1996-12

The analysis, simulation and control of cycloconverter drives for ship propulsion

Mercer, Christopher P.

Monterey, California. Naval Postgraduate School

NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA

THESIS

THE ANALYSIS, SIMULATION AND CONTROL OF CYCLOCONVERTER DRIVES FOR SHIP PROPULSION

by

Christopher P. Mercer

December 1996

Thesis Advisor: John G. Ciezki

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE December 1996.	3. REPORT TYPE AND DATES COVERED Master's Thesis

4. TITLE AND SUBTITLE. THE ANALYSIS, SIMULATION AND CONTROL OF CYCLOCONVERTER DRIVES FOR SHIP PROPULSION

5. FUNDING NUMBERS

6. AUTHOR(S) Mercer, Christopher, P.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(maximum 200 words)*

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This study provides the designing naval engineer with technical background information and design considerations for the application of a cycloconverter drive for ship propulsion in an integrated power system. The cycloconverter is a power electronic circuit which performs a single-stage conversion of an ac input voltage at one frequency to an ac output voltage of variable frequency and amplitude. Cycloconverters are generally used for low-speed, very large horsepower applications and with suitable closed-loop control can develop torque and speed responses suitable for ship propulsion. External performance characteristics and control issues for the cycloconverter are discussed, followed by a time-domain computer simulation of an integrated ship propulsion drive utilizing a cycloconverter.

From the technical background information, external performance characteristics and computer simulation analysis, the designing naval engineer can make educated decisions on the application of a cycloconverter drive for ship propulsion.

14. SUBJECT TERMS Cycloconverter, Integrated Power System, Surface Combatant 21, ACSL, Ship Propulsion, Dual Converter, Electric Drive

15. NUMBER OF PAGES 172

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

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THE ANALYSIS, SIMULATION AND CONTROL
OF
CYCLOCONVERTER DRIVES
FOR
SHIP PROPULSION

Christopher P. Mercer
Lieutenant, United States Navy
B.S., Maine Maritime Academy, 1988

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
December 1996

Author: [redacted]
Christopher P. Mercer

Approved by: [redacted]
John G. Ciezki, Thesis Advisor

[redacted]
Robert W. Ashton, Second Reader

[redacted]
Herschel H. Loomis, Jr., Chairman
Department of Electrical and Computer Engineering

ABSTRACT

Naval expeditionary forces of the future will require new, technologically advanced, multi-mission surface combatants. The design philosophy for future surface combatants stresses survivability, efficiency, and modularity through the use of a modern open-architecture consisting of commercial off-the-shelf and dual-use systems. An integrated propulsion and electrical power generation system which utilizes advanced, commercially viable power electronics and state-of-the-art control and monitoring systems is viewed as the appropriate system for the future surface combatant.

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I. INTRODUCTION

A. ELECTRIFYING SHIPS OF THE FUTURE

1. Future Naval Combatant Ships

The projection of power from the sea to the land, sea control and maritime supremacy, strategic deterrence, strategic sealift, and forward naval presence are the fundamental and enduring roles the U. S. naval forces play in providing for our nation's security. In support of these fundamental roles, naval expeditionary forces are routinely forward-deployed, designed and trained with the objectives of preventing conflicts, controlling crises and, if called upon, to fight and win wars. Forward-deployed naval expeditionary forces are essential elements for enabling the basic roles of the U. S. Navy. These naval forces normally consist of aircraft carrier battle groups and/or amphibious readiness groups. Consistent with the Navy's strategic concept paper, *Forward ...From the Sea*, and the Marine Corps concept of expeditionary warfare described in *Operational Maneuver From the Sea*, it is envisioned that these forces will increasingly be called upon to play larger and larger roles in regional conflicts.

Many of the surface combatants in today's naval expeditionary forces do not provide the multi-mission capabilities required to establish and ensure battlespace dominance in the littoral conflicts of the future. As these combatants are decommissioned, they will be replaced by new, highly advanced surface combatants designed to carry the war to the enemy. With the addition of these new surface combatants, U. S. Navy force level and structure will be crafted to provide technologically advanced naval expeditionary forces designed to operate wherever required.

The surface combatant of the future will be an integral part of these forces and will possess the multi-mission capability required to provide battle space dominance in joint maritime expeditionary force operations. In order to field the most advanced surface combatant, with the newest technologies, and with realistic fiscal constraints, new and streamlined acquisition approaches are being considered. The design of the vessel will be realized through a total ship system engineering method coupled with innovative acquisition techniques which field first-rate weapons systems and capitalize on advanced technology. The combat suite and the hull, mechanical and electrical systems which make up this complex total ship system will be designed and built to maximize the ship's capability while reducing the ship's entire life cycle cost. Acquisition cost will be reduced by employing standardized modular design and construction techniques which parallel applicable commercial practices. Systems will be designed for dual use (military and commercial) and will be easily upgradeable and scaleable. Operating and support cost will be reduced by designing and employing systems which reduce fuel consumption and reduce required workload and manpower. These more efficient, automated systems will employ a modular and open architecture to facilitate operation and maintenance. Commercial-of-the-shelf (COTS) items will be used to field the most technologically advanced systems at competitive costs. Systems will be arranged in a redundant and dispersed manner to increase survivability and provide graceful degradation of capabilities. The surface combatant of the 21st century will be optimized to leverage advanced technology and to perform multiple roles in both the open ocean and littoral warfare environments.

2. Propulsion System Options

The engineers designing the surface combatant for the 21st century are adopting a philosophy that embraces the characteristics described above. The emergent design decisions should result in an optimally configured ship. Of interest in this study is the selection of a propulsion plant for the 21st century combatant. The propulsion plant and support systems are targeted to all satisfy the basic traits discussed above, namely:

- Reliability
- Scaleability
- Modularity
- Upgradeability
- Capability
- Survivability
- Characteristics that reduce cost, such as:
    - COTS technology
    - Commonality
    - Dual use
    - Efficiency
    - Automation (which leads to reduced manning)

As a practical matter, there are only three options available in selecting a propulsion plant for a naval surface combatant. The first choice includes a plant with dedicated main propulsion engines and mechanical transmission systems. The second option is one that couples the main propulsion engines to electric drive transmission systems. The third architecture is a combination of the first and second.

Dedicated engines and mechanical transmission systems are typical of the propulsion plant in today's fleet. There are many choices to be made with respect to the main engines, transmission systems and propulsors. However, all the choices basically lead to ships designed and operated in a conventional manner. These systems result in ship designs with large main machinery spaces, rigid transmission paths, and limited arrangeability and redundancy.

Electric drive ships are more flexible in the arrangement and control of the propulsion plant and in some cases result in a reduction of space and weight for the same horsepower. An especially attractive configuration is the application of electric drive as a component of an integrated power system. An integrated power system (IPS) is a unified electrical power generation, propulsion and ship service distribution system [1]. Both the ship service and propulsion power are derived from the same prime mover and generator. Typical IPS designs reduce the number of engines required to generate electricity and propel the ship from as many as seven down to as few as three. Major reductions in fuel consumption can also be realized with associated reductions in operating and support costs throughout the life of the ship. Electric transmission provides the flexibility to disperse the power generation modules and provides for excellent and inexpensive redundancy. Advances in power electronics have increased the efficiency and reliability of electrical power distribution components while simultaneously reducing their size and weight. Advanced power electronics are ideally suited for modular design, digital control, and low maintenance.

Combined plants use elements from both mechanical and electric drive systems. This is usually done to increase efficiency for vessels with consistent operational requirements and schedules. Although the reduction in fuel consumption is attractive, these designs typically do not reduce the number of engines required and do not espouse the characteristics desired in the surface combatant of the future.

3. Advantages of Electric Motor Drives

From the brief discussion above, it is apparent that some variant of an integrated power system (IPS) is the most attractive alternative for supplying future combatant's propulsion and ship service requirements. The elimination of dedicated engines for both ship service electrical generation and main propulsion yields significant reductions in fuel consumption. The number of engines installed in the ship can be reduced significantly, and the engines that are installed can be sized so that they are more efficiently loaded. There is no need for controllable reversible pitch (CRP) propeller systems, reversing gears, or fluid couplings to provide astern maneuvering. In some applications reduction gears may be completely eliminated. An IPS introduces more flexibility in arranging the propulsion train since the engines do not need to be located in line with the propellers. Common machinery modules and the flexibility to disperse major redundant functions reduces costs and improves survivability [1]. Coupled with an appropriate machinery control system, electric drive can give smoother, faster speed response.

This study is concerned with the electric drive propulsion functions of an integrated power system. Figure 1-1 illustrates the propulsion power distribution system of a Lockheed Martin IPS concept. Power Generation Modules (PGM) develop 4160 Vac, 3-phase, 60 Hz power which is distributed with conventional switch gear in a dispersed and redundant manner. Propulsion Motor Modules (PMM) receive the 4160 Vac, 3-phase, 60 Hz power and drive the ships propellers with variable speed industrial grade motors and marine thrust bearings. The conversion of the propulsion power to 1000 Vdc for ship service zonal distribution is not depicted in Figure 1-1. [1, 2]

4. Cycloconverter Drives

The research work reported in this study focuses on an electric drive system and the particulars of controlling the propulsion motor. It is assumed that all other aspects of an IPS have been developed and are operational. It is also assumed that the converter within the PMM is a 3-phase, six-pulse, circulating current cycloconverter.

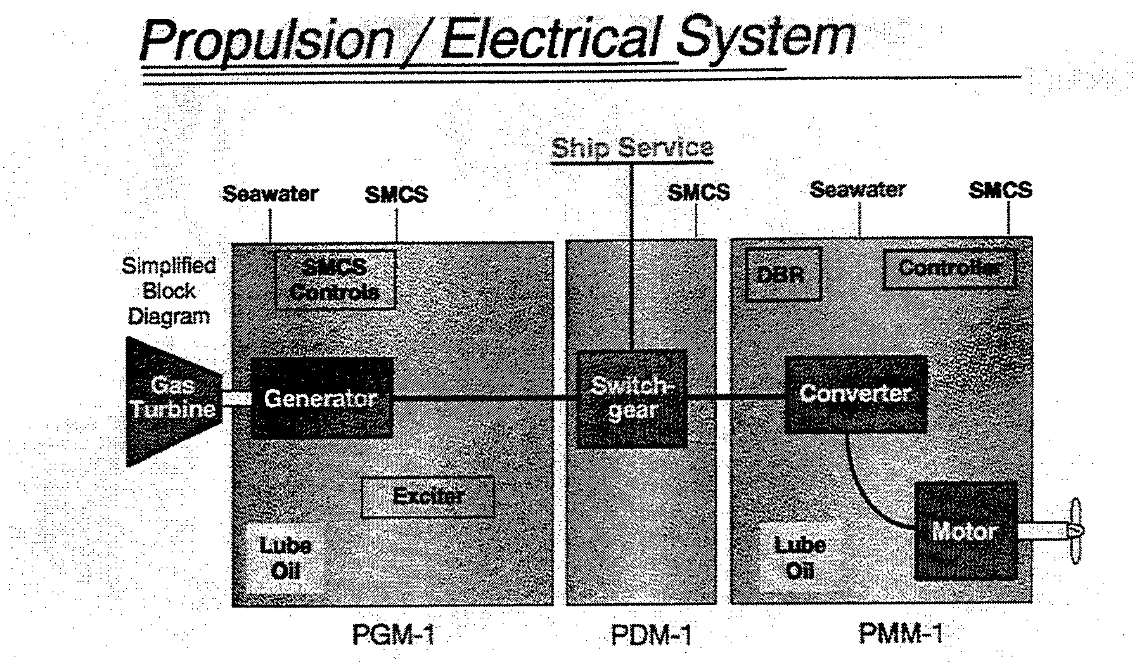

Figure 1-1. Propulsion Power System of the Lockheed Martin IPS [1].

The cycloconverter drive is a power electronic circuit which performs a single-stage conversion of an ac input voltage at one frequency to an ac output voltage of variable frequency and amplitude. Cycloconverters are generally used for low-speed, very large horsepower applications and with suitable control can develop excellent torque and speed response. Cycloconverters have several advantages over the typical dc link converter or indirect frequency changers. As stated above the cycloconverter is single-stage vice two-stage for the dc link type converter. Single-stage conversion decreases conduction losses because the load current ideally passes through only one power switching device versus at least two in the dc link converter. The single stage of conversion also allows the power factor of the load to be reflected directly to the input of the converter. In addition, cycloconverters are inherently capable of reverse power flow, so that with appropriate control, regeneration and dynamic breaking can be readily achieved. The cycloconverter also handles low motor speed without the torque pulsation and low motor and thyristor utilization associated with dc link converters. Despite these persuasive advantages, there are some issues and difficulties that must be resolved to implement a cycloconverter drive. Since the converter is a phase-controlled converter, distortion of the load voltage and line current and a lagging input displacement factor are to be expected and must be taken into consideration in the design. [3, 4, 5]

B. CURRENT APPLICATIONS OF CYCLOCONVERTER DRIVES

As stated above cycloconverters are typically used in low-speed, large horsepower variable-frequency, variable-speed drives for ac machine applications. The cycloconverter can continuously control output frequency and output voltage independently, and operate with loads of any power factor, including regenerative loads. In addition, the phase sequence of the output is simply reversed by means of the thyristor firing control circuit. As a consequence, the output operating characteristics are ideally suited for the control of ac ship propulsion motors, where efficiency, variable speed and four-quadrant operation are all important. The one limitation inherent to the cycloconverter is that there is an upper frequency limit associated with the output. For a six-pulse cycloconverter the maximum output frequency is approximately two-thirds of the input frequency placing practical limitations on the range of speed control. [6]

1. Ship Propulsion Applications

Cycloconverters are currently used in some marine propulsion applications. Examples include the propulsion plants of the ice breaker USCG Cutter Healy and Findland's icebreaker OTSO. Cycloconverter electric drive is gaining prominence in ice breaker propulsion applications because of its ability to provide high power and torque levels at low speeds with significant propeller interaction with huge fragments of ice. Figure 1-3 is the schematic arrangement of the Healy's propulsion and power plant. This power plant is a variant of an IPS in that both ship service and propulsion electrical power are derived from the same power generation systems. The cycloconverters are fed from a high-voltage bus and ship service is supplied via motor generator sets or ship service transformers. The propulsion motors are synchronous, 3-phase, dual wound machines rated at 15,000 hp and 160 rpm. The cycloconverter arrangement consists of two 3-phase, 6-pulse cycloconverters connected to the two 30 degree phase-displaced motor windings. The cycloconverters are connected to the main switchboard via phase-shifting (delta/delta and delta/star) transformers. [7, 8]

2. Industrial Applications

In addition to marine applications discussed above, the cycloconverter is found in many land-based industrial fields. Cycloconverters are commonly used in milling applications such as rolling, plate, and ball mill drives. Other drives using cycloconverters can be found in the cement industry and in many traction drive applications. An interesting application of the cycloconverter is in the Japanese National Railway's developmental magnetically levitated transportation system. Here the cycloconverter is used to control the thrust of a linear synchronous motor by controlling its output currents. [9-14]

C. APPROACH TO THE STUDY

Naval expeditionary forces of the future will require new, technologically advanced, muti-mission surface combatants. The design philosophy for future surface combatants stresses survivability, efficiency, and modularity through the use of a modern open architecture consisting of commercial off-the-shelf and dual-use systems. An integrated propulsion and electrical power generation system which utilizes advanced, commercially viable power

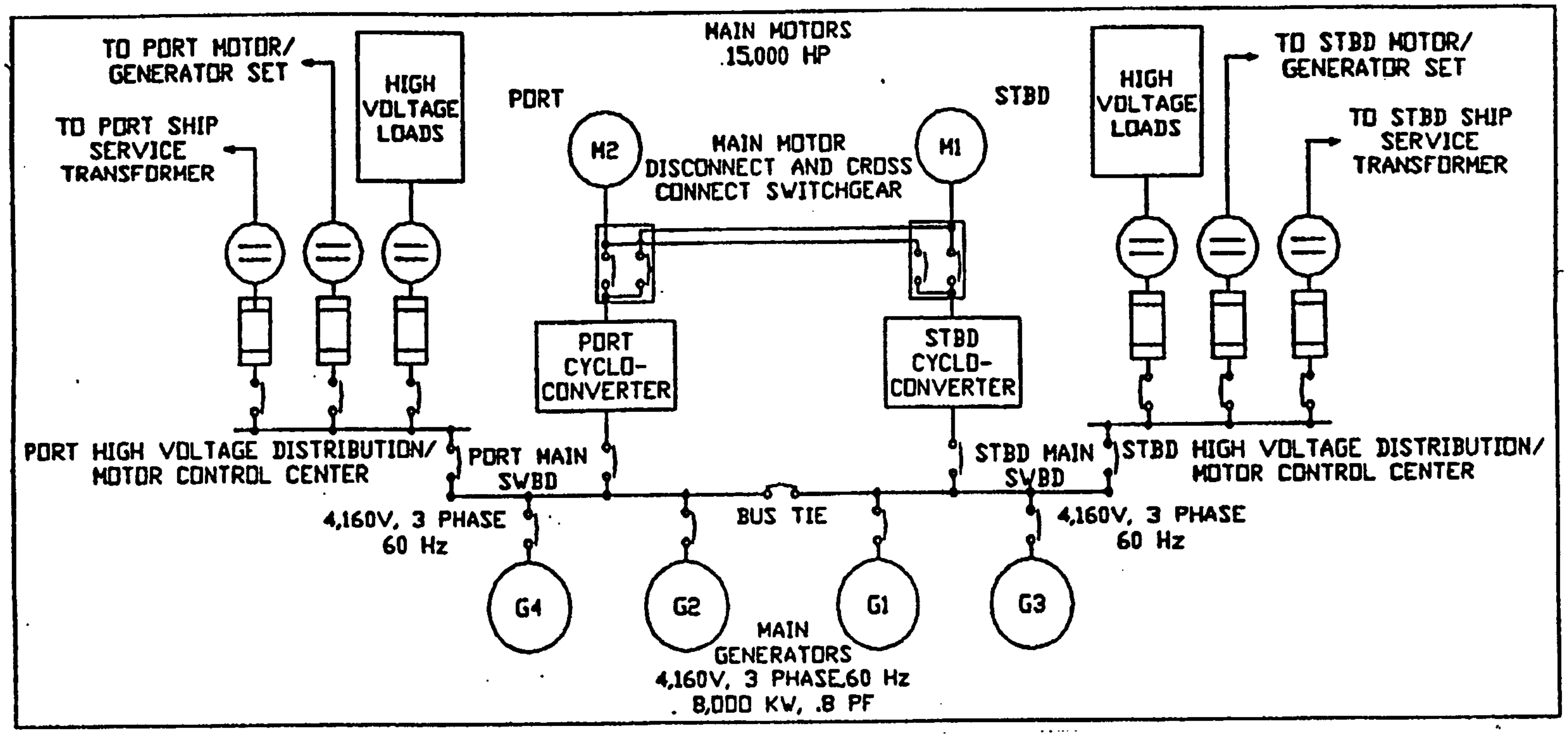

Figure 1-2. Electrical One-Line Diagram of USCGC Healy's Propulsion and Power Generation System [7].

electronics and state-of-the-art control and monitoring systems is viewed as the appropriate system for the future surface combatant. In view of this, the approach to this study is to provide the designing naval engineer with technical background information and design considerations for the application of a cycloconverter drive for ship propulsion in an integrated power system. External performance characteristics and control issues for the cycloconverter in this application are discussed, followed by a time-domain computer simulation of an integrated ship propulsion drive utilizing a cycloconverter. The intent is to present a broad system perspective supported by information on some specific design considerations associated with the use of a cycloconverter.

Chapters II contains a description of the cycloconverter power circuit and its basic operation. Thyristor firing pulse timing methods and cycloconverter control issues and operating modes are described in Chapter III. These two chapters provide the reader with an understanding of the converter's external performance characteristics and how these characteristics may be manipulated by various control schemes. Chapter IV contains a description of the strategy adopted to formulate the computer-based simulation and some background information on the programming language. In Chapter V the approach used to develop the full three-phase, six-pulse, circulating current cycloconverter simulation is described and some preliminary studies which serve to demonstrate its proper operation are presented. The modeling and simulation techniques for the propulsion motor and its control are described in Chapter VI. The integrated system simulation and analysis are documented in Chapter VII. From the technical background information, external performance characteristics and computer simulation analysis, it is hoped that the designing naval engineer can make educated decisions on the application of a cycloconverter drive for ship propulsion.

II. CYCLOCONVERTER BASICS

This chapter contains a general description of the basic cycloconverter power circuit topology followed by a discussion on the fundamentals of cycloconverter operation. This functional description includes sections on the cycloconverter's input and output characteristics. The chapter is concluded with the presentation of various converter topologies and some of their circuit specifics.

A. GENERAL DESCRIPTION

A cycloconverter is a power electronic circuit which converts an ac input voltage at one frequency and amplitude to an ac output voltage at a new frequency and amplitude. Using phase-control and line commutation principles to independently control the output frequency and amplitude, the cycloconverter acts as a single-stage power converter and, as such, is suitable for driving variable speed ac machines. Due to their cost and complexity, they have traditionally been reserved for applications requiring high performance at low speed and for particularly large horsepower applications. However, with advances in control techniques, they have developed drive performance characteristics comparable with those of dc machines.

1. Basic Cycloconverter Power Circuit

Figure 2-1 is a schematic of a three-phase, six-pulse cycloconverter circuit. The basic building block of this cycloconverter is the six-pulse Graetz bridge. A Graetz bridge is a two-quadrant, phase-controlled, line frequency thyristor converter (rectifier or inverter) [15]. Each phase of a multi-phase cycloconverter consists of two bridges or converters connected in anti-parallel. Such an arrangement provides four-quadrant operation with the load current naturally free to flow in both the positive and negative directions. Since each bridge supports

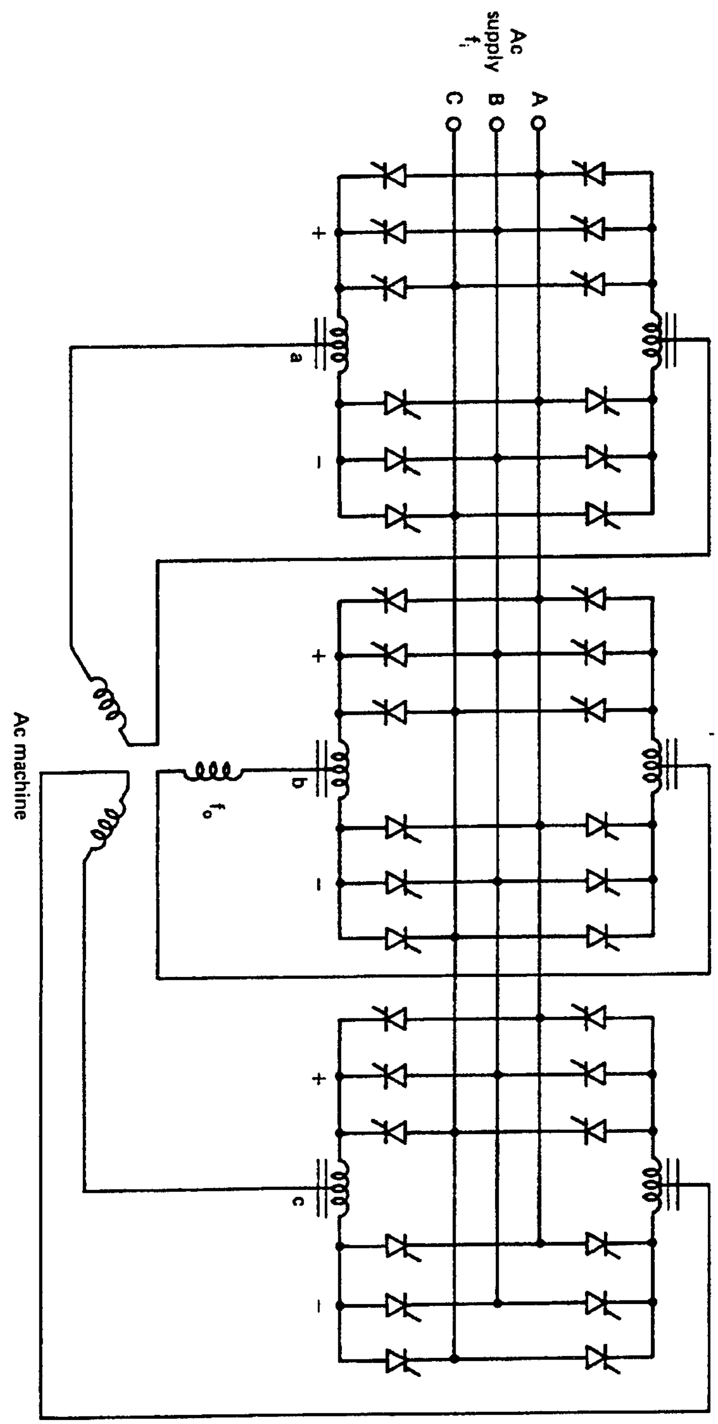

Figure 2-1. Three-Phase, Six-Pulse, Bridge Cycloconverter Circuit with Isolated Loads [8].

only two-quadrant operation, the anti-parallel configuration dictates that one bridge supply positive load current and the other supply negative load current. For each phase, these bridges are designated as the positive and negative converters depending on which polarity of load current each conducts. In Figure 2-1, the positive converter is denoted by a '+' while the negative converter is denoted by a '-'. Note that in the circuit topology depicted, isolation between the three phases of the converter is effected by isolating the loads. This eliminates any intercoupling effects of the commutation process between the phases. Other techniques for isolating the phases of bridge-type cycloconverters are discussed later in the chapter.

2. Functional Description

Figure 2-1 is just one of numerous cycloconverter topologies, all of which have various operating modes, and control techniques. Although the topologies are numerous, they all share the same basic principle of operation; a description of which provides the proper foundation for understanding the different modes of operation and control schemes.

a. Single-Phase Dual Converter

The single-phase dual converter is an appropriate circuit to analyze in order to gain an understanding of the more complex cycloconverter. Figure 2-2 (a) is a schematic of a basic single-phase dual converter. Figure 2-2 (b) illustrates typical circuit waveforms. Like the cycloconverter, it has two thyristor bridges connected in anti-parallel and provides four-quadrant operation (see Figure 2-2 (c)). However, the thyristor firing angles are regulated to provide an average dc voltage level at the output vice an ac voltage waveform for the cycloconverter.

The positive and negative converters which make up the dual converter are simple, phase-controlled rectifiers or inverters which, through proper thyristor firing regulation, can each provide a continuously controllable dc voltage of either polarity at their outputs. The basic control principle of the dual converter is to regulate the thyristor firing angles for both the positive and negative converters so that their dc voltages are always equal and of the same circuit polarity. If α_1 and α_2 are the delay angles from the natural points of commutation of the positive and negative converters, respectively, and assuming continuous current conduction, the average values of the output voltages are given by [16],

$$V_{o1} = \frac{2V_m}{\pi} \cos \alpha_1 \qquad (2\text{-}1)$$

and

$$V_{o2} = \frac{2V_m}{\pi} \cos \alpha_2 \qquad (2\text{-}2)$$

where, from Figure 2-2, the input ac voltage is given by

$$v = V_m \sin \omega t \qquad (2\text{-}3)$$

Since the objective is to have both converter outputs at the same voltage level and circuit polarity,

$$V_{o1} = - V_{o2} \qquad (2\text{-}4)$$

this requires that,

$$\cos \alpha_2 = - \cos \alpha_1 \qquad (2\text{-}5)$$

$$\cos \alpha_2 = \cos (\pi - \alpha_1) \qquad (2\text{-}6)$$

Therefore,

$$\alpha_2 = \pi - \alpha_1 \qquad (2\text{-}7)$$

If the firing angles are continuously controlled to satisfy the relationship of Equation 2-7, the mean dc voltage from each converter will be equal. The firing angle - dc terminal voltage ratio relationships of the individual two-quadrant converters which make up the dual converter are shown in Figure 2-3. The dc terminal voltage ratio is defined as,

$$r = \frac{\left(\dfrac{\pi V_{o1,2}}{2}\right)}{V_m} \qquad (2\text{-}8)$$

This figure graphically illustrates the relationships depicted in Equations 2-1 through 2-7. Key items include the operating range of α (0° - 180°) and that the dc terminal voltage is zero for both converters when $\alpha_1 = \alpha_2 = 90°$. [17]

Figure 2-2 (b) shows the waveforms associated with the ideal dual converter of Figure 2-2 (a). Although the mean dc value of V_{o1} and $-V_{o2}$ are equal, there are instantaneous differences between the ripple components of these waveforms. The plot of v_r shows this difference as a function of time. Due to the presence of this instantaneous inequality, it is not possible to merely connect the dc terminals of the positive and negative converters, as this would cause a theoretically infinite circulating ripple current. In practice, this circulating current is limited using circulating current reactors, or is eliminated altogether with the converter control scheme. This gives rise to two different operating modes -- circulating current mode and circulating current-free mode. [6] These operating modes will be discussed in later sections.

b. Single-Phase Cycloconverter

Using the topology of a single-phase dual converter, a single-phase cycloconverter is realized by changing the thyristor firing control circuit. It was shown above that by regulating the firing angle, the dual converter can be made to produce a continuously controllable mean dc voltage of either polarity and conduct current in both directions at its dc

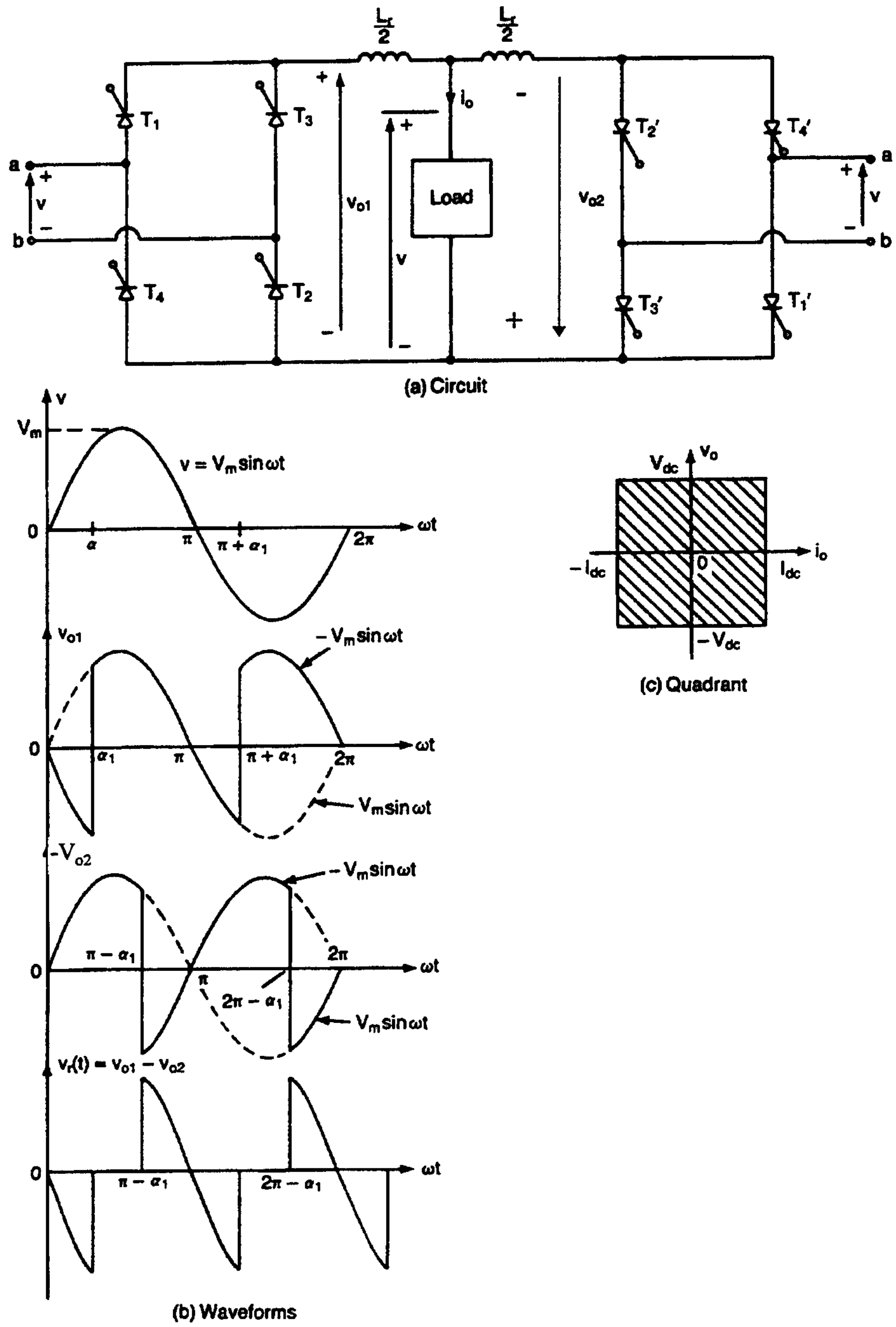

Figure 2-2. Single-Phase Dual Converter Circuit, Waveforms, and Quadrants of Operation [17].

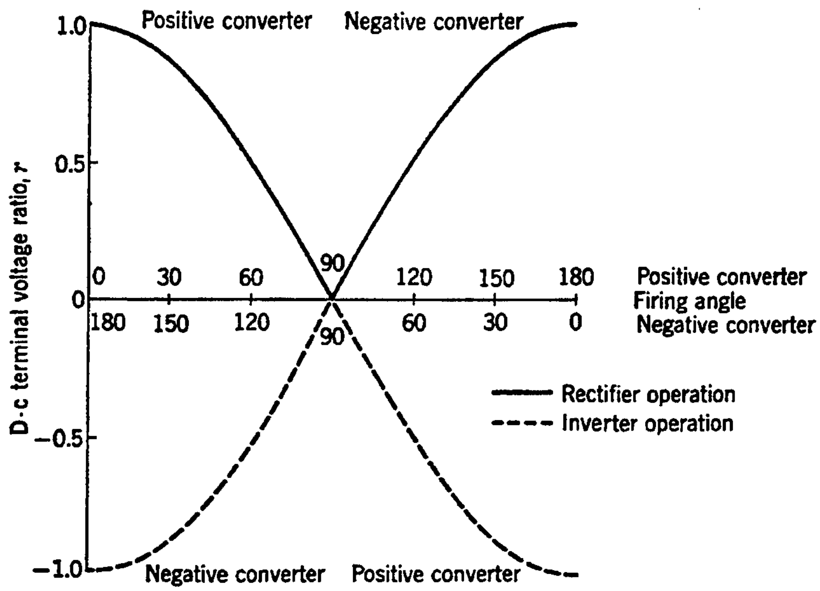

Figure 2-3. Firing Angle-DC Terminal Voltage Relationship for the Two Converters of the Dual Converter [6].

terminals. Referring back to Figure 2-3, if the firing angles of both converters were phase modulated in a continuous "to-and-fro" action, while maintaining the relationship of Equation 2-7, the dual converter would produce a continuously-varying mean voltage level, of first one and then the other polarity. The dual converter would then be a direct ac-to-ac frequency converter or cycloconverter.

3. Output Voltage Waveform

Output voltage waveshapes of a three-phase, six-pulse, circulating current cycloconverter are shown in Figure 2-4. The waveforms are composed of segments of the line-to-line ac input voltages, pieced together to form a predominant sinusoidal component of the desired output frequency. These input voltage segments are applied to the output through the

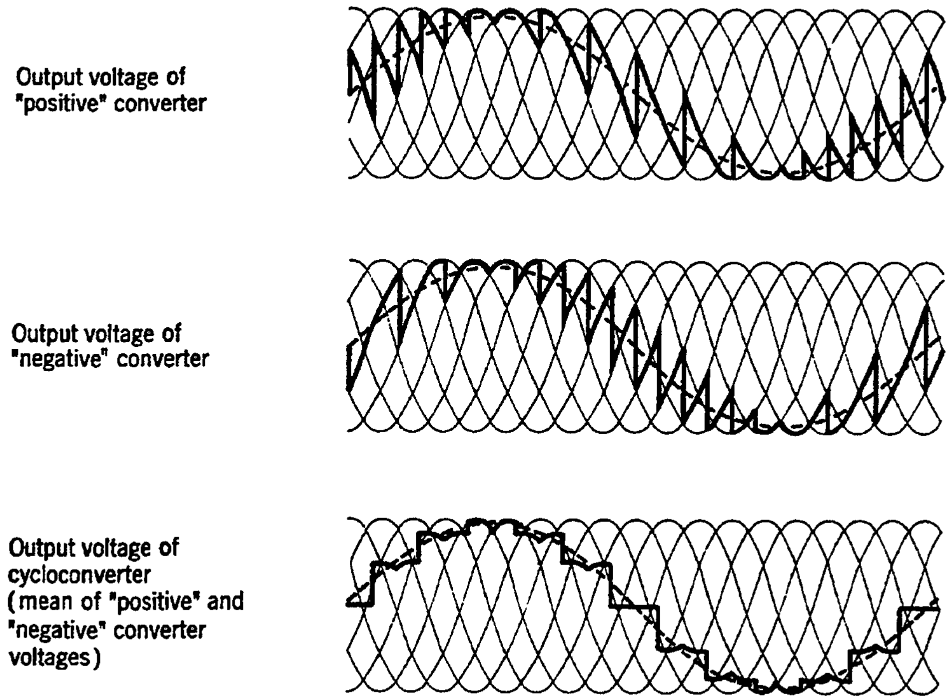

Figure 2-4. Output Voltage Waveforms for a Three-Phase, Six-Pulse, Circulating Current Cycloconverter [9].

action of the thyristor firing control circuit and the positive and negative converters which make up each phase of the cycloconverter. The output voltage waveshape primarily depends on the following factors [9]:

- The pulse number of the converter.
- The ratio between the output and input frequencies.
- The relative level of the output voltage.
- The displacement angle of the load.
- The method of control of the thyristor firing angle.

The appearance of the waveforms in Figure 2-4 suggests an output voltage rich in harmonics. In fact, there are many harmonic distortion terms in the output voltage, all of which can be placed in one of three categories – necessary, unnecessary, and practical distortion terms.[9]

The necessary distortion terms arise from the basic mechanism of the converter as the output waveform is "pieced together" from segments of the input voltage waves. With the dual converter and a steady dc output, these distortion terms generally follow a regular pattern and are exact integer multiples of the lowest harmonic frequency present (true harmonics). For phase-controlled converters the lowest harmonic frequency present is:

$$f_{h,lowest} = (P)(f_i) \tag{2-9}$$

Where $f_{h,lowest}$ is the lowest harmonic frequency present, P is the pulse number of the converter, and f_i is the input frequency. The circuit pulse number is equal to the number of discrete segments of the output terminal voltage waveform which are fabricated during each cycle of the input voltage, and is generally proportional to the number of thyristors in the circuit.

With the cycloconverter and an alternating output voltage resulting from the phase modulation of the thyristor firing angles, the necessary harmonic distortion spectrum is more complex. At low output-to-input frequency ratios, the necessary distortion terms of the cycloconverter output voltage are approximately equal to those of the comparable dual converter. However, as the output-to-input frequency ratio of the cycloconverter is increased, the two spectrums progressively diverge and eventually the harmonic content of the output voltage will become objectionable. (This is the basic limiting factor determining the maximum attainable useful output-to-input frequency ratio of the cycloconverter.) The harmonic components of the cycloconverter are not generally considered true harmonics because as the frequency ratio is increased, the components cease being integer multiples of the lowest harmonic frequency and in some cases cease to follow a regular pattern. The necessary distortion terms of the cycloconverter are mostly "beat frequency" components having frequencies which are both sums and differences of multiples of both the input and the output frequencies. For a six-pulse, single-phase cycloconverter the major necessary distortion terms are given by [15]:

$$f_h = 6pf_i \pm (2n + 1)f_o \qquad (2\text{-}10)$$

where p is an integer from 1 to infinity, n is an integer from 0 to infinity, f_h is the harmonic frequency, f_i is the input frequency and f_o is the output frequency. These frequencies are plotted in Figure 2-5 as a function of the output-to-input frequency ratio. This figure clearly shows the departure from the true harmonic spectrum of the dual converter (output-to-input frequency ratio of 0.0) to the complex harmonic spectrum of the cycloconverter with high frequency ratios. Although the maximum attainable output-to-input frequency ratio is application dependent, the typical performance fall-off is illustrated in Figure 2-5 and is generally considered to be the output-to-input frequency ratio where the predominant harmonic distortion components assume sub-harmonic frequencies. [6, 15]

Other distortion terms which are categorized as necessary are the distortion terms present as a result of the internal impedance of the input source. These terms cause "notches" in the output voltage waveform which give rise to small amounts of odd harmonic distortion.[6]

The next category of harmonic components are the unnecessary distortion terms. These terms are a result of a thyristor firing angle modulation process which does not control the timing of the firing pulses in the ideal manner. Ideally, the firing angle modulation and converter control process provides a linear voltage transfer characteristic. However, in some cases this linear method is not used or in cases where it is used, the reference voltage used to provide the linear voltage transfer may not be a perfect sinusoid. In both cases unnecessary distortion terms with integer multiple frequencies of the output frequency are present in the output voltage

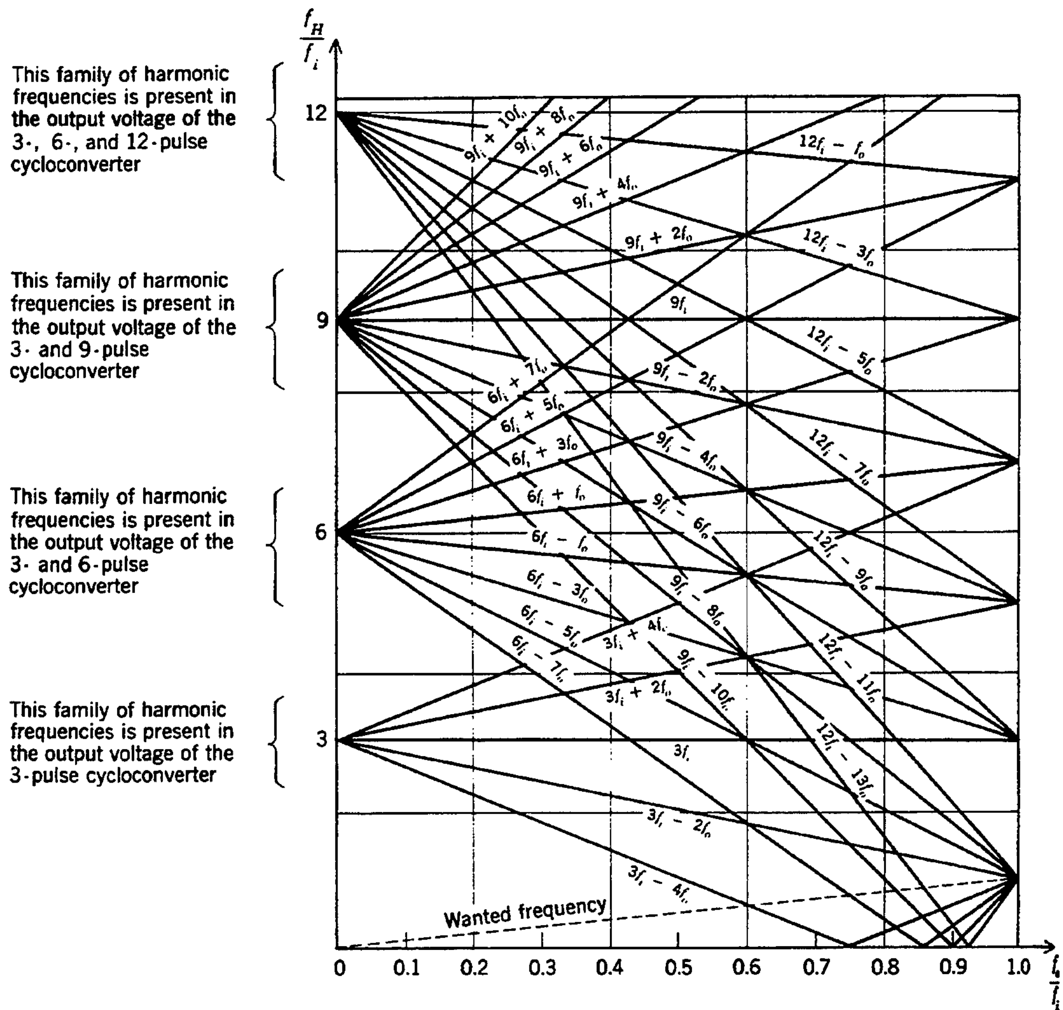

Figure 2-5. Harmonic Frequencies Present in the Output Voltage of a Cycloconverter [6].

waveform. [6] Thyristor firing pulse timing methods and converter control are discussed in Chapter III.

The final category of harmonic components comprises the practical distortion terms. These terms are a result of practical imperfections in the converter control and firing pulse circuits and usually involve timing errors. Other practical distortion terms arise from the nonlinear conduction voltage characteristic of the thyristor. This distortion can be made negligible if the converter output voltages are much greater than the forward conduction voltage of the thyristor.

Understanding the origins of the output voltage waveform distortion is a necessary factor in analyzing the use of a cycloconverter drive for ship propulsion. The distortion in the output voltage will undoubtedly produce oscillating torque on the propulsion drive train and will certainly effect the ac input system. A knowledge of what distortion can be eliminated or reduced will aid in determining filtering requirements and in determining the limits of performance of the cycloconverter drive.

4. Input System Effects

As stated above, the basic waveshape fabrication process produces a highly distorted output voltage and this process effects the ac input system. The major effects on the ac input system, with the cycloconverter seen as the load, are input current waveform distortion and a lagging displacement angle between the input current and the input voltage.

As with all rectifier-like converters, the basic operation of the cycloconverter gives rise to harmonic currents in the ac input system. The presence or absence of these harmonic components of the input current is dependent only on the pulse number of the converter circuit. For a *P*-pulse, rectifier-like converter, with a constant dc output voltage, the input line current contains the following harmonics [5]:

$$f_{h,n} = (nP \pm 1)f_i \qquad (2\text{-}11)$$

Where $f_{h,n}$ is the nth-harmonic frequency, n is an integer from 1 to infinity, P is the pulse number of the converter circuit, and f_i is the ac input frequency. These types of harmonics are also present in the input line current of the cycloconverter. However, since the output waveform fabrication process involves modulation of the firing angle, the input line current contains harmonics whose frequencies are given by [5]:

$$f_{h,n} = \left(nP \pm 1\right)f_i \pm mf_o \qquad (2\text{-}12)$$

where m is even for (nP) odd, and odd for (nP) even, and f_o is the cycloconverter output frequency.

In addition to the inherent harmonics which are produced by the basic waveform fabrication process, in single-phase or unbalanced three-phase circuits, the input line current contains harmonics having frequencies which are beat frequencies between the output and input frequencies. These harmonic components arise from the basic cycloconverter topology, whereby there is no energy storage elements connected between the input system and the output terminals. Consequently, the input system always directly "sees" the fluctuating power load at the output terminals, giving rise to the beat frequency harmonic components. The power "seen" by the input system is a constant for a three-phase balanced load; therefore, in these circuits the beat frequency harmonics are not present in the input line current, but instead circulate between the three phases of the converter. [6]

The cycloconverter also consumes a lagging quadrature component of the input line current. The phase control process inherently gives rise to a lagging displacement angle between the fundamental component of the input line current and the associated voltage. The phase delay of the thyristor firing angle is controlled to obtain the required mean output voltage and ensures voltages across the incoming and outgoing thyristors perpetuate a natural commutation of current from one thyristor to the other. For converters with a steady dc output, the input displacement angle ϕ is equal to the thyristor firing angle, α, and the input displacement factor, DF, is defined as follows:

$$DF = \cos \phi = \cos \alpha \qquad (2\text{-}13)$$

With the cycloconverter, where an output voltage waveform with a sinusoidal envelope is fabricated by modulating the firing angle, the lagging quadrature component of the input current is increased, thereby increasing the input displacement factor. Both of these factors (phase delay process and firing angle modulation) are produced even if the power factor of the load is unity or leading. The minimum theoretical input displacement angle (considering the phase delay and firing angle modulation factors) for the cycloconverter is 32.5° ($\cos \phi = 0.843$), and occurs with maximum relative output voltage across a load of unity displacement factor. The displacement angle of the input current is independent of the circuit pulse number, the number of output phases, and the frequency ratio. It is dependent only on the relative level of output voltage and the displacement factor of the load. [6]

Both external input effects of the cycloconverter (input waveform distortion and lagging input displacement angle) work to lower the input power factor. The input power factor can be viewed as a measure of how efficiently the converter is using the supplied power. A low power factor implies a less efficient use of power. The input power factor is defined as the ratio of the total mean input power to the total rms input volt-amperes. The mean input power depends only on the in-phase component of the input current, and the total rms input volt-amperes depends on the in-phase, quadrature, and distortion components. Therefore, improving the input power factor involves reducing the distortion of the input current, and maintaining the minimum input displacement angle. This is effected by increasing the pulse number of the converter circuit, supplying a balanced three-phase load, maintaining a low output-to-input frequency ratio, utilizing a high relative level of output voltage and supplying a load of unity displacement factor.[6]

B. THREE-PHASE CYCLOCONVERTER TOPOLOGIES

1. General Comments

The cycloconverter is commonly used to synthesize a three-phase output from a three-phase input. Many alternative thyristor arrangements and circuit topologies, with varying degrees of complexity, have been devised to perform this function. Reference [6] provides an excellent discussion of a number of alternative topologies which result from trade-offs between the number of thyristors, requirements for isolating transformers and interphase reactors, and required external circuit performance.

a. Pulse Numbers

As with all phase-controlled converters, the pulse number of the cycloconverter should be made as high as possible to reduces the harmonic content of the external voltage and current waveforms. The circuit pulse number is equal to the number of discrete segments of the output terminal voltage waveform which are fabricated during each cycle of the input voltage, and is generally proportional to the number of thyristors in the circuit. Therefore, increasing the pulse number of the circuit generally implies increasing the number of thyristors used to realize the converter. The higher the pulse number, the more "naturally perfect" is the conversion, and the more complete is the cancellation of external waveform harmonics. This reduces the harmonic load carried by the ac input system, and the harmonic voltages supplied to the load. However, increasing the number of thyristors adds converter and control circuit complexity and may not be economical, unless of course many thyristors are required anyway to realize the necessary output power. Figures 2-6, 2-7, and 2-8 show circuit topologies for three, six and twelve-pulse cycloconverters respectively. [6]

b. *Reactors*

There are two types of reactors commonly used in cycloconverter circuit topologies. Depending on the circuit and converter mode of operation, these reactors are not always required. The first type are circulating current reactors. As mentioned above, there are basically two modes of cycloconverter operation -- circulating current mode and non-circulating current mode. When operating in circulating current mode, reactors are placed between the output terminals of the positive and negative converters in order to limit the circulating current that arises from the instantaneous differences in the output ripple voltages and the self-induced circulating current inherent in the commutation process. The two modes of operation are discussed further in Chapter III. The second type of reactors that may be found in cycloconverter topologies are interphase reactors. These reactors are used when joining the outputs terminals of two independent commutating groups (i.e., two, three-pulse positive converters to make a six-pulse positive converter.) which have mutually displaced ac input voltages. It is the function of these reactors to maintain the independent operation of each commutation group by again supporting the instantaneous differences in the output ripple voltage of each group. Figure 2-9 shows the use of both circulating current and interphase reactors in a six-pulse, midpoint cycloconverter circuit. [6]

c. *Isolated Phases*

The symmetric bridge circuits of Figures 2-7 and 2-8 illustrate how the individual phases of cycloconverters are isolated. This isolation of phases from each other is necessary in all bridge-type cycloconverter circuits to avoid destructive intercoupling between the commutation processes of successive thyristor groups that would result from having a common point of connection between the input and output circuits of non-isolated phases. The

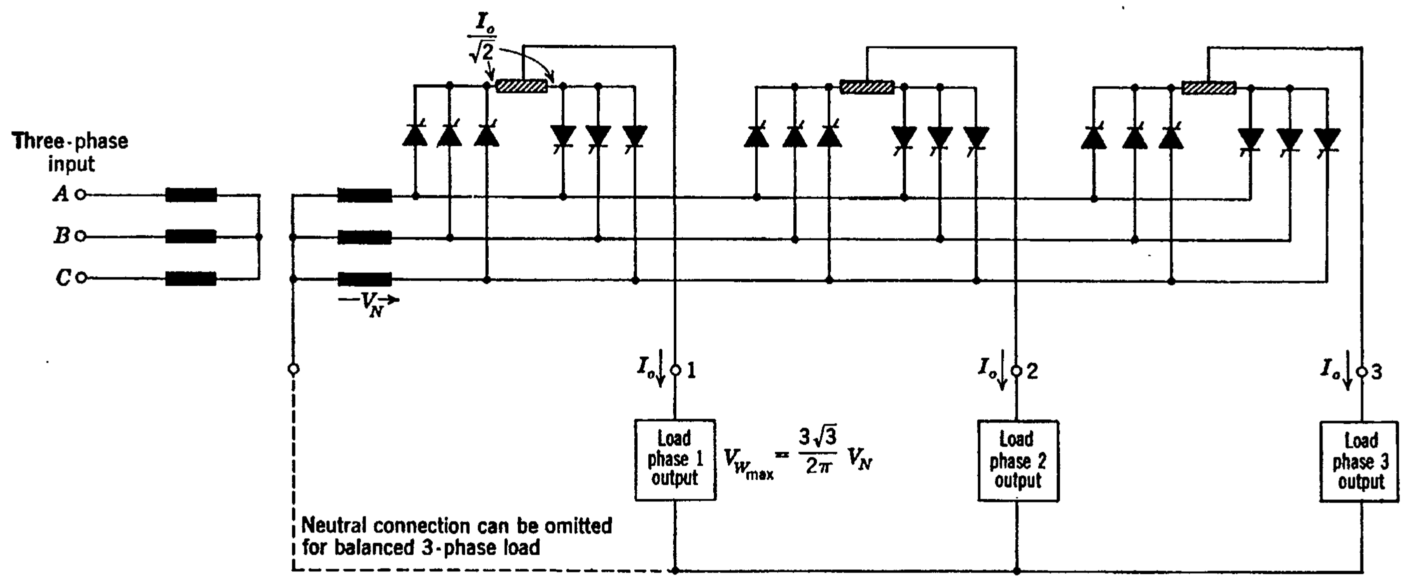

Figure 2-6. Three-Pulse, Midpoint Cycloconverter [6].

six-pulse circuit of Figure 2-7 isolates the phases at the output of each converter by treating the three-phase load as three separate single-phase loads. The 12-pulse circuit of Figure 2-8 isolates the phases at the input of each converter by utilizing input isolation transformers. The method of isolation employed is application dependent. Bridge circuits which isolate the phases at the output are typically used for three-phase ac machine loads since it is usually a simple matter to electrically isolate the three-phase windings of the machine. This type of application is particularly attractive for ship propulsion applications because the input transformers may be eliminated, reducing the weight, volume and cost of the drive. [6]

The preceding sections of this chapter serve to describe the basics of cycloconverter operation, external performance characteristics, and circuit topologies. The next chapter builds upon these fundamental concepts by discussing the major issues involved in controlling the cycloconverter.

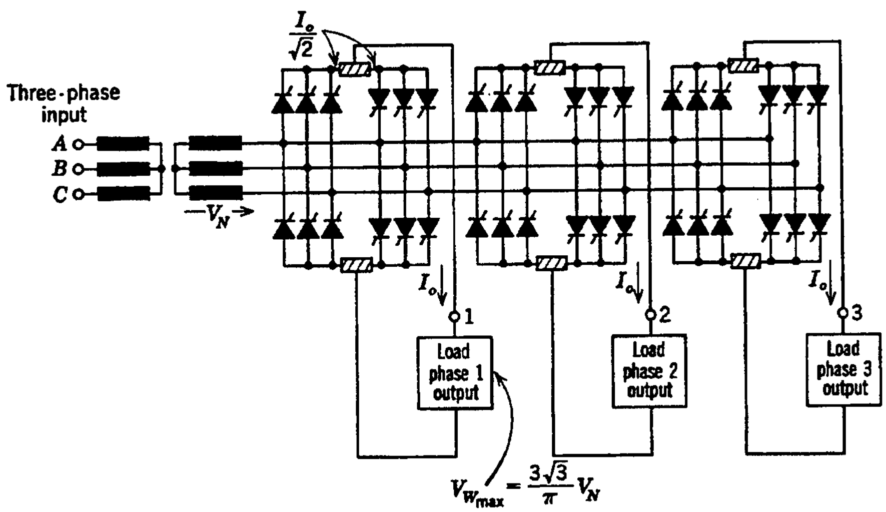

Figure 2-7. Six-Pulse Bridge Cycloconverter with Isolated Loads [6].

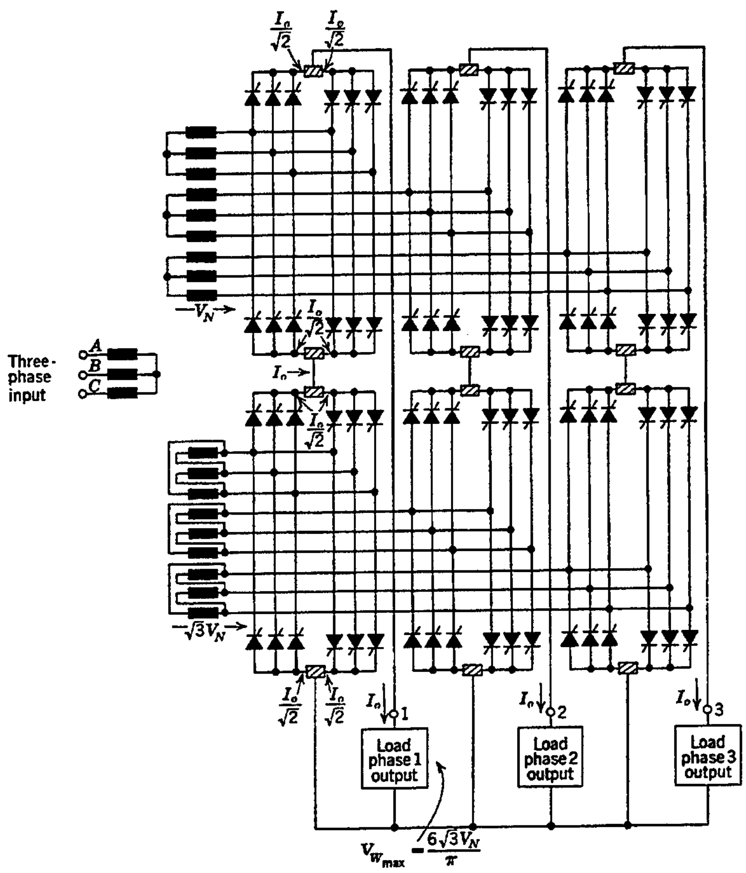

Figure 2-8. Twelve-Pulse, Bridge Cycloconverter [6].

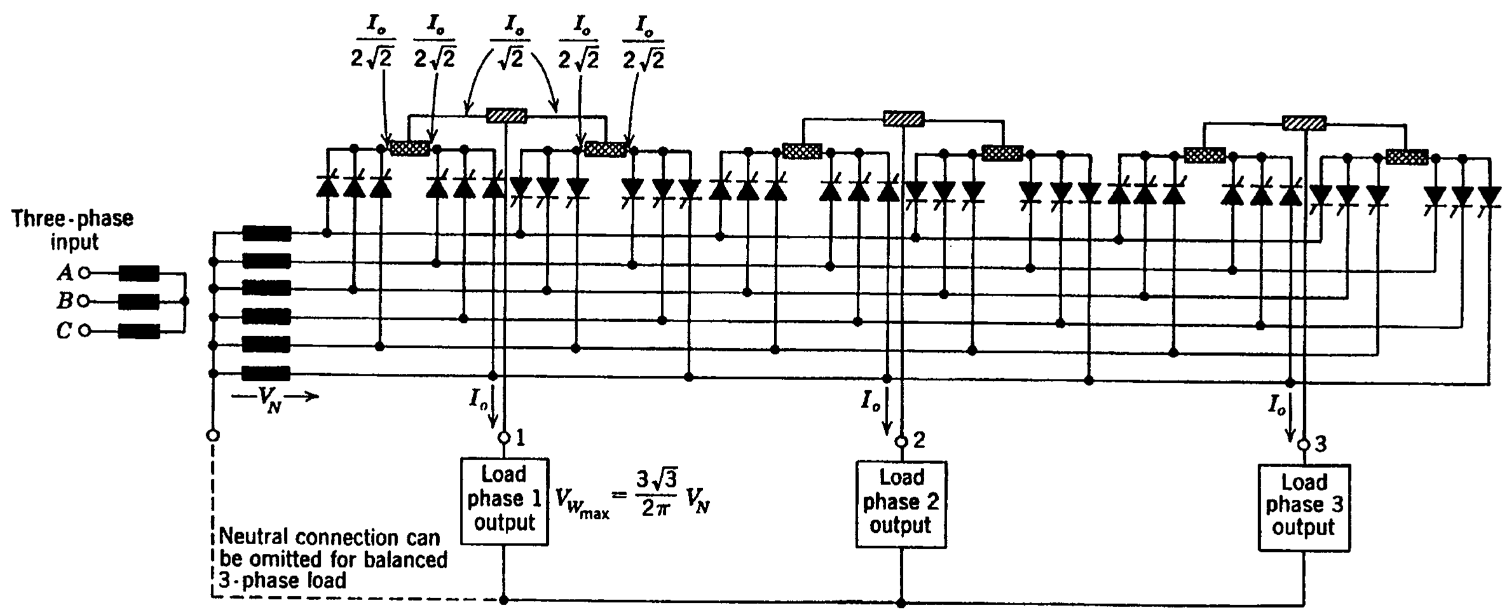

Figure 2-9. Six-Pulse, Midpoint Cycloconverter [6].

III. CYCLOCONVERTER CONTROL

Designing a cycloconverter for a specific application requires knowledge of the various cycloconverter topologies, their basic operations and external performance characteristics. In Chapter II an overview of these issues is provided and the proper foundation for understanding how the cycloconverter may be controlled to develop required external performance characteristics is set forth. In the most basic sense, control of the cycloconverter involves control of the thyristor firing pulse sequence and timing. The firing pulse method and control scheme determine the mode of operation of the converter and affect the wanted and unwanted characteristics of the input and output waveforms. This chapter introduces the major issues involved in selecting the appropriate thyristor firing pulse control of a cycloconverter.

A. THYRISTOR FIRING PULSE TIMING METHOD

As with all phase-controlled converters, the output voltage of the cycloconverter is adjusted by modifying the phase of the thyristor firing angles. There are many different methods of controlling the firing pulses to the thyristors, but the method that is most used and is considered the natural method of control is the cosine wave crossing method. It is the preferred method because among other advantageous properties, it produces the minimum possible total distortion of the output voltage waveform. [6]

1. Cosine Wave Crossing Pulse Timing Method

The cosine wave crossing pulse timing method is best described by considering a phase-controlled converter with a steady dc output. The input voltages, reference voltage, and thyristor cosine timing waves for a three thyristor commutating group with a steady dc output are illustrated in Figure 3-1. The basic principle is that the firing point for each thyristor is determined from the crossing point of an associated cosine timing wave with an analog reference voltage. For the situation depicted in Figure 3-1, each thyristor is fired approximately 30 degrees in delay of its associated timing wave's peak ($\alpha = 30°$). The cosine timing waves are derived from and synchronized to the converter ac input voltages and their phase is such that their peaks occur at the earliest possible commutation angle ($\alpha = 0°$) of the associated thyristor. Table 3-1 lists the timing waveforms for the three-phase, six-pulse converter of Figure 3-2. These same timing waveforms may be used for the negative converter pulse timing with the reference voltage inverted in order to satisfy Equation 2-7. For muti-phase converters, the same timing and reference waveforms are used in each phase with the phase angles modified as appropriate.

In the cosine wave comparison method, the individual thyristor firing angles are made to respond to an analog reference voltage in such a way that the cosine of the firing angle is proportional to the reference voltage. For such a system the relationship between the reference voltage and the mean output voltage is linear. The converter is essentially an amplifier with a linear voltage transfer characteristic. The cosine relationship between the firing angle and the reference voltage can be developed by considering that firing pulses are to be initiated when the cosine timing wave becomes instantaneously equal to the reference voltage, therefore [6],

$$\hat{V}_T \cos \theta_i = v_R \tag{3-1}$$

where $\hat{V}_T$ is the peak value of the timing wave, θ_i is the angle of the timing waveform, and v_R is the value of the reference voltage. At the intersection point $\theta_i = \alpha$,

$$\hat{V}_T \cos \alpha = v_R \tag{3-2}$$

and,

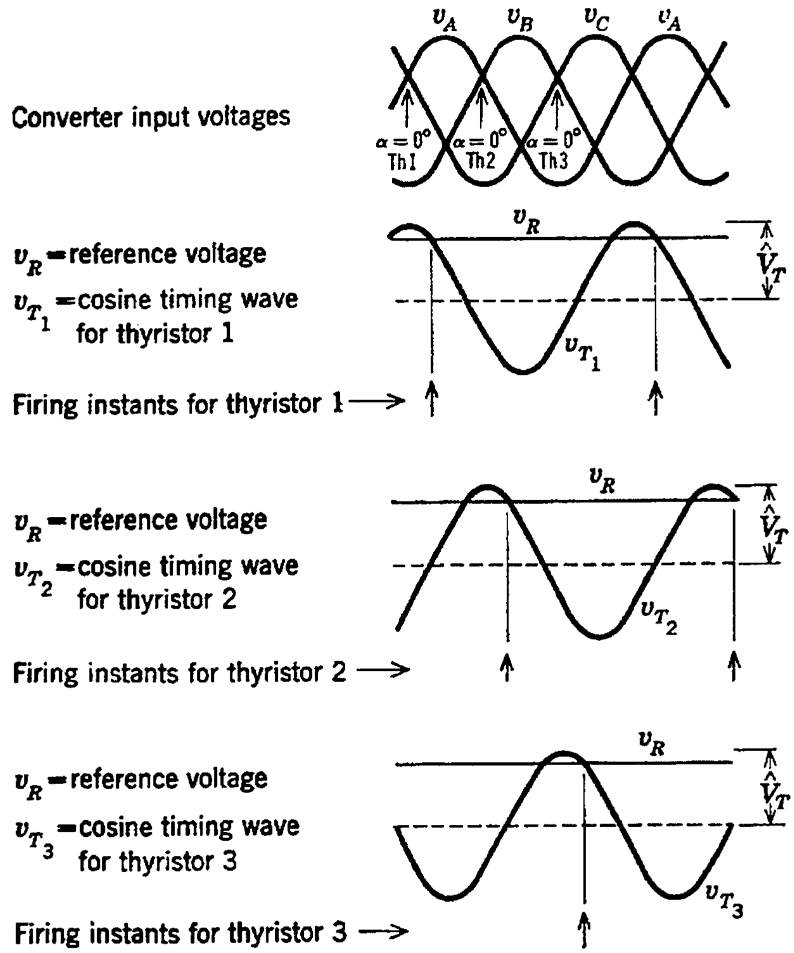

Figure 3-1. Waveforms Illustrating the Basic Principle of the Cosine Wave Crossing Method for Determining the Firing Instances of Thyristors of a Phase-Controlled Converter [6].

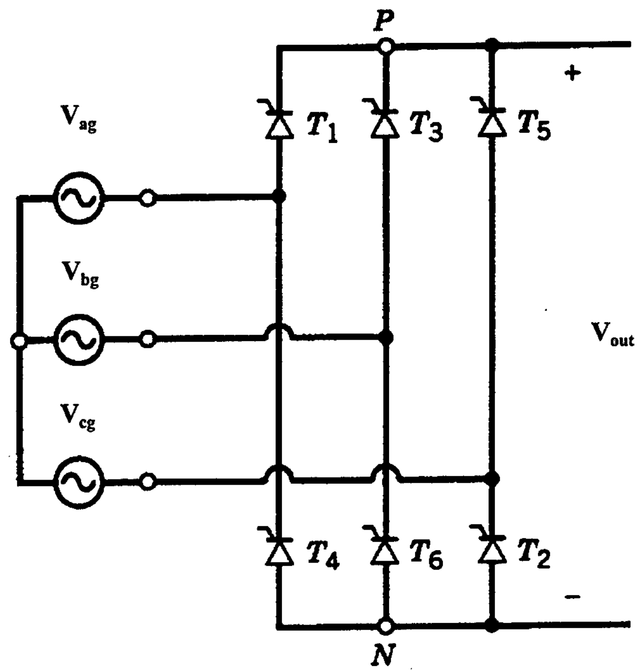

Figure 3-2. Three-Phase, Six-Pulse Converter [16].

Thyristor	Timing Waveform
T1	$-V_{ag}$
T2	V_{bc}
T3	V_{ba}
T4	$-V_{ac}$
T5	$-V_{bc}$
T6	$-V_{ba}$

Table 3-1. Thyristors and Associated Timing Waveforms for Converter of Figure 3-2.

$$\cos \alpha = \frac{v_R}{\hat{V}_T} \tag{3-3}$$

With the cycloconverter, a cosine relationship also holds between the firing angle and the reference voltage, but now the reference voltage is made to be a sinusoid. With the reference voltage positive, the firing angle is between 0° and 90° and with the reference voltage negative, the firing angle is made to be between 90° and 180°. Thus with an alternating sinusoidal reference voltage, a "to-and-fro" phase modulation of the firing angle about the 90° "quiescent" point is produced resulting in an output voltage waveform with a mean envelope corresponding exactly to the input reference voltage. The frequency of the firing angle modulation and the wanted component of the output voltage waveform is the frequency of the reference voltage. The depth of modulation is the amplitude of the reference voltage and it determines the relative output voltage of the cycloconverter. [6]

As mentioned above, this pulse timing method is considered the natural method because it produces the minimum possible output voltage distortion and it provides a linear voltage transfer characteristic. It is also considered to be self regulating because the cosine timing waveforms are derived from the ac input voltages, and any fluctuation in these input voltages will be reflected in the timing waves. With the reference voltage held as desired, the firing angles inherently shift with the fluctuating timing waves to maintain the proper output voltage.[6]

While the cosine wave crossing method is the preferred method of pulse timing, applying this method in an open-loop control scheme has some limitations. First, the linear and minimum distortion properties of this method do not hold when the load current becomes discontinuous. This gives rise to unnecessary distortion components in the output voltage waveform. However, even if the load current is completely continuous, this method will produce highly objectionable distortion components for some applications. These distortion components are present at certain output-to-input frequency ratios and have sub-harmonics or even zero frequency (dc). Although the amplitudes of these components are relatively small, if the load has low impedance at sub-harmonic frequencies, excessive current will flow at the output and magnetic circuit components may become saturated. Another limitation is practical imperfections in the pulse timing circuit. Timing errors are directly reflected in the output voltage waveform as unnecessary distortion and are particularly troublesome at low output voltage ratios.

The unnecessary distortion caused by the limitations of the open-loop cosine wave crossing method can be reduced and practically eliminated with the use of negative feedback in the control scheme. Figure 3-3 illustrates such a closed-loop control scheme. This control method determines the thyristor firing instances from the cosine wave crossing points with the feedback providing the necessary fine adjustments to the pulse timing to eliminate the objectionable distortion terms. The control system must be able to distinguish between the necessary and unnecessary distortion components of the output voltage, separate the objectionable components, and add them in a negative sense to the sinusoidal reference voltage at the input to the pulse timing circuit. [6]

2. Other Pulse Timing Methods

Other pulse timing methods have been successfully employed to control the output of the cycloconverter. These methods differ only in the shape of the timing waves. An example includes the use of a linear sawtooth timing wave synchronized to the zero crossing of the converter input voltage. A more fundamentally different pulse timing method is integral control.

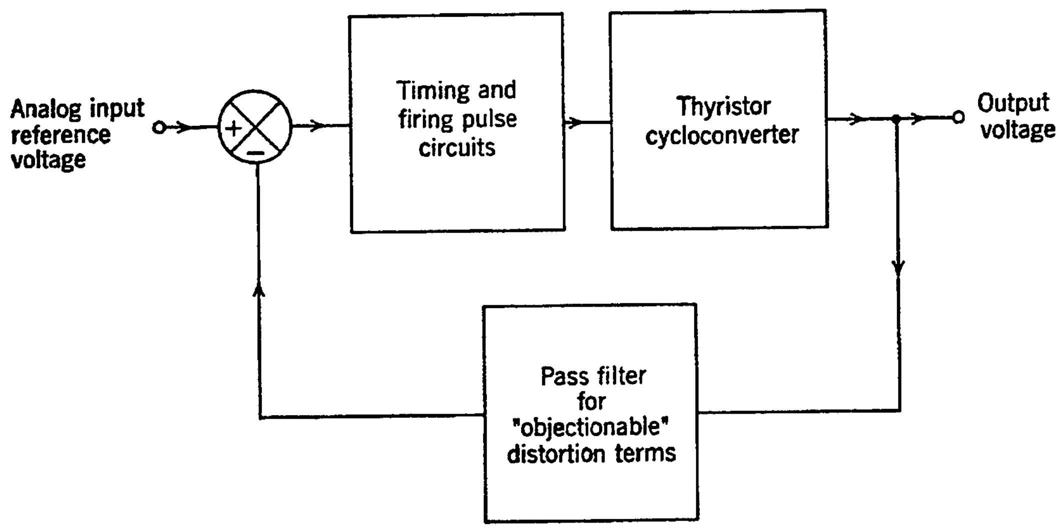

Figure 3-3. Negative Feedback Control Scheme for Suppression of "Objectionable" Harmonic Distortion Terms at the Output of the Cycloconverter [6].

This control is preferred for converters fed by ac systems with unsteady frequency (finite-inertia system). The basic principle is to apply the output ripple voltage to the input of an integrating circuit and initiate the firing pulses when the output of the integrating circuit is zero. Another fundamentally different method is the use of a phased-locked oscillator to initiate firing pulses with frequency and phase locked to the desired conditions at the output of the converter. Both of these methods require incorporation of closed-loop control to provide satisfactory results and neither enjoys the linearity and minimum distortion properties of the cosine wave crossing method. Reference [6] provides detailed discussions of these alternative pulse timing methods.

B. CYCLOCONVERTER CONTROL DIFFICULTIES

1. Operating Modes

As mentioned in Chapter II, there are basically two modes of operation for cycloconverters – circulating current mode and circulating current-free mode. The cycloconverter mode of operation is dependent on the method that is employed to control the thyristor firing pulses to the positive and negative converters. There are advantages and disadvantages inherent to both modes and in general the use of either or a combination of both modes is application dependent.

a. *Circulating Current Mode*

Circulating current mode is achieved by continuously applying the firing pulses from the firing pulse timing circuit to both the positive and negative converters without regard to the polarity of the load current. (This, as will be seen, is in contrast to the circulating current-free mode of operation.) In addition, circuits which operate entirely or partially in the circulating current mode are characterized by the presence of circulating current reactors between the output terminals of the positive and negative converters. Applying the firing pulses continuously to both converters results in the production of the same wanted alternating voltage component at both output terminals. The voltage at the midpoint of the reactors, where the load is applied, is the instantaneous average of the positive and negative output voltages. Typical output voltage waveforms for a cycloconverter operating with circulating current are shown in Figure 2-3. It is clear from these waveforms that the voltage waveform at the midpoint of the reactors has less harmonic distortion than the waveforms at the converter outputs. This apparent waveform improvement occurs because certain harmonics contained in the individual converter waveforms cancel one another and do not appear at the output terminals. [6]

The primary advantage of the circulating current mode of operation is its avoidance of discontinuous current conduction. Figure 3-4 (b) and (c) show idealized, ripple-free current waveforms for the positive and negative converters. The dotted-line curve is the output load current carried by the respective converter and the solid-line curve is the total current

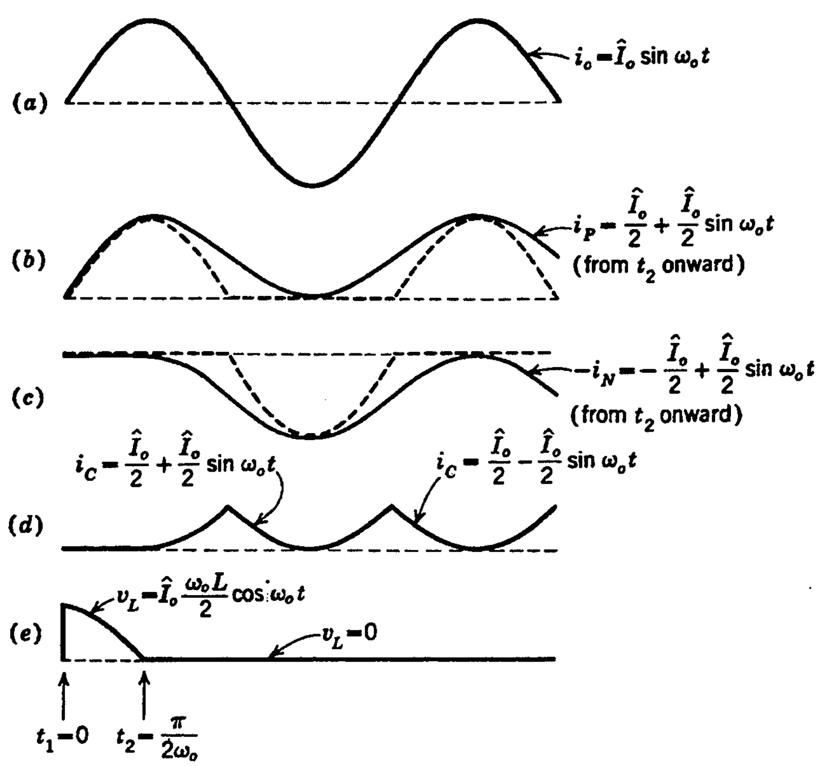

Figure 3-4. Waveforms of Ideal Cycloconverter in Circulating Current Mode [6].

carried by the respective converter. It is clear that operation with circulating current avoids discontinuous conduction. Operation of the cycloconverter with continuous current conduction significantly reduces the complexity of the control scheme and eliminates the control difficulties inherent with discontinuous conduction. As mentioned above, this mode of operation also produces an output voltage waveform with low unnecessary distortion, thereby improving the input power factor and increasing the range of output-to-input frequency ratios.[6]

These advantages do not come without expense. Operation in the circulating current mode imposes a substantial "wattless" load on the converter in addition to the "useful" load. This "wattless" load is a result of relatively large amounts of current circulating between the positive and negative converters. As mentioned in Chapter II, circulating current is produced due to the instantaneous differences in the ripple voltages of both converters. In addition to this circulating ripple current, the alternating output of the cycloconverter results in a trapped mmf in the reactors which gives rise to a self-induced component of circulating current. Figure 3-4 (d) illustrates the shape and magnitude of the total current circulating between the positive and negative converters, where $\hat{I}_o$ is the peak load current. The amount of circulating current can become relatively large. In fact, the average self-induced component of circulating current is approximately 0.57 times the average load current. For this reason, operation of cycloconverters in circulating current mode is restricted to applications where large amounts of circulating current can be tolerated. [6]

b. Circulating Current-Free Mode

With circulating current-free mode of operation, each 2-quadrant converter fabricates a voltage waveform at its output terminals and is allowed to conduct only during its associated half cycle of load current. The converter circuit topology does not require circulating current reactors since only one converter is in conduction at any one time allowing no current to circulate between the converters. However, the pulse firing control circuit is more complex. The control circuit for the firing pulses must effect a total blockage of each converter during its idle half cycle. This converter bank selection function, based on the polarity of the output load current, can introduce major control difficulties. In addition to the complex control, the output voltage contains more distortion than the circulating current mode because there is no cancellation of distortion components from the opposite converter's output. Even more distortion is produced during the cross-over from one converter to the next.[6]

In many practices and applications, the load current has a tendency to become discontinuous. Operating in the circulating current-free mode may cause discontinuous conduction and give rise to some converter control difficulties. A solution to this problem is to use a combination of both modes of operation, allowing circulating current to flow within certain specified periods of each output cycle. [6]

2. Discontinuous Current

With the high ripple content of the output voltage waveform applied to a load, the current drawn by that load will also contain ripple components. If the cycloconverter is operated in the circulating current mode, no amount of current ripple will cause discontinuous conduction in the individual converters. The energy trapped in the circulating current reactors forces both converters into continuous conduction, and causes a self-induced component of circulating current to flow. If, however, the cycloconverter is operated in the circulating current-free mode, the presence of ripple components in the output current could cause discontinuous conduction during a converter's active half cycle. If the current ripple components are small and the load current is continuous throughout the converter's active half cycle, the control of the converter is relatively straightforward. Here, the relationship between the converter firing angle and the mean output voltage is independent of the load. A prearranged firing pulse timing pattern results in the fabrication of the proper output voltage waveform, and converter bank selection is easily implemented by switching firing pulses at each load current zero crossing. However, if the load current does become discontinuous during a converter's output half cycle, two basic difficulties arise in controlling the operation of the cycloconverter. The first is a voltage distortion problem. The mean terminal voltage will no longer depend only upon the firing angle, but also on the degree of discontinuity of the output current. The second issue is the difficulty in implementing the bank selection process. With discontinuous current conduction it is not possible to use, indiscriminately, the zero values of the load current as the logic condition for bank selection. [6]

The solutions to the control difficulties associated with discontinuous conduction depend largely upon the circumstances and requirements of the particular application, especially the nature of the load and the desired quality of the output voltage waveform. The following sections discuss various techniques that may be used to solve these problems. [6]

3. Voltage Distortion

With discontinuous conduction the voltage transfer characteristic of the cycloconverter is no longer linear. As the converter operates further into discontinuous operation, the tracking error between the reference voltage and the mean output voltage becomes more pronounced. The output of the positive converter will become more positive and the output of the negative converter will become more negative. An obvious solution to the problem of voltage distortion due to discontinuous conduction is to avoid the discontinuous conduction altogether by operating the cycloconverter in circulating current mode. This may be the only solution if the load has a tendency to be discontinuous and the converter output voltage waveform is required to be of high quality and of high output-to-input frequency ratios. Again, with circulating current at least one converter is always in continuous conduction and hence the open-loop voltage transfer characteristic is retained, irrespective of load conditions. However, the current carried by each converter is substantially larger than that due to the load current alone, and may become objectionable. In this case, circulating current-free mode must be used, and a different solution to the voltage distortion problem must be found. [6]

The most common solution is to incorporate a negative feedback control loop to automatically compensate the firing angles to force the wanted output component to follow the reference voltage. This can be achieved by producing a control signal which is the integral of the error between the wanted output component and the sinusoidal reference voltage. This control signal can then be appropriately amplified and applied in the proper sense to the firing pulse timing circuit to properly compensate the firing angles. With this type of control loop, it is possible to eliminate most of the distortion due to the discontinuous conduction, but the cross-over distortion inherent in the circulating current-free mode of operation will still exist. The current cross-over distortion can be reduced by preadjusting the firing angle of the incoming converter so that it immediately delivers the correct level of voltage at its output. This type of closed-loop control no longer satisfies the positive and negative thyristor firing angle relationship of Equation 2-7. The firing angles will not be related and will be dependent on the characteristics of the load. [6]

4. Bank Selection

In situations where output voltage distortion is not a major concern and the tendency of the load current to become discontinuous is low, it may not be justifiable to operate the cycloconverter in circulating current mode. The question then becomes how to perform reliable bank selection in circulating current-free mode, when the output current may or may not have several zero crossings during the course of each output half cycle. There are basically three methods that can be utilized. The first is to initiate the bank selection upon the first detected zero crossing after some specified logic condition has been satisfied. The logic condition to be satisfied must identify the half-cycle point of the load current waveform. It may be a predetermined time, such as a half period of the output current, or it may be based on the polarity of the current in an adjacent phase of a multi-phase output. The second method, although hard to implement, is to initiate bank selection at the zero crossings of the fundamental component of the load current. The third method utilizes a closed-loop, voltage-sensing control which inherently selects the proper converter bank. Figure 3-5 shows a diagram of such a control scheme. Here, firing pulses are continuously applied to both converters, but a bias voltage is introduced between their voltage transfer characteristics so that there is no possibility for appreciable circulating current to flow. The control scheme effectively pulls the current-carrying converter into operation while pushing the other converter out of operation through the use of the output voltage feedback. This feedback automatically counteracts the bias voltage of whichever converter is fabricating the output voltage waveform. Reference [6] provides detailed discussions of each of these bank selection techniques.

This chapter has presented the major issues associated with cycloconverter control and the corresponding operating modes. Coupled with the fundamentals of Chapter II, this chapter provides the proper foundation for developing the models required in a computer-based simulation of the cycloconverter drive. The next chapter discusses the strategy for implementing such a simulation.

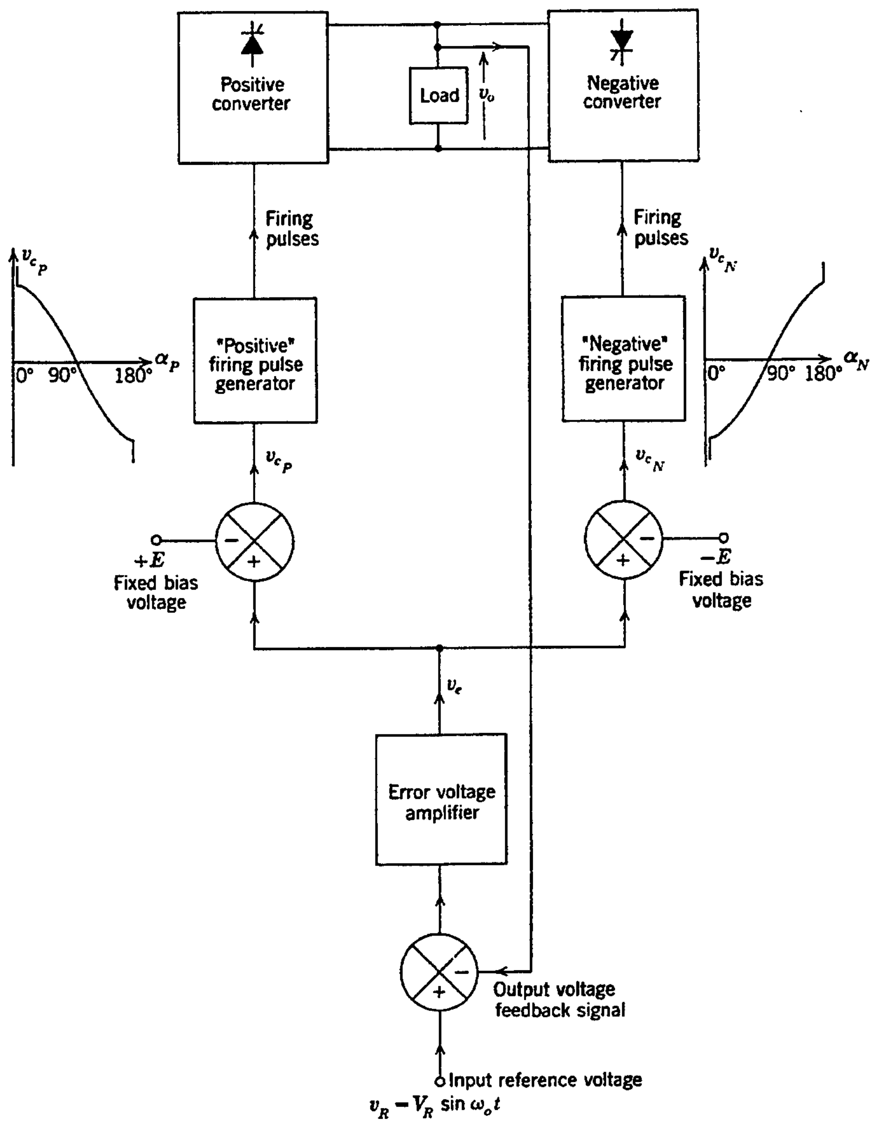

Figure 3-5. Control Scheme for a Cycloconverter Using the Voltage-Sensing Principle of Converter Bank Selection [6].

IV. COMPUTER SIMULATION

Previous chapters describe the basics of cycloconverter operation and control and present characteristic waveforms and design issues. In this chapter, the strategy for creating a digital simulation of the cycloconverter is introduced and the details of component integration addressed. This simulation can then be used to assess drive performance in an integrated system.

A. PURPOSE OF SIMULATION

A computer simulation is a powerful tool for making decisions on system design. Electric drive systems containing electronic converters, electric machines, multi-loop analog and digital control are difficult, if not impossible, to analyze and accurately predict the operational characteristics. Computer-based models formulated in simulation packages provide useful tools for generating representative studies of such systems without requiring hardware to be built. Properly functioning system models have proven to be invaluable to cost-effective system design. Hardware selection and system configurations can be evaluated to detect design flaws or limitations before substantial capital investment is made on the hardware side. As specific hardware is selected, the computer-based simulation is easily updated and system performance validated. It is for these reasons that a simulation which addresses the performance of a cycloconverter drive for ship propulsion is developed.

B. ADVANCED CONTINUOUS SIMULATION LANGUAGE

It is the goal of this study to provide the basis for a computer-based simulation that will provide the designing engineer a tool to explore the use of cycloconverter drives for ship propulsion. The creation of such a simulation begins with the choice of a programming language. The program of choice must facilitate the analysis and control of complex electromechanical systems. The Advanced Continuous Simulation Language (ACSL, pronounced "axle") is such a programming language. It provides for the modeling of time-dependent, nonlinear differential equations, and/or transfer functions, in an easily understood environment. Working from equation descriptions of the physical systems, ACSL statements are written to create computer-based mathematical models. Once developed, these models can be exercised interactively by the designer. Simulation runs, to study the system performance with different components and configurations, can then be performed and appropriate design decisions can be made.

There are basically two parts to the ACSL program -- the program, and the run-time commands. The program defines the system being modeled, and its structure is shown in Figure 4-1. The program is divided into five sections -- the INITIAL, DYNAMIC, DERIVATIVE, DISCRETE, and TERMINAL. The contents of each section are described in Figure 4-1. ACSL code consists of a combination of FORTRAN-like statements and special ACSL-specific statements. The run-time commands exercise the model (change parameters, run studies, plots variables, etc.). These run-time commands can be entered interactively or they may be contained in a command file which is linked to the main program. The ACSL statements contained in the program are read by the ACSL translator and translated to a FORTRAN compile file. FORTRAN code is then compiled, linked with the ACSL run-time library, and executed. The program is now in the run-time environment and run-time commands are read, decoded, and executed in sequence.[18]

Numerical integration algorithms are the heart of the simulation language. These algorithms calculate an estimate of the increment of each state variable over a time interval termed the time step. The time step controls the time interval at which the DERIVATIVE section is executed and affects the accuracy and stability of the algorithm. The size of the time step is defined in the program with the MAXTERVAL statement. Another time interval which is central to the simulation is the communication interval. This length of time is defined in the program with the CINTERVAL statement, and it controls the repetition rate at which the DYNAMIC section is executed and the interval at which data points are recorded for each logged variable. The integration routine is initialized when control transfers out of the INITIAL section. The integration routine integrates over a communication interval or until a terminating condition is met. The code in the DERIVATIVE section is used to evaluate the state variables. [18]

```
PROGRAM

  INITIAL
    Program flow proceeds sequentially through this section.  Statements contained in this section are
    executed and calculations are performed prior to the dynamic model.
  END

  DYNAMIC
    Statements contained in this section are executed every communication interval.  This section is an
    appropriate place to place output-related calculations (i.e. converting radians to degrees for plotting
    purposes).

    DERIVATIVE
      Statements in this section are executed every integration time step.  The code is automatically
      sorted by the ACSL translator.  All integration operations and determination of respective
      derivatives are located in this section.
    END

    DISCRETE
      Statements in this section are executed at discrete moments in time or at discrete events in the
      dynamic simulation.
    END

  END

  TERMINAL
    Statements in this section are executed at the end of each run.
  END

END
```

Figure 4-1. ACSL Program Structure.

An additional feature of ACSL is its MACRO capability. A MACRO is similar to a FORTRAN function or subroutine, except that they contain special ACSL symbols and statements. Once a MACRO is defined, it can be invoked in the main program as many times as needed. This feature facilitates duplicating structures in a program without having to explicitly rewrite code and rename variables. [18]

C. SIMULATION STRATEGIES

The simulations which are introduced and examined in the remaining chapters are all written in ACSL. The approach is to develop an accurate time-domain simulation which incorporates features of a three-phase ac input system, a model of a cycloconverter, a model of a ship propulsion motor, and a model of the propeller load and ship dynamics.

The level of detail to which the above systems may be modeled is dependent on several factors. Clearly, the level of analysis employed would have to be within the scope of the power electronic and electromechanical system analysis tools developed from various graduate level electrical power system courses. Similarly, the simulation of the system models would have to be handled well within the limits of the selected computer hardware and software systems. Considering these factors, only balanced three-phase and linear magnetic systems are considered for analysis and simulation. For much of the same reasoning, a six-pulse bridge-type cycloconverter topology is selected as the power circuit to model. The basic building block of the six-pulse bridge cycloconverter (the two-quadrant Graetz bridge) is a well documented and familiar circuit, which lends itself well to analysis and simulation. The circuit pulse number is high enough to produce output voltages of reasonably low harmonics, while not over taxing the capabilities of the computer program (and the computer programmer!). In addition, simulation of a converter with 36 thyristors and the associated firing control circuits leads to much faster run times than a converter with 72 thyristors, greatly facilitating the analysis of the integrated system.

The strategy adopted for crafting the simulation representation of the control of the thyristor firing angles was to keep the circuit model and logic as simple as possible. The concept being that during the development of the simulation, the output waveforms would be evaluated and additional firing angle control implemented as necessary. For this reason, the circulating current mode of cycloconverter operation is selected, eliminating the necessity to implement current hand-over control (bank selection) and ensuring that the converter maintains continuous current conduction. Additionally, this mode of operation theoretically provides a less distorted output voltage and a wider range of output-to-input frequency ratios. The practicality of the three-phase, six-pulse, circulating current cycloconverter is considered in the analysis of the integrated system.

The first step toward developing the integrated system necessitated developing a functioning three-phase cycloconverter. Once this is achieved and the external performance characteristics are analyzed, efforts are then turned towards the simulation of the propulsion motor and its control. A synchronous motor model is selected for several reasons. It is assumed that the input power factor of the cycloconverter would be objectionable if efforts were not taken to improve the displacement angle of the load and of the converter. As mentioned earlier, a contributing factor in improving the input power factor of the cycloconverter is to supply loads operating at unity power factor. The synchronous motor provides the facilities to operate at unity power factor. In addition, the synchronous motors are considered to be more robust and able to withstand more shock than an induction motor because of the larger stator to rotor air gap [15].

Once the motor is modeled, a model of a simple mechanical load can then be applied and a general concept of controlling the cycloconverter drive determined. The proposed control philosophy revolves around the application of vector control and field orientation to control the speed of the motor and eventually the speed of the ship. The motor and control scheme are first tested by applying sinusoidal ac voltages without the cycloconverter in the control loop. Once satisfactory performance is attained with the closed-loop control of the motor model and simple mechanical load, the cycloconverter is inserted into the control loop and the control system gains are adjusted appropriately.

Finally, with the cycloconverter, propulsion motor and vector control functioning properly, the simple mechanical load is replaced with a model of a typical destroyer-type propeller load with ship dynamics. With the full electric drive functioning, studies are performed to determine the characteristics and performance of the cycloconverter as a propulsion motor drive.

Since the objective of the simulation is to give a general overview of the electric drive system characteristics and performance and not to optimize the individual sub-components, the simulations assume mostly ideal conditions. The following is a list of the major assumptions employed in developing the simulation. The ac input system is assumed to be an infinite bus with no source impedance. Thus, source variations and the impacts of commutating reactance are not investigated. The thyristors in the cycloconverter are assumed to be ideal, with instantaneous switch commutation, no voltage drop across a closed switch, and no leakage current through an open switch. Therefore, a switch is effectively modeled as a short circuit while conducting and an open circuit while blocking. As such, switching losses are not accounted for, though provisions can be made to establish the switchings-per-cycle of output voltage. No attempt has been made to model such stochastic phenomena as timing and sampling errors, and parameter variations (such as with winding resistances). The analysis is also constrained to linear magnetic machines. This constraint is not very severe owing to the fact that the vector control will be operating to maintain the drive magnetically unsaturated.

The next chapter contains details on the cycloconverter simulation model development and the necessary validation studies.

V. PRELIMINARY SIMULATION STUDIES

This chapter contains some preliminary simulation studies performed while developing the simulation of the three-phase, six-pulse, circulating current cycloconverter and its thyristor pulse firing control.

A. SINGLE-PHASE DUAL CONVERTER

The strategy to be followed in developing the integrated system simulation centers around modeling the cycloconverter. In order to gain an understanding of the anti-parallel circuit topology and devise appropriate simulation techniques for developing the thyristor firing timing and sequence, a single-phase dual converter simulation is first developed. The ACSL program and associated command file for the dual converter simulation are included in Appendix A. With this relatively simple converter simulation, a central concept for thyristor switching and output voltage determination is developed. The switch states (on or off) of the converter are determined through comparison of the desired thyristor firing angle and the input voltage phase angle. This is accomplished through the use of SCHEDULE statements which detect the appropriate firing instants and transfer control to the respective DISCRETE section to change the state of the converter switches. Based on the switch positions at each integration time step, the appropriate input voltage is applied to the output terminals.

1. Analysis of Simulation

The purpose of this particular study is to ensure that the simulation methods of modeling the thyristor firing pulse sequence and timing in fact develop the proper output voltage waveforms. The program which is exercised simulates a 60 Hz, 120 volt (rms), ac input feeding a single-phase dual converter delivering power to an RL load consisting of a circulating current reactor (L_r = 40.0mH) and a load resistance (R_L = 10.0 Ω). The firing angle for the positive converter was selected to be fixed at 45 degrees. As a consequence of Equation 2-7, the negative firing angle is found to be 135 degrees. The input and output waveforms are plotted in Figure 5-1. With a 120 volt (rms) input and a firing angle of 45 degrees, from Equations 2-1 and 2-2:

$$V_{o1} = \frac{2\sqrt{2}120}{\pi}\cos 45^{\circ} = 76.4 \text{ volts} \tag{5-1}$$

and

$$-V_{o2} = \frac{2\sqrt{2}120}{\pi}\cos 135^{\circ} = 76.4 \text{ volts} \tag{5-2}$$

A comparison of Figure 2-2 and Figure 5-1 indicates that the simulated dual converter in fact develops the proper output waveforms.

B. THREE-PHASE CYCLOCONVERTER

The next step in the development of the full three-phase cycloconverter representation is to modify the single-phase dual converter and create a single-phase cycloconverter. Conceptually, this involves merely modulating the positive and negative firing angles in a continuous "to-and-fro" action about the 90 degree point, while maintaining their 180 degree relationship. However, with the firing angles continuously changing and in anticipation of a three-phase implementation, the simple comparison between the desired firing angle and the phase angle of the input voltage, which is used to schedule switch state changes in the dual converter, is abandoned. In its place a representation of the cosine wave crossing method, discussed in Chapter III, is inserted and validated. The cosine timing waveforms for each thyristor are developed from, and synchronized to, the input voltage. The conduction status of each thyristor is represented by a logical variable. Conduction is indicated by a logical TRUE

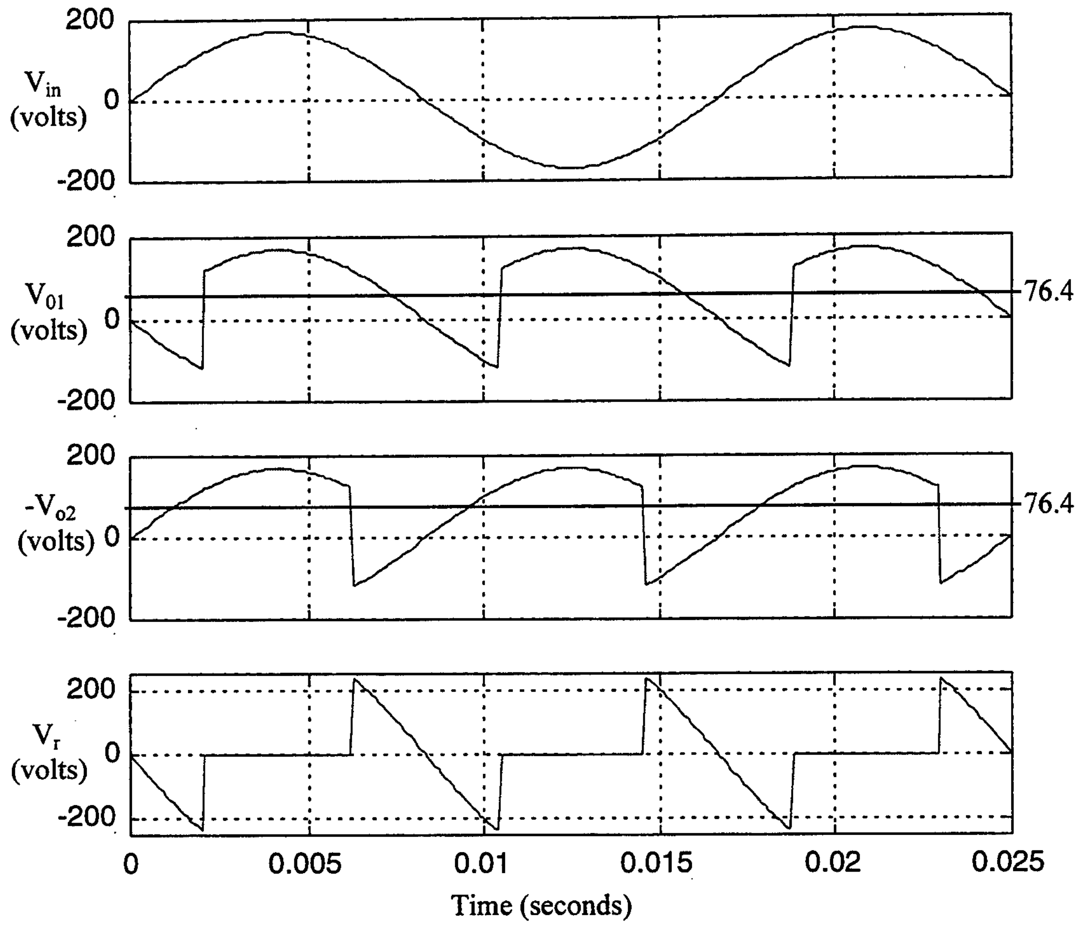

Figure 5-1. Voltage Waveforms of a Single Phase Dual Converter.

and blocking by a logical FALSE. A negative-going zero crossing of the reference waveform by the appropriate cosine timing waveform schedules a DISCRETE section in which the state of the incoming switch is made TRUE and that of the outgoing switch made FALSE. The logical state of each switch is then checked each integration time interval to establish which portion of the input voltages must be extracted and applied to the output.

As a logical step in the progression to three-phase operation, the single-phase cycloconverter is modified to accept a three-phase input and develop a single-phase output. This involves changing the topology of the cycloconverter by adding two more thyristors in both the positive and negative converters and creating the additional timing waveforms and corresponding switch logic statements. The simulation methods developed up to this point involve the use of two reference voltage waveforms, 12 cosine timing waves, 12 SCHEDULE statements and 12 DISCRETE sections to properly model just one phase of a three-phase cycloconverter. Implementation of a full three-phase cycloconverter with 36 thyristors using these methods would have exceeded the computer and program limitations. A more concise method to schedule switch state changes was required.

The primary limitations encountered involve the maximum number of BLOCKS ACSL supports on a 32-bit machine. BLOCKS are defined as the major sections of the program, as discussed in Chapter IV, and PROCEDURAL statements, which are placed in sections of code that are sorted (i.e. DISCRETE) to maintain a specified execution sequence of ACSL statements. The simulation package limitation motivated the development of an elegant method of modeling the sequence and timing of thyristor firing pulses using just one reference voltage waveform, six timing waveforms, and two DISCRETE sections for each phase of the converter. The idea is to control the firing angles of both the positive and negative converters of a given phase by utilizing a common input reference voltage in such a way as to guarantee that the firing angle relationship given by Equation 2-7 is maintained. Normally this would entail the development of an inverted reference voltage waveform and in some circuits, development of six additional timing waveforms for the complimentary converter. Visualizing the SCHEDULE statements as comparators in an actual firing pulse timing circuit, the operands in the mathematical arguments (conceptually the inputs to the comparator) are interchanged to develop the complimentary firing pulses. This permits the same reference voltage to be directly applied to both the positive and negative timing circuits, and also allows the cosine timing waveforms to be shared between the converters. The relationship between each timing waveform and the reference voltage waveform is continuously monitored for the negative zero-crossing condition. Once this condition is detected, control is transferred to the appropriate DISCRETE section to establish the next converter switch configuration. The logic statements contained in the DISCRETE section set the appropriate switch states based on the switch states that exist at the instant of control transfer. There is one such DISCRETE section per six-pulse bridge in the converter. The simulation program and associated command file for the full three-phase, six-pulse, circulating current cycloconverter is provided in Appendix B.

1. Analysis of Simulation

The following sections provide some analysis of the output voltage waveforms produced by the cycloconverter simulation listed in Appendix B. The purpose of these studies is to show that the model produces the proper output voltage waveforms, and that the harmonic content of these waveforms increases with decreasing relative output voltage and/or increasing output-to-input frequency ratio.

a. Proper Output Voltage Waveforms

The full three-phase cycloconverter simulation is first exercised to ensure that the proper output voltage waveforms are developed. In preparation for supplying a relatively large marine derivative motor in the advanced simulation studies, a wye-connected, 60 Hz, 4160 volt (line-to-line), three-phase input system is modeled. The output terminals are connected across a circulating current reactor (L_r=40.0 mH), and an RL load (R_L=10.0 Ω, and L_L= 500.0mH). The amplitude of the reference voltage is set at 3390.5 volts for full depth of modulation, providing the highest relative output voltage. The frequency of the reference voltage waveform is set at 20 Hz to provide an output voltage waveform of 20 Hz. Plots of the positive converter, negative converter, and mean output voltage waveforms over one period are provided in Figure 5-2. A comparison of Figures 2-4 and 5-2 indicates that the model in fact produces the proper output voltage waveforms.

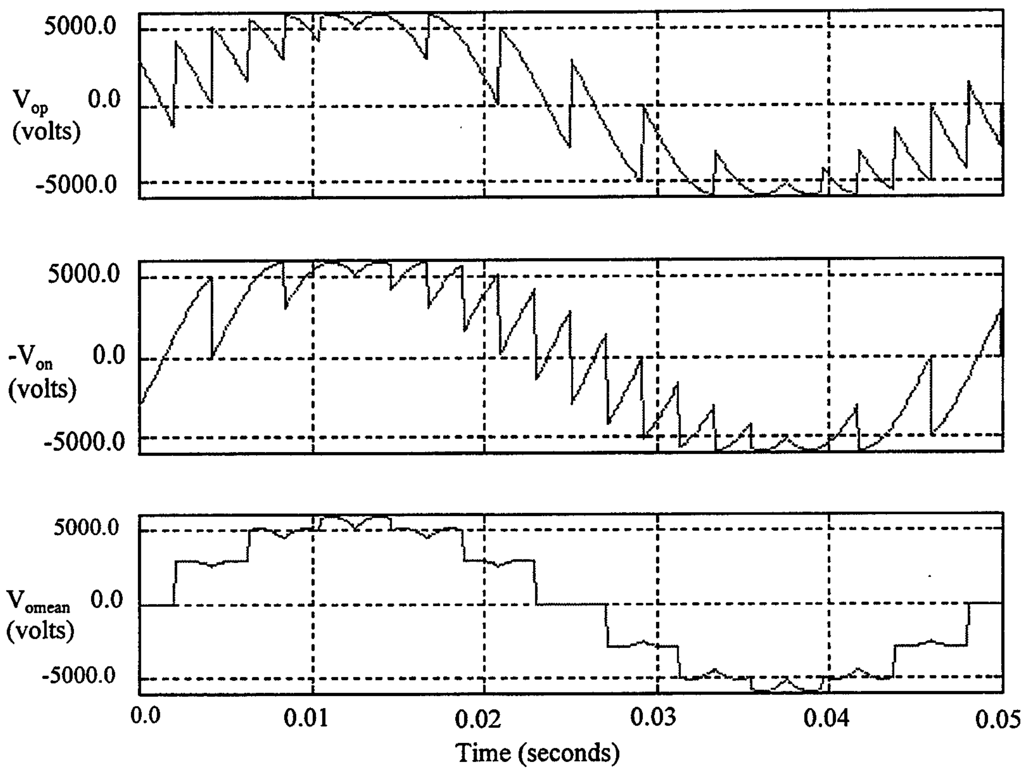

Figure 5-2. Output Voltage Waveforms for Simulated Six-pulse, Three-phase, Circulating Current Cycloconverter.

b. Relative Voltage Level

The same circuit model is exercised with a lower reference voltage waveform amplitude to illustrate the associated increase in the harmonic content of the output voltage. In this study the reference voltage waveform amplitude is set to 1000.0 V to provide an output voltage of approximately one-third of the input voltage. A plot of the output voltages with this reference waveform applied is provided in Figure 5-3. A comparison of Figures 5-2 and 5-3 shows that the positive and negative converter output voltages associated with the decreased depth of firing angle modulation are in fact lower in amplitude and higher in harmonic content. The increased harmonic distortion is also apparent in a comparison of the mean output voltages.

c. *Output-to-Input Frequency Ratio*

This study illustrates the decrease in harmonic content of the output voltage waveform associated with a decrease in output-to-input frequency ratio. In this case, a reference voltage waveform with full depth of modulation and a frequency of approximately 0.80 Hz is applied. Figure 5-4 shows the resultant output voltage waveforms potted over one period (1.26 seconds). A comparison with Figure 5-2 clearly indicates the decrease in harmonic content associated with low frequency ratios.

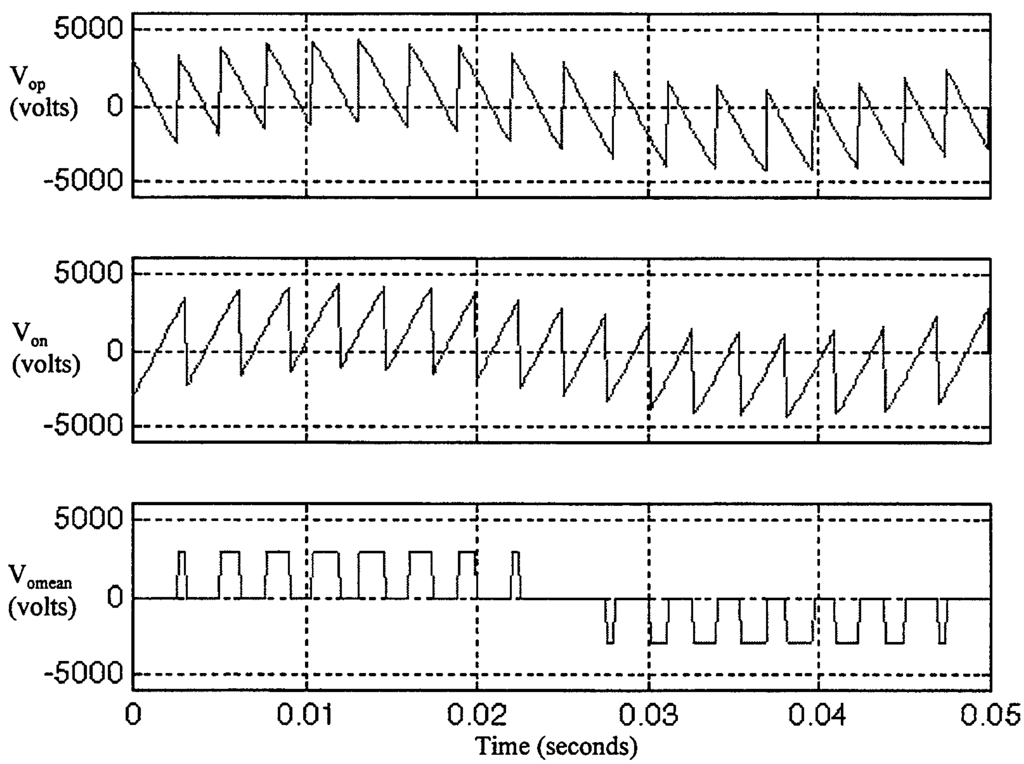

Figure 5-3. Output Voltage Waveforms with Reduced Depth of Modulation.

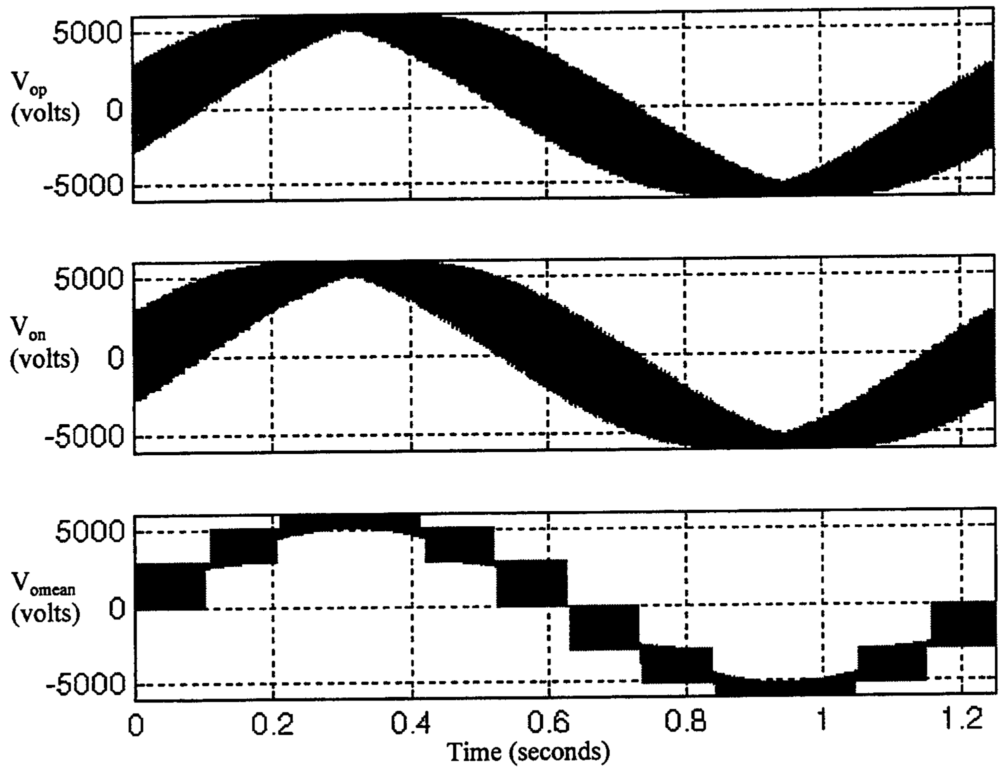

Figure 5-4. Output Voltage Waveforms with Low Output-to-Input Frequency Ratio.

d. Operational Limitations of Simulation

As the output-to-input frequency ratio was increased above two-thirds, significant waveform distortion was anticipated out of the simulation. The results did not seem to justify the label objectionable. However, since no plot of these objectionable waveforms were found from source documentation to perform comparisons with the simulation output, this matter could not be conclusively resolved. The simulation appears to develop output waveforms which are acceptable at all frequencies up to and including the input frequency. This is not viewed as being detrimental to the study as the cycloconverter will not be required to supply output frequencies of greater than two-thirds the input frequency.

This is also a good time to address the question of whether closed-loop control of the thyristor firing circuit is required to develop the proper output voltage waveforms. Since practical thyristor firing circuit timing inconsistencies, thyristor voltage drops, and source impedance were not considered in this study, their effects on the output voltage waveform are not present. In addition, the presence of sub-harmonic components in the output waveforms is not, at this point, a concern in this study. For these reasons and to keep the cycloconverter control as simple as possible, the open-loop control of the thyristor firing pulse sequence and timing is retained.

The next chapter extends the simulation discussion to the modeling of the synchronous machine and the control of the motor via field orientation. This will then set the stage for the integrated propulsion system.

VI. ADVANCED SIMULATION STUDIES

This chapter contains a discussion of the issues related to the selection of the synchronous machine as the propulsion motor and an explanation of the equations and parameters required to implement a digital simulation. The requirements for machine control necessitates a brief summary of vector control and field orientation and how this type of control is implemented in the simulation. Finally, some analysis on the performance of this control with a simple mechanical load is conducted both with and without the cycloconverter in the control loop and the results are presented.

A. SYNCHRONOUS MOTOR LOAD

As mentioned previously, a synchronous motor is selected for consideration in this study. Although induction motors are considered the workhorse in industry, the synchronous motor has some advantages when considered for ship propulsion applications. In particular, synchronous machines typically have significantly larger air gaps between the stator and rotor structures. The large air gap improves the shock performance of the drive and as such enhances that aspect of surface combatant design. The other major advantage is that the synchronous motor can be operated at unity power factor by proper control of the field winding current. This becomes an important characteristic when cycloconverters are considered for the motor drive because of the inherent lagging quadrature component of current consumed at the input. This will allow the total power plant kVA installed to be reduced and the efficiency of the drive to be maximized.

1. Simulation

Figure 6-1 illustrates the salient pole synchronous motor that is modeled. The circles with bullets or crosshairs denote distinct windings where the crosshair represents current referenced into the page and the bullet represents current out of the page. The rotor is equipped

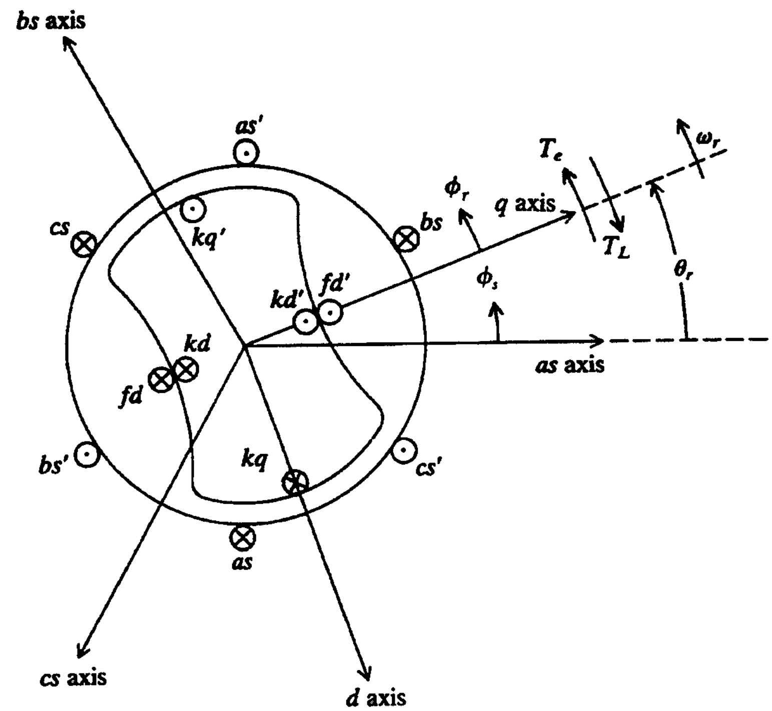

Figure 6-1. Two-Pole, Three-Phase, Salient Pole Synchronous Machine [19].

with a field winding (fd) and two short-circuited damper windings (kq and kd). The field winding is supplied a dc voltage via either a brush and slip ring assembly or via a brushless exciter system. The field winding has resistance r_{fd} and the damper windings have resistances r_{kq} and r_{kd}, respectively. The three stator windings are identical, sinusoidally-distributed windings, displaced 120 degrees with resistance r_s . It is common to represent the dynamic response of this motor by a set of detailed nonlinear differential equations [20]. These equations are based on the analysis of linear magnetic circuits and the conservation of energy. The equations are typically expressed in terms of the actual phase currents, voltages and flux linkages. This is termed the machine variable representation. Machine variables for the rotor are referred to windings with the same number of turns as the stator windings to facilitate a change of variables that significantly reduces the complexity of the equations. This winding referral is indicated by the presence of a superscript " ' " or so called "prime" quantities. The equations are then transformed to the rotor reference frame using Park's equations. The superscript " r " denotes stator variables which are transformed to the rotor reference frame. The resultant machine voltage equations are summarized as follows [20]:

$$V_{qs}^{r} = r_s\, i_{qs}^{r} + \frac{\omega_r}{\omega_b}\, \psi_{ds}^{r} + \frac{p}{\omega_b}\, \psi_{qs}^{r} \tag{6-1}$$

$$V_{ds}^{r} = r_s\, i_{ds}^{r} - \frac{\omega_r}{\omega_b}\, \psi_{qs}^{r} + \frac{p}{\omega_b}\, \psi_{ds}^{r} \tag{6-2}$$

$$V_{0s} = r_s\, i_{0s} + \frac{p}{\omega_b}\, \psi_{0s} \tag{6-3}$$

$$V_{kq}^{'} = r_{kq}^{'}\, i_{kq}^{'} + \frac{p}{\omega_b}\, \psi_{kq}^{'} \tag{6-4}$$

$$V_{fd}^{'} = r_{fd}^{'}\, i_{fd}^{'} + \frac{p}{\omega_b}\, \psi_{fd}^{'} \tag{6-5}$$

$$V_{kd}^{'} = r_{kd}^{'}\, i_{kd}^{'} + \frac{p}{\omega_b}\, \psi_{kd}^{'} \tag{6-6}$$

Where p is the Heaviside operator $\frac{d}{dt}$ and where the flux linkage per second equations are:

$$\psi_{qs}^{r} = X_q\, i_{qs}^{r} + X_{mq}\, i_{kq}^{'} \tag{6-7}$$

$$\psi_{kq}^{'} = X_{kq}^{'}\, i_{kq}^{'} + X_{mq}\, i_{qs}^{r} \tag{6-8}$$

$$\psi_{ds}^{r} = X_d\, i_{ds}^{r} + X_{mq}\left(i_{fd}^{'} + i_{kd}^{'}\right) \qquad (6\text{-}9)$$

$$\psi_{fd}^{'} = X_{fd}^{'}\, i_{fd}^{'} + X_{md}\left(i_{ds}^{r} + i_{kd}^{'}\right) \qquad (6\text{-}10)$$

$$\psi_{kd}^{'} = X_{kd}^{'}\, i_{kd}^{'} + X_{md}\left(i_{ds}^{r} + i_{fd}^{'}\right) \qquad (6\text{-}11)$$

and

$$X_q = X_{ls} + X_{mq} \qquad (6\text{-}12)$$

$$X_{kq}^{'} = X_{lkq}^{'} + X_{mq} \qquad (6\text{-}13)$$

$$X_d = X_{ls} + X_{md} \qquad (6\text{-}14)$$

$$X_{fd}^{'} = X_{lfd}^{'} + X_{md} \qquad (6\text{-}15)$$

$$X_{kd}^{'} = X_{lkd}^{'} + X_{md} \qquad (6\text{-}16)$$

The reactances containing a subscript "l "are leakage terms while the ones with subscript " m " are the magnetizing terms. The torque equation in terms of rotor reference frame quantities is given by:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{1}{\omega_b}\left(\psi_{ds}^{r}\, i_{qs}^{r} - \psi_{qs}^{r}\, i_{ds}^{r}\right) \qquad (6\text{-}17)$$

where P is the number of magnetic poles and ω_b is the base frequency in rad/sec. The ACSL MACRO which contains the code for this model is included in Appendix C.

The synchronous machine parameters used in the study were derived from past electric drive studies performed by the Naval Surface Warfare Center (NSWC) Annapolis Detachment [21]. The physical machine parameters and base values for electrical per unit quantities are listed in Table 6-1. Table 6-2 contains the per unit parameter values. These parameter values are considered appropriate for a direct drive propulsion motor intended for use in typical destroyer hulls with displacements up to 8500 tons.

Machine Base Values and Physical Parameters		
Parameter	**Value**	**Remarks**
Voltage (volts)	5,307	Base voltage for per unit quantities. $V_b = \frac{\sqrt{2}}{\sqrt{3}} V_{l-l}$
Current (amps)	4,673	Base current for per unit quantities. $I_b = \sqrt{2} I_{line}$
Rated Field Current (amps)	1,500	
Impedance (ohms)	1.136	Base impedance for per unit quantities. $Z_b = \frac{V_b}{I_b}$
kVA	37,200	$kVA_b = \frac{3}{2} V_b I_b$ Approximately 50,000 hp
Torque (lb-ft)	1.6×10^6	$T_b = \frac{\# \, poles}{2} \times \frac{HP_b}{2\pi f_b} \times 550$
Frequency (Hz)	55	$f_b = \frac{(RPM \times \# \, poles)}{120}$
Inertia (lb-ft^2)	5,000	An estimate based on previous studies.
# Poles	40	
RPM	164	
Dry Weight (lbs)	2,000	
Diameter (inches)	123	
Box Size (inches)	171	
Stackable Length (inches)	76	

Table 6-1. Synchronous Machine Base Values and Physical Parameters.

Per Unit Electrical Parameters	
Stator winding resistance, r_s	0.00913
kq winding resistance, r'_{kq}	0.07609
kd winding resistance, r'_{kd}	0.09342
Field winding resistance, r'_{fd}	0.00265
Stator winding leakage reactance, X_{ls}	0.16987
Rotor q-axis leakage reactance, X'_{lkq}	0.14787
Rotor d-axis leakage reactance, X'_{lkd}	0.17985
q-axis magnetizing reactance, X_{mq}	0.78384
d-axis magnetizing reactance, X_{md}	1.01905
Field winding leakage reactance, X'_{lfd}	0.101

Table 6-2. Synchronous Machine Per Unit Electrical Parameters.

B. VECTOR CONTROL

In order for an electric machine to be used for ship propulsion, it must have certain performance characteristics. Performance attributes such as fast response, four-quadrant operation, and good performance near zero speed are all necessities of an electric drive propulsion motor. In addition, the machine must provide controlled torque over a wide range of operating conditions. Historically, these performance requirements have been satisfied by the dc machine. The construction and operation of the dc machine inherently provides the torque control that is desired in such applications. However, the dc machine has some major disadvantages when compared to the ac machine. DC machines are typically much larger and heavier, with greater inertia than ac machines of the same horsepower. The commutator and brush assemblies are maintenance intensive, and in general the dc machine is considered less robust than ac machines. So the question then becomes, how to get the performance of a dc machine from an ac machine which has all the other desirable features of a propulsion motor. The answer lies with vector control and field orientation. [22]

In order to realize the fast accurate torque control discussed above, the machine and its control system must provide the following:

- An independently controlled armature current.
- An independently controlled or constant value of field flux.
- An independently controlled orthogonal spatial angle between the stator mmf field and the rotor mmf field.

If these three requirements are satisfied, the torque will instantaneously follow the current and give rise to instantaneous torque control. The construction of the dc machine inherently provides all three requirements, hence the desired torque control. An ac machine requires external controls to satisfy the torque control requirements. The control scheme which performs this function is termed vector control and field orientation. The term "Vector control" arises because the control scheme functions to control the motor current's amplitude and phase, and "field orientation" because the control also functions to control the field flux and armature mmf spatial orientation. [22]

The construction of the synchronous machine lends itself well to vector control and field orientation. The field winding is physically available and can be controlled independently, satisfying the second torque control requirement listed above. The physical position of the rotor dc field is fixed in space by the position of the rotor. The rotor position can thus be sensed to locate the field winding and this information used to specify commanded machine currents so as to maintain a desired space angle between the field winding and stator rotating mmf. With the synchronous machine modeled in q-d variables, vector control is achieved by developing desired stator currents which translate to fixed values of i_{qs}^r and i_{ds}^r. This instantaneous control over the phase of the stator current allows for the orthogonal field orientation of the stator mmf vector and the field winding in the d-axis of the q-d model. If the stator current is independently controlled, the orientation of the stator q-d currents can be maintained for all speeds including transient changes. This control would then satisfy the first and the last of the torque control requirements listed above. [22]

The vector control and field orientation torque control scheme devised for the propulsion motor drive is illustrated in Figure 6-2. Here, the commanded value of the d-axis current is set to zero. This forces the orthogonal spatial orientation between the rotor and stator fields, and as can be seen from Equation 6-17, allows the torque to be controlled independently by i_{qs}^r. The commanded value of i_{qs}^r, i_{qs}^{r*}, is generated from the difference between the commanded rotor speed and the actual rotor speed which is then passed through a PI controller which acts to achieve zero steady-state error. The commanded q an d-axis voltages are generated from the difference between the commanded and actual q and d-axis currents, respectively. These control signals are also passed through PI controllers to achieve zero steady-state current error. Finally, these commanded q and d-axis voltages are transformed to the stationary reference frame with Park's equations to develop reference voltage waveforms to control the thyristor firing angle of the cycloconverter. In the simulation, the resultant converter output voltage waveforms are then applied to the motor stator terminals, after being transformed to q-d variables. With these voltages applied, the proper stator currents are developed and hence the proper torque is developed to achieve the desired rotor speed.

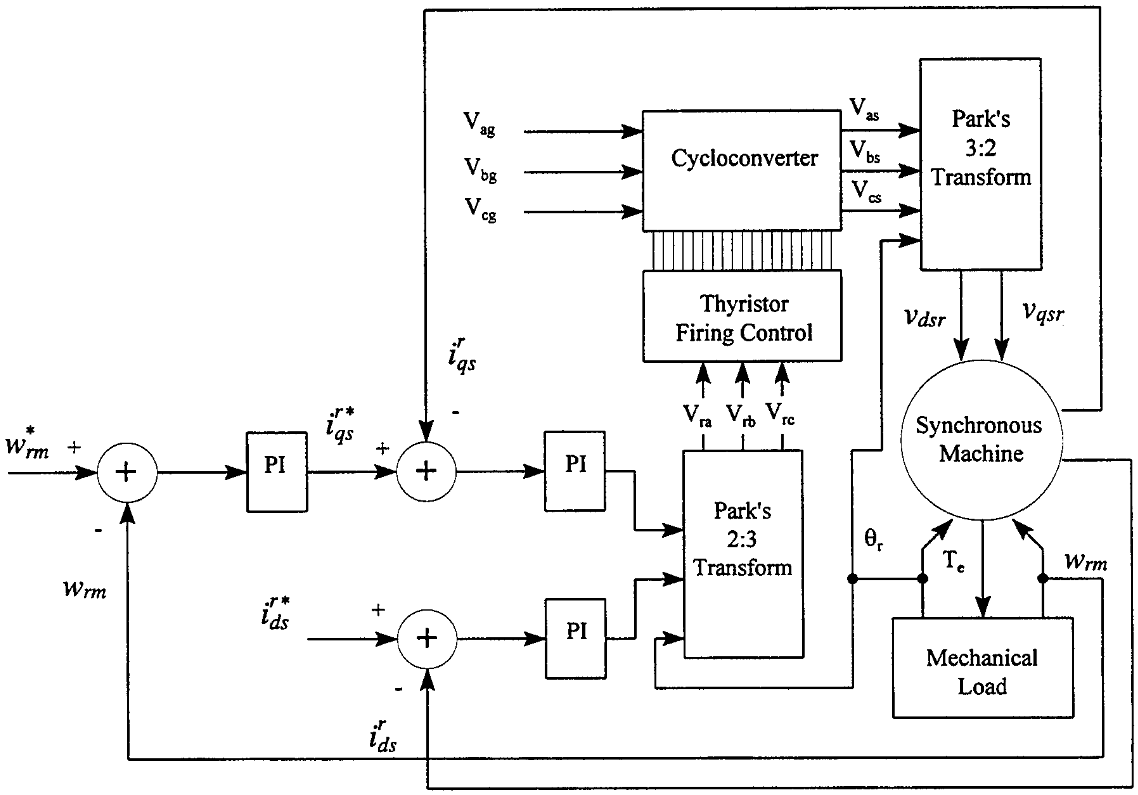

Figure 6-2. Vector Control and Field Orientation Scheme.

In addition to the vector control of Figure 6-2, some measure of control is required for the field excitation. Without feedback control, the field current will fluctuate widely and cause erratic machine behavior. What is devised is a first-order closed-loop control of the applied field voltage based on the motor air gap flux. The control scheme is illustrated in Figure 6-3. It functions to maintain a constant air gap flux by adjusting the voltage applied to the field winding.

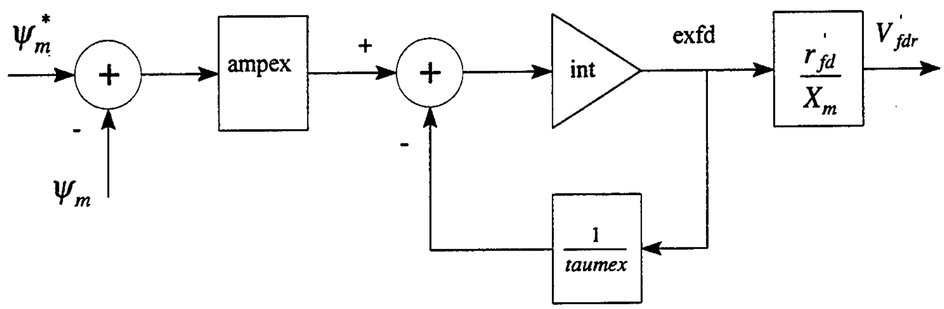

Figure 6-3. Field Excitation Control Scheme.

C. SIMULATION ANALYSIS

1. Synchronous Machine and Vector Control

In order to test the model of the synchronous machine and to determine gains for the vector control, a simulation is established whereby the sinusoidal reference voltage waveforms, V_{ra}, V_{rb} and V_{rc}, generated by the vector control scheme of Figure 6-2 are directly applied to the motor, effectively removing the cycloconverter from the control circuit. The idea being that these reference waveforms represent ideal cycloconverter output voltage waveforms, allowing the gains of the control system to be determined and the synchronous motor model to be tested without the complexity of the cycloconverter. A simple mechanical load is modeled and applied to the motor. The mechanical model is developed from the following relationship between torque and rotor speed [20]:

$$T_e = J \frac{d\omega_{rm}}{dt} + B_m \omega_{rm} + T_L \qquad (6\text{-}18)$$

where T_e is the electromagnetic torque, J is the inertia of the rotor and the connected mechanical load, ω_{rm} is the rotor speed, B_m is the damping coefficient related to the rotational mechanical system and T_L is the load torque (positive for a torque load on the shaft of the machine). An ACSL MACRO of this mechanical load is included in Appendix C.

Figures 6-4 through 6-6 are plots of system variables which describe the performance of the machine and the vector control. Again, the study idealizes the operation of the cycloconverter by assuming that the desired voltages are exactly synthesized by the control. Otherwise, the control setup is exactly as detailed in Figure 6-2. The purpose of the study is to illustrate the fast accurate torque control achieved with vector control and how excellent speed response can be obtained. A commanded speed signal was generated in the code and appears as ω_{rm}^* in Figure 6-4. The motor is asked to accelerate up to 9 rad/sec, operate at constant speed for one second, reverse and operate at -9 rad/sec for one second and finally decelerate back down to zero. The studies were conducted using per unit quantities to enhance the precision of the calculations. The normalized inertia was set to 0.1 sec while the damping coefficient was fixed at 0.05 sec. The load torque was assumed to be zero. The Figure 6-5 results illustrate excellent current tracking and demonstrate the proportional relationship between i_{qs}^r and the developed torque. Figure 6-6 illustrates the air-gap flux and how the field current is controlled to regulate it. The parameters used in the regulator listed in Figure 6-3 are ampex = 50, taumex = 0.01 and $\psi_m^* = 1.3$ per unit. The control gains used in this study are included in the following table.

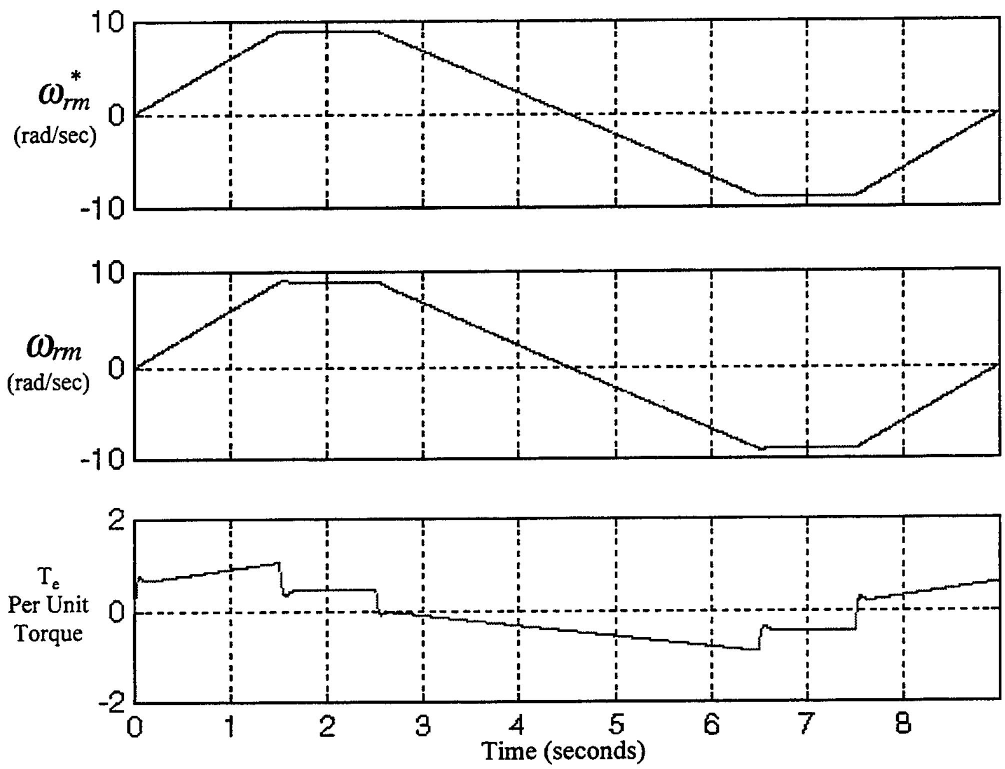

Figure 6-4. Transient Behavior of Synchronous Motor with Vector Control.

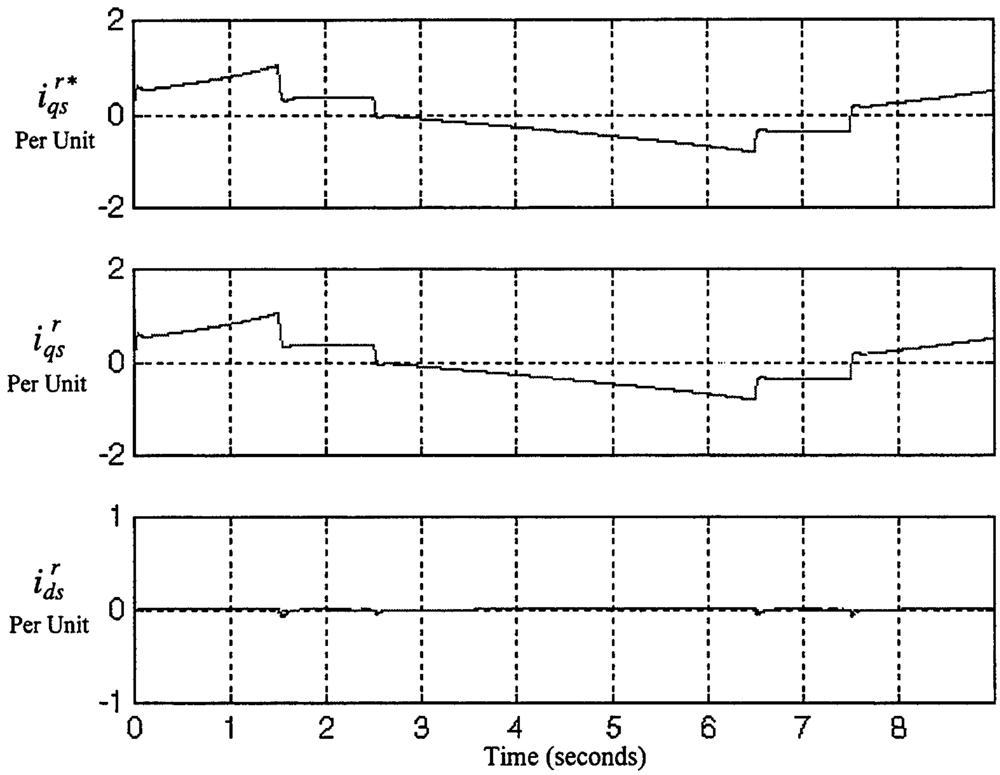

Figure 6-5. Transient Behavior of Synchronous Motor with Vector Control.

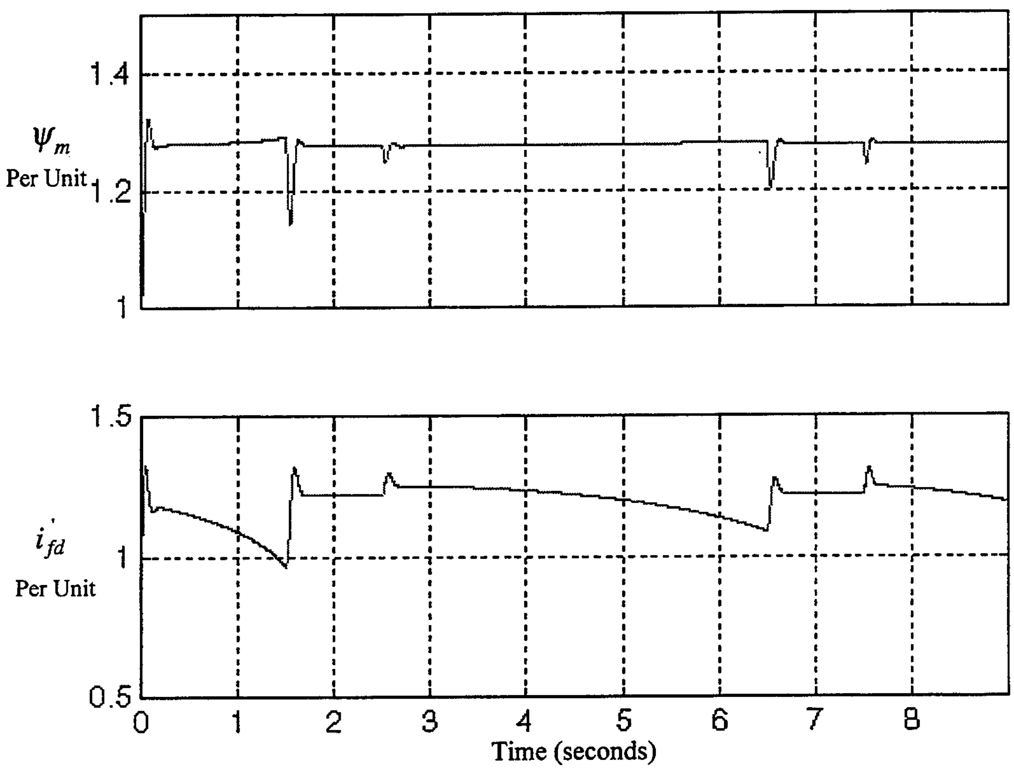

Figure 6-6. Transient Behavior of Synchronous Motor with Vector Control.

	Proportional	Integral
Speed	5.0	100
q-current	2.0	50
d-current	2.0	50

Table 6-3. Vector Control System Gains.

2. Cycloconverter and Permanent Magnet Synchronous Machine

Before proceeding to the next step of inserting the cycloconverter into the control loop, the affects of the distorted cycloconverter output voltages applied to a synchronous machine are examined. A permanent magnet synchronous machine model from Reference [20] was selected for this study for several reasons. The first reason is the simplicity of the control. Since the field is established by a permanent magnet, no field excitation control is required. Second, dynamic simulation data and analysis is readily available for this machine from Reference [20] which greatly facilitates the validation of the study.

To illustrate the operation of the cycloconverter without the added distraction of the speed control, the vector control scheme of Figure 6-2 was considered with inputs being the commanded d and q-axis currents. Commanded q and d-axis currents were predetermined and entered interactively in the run-time environment during the simulation run. The machine parameters are those described in Reference [20] and are not per unit. A damping coefficient of 0.01 N-m-s was selected to achieve operating speeds and currents of interest. Figure 6-7 illustrates the step increases in the commanded q-axis currents and the resultant increases in the rotor speed. The desired d-axis current is fixed at zero as before. Of interest to note in Figure 6-7 is the appearance of the q-axis current at each of the commanded levels. Over the initial 0.2 second interval, the commanded q-axis current is 2.0 amps and Figure 6-7 clearly illustrates how

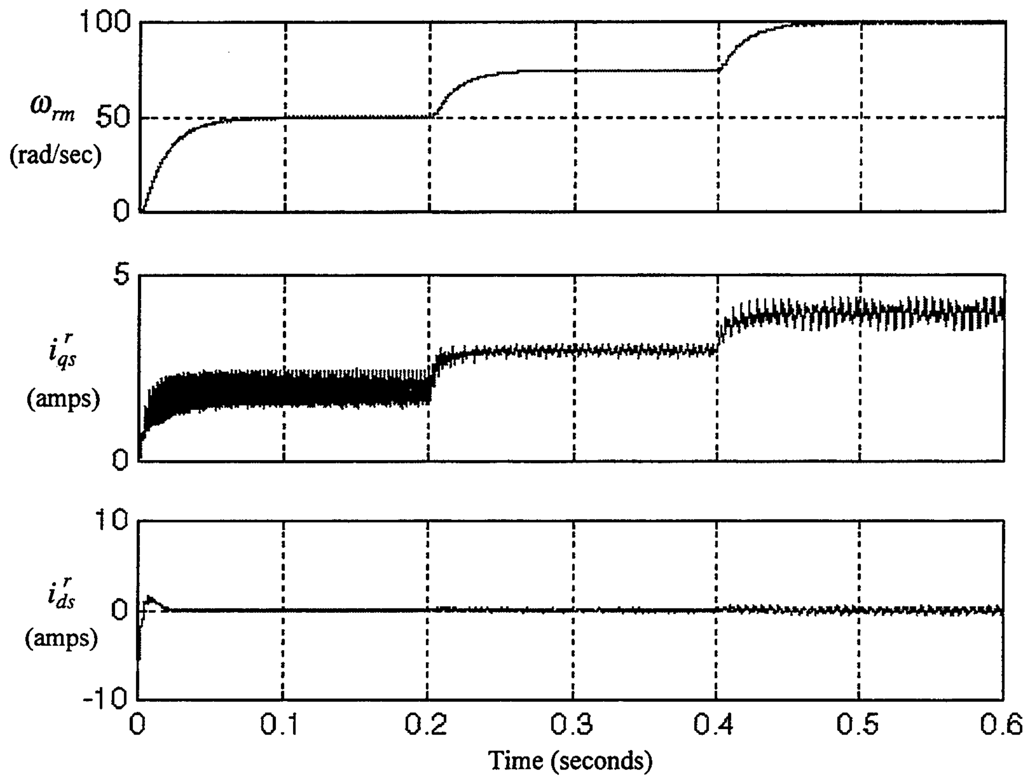

Figure 6-7. Transient Behavior of a Permanent Magnet Synchronous Machine with Cycloconverter Drive.

the actual current rapidly achieves an average value of 2.0 amps but with considerable harmonics. This is a direct result of the highly distorted cycloconverter output voltage waveforms applied to the motor. Figure 6-8 illustrates the reference voltage and mean output voltage from a single phase of the cycloconverter. During the initial time interval, the reference voltage is of relatively low amplitude and low frequency. The low amplitude of the reference waveform gives rise to a highly distorted mean output voltage. Over the second 0.2 second interval, the cycloconverter operates in a much more desirable mode. The commanded q-axis current is 3.0 amps and as Figure 6-7 depicts, the actual current once again tracks the commanded value with less harmonics. Here the amplitude and frequency of the reference voltage produce a cycloconverter output voltage waveform of relatively low distortion. The lower distortion is apparent in the plots of the q-axis current and developed electromagnetic torque. Over the last 0.2 second interval, the commanded q-axis current is increased to 4.0 amps. The waveforms once again show signs of objectionable distortion. A similar analysis of the reference voltage reveals that although the amplitude is relatively high, the output-to-input frequency ratio is increased which gives rise to greater harmonic content in the cycloconverter output voltage.

From this study, it is apparent that there exists some range of relative voltage level and output-to-input frequency ratio which is optimum and which is application dependent. In this study despite the large current and torque harmonics, the speed response depicted in Figure 6-7 is smooth. The problem or issue would be the amount of heat generated in the machine by the harmonic currents and the amount of distortion introduced at the 3-phase supply. As a result, the range of optimum operation should be identified during the conceptual design phases of the electric drive to establish the required input, output and control system characteristics .

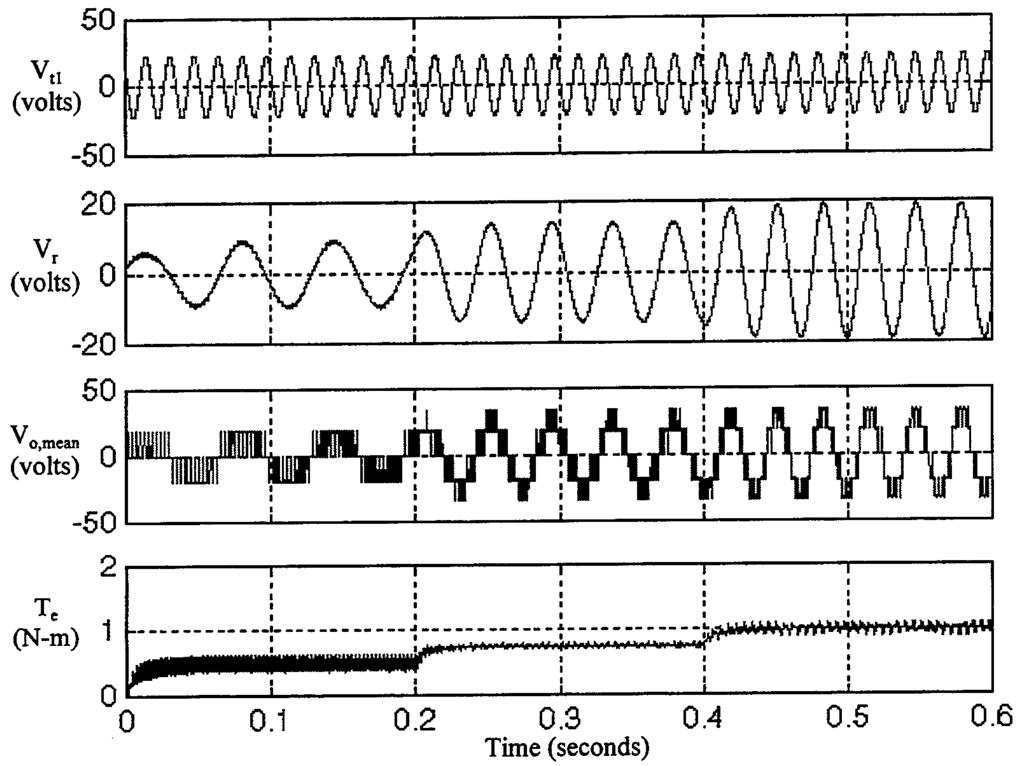

Figure 6-8. Transient Behavior of a Permanent Magnet Synchronous Machine with Cycloconverter Drive.

3. Cycloconverter and Synchronous Machine

With the results of the previous study with the permanent magnet machine indicating that the control scheme and cycloconverter can function to develop the proper torque and speed response, the next step is to apply the vector control and cycloconverter to the synchronous machine proposed for the propulsion system. Again, the simple mechanical load is applied to the motor and the same study illustrated in Figures 6-4 through 6-6 are performed. The parameters are once again in per unit and the control gains are those given in Table 6-3. In these studies the signals out of the PI current regulators are processed through a low-pass filter with a cutoff frequency of approximately 16 Hz. Without the filtering, the reference waveforms contained high-frequency components which disrupted the proper thyristor pulse firing sequence and timing. This filtering was not required on the permanent magnet machine of the previous study. The reason for this lies with how the machine parameters respond to the distorted waveforms which are applied. The synchronous machine parameters supplied by NSWC do not respond well to the applied cycloconverter output waveforms. A host of studies were conducted to investigate this effect. Efforts were made to filter the feedback current signals, modify the current regulator gains and scale the reference voltage signals but in the end, the response of the system seemed most dependent on the machine parameters. Future research may include identifying the relationship between cycloconverter harmonics and synchronous machine parameters. The results of the study are illustrated in Figures 6-9 through 6-11. Comparison of the studies with and without the cycloconverter give rise to some interesting observations. The plots of the q and d-axis currents show a high level of oscillation about the commanded values. This is due to the relatively high harmonic content of the cycloconverter output. These oscillations are also apparent in the air gap flux (Figure 6-11).

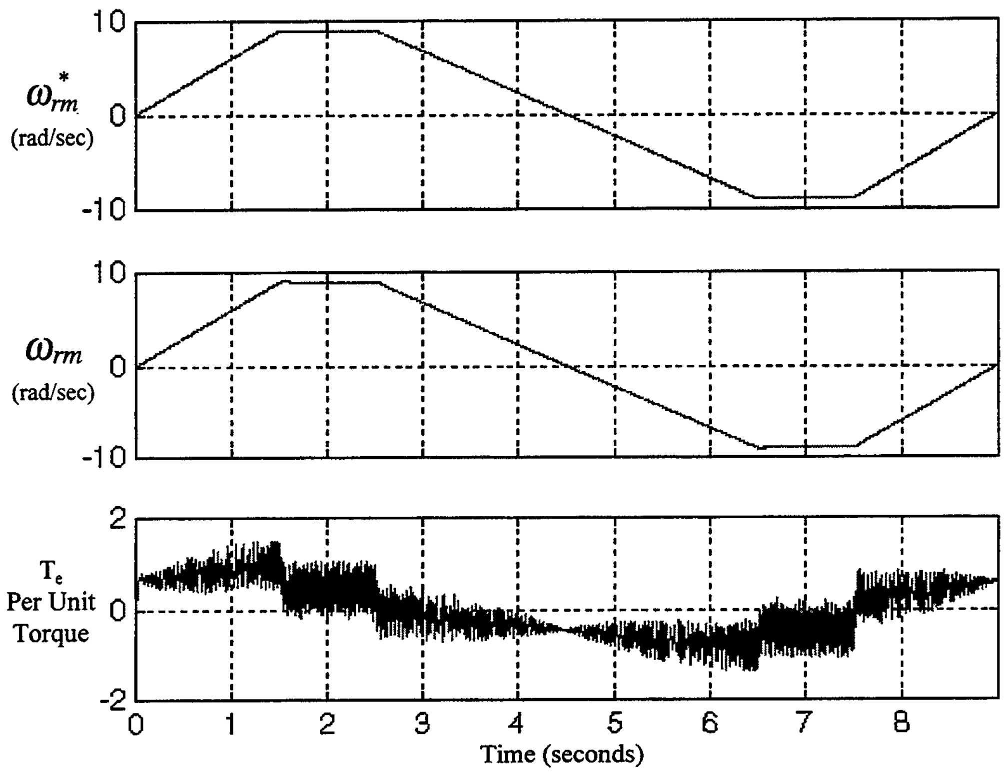

Figure 6-9. Transient Behavior of Synchronous Motor with Cycloconverter Drive.

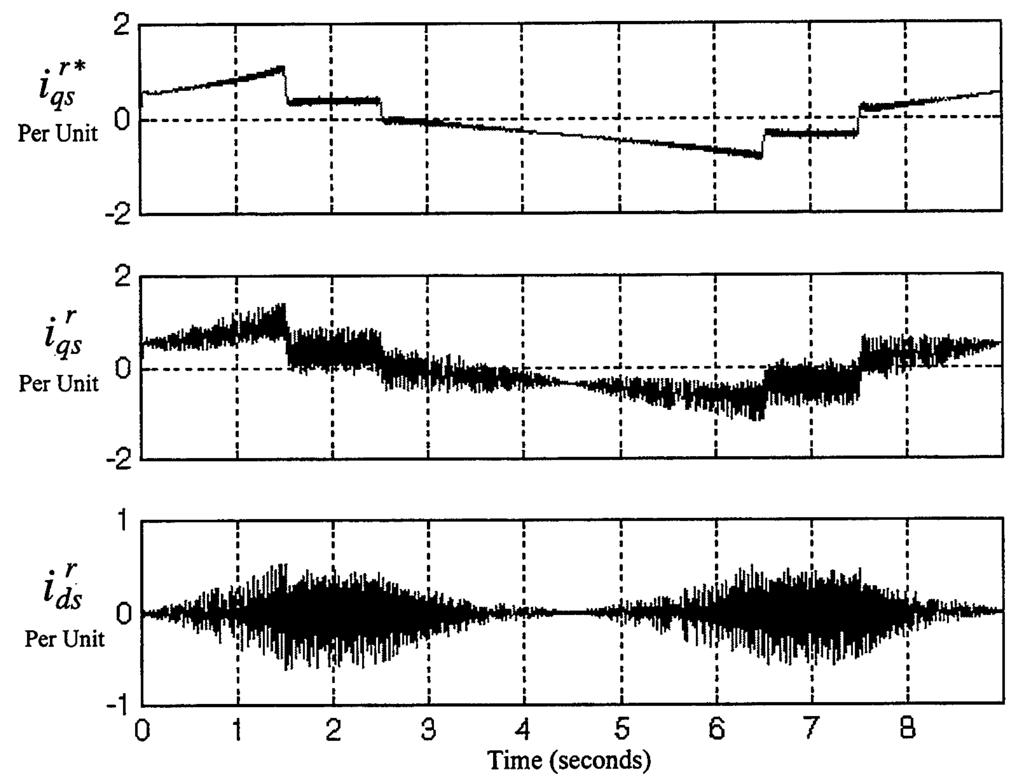

Figure 6-10. Transient Behavior of Synchronous Motor with Cycloconverter Drive.

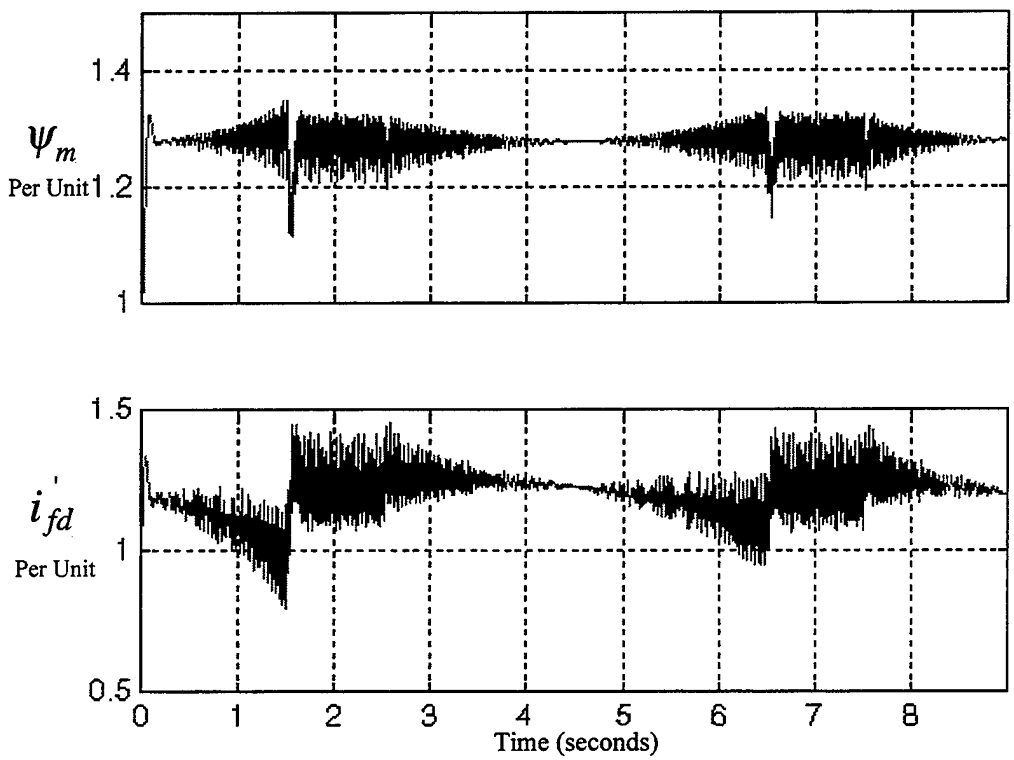

Figure 6-11. Transient Behavior of Synchronous Motor with Cycloconverter Drive.

With the control system modified by the addition of the filtering, which is necessary to eliminate the high-frequency components of the reference waveform, the cycloconverter did not perform as expected as the output-to-input frequency ratio was increased. Operation of the drive with motor speeds of over 10 radians per second (approximately 95 RPM) created objectionable oscillations and pulsations in the q and d-axis currents and in the electromagnetic torque. This is because the reference waveforms developed by the filtered control system could not reach an amplitude which would provide high relative output voltages. Consequently, the output voltage waveforms are highly distorted. Increases in the output-to-input frequency ratio as a result of higher commanded motor speeds increases the harmonic content of the applied voltages as would be expected. The elimination of the control signal filtering resulted in improper cycloconverter operation. The solution to this problem lies with the proper marriage of the propulsion motor and its power requirements to the available input system power so that the cycloconverter operates in the optimum region as illustrated with the permanent magnet machine. The permanent magnet motor simulation responded well to voltage waveforms of considerable harmonic distortion; therefore, filtering of the control signals is not required and the developed reference waveforms are allowed to achieve the full range of amplitude, thereby reducing the harmonic content of the cycloconverter output voltages.

The author was unable to find or determine machine parameters, other than those taken from NSWC, which would be appropriate for a propulsion motor of the size required to power a typical destroyer. It may be worthwhile to devote future efforts towards identifying additional prospective propulsion motors and identifying the interactions with the cycloconverter. The next chapter contains a description of the propeller load model and analysis of the cycloconverter electric drive propulsion system.

VII. INTEGRATED ANALYSIS

With the synchronous motor model and control scheme functioning as shown in Chapter VI, the study now turns to evaluating the drive in a ship propulsion application. This chapter provides some insight on how the drive might perform with typical destroyer-type propeller loads and hull dynamics. The simple mechanical load considered in the simulation model of Chapter VI is replaced by the propeller load with hull dynamics. Simulation runs are then performed to investigate the dynamic response of the motor and ship speed.

A. SIMULATION OF PROPELLER LOAD

The propeller load of a typical destroyer is a complex function of shaft rpm, propeller thrust, hull resistance, and ship speed. The analytical expressions used to model the interaction of these variables were taken from Reference [23]. These expressions were provided by NSWC, Annapolis and are representative of typical destroyer-type hulls and propellers. In order to accurately model the propeller load of a typical destroyer in a manageable fashion, the expressions were converted to per unit form. The per unit propeller torque may be expressed as [23],

$$T_L = 2.55\left\{0.632\left(\frac{\omega_r}{\omega_b}\right)\left|\frac{\omega_r}{\omega_b}\right| + 0.253\left|\frac{\omega_r}{\omega_b}\right|\sqrt{1.602\,V_p^2 + \left(\frac{\omega_r}{\omega_b}\right)^2} - 0.295\left[1.602\,V_p^2 + \left(\frac{\omega_r}{\omega_b}\right)^2\right]\right\} \qquad (7\text{-}1)$$

where $\dfrac{\omega_r}{\omega_b}$ is the normalized motor (equivalently, the propeller) speed and the propeller speed of advance through the water, V_p, is [23],

$$V_p = \left(1 - w_f\right) V_s \tag{7-2}$$

where w_f is the wake fraction and V_s is the per unit ship speed. The wake fraction is a measure of the average speed of the wake over the whole propeller disk, expressed as a fraction of the ship speed. This fraction characterizes the effects of viscous drag, wave making, and water velocity variations over the hull which all contribute to what is called the ship "wake." [24] As shown in Equation 7-2, the wake fraction is used to determine the speed of the propeller through the water. In the subsequent studies w_f is assumed to be constant and equal to 0.02 and $V_s = 1$ pu corresponds to a ship speed of 27 knots (45.57 ft/sec). The base torque is defined as the base electrical power supplied to the synchronous machine with base currents and voltages applied divided by the rated speed (377 rad/sec). Assuming balanced steady-state operation and unity power factor it can be determined as follows [23]:

$$\begin{aligned} T_{base} &= \frac{3\, V_{base}\, I_{base}}{\omega_{rm,base}} \\ &= 66.2 \times 10^3\ \mathrm{N \cdot m} = 49.18 \times 10^3\ \mathrm{ft \cdot lb} \end{aligned} \tag{7-3}$$

The per unit expression for propeller thrust is [23],

$$\begin{aligned} F_T = 1.0055\Bigg\{ & 2.342\left(\frac{\omega_r}{\omega_b}\right)\left|\frac{\omega_r}{\omega_b}\right| + 0.9296\left|\frac{\omega_r}{\omega_b}\right|\sqrt{1.602\, V_p^2 + \left(\frac{\omega_r}{\omega_b}\right)^2} \\ & -1.107\left[1.602\, V_p^2 + \left(\frac{\omega_r}{\omega_b}\right)^2\right]\Bigg\} \end{aligned} \tag{7-4}$$

where the base thrust is defined as the steady-state propeller thrust when $V_s = 1$ pu and, under these conditions, $F_T = 1$ pu with $F_{T,base} = 2.078 \times 10^5$ lb. The per unit ship dynamics may be expressed as [23],

$$pV_s = \frac{1}{H_s}\left(F_{T1} + F_{T2} - R_s\right) \tag{7-5}$$

where $p = \frac{d}{dt}$; F_{T1} and F_{T2} are the thrust developed by the two propellers; R_s is the per unit hull resistance; and the denominator, H_s, is [23]

$$H_s = \frac{M_s V_{s,base}}{F_{T,base}} \qquad (7\text{-}6)$$

In Equation 7-6, M_s is the ship mass (3.132×10^5 lb•sec²/ft). Substituting $V_{s,base} = 45.57$ ft/sec and $F_{T,base} = 2.078 \times 10^5$ lb into Equation 7-6 yields $H_s = 68.69$ sec. In subsequent studies it is assumed the ship is stationary or moving straight ahead so that $F_{T1} = F_{T2} = F_T$. It is also assumed that the propellers will be operated in an identical manner. An expression for the per unit ship resistance (ship resistance divided by $F_{T,base}$) is given in terms of the normalized ship speed as [23],

$$R_s = 1.256 V_s |V_s| \frac{V_s^2 - 1.981 V_s + 1.012}{V_s^2 - 1.975 V_s + 0.9944} \qquad (7\text{-}7)$$

A MACRO containing these expressions is included in Appendix D along with the main program for the 3-phase, 6-pulse, circulating current cycloconverter and vector control. The main program invokes both the propeller load MACRO and the synchronous machine MACRO to form the integrated electric drive system

B. ANALYSIS OF INTEGRATED SIMULATION

Before applying the MACRO of the propeller load to the cycloconverter drive some analysis is performed to gain insight into the interaction of shaft speed, propeller torque, and ship speed. The plots of Figure 7-1 illustrate the relationship between the propeller torque and the reduction gear input shaft speed for ship speeds of 0, 14 and 27 knots. Figure 7-2 illustrates the relationship between ship speed and the reduction gear input shaft speed. This curve was generated by solving the steady-state version of Equation 7-5 and provides insight into controlling the ship speed. As is fairly obvious, higher ship speeds are achieved by spinning the input shaft faster. Thus a correlation can be made between the desired motor speed and the desired ship speed. This is a static relationship and does not take into account maximizing the acceleration up to the final ship speed. It would appear that for maximum acceleration, the shaft should be operated at full speed for the majority of the time then brought down to the operating point indicated in Figure 7-2. The design of a closed-loop ship speed control was beyond the focus of this thesis.

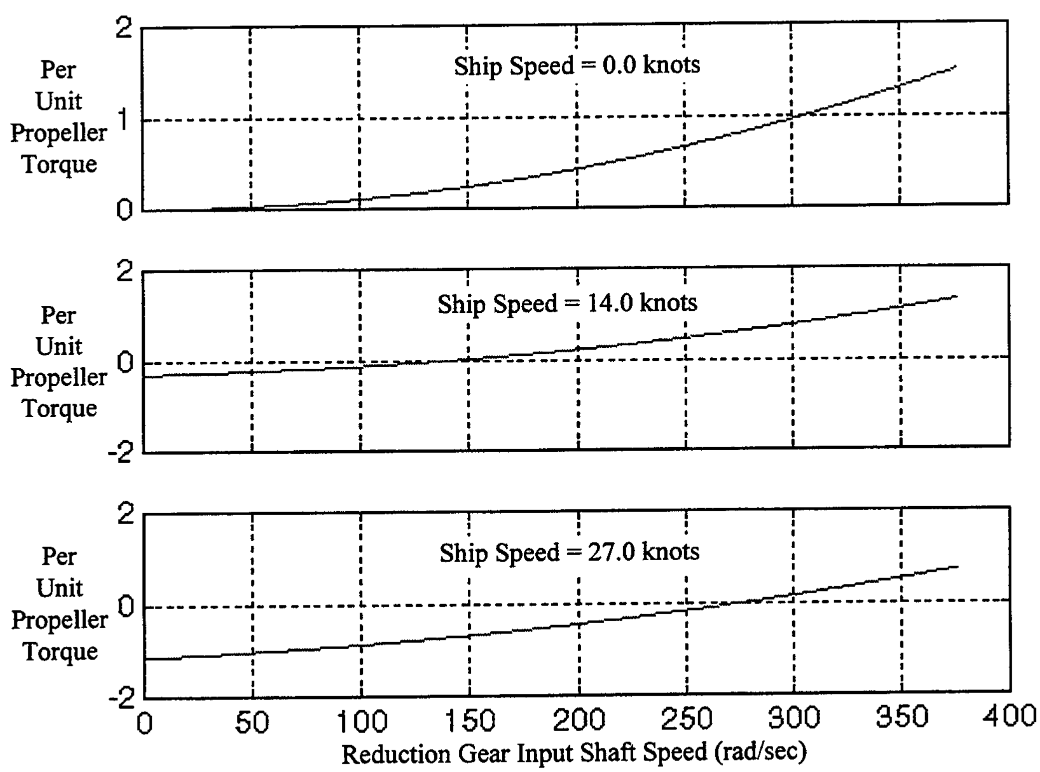

Figure 7-1. Per Unit Propeller Torque versus Reduction Gear Input Shaft Speed.

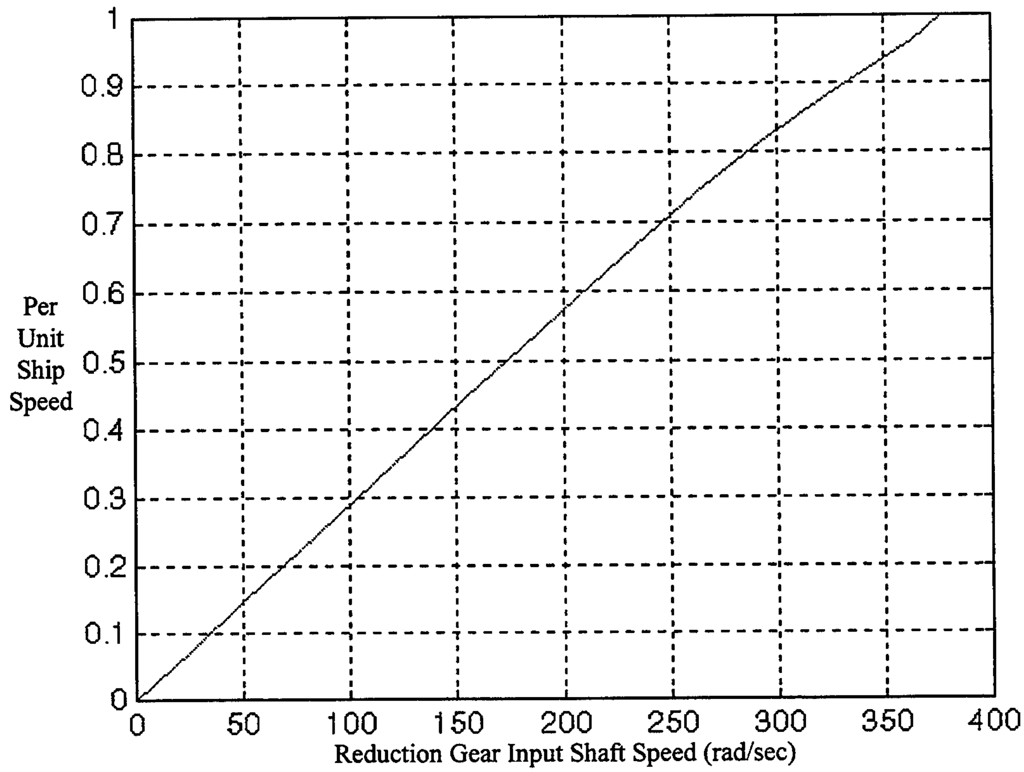

Figure 7-2. Per Unit Shaft Speed versus Reduction Gear Input Shaft Speed.

As mentioned previously, the propeller load and hull dynamics expressions were taken from the study of Reference [23]. In that study, the electric drive system developed rotor speeds from zero to 377 radians per second. The machine rotor was treated as the input shaft to a set of reduction gears which reduced the shaft rpm to speeds which are efficient for propeller operation. The electric drive considered in this study is direct drive (no reduction gears). In order to utilize the available propeller model, the electromagnetic torque developed by the synchronous machine is divided by a suitable ratio before being applied to the propeller load MACRO. Similarly, the shaft speed returned by the propeller load MACRO is divided by the same ratio. The ratio is determined by considering the rated speed of the synchronous motor

(17.17 rad/sec or 164 rpm) and the rated speed expected by the propeller load model (377 rad/sec or 3,600 rpm). The resultant ratio is 377:17.17 or 21.957.

Due to the considerable computer system resources and long simulation run times associated with exercising the integrated system model, the analysis is limited to two studies. The first is an acceleration of the ship to the steady-state speed associated with a shaft speed of 9 rad/sec or approximately 86 rpm. The second is a quick acceleration of the propulsion motor from zero to 14 rad/sec with the propeller seen as the load.

In the first study, the commanded motor speed is held at 9 rad/sec. As discussed above, the propeller load MACRO "sees" this speed as (9 x 21.957) rad/sec or 197.613 rad/sec. From Figure 7-2, the associated steady-state ship speed is approximately 0.575 pu or 15.5 knots. Once this shaft speed is developed, the ship is allowed to accelerate up to its steady-state speed. Figures 7-3 through 7-5 shows the dynamic response of the integrated electric drive system. Clearly the dynamics of the machine are much faster than those of the ship. The ship acceleration required a run of over 80 seconds which translated into a simulation study lasting approximately 60 minutes on a SPARC10 workstation. Owing to the wide separation of the time scales of the dynamics of the electric drive and ship, additional lengthy studies provided no further insight into the cycloconverter drive operation and are not presented here. Of interest is the large bands of "noise" which surround the average values of the electromagnetic torque and q and d-axis currents. The variation in torque represented by this "noise" would most certainly be induced into the propulsion shafting and could possibly excite torsional resonance of the propulsion motor-line shaft system [15].

The second study is illustrated in Figures 7-6 through 7-9. In this study the transient behavior of the drive is observed when the motor is commanded to accelerate from zero to 14 rad/sec. The focus of this study is the on the response of the cycloconverter rather than on the

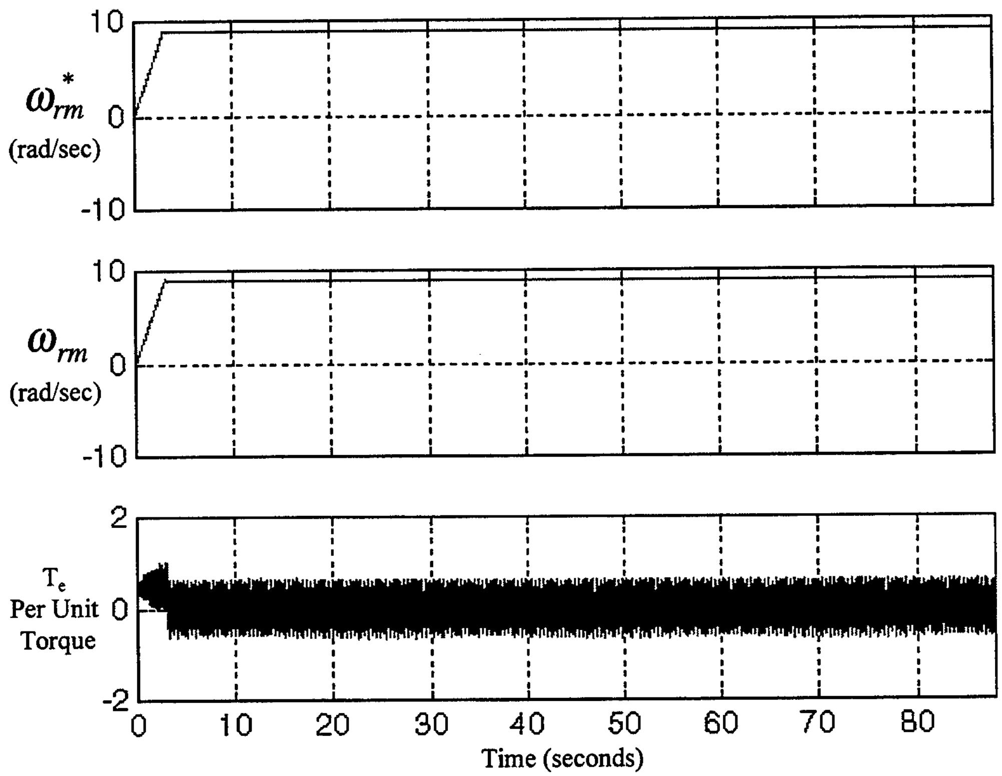

Figure 7-3. Dynamic Response of Cycloconverter Propulsion Motor Drive.

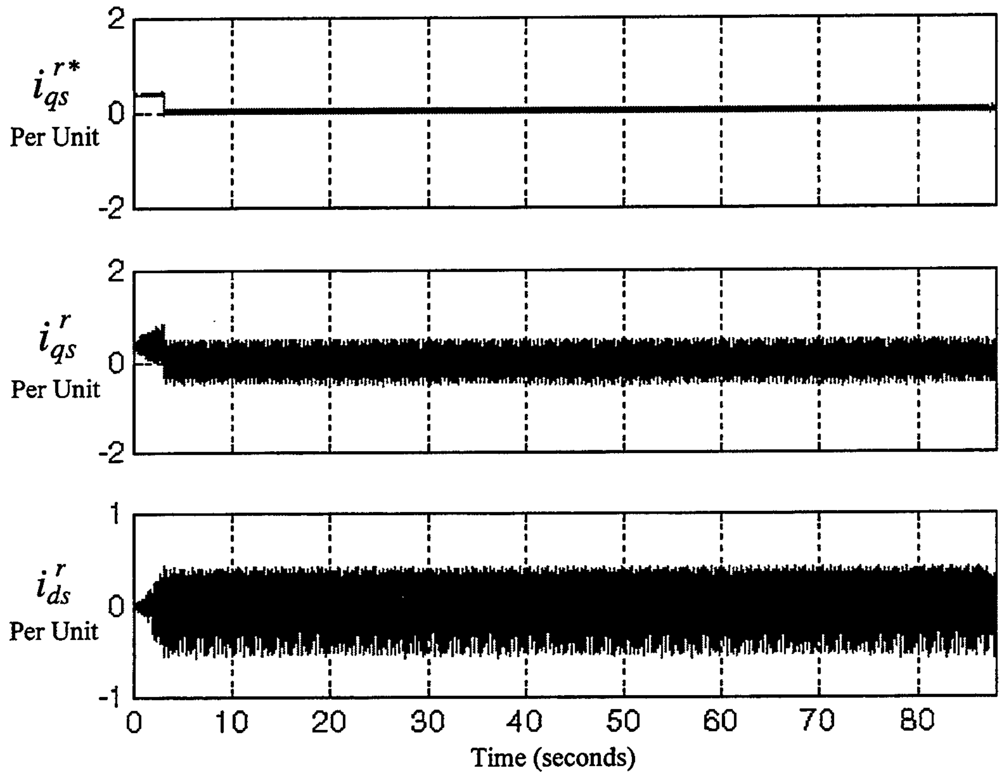

Figure 7-4. Dynamic Response of Cycloconverter Propulsion Motor Drive.

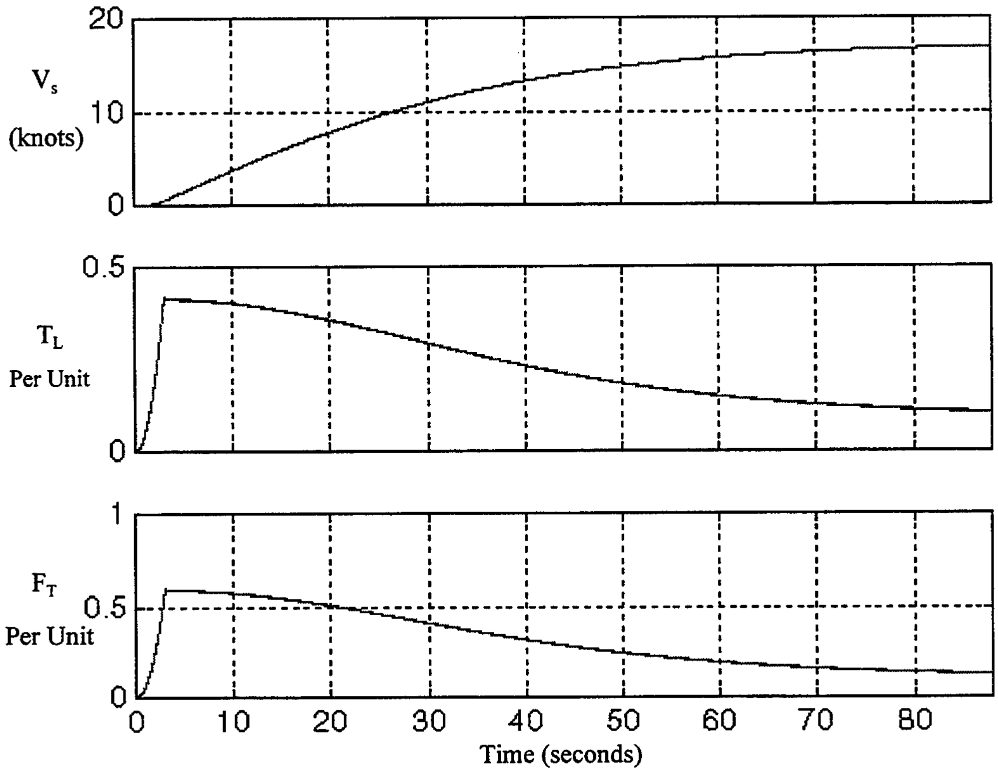

Figure 7-5. Dynamic Response of Cycloconverter Propulsion Motor Drive.

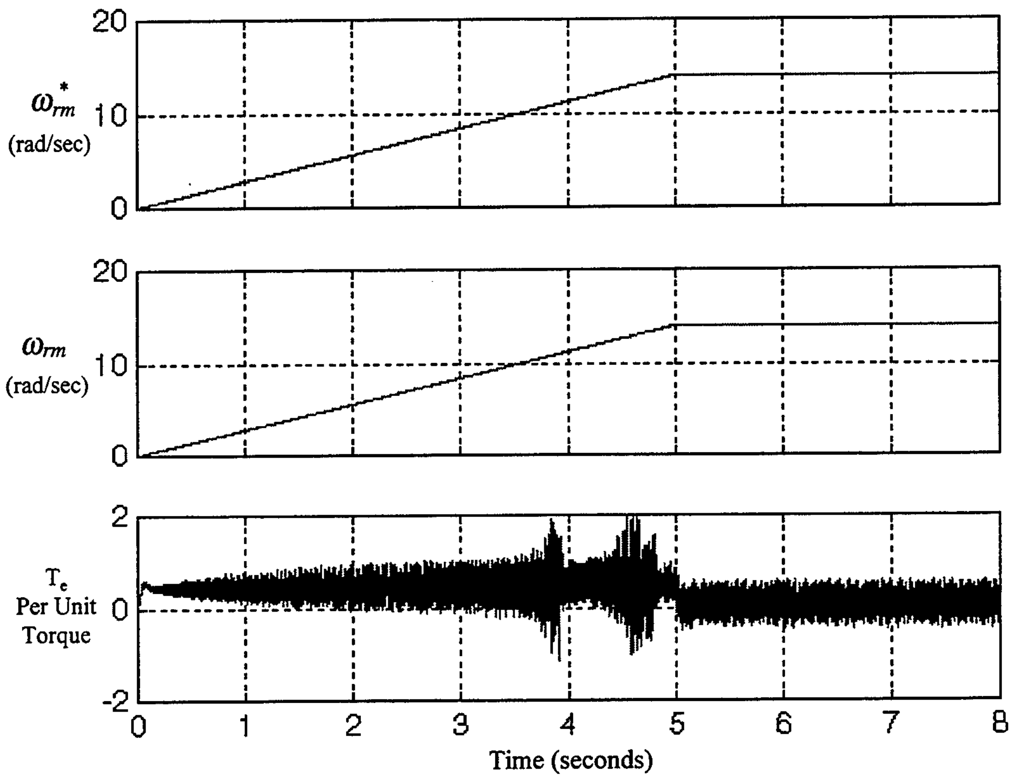

Figure 7-6. Transient Behavior of Cycloconverter Propulsion Motor Drive.

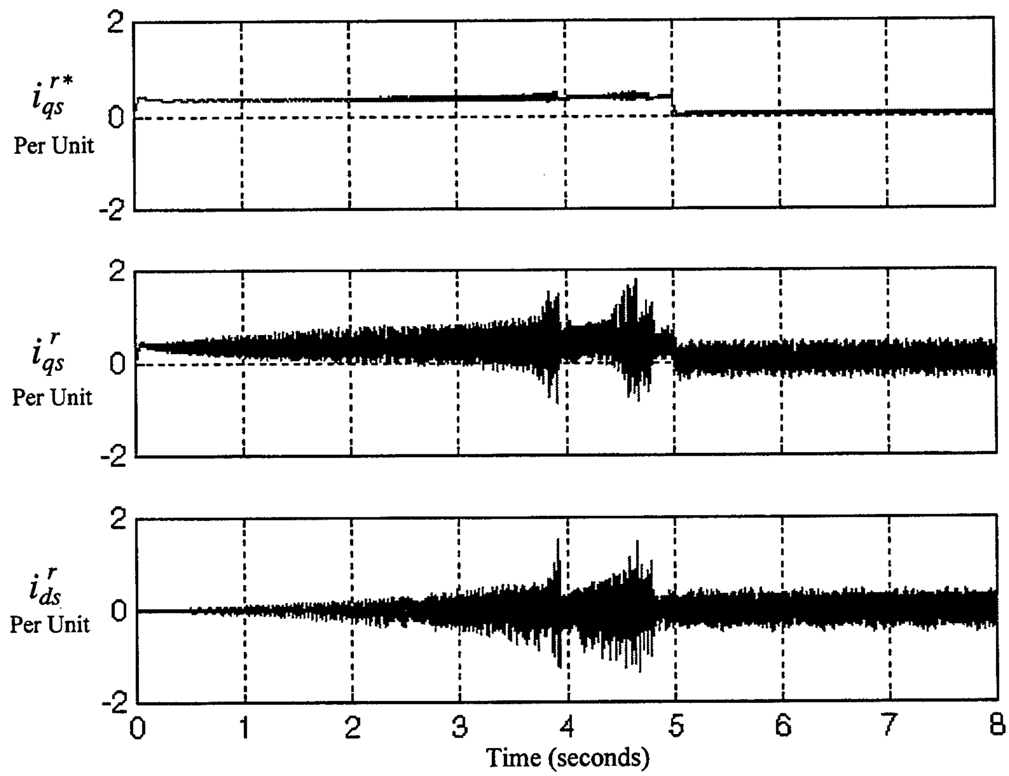

Figure 7-7. Transient Behavior of Cycloconverter Propulsion Motor Drive.

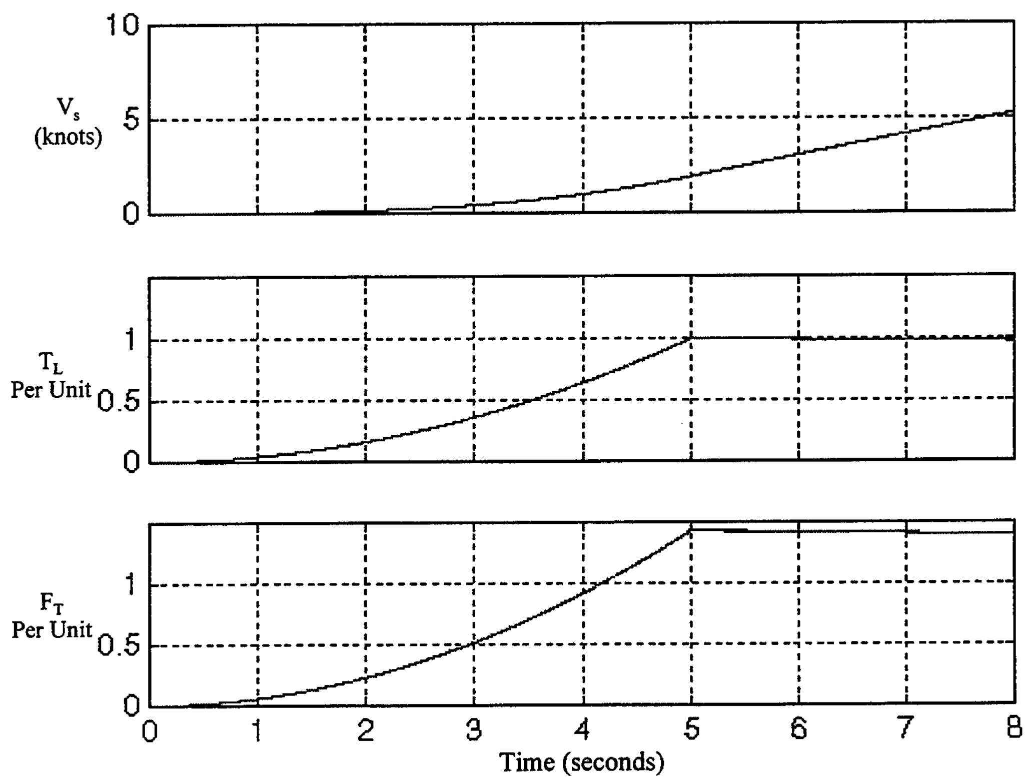

Figure 7-8. Transient Behavior of Cycloconverter Propulsion Motor Drive.

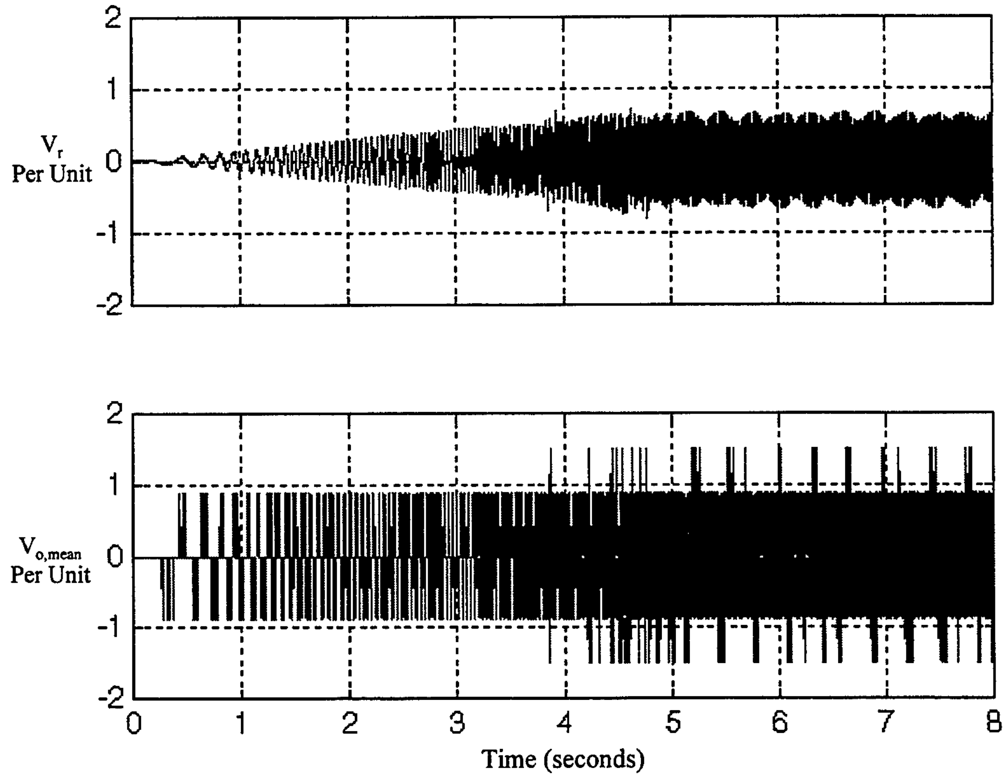

Figure 7-9. Transient Behavior of Cycloconverter Propulsion Motor Drive.

response of the ship. As alluded to in Chapter VI, the cycloconverter drive produces objectionable harmonics at high output-to-input frequency ratios. What is noticeable is that the variations get so bad that at two points during the run, the drive becomes erratic and produces huge torque pulsations. Figure 7-9 illustrates the high-frequency variations of the reference waveform and the distorted cycloconverter output voltage which results.

Clearly some modifications to the drive simulated in this study is required if it is to be considered for use in a surface combatant. The modification may only entail selecting a different motor. As shown in Chapter VI, the permanent magnet machine seemed to respond well to the cycloconverter drive. Conversely, this drive and motor may be made to operate as desired with a modification of the speed and current control systems which generate the cycloconverter modulating waveforms. It is the author's opinion that new machine parameters should be consulted before further control modifications are considered. In any case, as expected, the distortion of the cycloconverter output voltage waveforms is the limiting factor at this stage of analysis. Despite the harmonics issue, it is clear that a vector-controlled cycloconverter synchronous machine electric drive can be simulated and that the simulation can be used to predict the performance and suitability of the drive.

VIII. CONCLUSION

A. CYCLOCONVERTERS FOR SHIP PROPULSION

From the brief discussion in Chapter I, it is shown that an integrated power system (IPS) possesses attractive characteristics and is well suited for application in future surface combatants. An IPS facilitates the reduction in the number of engines or prime movers that must be installed in the ship. With reduced numbers of engines installed comes reduced fuel consumption and reduced maintenance workload. Both reductions significantly reduce the operating and support costs throughout the life cycle of the ship. In addition, the use of an IPS eliminates the need for controllable reversible pitch (CRP) propeller systems, reversing gears, fluid couplings and in some cases reduction gears. An IPS introduces flexibility in arrangement, automation and control advances with open architectures, common and modular design of equipment, and the facility to provide separation and redundancy in new and imaginative ways to improve survivability.

The external performance characteristics and basic control issues discussed in Chapters II and III are included to provide the designing naval or electrical power engineer with technical background information and design considerations for the application of a cycloconverter drive for ship propulsion in an integrated power system. The analysis of the time-domain computer simulations of Chapters V, VI, and VII serve to present a broad system perspective of such a drive and to provide the basis for future work in this area. The analysis shows that with an appropriate machinery control system, this electric drive system can give smooth, fast speed response.

The naval engineers involved in the design of the next generation surface combatant require conceptual and design information for various electric drive options. This study provides the technical background information, external performance characteristics and computer simulation analysis that can be use in making educated decisions on the application of a cycloconverter drive for ship propulsion.

B. FUTURE WORK

The work presented in this thesis represents the basis for many different aspects of future research. In keeping with the broad system perspective, the models and simulation from this work can be modified in a number of ways and the system performance evaluated. New studies on the effects of different motor and cycloconverter control schemes can be undertaken using this study as a baseline and a tool for selection of control gains. Of particular interest are studies which focus on the difference in the drive's performance based on the cycloconverter mode of operation and the addition of regenerative and/or dynamic braking capabilities. In addition, the material in this study can be used to evaluate the effects of the cycloconverter as a load on the electrical power distribution system of an IPS. From such an extension, issues such as input current waveform distortion and input power factor may be analyzed and practical electrical load and power efficiency calculations performed.

Taking a more fundamental approach, future work could focus on the cycloconverter and its optimization. Analysis of the total harmonic distortion of both the input and output waveforms associated with different closed-loop thyristor firing control schemes could be performed using this work as its foundation. The simulations provided could be modified to include the non-ideal characteristics of the thyristor and control system to more accurately model the converter for efficiency calculations and realistic hardware selections. These simulations could also be extended to 12-pulse and 72 thyristor cycloconverters to compare the performance of these drives to the six-pulse converters.

The Navy's technical community is actively searching for innovative electric drive concepts. The use of cycloconverter drives for ship propulsion is an area which should be explored for the electric drive systems of the future. This work serves as a basis for many future studies, some of which may yield the right mix of performance, innovation, and cost-effectiveness.

APPENDIX A. ACSL PROGRAM CODE FOR DUAL CONVERTER SIMULATION

```
! ACSL program for a model of a single phase dual converter.

PROGRAM

INITIAL

! Maximum integration step size.

        MAXTERVAL maxt = 1.0e-5

! Data communication interval.

        CINTERVAL cint = 1.0e-4

! Integration algorithm, R.K. 4th.

        ALGORITHM ialg = 5
        NSTEPS    nstp = 1

! Stop point for integration.

    CONSTANT tstop = 0.08

! General simulation parameters and variables.

        PARAMETER (pi = 3.14159)
        rad180 = ACOS(-1.0)
        rad360 = 2.0*rad180
        xx = 0.0

! Logical variables to model each switch in the dual converter.

        LOGICAL T1,T2,T3,T4,T1P,T2P,T3P,T4P

! Logical variables for initial state of each switch in the dual converter.

        LOGICAL T1I,T2I,T3I,T4I,T1PI,T2PI,T3PI,T4PI

! Set initial condition of each switch in the converter.

        CONSTANT T1I = .TRUE.
        CONSTANT T2I = .TRUE.
        CONSTANT T3I = .FALSE.
        CONSTANT T4I = .FALSE.
        CONSTANT T1PI = .FALSE.
        CONSTANT T2PI = .FALSE.
        CONSTANT T3PI = .TRUE.
        CONSTANT T4PI = .TRUE.
```

```
        T1 = T1I
        T2 = T2I
        T3 = T3I
        T4 = T4I
        T1p = T1PI
        T2p = T2PI
        T3p = T3PI
        T4p = T4PI

! ac input system parameters.

        CONSTANT ws = 377.0
        CONSTANT V = 120.0

! Thyristor firing angle in radians.

        CONSTANT ALPHA = 1.5708

! Circulating current reactor and load circuit parameters.

        CONSTANT RL = 10.0
        CONSTANT Lr = 40.0e-3

END ! "of initial"

DYNAMIC

! Terminates the run when time is greater than or equal to tstop, minus half a
! communication interval.

        TERMT (t .GE. (tstop-0.5*cint))

        DERIVATIVE

! Input system waveform development.

                THETAS = INTEG(ws,0.0)
                Vin = sqrt(2.0) * V * sin(THETAS)

! Circulating current reactor and load circuit state variables.

                pi1 = (2.0/Lr) * (Vo1 - (i1 + i2) * RL)
                pi2 = (2.0/Lr) * (Vo2 - (i1 + i2) * RL)
                i1 = INTEG(pi1, 0.0)
                i2 = INTEG(pi2, 0.0)
                Io = i1 + i2
                Vo = Io * RL
                Vr = Vo1 - Vo2

! Determine switchin instants.

                SCHEDULE D1 .XP. THETAS - (pi - ALPHA)
```

```
            SCHEDULE D2 .XP. THETAS - (pi + ALPHA)
            SCHEDULE D3 .XP. THETAS - (2.0*pi - ALPHA)
            SCHEDULE D4 .XP. THETAS - (ALPHA)
            SCHEDULE D5 .XP. Vin

! Calculate average voltages.

            Voavg = (1/0.0083333) * INTEG(xx * Vo, 0.0)
            Vo2avg = (1/0.0083333) * INTEG(xx * Vo2, 0.0)
            Vo1avg = (1/0.0083333) * INTEG(xx * Vo1, 0.0)
            SCHEDULE VAVGON .XP. t - 0.00555555
            SCHEDULE VAVGOFF .XP. t - (0.00555555 + 0.0083333)

! Determine output voltage of the positive converter.

            PROCEDURAL (Vo1 = T1,T2,T3,T4,Vin)

                IF (T1 .AND. T2) THEN
                    Vo1 = Vin
                END IF

                IF (T3 .AND. T4) THEN
                    Vo1 = -Vin
                END IF

            END ! "of procedural"

! Determine output voltage of the negative converter.

            PROCEDURAL (Vo2 = T1P,T2P,T3P,T4P,Vin)

                IF (T1P .AND. T2P) THEN
                    Vo2 = -Vin
                END IF

                IF (T3P .AND. T4P) THEN
                    Vo2 = Vin
                END IF

            END ! "of procedural"


        END ! "of derivative"

! Sets switch position based on the firing angle.

        DISCRETE D1
            T1P = .TRUE.
            T2P = .TRUE.
            T3P = .FALSE.
            T4P = .FALSE.
        END
```

```
DISCRETE D2
        T1 = .FALSE.
        T2 = .FALSE.
        T3 = .TRUE.
        T4 = .TRUE.
END

DISCRETE D3
        T1P = .FALSE.
        T2P = .FALSE.
        T3P = .TRUE.
        T4P = .TRUE.
END

DISCRETE D4
        T1 = .TRUE.
        T2 = .TRUE.
        T3 = .FALSE.
        T4 = .FALSE.
END

DISCRETE D5

        THETAS = 0.0

        IF(ALPHA .EQ. 0.0) THEN
                T1 = .TRUE.
                T2 = .TRUE.
                T3 = .FALSE.
                T4 = .FALSE.
        END IF

        IF(ALPHA .EQ. 3.14159265359) THEN
                T1P = .TRUE.
                T2P = .TRUE.
                T3P = .FALSE.
                T4P = .FALSE.
        END IF

END

! Logical variable for calculating average values over one cycle.
DISCRETE VAVGON
        xx = 1.0
END

DISCRETE VAVGOFF
        xx = 0.0
END

END ! "of dynamic"
END ! "of program"
```

```
! Command file for single phase dual converter

s strplt = .t.                  ! "one variable per x-axis"
s calplt = .f.
s devplt = 1                    ! "6 for X-windows"
                                ! "5 for postscript"

s ppoplt = .f.                  ! "true rotates plot 90 deg"

s xinspl = 6                    ! "x-axis plot units"

s weditg = .f.                  ! "false suppresses data write"
                                ! "each time SCHEDULE occurs"

s nrwitg = .f.                  ! "true enables accumulation of data"

s dpnplt = .f.

prepar t, Vo1, Vo2, Vin, Vr, Vo, Io, i1, i2

proced study1                   ! "Alpha 45"

      s nrwitg = .t.

      s T1I = .FALSE.
      s T2I = .FALSE.
      s T3I = .TRUE.
      s T4I = .TRUE.
      s T1PI = .FALSE.
      s T2PI = .FALSE.
      s T3PI = .TRUE.
      s T4PI = .TRUE.

      s tstop = 0.025
      s ALPHA = 0.78539816340
      start

      d Voavg, Vo1avg, Vo2avg

      s title = 'SINGLE PHASE DUAL CONVERTER, Alpha = 45'
      plot /color = 0 /xtag ='(sec)' /xlo=0.0 /xhi=0.025,&
      Vr /tag='(volts)'/lo=-250/hi=250,Vo2 /tag='(volts)',&
      Vo1 /tag='(volts)',Vin /tag='(volts)'

      s devplt = 5
      s plt = 1
      s title = 'SINGLE PHASE DUAL CONVERTER, Alpha = 45'
      plot /color = 0 /xtag ='(sec)' /xlo=0.0 /xhi=0.025,&
      Vr /tag='(volts)'/lo=-250/hi=250,Vo2 /tag='(volts)',&
      Vo1 /tag='(volts)',Vin /tag='(volts)'

end
```

APPENDIX B. ACSL PROGRAM CODE FOR CYCLOCONVERTER SIMULATION

```
! Three-phase, six-pulse, circulating current cycloconverter simulation program.

PROGRAM

INITIAL

! Maximum integration step size.

        MAXTERVAL maxt = 1.0e-5

! Data communication interval.

        CINTERVAL cint = 1.0e-4

! Integration algorithm, R.K. 4th.

        ALGORITHM ialg = 5
        NSTEPS    nstp = 1

! Stop point for integration.

    CONSTANT tstop = 0.05

! General simulation parameters and variables.

        PARAMETER (pi = 3.14159)
        rad180 = ACOS(-1.0)
        rad60 = rad180/3.0
        rad120 = 2.0 * rad60
        rad240 = 4.0 * rad60
        rad300 = 5.0 * rad60
        rad360 = 6.0 * rad60
        xx = 0.0

! Logical variables to model each switch in the cycloconverter.

        LOGICAL T1a,T2a,T3a,T4a,T5a,T6a,T1Na,T2Na,T3Na,T4Na,T5Na,T6Na,&
                T1b,T2b,T3b,T4b,T5b,T6b,T1Nb,T2Nb,T3Nb,T4Nb,T5Nb,T6Nb,&
                T1c,T2c,T3c,T4c,T5c,T6c,T1Nc,T2Nc,T3Nc,T4Nc,T5Nc,T6Nc

! Logical variables for initial state of each switch in the cycloconverter.

        Logical T1Ia,T2Ia,T3Ia,T4Ia,T5Ia,T6Ia,T1NIa,T2NIa,T3NIa,T4NIa,T5NIa,T6NIa,&
                T1Ib,T2Ib,T3Ib,T4Ib,T5Ib,T6Ib,T1NIb,T2NIb,T3NIb,T4NIb,T5NIb,T6NIb,&
                T1Ic,T2Ic,T3Ic,T4Ic,T5Ic,T6Ic,T1NIc,T2NIc,T3NIc,T4NIc,T5NIc,T6NIc
```

```
! Logical variables to implement thyristor pulse timing.

        LOGICAL P1ap,P2ap,P3ap,P4ap,P5ap,P6ap,P1an,P2an,P3an,P4an,P5an,P6an,&
                P1bp,P2bp,P3bp,P4bp,P5bp,P6bp,P1bn,P2bn,P3bn,P4bn,P5bn,P6bn,&
                P1cp,P2cp,P3cp,P4cp,P5cp,P6cp,P1cn,P2cn,P3cn,P4cn,P5cn,P6cn

! Set initial state of each swith in the cycloconverter.

        CONSTANT T1Ia = .FALSE.
        CONSTANT T2Ia = .FALSE.
        CONSTANT T3Ia = .FALSE.
        CONSTANT T4Ia = .FALSE.
        CONSTANT T5Ia = .TRUE.
        CONSTANT T6Ia = .TRUE.

        CONSTANT T1NIa = .FALSE.
        CONSTANT T2NIa = .TRUE.
        CONSTANT T3NIa = .TRUE.
        CONSTANT T4NIa = .FALSE.
        CONSTANT T5NIa = .FALSE.
        CONSTANT T6NIa = .FALSE.

        T1a = T1Ia
        T2a = T2Ia
        T3a = T3Ia
        T4a = T4Ia
        T5a = T5Ia
        T6a = T6Ia

        T1Na = T1NIa
        T2Na = T2NIa
        T3Na = T3NIa
        T4Na = T4NIa
        T5Na = T5NIa
        T6Na = T6NIa

        CONSTANT T1Ib = .FALSE.
        CONSTANT T2Ib = .FALSE.
        CONSTANT T3Ib = .FALSE.
        CONSTANT T4Ib = .TRUE.
        CONSTANT T5Ib = .TRUE.
        CONSTANT T6Ib = .FALSE.

        CONSTANT T1NIb = .FALSE.
        CONSTANT T2NIb = .FALSE.
        CONSTANT T3NIb = .TRUE.
        CONSTANT T4NIb = .TRUE.
        CONSTANT T5NIb = .FALSE.
        CONSTANT T6NIb = .FALSE.
```

```
T1b = T1Ib
T2b = T2Ib
T3b = T3Ib
T4b = T4Ib
T5b = T5Ib
T6b = T6Ib

T1Nb = T1NIb
T2Nb = T2NIb
T3Nb = T3NIb
T4Nb = T4NIb
T5Nb = T5NIb
T6Nb = T6NIb

CONSTANT T1Ic = .FALSE.
CONSTANT T2Ic = .FALSE.
CONSTANT T3Ic = .TRUE.
CONSTANT T4Ic = .TRUE.
CONSTANT T5Ic = .FALSE.
CONSTANT T6Ic = .FALSE.

CONSTANT T1NIc = .FALSE.
CONSTANT T2NIc = .FALSE.
CONSTANT T3NIc = .FALSE.
CONSTANT T4NIc = .TRUE.
CONSTANT T5NIc = .TRUE.
CONSTANT T6NIc = .FALSE.

T1c = T1Ic
T2c = T2Ic
T3c = T3Ic
T4c = T4Ic
T5c = T5Ic
T6c = T6Ic

T1Nc = T1NIc
T2Nc = T2NIc
T3Nc = T3NIc
T4Nc = T4NIc
T5Nc = T5NIc
T6Nc = T6NIc

! Frequency and RMS amplitude of a-c input voltages.

CONSTANT ws = 377.0
CONSTANT V = 2401.77711983

! Frequency and depth of modulation of sinusoidal reference voltage.
```

```
        CONSTANT wo = 125.666666667
        CONSTANT dm = 3396.59


! Circulating current reactor inductance.

        CONSTANT Lr = 40.0e-3

! Load resistance and inductance.

        CONSTANT RL = 10.0
        CONSTANT LL = 500.0e-3
        CONSTANT CL = 2000.0e-6

END ! "of initial"

DYNAMIC

! Terminates run when time is greater than or equal to tstop, minus half a
! communication interval.

        TERMT (t .GE. (tstop-0.5*cint), 'Termination on tstop')

        DERIVATIVE

! Develop a-c input voltages.

                THETAS = INTEG(ws,0.0)
                vag = sqrt(2.0) * V * sin(THETAS)
                vbg = sqrt(2.0) * V * sin(THETAS - rad120)
                vcg = sqrt(2.0) * V * sin(THETAS + rad120)

! Determine ac input line-to-line voltages.

                vab = vag - vbg
                vac = vag - vcg
                vba = vbg - vag
                vbc = vbg - vcg
                vca = vcg - vag
                vcb = vcg - vbg

! Develop sinusoidal reference voltages.

                THETAr = INTEG(wo,0.0)
                vra = dm * sin (THETAr)
                vrb = dm * sin (THETAr - rad120)
                vrc = dm * sin (THETAr + rad120)

! Develop cosine timing waveforms.

                vt1 = -vbg
```

```
vt2 =  vag
vt3 = -vcg
vt4 =  vbg
vt5 = -vag
vt6 =  vcg

! Determine when cosine timing waveforms equal the sinusoidal reference voltage
! and initiate converter switch logic change.

SCHEDULE Dap .XN. vt1 - vra
SCHEDULE Dap .XN. vt2 - vra
SCHEDULE Dap .XN. vt3 - vra
SCHEDULE Dap .XN. vt4 - vra
SCHEDULE Dap .XN. vt5 - vra
SCHEDULE Dap .XN. vt6 - vra

SCHEDULE Dan .XN. vra - vt1
SCHEDULE Dan .XN. vra - vt2
SCHEDULE Dan .XN. vra - vt3
SCHEDULE Dan .XN. vra - vt4
SCHEDULE Dan .XN. vra - vt5
SCHEDULE Dan .XN. vra - vt6

SCHEDULE Dbp .XN. vt1 - vrb
SCHEDULE Dbp .XN. vt2 - vrb
SCHEDULE Dbp .XN. vt3 - vrb
SCHEDULE Dbp .XN. vt4 - vrb
SCHEDULE Dbp .XN. vt5 - vrb
SCHEDULE Dbp .XN. vt6 - vrb

SCHEDULE Dbn .XN. vrb - vt1
SCHEDULE Dbn .XN. vrb - vt2
SCHEDULE Dbn .XN. vrb - vt3
SCHEDULE Dbn .XN. vrb - vt4
SCHEDULE Dbn .XN. vrb - vt5
SCHEDULE Dbn .XN. vrb - vt6

SCHEDULE Dcp .XN. vt1 - vrc
SCHEDULE Dcp .XN. vt2 - vrc
SCHEDULE Dcp .XN. vt3 - vrc
SCHEDULE Dcp .XN. vt4 - vrc
SCHEDULE Dcp .XN. vt5 - vrc
SCHEDULE Dcp .XN. vt6 - vrc

SCHEDULE Dcn .XN. vrc - vt1
SCHEDULE Dcn .XN. vrc - vt2
SCHEDULE Dcn .XN. vrc - vt3
SCHEDULE Dcn .XN. vrc - vt4
SCHEDULE Dcn .XN. vrc - vt5
SCHEDULE Dcn .XN. vrc - vt6
```

```
! Load and circulating current reactor circuit analysis.

        DENOM = ((Lr/2.0)+LL)*((Lr/2.0) + LL) - LL**2.0

! A-phase.

        pipa = (1.0/DENOM)*((Lr/2.0+LL)*(-RL*(ipa-ina)+vopa)+(LL)*(RL*(ipa-ina)-vona))
        pina = (1.0/DENOM)*((Lr/2.0+LL)*(RL*(ipa-ina)-vona)+(LL)*(-RL*(ipa-ina)+vopa))
        ipa = BOUND(0.0, 1000.0, LIMINT(pipa, 0.0, 0.0, 1000.0))
        ina = BOUND(0.0, 1000.0, LIMINT(pina, 0.0, 0.0, 1000.0))
        vomeana = (vopa+vona)/2.0
        dva = vopa - vona

! B-phase.

        pipb = (1.0/DENOM)*((Lr/2.0+LL)*(-RL*(ipb-inb)+vopb)+(LL)*(RL*(ipb-inb)-vonb))
        pinb = (1.0/DENOM)*((Lr/2.0+LL)*(RL*(ipb-inb)-vonb)+(LL)*(-RL*(ipb-inb)+vopb))
        ipb = BOUND(0.0, 1000.0, LIMINT(pipb, 0.0, 0.0, 1000.0))
        inb = BOUND(0.0, 1000.0, LIMINT(pinb, 0.0, 0.0, 1000.0))
        vomeanb = (vopb+vonb)/2.0
        dvb = vopb - vonb

! C-phase.

        pipc = (1.0/DENOM)*((Lr/2.0+LL)*(-RL*(ipc-inc)+vopc)+(LL)*(RL*(ipc-inc)-vonc))
        pinc = (1.0/DENOM)*((Lr/2.0+LL)*(RL*(ipc-inc)-vonc)+(LL)*(-RL*(ipc-inc)+vopc))
        ipc = BOUND(0.0, 1000.0, LIMINT(pipc, 0.0, 0.0, 1000.0))
        inc = BOUND(0.0, 1000.0, LIMINT(pinc, 0.0, 0.0, 1000.0))
        vomeanc = (vopc+vonc)/2.0
        dvc = vopc - vonc

! Calculate average values of output voltages and output current.

        To = 1/(wo/( 2.0 * pi))
        Vcaavg =  (1/To) * INTEG(xx * vca, 0.0)
        Vopaavg = (1/To) * INTEG(xx * vopa, 0.0)
        Vonaavg = (1/To) * INTEG(xx * vona, 0.0)
        Ipaavg = (1/To) * INTEG(xx * ipa, 0.0)
        Inaavg = (1/To) * INTEG(xx * ina, 0.0)
        Ioaavg = (1/To) * INTEG(xx * ioa, 0.0)

        SCHEDULE VAVGON .XP. t - 0.03
        SCHEDULE VAVGOFF .XP. t - (0.03 + To)

! Determine the positive converter output voltage based on the switch positions.

        PROCEDURAL (vopa,vopb,vopc = T1a,T2a,T3a,T4a,T5a,T6a,vag,vbg,vcg,&
                    T1b,T2b,T3b,T4b,T5b,T6b,T1c,T2c,T3c,T4c,T5c,T6c)
```

```
! A-phase, positive converter output voltage.

        IF (T1a .AND. T2a) THEN
                vopa = vag - vcg
        END IF

        IF (T2a .AND. T3a) THEN
                vopa= vbg - vcg
        END IF

        IF (T3a .AND. T4a) THEN
                vopa = vbg - vag
        END IF

        IF (T4a .AND. T5a) THEN
                vopa = vcg - vag
        END IF

        IF (T5a .AND. T6a) THEN
                vopa = vcg - vbg
        END IF

        IF (T6a .AND. T1a) THEN
                vopa = vag - vbg
        END IF

! B-phase, positive converter output voltage.

        IF (T1b .AND. T2b) THEN
                vopb = vag - vcg
        END IF

        IF (T2b .AND. T3b) THEN
                vopb= vbg - vcg
        END IF

        IF (T3b .AND. T4b) THEN
                vopb = vbg - vag
        END IF

        IF (T4b .AND. T5b) THEN
                vopb = vcg - vag
        END IF

        IF (T5b .AND. T6b) THEN
                vopb = vcg - vbg
        END IF

        IF (T6b .AND. T1b) THEN
                vopb = vag - vbg
        END IF
```

```
! C-phase, positive converter output voltage.

                    IF (T1c .AND. T2c) THEN
                        vopc = vag - vcg
                    END IF

                    IF (T2c .AND. T3c) THEN
                        vopc= vbg - vcg
                    END IF


                    IF (T3c .AND. T4c) THEN
                        vopc = vbg - vag
                    END IF

                    IF (T4c .AND. T5c) THEN
                        vopc = vcg - vag
                    END IF

                    IF (T5c .AND. T6c) THEN
                        vopc = vcg - vbg
                    END IF

                    IF (T6c .AND. T1c) THEN
                        vopc = vag - vbg
                    END IF

                END ! "of procedural"

! Determine the negative converter output voltage based on the switch positions.

                PROCEDURAL (vona,vonb,vonc = T1Na,T2Na,T3Na,T4Na,T5Na,T6Na,vag,vbg,vcg,&
                      T1Nb,T2Nb,T3Nb,T4Nb,T5Nb,T6Nb,T1Nc,T2Nc,T3Nc,T4Nc,T5Nc,T6Nc)

! A-phase, negative converter output voltage.

                    IF (T1Na .AND. T2Na) THEN
                        vona = vag - vcg
                    END IF

                    IF (T2Na .AND. T3Na) THEN
                        vona = vbg - vcg
                    END IF

                    IF (T3Na .AND. T4Na) THEN
                        vona = vbg - vag
                    END IF

                    IF (T4Na .AND. T5Na) THEN
                        vona = vcg - vag
                    END IF
```

```
        IF (T5Na .AND. T6Na) THEN
                vona = vcg - vbg
        END IF

        IF (T6Na .AND. T1Na) THEN
                vona = vag - vbg
        END IF

! B-phase, negative converter output voltage.

        IF (T1Nb .AND. T2Nb) THEN
                vonb = vag - vcg
        END IF

        IF (T2Nb .AND. T3Nb) THEN
                vonb = vbg - vcg
        END IF

        IF (T3Nb .AND. T4Nb) THEN
                vonb = vbg - vag
        END IF

        IF (T4Nb .AND. T5Nb) THEN
                vonb = vcg - vag
        END IF

        IF (T5Nb .AND. T6Nb) THEN
                vonb = vcg - vbg
        END IF

        IF (T6Nb .AND. T1Nb) THEN
                vonb = vag - vbg
        END IF

! C-phase, negative converter output voltage.

        IF (T1Nc .AND. T2Nc) THEN
                vonc = vag - vcg
        END IF

        IF (T2Nc .AND. T3Nc) THEN
                vonc = vbg - vcg
        END IF

        IF (T3Nc .AND. T4Nc) THEN
                vonc = vbg - vag
        END IF

        IF (T4Nc .AND. T5Nc) THEN
                vonc = vcg - vag
        END IF
```

```
                IF (T5Nc .AND. T6Nc) THEN
                        vonc = vcg - vbg
                END IF

                IF (T6Nc .AND. T1Nc) THEN
                        vonc = vag - vbg
                END IF

        END ! "of procedural"

    END ! "of derivative"

! Positive converter switch logic.
! A-phase.

    DISCRETE Dap

        P1ap = .FALSE.
        P2ap = .FALSE.
        P3ap = .FALSE.
        P4ap = .FALSE.
        P5ap = .FALSE.
        P6ap = .FALSE.

        IF (T1a.and.T2a) THEN
                P1ap = .FALSE.
                P2ap = .TRUE.
                P3ap = .TRUE.

        ELSE IF (T2a.and.T3a) THEN
                P2ap = .FALSE.
                P3ap = .TRUE.
                P4ap = .TRUE.

        ELSE IF (T3a.and.T4a) THEN
                P3ap = .FALSE.
                P4ap = .TRUE.
                P5ap = .TRUE.

        ELSE IF (T4a.and.T5a) THEN
                P4ap = .FALSE.
                P5ap = .TRUE.
                P6ap = .TRUE.

        ELSE IF (T5a.and.T6a) THEN
                P5ap = .FALSE.
                P6ap = .TRUE.
                P1ap = .TRUE.
```

```
        ELSE IF (T6a.and.T1a) THEN
                P6ap = .FALSE.
                P1ap = .TRUE.
                P2ap = .TRUE.

        END IF

        T1a = P1ap
        T2a = P2ap
        T3a = P3ap
        T4a = P4ap
        T5a = P5ap
        T6a = P6ap
    END

! B-phase.

    DISCRETE Dbp

        P1bp = .FALSE.
        P2bp = .FALSE.
        P3bp = .FALSE.
        P4bp = .FALSE.
        P5bp = .FALSE.
        P6bp = .FALSE.

        IF (T1b.and.T2b) THEN
                P1bp = .FALSE.
                P2bp = .TRUE.
                P3bp = .TRUE.

        ELSE IF (T2b.and.T3b) THEN
                P2bp = .FALSE.
                P3bp = .TRUE.
                P4bp = .TRUE.

        ELSE IF (T3b.and.T4b) THEN
                P3bp = .FALSE.
                P4bp = .TRUE.
                P5bp = .TRUE.

        ELSE IF (T4b.and.T5b) THEN
                P4bp = .FALSE.
                P5bp = .TRUE.
                P6bp = .TRUE.

        ELSE IF (T5b.and.T6b) THEN
                P5bp = .FALSE.
                P6bp = .TRUE.
                P1bp = .TRUE.
```

```
            ELSE IF (T6b.and.T1b) THEN
                    P6bp = .FALSE.
                    P1bp = .TRUE.
                    P2bp = .TRUE.

            END IF

            T1b = P1bp
            T2b = P2bp
            T3b = P3bp
            T4b = P4bp
            T5b = P5bp
            T6b = P6bp
        END

! C-phase.

        DISCRETE Dcp

            P1cp = .FALSE.
            P2cp = .FALSE.
            P3cp = .FALSE.
            P4cp = .FALSE.
            P5cp = .FALSE.
            P6cp = .FALSE.

            IF (T1c.and.T2c) THEN
                    P1cp = .FALSE.
                    P2cp = .TRUE.
                    P3cp = .TRUE.

            ELSE IF (T2c.and.T3c) THEN
                    P2cp = .FALSE.
                    P3cp = .TRUE.
                    P4cp = .TRUE.

            ELSE IF (T3c.and.T4c) THEN
                    P3cp = .FALSE.
                    P4cp = .TRUE.
                    P5cp = .TRUE.

            ELSE IF (T4c.and.T5c) THEN
                    P4cp = .FALSE.
                    P5cp = .TRUE.
                    P6cp = .TRUE.

            ELSE IF (T5c.and.T6c) THEN
                    P5cp = .FALSE.
                    P6cp = .TRUE.
                    P1cp = .TRUE.
```

```
        ELSE IF (T6c.and.T1c) THEN
                P6cp = .FALSE.
                P1cp = .TRUE.
                P2cp = .TRUE.

        END IF

        T1c = P1cp
        T2c = P2cp
        T3c = P3cp
        T4c = P4cp
        T5c = P5cp
        T6c = P6cp
    END

! Switch logic for Negative converters.
! A-phase.

    DISCRETE Dan

        P1an = .FALSE.
        P2an = .FALSE.
        P3an = .FALSE.
        P4an = .FALSE.
        P5an = .FALSE.
        P6an = .FALSE.

        IF (T1Na.and.T2Na) THEN
                P1an = .FALSE.
                P2an = .TRUE.
                P3an = .TRUE.

        ELSE IF (T2Na.and.T3Na) THEN
                P2an = .FALSE.
                P3an = .TRUE.
                P4an = .TRUE.

        ELSE IF (T3Na.and.T4Na) THEN
                P3an = .FALSE.
                P4an = .TRUE.
                P5an = .TRUE.

        ELSE IF (T4Na.and.T5Na) THEN
                P4an = .FALSE.
                P5an = .TRUE.
                P6an = .TRUE.

        ELSE IF (T5Na.and.T6Na) THEN
                P5an = .FALSE.
                P6an = .TRUE.
                P1an = .TRUE.
```

```
        ELSE IF (T6Na.and.T1Na) THEN
                P6an = .FALSE.
                P1an = .TRUE.
                P2an = .TRUE.

        END IF

        T1Na = P1an
        T2Na = P2an
        T3Na = P3an
        T4Na = P4an
        T5Na = P5an
        T6Na = P6an

    END

! B-phase.

    DISCRETE Dbn

        P1bn = .FALSE.
        P2bn = .FALSE.
        P3bn = .FALSE.
        P4bn = .FALSE.
        P5bn = .FALSE.
        P6bn = .FALSE.

        IF (T1Nb.and.T2Nb) THEN
                P1bn = .FALSE.
                P2bn = .TRUE.
                P3bn = .TRUE.

        ELSE IF (T2Nb.and.T3Nb) THEN
                P2bn = .FALSE.
                P3bn = .TRUE.
                P4bn = .TRUE.

        ELSE IF (T3Nb.and.T4Nb) THEN
                P3bn = .FALSE.
                P4bn = .TRUE.
                P5bn = .TRUE.

        ELSE IF (T4Nb.and.T5Nb) THEN
                P4bn = .FALSE.
                P5bn = .TRUE.
                P6bn = .TRUE.

        ELSE IF (T5Nb.and.T6Nb) THEN
                P5bn = .FALSE.
                P6bn = .TRUE.
                P1bn = .TRUE.
```

```
        ELSE IF (T6Nb.and.T1Nb) THEN
                P6bn = .FALSE.
                P1bn = .TRUE.
                P2bn = .TRUE.

        END IF

        T1Nb = P1bn
        T2Nb = P2bn
        T3Nb = P3bn
        T4Nb = P4bn
        T5Nb = P5bn
        T6Nb = P6bn

    END

! C-phase.

    DISCRETE Dcn

        P1cn = .FALSE.
        P2cn = .FALSE.
        P3cn = .FALSE.
        P4cn = .FALSE.
        P5cn = .FALSE.
        P6cn = .FALSE.

        IF (T1Nc.and.T2Nc) THEN
                P1cn = .FALSE.
                P2cn = .TRUE.
                P3cn = .TRUE.

        ELSE IF (T2Nc.and.T3Nc) THEN
                P2cn = .FALSE.
                P3cn = .TRUE.
                P4cn = .TRUE.

        ELSE IF (T3Nc.and.T4Nc) THEN
                P3cn = .FALSE.
                P4cn = .TRUE.
                P5cn = .TRUE.

        ELSE IF (T4Nc.and.T5Nc) THEN
                P4cn = .FALSE.
                P5cn = .TRUE.
                P6cn = .TRUE.

        ELSE IF (T5Nc.and.T6Nc) THEN
                P5cn = .FALSE.
                P6cn = .TRUE.
                P1cn = .TRUE.
```

```
            ELSE IF (T6Nc.and.T1Nc) THEN
                P6cn = .FALSE.
                P1cn = .TRUE.
                P2cn = .TRUE.

            END IF

            T1Nc = P1cn
            T2Nc = P2cn
            T3Nc = P3cn
            T4Nc = P4cn
            T5Nc = P5cn
            T6Nc = P6cn

        END

! Output voltage average value operator.

        DISCRETE VAVGON
            xx = 1.0
        END

        DISCRETE VAVGOFF
            xx = 0.0
        END

END ! "of dynamic"

END ! "of program"
```

```
! Command file for 3-phase, 6-pulse, circulating current cycloconverter

s strplt = .t.                          ! "one variable per x-axis"
s calplt = .f.

s devplt = 1                            ! "6 for X-windows"
                                        ! "5 for postscript"

s ppoplt = .f.                          ! "true rotates plot 90 deg"

s xinspl = 6                            ! "x-axis plot units"

s weditg = .f.                          ! "false suppresses data write"
                                        ! "each time SCHEDULE occurs"

s nrwitg = .f.                          ! "true enables accumulation of data"

s dpnplt = .f.

PREPARE t,vopa,vona,vomeana

proced study1

        s T1Ia = .FALSE.
        s T2Ia = .FALSE.
        s T3Ia = .FALSE.
        s T4Ia = .TRUE.
        s T5Ia = .TRUE.
        s T6Ia = .FALSE.

        s T1NIa = .TRUE.
        s T2NIa = .TRUE.
        s T3NIa = .FALSE.
        s T4NIa = .FALSE.
        s T5NIa = .FALSE.
        s T6NIa = .FALSE.

        s T1Ib = .FALSE.
        s T2Ib = .FALSE.
        s T3Ib = .TRUE.
        s T4Ib = .TRUE.
        s T5Ib = .FALSE.
        s T6Ib = .FALSE.

        s T1NIb = .TRUE.
        s T2NIb = .TRUE.
        s T3NIb = .FALSE.
        s T4NIb = .FALSE.
        s T5NIb = .FALSE.
        s T6NIb = .FALSE.
```

```
        s T1Ic = .TRUE.
        s T2Ic = .TRUE.
        s T3Ic = .FALSE.
        s T4Ic = .FALSE.
        s T5Ic = .FALSE.
        s T6Ic = .FALSE.

        s T1NIc = .FALSE.
        s T2NIc = .FALSE.
        s T3NIc = .TRUE.
        s T4NIc = .TRUE.
        s T5NIc = .FALSE.
        s T6NIc = .FALSE.

        start

        s title = 'Converter Output Voltages with wo=188.5 '
        plot /xtag ='(sec)' ,&
                vomeana/type=030/lo=-6000.0 /hi=6000.0/tag='(volts)',&
                vona/type=010/lo=-6000.0 /hi=6000.0/tag='(volts)',&
        vopa/type=010/lo=-6000.0 /hi=6000.0/tag='(volts)'


        s devplt = 5

        s plt = 12
        s title = 'Converter Output Voltages with wo=188.5 '
        plot /xtag ='(sec)' ,&
                vomeana/type=030/lo=-6000.0 /hi=6000.0/tag='(volts)',&
                vona/type=010/lo=-6000.0 /hi=6000.0/tag='(volts)',&
        vopa/type=010/lo=-6000.0 /hi=6000.0/tag='(volts)'

end ! of study1
```

APPENDIX C. ACSL PROGRAM CODE SYNCRONOUS MOTOR AND MECHANICAL LOAD MODELS

```
"****************************************************************
"****************************************************************
"        Author: John G. Ciezki                                 "
"        Last Revised: 26 Apr 94                                "
"        Developed For: Personal Use                            "
"                                                               "
"        MACRO Title: sm3rot                                    "
"                                                               "
"        DESCRIPTION:                                           "
"                                                               "
"        ASSUMPTIONS:                                           "
"                                                               "
"                                                               "
"        VARIABLE DEFINITION                                    "
"                                                               "
"              CONCATENATION                                    "
"        z        -    three phase synchronous machine identifier "
"                                                               "
"                      INPUTS                                   "
"        vqsr     -    q-axis stator voltage, rotor reference frame (V) "
"        vdsr     -    d-axis stator voltage, rotor reference frame (V) "
"        v0s      -    zero sequence stator voltage (V)         "
"        vfdr     -    referred field voltage, rot ref frame (V) "
"        wrm      -    rotor mechanical speed (rad/sec)         "
"        wb       -    base electrical angular velocity (rad/sec) "
"                                                               "
"                      OUTPUTS                                  "
"        iqsr     -    q-axis stator current, rot ref frame (A) "
"        idsr     -    d-axis stator current, rot ref frame (A) "
"        ikq1r    -    #1 q-axis referred damper current (A)    "
"        ikq2r    -    #2 q-axis referred damper current (A)    "
"        ikdr     -    d-axis referred damper current (A)       "
"        ifdr     -    d-axis referred field current (A)        "
"        i0s      -    zero sequence stator current (A)         "
"        Te       -    electromagnetic torque, positive for     "
"                      motor action (N-m)                       "
"                                                               "
"                      PARAMETERS                               "
"        rs&z     -    stator phase winding resistance (ohms)   "
"        rkq1&z   -    #1 q-axis referred damper resistance (ohms) "
"        rkq2&z   -    #2 q-axis referred damper resistance (ohms) "
"        rkd&z    -    d-axis referred damper resistance (ohms) "
"        rfd&z    -    d-axis referred field resistance (ohms)  "
"        Xmq&z    -    q-axis magnetizing reactance (ohms)      "
"        Xq&z     -    q-axis reactance (ohms)                  "
"        Xkq1&z   -    #1 q-axis referred damper self inductance (ohms) "
"        Xkq2&z   -    #2 q-axis referred damper self inductance (ohms)"
"        Xmd&z    -    d-axis magnetizing reactance (ohms)      "
"        Xd&z     -    d-axis reactance (ohms)                  "
```

```
"    Xkd&z  -      d-axis referred damper self inductance (ohms)         "
"    Xfd&z  -      d-axis referred field  self inductance (ohms)         "
"    poles&z -     number of machine poles                               "
"                                                                        "
"             INTERNAL (STATE OR STATE RELATED)                          "
"    siqsr&z -     q-axis stator flux linkage/sec, rotor reference       "
"                  frame (V)                                             "
"    sidsr&z -     d-axis stator flux linkage/sec, rotor reference       "
"                  frame (V)                                             "
"    si0sr&z -     zero sequence stator flux linkage/sec  (V)            "
"    sikq1r&z -    #1 q-axis referred damper flux linkage/sec,           "
"                  rotor reference frame (V)                             "
"    sikq2r&z -    #2 q-axis referred damper flux linkage/sec,           "
"                  rotor reference frame (V)                             "
"    sikdr&z -     d-axis referred damper flux linkage/sec, rotor        "
"                  reference frame (V)                                   "
"    sifdr&z -     d-axis referred field  flux linkage/sec, rotor        "
"                  reference frame (V)                                   "
"    psiqsr&z -    derivative of siqsr&z (V/sec)                         "
"    psidsr&z -    derivative of sidsr&z (V/sec)                         "
"    psi0sr&z -    derivative of si0sr&z (V/sec)                         "
"    psikq1r&z -   derivative of sikq1r&z (V/sec)                        "
"    psikq2r&z -   derivative of sikq2r&z (V/sec)                        "
"    psikdr&z -    derivative of sikdr&z (V/sec)                         "
"    psifdr&z -    derivative of sifdr&z (V/sec)                         "
"                                                                        "
"              INTERNAL (NOT STATE RELATED)                              "
"    Xd3&z  -      constant helpful in determining d-axis currents       "
"                          (ohms**3)                                     "
"    ad11&z -      | idsr |   | ad11&z ad12&z ad13&z |  |sidsr&z|      "
"    ad12&z -      | ifdr | = | ad12&z ad22&z ad23&z |  |sifdr&z|      "
"    ad13&z -      | ikdr |   | ad13&z ad23&z ad33&z |  |sikdr&z|      "
"    ad22&z -                                                            "
"    ad23&z -                                                            "
"    ad33&z -                                                            "
"    Xq3&z  -      constant helpful in determining q-axis currents       "
"                          (ohms**3)                                     "
"    bq11&z -      | iqsr |   | bq11&z bq12&z bq13&z |  |siqsr&z |     "
"    bq12&z -      | ikq1r| = | bq12&z bq22&z bq23&z |  |sikq1r&z|     "
"    bq13&z -      | ikq2r|   | bq13&z bq23&z bq33&z |  |sikq2r&z|     "
"    bq22&z -                                                            "
"    bq23&z -                                                            "
"    bq33&z -                                                            "
"    siqsric&z -   q-axis flux linkage/sec initial condition (V)         "
"    sidsric&z -   d-axis flux linkage/sec initial condition (V)         "
"    si0sric&z -   zero seq. flux linkage/sec initial condition (V)      "
"    sikq1ric&z -  #1 q-axis referred damper flux linkage/s i.c.(V)      "
"    sikq2ric&z -  #2 q-axis referred damper flux linkage/s i.c.(V)      "
"    sikdric&z -   d-axis referred damper flux linkage/sec i.c. (V)      "
"    sifdric&z -   d-axis referred field  flux linkage/sec i.c. (V)      "
"    wr&z    -     rotor electrical angular velocity (rad/sec)           "
"                                                                        "
```

```
"*******************************************************************"
"*******************************************************************"


MACRO sm31kq(z,vqsr,vdsr,v0s,vfdr,wrm,wb,iqsr,ikqr, &
        idsr,ifdr,ikdr,i0s,Te, &
        prs,prkq,prfd,prkd, &
        pXmq,pXq,pXkq,pXmd,pXd,pXkd,pXfd, &
        ppoles)
INITIAL

      CONSTANT prs
      CONSTANT prkq
      CONSTANT prfd
      CONSTANT prkd
      CONSTANT pXmq
      CONSTANT pXq
      CONSTANT pXkq
      CONSTANT pXmd
      CONSTANT pXd
      CONSTANT pXkd
      CONSTANT pXfd
      CONSTANT ppoles

      "Determine the stator leakage reactance"
      Xls&z = Xq&z - Xmq&z

      "A convenient constant for determining q-axis currents"
      Xq2&z = Xq&z*Xkq&z - Xmq&z*Xmq&z

      "determine the array elements for relating q-axis flux"
      "linkage per sec vars to q-axis currents"
      bq11&z = Xkq&z/Xq2&z
      bq12&z = -Xmq&z/Xq2&z
      bq21&z = -Xmq&z/Xq2&z
      bq22&z = Xq&z/Xq2&z

   "A convenient constant for determining d-axis currents"
   Xd3&z = Xmd&z*Xmd&z*(2.0*Xmd&z-Xd&z-Xkd&z-Xfd&z)+Xd&z*Xfd&z*Xkd&z

      "determine the array elements for relating d-axis flux linkage"
      "per second variables to the d-axis currents"
      ad11&z = (Xfd&z*Xkd&z - Xmd&z*Xmd&z)/Xd3&z
      ad12&z = (Xmd&z*Xmd&z - Xkd&z*Xmd&z)/Xd3&z
      ad13&z = (Xmd&z*Xmd&z - Xfd&z*Xmd&z)/Xd3&z
      ad22&z = (Xd&z*Xkd&z - Xmd&z*Xmd&z)/Xd3&z
      ad23&z = (Xmd&z*Xmd&z - Xd&z*Xmd&z)/Xd3&z
      ad33&z = (Xd&z*Xfd&z - Xmd&z*Xmd&z)/Xd3&z

      "Set the state variable initial conditions"
      "----set in main program"
```

```
        "CONSTANT siqsric&z  = 0.0"
        "CONSTANT sidsric&z  = 0.0"
        "CONSTANT si0sric&z  = 0.0"
        "CONSTANT sikqric&z  = 0.0"
        "CONSTANT sifdric&z  = 0.0"
        "CONSTANT sikdric&z  = 0.0"

END

        "Determine the rotor electrical speed from the mechanical speed"
        wr&z = 0.5*poles&z*wrm

        "Calculate the q-axis currents from q-axis flux linkages/sec"
        iqsr  = bq11&z*siqsr&z + bq12&z*sikqr&z
        ikqr =  bq21&z*siqsr&z + bq22&z*sikqr&z

        "Calculate the d-axis currents from d-axis flux linkages/sec"
        idsr = ad11&z*sidsr&z + ad12&z*sifdr&z + ad13&z*sikdr&z
        ifdr = ad12&z*sidsr&z + ad22&z*sifdr&z + ad23&z*sikdr&z
        ikdr = ad13&z*sidsr&z + ad23&z*sifdr&z + ad33&z*sikdr&z

        "Calculate the 0 sequence stator current"
        i0s = si0sr&z/Xls&z

        "Establish the state variable derivative equations"
        psiqsr&z  = -rs&z*wb*iqsr - wr&z*sidsr&z + wb*vqsr
        psidsr&z  = -rs&z*wb*idsr + wr&z*siqsr&z + wb*vdsr
        psi0sr&z  = -rs&z*wb*i0s  + wb*v0s
        psikqr&z = -rkq&z*wb*ikqr
        psifdr&z  = -rfd&z*wb*ifdr + wb*vfdr
        psikdr&z  = -rkd&z*wb*ikdr

        "Integrate the state variables"
        siqsr&z  = INTEG(psiqsr&z, siqsric&z)
        sidsr&z  = INTEG(psidsr&z, sidsric&z)
        si0sr&z  = INTEG(psi0sr&z, si0sric&z)
        sikqr&z =  INTEG(psikqr&z, sikqric&z)
        sifdr&z  = INTEG(psifdr&z, sifdric&z)
        sikdr&z  = INTEG(psikdr&z, sikdric&z)

        "Compute the developed electromagnetic torque"
        "Te = 0.75*poles&z*(sidsr&z*iqsr - siqsr&z*idsr)/wb"
        Te = sidsr&z*iqsr - siqsr&z*idsr    !"in per unit"

MACRO END
```

```
"***********************************************************************"
"***********************************************************************"
"       Author: John G. Ciezki                                    "
"       Last Revised: 26 Apr 94                                   "
"       Developed For: Personal Use                                       "
"                                                                         "
"       MACRO Title: dcmechld1                                   "
"                                                                         "
"       DESCRIPTION:                                              "
"         This MACRO models the mechanical dynamics of a rotational "
"         inertia and damping with an applied torque.             "
"                                                                         "
"       ASSUMPTIONS:                                                      "
"         Bending modes are ignored                                       "
"                                                                         "
"                                                                         "
"       VARIABLE DEFINITION                                               "
"                                                                         "
"              CONCATENATION                                      "
"       z       -       identifies the rotational load                    "
"                                                                         "
"                       INPUTS                                            "
"       Te      -       applied electromagnetic torque (N-m)    "
"                       in direction of increasing rotor angle            "
"       TL      -       applied load torque (N-m)                "
"                       pos in direction of decreasing rotor angle "
"       wric    -       initial rotor speed (rad/sec)                     "
"       thric   -       initial rotor position (rad)             "
"       B       -       net damping of machine and load (N-m-s)"
"       J       -       net inertia of machine and load (kg-m-m) "
"                                                                         "
"                       OUTPUTS                                           "
"       wr      -       rotor speed in (rad/sec)                 "
"       thr     -       rotor position in (rad)                           "
"                                                                         "
"                       PARAMETERS                                        "
"       none                                                              "
"                                                                         "
"              INTERNAL (STATE OR STATE RELATED)  "
"       pwr&z  -        derivative of the rotor speed                     "
"       pthr&z -        derivative of the rotor position         "
"                                                                         "
"                 INTERNAL (NOT STATE RELATED)           "
"       none                                                              "
"                                                                         "
"***********************************************************************"
"***********************************************************************"

! "!!!!!!!!!!!!!!!!  MACRO DEFINITION BEGINS HERE  !!!!!!!!!!!!!!!!"

MACRO dcmechld1(z,Te,TL,wric,thric,B,J,wr,thr)
```

```
    "determine the derivative of the rotor speed"
    pwr&z= -(B/J)*wr + (Te-TL)/J

    "determine the derivative of the rotor position"
    pthr&z= wr

    "integrate the state variables"
    wr= INTEG(pwr&z, wric)
    thr= INTEG(pthr&z, thric)

MACRO END
```

APPENDIX D. ACSL PROGRAM CODE FOR ELECTRIC DRIVE SIMULATION

```
"*******************************************************************"
"*******************************************************************"
"       Author: C. P. Mercer                                        "
"       Last Revised: 15 DEC 96                                     "
"       Developed For: Cycloconverter Drive / Ship Propulsion Thesis "
"                                                                   "
"       MACRO Title: propload                                       "
"                                                                   "
"       DESCRIPTION:                                                "
"         This MACRO models the mechanical dynamics of a typical    "
"         destroyer-type propeller and hull resistance.             "
"                                                                   "
"       ASSUMPTIONS:                                                "
"         Bending modes are ignored                                 "
"                                                                   "
"                                                                   "
"       VARIABLE DEFINITION                                         "
"                                                                   "
"               CONCATENATION                                       "
"       z       -       identifies the rotational load              "
"                                                                   "
"                       INPUTS                                      "
"       Te      -       applied electromagnetic torque (ft-lb)      "
"                       in direction of increasing rotor angle      "
"       Tbase   -       base motor torque (ft-lb)                   "
"       wric    -       initial rotor speed (rad/sec)               "
"       thric   -       initial rotor position (rad)                "
"       B       -       net damping of machine and load (ft-lb-s)   "
"       Jm      -       net inertia of machine (ft-lb-sec^2)        "
"       Vspuic  -       initial per unit ship speed                 "
"       wb      -       base angular frequency (rad/sec)            "
"                                                                   "
"                                                                   "
"                       OUTPUTS                                     "
"       wr      -       rotor speed in (rad/sec)                    "
"       thr     -       rotor position in (rad)                     "
"       Vs      -       ship speed in (knots)                       "
"                                                                   "
"                                                                   "
"                       PARAMETERS                                  "
"       Jp      -       shafting and propeller inertia (ft-lb-sec^2) "
"       wf      -       wake factor                                 "
"       FTbase  -       base ship thrust (lb)                       "
"       Vsbase  -       base ship speed    (ft/sec)                 "
"       Ms      -       ship mass (lb-sec^2/ft)                     "
"                                                                   "
"                                                                   "
"               INTERNAL (STATE OR STATE RELATED)                   "
"       pwr&z   -       derivative of the rotor speed               "
```

```
"       pthr&z  -          derivative of the rotor position                     "
"                                                                               "
"                       INTERNAL (NOT STATE RELATED)                            "
"       none                                                                    "
"                                                                               "
"*******************************************************************************"
"*******************************************************************************"


MACRO propload(z,Tem,Tbase,wric,thric,Vspuic,B,Jm,wb,wr,thr,Vs)


        Ms = 3.132e5              ! lb-sec^2/ft
        Vsbase = 45.57            ! ft/sec
        FTbase = 2.078e5          ! lb
        wf = 0.02                 ! Wake factor
        Jp = 33.33                ! Line shafting and propeller
                                  ! inertia ft-lb-sec^2

        "determine total drive train inertia"
        JT = Jm + Jp

        "determine denominator for derivative of ship speed equation"
        Hs = (Ms * Vsbase)/FTbase

        "determine per unit ship thrust"
        FTpu = 1.0055*(2.324*(wr/wb)*abs(wr/wb)+&
             0.9296*abs(wr/wb)*sqrt(1.602*Vp**2&
                 +(wr/wb)**2)-1.107*(1.602*Vp**2+(wr/wb)**2))

        "determine ship thrust"
        FT = FTpu * FTbase

        "determine per unit propeller torque"
        TLpu = 2.55*(0.632*(wr/wb)*abs(wr/wb)+&
                 0.253*abs(wr/wb)*sqrt(1.602*Vp**2&
                 +(wr/wb)**2)-0.295*(1.602*Vp**2+(wr/wb)**2))

        "determine propeller torque"
        TL = TLpu * Tbase

        "determine per unit propeller speed"
        Vp = (1-wf)*Vspu

        "determine per unit ship hull resistance"
        Rs = 1.256*Vspu*abs(Vspu)*(Vspu**2-1.981*Vspu+1.012)/&
            (Vspu-1.975*Vspu+0.9944)

        "determine the derivative of the rotor speed"
        pwr&z = -(B/JT)*wr + (Tem-TL)/JT
```

```
    "determine the derivative of the rotor position"
    pthr&z = wr

    "determine the derivative of the per unit ship speed"
    pVspu&z = (2.0*FTpu - Rs)/Hs

    "integrate the state variables"
    wr = INTEG(pwr&z, wric)
    thr = INTEG(pthr&z, thric)
    Vspu = INTEG(pVspu&z,Vspuic)

    "determine ship speed in knots"
    Vs = Vspu * Vsbase * 0.5925

MACRO END
```

```
! Integrated electric drive propulsion system program.

INCLUDE 'prop.mac'
INCLUDE '../sm31kqpu.mac'
INCLUDE '../dcmechld1.mac'

PROGRAM

INITIAL

! Maximum integration step size.

        MAXTERVAL maxt = 1.0e-5

! Data communication interval.

        CINTERVAL cint = 1.0e-4

! Integration algorithm, R.K. 4th.

        ALGORITHM ialg = 5
        NSTEPS    nstp = 1

! Stop point for integration.

    CONSTANT tstop = 0.5

! General simulation parameters and variables.

        PARAMETER (pi = 3.14159)
        rad180 = ACOS(-1.0)
        rad60 = rad180/3.0
        rad120 = 2.0 * rad60
        rad240 = 4.0 * rad60
        rad300 = 5.0 * rad60
        rad360 = 6.0 * rad60

! Logical variables to model each switch in the cycloconverter.

LOGICAL T1a,T2a,T3a,T4a,T5a,T6a,T1Na,T2Na,T3Na,T4Na,T5Na,T6Na, &
        T1b,T2b,T3b,T4b,T5b,T6b,T1Nb,T2Nb,T3Nb,T4Nb,T5Nb,T6Nb,&
        T1c,T2c,T3c,T4c,T5c,T6c,T1Nc,T2Nc,T3Nc,T4Nc,T5Nc,T6Nc

! Logical variables for initial state of each switch in the cycloconverter.


Logical T1Ia,T2Ia,T3Ia,T4Ia,T5Ia,T6Ia,T1NIa,T2NIa,T3NIa,T4NIa,T5NIa,T6NIa, &
        T1Ib,T2Ib,T3Ib,T4Ib,T5Ib,T6Ib,T1NIb,T2NIb,T3NIb,T4NIb,T5NIb,T6NIb, &
        T1Ic,T2Ic,T3Ic,T4Ic,T5Ic,T6Ic,T1NIc,T2NIc,T3NIc,T4NIc, T5NIc,T6NIc
```

```
! Logical variables to implement thyristor pulse timing.

LOGICAL P1ap,P2ap,P3ap,P4ap,P5ap,P6ap,P1an,P2an,P3an,P4an,P5an,P6an,&
        P1bp,P2bp,P3bp,P4bp,P5bp,P6bp,P1bn,P2bn,P3bn,P4bn,P5bn,P6bn,&
        P1cp,P2cp,P3cp,P4cp,P5cp,P6cp,P1cn,P2cn,P3cn,P4cn,P5cn,P6cn

! Set initial state of each swith in the cycloconverter.

    CONSTANT T1Ia = .TRUE.
    CONSTANT T2Ia = .FALSE.
    CONSTANT T3Ia = .FALSE.
    CONSTANT T4Ia = .FALSE.
    CONSTANT T5Ia = .FALSE.
    CONSTANT T6Ia = .TRUE.

    CONSTANT T1NIa = .TRUE.
    CONSTANT T2NIa = .TRUE.
    CONSTANT T3NIa = .FALSE.
    CONSTANT T4NIa = .FALSE.
    CONSTANT T5NIa = .FALSE.
    CONSTANT T6NIa = .FALSE.

    T1a = T1Ia
    T2a = T2Ia
    T3a = T3Ia
    T4a = T4Ia
    T5a = T5Ia
    T6a = T6Ia

    T1Na = T1NIa
    T2Na = T2NIa
    T3Na = T3NIa
    T4Na = T4NIa
    T5Na = T5NIa
    T6Na = T6NIa

    CONSTANT T1Ib = .TRUE.
    CONSTANT T2Ib = .FALSE.
    CONSTANT T3Ib = .FALSE.
    CONSTANT T4Ib = .FALSE.
    CONSTANT T5Ib = .FALSE.
    CONSTANT T6Ib = .TRUE.

    CONSTANT T1NIb = .TRUE.
    CONSTANT T2NIb = .TRUE.
    CONSTANT T3NIb = .FALSE.
    CONSTANT T4NIb = .FALSE.
    CONSTANT T5NIb = .FALSE.
    CONSTANT T6NIb = .FALSE.

    T1b = T1Ib
    T2b = T2Ib
```

```
T3b = T3Ib
T4b = T4Ib
T5b = T5Ib
T6b = T6Ib

T1Nb = T1NIb
T2Nb = T2NIb
T3Nb = T3NIb
T4Nb = T4NIb
T5Nb = T5NIb
T6Nb = T6NIb

CONSTANT T1Ic = .TRUE.
CONSTANT T2Ic = .FALSE.
CONSTANT T3Ic = .FALSE.
CONSTANT T4Ic = .FALSE.
CONSTANT T5Ic = .FALSE.
CONSTANT T6Ic = .TRUE.

CONSTANT T1NIc = .TRUE.
CONSTANT T2NIc = .TRUE.
CONSTANT T3NIc = .FALSE.
CONSTANT T4NIc = .FALSE.
CONSTANT T5NIc = .FALSE.
CONSTANT T6NIc = .FALSE.

T1c = T1Ic
T2c = T2Ic
T3c = T3Ic
T4c = T4Ic
T5c = T5Ic
T6c = T6Ic

T1Nc = T1NIc
T2Nc = T2NIc
T3Nc = T3NIc
T4Nc = T4NIc
T5Nc = T5NIc
T6Nc = T6NIc

! Frequency and RMS amplitude of a-c input voltages.

CONSTANT ws = 377.0
CONSTANT V = 0.71
Vpk = sqrt(2.0)*V

! Field excitation and synchronous motor initial conditions.

CONSTANT exfdic = 1.0
ifdr1ic = exfdic/Xmd1     !"Initial field current"
CONSTANT siqsric1 = 0.0
CONSTANT si0sric1 = 0.0
```

```
        CONSTANT sikqric1 = 0.0
        sidsric1 = Xmd1*ifdr1ic
        sifdric1 = Xfd1*ifdr1ic
        sikdric1 = Xmd1*ifdr1ic

        CONSTANT thric1 = 0.0   ! " rotor position i.c."
        vra=Kp2*iqsrstar*cos(thric1)
        vrb=Kp2*iqsrstar*cos(thric1-rad120)
        vrc=Kp2*iqsrstar*cos(thric1+rad120)
        CONSTANT wrmss = 9.0
        CONSTANT tacc = 3.0
        CONSTANT tss = 1000.0
        CONSTANT tdec = 1001.0
        slope1 = wrmss/tacc
        slope2 = 0.0
        slope3 = -wrmss/(tdec-tss)
        wrmslope = slope1


END ! "of initial"

DYNAMIC

! Terminates run when time is greater than or equal to tstop, minus half a
! communication interval.

        TERMT (t .GE. (tstop-0.5*cint), 'Termination on tstop')

        DERIVATIVE

! Develop a-c input voltages.

                THETAS = INTEG(ws,0.0)
                vag = sqrt(2.0) * V * cos(THETAS)
                vbg = sqrt(2.0) * V * cos(THETAS - rad120)
                vcg = sqrt(2.0) * V * cos(THETAS + rad120)

                vab = vag - vbg
                vac = vag - vcg
                vba = vbg - vag
                vbc = vbg - vcg
                vca = vcg - vag
                vcb = vcg - vbg


! Develop cosine timing waveforms.

                vt1 = -vbg
                vt2 =  vag
                vt3 = -vcg
                vt4 =  vbg
                vt5 = -vag
```

```
          vt6 =  vcg

! Determine when cosine timing wave equals the sinusoidal reference voltage
! and initiate converter switch logic change.

          SCHEDULE Dap .XN. vt1 - vra
          SCHEDULE Dap .XN. vt2 - vra
          SCHEDULE Dap .XN. vt3 - vra
          SCHEDULE Dap .XN. vt4 - vra
          SCHEDULE Dap .XN. vt5 - vra
          SCHEDULE Dap .XN. vt6 - vra

          SCHEDULE Dan .XN. vra - vt1
          SCHEDULE Dan .XN. vra - vt2
          SCHEDULE Dan .XN. vra - vt3
          SCHEDULE Dan .XN. vra - vt4
          SCHEDULE Dan .XN. vra - vt5
          SCHEDULE Dan .XN. vra - vt6

          SCHEDULE Dbp .XN. vt1 - vrb
          SCHEDULE Dbp .XN. vt2 - vrb
          SCHEDULE Dbp .XN. vt3 - vrb
          SCHEDULE Dbp .XN. vt4 - vrb
          SCHEDULE Dbp .XN. vt5 - vrb
          SCHEDULE Dbp .XN. vt6 - vrb

          SCHEDULE Dbn .XN. vrb - vt1
          SCHEDULE Dbn .XN. vrb - vt2
          SCHEDULE Dbn .XN. vrb - vt3
          SCHEDULE Dbn .XN. vrb - vt4
          SCHEDULE Dbn .XN. vrb - vt5
          SCHEDULE Dbn .XN. vrb - vt6

          SCHEDULE Dcp .XN. vt1 - vrc
          SCHEDULE Dcp .XN. vt2 - vrc
          SCHEDULE Dcp .XN. vt3 - vrc
          SCHEDULE Dcp .XN. vt4 - vrc
          SCHEDULE Dcp .XN. vt5 - vrc
          SCHEDULE Dcp .XN. vt6 - vrc

          SCHEDULE Dcn .XN. vrc - vt1
          SCHEDULE Dcn .XN. vrc - vt2
          SCHEDULE Dcn .XN. vrc - vt3
          SCHEDULE Dcn .XN. vrc - vt4
          SCHEDULE Dcn .XN. vrc - vt5
          SCHEDULE Dcn .XN. vrc - vt6

! A-phase.
          vomeana = (vopa+vona)/2.0
! B-phase.
          vomeanb = (vopb+vonb)/2.0
! C-phase.
```

```
        vomeanc = (vopc+vonc)/2.0

! Invoke the synchronous machine macro.

    sm31kq(1,vqsr1,vdsr1,v0s1,vfdr1,wrm1,wb,iqsr1,ikqr1,idsr1,ifdr1,&
        ikdr1,i0s1,Te1,"rs1=0.00913","rkq1=0.07609",&
        "rfd1=0.00265","rkd1=0.09342","Xmq1=0.78384",&
        "Xq1=0.95371","Xkq1=0.93171",&
        "Xmd1=1.01905","Xd1=1.18892","Xkd1=1.1989","Xfd1=1.3494",&
        "poles1=40.0")

! Exciter control

      CONSTANT ampmex = 50.0
      CONSTANT taumex = 0.01
      CONSTANT siref = 1.3
      simq = Xmq1*(iqsr1+ikqr1)
      simd = Xmd1*(idsr1+ikdr1+ifdr1)
      sim = sqrt(simq*simq + simd*simd)
      pexfd = (-exfd + ampmex*(siref-sim))/taumex
      exfd = INTEG(pexfd, exfdic)
      vfdr1 = rfd1*exfd/Xmd1

! Transform the cycloconverter output voltages to the rotor reference frame.

      vqsr1 = (2.0/3.0)*(vomeana*cos(thr1)+vomeanb*cos(thr1-rad120)+&
            vomeanc*cos(thr1+rad120))
      vdsr1 = (2.0/3.0)*(vomeana*sin(thr1)+vomeanb*sin(thr1-rad120)+&
            vomeanc*sin(thr1+rad120))
      CONSTANT v0s1=0.0

! Invoke the propeller load MACRO.
! Parameters for the propeller load.

      CONSTANT B1 = 0.0       ! " friction damping coefficient"
      CONSTANT wric1 = 0.0    ! " rotor speed initial cond."
      CONSTANT wb = 377.0
      CONSTANT gearrat=21.957
      CONSTANT Jm = 580.0
      CONSTANT Tbase = 49.18e3
      CONSTANT Vspuic = 0.0
      Tem = Te1*72.87e4
      propload(1,Tem,Tbase,wric1,thric1,Vspuic,B1,Jm,wb,wrot,throt,Vs)
      wrm1 = wrot/gearrat
      thrm1 = throt/gearrat
      thr1 = poles1 * 0.5 * thrm1

! Vector Control of the synchronous machine.

! Outer speed control loop to generate commanded q and d axis currents
! from commanded rotor(ship) speed and actual rotor(ship) speed.
```

```
        CONSTANT ki1 = 100.0
        CONSTANT kp1 = 5.0

        wrmstar = INTEG(wrmslope,0.0)

        SCHEDULE cs1 .XP. t-tacc
        SCHEDULE cs2 .XP. t-tss
        SCHEDULE cs3 .XP. t-tdec

        pzrm = wrmstar - wrm1
        zrm = INTEG(pzrm,0.0)
        iqsrstar = ki1*zrm + kp1*pzrm
        CONSTANT idsrstar = 0.0

! Inner voltage control loop to generate commanded q and d axis voltage
! waveforms from commanded q and d axis currents and actual q and d
! axis currents.

        CONSTANT ki2 = 50.0
        CONSTANT kp2 = 2.0
        CONSTANT ki3 = 50.0
        CONSTANT kp3 = 2.0
        CONSTANT vosrstar = 0.0

        pzqsr = iqsrstar - iqsr1
        zqsr = INTEG(pzqsr,0.0)
        vqsrstaro = ki2*zqsr + kp2*pzqsr

        pzdsr = idsrstar - idsr1
        zdsr = INTEG(pzdsr,0.0)
        vdsrstaro = ki3*zdsr + kp3*pzdsr

        CONSTANT wo = 100.0
        pxn = -wo*xn + wo*vqsrstaro
        xn = INTEG(pxn, 0.0)
        pxm = -wo*xm + wo*vdsrstaro
        xm = INTEG(pxm, 0.0)

        vmag = sqrt(xn*xn + xm*xm)
        IF (vmag .GE. (Vpk-0.005)) THEN
                vqsrstar = xn*(Vpk-0.005)/vmag
                vdsrstar = xm*(Vpk-0.005)/vmag
        ELSE
                vqsrstar = xn
                vdsrstar = xm
        ENDIF

        vra=vqsrstar*cos(thr1)+vdsrstar*sin(thr1)+vosrstar
        vrb=vqsrstar*cos(thr1-rad120)+vdsrstar*sin(thr1-rad120)+vosrstar
        vrc=vqsrstar*cos(thr1+rad120)+vdsrstar*sin(thr1+rad120)+vosrstar

! Determine the positive converter output voltage based on thositions.
```

```
PROCEDURAL (vopa,vopb,vopc = T1a,T2a,T3a,T4a,T5a,T6a,vag,vbg,vcg,&
                T1b,T2b,T3b,T4b,T5b,T6b,T1c,T2c,T3c,T4c,T5c,T6c)

! A-phase, positive converter output voltage.

        IF (T1a .AND. T2a) THEN
            vopa = vag - vcg
        END IF

        IF (T2a .AND. T3a) THEN
            vopa= vbg - vcg
        END IF

        IF (T3a .AND. T4a) THEN
            vopa = vbg - vag
        END IF

        IF (T4a .AND. T5a) THEN
            vopa = vcg - vag
        END IF

        IF (T5a .AND. T6a) THEN
            vopa = vcg - vbg
        END IF

        IF (T6a .AND. T1a) THEN
            vopa = vag - vbg
        END IF

! B-phase, positive converter output voltage.

        IF (T1b .AND. T2b) THEN
            vopb = vag - vcg
        END IF

        IF (T2b .AND. T3b) THEN
            vopb= vbg - vcg
        END IF

        IF (T3b .AND. T4b) THEN
            vopb = vbg - vag
        END IF

        IF (T4b .AND. T5b) THEN
            vopb = vcg - vag
        END IF

        IF (T5b .AND. T6b) THEN
            vopb = vcg - vbg
        END IF
```

```
                IF (T6b .AND. T1b) THEN
                        vopb = vag - vbg
                END IF

! C-phase, positive converter output voltage.

                IF (T1c .AND. T2c) THEN
                        vopc = vag - vcg
                END IF

                IF (T2c .AND. T3c) THEN
                        vopc= vbg - vcg
                END IF

                IF (T3c .AND. T4c) THEN
                        vopc = vbg - vag
                END IF

                IF (T4c .AND. T5c) THEN
                        vopc = vcg - vag
                END IF

                IF (T5c .AND. T6c) THEN
                        vopc = vcg - vbg
                END IF

                IF (T6c .AND. T1c) THEN
                        vopc = vag - vbg
                END IF

        END ! "of procedural"


PROCEDURAL (vona,vonb,vonc=T1Na,T2Na,T3Na,T4Na,T5Na,T6Na,vag,vbg,vcg,&
        T1Nb,T2Nb,T3Nb,T4Nb,T5Nb,T6Nb,T1Nc,T2Nc,T3Nc,T4Nc,T5Nc,T6Nc)

! A-phase, negative converter output voltage.

                IF (T1Na .AND. T2Na) THEN
                        vona = vag - vcg
                END IF

                IF (T2Na .AND. T3Na) THEN
                        vona = vbg - vcg
                END IF

                IF (T3Na .AND. T4Na) THEN
                        vona = vbg - vag
                END IF

                IF (T4Na .AND. T5Na) THEN
                        vona = vcg - vag
```

```
        END IF

        IF (T5Na .AND. T6Na) THEN
                vona = vcg - vbg
        END IF

        IF (T6Na .AND. T1Na) THEN
                vona = vag - vbg
        END IF

! B-phase, negative converter output voltage.

        IF (T1Nb .AND. T2Nb) THEN
                vonb = vag - vcg
        END IF

        IF (T2Nb .AND. T3Nb) THEN
                vonb = vbg - vcg
        END IF

        IF (T3Nb .AND. T4Nb) THEN
                vonb = vbg - vag
        END IF

        IF (T4Nb .AND. T5Nb) THEN
                vonb = vcg - vag
        END IF

        IF (T5Nb .AND. T6Nb) THEN
                vonb = vcg - vbg
        END IF

        IF (T6Nb .AND. T1Nb) THEN
                vonb = vag - vbg
        END IF

! C-phase, negative converter output voltage.

        IF (T1Nc .AND. T2Nc) THEN
                vonc = vag - vcg
        END IF

        IF (T2Nc .AND. T3Nc) THEN
                vonc = vbg - vcg
        END IF

        IF (T3Nc .AND. T4Nc) THEN
                vonc = vbg - vag
        END IF

        IF (T4Nc .AND. T5Nc) THEN
                vonc = vcg - vag
```

```
                END IF

                IF (T5Nc .AND. T6Nc) THEN
                        vonc = vcg - vbg
                END IF

                IF (T6Nc .AND. T1Nc) THEN
                        vonc = vag - vbg
                END IF

        END  ! "of procedural"

    END  ! "of derivative"

! Desired machine rotor speed discrete blocks.

    DISCRETE cs1
            wrmslope = slope2
    END
    DISCRETE cs2
            wrmslope = slope3
    END
    DISCRETE cs3
            wrmslope = slope2
    END

! Positive converter switch logic.
! A-phase.

    DISCRETE Dap

            P1ap = .FALSE.
            P2ap = .FALSE.
            P3ap = .FALSE.
            P4ap = .FALSE.
            P5ap = .FALSE.
            P6ap = .FALSE.

            IF (T1a.and.T2a) THEN
                    P1ap = .FALSE.
                    P2ap = .TRUE.
                    P3ap = .TRUE.

            ELSE IF (T2a.and.T3a) THEN
                    P2ap = .FALSE.
                    P3ap = .TRUE.
                    P4ap = .TRUE.

            ELSE IF (T3a.and.T4a) THEN
                    P3ap = .FALSE.
                    P4ap = .TRUE.
                    P5ap = .TRUE.
```

```
        ELSE IF (T4a.and.T5a) THEN
            P4ap = .FALSE.
            P5ap = .TRUE.
            P6ap = .TRUE.

        ELSE IF (T5a.and.T6a) THEN
            P5ap = .FALSE.
            P6ap = .TRUE.
            P1ap = .TRUE.

        ELSE IF (T6a.and.T1a) THEN
            P6ap = .FALSE.
            P1ap = .TRUE.
            P2ap = .TRUE.

        END IF

        T1a = P1ap
        T2a = P2ap
        T3a = P3ap
        T4a = P4ap
        T5a = P5ap
        T6a = P6ap
    END

! B-phase.

    DISCRETE Dbp

        P1bp = .FALSE.
        P2bp = .FALSE.
        P3bp = .FALSE.
        P4bp = .FALSE.
        P5bp = .FALSE.
        P6bp = .FALSE.

        IF (T1b.and.T2b) THEN
            P1bp = .FALSE.
            P2bp = .TRUE.
            P3bp = .TRUE.

        ELSE IF (T2b.and.T3b) THEN
            P2bp = .FALSE.
            P3bp = .TRUE.
            P4bp = .TRUE.

        ELSE IF (T3b.and.T4b) THEN
            P3bp = .FALSE.
            P4bp = .TRUE.
            P5bp = .TRUE.
```

```
        ELSE IF (T4b.and.T5b) THEN
                P4bp = .FALSE.
                P5bp = .TRUE.
                P6bp = .TRUE.

        ELSE IF (T5b.and.T6b) THEN
                P5bp = .FALSE.
                P6bp = .TRUE.
                P1bp = .TRUE.

        ELSE IF (T6b.and.T1b) THEN
                P6bp = .FALSE.
                P1bp = .TRUE.
                P2bp = .TRUE.

        END IF

        T1b = P1bp
        T2b = P2bp
        T3b = P3bp
        T4b = P4bp
        T5b = P5bp
        T6b = P6bp
    END

! C-phase.

    DISCRETE Dcp

        P1cp = .FALSE.
        P2cp = .FALSE.
        P3cp = .FALSE.
        P4cp = .FALSE.
        P5cp = .FALSE.
        P6cp = .FALSE.

        IF (T1c.and.T2c) THEN
                P1cp = .FALSE.
                P2cp = .TRUE.
                P3cp = .TRUE.

        ELSE IF (T2c.and.T3c) THEN
                P2cp = .FALSE.
                P3cp = .TRUE.
                P4cp = .TRUE.

        ELSE IF (T3c.and.T4c) THEN
                P3cp = .FALSE.
                P4cp = .TRUE.
                P5cp = .TRUE.

        ELSE IF (T4c.and.T5c) THEN
```

```
                P4cp = .FALSE.
                P5cp = .TRUE.
                P6cp = .TRUE.

          ELSE IF (T5c.and.T6c) THEN
                P5cp = .FALSE.
                P6cp = .TRUE.
                P1cp = .TRUE.

          ELSE IF (T6c.and.T1c) THEN
                P6cp = .FALSE.
                P1cp = .TRUE.
                P2cp = .TRUE.

          END IF

          T1c = P1cp
          T2c = P2cp
          T3c = P3cp
          T4c = P4cp
          T5c = P5cp
          T6c = P6cp
     END

! Switch logic for Negative converters.
! A-phase.

     DISCRETE Dan

          P1an = .FALSE.
          P2an = .FALSE.
          P3an = .FALSE.
          P4an = .FALSE.
          P5an = .FALSE.
          P6an = .FALSE.

          IF (T1Na.and.T2Na) THEN
                P1an = .FALSE.
                P2an = .TRUE.
                P3an = .TRUE.

          ELSE IF (T2Na.and.T3Na) THEN
                P2an = .FALSE.
                P3an = .TRUE.
                P4an = .TRUE.

          ELSE IF (T3Na.and.T4Na) THEN
                P3an = .FALSE.
                P4an = .TRUE.
                P5an = .TRUE.

          ELSE IF (T4Na.and.T5Na) THEN
```

```
                P4an = .FALSE.
                P5an = .TRUE.
                P6an = .TRUE.

        ELSE IF (T5Na.and.T6Na) THEN
                P5an = .FALSE.
                P6an = .TRUE.
                P1an = .TRUE.

        ELSE IF (T6Na.and.T1Na) THEN
                P6an = .FALSE.
                P1an = .TRUE.
                P2an = .TRUE.

        END IF

        T1Na = P1an
        T2Na = P2an
        T3Na = P3an
        T4Na = P4an
        T5Na = P5an
        T6Na = P6an

    END

! B-phase.

    DISCRETE Dbn

        P1bn = .FALSE.
        P2bn = .FALSE.
        P3bn = .FALSE.
        P4bn = .FALSE.
        P5bn = .FALSE.
        P6bn = .FALSE.

        IF (T1Nb.and.T2Nb) THEN
                P1bn = .FALSE.
                P2bn = .TRUE.
                P3bn = .TRUE.

        ELSE IF (T2Nb.and.T3Nb) THEN
                P2bn = .FALSE.
                P3bn = .TRUE.
                P4bn = .TRUE.

        ELSE IF (T3Nb.and.T4Nb) THEN
                P3bn = .FALSE.
                P4bn = .TRUE.
                P5bn = .TRUE.

        ELSE IF (T4Nb.and.T5Nb) THEN
```

```
                P4bn = .FALSE.
                P5bn = .TRUE.
                P6bn = .TRUE.

        ELSE IF (T5Nb.and.T6Nb) THEN
                P5bn = .FALSE.
                P6bn = .TRUE.
                P1bn = .TRUE.

        ELSE IF (T6Nb.and.T1Nb) THEN
                P6bn = .FALSE.
                P1bn = .TRUE.
                P2bn = .TRUE.

        END IF

        T1Nb = P1bn
        T2Nb = P2bn
        T3Nb = P3bn
        T4Nb = P4bn
        T5Nb = P5bn
        T6Nb = P6bn

    END

! C-phase.

    DISCRETE Dcn

        P1cn = .FALSE.
        P2cn = .FALSE.
        P3cn = .FALSE.
        P4cn = .FALSE.
        P5cn = .FALSE.
        P6cn = .FALSE.

        IF (T1Nc.and.T2Nc) THEN
                P1cn = .FALSE.
                P2cn = .TRUE.
                P3cn = .TRUE.

        ELSE IF (T2Nc.and.T3Nc) THEN
                P2cn = .FALSE.
                P3cn = .TRUE.
                P4cn = .TRUE.

        ELSE IF (T3Nc.and.T4Nc) THEN
                P3cn = .FALSE.
                P4cn = .TRUE.
                P5cn = .TRUE.

        ELSE IF (T4Nc.and.T5Nc) THEN
```

```
            P4cn = .FALSE.
            P5cn = .TRUE.
            P6cn = .TRUE.

        ELSE IF (T5Nc.and.T6Nc) THEN
            P5cn = .FALSE.
            P6cn = .TRUE.
            P1cn = .TRUE.

        ELSE IF (T6Nc.and.T1Nc) THEN
            P6cn = .FALSE.
            P1cn = .TRUE.
            P2cn = .TRUE.

        END IF

        T1Nc = P1cn
        T2Nc = P2cn
        T3Nc = P3cn
        T4Nc = P4cn
        T5Nc = P5cn
        T6Nc = P6cn

    END

END ! "of dynamic"

END ! "of program"
```

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