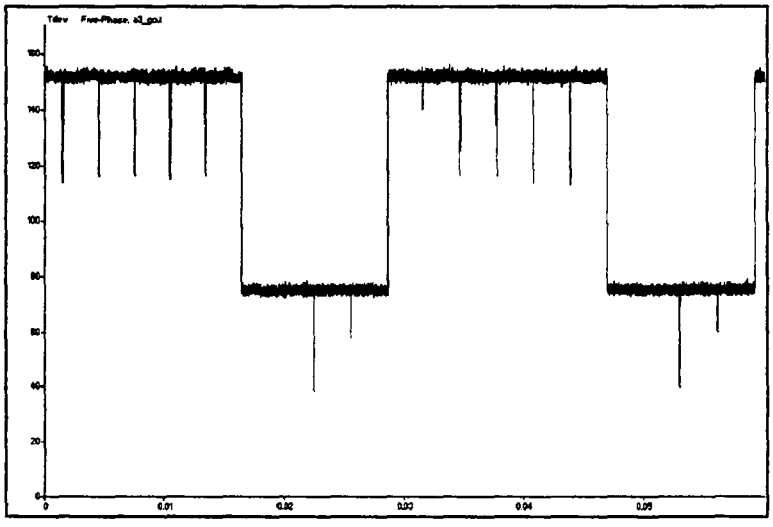


Figure 3.5-2 Five-Phase System, One Transistor Open

For one transistor open , the torque is 80 % of the nominal average torque. From the torque waveform can be seen where the failed states and non-failed states contribute torque for the overall torque of the motor.

3.5.2 Current Limited and Two Transistors Open

If two transistors, in one leg of the inverter, fail then only two states are not affected (case #1) and eight states are affected(case #2). The failure affected conduction states can only provide one-half the full torque.

$$T_{DEV/CYCLE} = \frac{2 * T_{5FULL} + 8 * \frac{1}{2} * T_{5FULL}}{10} = \frac{6}{10} * T_{5FULL} \approx 0.60 * T_{5FULL} \qquad \{3.24\}$$

The average torque for the five-phase motor with two transistors open is 60 % of the nominal average torque. The simulated results help to illustrate the torque waveform for the failure of two transistors. Figure 3.5-3 shows the torque of the five-phase motor for two transistors failed.

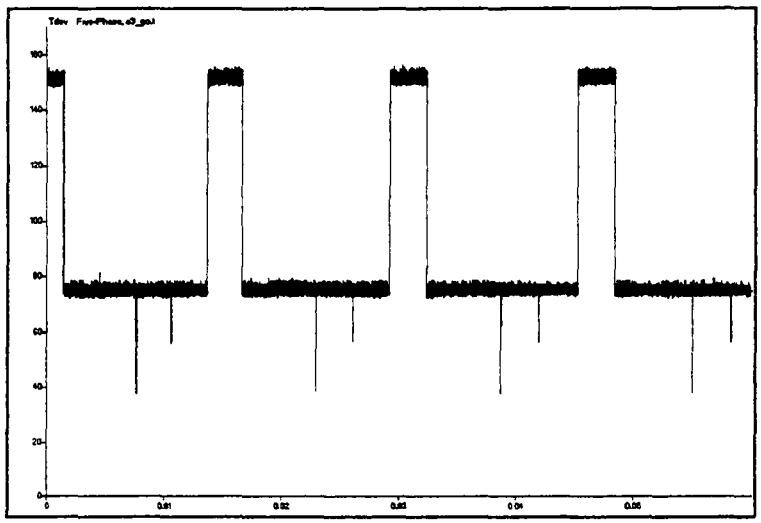


Figure 3.5-3 Five-Phase System , Two Transistors Open

3.6 Comparison of Starting Torque for Equivalent Systems

The value of torque is the product of a motor winding constant, the linked flux, and the current in the windings. By grouping the flux and winding constant into one constant term the relationship takes a more familiar form.

$$T_{DEV} = K_V * I \qquad \{3.25\}$$

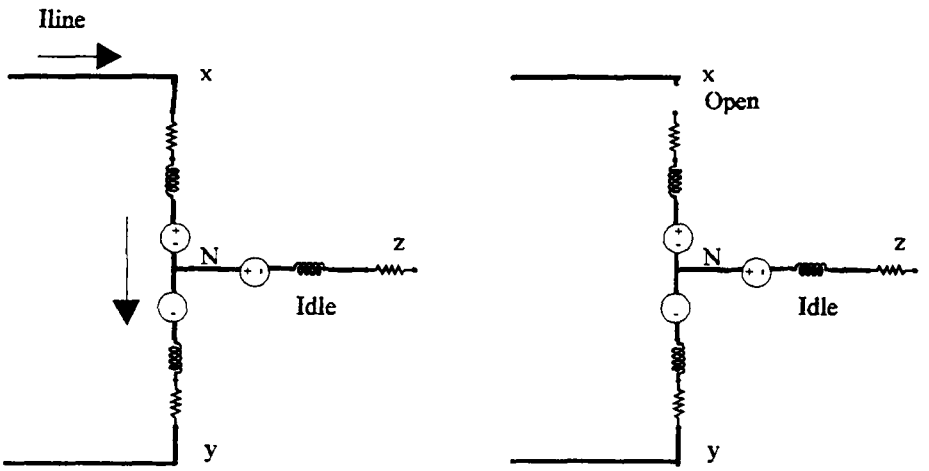
Using the flux density shape per rotor position, the voltage constant, and the current in the windings, the torque can be calculated at zero speed. Equation {3.26} can be used to calculate torque at zero speed.

$$T_{DEV} = K_V * \sum_{j}^{N} i_j(\theta) * f_j(\theta) \qquad \{3.26\}$$

The term, " $f_j(\theta)$ ", is the normalized flux density shape as a function of rotor position. The torque produced is based on the shape of the flux density, and current as a function of rotor position. Torque is not a function of rotor speed, but is function of the rotor position.

3.6.1 Starting Torque for Three-Phase System

A three-phase motor with two poles has six possible rotor positions. With a failure of one or two transistors in a leg of the inverter, the three-phase motor will have two types of winding configurations. Figure 3.6-1 shows the two types of winding configurations for the three-phase motor after a failure of a transistor. The torque available at start will depend on the rotor position and the level of current in the windings. During case #1, 100% of the full torque is possible. Case #2 is where the path through the two windings in series is no longer possible and no torque can be developed over those poles.



Three-Phase Case #1 Three-Phase Case #2

Figure 3.6-1 Winding Configurations for Three-Phase Starting Torque

3.6.2 Starting Torque for Three-Phase System with One Transistor Open

After the failure of one transistor, four of the six possible rotor positions will be the condition of case #1, and four rotor positions will be the condition of case #2. The amount of full torque will depend on the maximum level of current through the phase winding. During case #2 no torque can be developed, because there is zero current in the phase windings. With one transistor failed in the three-phase motor system, there can be no torque developed at start for one-third of the rotor positions. In Figure 3.6-2, the starting torque in shown for one rotation of the rotor(for a two pole machine). The starting torque is the peak rated torque for rotor positions that are not affected by the failure. The rotor positions where no torque can be developed are clearly evident.

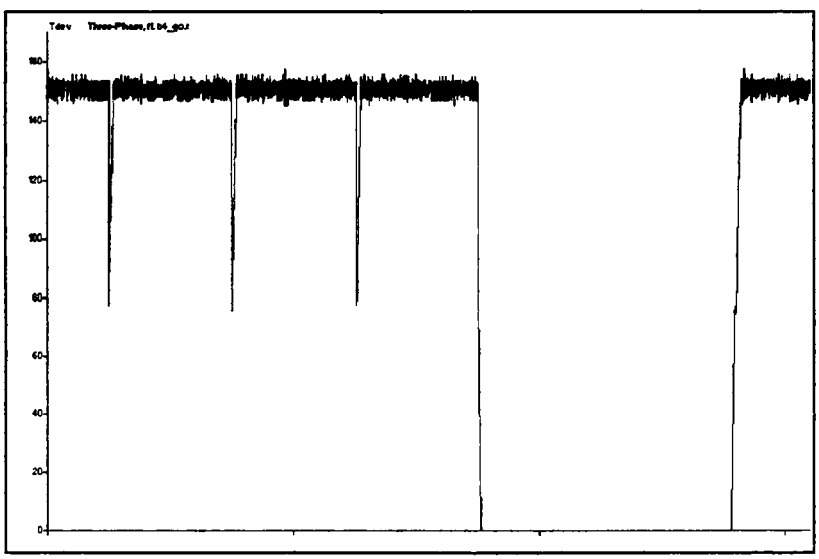


Figure 3.6-2 Starting Torque for Three Phase System with One Transistor Open

3.6.3 Starting Torque for Three-Phase Motor with Two Transistors Open

If two transistors are open, or one phase winding is open, then four of six rotor positions will be the case #2 condition and only two of the rotor positions will be the case #1 condition. Again the torque available at start will depend on which motor phase is affected and the position of the rotor. With two transistors open the three-phase system will not produce any torque at start, for two-thirds of the rotor positions. In Figure 3.6-3 the starting torque for one rotation of a two pole machine is illustrated. The peak torque is the rated torque, but two thirds of the rotor positions have zero torque.

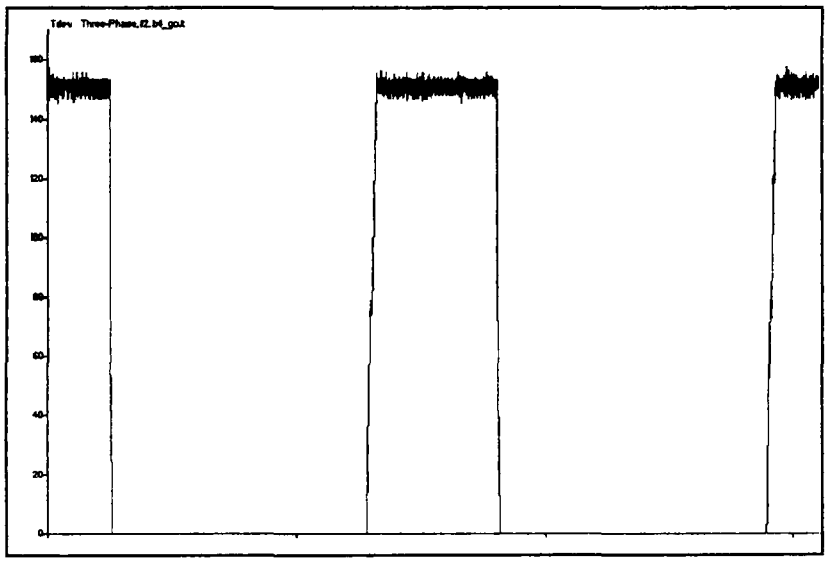


Figure 3.6-3 Starting Torque for Three Phase System with Two Transistors Open

The three-phase motor will produce peak nominal torque during the conduction states not affected by the failure, but the torque drops to zero during the periods affected by the failure. Table 3.6-1 summarizes the starting torque for the three-phase motor. The three-

phase motor with one transistor failed can only produce torque for two-thirds of the rotor positions. The three-phase motor with two transistors open only produces torque for one-third of the rotor positions.

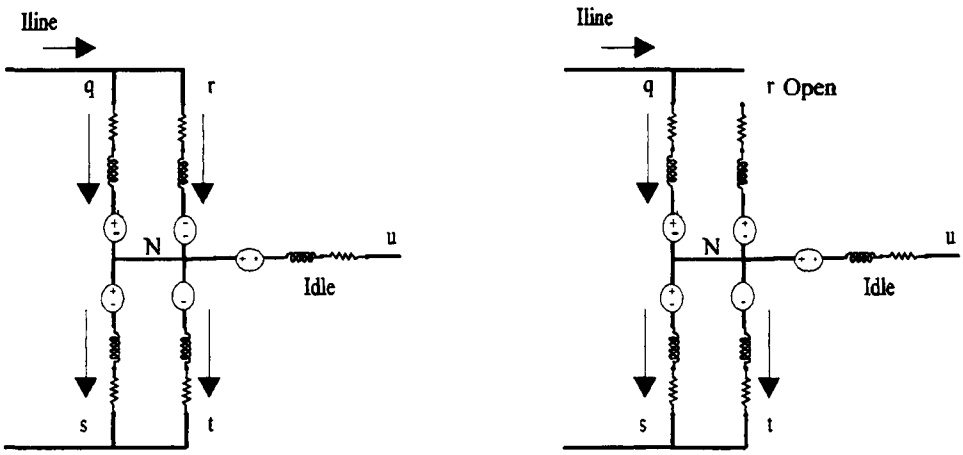
Table 3.6-1 Three-Phase Motor Starting Torque

Failure Mode	Rotor Position	% of Full Torque	Probability
One Transistor Open	Case #1	100%	66.67%
	Case #2	0 %	33.33%
Two Transistors Open	Case #1	100%	33.33%
	Case #2	0 %	66.67%

3.6.4 Starting Torque for Five-Phase System:

A five-phase two-pole motor will have ten possible rotor positions. With the failure of one or two transistors in one leg of the inverter, the five-phase motor has two types of circuit configurations, as shown in Figure 3.6-4 (case #1 and case #2). Case #1 has all four windings active and the full rated torque is possible. Case #2 has only three of the windings carrying current. The starting torque will depend on the number of windings active, and the amount of current in each winding. For a five-phase motor with one of the two types of failures, the winding configuration, case #1 or case #2, will depend on which transistors failed, and the position of the rotor.

For the equivalent five-phase system the phase current will be limited to the rated phase current value as discussed in section 3.5. The limiting of the phase currents reduces the torque capabilities of the system, but ensures the operation at safe transistor current levels. Without a restriction on the phase currents some of the currents would exceed the equivalent five-phase inverter transistor rating.



Five-Phase Case #1 Five-Phase Case #2

Figure 3.6-4 Winding Configurations for Five-Phase StartingTorque

3.6.5 Starting Torque of the Five-Phase System with One Transistor Open

When one transistor fails in a five-phase two-pole motor system, four of the ten rotor positions are affected. As represented in Figure 3.6-4, there are two types of winding configurations, labeled as case#1 and case #2. After the failure of one transistor, six of the ten possible rotor positions will be the condition of case #1, and four rotor positions will be the condition of case #2. During case #1, 100% of the rated torque is possible. During case #2 only one-half of the rated torque is possible. The amount of torque will depend

on the maximum level of current through the phase windings. In Figure 3.6-5 the starting torque over two rotations for a two pole machine is illustrated. After one transistor fails the five-phase motor will always have at least starting torque that is 50% of full torque.

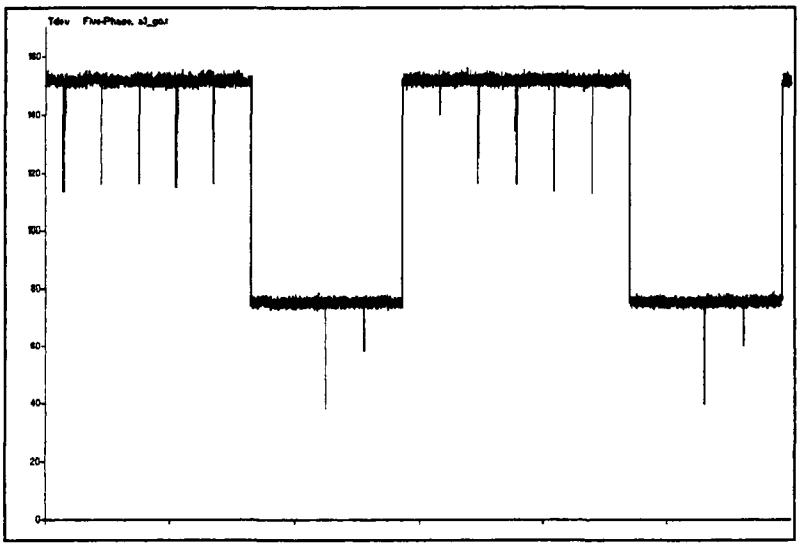


Figure 3.6-5 Starting Torque for Five Phase System with One Transistor Open

3.6.6 Starting Torque of Five-Phase System with Two Transistors Open

If two transistors are open, or one phase winding is open, then eight of the ten rotor positions will be the case #2 condition and only two rotor positions will be the case #1 condition. Again the torque available at start will depend on which motor phase is affected and the position of the rotor. The eight affected winding configurations can only develop one-half of full torque. Even with one phase eliminated the five-phase motor has

starting torque capability that is at least 50% of full torque. In Figure 3.6-6 the starting torque is shown for two rotations of a two pole machine.

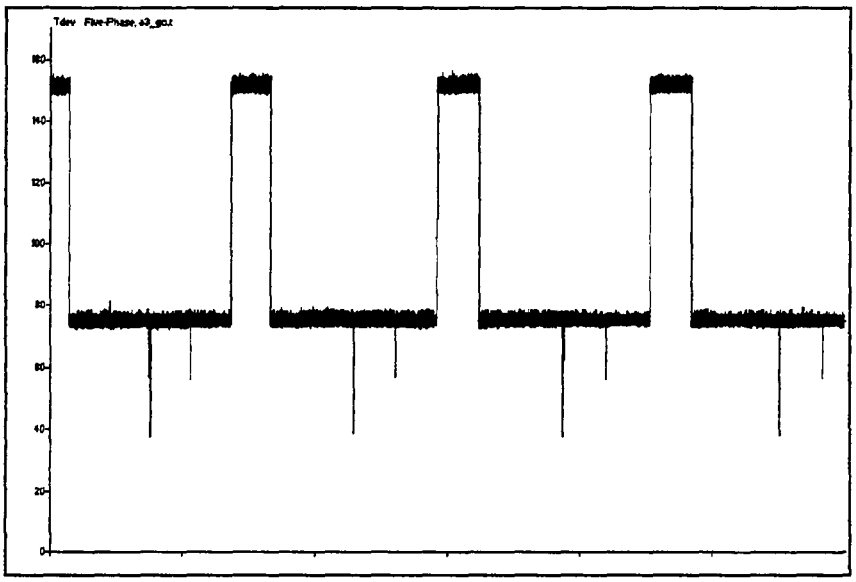


Figure 3.6-6 Starting Torque for Five Phase System with Two Transistors Open

The starting torque for the five-phase motor is summarized in Table 3.6-2. The starting torque for the five-phase motor never falls below 50% of the nominal torque. With one transistor open the torque will be the full nominal torque for 60 % of the rotor positions, and will be 50% of the full nominal torque for 40% of the rotor positions. When two transistors fail, the starting torque will be the full nominal value for only 20 % of the rotor positions, and will be one-half for 80% of the rotor positions.

Table 3.6-2 Five-Phase Motor Starting Torque

Failure Mode	Rotor Position	% of Full Torque	Probability
One Transistor Open	Case #1	100%	60%
	Case #2	50%	40%
Two Transistors Open	Case #1	100%	20%
	Case #2	50%	80%

3.6.7 Summary of Three and Five Phase Starting Torque

The possibility that the motor will start depends on the torque capability at zero speed. For a fully functional brushless dc motor system the more current in the phase windings, the more torque developed. The torque available at zero speed will be diminished or eliminated depending on whether the windings can be excited. The summary of the starting torque capabilities of the three and five phase systems is listed in Table 3.6-3.

The five-phase motor can produce at least 50% of full torque at start for any rotor position. For a three-phase motor system with failures, the ability to start will depend on the rotor position. For one transistor open the three-phase system will not produce any torque for one-third of the rotor positions. For two transistors open the three-phase system will not produce torque for two-thirds of the rotor positions. Without moving the rotor, the three-phase motor will not be able to start if one or two transistors are open.

Table 3.6-3 Summary of Starting Torque Capabilities

Failure Mode	Rotor Position	Five-Phase % of Full Torque	Probability for Five-Phase Motor	Three-Phase % of Full Torque	Probability of Three-Phase Motor
One Transistor Open	Case #1	100%	60%	100 %	66.67 %
	Case #2	50%	40%	0 %	33.33 %
Two Transistors Open	Case #1	100%	20%	100 %	33.33 %
	Case #2	50%	80%	0 %	66.67 %

4. Conclusions

The focus of this study was to evaluate the torque production of the three and five phase brushless dc motor systems after a failure in one leg of the inverter circuit. The two primary failure modes, one transistor open, and two transistors open, were used as the basis of the comparisons. The three and five phase motor systems are different, but the equivalent systems are equal with respect to physical size, dc supply voltage, dc supply current, rated power, and rated torque. Because the five-phase motor always has four phase windings active and the equivalent machines are to be interchangeable at the dc supply terminals, the phase resistance is twice and the phase current is half the value of the three-phase motor.

The five-phase system requires an inverter with ten transistors, while the three-phase system only requires six transistors. The transistor current of the equivalent five-phase inverter will be one-half the transistor current of the equivalent three-phase inverter. Therefore the total volt-ampere product of the five-phase inverter is five-sixths the value of the three-phase inverter. The amount of silicon required for the pre-failure equivalent five-phase inverter is less than the equivalent three-phase inverter. To bring the two inverters up to an equal basis, the five-phase inverter's volt-ampere product is to be set equal to the three-phase

inverter's volt-ampere product. Now the five-phase inverter's transistors have a device current limit 20% greater than the nominal requirement.

After a failure in one leg of the inverter, some of the five-phase transistors will carry line current which is twice the pre-failure transistor current. A conservative specification for the device current limit is typically twice the system's requirement. With a conservative design and the device current limit increased 20 % for equal volt-ampere products, the five-phase inverter will be able to sustain the increased post-failure currents. Now the five-phase system produces the full value of torque, even after a failure of one or two transistors in one leg of the inverter.

To ensure the reliable operation of the five-phase system after a failure, the phase currents could be limited to the maximum device rating. With the phase currents never exceeding the maximum nominal limit, the torque capability of the five-phase motor is reduced. The current-limited torque capability of the five-phase system when one transistor fails is 80% of full nominal torque, whereas the three-phase system is capable of only 66.67%. The failure of two transistors in one leg of the inverter causes the current-limited torque capability of the five-phase system to be 60% of full nominal torque, whereas the three-phase system is capable of only 33.33% of full torque. The equivalent five-phase system has greater ability to produce torque after a failure in one leg of the inverter.

After a failure, a three-phase system can remain in motion at reduced torque capability, but with one transistor failed the motor will not be able to start for one-third of the rotor positions. When two transistors fail, the three-phase motor can not produce torque for two-thirds of the rotor positions. The current limited five-phase system can develop at least 50% of full starting torque, even with one complete phase eliminated. The equivalent five-phase system can start even though one inverter leg has failed. The results show that the post-failure performance of the five-phase system is better than the three-phase system. For any application that requires high performance and reliability, the five-phase system is the better choice.

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Appendices

Appendix A

Appendix A :Baseline Motor for Models

The motor used in the simulations is based on a motor manufactured by Unique Mobility Inc. The modeled motor is primarily defined by the back emf constant, maximum supply voltage, maximum current, transistor volt-ampere ratings, phase resistance and phase inductance.

The motor system is rated at 42.9 hp/32 KWatts and a continuous torque of 154 Nm at 2000 rpm. The brushless motor has a base speed of 2000 rpm and a top speed of 8000 rpm. The design utilizes high energy Neodymium Iron Boron (NdFeB) magnets. The back emf constant is 27 Volts/ Krpm, and the maximum inverter current is 300 amperes. The phase resistance is 0.0075 Ohms, and the phase inductance is 12.5 μHenries. Liquid cooling and phase advance is used to increase the range of performance.

The brushless dc motor is supplied and controlled by a pulse width modulated (PWM) voltage source inverter. The inverter is formed from three half-bridge , 600 ampere insulated gate bipolar transistor (IGBT) modules. The supply is controlled by a microprocessor and uses a transistor switching frequency of 20 Khz. The nominal dc voltage input for the supply is 180 volts.

Appendix B

Appendix B : Simnon Simulated Models

The simulation software, Simnon, by the Lund Institute of Technology, is designed for solving systems of ordinary differential and difference equations and for simulating dynamic systems. The Simnon version used was Ver. 1.0 Student Version for Windows, by SSPA Systems. Simnon allows the description of systems as interconnected sub-systems, whose behavior is characterized by differential equations or by difference equations. The modular organization of the Simnon language is especially helpful in developing a complex system. In Figure B-1 a block diagram of the Simnon model of the five-phase brushless dc motor system is shown.

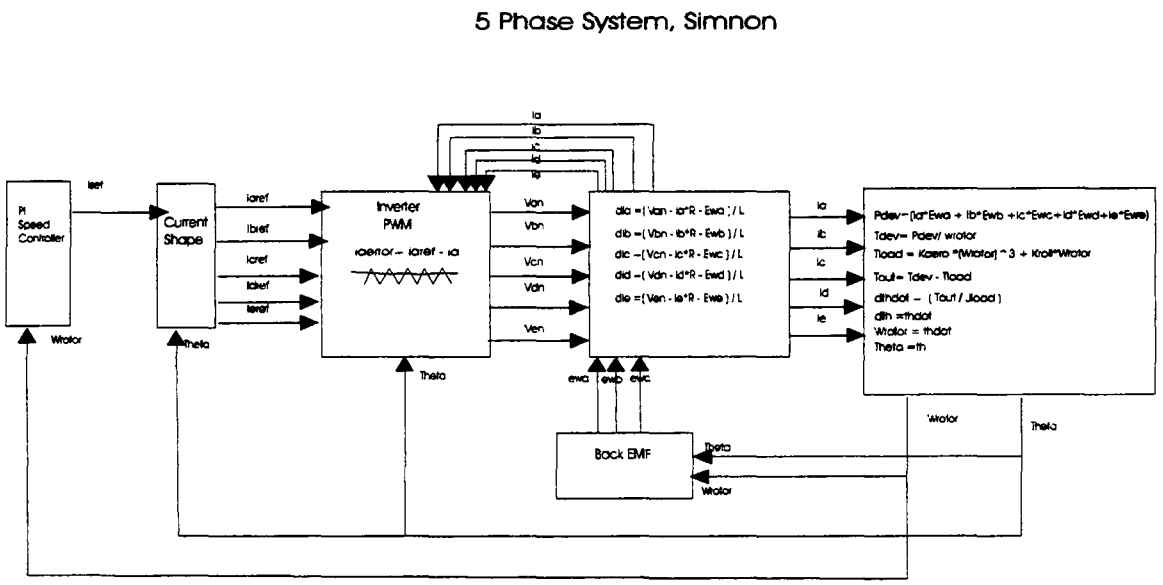


Figure B-1 Block Diagram of Simnon Five-Phase Motor System Model

A model for the three phase system and for the five phase system were developed and run to illustrate the behavior of the brushless dc motor systems. Modeled is a PWM supplied,

current controlled brushless dc motor system. The block diagram of the three-phase system modeled in Simnon is shown in Figure B-2.This is the full system with the speed controlled by a PI controller. The current of each phase is measured and fed back to the inverter control. The speed and angle are measured and used as feed back.

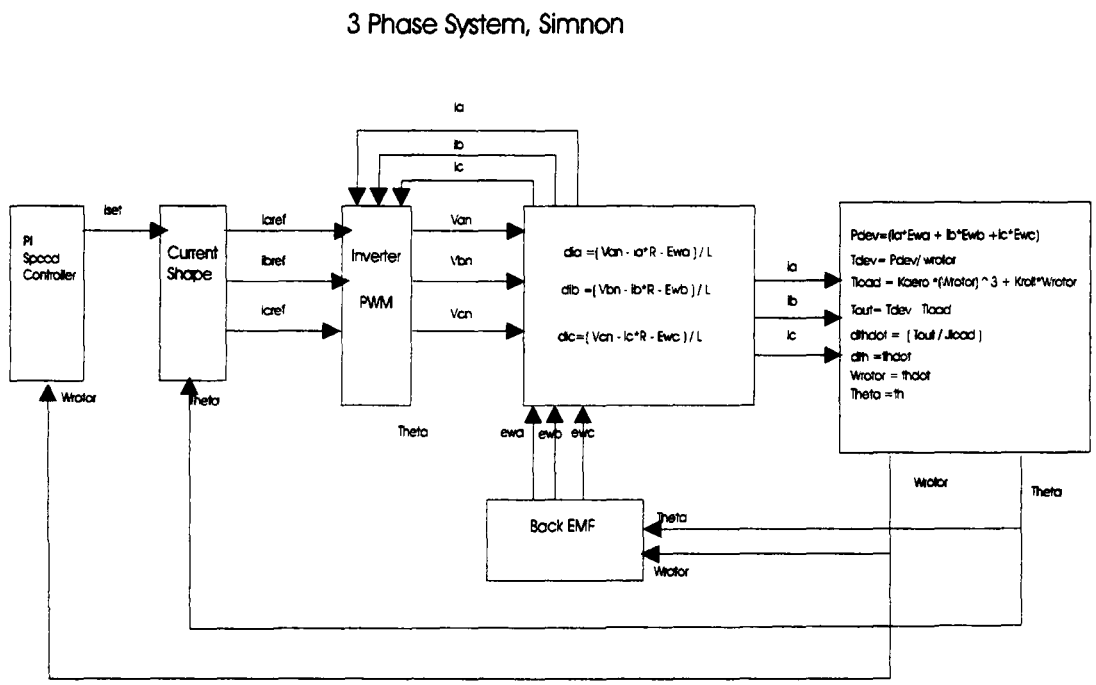


Figure B-2 Three-Phase System Block Diagram of Simnon Model

Simnon allows use of basic programming statements to create conditional structures. The user interacts with the system by typing commands. Parameters, initial conditions and system descriptions can be modified interactively. The results are displayed graphically on the screen. The windows version is especially user friendly and easy to implement. Simnon was used for the dynamic modeling because the number of iterations is extremely long, especially for the PWM supply.

Appendix C

Appendix C : PSpice Simulated Models

The software used for the simulations of this study was PSpice. PSpice is an electrical circuit analysis software published by MicroSim Corp. The version used for this study was PSpice for IBM-PC Extended DOS Ver. 6.2, Evaluation Version. PSpice's basic building blocks are passive elements such as: resistors, capacitors, inductors, switches, and some active elements such as voltage sources, current sources, and voltage controlled current sources. The program reads your circuit specification text file and translates it to a model. In Figure C-1is a drawing of the five-phase brushless dc motor systems circuit as described in the PSpice text files.

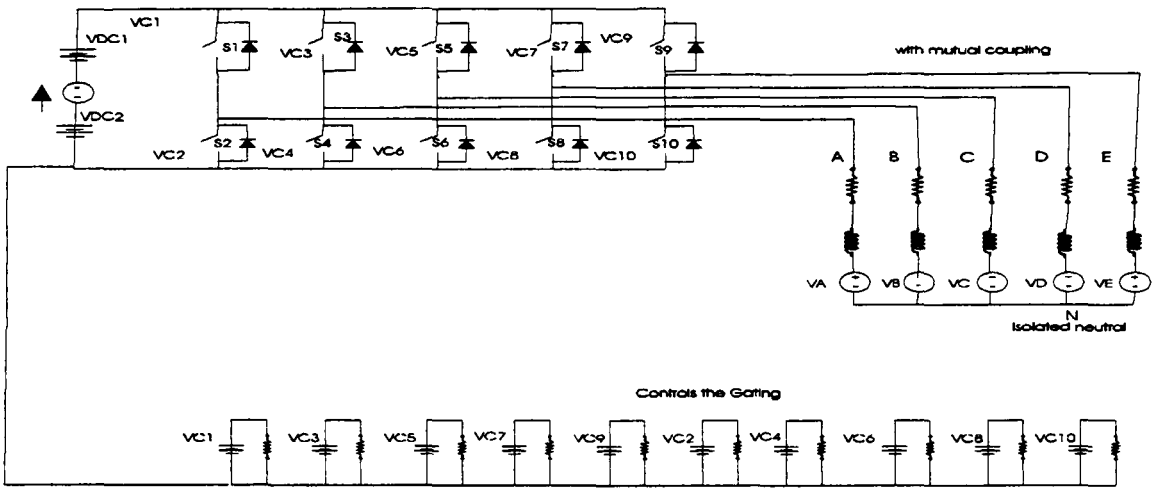


Figure C-1 PSpice Model of Five-Phase System

PSpice then does static and transient analysis on the circuit model. Once the simulation analysis is complete , all the circuit parameters are stored, and are available to be examined and displayed. PSpice is widely accepted as a circuit modeling and simulation tool. The three-phase system is described by a text file, but is shown schematically in Figure C-2

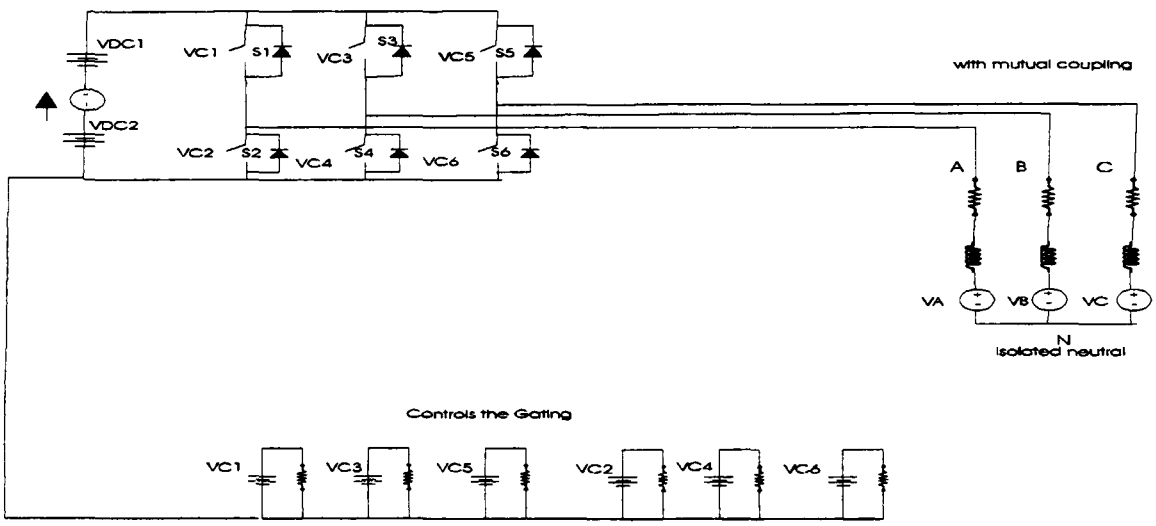


Figure C-2 Three-Phase System PSpice Model

VITA

Brian Lain was born in Bradenton Florida on May 19, 1963. He graduated from Manatee High School in May 1981. He attended Manatee Community College where he completed in May 1986, an A.S. degree in Electronic Technology, and a A.A. degree in Pre-Engineering. He attended the University of Florida, to complete a Bachelor of Science degree in Electrical Engineering on June 10, 1989. He joined Pratt&Whitney Aerospace, in West Palm Beach, on July 24, 1989, as part of the Control Systems Department. While at Pratt&Whitney, he led a team to develop a total temperature sensor for the PW5000 jet engine. He was admitted to the College of Engineering at the University of Tennessee in Knoxville, TN, in the Fall of 1993. He was hired as a Graduate Assistant in the Department of Electrical Engineering, and continued to work under an assistantship until completing his graduate degree. He served as the head of the IEEE Branch from April 1994 until April 1995. He interned at Philips Consumer Electronics in Knoxville, in the power supply design group during the Summer of 1994. He defended his thesis on Monday August 12, 1996, and received his Master of Science in Electrical Engineering degree in December 1996.