

# NAVAL POSTGRADUATE SCHOOL Monterey, California



## THESIS

SHIPBOARD MORE-ELECTRIC

by

Kenneth D. Filor

September, 1995

Thesis Advisor:

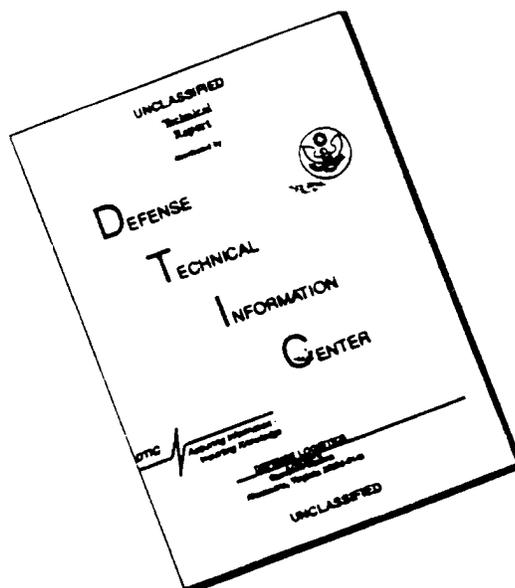
John G. Ciezki

Approved for public release; distribution is unlimited.

19960401 008

DTIC QUALITY INSPECTED 1

# DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

# REPORT DOCUMENTATION PAGE

*Form Approved*  
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time reviewing instructions, searching existing data sources gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE September 1995	3. REPORT TYPE AND DATES COVERED Master's Thesis
----------------------------------	----------------------------------	---

4. TITLE AND SUBTITLE SHIPBOARD MORE-ELECTRIC	5. FUNDING NUMBERS
--	--------------------

6. AUTHOR(S) Kenneth D. Filor	5. FUNDING NUMBERS
----------------------------------	--------------------

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Electrical Engineering Dept. 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 United States Government.

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

13. ABSTRACT *(Maximum 200 words)*  
The rapidly expanding fields of digital control and advanced power electronic circuitry enable researchers and designers to investigate novel approaches of providing shipboard service power requirements. The Shipboard More-Electric concept is based on using high efficiency DC-DC PWM converter modules in place of existing low efficiency high maintenance power distribution systems in the future generation Navy combatant design. This thesis describes the design and implementation of a reduced-order model of a Primary Ship Service Converter Module (PSSCM). Using the Advanced Continuous Simulation Language (ACSL), the PSSCM is simulated to predict performance and stability. Various voltage sources, loads and controllers are studied to ensure the suitability and reliability of the system.

14. SUBJECT TERMS SHIPBOARD MORE-ELECTRIC	15. NUMBER OF PAGES 136
	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
---	--	---	----------------------------------



Approved for public release; distribution unlimited.

**SHIPBOARD MORE-ELECTRIC**

**Kenneth D. Filor**  
Lieutenant, United States Navy  
B.S., Indiana Institute of Technology, 1988

Submitted in partial fulfillment of the  
requirements for the degrees of

**MASTER OF SCIENCE IN ELECTRICAL ENGINEERING**

from the

**NAVAL POSTGRADUATE SCHOOL**  
**September 1995**

Author:

*Kenneth D. Filor*

\_\_\_\_\_  
Kenneth D. Filor

Approved By:

*John G. Ciezki*

\_\_\_\_\_  
John G. Ciezki, Thesis Advisor

*Robert W. Ashton*

\_\_\_\_\_  
Robert W. Ashton, Second Reader

*Michael A. Morgan*

\_\_\_\_\_  
Michael A. Morgan, Chairman,  
Department of Electrical and Computer Engineering



## ABSTRACT

The rapidly expanding fields of digital control and advanced power electronic circuitry enable researchers and designers to investigate novel approaches of providing shipboard service power requirements. The Shipboard More-Electric concept is based on using high efficiency DC-DC PWM converter modules in place of existing low efficiency high maintenance power distribution systems in the future generation Navy combatant design.

This thesis describes the design and implementation of a reduced-order model of a Primary Ship Service Converter Module (PSSCM). Using the Advanced Continuous Simulation Language (ACSL), the PSSCM is simulated to predict performance and stability. Various voltage sources, loads and controllers are studied to ensure the suitability and reliability of the system.



# TABLE OF CONTENTS

I.	INTRODUCTION .....	1
II.	THE MORE-ELECTRIC SYSTEM .....	3
	A. THE MORE-ELECTRIC CONCEPT .....	3
	B. THE MORE-ELECTRIC ARCHITECTURE .....	3
	1. Electric Propulsion .....	3
	2. Direct Current Zonal Electric Distribution (DC ZED) .....	3
	C. RESEARCH STATUS .....	4
III.	DC-DC BUCK CONVERTER .....	7
	A. WHY THE DC BUCK CONVERTER .....	7
	B. GENERAL BUCK CONVERTER CONFIGURATION AND OPERATION .....	7
	1. Switch-Closed Configuration .....	9
	2. Switch-Open Configuration .....	10
	C. MODES OF OPERATION .....	11
	1. Determining the Mode of Operation .....	11
	D. PSSCM SYSTEM .....	12
IV.	VOLTAGE CONTROLLERS FOR PSSCM .....	17
	A. THE PID VOLTAGE CONTROLLER .....	17
	B. THE FUNCTION CONTROL VOLTAGE CONTROLLER .....	21
	C. THE MULTI-LOOP VOLTAGE CONTROLLER .....	23
	D. CONTROLLER COMPARISON AND IMPLEMENTATION FOR PSSCM .....	25
	1. Implementation of PID Controller in ACSL .....	28
	2. Implementation of Control Function Controller in ACSL .....	28
	3. Implementation of Multi-Loop Controller in ACSL .....	28
	4. Controller Simulation Comparisons .....	29
V.	BASIC PSSCM SIMULATIONS .....	35
	A. CONSTANT SOURCE/VARIABLE LOAD SIMULATIONS .....	35
	1. Ideal Buck Converter Configuration .....	35
	2. Basic Buck Converter with Regulated Output Voltage .....	39
	B. ACTIVE SOURCE/VARIABLE LOAD SIMULATIONS .....	46
	1. Design of Active Source .....	46
	2. Variable Resistive Load Simulations .....	47
	3. Induction Motor Simulations .....	53
VI.	ADVANCED PSSCM SIMULATIONS .....	61
	A. DUAL CONVERTER PARALLEL CONFIGURATION .....	61
	B. DUAL CONVERTER SERIES CONFIGURATION .....	68
	C. DUAL CONVERTERS--INTERLACE CONFIGURATION .....	72
VII.	CONCLUSION .....	75
	A. OVERVIEW OF SHIPBOARD MORE -ELECTRIC .....	75
	B. SUMMARY OF RESULTS .....	75

C. FUTURE RESEARCH CONSIDERATIONS .....	76
REFERENCES .....	77
APPENDIX A. MATLAB PROGRAM FOR FINDING VOLTAGE CONTROLLER GAINS .....	79
APPENDIX B. IMPLEMENTATION OF CONTROLLERS IN ACSL .....	81
APPENDIX C. BASIC BUCK CONVERTER FOR CONTINUOUS AND DISCONTINUOUS MODES OF OPERATION .....	82
APPENDIX D. PSSCM REDUCED-ORDER MODEL CONFIGURATION WITH MULTI-LOOP CONTROLLER WITH FIXED SOURCE .....	86
APPENDIX E. PSSCM CONFIGURATION WITH MULTI-LOOP CONTROLLER FOR ACTIVE SOURCE .....	89
APPENDIX F. MACRO FOR INDUCTION MACHINE .....	100
APPENDIX G. STEAM TURBINE DRIVEN SYNCHRONOUS MACHINE WITH EXCITOR CONTROL-ACTIVE SOURCE INCLUDING RECTIFIER AND FILTER .....	103
INITIAL DISTRIBUTION LIST.....	123

## LIST OF FIGURES

Figure 2.1	The More-Electric System.....	5
Figure 3.1	DC Buck Configuration .....	8
Figure 3.2	Switch-Closed Configuration.....	9
Figure 3.3	Switch-Open Configuration .....	10
Figure 3.4	PSSCM Schematic [3] .....	13
Figure 3.5	PSSCM Configuration .....	16
Figure 4.1	Low-Frequency Equivalent Buck Converter .....	22
Figure 4.2	Simplified PSSCM Configuration .....	26
Figure 4.3	PSSCM Pole Placement .....	27
Figure 4.4	PID Voltage Controller Response .....	31
Figure 4.5	Function Control Controller Response .....	32
Figure 4.6	Multi-Loop Controller Response .....	33
Figure 5.1	$I_{L1}$ Continuous and Discontinuous Mode .....	36
Figure 5.2	Step Changes in Resistance-Constant Input/Output Voltage .....	38
Figure 5.3	Step Changes in Load Resistance--Constant Input Source .....	42
Figure 5.4	Resistive Load Step Change for Constant Source (Initial step 25 ohms)..	43
Figure 5.5	Resistive Load Step Change for Constant Source (Initial step 50 ohms)..	44
Figure 5.6	Constant Source Full Load Step Change .....	45
Figure 5.7	Active Source Configuration .....	46
Figure 5.8	Small Step Changes in Load Resistance with Active Source.....	49
Figure 5.9	Analysis of Load Step from 5.625 to 25 ohms with Active Source.....	50
Figure 5.10	Analysis of Load Step from 5.625 to 50 ohms with Active Source.....	51
Figure 5.11	Active Source Full Load Step Change .....	52
Figure 5.12	Variable Resistance Simulation with Induction Motor .....	56
Figure 5.13	Variable Resistance Simulation with Induction Motor .....	57
Figure 5.14	Induction Motor Simulation with R=100 ohms .....	58
Figure 5.15	Induction Motor Simulation with R=100 ohms .....	59
Figure 6.1	Dual Converter Parallel Configuration .....	61
Figure 6.2	Steam Turbine with 3-Phase Synchronous Machine .....	63
Figure 6.3	Simulations of Dual Zones with Induction Motors .....	64
Figure 6.4	Simulations of Dual Zones with Induction Motors .....	65
Figure 6.5	Inter-Zonal Effects .....	66
Figure 6.6	Inter-Zonal Effects .....	67
Figure 6.7	Dual Converter Series Configuration.....	68
Figure 6.8	Simulation Effects Caused by Secondary SSCM .....	70
Figure 6.9	Simulation Effects Caused by Secondary SSCM .....	71
Figure 6.10	Dual Converter Interlace Configuration .....	72



## LIST OF TABLES

Table 4.1	PSSCM PARAMETERS .....	26
Table 5.1	Data for Different Load Resistance Conditions .....	39
Table 5.2	Effects of Resistance Changes on Induction Motor .....	55

## I. INTRODUCTION

As technology advances, new and better methods are being researched and developed for providing higher performance and realizing cost savings in shipboard power systems. In an attempt to improve reliability, enhance survivability, and broaden both commonality and flexibility, conventional circuit topologies are being replaced by state of the art high efficiency PWM converters.

The latest concept of distributing DC power for both the ship's service power and the ship's propulsion systems is known as the Integrated Power System (IPS). The DC power is delivered to all zones in the ship through a port and starboard bus from the main turbine generators. Through isolating the various zones so that there are no interzone electrical connections, the generic description Zonal Electric Distribution (ZED) is arrived at. The Primary Ship Service Converter Module (PSSCM) is the key to providing each zone with regulated and stable power. Each zone contains both DC and AC load requirements. A representation of a PSSCM, upon employing various assumptions and reductions, can be simulated using the Advanced Continuous Simulation Language (ACSL). The PSSCM in the reduced form is a DC-DC Buck converter. The concepts and operations of the Buck converter are analyzed and applied to simulate the PSSCM which is then integrated together with some typical zone loads. Several studies are analyzed to determine the stability and performance of the PSSCM. Fixed constant sources and active sources are specified to investigate and critique the performance of the PSSCM.

To enhance the stability of the PSSCM, several controllers are implemented to control the output voltage through modulation of the duty cycle. From the three voltage controllers analyzed, it is shown that the multi-loop controller had the most desirable performance. The controller increases the quality of the output voltage by reducing the oscillations, voltage spikes and response times during transients.

In order to assess zone power and transient recovery requirements for SSCM's, a number of simulations are performed including changes in load resistance and the start-up

of an inverter-driven induction machine. Simulations are also performed to study the effects of two PSSCMs running simultaneously from the same power source, effectively modeling a two zone configuration. A normal destroyer-size combatant may incorporate eight or more electrical zones. The final issue considered is a paralleled combination of Buck converters where the control signals are interlaced in an attempt to exploit further control of the output voltage.

## **II. THE MORE-ELECTRIC SYSTEM**

### **A. THE MORE-ELECTRIC CONCEPT**

The Navy's move toward more-electric is an attempt to find alternatives to the present distribution architectures which provide ship propulsion and ship service power requirements. The integrated nature of this endeavor stems from the requirement that the ship's service power must be derived from the same source as the ship's main propulsion. It is believed that this topology will provide increased efficiency and cost reductions. By minimizing the number of piece parts and by using pre-designed modules with standard components, the More-Electric ship alternative is intended to reduce the acquisition and life cycle costs. In addition, it is the goal of the more-electric ship to maintain the performance capabilities of combat vessels and readily facilitate future modifications and upgrades[1].

### **B. THE MORE-ELECTRIC ARCHITECTURE**

#### **1. Electric Propulsion**

The generator is driven by a 22 MW Intercooled Recuperative (ICR) gas turbine engine at 3600 rpm. This is the next generation gas turbine which the Navy is developing to replace or upgrade the LM2500. The ICR turbine offers superior transient performance over the LM2500 without an increase in size or weight. The turbine drives a permanent magnet synchronous generator with multiple phase windings. Each winding has an independent rectifier circuit which supplies either the DC ship propulsion or the DC ship service bus.

#### **2. Direct Current Zonal Electric Distribution (DC ZED)**

Zonal Electric Distribution (ZED) is a system-oriented approach for supplying power to the primary and secondary loads present on a typical Navy ship. The DC ZED was selected over an AC ZED because of the available split-plant configuration, the near instantaneous power transfer, the added control flexibility, and the inherent current-limit

protection built into the power electronic equipment. Due to advancements in power electronics which include greater device current densities, increased reliability and efficiency, and reduction in costs, DC distribution is now a feasible alternative to conventional AC systems[2]. The disadvantages inherent to DC ZED are arcing, fault detection (no zero crossing), and isolation.

The DC ZED is sectioned into a port and a starboard bus with each bus linking a zone through a Primary Shipboard Service Converter Module (PSSCM). The design of two buses, one on the port and the other on the starboard, provides the ship with redundancy in case of repair or ship casualty. The PSSCM's supply the appropriate DC voltage to the Ship Service Inverter Module (SSIM's) and Ship Service Converter Module (SSCM's) in each zone. The SSIM's deliver power to the AC loads, while the SSCM's supply the DC loads in each zone. Figure 2-1 illustrates the architecture of the More-Electric System [1].

### C. RESEARCH STATUS

The Naval Surface Warfare Center (NSWC) at Annapolis, Maryland and the Power Systems Group (PSG) of Power Paragon Inc. have combined efforts to produce a Primary Ship Service Converter Module. The entire project, including design, manufacturing and testing the SSCM units will be a joint effort. The PSSCM is a DC-DC Buck type converter. This PSSCM will be designed and a prototype developed, installed, and operated in the laboratory of the NSWC for DC ZED's system performance evaluations. PSG is presently working on the power portion design of the PSSCM system. NSWC and NPS are presently researching the control portion of the PSSCM system. The Advanced Surface Machinery Programs (ASMP) office at NSWC has designed a Reduced Scale Advanced Development (RSAD) model for the purpose of promoting the DC ZED. A Full Scale Advanced Development (FSAD) model will facilitate the validation and appropriate modification of the computer models presently being used to assess stability and performance characteristics [1],[3].

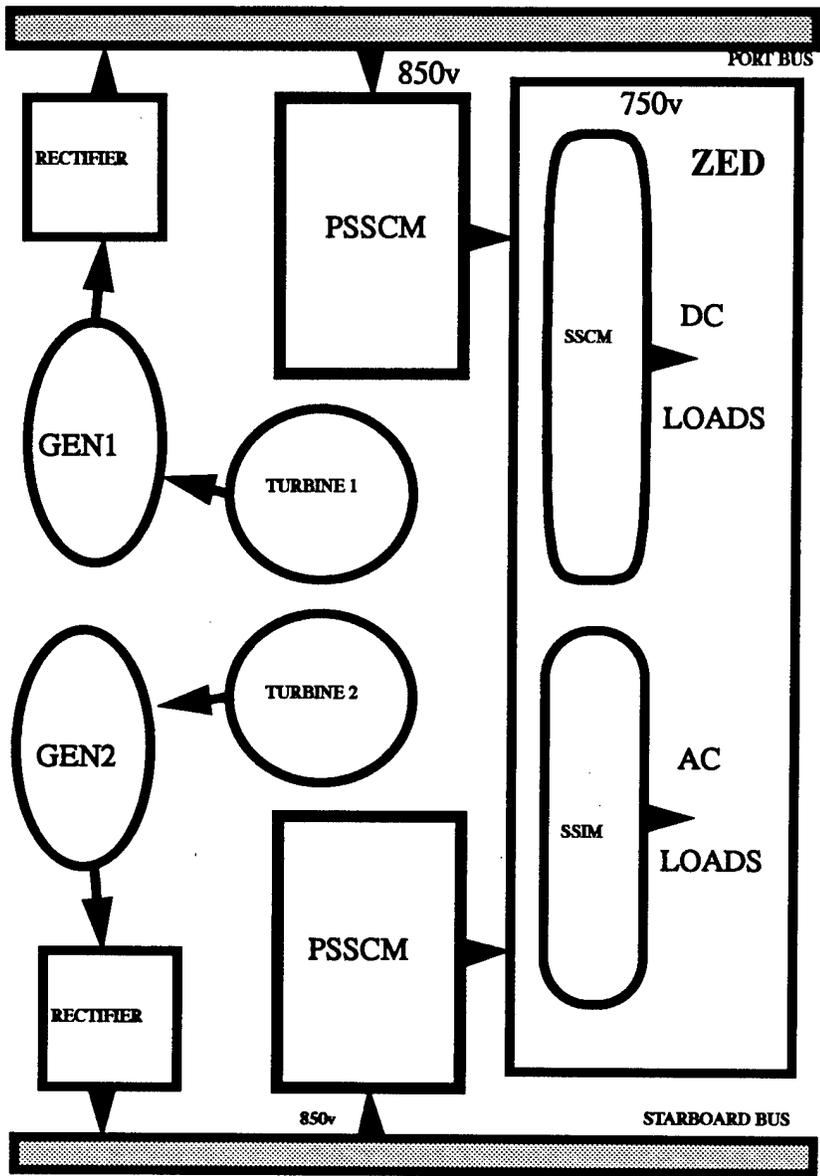


Figure 2.1: The More-Electric System.



### **III. DC-DC BUCK CONVERTER**

#### **A. WHY THE DC BUCK CONVERTER**

The biggest consideration in the use of step-down converters over conventional linear control circuits is efficiency. Converters can operate at efficiencies greater than 90%, while conventional voltage divider circuits operate with much larger power losses, less efficiency and have no capacity to regulate the output voltage.

The four basic Switched-Mode PWM DC-DC converters are the Buck, Boost, Buck-Boost and Cuk. The Buck converter steps down a large voltage to a usable lower level. The Boost converter as the name implies, increases an existing voltage, while the Buck-Boost and Cuk can either step-up or step-down a given source to a desired voltage level. The Cuk converter is an inverse dual of the Buck-Boost converter.

In the More-Electric shipboard design, the voltage level will be at a maximum level when it leaves the integrated generator/rectifier unit. After being distributed, the DC voltage must then be reduced within each zone by a PSSCM. In each zone, the voltage may be further reduced by additional SSCM's. It is apparent that the More-Electric shipboard design requires only step-down converters, therefore the Buck converter is the best choice for the PSSCM.

#### **B. GENERAL BUCK CONVERTER CONFIGURATION AND OPERATION**

The basic DC Buck converter is shown in Figure 3-1.  $E_1$  is the input voltage. The output voltage across the capacitor is  $V_{c1}$ . The capacitor is assumed to be large so that the AC portion of the voltage is relatively small and can be neglected for various purposes of analysis. The diode, D1, is assumed to be an ideal diode and thus has zero voltage drop when forward biased and carries zero current when reverse biased. The usual 0.7 to 2.0 volt diode voltage drop can be reasonably neglected in the remainder of the analysis because the circuit voltages under consideration are much larger. The placement of the diode in the circuit provides a path for the inductor current when the switch is open. The switch, S1, is

assumed to be an ideal switch with two states, open or closed. If the switch is open and D1 is conducting, the voltage across the switch is E1 volts. When the switch is closed, it is assumed that the voltage across the switch instantaneously transitions from E1 volts to zero volts. Switching transients and switch power loss are ignored for convenience. The switch is turned on and off at a frequency generally between 5 kHz and 20 kHz for high-power applications. The switching process introduces a ripple in the output voltage. For the analysis and modeling presented in this work, harmonic losses and power factor considerations are assumed to be negligible.

Even though the switching frequency is constant, the ratio between the switch on and off time will vary according to some prescribed control law. The ratio of the switch on-time to the switching period is termed the duty cycle without any other consideration, this periodic switching will introduce considerable harmonics into the rest of the circuit. The positioning of the Buck chopper inductor and capacitor establishes a low-pass filter with cutoff frequency  $\omega_o = 1/\sqrt{L_1 \cdot C_1}$  which filters out much of the switching harmonics before they reach the output load, R1.

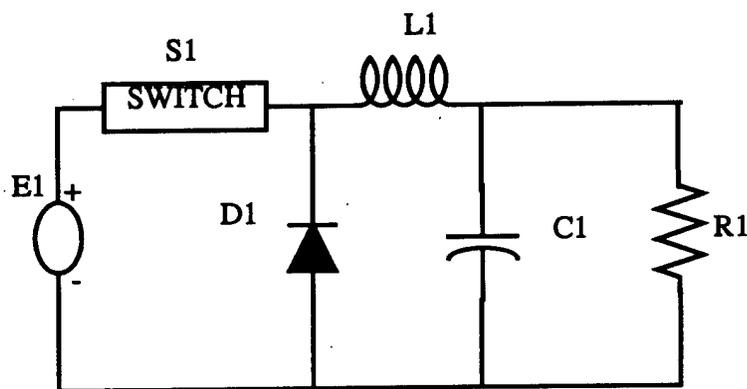


Figure 3.1: DC Buck Configuration

## 1. Switch-Closed Configuration

When the switch is closed the Buck Chopper circuit topology is given by Figure

3.2. In this mode, the diode is reverse biased and can be ignored.

By Kirchoff's voltage law, the following equations are derived:

$$E1 = V_{L1} + V_{C1} \quad (3.1)$$

$$E1 = L1 * p(i_{L1}) + V_{C1} \quad (3.2)$$

$$p(i_{L1}) = (E1 - V_{C1}) / L1 \quad (3.3)$$

$$I_{max} - I_{min} = ((E1 - V_{C1}) / L1) * (D * T) \quad (3.4)$$

Note that  $p$  is the Heaviside operator,  $T$  is the switch period and equal to the inverse frequency and  $D$ , the duty cycle, is the portion of the time the switch is on during each period ( $0 < D < 1$ ).

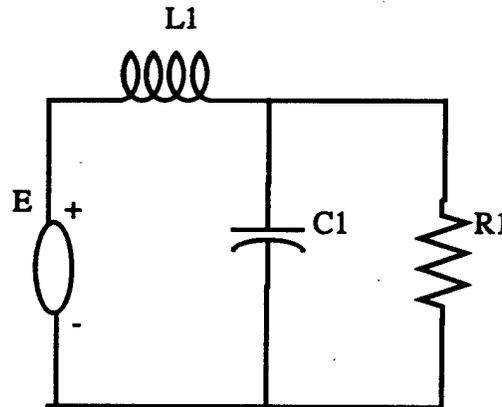


Figure 3.2: Switch-Closed Configuration

## 2. Switch-Open Configuration

When the switch, S1, is open the Buck Chopper circuit topology is given by Figure 3.3.

Again by Kirchoff's voltage law, the following equations are derived

$$0 = V_{L1} + V_{C1} \quad (3.5)$$

$$0 = L1 \cdot p(i_{L1}) + V_{C1} \quad (3.6)$$

$$p(i_{L1}) = -V_{C1} / L1 \quad (3.7)$$

$$I_{max} - I_{min} = (V_{C1} / L1) \cdot (D' \cdot T) \quad (3.8)$$

Note that D' is the complement of the duty cycle and represents the ratio of time that the switch is off to the switching frequency ( $D + D' = 1$ ). If (3.4) and (3.8) are simultaneously solved, the following equation is derived:

$$V_{C1} = D \cdot E1 \quad (3.9)$$

Note that the output voltage,  $V_{c1}$ , is proportional to the input voltage,  $E1$ , and is directly adjusted by the duty cycle. Equation (3.9) is valid if all components are ideal, wire loss is negligible, inductive resistance is neglected, and continuous inductor current is assumed.

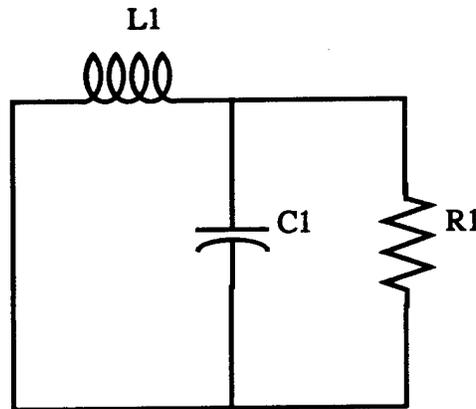


Figure 3.3: Switch-Open Configuration

## C. MODES OF OPERATION

In the previous discussion and equation derivations, the continuous current mode of operation was assumed. As the name implies, the continuous current mode occurs when the current through the inductor is always positive. If the current through the inductor becomes zero for a portion of the switching period, then the converter is said to be operating in the discontinuous current mode. In the discontinuous current mode the converter is found to be less stable, and higher peak currents are required to supply the same average output current as in the continuous current mode. As a result, device ratings must be increased if operation in the discontinuous mode is desired.

### 1. Determining the Mode of Operation

The mode of operation, whether continuous or discontinuous, depends on the switching frequency, the load resistance, the duty cycle and the inductor size. If the load resistance, switching frequency and duty cycle are known then the critical value of inductance can be found. The critical inductor value is the determining factor in assessing the steady-state operating mode.

For continuous conduction, the average inductor current is given by

$$i_{L1} = (I_{max} + I_{min}) / 2 \quad (3.10)$$

The current through the inductor is equal to the combined current drawn by the capacitor and resistor. The average capacitor current is zero for an ideal component and the current through the load is equal to the voltage across the capacitor divided by the load resistance. From the above, it follows that

$$i_{L1} = i_{C1} + i_{R1} \quad (3.11)$$

$$i_{L1} = 0 + V_{C1} / R1 \quad (3.12)$$

If (3.10) is substituted in for  $i_{L1}$  in (3.12), and (3.8) is used to substitute for  $I_{max}$  while  $I_{min}$  is set to zero, the following expression for critical inductance can be derived:

$$L1 > (D' * R1 * T) / 2 \quad (3.13)$$

Since  $D'$  is less than one,  $L1$  can be selected greater than  $(R1 \cdot T)/2$  to insure continuous current mode operation.

#### **D. PSSCM SYSTEM**

The primary ship's service converter power design, illustrated in Figure 3.4, can be reduced to the basic Buck converter configuration already introduced in Figure 3.1. The 100 kw PSSCM was designed by the Power System Group. Several assumptions are required to obtain the simplified representation. This section will discuss the assumptions made and the basic component design of the PSSCM. Though there are several methodologies that may be employed to achieve the desired converter specifications, the component design presented here is based on the Power System Group analysis [3].



The choice of inductor size for the Buck converter is based on (3.14) and (3.15). The change in current is equal to the average current divided by the time. Recall, time is the inverse of frequency, and the switching frequency was selected to be 5 kHz. Given an output power of 100 kW and an output voltage of 750 volts, the rated average current is found to be 133 amps. The values of the minimum and maximum currents referred to in (3.10) are discussed in Chapter V.

$$p(I_{L1}) = \frac{I_{L1}}{T} = \frac{133}{200e-6} = 665,000 \text{amps/sec} \quad (3.14)$$

The specifications for the input voltage is a nominal 850 volts with an admissible variation of +/-25 volts. The specification for the output voltage is 750 volts. Conservatively, the maximum voltage anticipated across the inductor is 900 volts. This is a conservative value since the maximum input voltage is specified at 875 volts. The maximum voltage across the inductor occurs at start-up when the initial condition on the capacitor voltage is zero. Solving (3.3) for L1 upon substituting for the maximum inductor voltage yields

$$L1 = \frac{V_{L1}}{p(I_{L1})} = \frac{900}{665,000} = 1.35 \text{mH} \quad (3.15)$$

The actual circuit realization uses two 675uH inductors in series, instead of one 1.35mH inductor, to reduce the inductor internal capacitance effects. The inductors are identified by L2 and L3 in Figure 3.4.

The magnetic energy stored in the inductor is denoted as  $e_{L1}$ . This energy is a function of the inductor size and the inductor current. In particular for rated current, the energy is given by

$$e_{L1} = \frac{L1 * I_{L1}^2}{2} = \frac{1.35e-3}{2} (133)^2 = 12 \text{Joules} \quad (3.16)$$

The standard rule-of-thumb specifies that the minimum capacitor storage energy should be on the order of 10 times the rated inductor storage energy. The minimum capacitor value is then obtained from

$$C_{min} = \frac{2 \cdot e_{Cl}}{V_C^2} = \frac{2 \cdot (10 \cdot 12)}{750^2} = 426 \mu f \quad (3.17)$$

The PSG design uses a capacitance of 2600 $\mu$ f which is a factor of six times the minimum required. The 2600 $\mu$ f capacitance is realized by combining two parallel combinations of three 3900  $\mu$ f capacitors in series. These capacitors are illustrated in Figure 3.4 and are identified by C29 through C31 and C35 through C37. For a 2600 $\mu$ f output capacitor, the anticipated peak-to-peak ripple voltage is 0.1257 volts, as specified by

$$\Delta V_C = \frac{(I_{max} - I_{min}) T}{8 \cdot C1} \quad (3.18)$$

The switch, S1, is an Insulated Gate Bipolar Transistor (IGBT). The 400 amp 1700 volt IGBT is gated on by an appropriate driver, not illustrated in the figure. The input to the gate driver establishes the duty cycle and the frequency of the switch. The duty cycle is determined by the type of controller used. A through discussion of controllers and controller design is presented in Chapter IV.

The main Buck converter power diode is identified in Figure 3.4 as CR1. To reduce transient voltage ringing, turn-off switching losses and IGBT voltage stresses, two snubber circuits are implemented across the IGBT. For identical reasons two snubber circuits are included across the power diode. Since in formulating the ACSL simulations it is assumed that the snubber circuits are properly designed and the switching behave in an ideal manner, these circuit elements are omitted. Resistors R29 through R31 and R35 through R37 are bleeder resistors. These resistors are 7.5 k ohms and are needed for 2 reasons: to equalize the voltage distribution between series capacitors and to discharge the capacitor static charges after power shut down. The bleeder resistors are ignored in the ACSL simulations. The total bleeder resistance is equivalent to 11.25 k ohms. This is negligible in parallel

combination with the load resistance, since the load resistance must remain below 114.75 ohms for the converter to remain in the continuous mode of operation. In order to obtain 100 kW across the output with an output voltage of 750 volts the load resistance must equal 5.625 ohms. A resistance load smaller than 5.625 ohms will require the converter to supply higher than rated power.

The meter devices and LED indicators at the input and the output terminals of Figure 3.4 are ignored because they draw negligible amounts of current. The LRC input filter is designed for a 12-pulse rectifier configuration. The ACSL simulations including active sources, discussed in Chapter V, are implemented with a 6-pulse rectifier. The appropriate LRC input filter design is documented in Chapter V. Figure 3.5 illustrates the PSSCM configuration based on the given design and simplifying assumptions. By (3.19), the cutoff frequency for the converter output filter is found to be 85 Hz, which is well below the intended switching frequency of 5 kHz.

$$f_c = \frac{1}{2 * \pi * \sqrt{L1 * C1}} \quad (3.19)$$

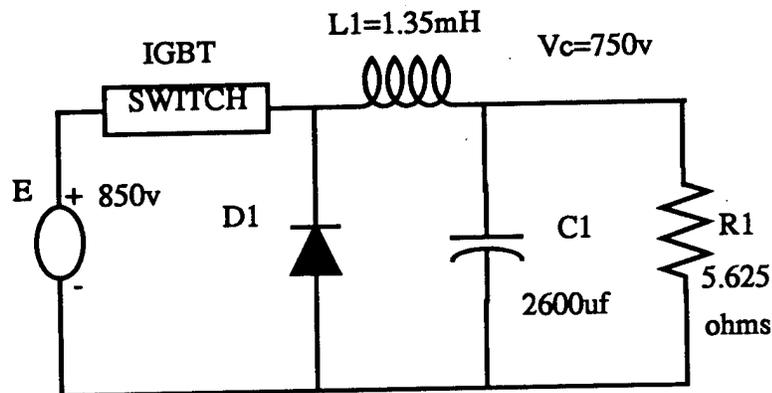


Figure 3.5: PSSCM Configuration

## IV. VOLTAGE CONTROLLERS FOR PSSCM

Several strategies exist to control the duty cycle of a converter. The simplest control implementation is a fixed duty cycle. The fixed duty cycle does not, however, yield acceptable dynamic response in the presence of varying loads or varying source voltages. A slightly more sophisticated controller is the Direct Duty Ratio controller. This is a simple controller in which the output voltage is compared to a desired voltage and multiplied by a gain constant to obtain the duty cycle. Though simple to implement and design, the resultant settling time and overshoot of the output voltage is still unacceptable. This chapter includes a discussion covering the performance, characteristics and function of three reliable PSSCM controllers: the PID, the Function Control and the standard Multi-Loop controller.

In assessing the implementation of these control strategies, attention will be focused on the attractive aspects of each. Three desirable features common to any control strategy are given as follows [4]:

1. The output voltage of the regulator remains unchanged even though there are disturbances from either the supply voltage or load current.
2. The closed-loop equation should predict the performance of the regulator.
3. The control circuit should be simple and flexible.

### A. THE PID VOLTAGE CONTROLLER

The PID voltage controller is comprised of a proportional, integral and derivative gain constant and hence the name PID. The equation governing the change in duty cycle about the nominal value is given by (4.1). It is a function of the change in output voltage from the desired reference voltage, the integral of this change, and the derivative of this change times various gains. There are no feedforward components from the input voltage or feedback components from the inductor or output current. If the capacitor is selected large enough, the derivative term contribution should be small.

$$\Delta d = -K_d p(\Delta V_{C1}) - K_p \Delta V_{C1} - K_i \int \Delta V_{C1} dt \quad (4.1)$$

The first step in deriving the gain constants is to utilize equations (3.2)-(3.3) to derive the state-space averaged model. Equations (3.2) and (3.3) model the inductor current dynamics when the switch is in the closed and open positions, respectively. Multiplying through by the appropriate time duration that each equation is valid,  $d$  or  $d'$ , equations (4.2) and (4.3) are derived.

$$p(i_{L1}) * d = d * (E1 - V_{C1}) / L1 \quad (4.2)$$

$$p(i_{L1}) * d' = d' * (-V_{C1} / L1) \quad (4.3)$$

Since  $d + d' = 1$ , the addition of (4.2) and (4.3) yields the averaged state-space representation given in (4.4).

$$p(\hat{i}_{L1}) = \left( \frac{1}{L1} \right) (d * E - \hat{V}_{C1}) \quad (4.4)$$

where the hat, “ $\hat{\phantom{x}}$ ”, denotes averaged quantities.

The output voltage is made available to the controller by sensing the voltage across the capacitor. The equation describing the dynamic behavior of  $V_{C1}$  is given by

$$V_{C1} = (1/C1) * \int i_C (dt) \quad (4.5)$$

The capacitor current is equal to the difference between the inductor current and the resistive load current. The current through the load is equal to the voltage across the load divided by the load resistance.

$$i_C = i_{L1} - V_{C1} / R1 \quad (4.6)$$

The averaged voltage state equation is obtained by combining (4.5) and (4.6) and taking the derivative. This yields

$$p(\hat{V}_{C1}) = \frac{1}{C1} \left( \hat{i}_{L1} - \left( \frac{\hat{V}_{C1}}{R1} \right) \right) \quad (4.7)$$

where  $\hat{V}_{C1}$  is the average capacitor voltage and  $\hat{i}_{L1}$  is the average inductor current.

Linearizing the averaged state equations, (4.4) and (4.7), about an operating point gives

$$p(\Delta \hat{i}_{L1}) = \left( \frac{1}{L1} \right) (\Delta d * E - \Delta \hat{V}_{C1}) \quad (4.8)$$

$$p(\Delta \hat{V}_{C1}) = \frac{1}{C1} \left( \Delta \hat{i}_{L1} - \left( \frac{\Delta \hat{V}_{C1}}{R1} \right) \right) \quad (4.9)$$

Substituting (4.8) and (4.9) into (4.1) and rearranging yields

$$p(\Delta d) = \left( \frac{K_p}{R1 * C1} - K_i + \left( \frac{1}{L1 * C1} - \frac{1}{R1^2 * C1^2} \right) K_d \right) \Delta \hat{V}_{C1} + \left( \frac{K_d}{R1 * C1^2} - \frac{K_p}{C1} \right) \Delta \hat{i}_{L1} + \left( \frac{E}{L1 * C1} \right) K_d \Delta d \quad (4.10)$$

Combining (4.8), (4.9) and (4.10), the linearized system is rewritten in matrix form as

$$P \begin{bmatrix} \Delta \hat{V}_{C1} \\ \Delta \hat{i}_{L1} \\ \Delta d \end{bmatrix} = \begin{bmatrix} -1 & 1 & 0 \\ \frac{1}{R1 * C1} & \frac{1}{C1} & 0 \\ -1 & 0 & \frac{E}{L1} \\ aa & bb & cc \end{bmatrix} \begin{bmatrix} \Delta \hat{V}_{C1} \\ \Delta \hat{i}_{L1} \\ \Delta d \end{bmatrix} \quad (4.11)$$

where

$$aa = \frac{K_p}{R1 * C1} - K_i + \left( \frac{1}{L1 * C1} - \frac{1}{R1^2 * C1^2} \right) K_d \quad (4.12)$$

$$bb = \frac{K_d}{R1 * C1^2} - \frac{K_p}{C1} \quad (4.13)$$

$$cc = \left( \frac{E}{L1 * C1} \right) K_d \quad (4.14)$$

This system of equations is in the standard state space form,  $px = Ax$ , where  $x$  is the state vector and  $A$  is the system matrix

$$A = \begin{bmatrix} \frac{-1}{R1 \cdot C1} & \frac{1}{C1} & 0 \\ \frac{-1}{L1} & 0 & \frac{E}{L1} \\ aa & bb & cc \end{bmatrix} \quad (4.15)$$

The roots of A-SI are termed the eigenvalues (or poles) of the system and dictate the stability and transient behavior about an operating point. Since A is a three-by-three matrix, the system has 3 poles in the transfer function. For the system considered, these poles are found from

$$A - IS = \begin{bmatrix} \frac{-1}{R1 \cdot C1} - S & \frac{1}{C1} & 0 \\ \frac{-1}{L1} & -S & \frac{E}{L1} \\ aa & bb & cc - S \end{bmatrix} \quad (4.16)$$

The characteristic equation of this third-order system is obtained from the determinant of (4.16)

$$S^3 + bS^2 + cS + d \quad (4.17)$$

Where the coefficients are

$$b = \frac{1}{R1 \cdot C1} - cc \quad (4.18)$$

$$c = \frac{1}{L1 \cdot C1} - \frac{cc}{R1 \cdot C1} - \frac{E1 \cdot bb}{L1} \quad (4.19)$$

$$d = \frac{E1 \cdot aa}{C1 \cdot L1} - \frac{cc}{C1 \cdot L1} + \frac{E \cdot bb}{L1 \cdot R1 \cdot C1} \quad (4.20)$$

Since the coefficients of the characteristic equation are a function of the gain constants, the selection of the gain values will affect the stability of the system. The gain constants are obtained by simultaneously solving (4.18) through (4.20)

$$K_d = \left( \frac{L1 \cdot C1}{E1} \right) \left( b - \frac{1}{R1 \cdot C1} \right) \quad (4.21)$$

$$K_p = \left( \frac{L1 \cdot C1}{E1} \right) \left( c - \frac{1}{L1 \cdot C1} \right) \quad (4.22)$$

$$K_i = \left( \frac{L1 \cdot C1}{E1} \right) d \quad (4.23)$$

The required controller gains can thus be specified once a desired characteristic equation is selected and the system parameters are known.

## B. THE FUNCTION CONTROL VOLTAGE CONTROLLER

The information used to implement the Function Controller is found in [4]. The output voltage,  $V_c$ , is a function of the input voltage,  $E$ , the duty cycle,  $d$ , and other intermediate variables of the switch converter known as  $x$ :

$$V_c = f(E, x, d) \quad (4.24)$$

The duty ratio is a function of the output voltage, reference voltage,  $V_{ref}$ , and a combination of variables of the switching converter known as  $y$ :

$$d = f(y, V_c, V_{ref}) \quad (4.25)$$

The key element of the derivation of the duty cycle for the Function Control is to have the output voltage,  $V_c$ , proportional to only the reference voltage,  $V_{ref}$ . In order to accomplish this, the duty cycle equations for the operating point and control circuit must be equivalent. The operating point equation and the control circuit equation respectively can be obtained from (4.24):

$$d_{op} = h(E, x, V_c) \quad (4.26)$$

$$d_{cc} = h(E, x, K(V_{ref} - V_c)) \quad (4.27)$$

Setting (4.26) and (4.27) equivalent gives  $V_c = K(V_{ref} - V_c)$ , which in turn yields,

$$V_c = \frac{K}{K + 1} V_{ref} \quad (4.28)$$

where for large  $K$ ,  $V_c$  is approximately equal to  $V_{ref}$ . The output voltage is now a function of only the reference voltage. By Kirchhoff's voltage law the following equations can be

derived from the low-frequency averaged equivalent circuit of a Buck converter shown in Figure 4.1. In this representation the switch is modeled by the average current assumed to flow through it while the diode is modeled by the assumed average voltage across it. At low frequencies the inductor voltage and the capacitor current is negligible.

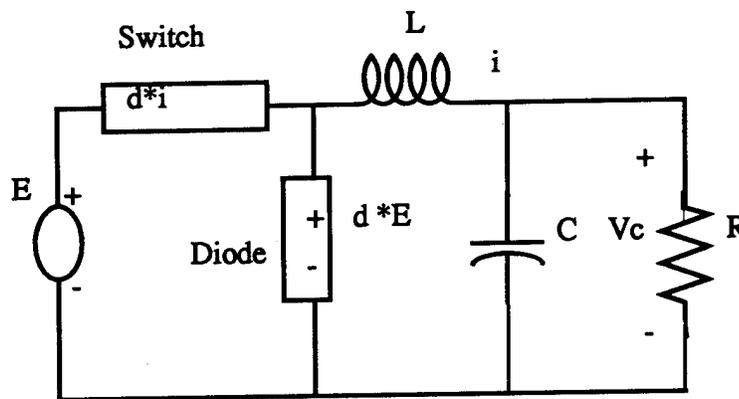


Figure 4.1: Low-Frequency Equivalent Buck Converter

The capacitor voltage is given by

$$V_c = d \cdot E - L \cdot p(i_L) \quad (4.29)$$

By rearranging (4.29) the duty cycle can be derived for the operating point:

$$d = (V_c + L \cdot p(i_L)) / E \quad (4.30)$$

By substituting the control parameter equation (4.28) into equation (4.30), the duty cycle is obtained as

$$d = (K(V_{ref} - V_c) + L \cdot p(i_L)) / E \quad (4.31)$$

The duty cycle for the Function Control is a function of the difference in output voltage and one desired reference voltage, the derivative of the current through the inductor and the input voltage. In particular as seen in (4.31), the duty cycle is obtained by dividing through by E, the feedforward input voltage. Division circuits are usually more complicated to implement than normal gain circuits because of the extra hardware

involved. An analog divider followed by a multiplier, a ratio-comparator, or a digital interface circuit can be used.

### C. THE MULTI-LOOP VOLTAGE CONTROLLER

The multi-loop controller is a multi-variable feedback control in which the output voltage and the inductor current are both used to adjust the duty cycle. The state variable components of current and voltage are both incorporated into the duty cycle perturbation. This controller has no voltage derivative component nor input voltage feedforward component. The variation in duty cycle is given by

$$\Delta d = -h_i \Delta \hat{i}_{L1} - h_v \Delta \hat{V}_{C1} - h_n \int \Delta \hat{V}_{C1} dt \quad (4.32)$$

The analysis of the multi-loop controller is similar to that of the PID voltage controller. Upon taking the derivative of (4.32) and substituting (4.8) and (4.9), the following state equation is derived

$$p(\Delta d) = \left( h_i + \frac{h_v}{C1 * R1} - h_n \right) \Delta \hat{V}_{C1} - \left( \frac{h_v}{C1} \right) \Delta \hat{i}_{L1} + \left( h_i \frac{E}{L1} \right) \Delta d \quad (4.33)$$

The linearized system in matrix form is written as

$$p \begin{bmatrix} \Delta \hat{V}_{C1} \\ \Delta \hat{i}_{L1} \\ \Delta d \end{bmatrix} = \begin{bmatrix} \frac{-1}{R1 * C1} & \frac{1}{C1} & 0 \\ \frac{-1}{L1} & 0 & \frac{E}{L1} \\ am & bm & cm \end{bmatrix} \begin{bmatrix} \Delta \hat{V}_{C1} \\ \Delta \hat{i}_{L1} \\ \Delta d \end{bmatrix} \quad (4.34)$$

where

$$am = h_i + \frac{h_v}{C1 * R1} - h_n \quad (4.35)$$

$$bm = \frac{-h_v}{C1} \quad (4.36)$$

$$cm = h_i \frac{E}{L1} \quad (4.37)$$

This system of equations is once again in the standard state space form,  $\dot{x} = Bx$ , where  $x$  is the state vector and  $B$  is the system matrix

$$B = \begin{bmatrix} \frac{-1}{R1 \cdot C1} & \frac{1}{C1} & 0 \\ \frac{-1}{L1} & 0 & \frac{E}{L1} \\ a_m & b_m & c_m \end{bmatrix} \quad (4.38)$$

The characteristic equation may be found from

$$B - IS = \begin{bmatrix} \frac{-1}{R1 \cdot C1} - S & \frac{1}{C1} & 0 \\ \frac{-1}{L1} & -S & \frac{E}{L1} \\ a_m & b_m & c_m - S \end{bmatrix} \quad (4.39)$$

As discussed before, the poles of any third-order system are determined from the characteristic equation. Using standard linear algebra techniques, the characteristic equation of the multi-loop system may be explicitly written as

$$S^3 + b_m S^2 + c_m S + d_m \quad (4.40)$$

where the coefficients are found to be

$$b_m = \frac{L1 + R1 \cdot C1 \cdot E \cdot h_i}{L1 \cdot C1 \cdot R1} \quad (4.41)$$

$$c_m = \frac{E \cdot h_i + R1 + R1 \cdot E \cdot h_v}{L1 \cdot C1 \cdot R1} \quad (4.42)$$

$$d_m = \frac{E \cdot h_n}{L1 \cdot C1} \quad (4.43)$$

The gain constants are obtained by simultaneously solving (4.41) through (4.43). This yields

$$h_i = \frac{L1 \cdot C1 \cdot R1 (b_m) - L1}{E \cdot R1 \cdot C1} \quad (4.44)$$

$$h_n = \frac{L1 * C1(dm)}{E1} \quad (4.45)$$

$$h_v = \frac{L1 * C1 * R1(cm) - E1(h_i) - R1}{E1 * R1} \quad (4.46)$$

#### D. CONTROLLER COMPARISON AND IMPLEMENTATION FOR PSSCM

The PSSCM specifications determined by the Power System Group are shown in Table 4.1 [3]. The PSSCM configuration is based on the assumptions introduced in Chapter III and the specifications listed in Table 4.1. The simplified circuit is shown in Figure 4.2.

The response time and performance for all three controllers discussed in this chapter are a function of the control gains. Based on a desired characteristic polynomial, expressions for these gains were derived in closed form. The multi-loop gains and the PID voltage controllers gains determine the closed-loop pole locations of the system. The characteristic equations of these two systems are third order. There are several techniques for specifying the pole locations. The following pole design gave the best results. The placement of the non-dominant pole should be approximately one decade less than the switching frequency. The switching frequency in radians/sec is 31.4 krad/sec, therefore the first pole will be fixed at 3 krad/sec. To avoid large overshoots, the dominant poles are situated in the over damped zone. The second and third pole are complex conjugates and are positioned at 300 +/- 200j. The pole placements are illustrated in Figure 4.3. The poles listed in Figure 4.3 lead to the characteristic equation

$$S^3 + 3600S^2 + 1.93e6S + 3.9e8 \quad (4.47)$$

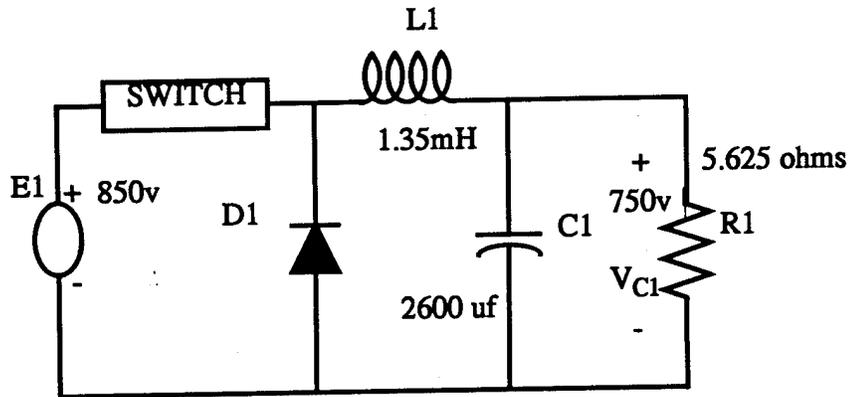


Figure 4.2: Simplified PSSCM Configuration

TABLE 4.1: PSSCM PARAMETERS

Parameters	Values
power	100kw
E1	850v +/- 25v
V <sub>C1</sub>	750v
R1	5.625 ohms
C1	2600 uf
L1	1.35 mH
frequency	5 khz
nominal D	.8824

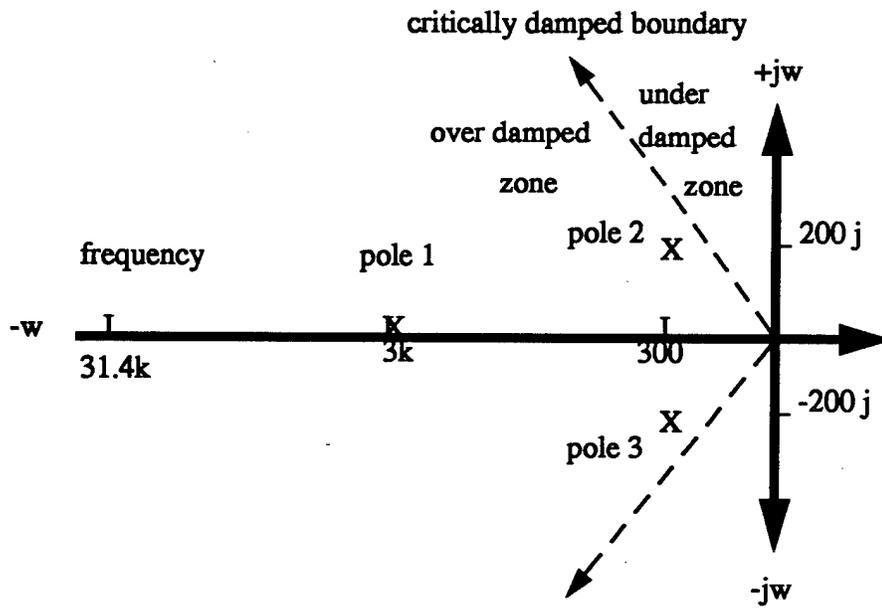


Figure 4.3: PSSCM Pole Placement

### 1. Implementation of PID Controller in ACSL

Using the coefficients in (4.47) and the parameters listed in Table 4.1, (4.21) through (4.23) are evaluated and provide the gains

$$K_d = 1.458e - 5 \quad (4.48)$$

$$K_p = .0068 \quad (4.49)$$

$$K_i = 1.6105 \quad (4.50)$$

The MATLAB file for calculating these gains is listed in Appendix A. The ACSL command for obtaining the duty cycle for this controller is also provided in Appendix B. The derivative component of the control is implemented by a differentiation over a first order lag.

### 2. Implementation of Control Function Controller in ACSL

The Function Controller was designed with an arbitrary gain,  $K=50$ . Therefore using (4.28),  $V_{ref}$  is found to be 765 volts. The ACSL command for obtaining the duty cycle for with this controller is also listed in Appendix B.

### 3. Implementation of Multi-Loop Controller in ACSL

The multi-loop gains can be obtained by stepping through the same procedures as given for the PID controller. Substituting the coefficients of (4.47) and the parameters listed in Table 4.1 into (4.44) through (4.46), the following values for gains are obtained:

$$h_i = 0.0056 \quad (4.51)$$

$$h_n = 1.6105 \quad (4.52)$$

$$h_v = 1.6105 \quad (4.53)$$

The MATLAB file for calculating these gains is also listed in Appendix A and the ACSL command for determining the duty cycle is given in Appendix B.

#### 4. Controller Simulation Comparisons

To contrast the performance of the controllers discussed in the previous sections, an identical ACSL simulation was structured and executed for each. In the program, the current is obtained by integrating the derivative portion of the current given by (3.3) and (3.7), respectively, for the switch-on and switch-off durations. The voltage is obtained by integrating the current in the Buck capacitor and dividing by the capacitor value of 2600uf. The detailed models of the controllers and Buck converter are used in the simulations. The simulation runs for 2.0 seconds with an input voltage drop at 1.0 second and a resistance increase at 1.5 seconds. At 1.0 seconds the input voltage to the converter is reduced from 850 volts to 800 volts. This voltage drop represents a change of approximately 6 percent. At 1.5 seconds the resistance is increased by a factor of four from 5.625 ohms to 22.5 ohms. Figures 4.4 through 4.6 illustrate the results. The output voltage and inductor current and the duty cycle are presented in each figure for comparison purposes. The start-up transition prior to 0.5 seconds is omitted, so that the resistor load changes and voltage source change can be enhanced in the illustrations.

The simulation results show the Function Control controller yields the least acceptable transient behavior. Though it performs fairly well, it does not have the quick response time desired. It takes several tenths of a second to stabilize following a transient. The PID voltage controller and the multi-loop controller have a response time approximately 100 times faster. Lacking an integrator in its structure, the Function controller is not capable of guaranteeing zero steady-state error in the output voltage response. The best feature of the Function Control controller is that the output voltage peak spikes are limited in magnitude. The maximum, a spike of approximately 6.5 volts, occurs when the load resistance is increased. This spike, however, is only a 0.87 percent change from the desired output voltage level.

The graphs show that the PID voltage controller and the multi-loop controller perform remarkably similar. Close analysis reveals that the PID voltage controller is in fact similar to the multi-loop controller because the capacitor current is related to the capacitor

voltage and the inductor current is related to the inductor voltage by the following equations:

$$i_{C1} = C1 * p(V_{C1}) \quad (4.54)$$

$$i_{L1} = \left( \frac{1}{L1} \right) \int V_{L1} dt \quad (4.55)$$

The PID voltage controller appeared to respond to the source voltage drop with little noticeable effect on the output voltage, while the multi-loop controller had a slight ripple of 2 volts in the output voltage. This represents a variation of only 0.267 percent, which for all practical purposes is also negligible. The load increase was handled slightly better by the multi-loop controller than the PID voltage controller because the PID voltage controller had the inductor current spike down close to the discontinuous mode of operation. The current spike of the multi-loop controller is approximately 12 amps, which is less than half that experienced with the PID controller. Both controllers had approximately equal output voltage responses with a maximum peak spike of 8 volts which is only a one percent deviation. It can be seen that both of these converters compensated for the changes in load and input voltage within milli-seconds and are reliable at maintaining a desired output voltage. Realistically, since load changes are more common to the proposed system than step voltage source disturbances, the performance of the multi-loop controller is selected as the candidate for future study in simulations proposed in Chapters V and VI.

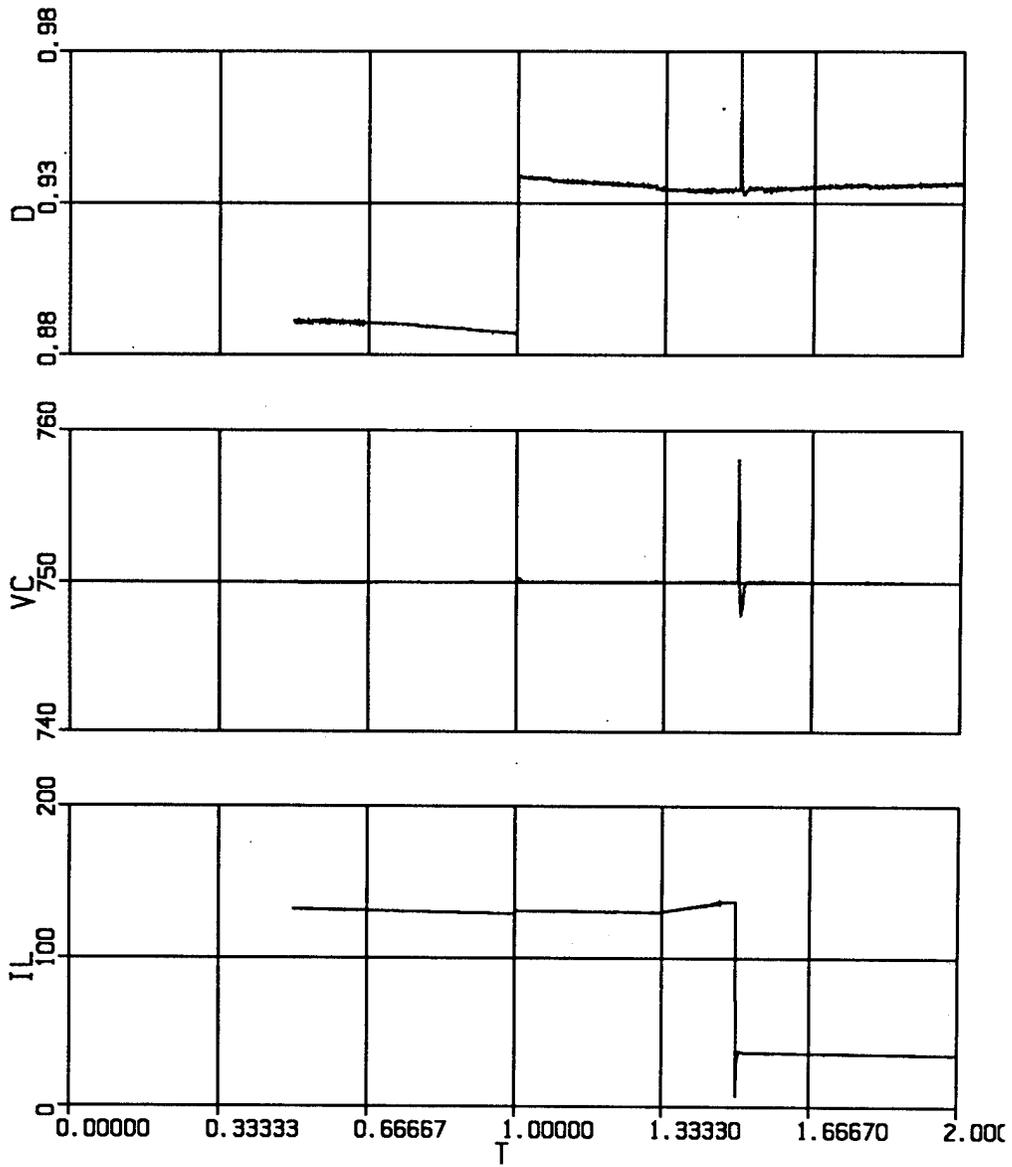


Figure 4.4: PID Voltage Controller Response

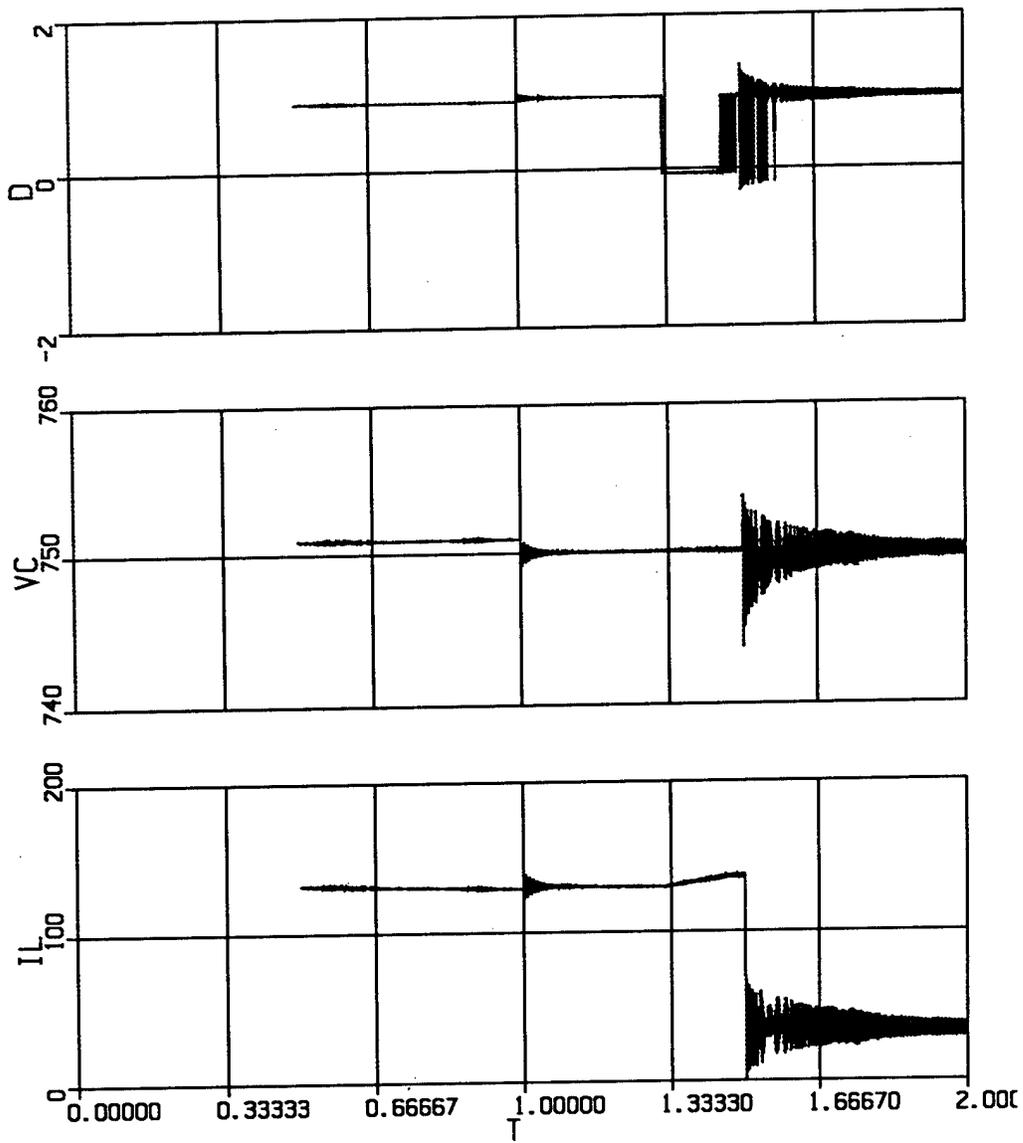


Figure 4.5: Function Control Controller Response

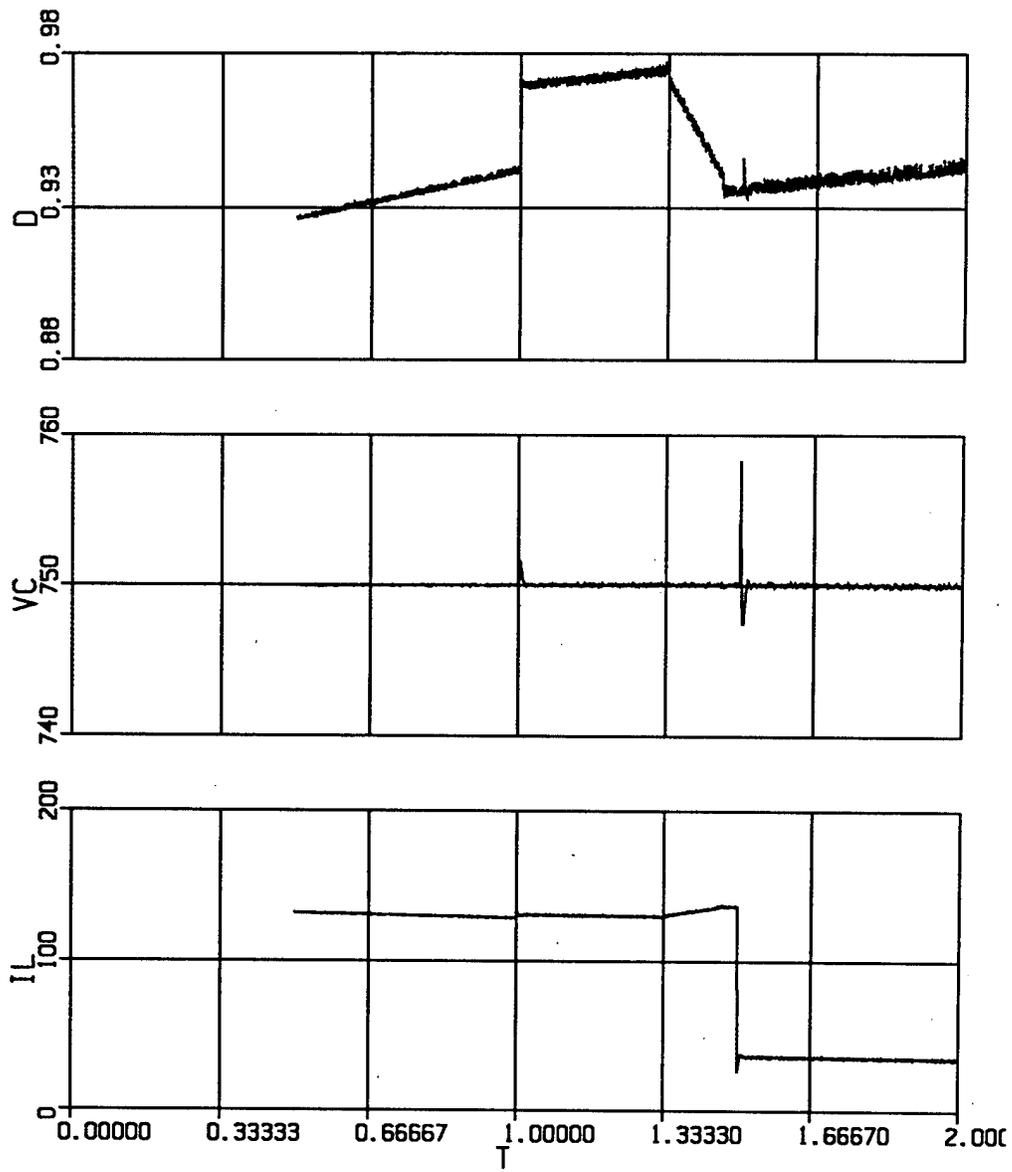


Figure 4.6: Multi-Loop Controller Response



## V. BASIC PSSCM SIMULATIONS

In this chapter, simulation results are presented for various PSSCM studies incorporating the multi-loop control. The studies include step changes in the load resistance, a soft source voltage, and a vector-controlled induction machine start-up. A set of representative results is presented together with critical analysis.

### A. CONSTANT SOURCE/VARIABLE LOAD SIMULATIONS

In this section, the main focus is to uncover the limits and ranges of current, voltage, and power for various resistive loads on a PSSCM. The ideal limits and ranges are calculated from an average-value Buck converter model, while the simulated performance is obtained from the detailed model with the multi-loop controller.

#### 1. Ideal Buck Converter Configuration

This section documents the simulation results from an ACSL program that models a fixed input voltage to the PSSCM and maintains a constant output voltage. The output voltage is set at 750 and the input voltage is set at 850. The duty cycle varies depending on which mode of operation the converter is operating in. The two modes of operation, as discussed in Chapter III, are continuous current and discontinuous current. The load resistance value will dictate the operating mode since the frequency and the inductor parameters are already fixed. Equation (3.13) establishes the boundary condition for the two modes. Rearranging, an expression for the critical resistance is given by

$$R_1 = \frac{2*L_1*freq}{d^2} \quad (5.1)$$

Using (5.1), the critical value of resistance is found to be 114.75 ohms. Any resistive load less than that will keep the converter in continuous mode, while a resistive load above that level will cause the converter to operate in discontinuous mode.

Figure 5.1 shows the inductor current plotted for 4.0 ms. In this study the resistance value is changed from 5.625 ohms to 114.75 ohms at 1.2 ms and then to 150 ohms at 2.4 ms. As shown in Figure 5.1, the inductor current goes from continuous operation with a minimum current of 126.8 amps to discontinuous mode with zero minimum current. While operating with the critical value of load resistance, the current only instantaneously reaches zero, while after 2.4 ms, operating with 150 ohm resistance, the current is zero for a duration of 20.6 us. This is approximately 10 percent of the duty cycle.

Figure 5.2 shows the inductor current and load power for a series of simulated step changes in load resistance. The load resistance varies from 5.625 to 150 ohms. The step changes include a doubling of resistance from 5.625 to 11.25, then to 25 ohms, then increases in steps of 25 ohms to 150 ohms. As the load resistance doubles, the current and power are reduced in half. Table 5.1 contains the ACSL computed results of the minimum and maximum current, the load power and the mode of operation. The table also contains the duty cycle, D, and an additional parameter D2. D2 indicates the point in a given cycle at which the current goes discontinuous.

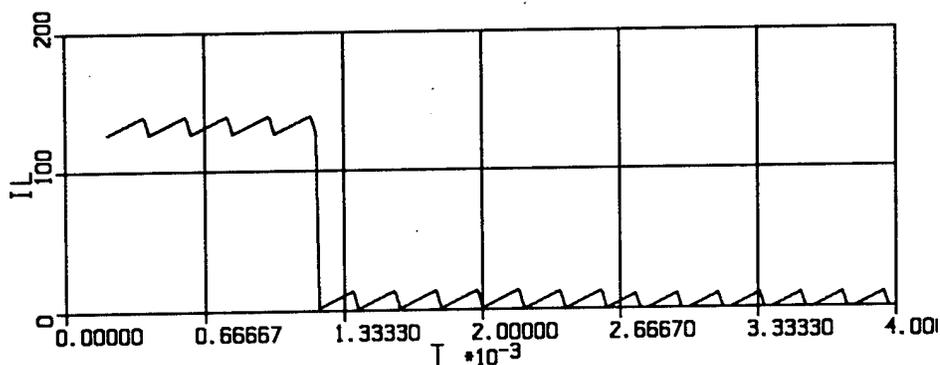


Figure 5.1:  $I_{L1}$  Continuous and Discontinuous Mode

Note that in discontinuous mode the duty cycle is different than in continuous operation. When the switch is closed during continuous operation, the current is linearly reduced, but in discontinuous operation the current goes non-linear at D2. The ACSL program for the ideal Buck with constant input voltage and steady-state output voltage is included in Appendix C.

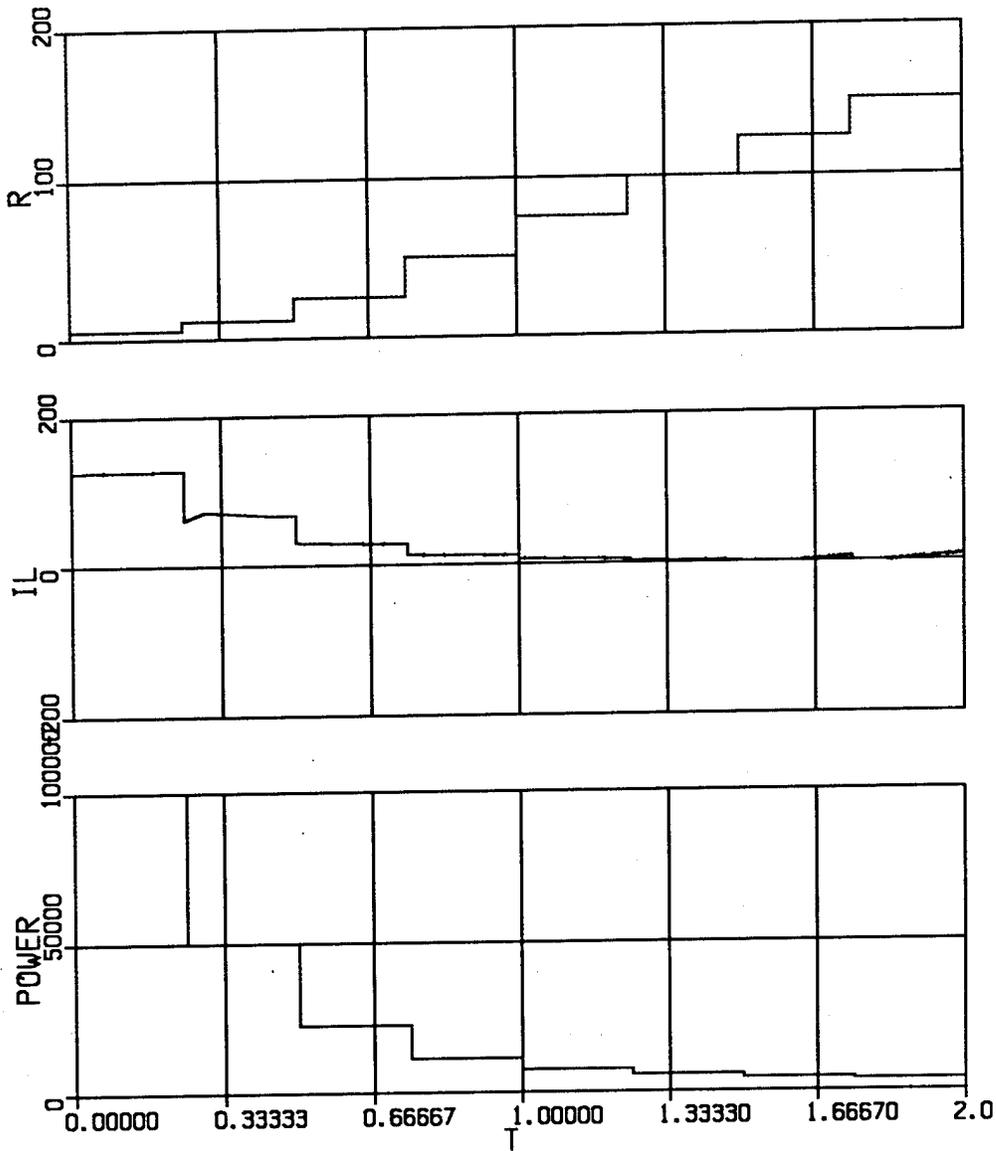


Figure 5.2: Step Changes in Resistance-Constant Input/Output Voltage

**TABLE 5.1: Data for Different Load Resistance Conditions**

R1(ohms)	$i_{min}$ (amps)	$i_{max}$ (amps)	Power (Watts)	operation mode	D	D2
5.625	126.80	139.87	100k	cm	.8823	NA
11.25	60.13	73.20	50k	cm	.8823	NA
25	23.46	36.54	22.5k	cm	.8823	NA
50	8.46	21.54	11.25k	cm	.8823	NA
75	3.46	16.54	7.50k	cm	.8823	NA
100	0.96	14.04	5.63k	cm	.8823	NA
125	0.0	12.53	4.50k	dcm	.845	.958
150	0.0	11.43	3.75k	dcm	.772	.875

## 2. Basic Buck Converter with Regulated Output Voltage

In this section, the simulation results of the Buck converter with stepped load resistance are presented. The input voltage source to the converter is fixed at 850 volts. The multi-loop controller introduced in Chapter IV is used to establish the duty cycle of the converter. The stability of the output voltage and the behavior of the inductor current are the main focus of these studies. The ACSL program for the simulations in this section is included in Appendix D. As typical PSSCM loads will guarantee continuous current operation, the stepped resistance values will be kept below the critical value. The output voltage is determined by integrating over the capacitor current and dividing by the capacitance

$$V_{C1} = \frac{1}{C1} \int i_{C1} dt \quad (5.2)$$

where,

$$i_{C1} = i_{L1} - i_{R1} \quad (5.3)$$

Figure 5.3 illustrates the simulation results for the output voltage and inductor current for step changes in load from 5.625 to 100 ohms. The output voltage is well regulated with only small voltage transients. The largest transient occurs when the load is increased from 5.625 ohms to 11.25 ohms with a voltage spike of approximately 5 volts. This transient is deemed negligible, representing only a 0.66 percent variation in the nominal 750 volt output voltage. As the resistance approximately doubles from 11.2 to 25, 25 to 50, and 50 to 100 ohms, the magnitude of the output voltage transients decrease by approximately 50 percent during each step change.

Figure 5.4 illustrates step changes in load resistance from 5.625 to 25, 25 to 100, 100 to 25, and 25 to 5.625 ohms. Each step change is four times the previous value for increasing increments and one-fourth for decreasing increments. A small voltage spike occurs at 0.2 seconds when the resistance changes from 5.625 to 25 ohms. The spike at this point is approximately 8 volts which is one percent of the nominal output voltage. The largest spike occurs at 0.8 seconds when the load resistance decreases from 25 to 5.625 ohms. The transient spike is approximately 25 volts, which represents a 3.3 percent variation from the nominal output voltage. At this point there is also a noticeable 35 amp current spike in the inductor current. This overshoot is approximately 23 percent.

Figure 5.5 illustrates larger increases in load step changes. The changes are from 5.625 to 50, 50 to 100, 100 to 50, and 50 back to 5.625 ohms. There is an approximate 10 volt spike as the load resistance increases from 5.625 to 50 ohms. This is roughly a 1.3 percent variation from the output voltage which is only slightly larger than the 8 volt spike from 5.625 to 25 ohms. However, there is enough of a decrease in current to cause the inductor current to instantaneously go discontinuous. Again, the largest spike occurs at 0.8 seconds as the load resistance decreases from 50 to 5.625 ohms. The spike is about 30.6 volts which is 4 percent of the nominal output voltage. At this point the current overshoot is approximately 45 amps or 35 percent.

Figure 5.6 illustrates step changes in load resistance from 5.625 to 100 ohms and then back down to 5.625 ohms. As the resistance is increased, the inductor current goes discontinuous for a few milli-seconds and a voltage spike of approximately 12.5 volts is observed. At 0.6 seconds when the resistance drops back down, the current overshoot is the greatest, approximately 35 amps or 38 percent. The largest voltage spike, 35 volts, also occurs at this point. Though representing the largest spike, it is still only 5 percent of the nominal output voltage. The multi-loop controller adequately regulates the output voltage for large and small changes in load resistance.

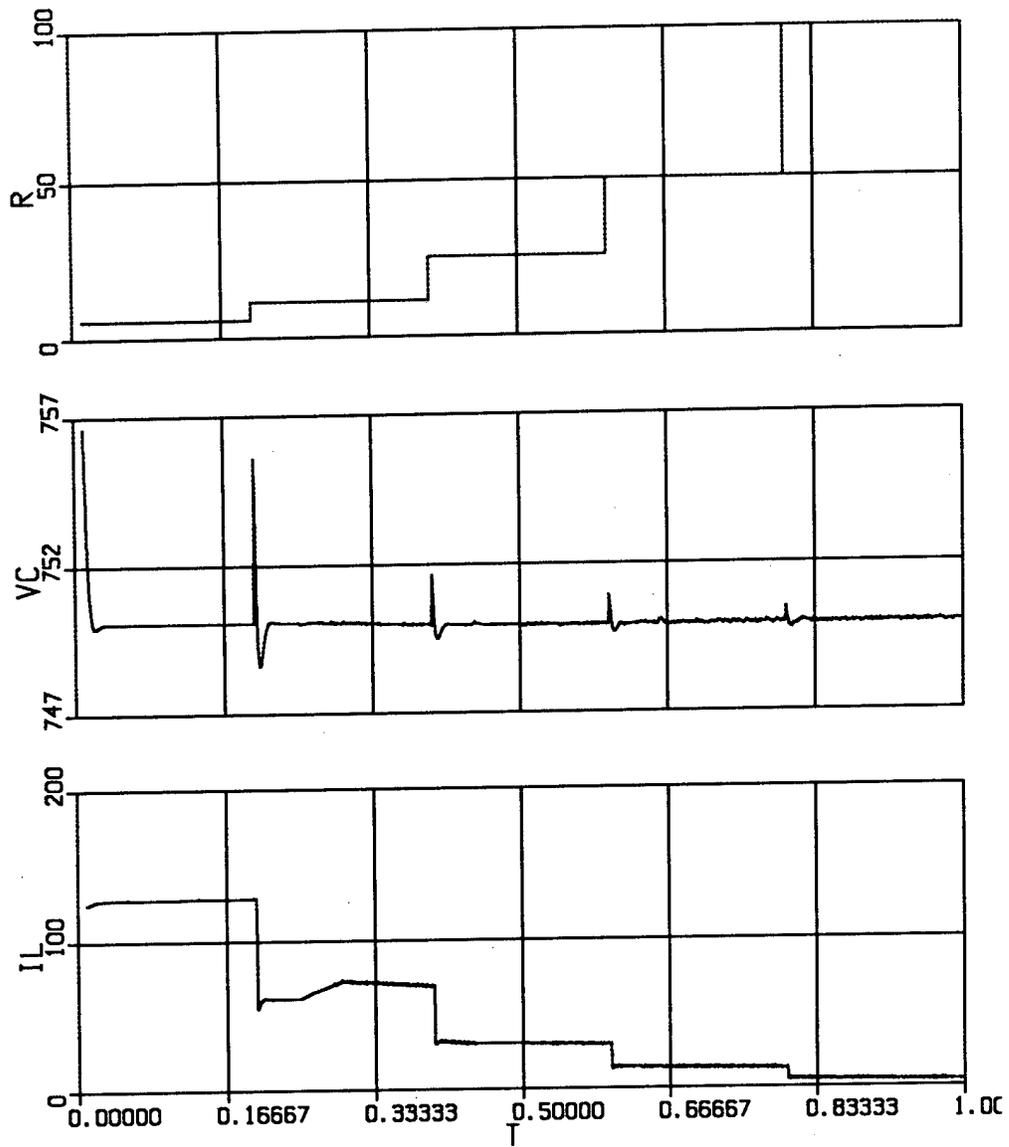


Figure 5.3: Step Changes in Load Resistance--Constant Input Source

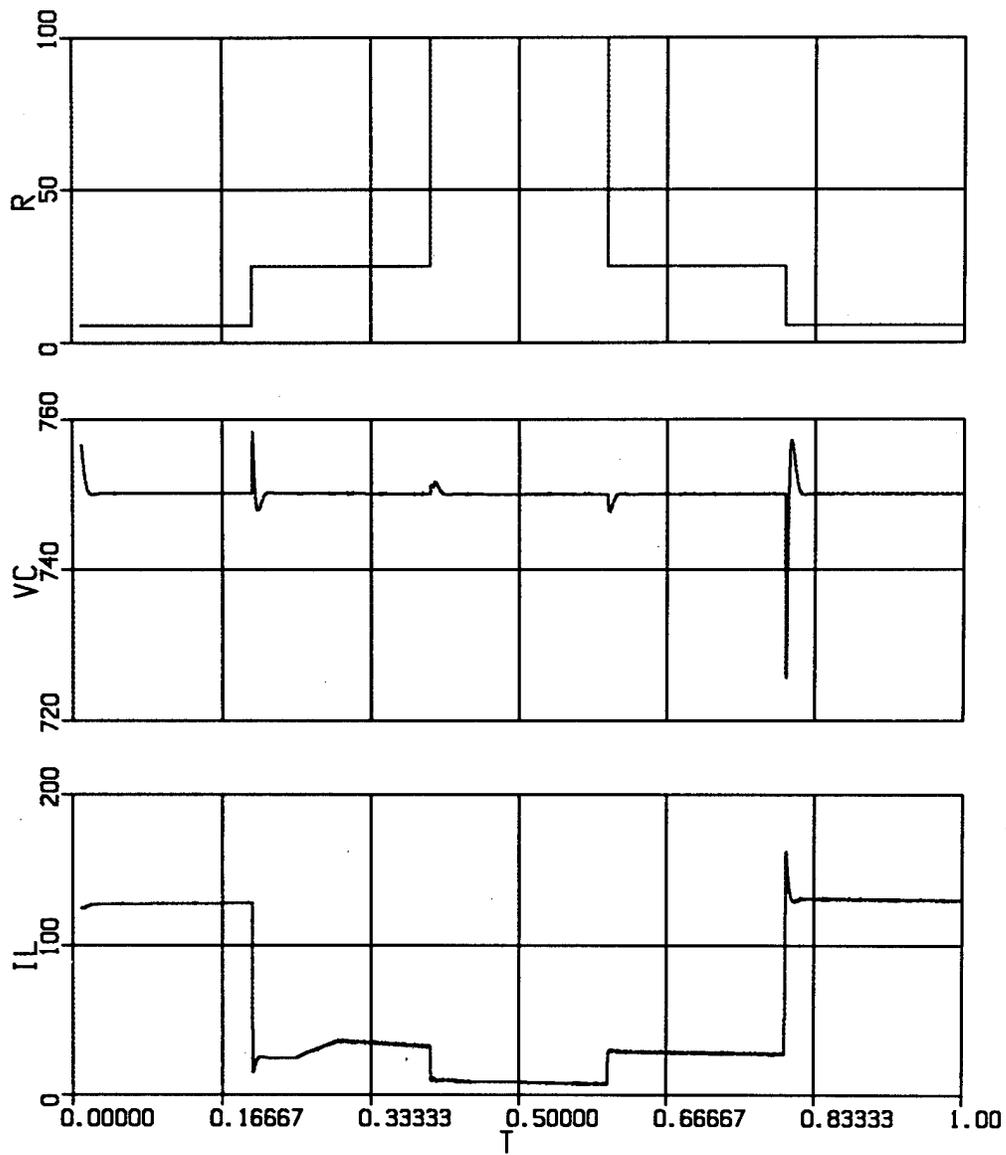


Figure 5.4: Resistive Load Step Change for Constant Source (Initial step 25 ohms)

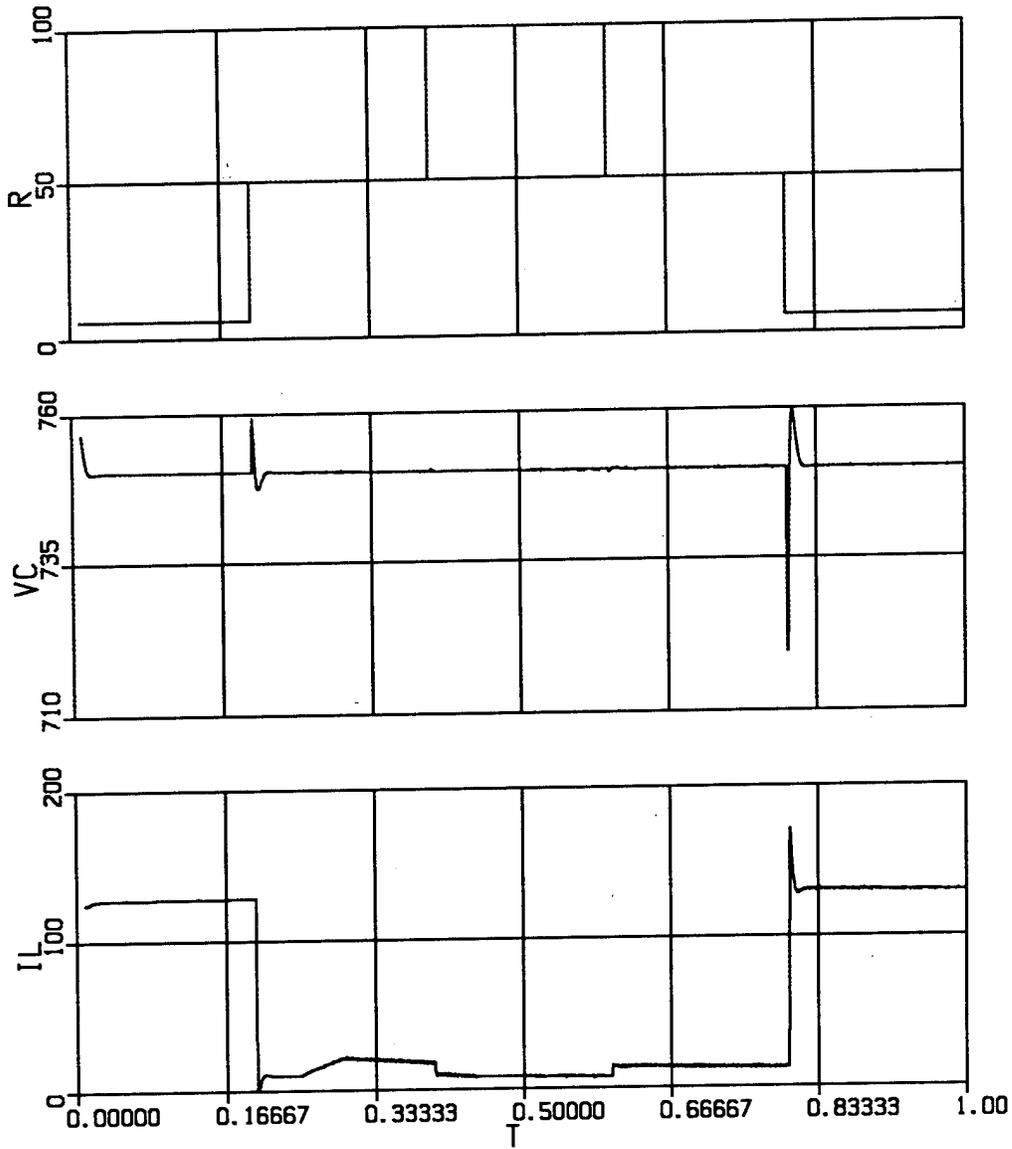


Figure 5.5: Resistive Load Step Change for Constant Source (Initial step 50 ohms)

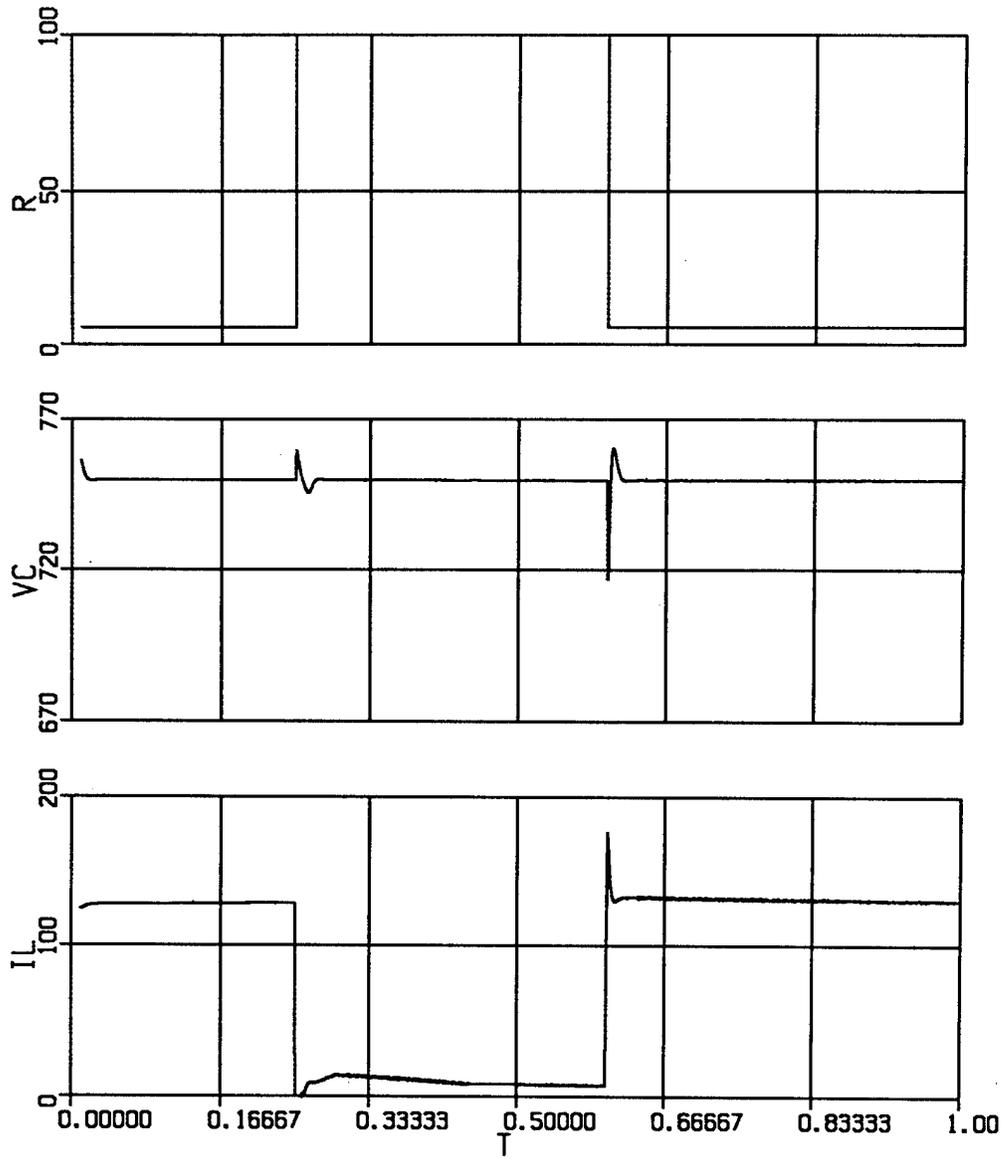


Figure 5.6: Constant Source Full Load Step Change

## B. ACTIVE SOURCE/VARIABLE LOAD SIMULATIONS

In this section, the operation and implementation of an active source is introduced. This source is then connected to the PSSCM and operation under various load conditions is investigated. In particular, studies are presented for changes in load resistance and the application of an inverter/induction motor load.

### 1. Design of Active Source

The active source configuration has a 3-phase voltage source, a rectifier stage and a low-pass filter stage as depicted in Figure 5.7. This is an “active” source because the output voltage,  $E$ , will vary as the current drawn from the rectifier varies.

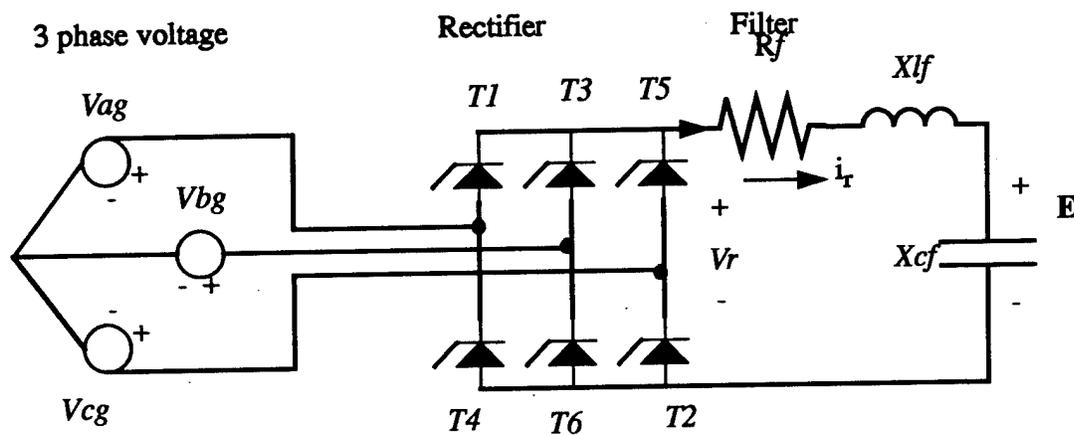


Figure 5.7: Active Source Configuration

The 3-phase line-to-neutral voltage source can be converted to a 3-phase line-to-line voltage source by scaling the amplitude by the square root of three and shifting the phases by thirty degrees. The line-to-neutral voltages are denoted by  $V_{ag}$ ,  $V_{bg}$  and  $V_{cg}$  while the line-to-line voltages are given by  $V_{ab}$ ,  $V_{bc}$  and  $V_{ca}$ . The 3-phase bridge rectifier

converts the 3-phase AC voltages to a DC voltage with harmonics at multiples of six times the source frequency. The average voltage out is  $0.955 V_{\max(abc)}$ . The rectifier is referred to as a six-pulse converter because, for continuous  $i_p$ , there are 6 segments to each period in the output waveform. A detailed discussion of the operation of the rectifier may be found in Chapter 5 of Fisher *Power Electronics* [5]. The RLC low-pass filter reduces the ripple voltage to a smooth usable DC voltage. The fundamental frequency of the ripple is 360 Hz for a 3-phase 6-pulse bridge rectifier. For a 12-pulse rectifier the ripple frequency is 720 Hz. Equation (3.18) dictates the necessary constraints required to specify a suitable cutoff frequency to eliminate the harmonics caused by the rectifier. The filter design used in the active source has a 10.3 Hz cut-off frequency which is well below the harmonics caused by the rectifier. The design values for the filter impedances  $X_{lf}$ ,  $X_{cf}$  and  $R_f$  are 4.725, 0.1332 and 0.236 ohms respectively. Appendix E contains a listing of the ACSL program for the active source.

## 2. Variable Resistive Load Simulations

Simulation studies identical to those presented for the fixed source in Section 3.B are shown in Figures 5.7 through 5.10 using the active source. The transient overshoot magnitudes in the output voltage and inductor current are similar to those encountered with the constant source. This holds for small and large step changes in load resistance, up or down. The primary difference between the active source simulations and the fixed constant source simulations is that the active source takes longer to adjust to the changes in load. In particular, the active source requires a longer time to respond as the load resistance is stepped upward. The second difference is that the active source has a slight ripple in the output voltage. As the load resistance increases, the ripple decreases. At the minimum load resistance level, the peak-to-peak ripple is only about 2.5 volts. This is a 0.33 percent variation in the output voltage. To try to increase the PSSCM performance, the multi-loop controller gain constants discussed in Chapter IV were set to a variable mode; that is, the

parameters  $h_v$ ,  $h_i$  and  $h_n$  were changed on-the-fly as the load resistance was changed. The results of these simulations showed no improvement in response and in general, comparable levels of performance as illustrated in the simulations with constant gain parameters.

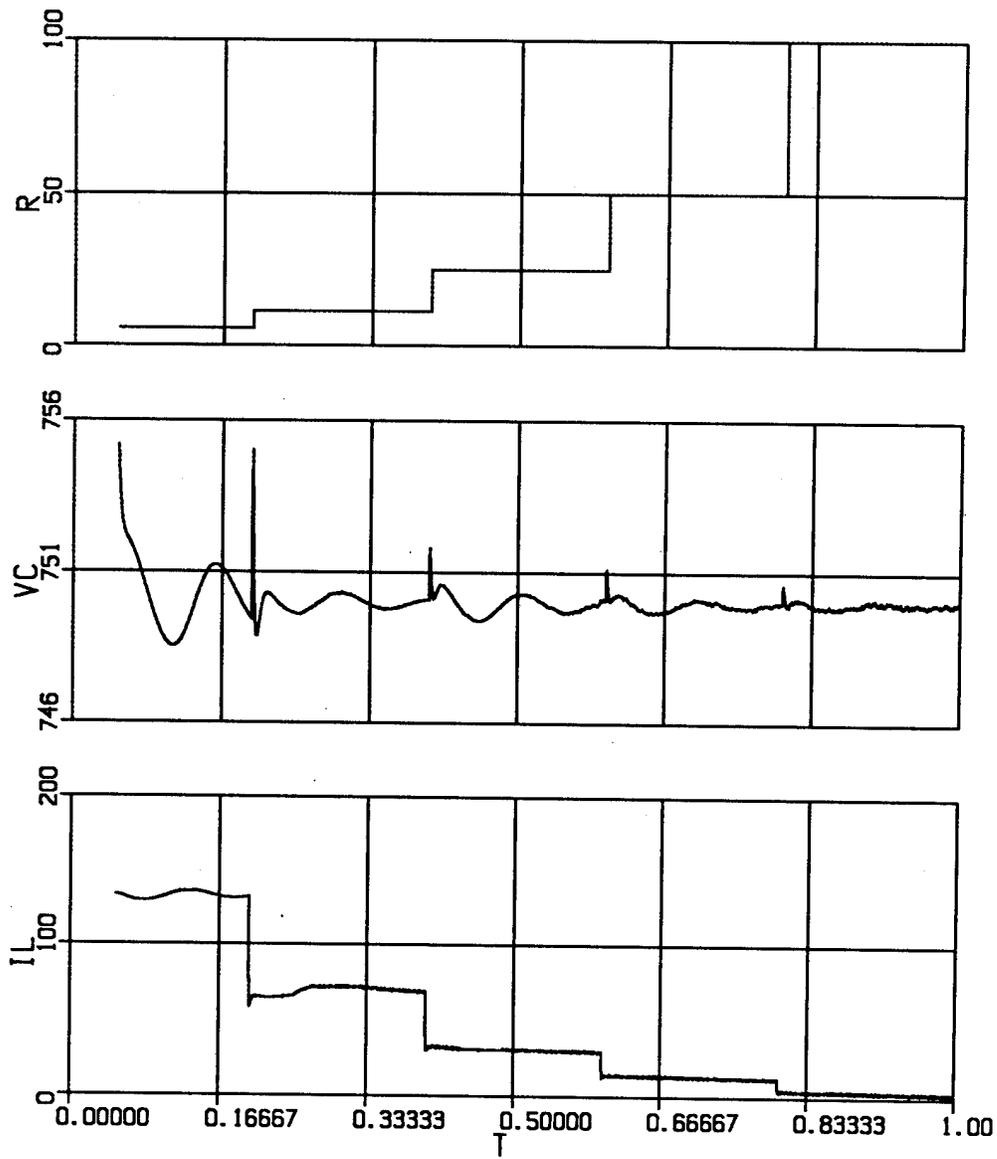


Figure 5.8: Small Step Changes in Load Resistance with Active Source

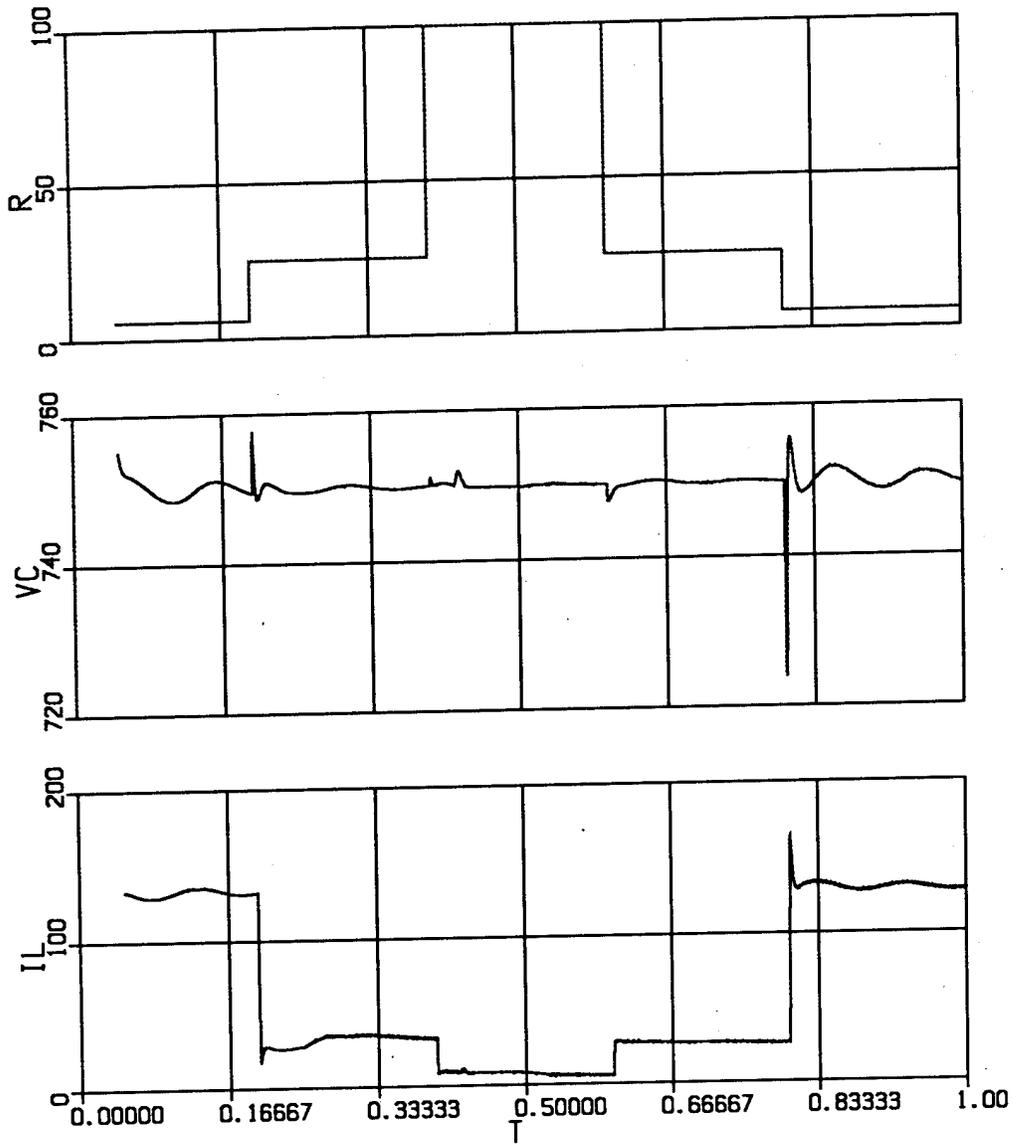


Figure 5.9: Analysis of Load Step from 5.625 to 25 ohms with Active Source

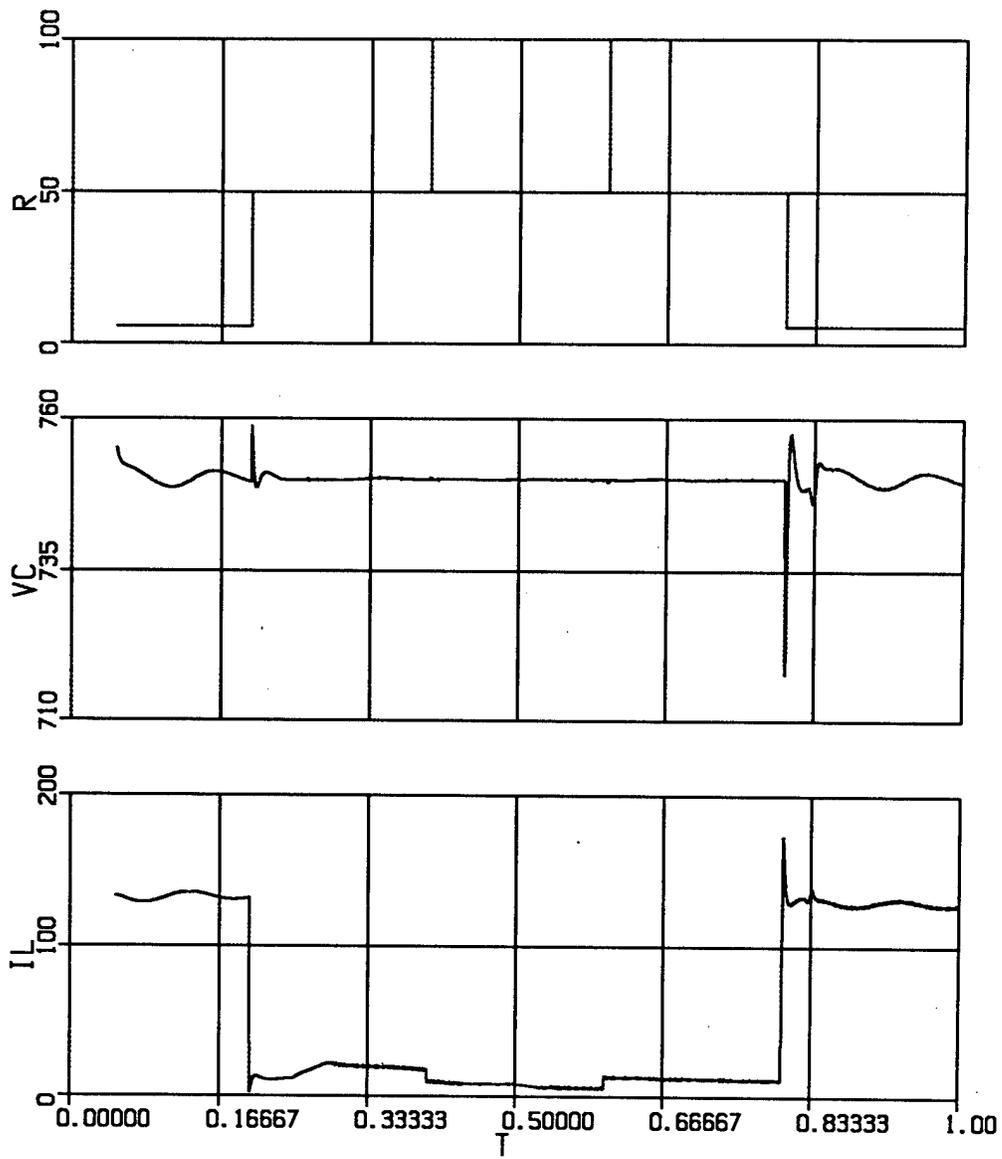


Figure 5.10: Analysis of Load Step from 5.625 to 50 ohms with Active Source

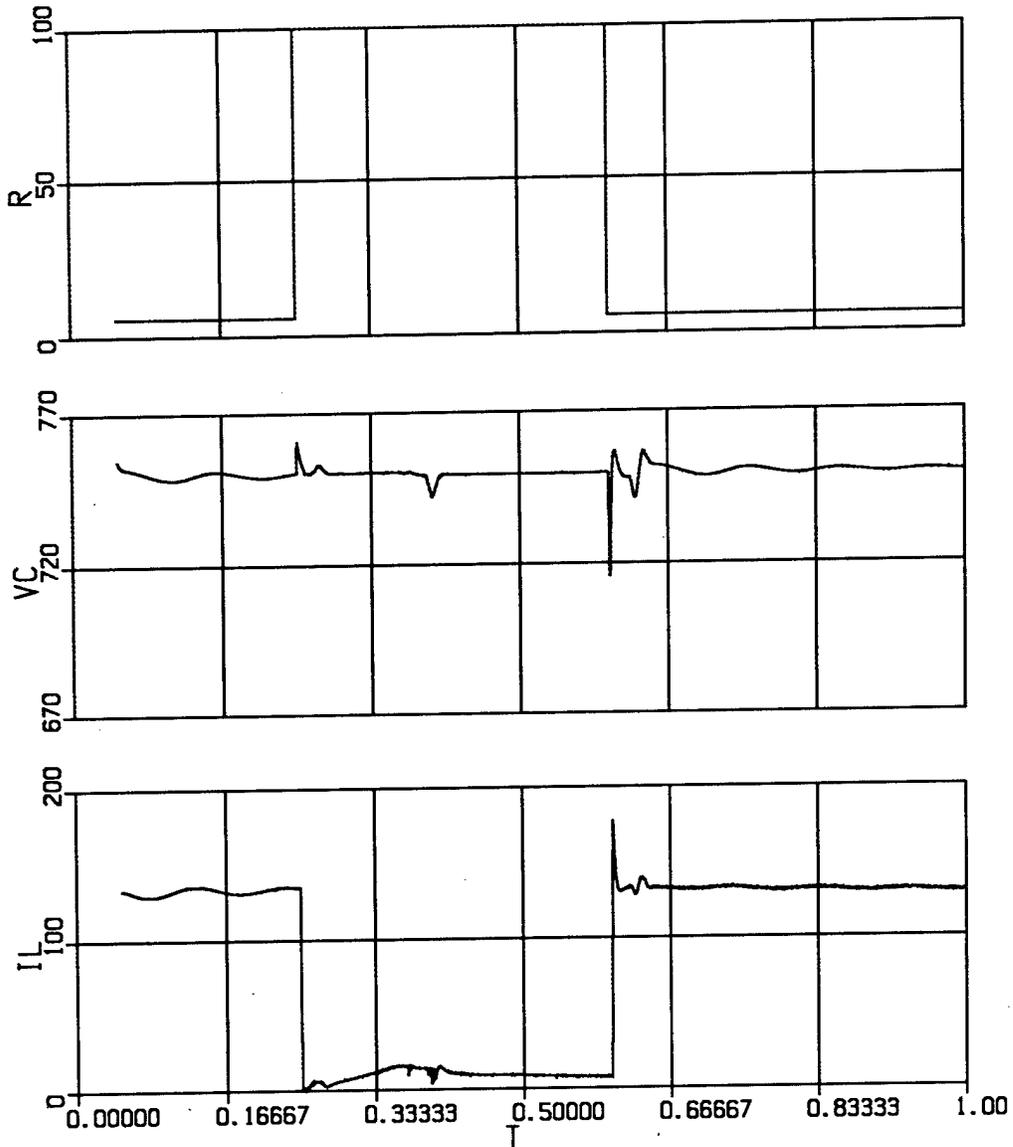


Figure 5.11: Active Source Full Load Step Change

### 3. Induction Motor Simulations

A 460 Volt 50 hp induction machine model was incorporated as a load on the Buck converter and various simulation studies were conducted. The machine parameters for the induction motor are listed in Chapter 4 of *Analysis of Electric Machinery* [6]. The rated speed is 1705 rpm which is equal to 178.55 rad /sec. The 460 volt ac power required to run the motor must be generated by a Ship Service Inverter Module (SSIM). The power to the SSIM is the 750 volt dc power provide by the PSSCM. The inverter peak phase voltage is  $2/\pi$  of the 750 volt input to the SSIM, which is 478 volts. The initial SSIM was configured as a six-step polyphase inverter system [5]. Without any current regulation, upon start-up this system drew unacceptable levels of current from the PSSCM. As a result, it also caused the inductor current to fluxuate between the continuous and discontinuous modes of operation.

The SSIM configuration employed in the ACSL simulations uses a hysteresis current controller. Chapter 2 of *Current Control of VSI-PWM Inverters* [7] and chapter 17 of *Mohan Power Electronics* [8] contain discussions on the operation of the hysteresis controller.

The hysteresis controlled PWM scheme is inherently current limiting, so large inrush currents caused by the induction machine are controllable. The hysteresis controller in conjunction with a vector controller changes both the commanded currents and the commanded current frequency. The vector controller, by fixing all of the rotor flux to be along the d-axis of the synchronous reference frame, provides near instantaneous torque control. The commanded current,  $i_{as}^*$ , is determined by the vector controller. The phase current,  $i_{as}$ , is subtracted from the command current in order to obtain the current error. If the current error is positive than the current is reduced by closing the top switch of the inverter leg. If the current error is negative than the current is increased by closing the other switch in the inverter leg. These switches are thus toggled on and off in what is termed a

pulse-width-modulation pattern. The same principle applies to the other two legs of the inverter.

The current and voltage equations used in the ACSL program to convert between the stationary and synchronous reference frame are derived in Krause, *Electromechanical Motion Devices* [9]. Appendix E contains the ACSL code for the simulation of the inverter and hysteresis controller in conjunction with the active source. Appendix F contains the induction machine macro which is required by the ACSL program in Appendix E.

Figures 5.12 and 5.13 portray the simulation results of the PSSCM operating with an induction motor and variable load resistance. In this simulation the load resistor is increased from 10 ohms to 20 ohms at 1.0 seconds, from 20 to 50 ohms at 2.0 seconds, and 50 ohms to 100 ohms at 3.0 seconds. The induction motor is in parallel with the load resistance, and is turned on at 0.05 seconds and reaches full speed in approximately 1.0 second. The change in resistance has negligible effect on the output voltage which would be expected because the parallel combination of motor resistance with the Buck resistor reduces the total load resistance. Though the average output voltage remains at a steady 750 volts the induction motor increases the ripple effect by about +/- 8 volts. The induction motor appears as approximately a 400 ohms average resistance at turn on and reduces to approximately 30 ohms at the 1705 rpm rated speed. Once the induction motor reaches rated speed, changes in the load resistance appears to have no effect on the motor speed. Even when the load resistor is removed, the maximum total average resistance not exceed 30 ohms at rated speed. The power required by the induction motor at rated speed is 18,750 watts. Table 5.2 contains the average value results of the simulations in Figures 5.12 and 5.13.

Figures 5.14 and 5.15 contain the simulation results of an induction motor in parallel with a load resistance of 100 ohms. The motor starts at 0.05 seconds and the study extends to 4.0 seconds. Before the induction motor is put on-line, the external resistance is equal to the converter load resistor. Under these conditions, the current operates near the boundary of the discontinuous mode. When the induction motor is put-on line the total

average resistance falls to about 80 ohms. This represents the parallel combination of the average 400 ohm resistance introduced by the induction motor and the 100 ohm load resistor. Once the motor reaches rated speed the average parameter values are the same as those documented in Table 5.2 with the 100 ohm resistor.

**TABLE 5.2: Effects of Resistance Changes on Induction Motor**

R ohms	R <sub>inv</sub> ohms	R <sub>total</sub> ohms	WRM r.p.m.	P <sub>inv</sub> kw	P <sub>total</sub> kw	Vc volts	I <sub>L</sub> amps
20	30	12	1705	18.75	47.0	750	62.5
50	30	19	1705	18.75	30.0	750	40.0
100	30	23	1705	18.75	24.5	750	32.6

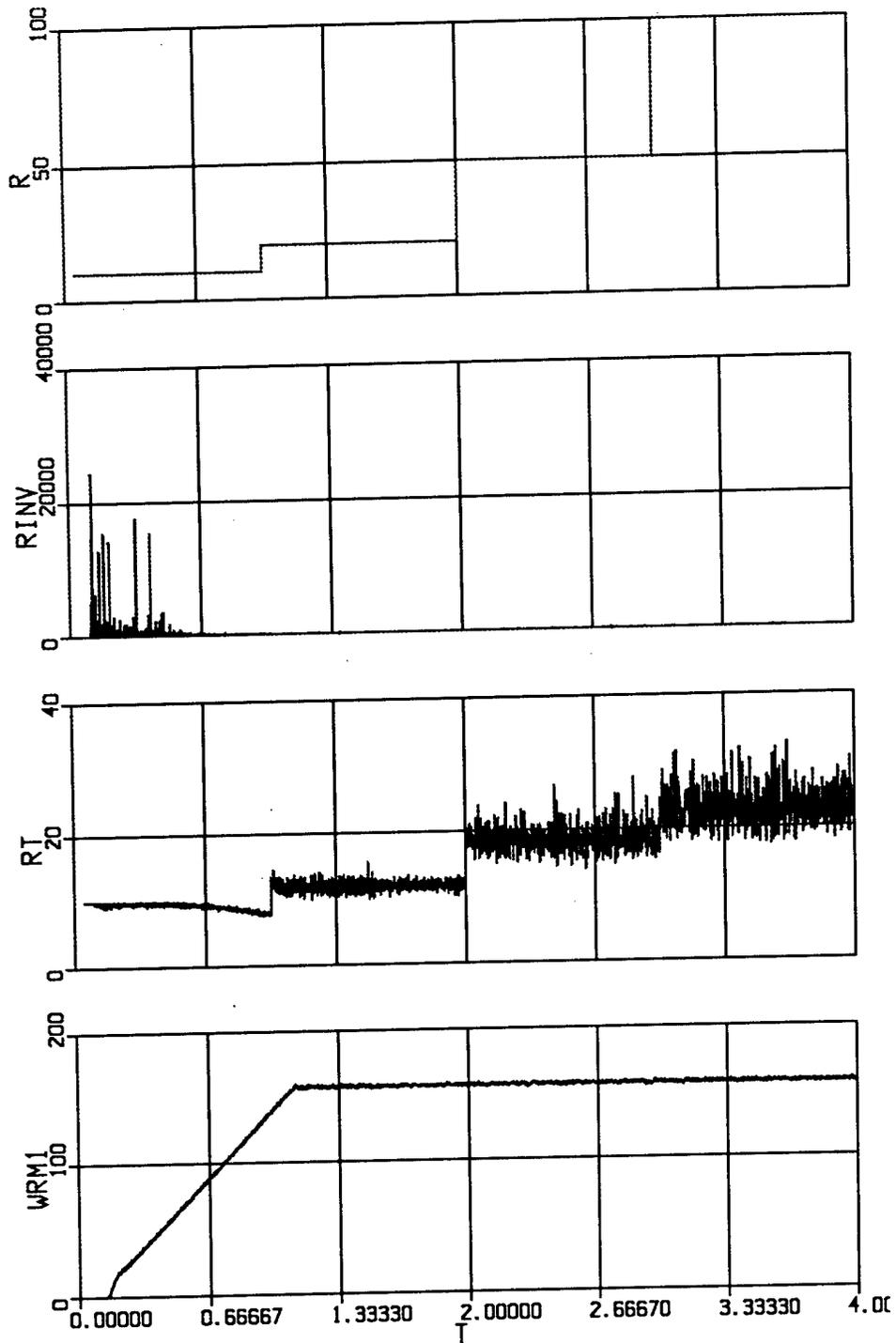


Figure 5.12: Variable Resistance Simulation with Induction Motor

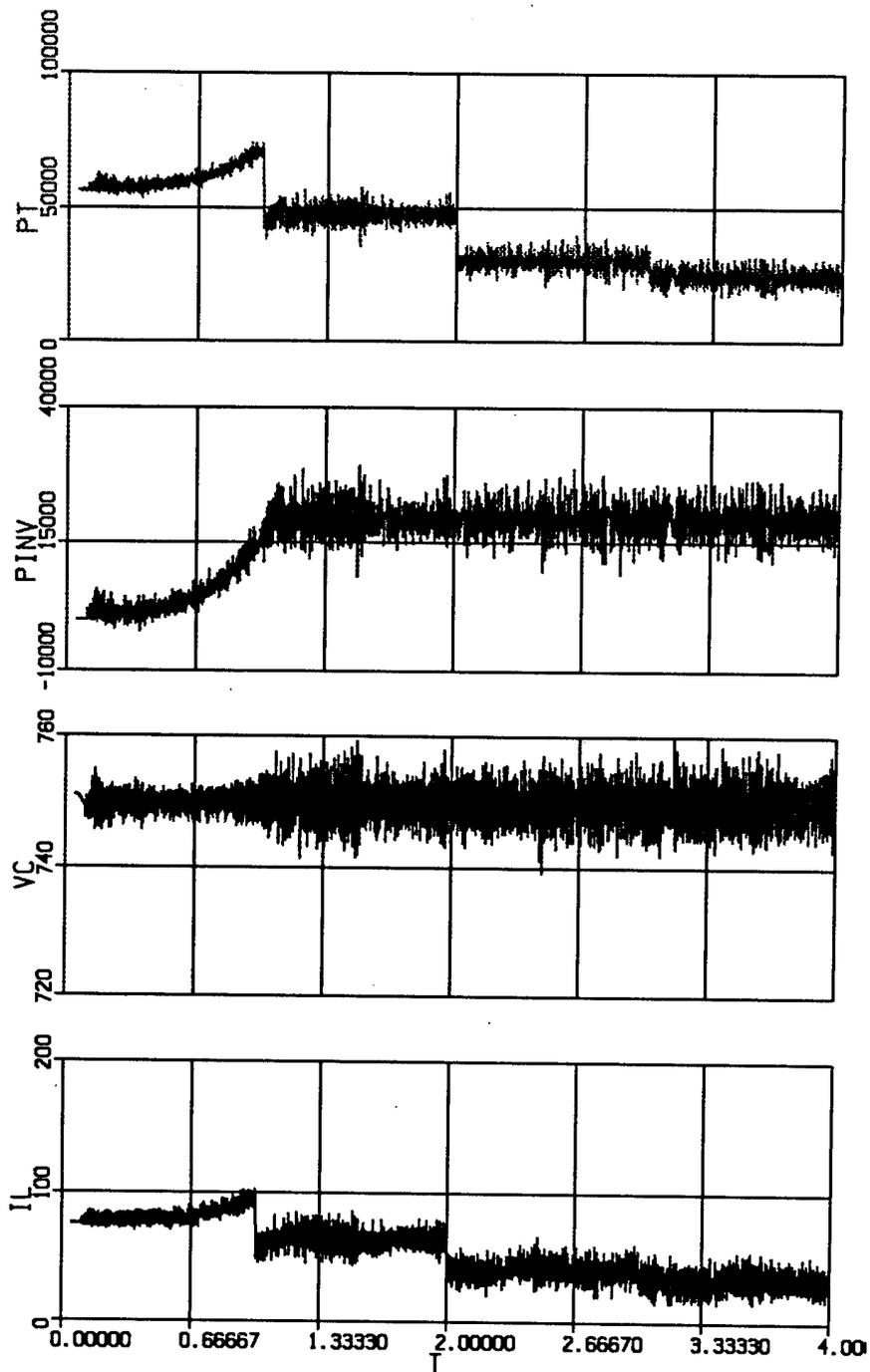


Figure 5.13: Variable Resistance Simulation with Induction Motor

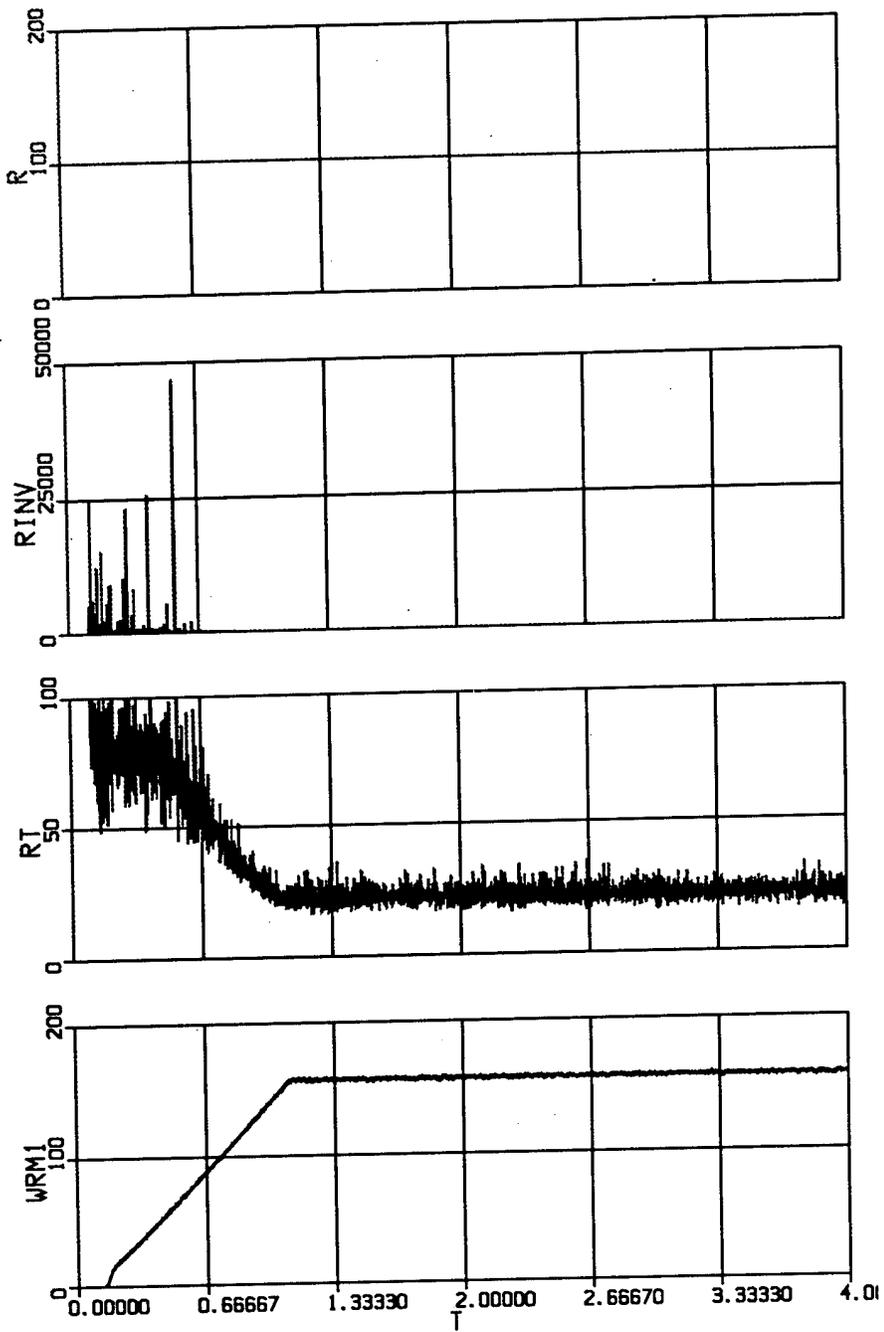


Figure 5.14: Induction Motor Simulation with R=100 ohms

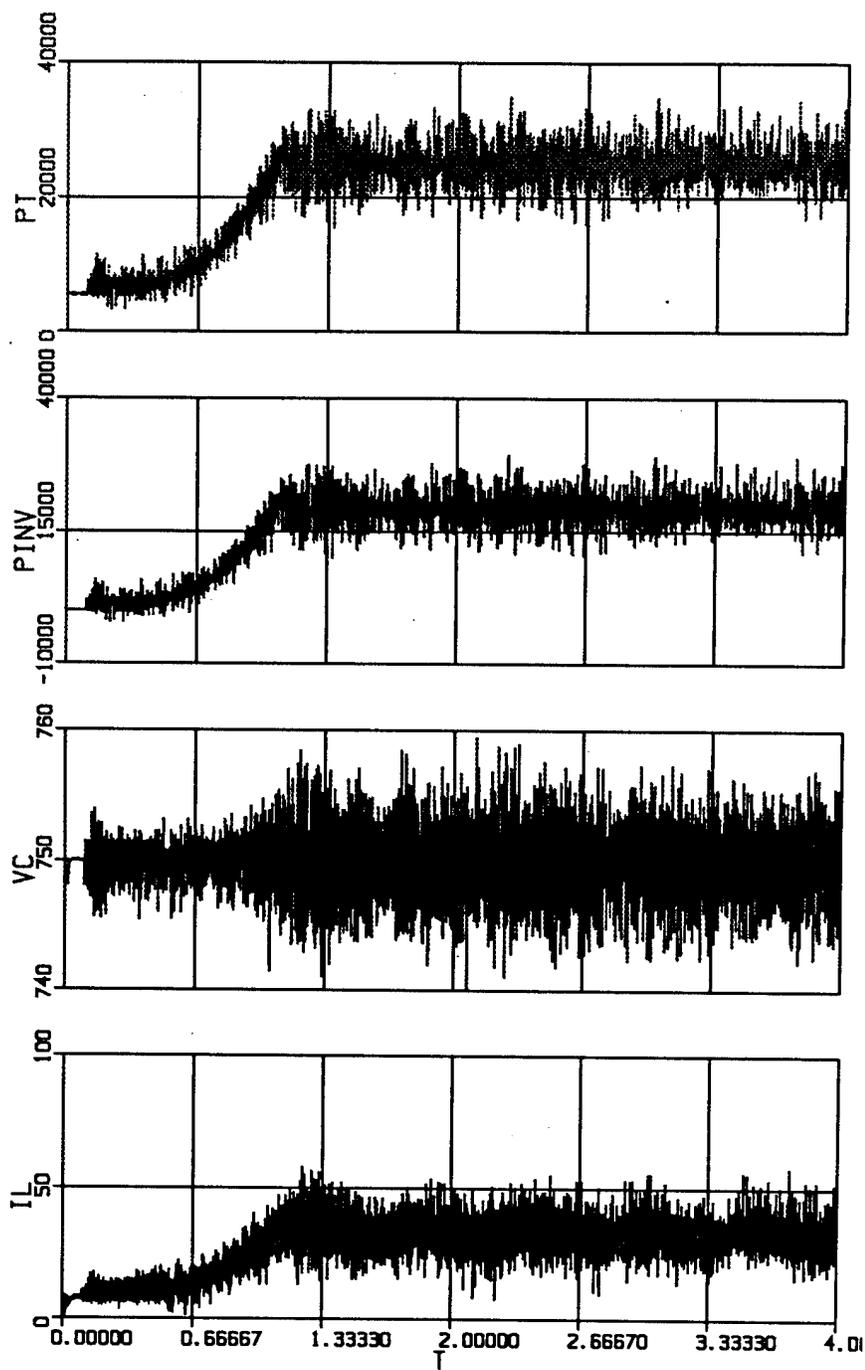


Figure 5.15: Induction Motor Simulation with R=100 ohms



## VI. ADVANCED PSSCM SIMULATIONS

In this chapter, the performance, characteristics and functionality of three specially configured dual converter systems are discussed and various simulation study results are presented.

### A. DUAL CONVERTER PARALLEL CONFIGURATION

The dual converter parallel configuration represents two separate PSSCMs regulating two independent zones off of the same bus as illustrated in Figure 6.1. The bus voltage is supplied by the active source discussed in Chapter V. The topological configurations for each of the PSSCMs are identical.

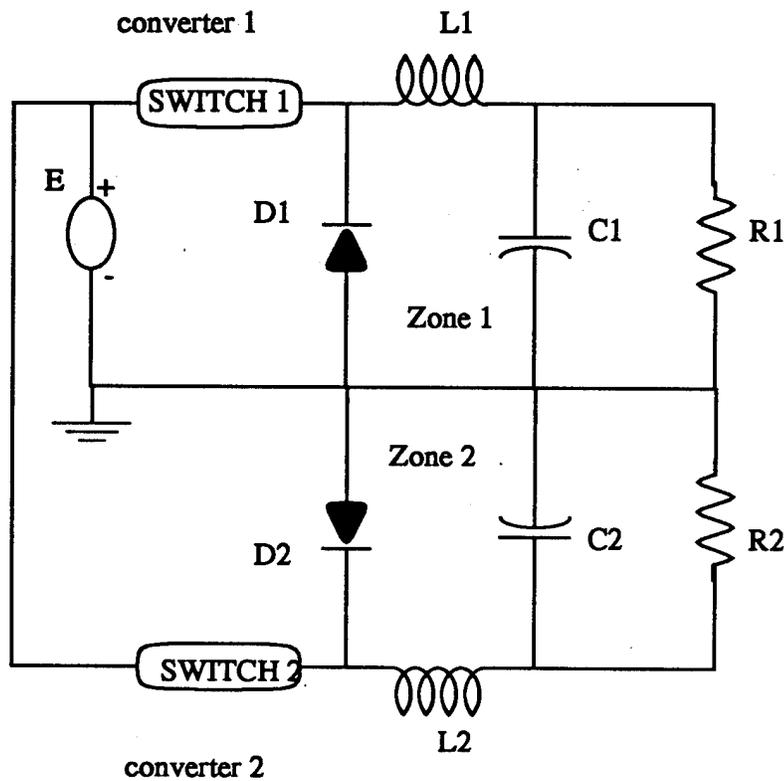


Figure 6.1: Dual Converter Parallel Configuration

Figures 6.2 and 6.3 illustrate simulation study results for both converters running 460 volt induction motors. Initially both converters have 100 ohm load resistors. At 1.0 second the induction motor in zone 1 is put on-line, and at 3.0 seconds the induction motor in zone 2 is put on-line. At the time the induction motor is put on line, the associated hysteresis inverter is also activated. The output voltages for both converters are found to be regulated at 750 volts with a +/- 12 volt variation. Each PSSCM is regulated by an independent multi-loop controller. The average inductor currents of both converters are near discontinuous until the motor is put on-line, then the currents increase to an average of approximately 65 amps at rated speed. Due to the designed ramp up of the commanded rotor speed, there is no noticeable effect on converter 1 when the second induction motor in zone 2 is put on-line. There is, however, a noticeable drop in the supply voltage. The bus voltage drops by about 13 volts when each induction motor is started. To simulate more than 2 zones a more stable active source should be used.

Figures 6.4 and 6.5 illustrate the inter-zonal effects of zone 2 transients leading to disturbances in zone 1. In particular, this simulation illustrates an induction motor operating in steady state in zone 1 while a large change in load resistance occurs in zone 2. At 2.5 seconds the zone 2 load resistance is stepped up from 5.625 ohms to 100 ohms and at 3.2 seconds the resistance is reduced back to 5.625 ohms. When the resistance is stepped up in zone 2, the voltage and inductor current in zone 1 has no noticeable transients, but when the resistance is stepped back down to 5.625 ohms there is some noticeable effects. The output voltage in zone 1 has transients of +/- 40 volts caused by the large power requirements of zone 2. In fact, the power requirement increases from 5.6 kw to 100 kw a factor of nearly 18 times. The power supply to the converters experiences large transients of approximately 100 volts caused by both the increase and decrease in load resistance in zone 1.

To simulate additional zones a steam turbine with a three-phase exciter can be used. The block diagram of this active source is illustrated in Figure 6.2. Appendix G contains the ACSL command for this active source including the macros required for simulation.

Single zone simulations performed with this active source were found to be equivalent to those presented for a constant fixed source. This follows because of the large capacity of the associated turbine/generator combination.

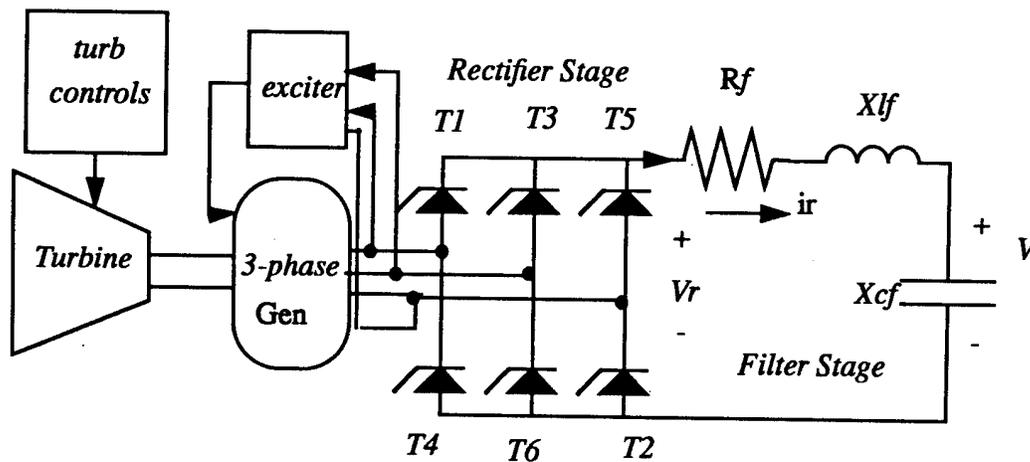


Figure 6.2: Steam Turbine with 3-Phase Synchronous Machine

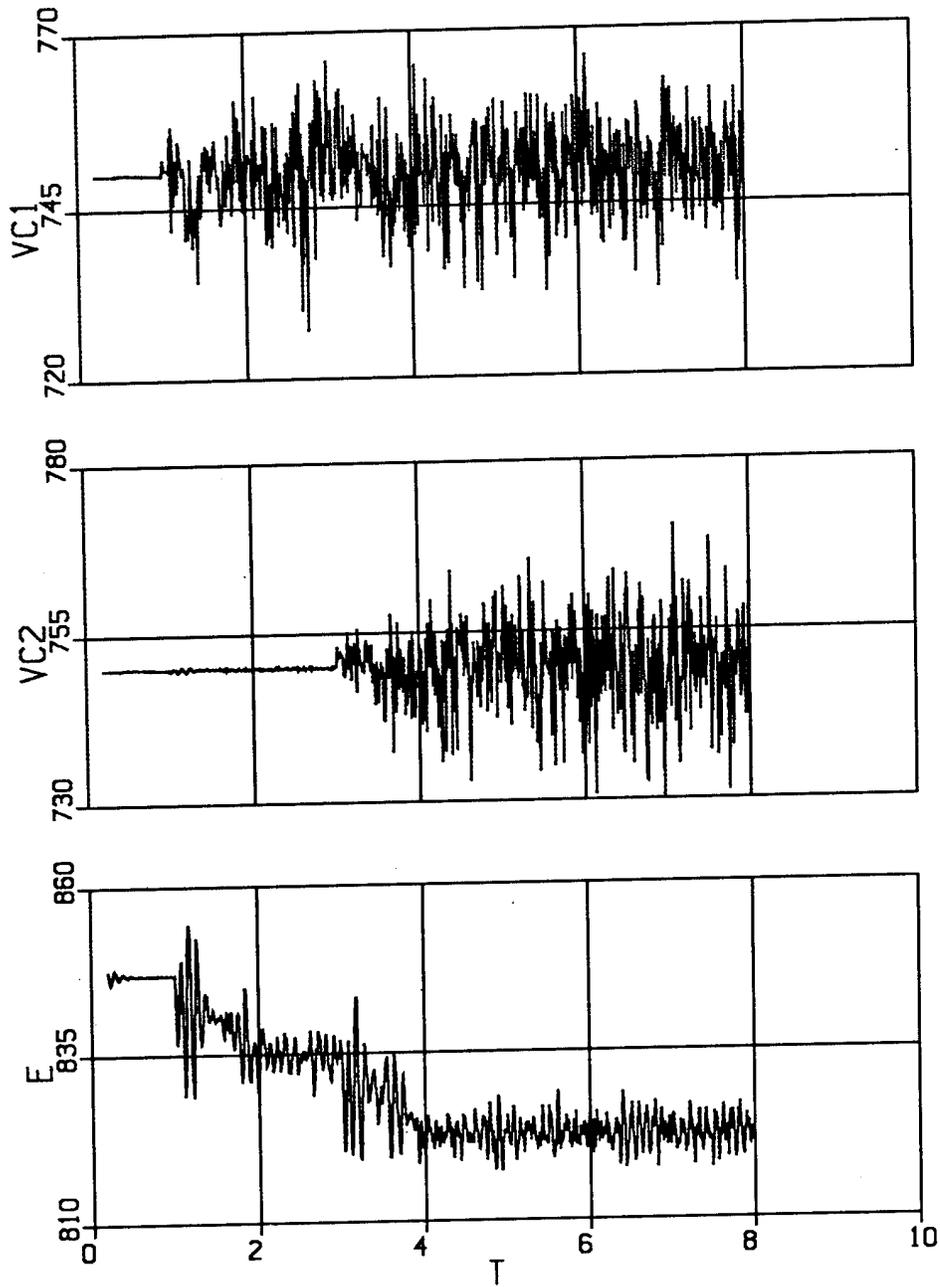


Figure 6.3: Simulations of Dual Zones with Induction Motors

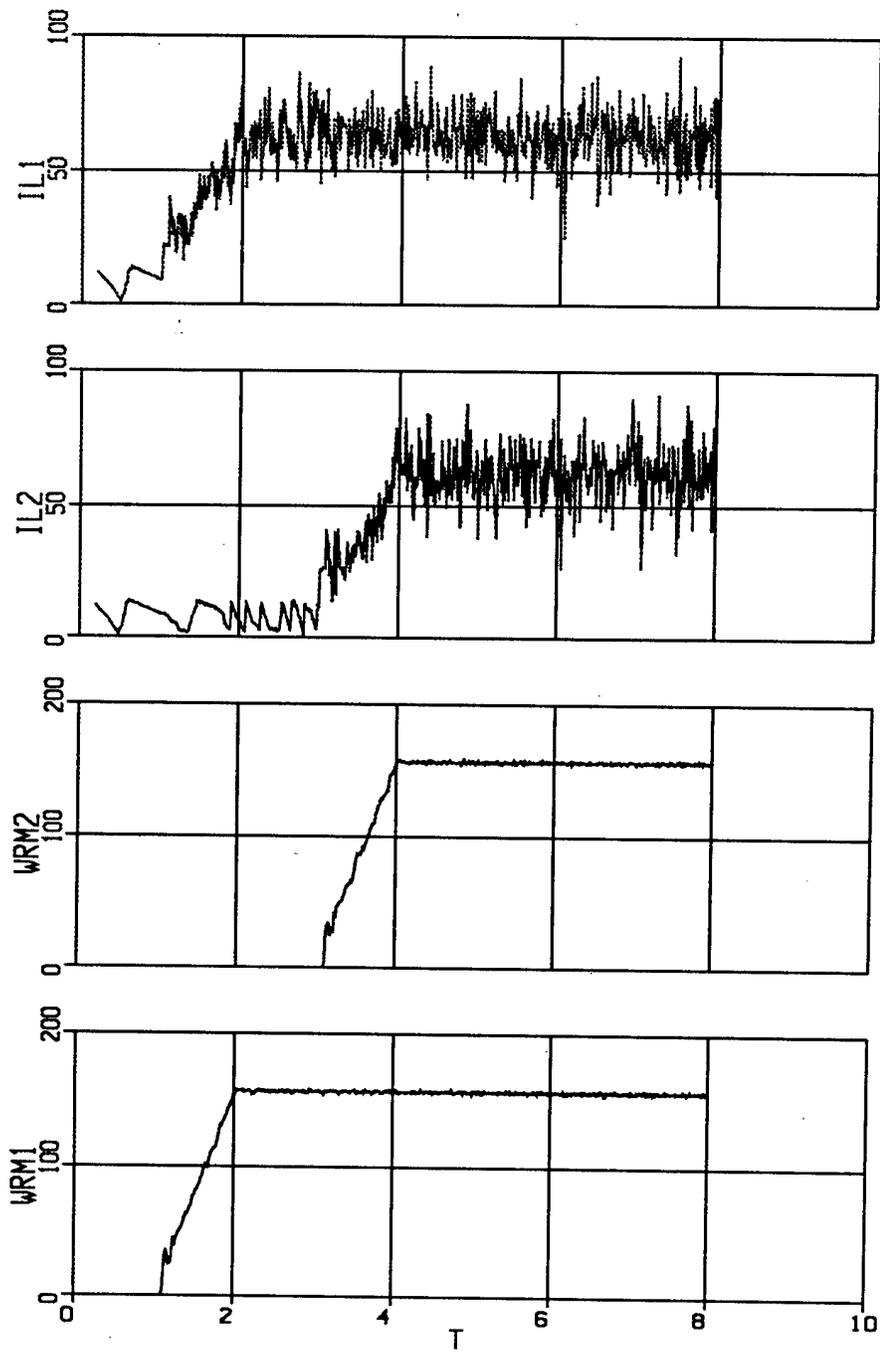


Figure 6.4: Simulations of Dual Zones with Induction Motors

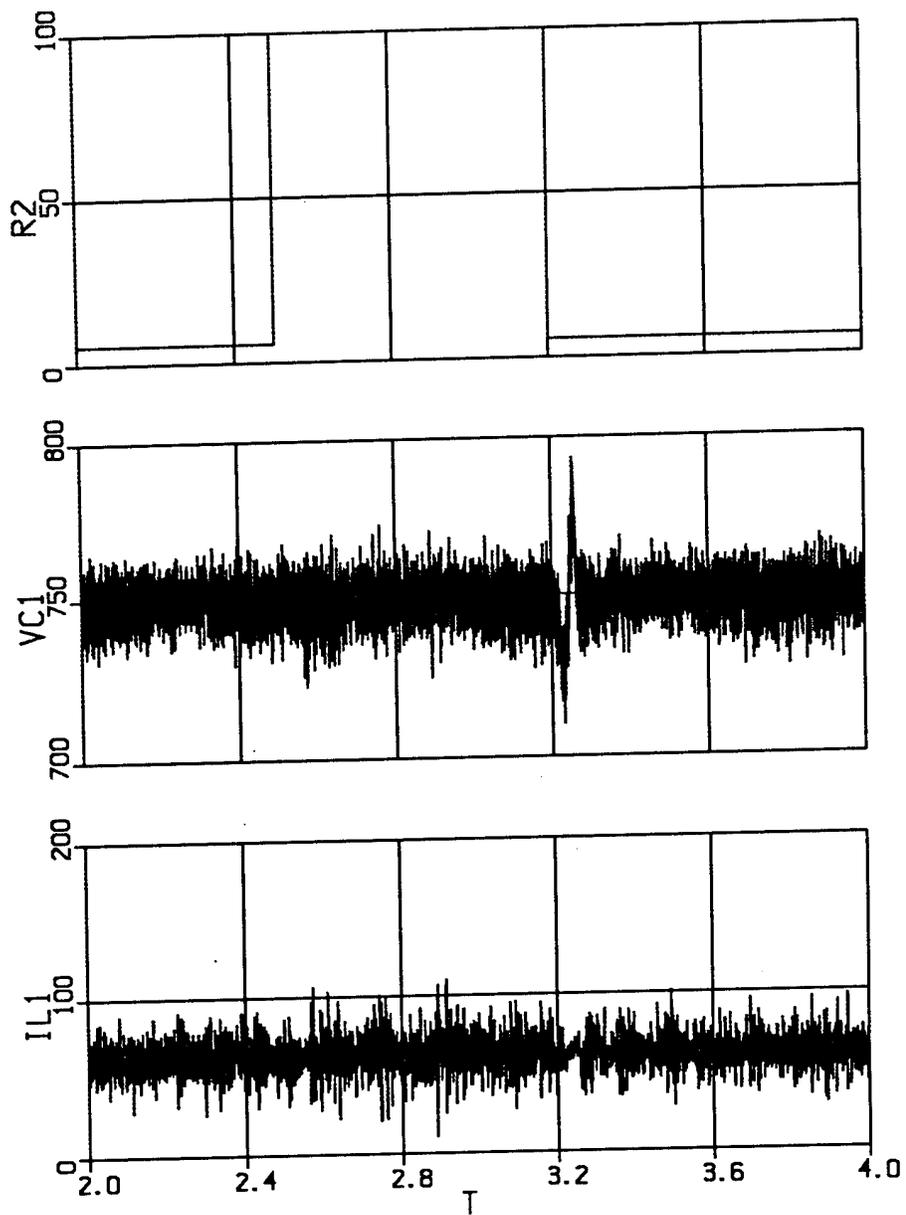


Figure 6.5: Inter-Zonal Effects

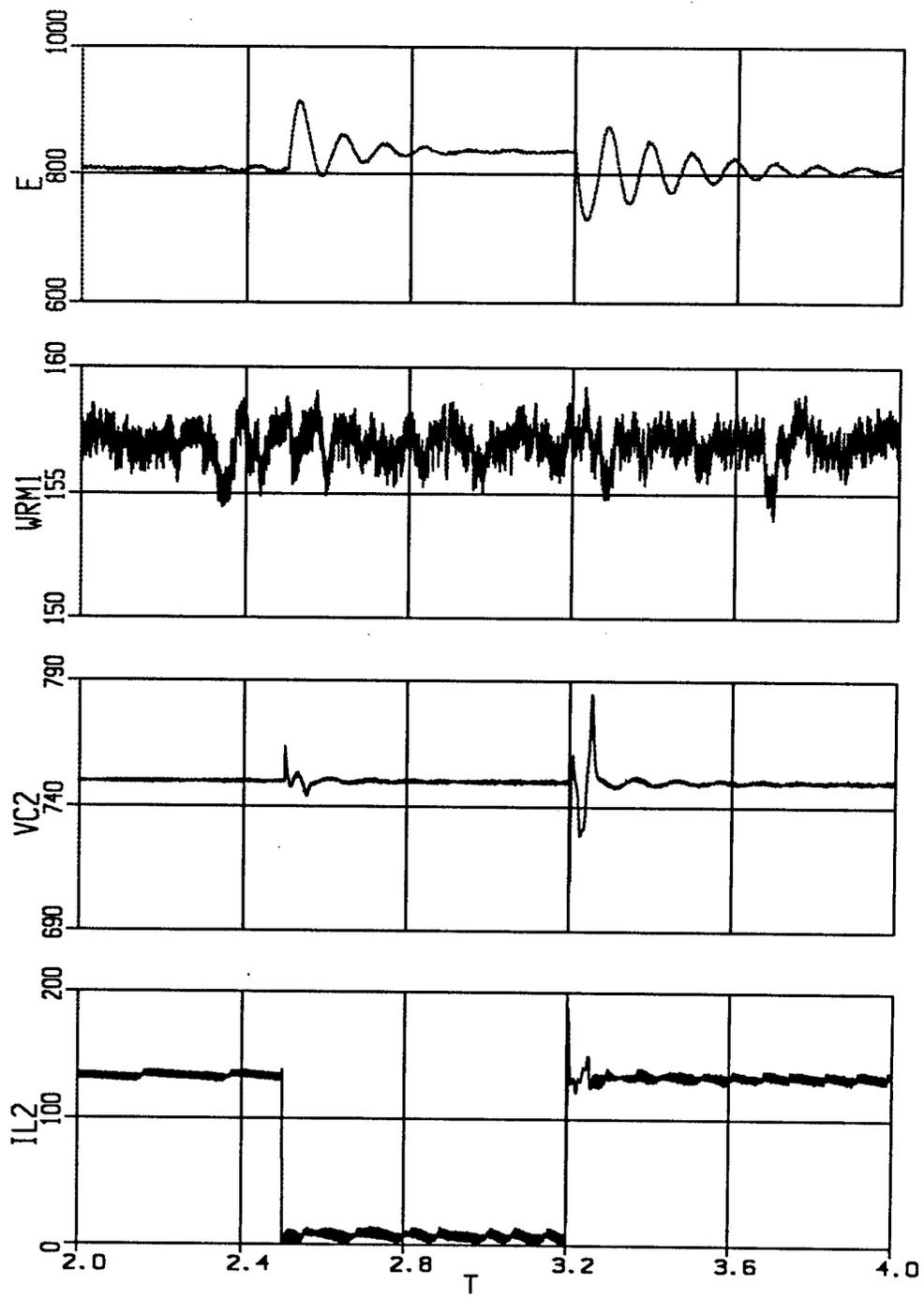


Figure 6.6: Inter-Zonal Effects

## B. DUAL CONVERTER SERIES CONFIGURATION

The dual converter series configuration simulates the PSSCM providing a regulated source of 750 volts to a second SSCM in the same zone. The secondary SSCM converts the 750 volt DC source to 500 volts DC. The 500 volt conversion was arbitrarily selected for simulation purposes. This section presents an analysis of the stability and performance of the primary system with changes in load resistance on the secondary system.

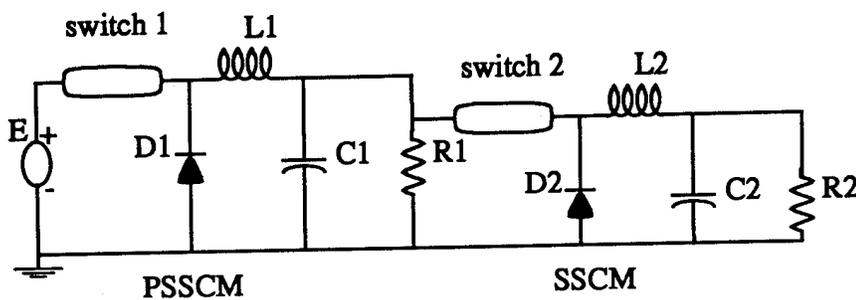


Figure 6.7: Dual Converter Series Configuration

Figures 6.8 and 6.9 illustrate simulations of the primary and secondary systems as the secondary converter is put on-line and the load resistance is varied. The input voltage to the primary converter is held constant at 850 volts and the resistor,  $R1$ , is 100 ohms. Both converters have the same inductor and capacitor component values, switching frequency, and multi-loop controller design. At 0.2 seconds the secondary converter is activated with the output voltage starting from an initial condition of zero. Because of the large transient power requirements, the output voltage of the primary converter experiences a sudden drop from 750 to 600 volts. This is a transient of 150 volts, which corresponds to 20.0 percent. The inductor current of the primary converter spikes up with an overshoot of 195 amps. The power required is 50 kW for a resistor of 5 ohms at 500 volts, which is 50 percent of the

maximum power specifications for a SSCM. The primary converter power requirement is increased from 7.23 kW for a 100 ohm resistor to 68 kW.

These transients are not tolerable and must be reduced by having a larger secondary converter resistance, adding a dampening network and/or ramping the turn-on phase of the secondary converter. At 0.4 seconds the resistance of the secondary converter is stepped up from 5 ohms to 40 ohms and at 0.7 seconds the resistor is decreased back down to 5 ohms. A value of 40 ohms was used as the maximum resistance because at 41 ohms the current goes discontinuous. The changes in load resistance of the secondary converter have little effect on the primary converter output voltage. Figures 6.8 and 6.9 illustrate the duty cycles for both primary and secondary controllers, represented by D1 and D2 respectively.

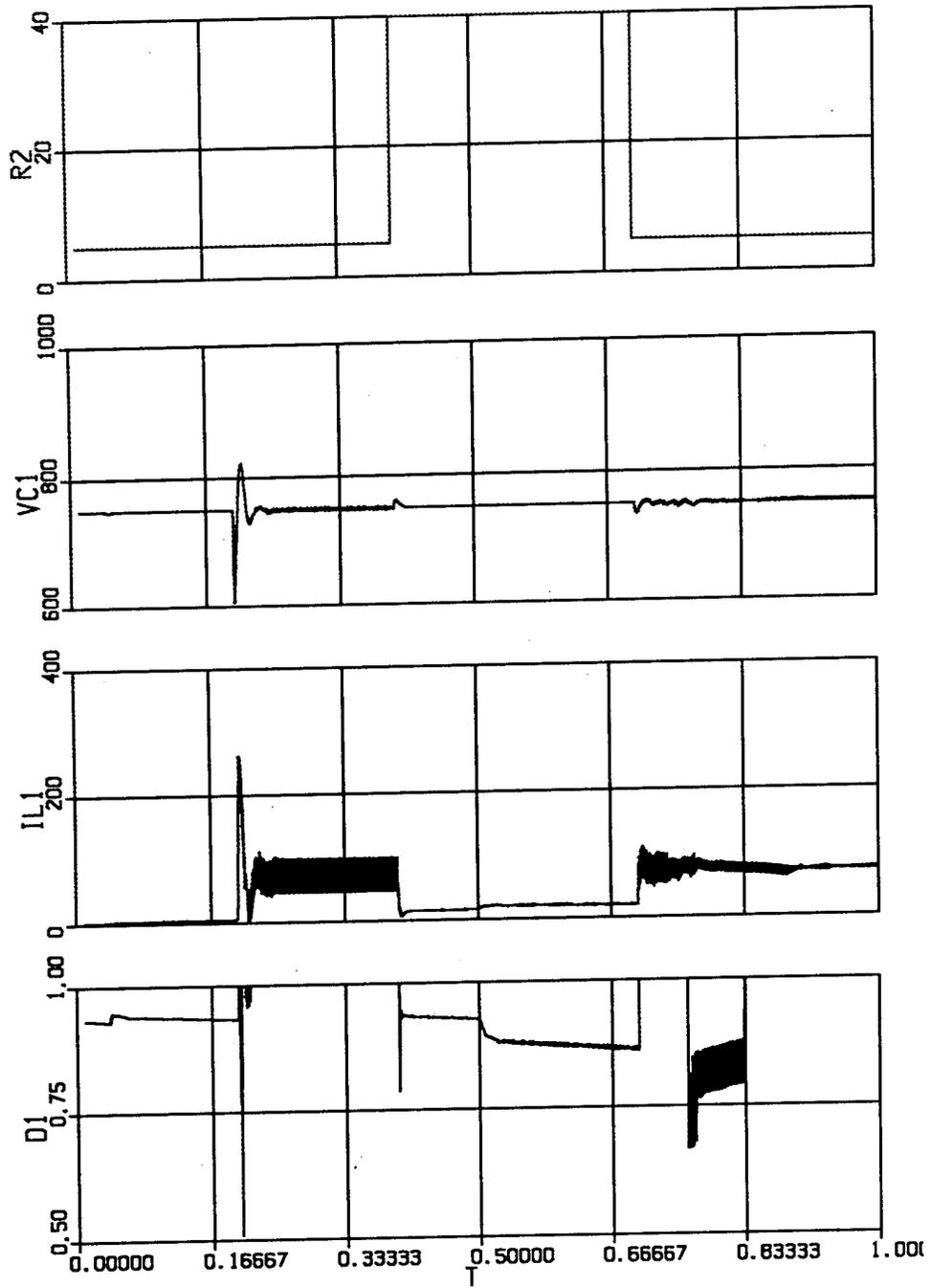


Figure 6.8: Simulation Effects Caused by Secondary SSCM

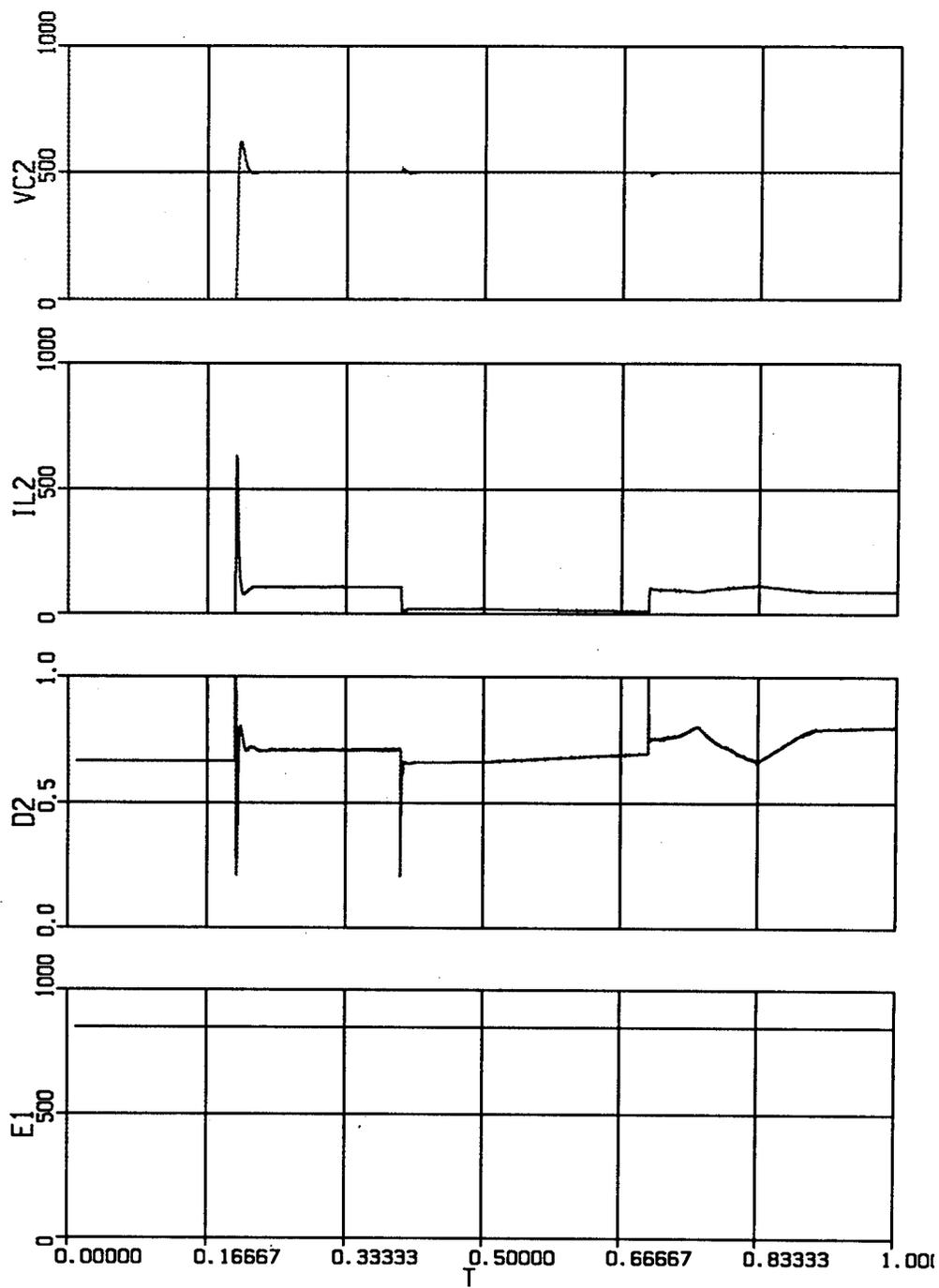


Figure 6.9: Simulation Effects Caused by Secondary SSCM

### C. DUAL CONVERTERS--INTERLACE CONFIGURATION

The interlace configuration represents an attempt to provide a zone with a more stable voltage source by integrating two partial Buck converter topologies together in a PSSCM. The design uses two multi-loop controllers to provide the voltage regulation for a given load as shown in Figure 6.10.

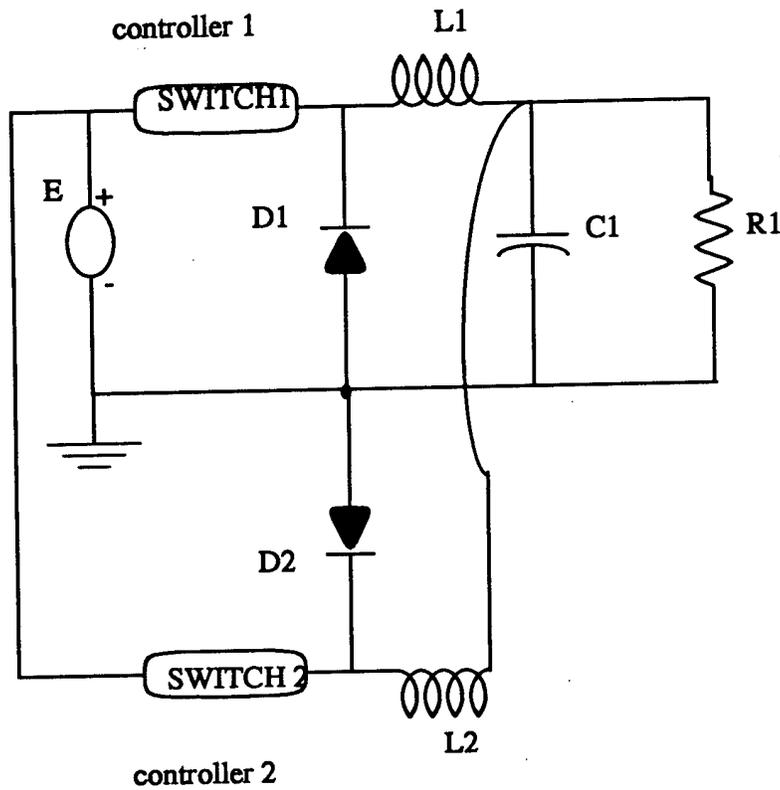


Figure 6.10: Dual Converter Interlace Configuration

Ideally, with 2 controllers providing regulation, the PSSCM performance should be enhanced, and the average currents through the switches and inductors should be reduced. To better analyze this system a constant source of 850 volts is supplied to the converters.

Several simulations were performed in an attempt to enhance the performance of the PSSCM. Depending on the simulation performed, at least one of the following parameters was changed: the switching frequency, the inductor values, the multi-loop controller parameters and/or the nominal duty cycle. The attempt to improve the performance of the PSSCM was unsuccessful. In most cases the performance was degraded using the interlaced controllers.



## VII. CONCLUSION

### A. OVERVIEW OF SHIPBOARD MORE -ELECTRIC

The design of the Primary Ship Service Converter Module (PSSCM) controls is the key to providing each zone with regulated and stable power. A representation of a PSSCM, upon employing various assumptions and reductions, was simulated using the Advanced Continuous Simulation Language (ACSL). After applying several assumptions, the PSSCM was reduced to a basic DC-DC Buck converter. Fixed constant sources and active sources were specified to investigate and critique the performance of the PSSCM.

To enhance the stability of the PSSCM, several controllers were implemented to control the duty cycle. From the three voltage controllers analyzed, the multi-loop controller yielded the most desirable performance. The multi-loop controller regulated the output voltage the most effectively by reducing the oscillations, voltage spikes and response times during transients.

### B. SUMMARY OF RESULTS

The basic concepts of the Buck converter were introduced and applied to both simulate the PSSCM and integrate it together with some typical zone loads. Several studies were analyzed to determine the stability and performance of the PSSCM. For the multi-loop controller, it has been shown that this regulation holds across the spectrum of large and small increases and decreases in load resistance. The PSSCM behavior is stable for both active and fixed sources. The power requirements of the PSSCM remain within tolerance as long as the total output converter resistance is maintained above 5.625 ohms. Appropriate regulation of the currents required by active loads, such as induction machines, must be maintained for the PSSCM to operate properly. It was shown that a vector controlled inverter system possessed the current controlling capabilities required for successful operation with a PSSCM.

The simulations performed to study the effects of two PSSCM running simultaneously from the same power source illustrated that inter-zonal effects are present for large changes in power requirements. The effects of putting secondary converters on-line are significant and must be considered to avoid intolerable disturbances. Though for less demanding conditions, it has been shown that this regulation holds across the spectrum of typical load resistance changes and induction machine operations. To increase the stability of the converters a damping resistor or a RC damping network can be included. A damping network would enhance the transient time and overshoot performance. Though additional component cost, weight and space limitation should be considered.

The effort to increase the performance, reliability and efficiency of the Buck converter by interlacing the control signals applied to paralleled converters was unsuccessful.

### C. FUTURE RESEARCH CONSIDERATIONS

The steam turbine active source discussed in Chapter VI can be implemented together with several representative zones. This larger scale analysis would give a better representation and further insight into the performance and stability issues, especially inter-zonal effects. A 12-pulse rectifier system can be designed and implemented to replace the 6-pulse rectifier system discussed in Chapter V. The non-ideal effects caused by the inductor resistance and switch resistance can be incorporated into the analysis to get a more comprehensive model of the SSCM.

By including in the analysis and simulations snubber circuits, AC filtering capacitors, bleeder resistors and other non-ideal effects discussed in Chapter III, the efficiency of the PSSCM can be better assessed.

## REFERENCES

- [1] Ciezki, J.G., and R.W. Ashton, "Itinerary and Travel Research Summary," April 1994.
- [2] Blalock, H.G., "Power Electronic Converter Simulation, Real Time Control and Hardware-in-the-loop Testing for a Shipboard Integrated Power System," Engineer Thesis, Naval Postgraduate School, Monterey, CA, 1994.
- [3] Power System Group, "*Shipboard Service Converter Module (SSCM) 100 kw DC/DC Converter Conceptual Design*," Power Paragon Company, Rev A, 1995.
- [4] Liu, Y.F., S.P. Huang, "*Function Control-A Novel Strategy to Achieve Improved Performance if the DC-to-DC Switching Regulators*," *IEEE INDELEC* vol. 42, April 1995, pp. 186-191.
- [5] Fisher, M.J., "*Power Electronics*," PWS-Kent Publishing Company, Boston, MA, 1991.
- [6] Krause, P.C., O. Wascyncuk, "*Analysis of Electric Machinery*," McGraw-Hill Book Company, New York, NY 1986.
- [7] Broad, D.M., "Current Control of VSI-PWM Inverters," Engineer Thesis, University of Wisconsin-Madison, Wisconsin, 1994.
- [8] Mohan, N., T.M. Undeland, W.P. Robbins, "*Power Electronics: Converters Applications and Design*," Wiley, NY, 1989.
- [9] Krause, P.C., "*Electromechanical Motion Devices*," McGraw-Hill Book Company, New York, NY 1989.



## APPENDIX A. MATLAB PROGRAM FOR FINDING VOLTAGE CONTROLLER GAINS

```
% Determine control parameter gains for controllers for PSSCM
%
f=5e3;
T=1/f;
E=850;
Vc=750;
D=Vc/E;
d=0.0;
dcap = (D + d)*T;
Z=D*T;
r1=5.625;
r2=11.25;
r=5.625;
c=2600e-6;
L=1.35e-3;
w=2*pi*f;
m1=-300 +j*200;
m2=-300 -j*200;
m3=-3000;
m=[m1,m2,m3];
chm=poly(m); % results gives: 1 3600 1.93e6 3.9e8
%
% PID voltage controller gains:
kd= (L*c/E)*(chm(2) - (1/(r*c))) % 1.458e-5
kp= (L*c/E)*(chm(3) - 1/(L*c)) % .0068
```

ki= (c\*L/E)\*(chm(4)) % 1.6105

aa= kp/(r\*c) - ki + (-1/((r\*c)^2)) + 1/(L\*c))\*kd;

bb= kd/(r\*c^2) - kp/c;

cc= (-E/(L\*c))\*kd;

A=[-1/(r\*c) , 1/c ,0; -1/L , 0 , E/L; aa ,bb, cc];

% multi-loop controller gains:

hI= (chm(2)\*(L\*r\*c) - L)/(E\* r \*c) % .0056

hN= chm(4)\*(L\*c)/E % 1.6105

hV= (chm(3)\*(L\*r\*c) -E\*hI - r)/(E\*r)% .0058

## APPENDIX B. IMPLEMENTATION OF CONTROLLERS IN ACSL

### 1.) PID voltage controller

$$K_d = 1.458e-5$$

$$K_i = 1.6105$$

$$K_p = 0.0068$$

$$\text{delVc} = (V_c - V_{cD})$$

$$V_{cx} = \text{INTEG}(\text{delVc}, 0.0)$$

$$f_{vh} = \text{INTEG}(V_{cy}, 0.0)$$

$$V_{cy} = (K_d * \text{delVc} - \text{INTEG}(V_{cy}, 0.0)) / (TD)$$

$$\text{delID} = -K_p * \text{delVc} - V_{cy} - K_i * V_{cx}$$

$$D = \text{BOUND}(1.0e-5, 1.0, V_{cD}/E + \text{DelID})$$

### 2.) Function Control controller

$$K_{vc} = 50.0$$

$$V_{ref} = 764.0$$

$$D = (K_{vc} * (V_{ref} - V_c) + L * pIL) / E$$

### 3.) Multi-loop controller

$$h_I = 0.0056$$

$$h_N = 1.6105$$

$$h_V = 0.0058$$

$$\text{delILd} = (I_L - V_{cD}/R)$$

$$\text{delVc} = (V_c - V_{cD})$$

$$V_{cx} = \text{INTEG}(\text{delVc}, 0.0)$$

$$\text{!delID} = -h_V * \text{delVc} - h_I * \text{delILd} - h_N * V_{cx}$$

$$!D = \text{BOUND}(1.0e-5, 1.0, V_{cD}/E + \text{DelID})$$

## APPENDIX C. BASIC BUCK CONVERTER FOR CONTINUOUS AND DISCONTINUOUS MODES OF OPERATION

### 1.) ACSL PROGRAM WITH CONSTANT OUTPUT VOLTAGE

!

PROGRAM

INITIAL

MAXTERVAL maxt = 1.0e-5 !"maximum integration step size"

MINTERVAL mint = 1.0e-9

CINTERVAL cint = 5.0e-6 !"data communication interval"

ALGORITHM ialg = 5 !"integration algorithm"

! "4--R.K. 2nd, 5--R.K. 4th"

NSTEPS nstp = 1

CONSTANT tstop = 1.0 !"stop point for integration"

CONSTANT FreqT = 5.0e+3 !"switch frequency"

IL=126.8

TD= 1.0/FreqT ! "switching time length"

iminx=0.1

WW = TD ! "dumby variable for schedule use"

MIN1 = 0.0 ! "value for comparison purposes only"

slope = 1.0 ! "used for incrementing WW for schedule"

LOGICAL TSC1, TSO1 ! "TSC1 = time switch closed for converter"

TSC1 = .true. ! "TSO1 = time switch open for converter"

TSO1 = .false.

LOGICAL CM, NCM ! "CM = continuous mode"

CM = .true. ! "NCM = discontinuous mode"

NCM = .false.

```

LOGICAL TD2O, TD2A  ! "TD2O = time D2 is off during discontinuous mode"
TD2O = .false.    ! "TD2A = time D2 is active during discontinuous mode"
TD2A = .true.    ! "D2 is the time the induction curent becomes zero"
END ! "of initial"

DYNAMIC

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

DERIVATIVE

CONSTANT E= 850.0 ! "voltage source for Buck"
CONSTANT Vc= 750.0  ! "voltage across the load of Buck
! (note: this is for constant load R)"
CONSTANT L = 1.35e-3  ! "Buck inductance"
CONSTANT C = 2600.0e-6  !" buck capacitance"
CONSTANT R = 5.625    ! "load resistance of buck"
Imin = BOUND(0.0, 1.0e+3,Iminx) ! "current limit across inductor
!never goes below zero"
SCHEDULE finalCM1 .xn. IL - min1 ! "when inductor current (IL)
! "goes to zero the conveter goes discontinuous "
PROCEDURAL(D2,D,Imax,Iminx = Vc,E,L,R,TD)    !"find D = time ratio of
!switch on/off"
IF (CM) THEN                                ! "continuous mode"
  D = Vc/E
  Imax= D*E*((1.0/R)+((1.0-D)*TD/(2*L)))
  Iminx= D*E*((1.0/R)-((1.0-D)*TD/(2*L)))
ELSE                                         ! "Discontinuous mode"
  k = (Vc/E)**2.0 / (2.0*(1.0 - Vc/E))
  D = sqrt((4.0*L*k)/(R*TD))
  D2 = (D/2.0)*(1.0 + sqrt(1.0 + (2.0/k)))

```

```

    Imax = (Vc/L)*(D2-D)*TD
    Iminx = (Vc/R) - (Vc/(2.*L))*(1.-D)*TD
ENDIF
END

WT = INTEG(slope, 0.0)
SCHEDULE final1B .xz. WT - D*WW ! "needed to initiate TSC1 to TSO1 at D"
SCHEDULE final2B .xz. WT - WW ! "needed to initiate TSO1 to TSC1
! at new cycle"
SCHEDULE finalD2 .xz. WT - D2*WW ! "needed to initiate location IL
! goes to zero during cycle"
PROCEDURAL(pIL = E,Vc,L,TSC1,TSO1,CM,NCM,Imax, diff)
! "finds slope of IL"
IF ((TSC1) .AND. (CM)) THEN
    pIL = (E-Vc)/L
ELSEIF ((TSO1) .AND. (CM)) THEN
    pIL = -Vc/L
EISEIF ((TSC1) .AND. (NCM)) THEN
    pIL = (E - Vc)/L
EISEIF ((TSO1) .AND. (TD2A)) THEN
    pIL = - (Vc/L)
ELSE
    pIL = 0.0
ENDIF
END

IL = INTEG(pIL, 0.01) ! "finds IL"
power = (Vc**2.0)/R
END ! "of derivative"
DISCRETE final1B
TSC1 = (.false.)
TSO1 = (.true.)

```

```
END
DISCRETE final2B
  TSC1 = (.true.)
  TSO1 = (.false.)
  TD2A = (.true.)
  TD2O = (.false.)
  WT = 0.0
  IL=Imin
END
DISCRETE finalCM1
  CM = (.false.)
  NCM = (.true.)
END
DISCRETE finalCM2
  CM = (.true.)
  NCM = (.false.)
  TSC1 = (.true.)
  TSO1 = (.false.)
  TD2A = (.true.)
  TD2O = (.false.)
  WT =0.0
END
DISCRETE finalD2
  TD2O = (.true.)
  TD2A = (.false.)
END
END ! "of dynamic"
END ! "f program"
```

## APPENDIX D. PSSCM REDUCED-ORDER MODEL CONFIGURATION WITH MULTI-LOOP CONTROLLER WITH FIXED SOURCE

PROGRAM

INITIAL

MAXTERVAL maxt = 1.0e-5 !"maximum integration step size"

MINTERVAL mint = 1.0e-9

CINTERVAL cint = 5.0e-6 !"data communication interval"

ALGORITHM ialg = 5 !"integration algorithm"

! "4--R.K. 2nd, 5--R.K. 4th"

NSTEPS nstp = 1

CONSTANT tstop = 1.0 !"stop point for integration"

CONSTANT FreqT = 5.0e+3 !"switch frequency"

TD = 1.0/FreqT !"switching time length"

WW = TD !"dummy variable for schedule use"

slope = 1.0 !"used for incrementing WW for schedule"

LOGICAL TSC1, TSO1 !"TSC1 = time switch closed for converter"

TSC1 = .true. !"TSO1 = time switch open for converter"

TSO1 = .false.

Vcy=0.0 !" i.c. for D part of PID controller

Vc = 750.0 !" initial voltage across the load of Buck"

DelD = 0.0 !" initial perturbation of D "

END !"of initial"

DYNAMIC

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

DERIVATIVE

CONSTANT E= 850.0 !"voltage source for Buck"

CONSTANT Vcd= 750.0 !"desired voltage across the load of Buck"

```

CONSTANT L = 1.35e-3    ! "Buck inductance"
CONSTANT C = 2600.0e-6 ! " buck capacitance"
CONSTANT R = 5.625     ! "load resistance of buck"
WT = INTEG(slope, 0.0)
SCHEDULE final1B .xz. WT - D*WW    ! "needed to initiate TSC1 to TSO1 at D"
SCHEDULE final2B .xz. WT - WW      ! "needed to initiate TSO1 to TSC1
! at new cycle"
PROCEDURAL(pIL = E,Vc,L,TSC1,TSO1) ! "finds slope of IL"
IF (TSC1) THEN
    pIL= (E-Vc)/L
ELSEIF (TSO1) THEN
    pIL = -Vc/L
ENDIF
END
IL= BOUND(0.0,1000.0, LIMINT(pIL,0.0,0.0,1000.0)) ! "finds IL"
ir= Vc/R
ic= IL- ir
Vc= (1/c)*INTEG(ic, 0.0)
! Multiloop controller
hI=0.0056
hN=1.6105
hV=0.0058
delILd = (IL - VcD/R)
delVc = (Vc - VcD)
Vcx = INTEG(delVc,0.0)
delD= -hV*delVc - hI*delILd - hN*Vcx
D = BOUND(1.0e-5,1.0, VcD/E + DelD)
END ! "of derivative"

```

DISCRETE final1B

TSC1 = (.false.)

TSO1 = (.true.)

WTX = 0.0

END

DISCRETE final2B

TSC1 = (.true.)

TSO1 = (.false.)

WT = 0.0

END

END ! "of dynamic"

END ! "f program"

## APPENDIX E. PSSCM CONFIGURATION WITH MUTI-LOOP CONTROLLER FOR ACTIVE SOURCE

```
!" This program runs a 460v 50hp induction motor
INCLUDE 'MACROS/im3arb.mac' !" induction machine macro"
PROGRAM
INITIAL
MAXTERVAL maxt = 1.0e-5 !"maximum integration step size"
MININTERVAL mint = 1.0e-7
CINTERVAL cint = 4.0e-3 !"data communication interval"
ALGORITHM ialg = 5 !"integration algorithm"
    !"4--R.K. 2nd, 5--R.K. 4th"
NSTEPS nstp = 1
CONSTANT tstop = 3.0 !"stop point for integration"
CONSTANT tpio3 = 2.0943951 !"two pi over three"
sqrt3 = SQRT(3.0)
CONSTANT wrmpk = 157.0 !"in rad/sec = 1500 RPM"
CONSTANT tacc = 1.0 !"time to accelerate"
CONSTANT tcbinv = 0.1 !"time at which inverter connected"
LOGICAL cbinv !"connects to inverter/motor"
cbinv = .FALSE. !"initially disconnected"
CONSTANT FreqT = 5.0e+3 !"switch frequency"
CONSTANT Vmag = 890.0 !"votage magnitude of generated source"
CONSTANT L = 1.35e-3 ! SSCM component values
CONSTANT C = 2600e-6
CONSTANT R = 5.625
spin = 0.0 !" angle for rectifier turn on/off diode
```

```

iS = 0.0          !" ic current through converter switch"
ir1 = 0.0 !" ic current through R"
IL = 0.0  !" ic through inductor"
iavginv = 0.0 !"initial average inveter current"
VEic= Vmag*(.95493)  !" ic for voltage source E"
delD = 0.0          !" initial pertubation of duty cycle"
TD= 1.0/FreqT !"time duration for one duty cycle"
WW = TD            !" variables for control of duty cycle"
slope = 1.0
CONSTANT VcD = 750.0  !" inverter input voltage"
! "gives max volt of 460"
! " rms line-to-line"
D = .8824          !"D=Vc/E"
LOGICAL TSC1, TSO1 ! "TSC1 = time switch closed for converter"
TSC1 = .true. ! "TSO1 = time switch open for converter"
TSO1 = .false.
LOGICAL Multiloop
Multiloop = .true.
LOGICAL T1r,T2r,T3r,T4r,T5r,T6r !"Recifier logic"
T1r =.true.
T2r =.true.
T3r =.false.
T4r =.false.
T5r =.false.
T6r =.false.
! "set the initial ramp up rate for the desired"
! "induct motor speed"
IF (cbinv) THEN

```

```

pin = wrmpk/tacc
ELSE
pin = 0.0
ENDIF
! "initialize inverter switch states to all lower closed"
SA = .false.
SB = .false.
SC = .false.
CONSTANT TLrated = 165.0 !"rated motor load torque"
END ! "of initial"
DYNAMIC
TERMT (t .GE. (tstop-0.5*cint))
DERIVATIVE
CONSTANT B1 = 0.0 ! " friction damping coefficient"
CONSTANT J1 = 0.07 ! " inertia of load and motor"
! " assumed equal to 0.035 kg-m2"
CONSTANT wrmic1 = 0.0 ! " rotor speed initial cond."
CONSTANT thrmic1 = 0.0 ! " rotor position i.c."
CONSTANT hyst = 1.0 !"hysteresis level for curr control"
CONSTANT idsestar = 27.56 !"sets sidre = 360.48"
CONSTANT v0s1 = 0.0
CONSTANT PI = 3.141593
CONSTANT KKK = 2.094395 ! "(2*pi)/3, constant for 3 phase"
CONSTANT Wb= 377.0
CONSTANT Rlf= 0.236 !"Filter component values
CONSTANT Xcf= 0.1332
CONSTANT Xlf= 4.725
CONSTANT kp = 5.0!"proportional gain for spd control"

```

```

CONSTANT ki = 200.0!"integral gain for speed control"
! "generates the desired rotor speed"
wrmdes = INTEG(pin, 0.0)
!"schedule when ramp up of speed is over"
SCHEDULE rampoff .XP. t-tacc-tcbinv
! "schedule when ramp up of speed begins"
SCHEDULE invon .XP. t-tcbinv
Vab = Vmag*cos(spin + (KKK/4.0)) ! "3 phase source"
Vbc = Vmag*cos(spin - 3*(KKK/4.0))
Vca = Vmag*cos(spin + 5*(KKK/4.0))
CONSTANT a1 = 3600 !"coefficinents for characteristic equation"
CONSTANT b2 = 1.93e6
CONSTANT c3 = 3.9e8
spin=INTEG(377.0, 0.0) !"regulates the rectifier switching speed"
!"produces the rectified output from the 3 phase source
PROCEDURAL(Vr = T1r,T2r,T3r,T4r,T5r,T6r,Vca,Vbc,Vab)
  IF ( (T1r) .AND. (T2r)) THEN !"Vr is rippled DC voltage"
    Vr=-Vca
  ELSEIF ((T2r) .AND. (T3r)) THEN
    Vr=Vbc
  ELSEIF ((T3r) .AND. (T4r)) THEN
    Vr=-Vab
  ELSEIF ((T4r) .AND. (T5r)) THEN
    Vr=Vca
  ELSEIF ((T5r) .AND. (T6r)) THEN
    Vr=-Vbc
  ELSEIF ( (T1r) .AND. (T6r)) THEN
    Vr= Vab

```

```

ENDIF
END
!"Turns on and off thyristors for rectifier
SCHEDULE final1r .XP. spin - (2.0*PI )
SCHEDULE final2r .XP. spin - (PI/3.0 )
SCHEDULE final3r .XP. spin - ((2.0/3.0)*PI )
SCHEDULE final4r .XP. spin - (PI )
SCHEDULE final5r .XP. spin - ((4.0/3.0)*PI )
SCHEDULE final6r .XP. spin - ((5.0/3.0)*PI )
! " LOW PASS FILTER"
Lf=Xlf/Wb
pir=(Vr - Vi - Rlf*ir1)/Lf
ir1=LIMINT(pir, 0.0, 0.0,8000.0)
pVi=(ir1-iS)*(wb*Xcf)
Vi=INTEG(pVi, VEic) ! "Smooth dc voltage"
! "BUCK CONVERTER"
E = Vi !"Input voltage to Buck converter"
WT = INTEG(slope, 0.0) !"Ramp control for control frequency"
SCHEDULE final1B .xz. WT - D*WW !"Controls switching cycle"
SCHEDULE final2B .xz. WT - WW !"Controls time cycle"
!"Control to determine current through the switch and inductor"
PROCEDURAL(pIL,iS = E,Vc,L,TSC1,TSO1,IL)
IF (TSC1) THEN
    pIL= (E-Vc)/L
    iS = IL
ELSEIF (TSO1) THEN
    pIL = -Vc/L
    iS = 0.0
ELSE

```

```

pIL= 0.0
iS = 0.0
ENDIF
END
IL= BOUND(0.0,1000.0, LIMINT(pIL,0.0,0.0,1000.0)) !"Inductor current
! "must not go below zero"
ir=Vc/R !"current through the resistor
ic= IL-iinv -ir !"Current through the capacitor
!" Vc is the output voltage of converter"
Vc= (1/c)*INTEG(ic, 1.95) !"750/(c=2.6e-3) = 1.95 "
Vcx = INTEG(delVc,0.0)
Rim= BOUND(1.0e-2,1000.0 ,Vc/(i1 + 1.0e-6))
! Multiloop controller
E1= 850.0
D = BOUND(1.0e-5,1.0, .8824 + DelD)
! hI=(a1*(L*R*C) - L)/(E1* R *C)
hi= .00571154
! hN=c3*(L*C)/E1
hN= 1.61047
! hV=(b2*(L*R*C) -E1*hi - R)/(E1*R)
hV= .00673618
PROCEDURAL(delD,delIld,delVc =Vcx,VcD,R,IL,VC)
! " determines change in current"
IF (multiloop) THEN !"and voltage while converter is on"
    delIld = (IL - VcD/R - iavginv) !
    delVc = (Vc - VcD)
    delD = -hV*delVc - hI*delIld - hN*Vcx
    else
    delD =0.0
    delIld = 0.0
    delVc = 0.0
ENDIF
END
avgil= INTEG(iinv,0.0)
PROCEDURAL(Rinv,Rt=iavginv,cbinv,R) !"determines resistance with I.M."
IF (abs(iavginv) .LT. .0001) THEN
Rinv=0.0
Rt=R
ELSEIF (cbinv) THEN
    Rinv=Vc/abs(iavginv)
    Rt = (Rinv*R)/(Rinv + R)
else
Rinv=0.0

```

```
Rt=R
ENDIF
END
```

```
CONSTANT wb1 = 377.0
! "----invoke induction motor MACRO"
im3arb(1,vqss1,vdss1,v0s1,wrml,wb1,0.0,iqss1,idss1,i0s1, &
      iqrs1,idrs1,iOr1,Te1,"rs1 = 0.087", "rr1 = 0.228", &
      "Xm1 = 13.08", "Xss1 = 13.382", "Xrr1 = 13.382", &
      "poles1 = 4.0")
! "----given the stationary reference frame currents"
! " establish the machine currents"
ias1 = iqss1
ibs1 = -0.5*(iqss1+sqrt3*idss1)
ics1 = -ias1 - ibs1
! "determine the desired slip angle: the - thr"
thsldes = INTEG(wsldes, 0.0)
! "determine the desired synchronous ref. frame angle"
thedes = thsldes + 0.5*poles1*thrm1
iasdes = iqsestar*COS(thedes) + idsestar*SIN(thedes)
ibsdess = iqsestar*COS(thedes-tpio3) + idsestar*SIN(thedes-tpio3)
icsdes = -iasdes - ibsdess
! "----derive a simple speed control"
speederr = wrmdes - wrml
px1 = speederr
x1 = INTEG(px1, 0.0)
iqsestar = kp*speederr + ki* x1
! "----develop the inverter hysteresis controls"
PROCEDURAL(vas1,vbs1,vcs1,iinv=SA,SB,SC,ias1,ibs1,ics1, &
      iasdes,ibsdess,icsdes,Vc,cbinv)
! "initialize pole voltages to zero"
vap = 0.0
vbp = 0.0
vcp = 0.0
! "initialize currents into top leg switches zero"
iina = 0.0
iinb = 0.0
iinc = 0.0
! "if the top switch is closed then the pole voltage"
! "equals the input voltage and the current through "
! "that switch equals the phase current"
if (SA) then
vap = Vc
```

```

iina = ias1
endif
if (SB) then
vbp = Vc
iinb = ibs1
endif
if (SC) then
vcp = Vc
iinc = ics1
endif
! "calculate the current into the inverter"
IF (cbinv) THEN
iinb = iina + iinb + iinc
ELSE
iinb = 0.0
ENDIF
i1=iinv
! "calculate the neutral to neg input line voltage"
vnp = (vap+vbp+vcp)/3.0
! "calculate the phase voltages"
vas1 = vap - vnp
vbs1 = vbp - vnp
vcs1 = vcp - vnp
END
! "---- mechanical interface "
IF (cbinv) THEN
! "----Given the machine voltages, determine the stat. ref"
! "frame voltages"
vqss1 = vas1
vdss1 = (-vas1-2.0*vbs1)/sqrt3
pwr1 = (Te1 - TL1)/J1
pthrm1 = wrm1
! "----establish the reference machine currents"
! "calculate the desired slip frequency"
wsldes = wb1*rr1*iqsestar/(Xrr1*idsestar)
ELSE
vqss1 = 0.0
vdss1 = 0.0
pwr1 = 0.0
pthrm1 = 0.0
wsldes = 0.0
ENDIF
nwr1 = wrm1/188.5

```

```

pctTL1 = 0.11799 - 0.53915*abs(nwrm1) + 1.7*nwrm1*nwrm1 - &
    0.28554*nwrm1*nwrm1*abs(nwrm1)
PROCEDURAL(TL1=pctTL1,TLrated,nwrm1)
IF (nwrm1 .LT. 0.0) THEN
TL1 = -pctTL1*TLrated
ELSE
TL1 = pctTL1*TLrated
ENDIF
END
wrm1 = INTEG(pwrm1, wrmic1)
thrm1 = INTEG(pthrm1, thrmic1)
iinvt = INTEG(iinv, 0.0)
    Pt=(Vc**2)/Rt
    Pinv =Vc*iinv
END ! "of derivative"
!" turns on/off the rectifier thyristors"
DISCRETE final1r
    T2r=(.true.)
    T6r=(.false.)
spin= spin -2.0*PI
end
DISCRETE final2r
    T3r=(.true.)
    T1r=(.false.)
end
DISCRETE final3r
    T4r=(.true.)
    T2r=(.false.)
end
DISCRETE final4r
    T5r=(.true.)
    T3r=(.false.)
end
DISCRETE final5r
    T6r=(.true.)
    T4r=(.false.)
end
DISCRETE final6r
    T1r=(.true.)
    T5r=(.false.)
end
DISCRETE final1B!"opens converter switch"
    TSC1 = (.false.)

```

```

TSO1 = (.true.)
iS = 0.0
END
DISCRETE final2B          !" closes converter switch"
  TSC1 = (.true.)
  TSO1 = (.false.)
  WT = 0.0
END
DISCRETE average!"sets up measurement for avg inveter"
INTERVAL tsample= 0.002!"current"
  iavginv= avgil/tsample
  avgil= 0.0
END
DISCRETE invon
  pin = wrmpk/tacc      !"set ramp up rate for des spd"
  cbinv = .TRUE.      !"turn inverter on"
END
DISCRETE rampoff
  pin = 0.0
  wrmdes = 157.0
END
DISCRETE aveiin
INTERVAL tsamp = 0.002
  aveiin = iinvint/tsamp
  IF (aveiin .ne. 0.0) THEN
    avezin = Vc/aveiin
  ENDIF
  iinvint = 0.0
END
DISCRETE swchnng
INTERVAL tsamp2 = 0.0002
  !"calculate phase current errors"
  iaserr = iasdes - ias1
  ibserr = ibsdes - ibs1
  icserr = icsdes - ics1
  !"if phase a error is greater than +hyst close top switch"
  if (iaserr .GT. hyst) then
    SA = .true.
  endif
  !"if phase a error is less than -hyst close bot switch"
  if (iaserr .LT. -hyst) then
    SA = .false.
  endif
endif

```

```
! "if neither condition is true, switch status stays same"  
if (ibserr .GT. hyst) then  
  SB = .true.  
endif  
if (ibserr .LT. -hyst) then  
  SB = .false.  
endif  
if (icserr .GT. hyst) then  
  SC = .true.  
endif  
if (icserr .LT. -hyst) then  
  SC = .false.  
endif  
END  
END ! "of dynamic"  
END ! "of program"
```

## APPENDIX F. MACRO FOR INDUCTION MACHINE

"z-induction machine identifier"

""

" INPUTS"

"vqs-q-axis stator voltage in the warb frame(V) "

"vds-d-axis stator voltage in the warb frame(V) "

"v0s-zero seq. stator voltage in the warb frame(V) "

"wrm-rotor mechanical speed (rad/sec)"

"wb-base electrical angular velocity (rad/sec)"

"warb-speed of the reference frame (rad/sec)"

""

" OUTPUTS"

"iqs-q-axis stator current in the warb frame (A) "

"ids-d-axis stator current in the warb frame (A) "

"i0s-zero seq. stator current in the warb frame (A) "

"iqr-q-axis rot-ref current in the warb frame (A) "

"idr-d-axis rot-ref current in the warb frame (A) "

"i0r-zero seq. rot-ref current in the warb frame (A) "

"Te-electromagnetic torque, positive for motor"

"action (N-m)"

""

" PARAMETERS"

"rs&z-stator winding resistance (ohms)"

"rr&z-rotor-referred winding resistance (ohms)"

"Xm&z-stator magnetizing reactance (ohms)"

"Xss&z-stator self reactance (ohms)"

"sidsic&z -d-axis stator flux linkage/sec initial cond. (V)"

"si0sic&z -0-seq. stator flux linkage/sec initial cond. (V)"

"siqric&z -q-axis rot-ref flux linkage/sec i.c. (V)"

"sidric&z -d-axis rot-ref flux linkage/sec i.c. (V)"

"si0ric&z -0-seq. rot-ref flux linkage/sec i.c. (V)"

"D&z-constant helpful in determining currents (ohms2)"

"Xls&z-stator leakage reactance (ohms)"

"Xlr&z-rotor-referred leakage reactance (ohms)"

"wr&z-rotor electrical speed (rad/sec)"

""

\*\*\*\*\*

MACRO im3arb(z,vqs,vds,v0s,wrm,wb,warb,iqs,ids,i0s,iqr,idr,i0r,Te, &  
prs,pr,pXm,pXss,pXrr,ppoles)

INITIAL

```

CONSTANT prs
CONSTANT prr
CONSTANT pXm
CONSTANT pXss
CONSTANT pXrr
CONSTANT ppoles

```

```
! "A convenient constant for determining the currents"
```

$$D\&z = X_{ss\&z} * X_{rr\&z} - X_{m\&z} * X_{m\&z}$$

```
! "Establish the stator and rotor-referred leakage reactance"
```

$$X_{ls\&z} = X_{ss\&z} - X_{m\&z}$$

$$X_{lr\&z} = X_{rr\&z} - X_{m\&z}$$

```
! "assign the flux linkage per second initial conditions"
```

$$\text{CONSTANT } si_{qsic\&z} = 0.0$$

$$\text{CONSTANT } si_{dsic\&z} = 0.0$$

$$\text{CONSTANT } si_{0sic\&z} = 0.0$$

$$\text{CONSTANT } si_{qric\&z} = 0.0$$

$$\text{CONSTANT } si_{dric\&z} = 0.0$$

$$\text{CONSTANT } si_{0ric\&z} = 0.0$$

```
END
```

```
! "Compute the rotor electrical speed given the mechanical speed"
```

$$w_{r\&z} = 0.5 * \text{poles}\&z * w_{rm}$$

```
! "Determine the machine currents from the state variables"
```

$$i_{qs} = (X_{rr\&z} * si_{qs\&z} - X_{m\&z} * si_{qr\&z}) / D\&z$$

$$i_{ds} = (X_{rr\&z} * si_{ds\&z} - X_{m\&z} * si_{dr\&z}) / D\&z$$

$$i_{qr} = (X_{ss\&z} * si_{qr\&z} - X_{m\&z} * i_{qs}) / D\&z$$

$$i_{dr} = (X_{ss\&z} * si_{dr\&z} - X_{m\&z} * i_{ds}) / D\&z$$

```
! "The zero sequence currents"
```

$$i_{0s} = si_{0s\&z} / X_{ls\&z}$$

$$i_{0r} = si_{0r\&z} / X_{lr\&z}$$

```
! "Calculate the derivative of the flux linkage per second"
```

$$p_{si_{qs\&z}} = -r_{s\&z} * w_b * i_{qs} - w_{arb} * si_{ds\&z} + w_b * v_{qs}$$

$$p_{si_{ds\&z}} = -r_{s\&z} * w_b * i_{ds} + w_{arb} * si_{qs\&z} + w_b * v_{ds}$$

$$p_{si_{qr\&z}} = -r_{r\&z} * w_b * i_{qr} - (w_{arb} - w_{r\&z}) * si_{dr\&z}$$

$$p_{si_{dr\&z}} = -r_{r\&z} * w_b * i_{dr} + (w_{arb} - w_{r\&z}) * si_{qr\&z}$$

```
psi0s&z = -rs&z*wb*i0s + wb*v0s
psi0r&z = -rr&z*wb*i0r
```

```
! "Integrate the derivatives to arrive at the state variable"
```

```
siqs&z = INTEG(psiqs&z, siqsic&z)
sids&z = INTEG(psids&z, sidsic&z)
si0s&z = INTEG(psi0s&z, si0sic&z)
siqr&z = INTEG(psiqr&z, siqric&z)
sidr&z = INTEG(psidr&z, sidric&z)
si0r&z = INTEG(psi0r&z, si0ric&z)
```

```
! "Compute the developed electromagnetic torque"
```

```
Te = 0.75*poles&z*(siqr&z*idr - sidr&z*iqr)/wb
```

```
MACRO END
```

```
"Xrr&z-rotor-referred self reactance (ohms)"
```

```
"poles&z -number of machine poles"
```

```
""
```

```
"INTERNAL (STATE OR STATE RELATED)"
```

```
"siqs&z-q-axis stator flux linkage/sec warb frame (V) "
```

```
"sids&z-d-axis stator flux linkage/sec warb frame(V) "
```

```
"si0s&z-0-seq. stator flux linkage/sec warb frame(V) "
```

```
"siqr&z -q-axis rot-ref flux link/sec warb frame (V) "
```

```
"sidr&z -d-axis rot-ref flux link/sec warb frame (V) "
```

```
"si0r&z -0-seq. rot-ref flux link/sec warb frame (V) "
```

```
"psiqs&z -derivative of siqs&z (V/sec)"
```

```
"psids&z -derivative of sids&z (V/sec)"
```

```
"psi0s&z -derivative of si0s&z (V/sec)"
```

```
"psiqr&z -derivative of siqr&z (V/sec)"
```

```
"psidr&z -derivative of sidr&z (V/sec)"
```

```
"psi0r&z -derivative of si0r&z (V/sec)"
```

```
""
```

```
" INTERNAL (NOT STATE RELATED)"
```

```
"siqsic&z -q-axis stator flux linkage/sec initial cond. (V)"
```

## APPENDIX G. STEAM TURBINE DRIVEN SYNCHRONOUS MACHINE WITH EXCITOR CONTROL-ACTIVE SOURCE INCLUDING RECTIFIER AND FILTER

### 1.) ACSL Program

```
INCLUDE 'MACROS/sm31kq.mac'  
INCLUDE 'MACROS/Lncomconv3.mac'  
PROGRAM  
INITIAL  
MAXINTERVAL maxt = 1.0e-7  !"maximum integration step size"  
MININTERVAL mint = 1.0e-9  
"To accelerate the simulations for Rlarge > 100"  
"start with ialg = 5, then at 0.1 switch to Gears"  
"ialg =2 with maxt=1.0e-4"  
CINTERVAL cint = 1.0e-3  !"data communication interval"  
ALGORITHM ialg = 5      !"integration algorithm"  
      !"4--R.K. 2nd, 5--R.K. 4th"  
NSTEPS  nstp = 1  
      CONSTANT tstop = 1.0      !"stop point for integration"  
PARAMETER (twopi = 6.283185307)  
a120 = twopi/3.0  
"INITIAL section for 501 ssgt model"  
CONSTANT nref = 1.0  !"per unit speed ref for cntrl"  
CONSTANT kc1 = 22.5  !"PI controller gain"  
CONSTANT tc1 = 0.55  !"PI controller time constant"  
CONSTANT tfv = 0.01, tft = 0.05  
CONSTANT cgt1 = 1.3523, cgt2 = 0.251, wfos = 0.23  
CONSTANT cgn = 0.5  
CONSTANT qldic = 0.0  !"Initial prime movr torque"  
qloadi = qldic  
wfic = qloadi/cgt1 + cgt2  
wfinic = wfic  
uctric = (wfinic - wfos)  
"INITIAL section for exciter model"  
CONSTANT kee1 = 1.0, tee1 = 0.1  
CONSTANT vre1ul = 8.4, vre1ll = 0.0  
CONSTANT kae1 = 400.0, tae1 = 0.01, kfe1 = 0.01  
CONSTANT talfe1 = 0.15, ta2fe1 = 0.06, ta3fe1 = 0.0  
CONSTANT exfdic = 1.0, vbusic = 1.0  
vreli = exfdic/kee1  
vfe1xi = vreli  
vfe1yi = kfe1*vfe1xi
```

```

voref = vbusic + vreli/kael
"INITIAL section for synchronous machine"
"---initial flux linkages at 1pu voltage and zero current"
vgen = 1.0
nwrmic2 = 1.0  !"normalized initial speed"
sikqric2 = 0.0
sikdric2 = exfdic
sifdric2 = exfdic + (0.136829/1.768)*exfdic
siqsrlic2 = 0.0
sidsric2 = 1.0
siOsrlic2 = 0.0
"INITIAL section for the 100kW buck converter load"
CONSTANT VcD = 550.0      !" Desired output voltage"
CONSTANT Rin1 = 7500.0
CONSTANT Cin1 = 3900.0e-6!"input filter capacitance"
CONSTANT Lin1 = 200.0e-6  !"input filter inductance"
CONSTANT iLinic1 = 0.0!"Lin1 ic current"
CONSTANT Vcapini1 = 0.0!"Cin1 ic voltage"
CONSTANT dutymax = 0.6!"max duty cycle"
CONSTANT Rout1 = 5.625!"rated load resistance"
CONSTANT L = 1.35e-3     !"Buck inductance"
CONSTANT C = 2600.0e-6  !" buck capacitance"
CONSTANT Vbase = 540.0!"base voltage 3.125MVA SM"
"peak phase voltage"
CONSTANT Ibase = 3.858e3!"base current 3.125MVA SM"
"peak phase current"
Vc = 0.0
CONSTANT tacc = 0.5!"time to bring voltage up"
CONSTANT tbuckon = 2.0!"time buck 1 turned on"
LOGICAL backup,Ibackup,multiloop
backup = .True.
Ibackup = .false.
multiloop = .TRUE.
ramprate = dutymax/tacc
pduy = 0.0
LOGICAL cb1,contmode
cb1 = .FALSE.      !"cb connecting buck1 to bus"
contmode = .TRUE.
CONSTANT FreqT = 5.0e+3  !"switch frequency"
TD = 1.0/FreqT        !"switching time length"
    WW = TD           !"dummy variable for schedule use"
slope = 1.0           !"used for incrementing WW for schedule"
CONSTANT k=25.0      !" factor for estimateing pole location for M.L. control"

```

```

LOGICAL TSC1, TSO1      ! "TSC1 = time switch closed for converter"
TSC1 = .true.          ! "TSO1 = time switch open for converter"
TSO1 = .false.
END ! "of initial"
DYNAMIC
TERMT (t .GE. (tstop-0.5*cint))
DERIVATIVE
CONSTANT wb1 = 377.0
"----determine the rotor angle for machine 2"
CONSTANT delic2 = 0.0
pdel2 = 0.0
del2 = INTEG(pdel2, delic2)
"----convert the synchronous ref frame volt. to rotor frame"
vqsr2 = COS(del2)*vqse2 - SIN(del2)*vdse2
vdsr2 = SIN(del2)*vqse2 + COS(del2)*vdse2
CONSTANT wb2 = 377.0
sm31kq(2,vqsr2,vdsr2,v0s2,vfdr2,wrm2,wb2, &
iqsr2,ikqr2,idsr2,ifdr2,ikdr2,i0s2,Te2, &
"rs2=0.00515","rkq2=0.0613", &
"rfd2=0.00111","rkd2=0.023968","Xmq2=1.0", &
"Xq2=1.08","Xkq2=1.329787", &
"Xmd2=1.768","Xd2=1.848","Xkd2=2.101829", &
"Xfd2=1.904829","poles2=2.0")
"----convert the rotor ref frame currents to e-frame"
iqse2 = COS(del2)*iqsr2 + SIN(del2)*idsr2
idse2 = -SIN(del2)*iqsr2 + COS(del2)*idsr2
"----establish the rotor angle and the synchronous angle"
thrm2 = INTEG(wrm2, 0.0)
"find e-frame voltages for input to SM macro"
vqse2 = 2.0*(COS(thrm2)*vas2+COS(thrm2-a120)*vbs2 + &
COS(thrm2+a120)*vcs2)/3.0
vdse2 = 2.0*(SIN(thrm2)*vas2+SIN(thrm2-a120)*vbs2 + &
SIN(thrm2+a120)*vcs2)/3.0
v0s2 = (vas2+vbs2+vcs2)/3.0
"----convert the e-frame currents to abc-variables"
"inputs to Lncmconv "
ias2 = COS(thrm2)*iqse2 + SIN(thrm2)*idse2
ibs2 = COS(thrm2-a120)*iqse2 + SIN(thrm2-a120)*idse2
ics2 = -ias2 - ibs2
"synchronous machine rotor dynamics"
CONSTANT Hsm = 2.137
pnwrm2 = (Te2-Tpm)/(2.0*Hsm) !"norm. deriv of speed"
nwr2 = INTEG(pnwrm2, nwrmic2)

```

```

wrm2 = wb2*nwrm2
dngr = (Te2-Tpm)/(2.0*Hsm) !"norm. deriv of speed"
ngt = nwrm2
"----invoke the rectifier model"
Lncomconv(1,(-ias2),(-ibs2),(-ics2),Idc1,.true.,.true., &
.true.,.true.,.true.,.true.,vdc1,vas2,vbs2, &
vcs2,"rlo1=0.0001","rhi1=1000.0")
"----dc link dynamics"
CONSTANT rdc1 = 0.005
CONSTANT Ldc1 = 0.013
pidc1 = -rdc1*Idc1/Ldc1 + (vdc1-vcap)/Ldc1
Idc1 = INTEG(pidc1, 0.0)
CONSTANT Ccap = 0.1
CONSTANT rcap=10.0
PROCEDURAL(pvcap=Idc1,vcap,isw1,Ibase,Ccap,rcap)
IF (cb1) THEN
"buck converter1 connected"
pvcap = (Idc1-vcap/rcap-isw1/Ibase)/Ccap
ELSE
"buck converter1 disconnected"
pvcap = (Idc1-vcap/rcap)/Ccap
ENDIF
END!"of procedural"
vcap = INTEG(pvcap, 0.0)
"----Calculate the generator terminal voltage magnitude"
vgen = SQRT(vqse2*vqse2 + vdse2*vdse2)
"----Implement the exciter dynamic model"
eg1xr = vgrf - vgen - vfe1b
dvre1 = (eg1xr*kae1 - vre1)/tae1
vre1 = LIMINT(dvre1, vre1i, vre1ll, vre1ul)
vfe1x = INTEG((vre1-vfe1x)/ta2fe1, vfe1xi)
vfe1a = (ta3fe1/ta2fe1)*(vre1-vfe1x) + vfe1x
vfe1b = (kfe1*vfe1a - vfe1y)/ta1fe1
vfe1y = INTEG(vfe1b, vfe1yi)
dexfd = (vre1 - exfd*kee1)/tee1
exfd = INTEG(dexfd, exfdic)
vfdr2 = rfd2*exfd/Xmd2
"----SSGT Model"
"input: ngt (per unit gen speed)"
"output: Tpm (power turb tork pu on 3125 kVA base)"
"Controller"
nerr = nref - ngt !"normalized speed error"
ductr = -kc1*dngr + (kc1/tc1)*nerr

```

```

uctr = INTEG(ductr, uctric)
"Fuel Valve and Combustor eqns"
wfin = uctr + wfos
REALPL(wfv = tfv,wfin,wfinic)
REALPL(wf = tft, wfv,wfic)
qgtpu = cgt1*(wf-cgt2)+cgn*(1.0-ngt) !"pu on 2675 kVA"
Tpm = -qgtpu*2675.0/3125.0
"----invoke the rectifier model"
Lncomconv(1,(-ias2),(-ibs2),(-ics2),Idc1,.true.,.true., &
.true.,.true.,.true.,.true.,vdc1,vas2,vbs2, &
vcs2,"rlo1=0.0001","rhi1=1000.0")
"----dc link dynamics"
CONSTANT rdc1 = 0.005
CONSTANT Ldc1 = 0.013
pidc1 = -rdc1*Idc1/Ldc1 + (vdc1-vcap)/Ldc1
Idc1 = INTEG(pidc1, 0.0)
CONSTANT Ccap = 0.1
CONSTANT rcap=10.0
PROCEDURAL(pvcap=Idc1,vcap,isw1,Ibase,Ccap,rcap)
IF (cb1) THEN
"buck converter1 connected"
pvcap = (Idc1-vcap/rcap-isw1/Ibase)/Ccap
ELSE
"buck converter1 disconnected"
pvcap = (Idc1-vcap/rcap)/Ccap
ENDIF
END!"of procedural"
vcap = INTEG(pvcap, 0.0)
"----Calculate the generator terminal voltage magnitude"
vgen = SQRT(vqse2*vqse2 + vdse2*vdse2)
"----Implement the exciter dynamic model"
eg1xer = vgrep - vgen - vfelb
dvrel = (eg1xer*kael - vre1)/tael
vre1 = LIMINT(dvrel, vreli, vrell, vre1ul)
vfelx = INTEG((vre1-vfelx)/ta2fel, vfelxi)
vfel1a = (ta3fel/ta2fel)*(vre1-vfelx) + vfelx
vfel1b = (kfel*vfel1a - vfely)/talfel
vfely = INTEG(vfel1b, vfelyi)
dexfd = (vre1 - exfd*keel)/tee1
exfd = INTEG(dexfd, exfdic)
vfd2 = rfd2*exfd/Xmd2
"----SSGT Model"
"input: ngt (per unit gen speed)"

```

```

"output: Tpm (power turb tork pu on 3125 kVA base"
"Controller"
nerr = nref - ngd    !"normalized speed error"
ductr = -kc1*dngt + (kc1/tc1)*nerr
uctr = INTEG(ductr, uctric)
"Fuel Valve and Combustor eqns"
wfin = uctr + wfos
REALPL(wfv = tfv,wfin,wfinic)
REALPL(wf = tft, wfv,wfic)
qgtpu = cgt1*(wf-cgt2)+cgn*(1.0-ngt) !"pu on 2675 kVA"
Tpm = -qgtpu*2675.0/3125.0
"implement BUCK converter load eqns"
"----input filter eqns"
vbuckin = Vbase*vcap
piLin1 = (vbuckin-vcapin1)/Lin1
iLin1 = INTEG(piLin1, iLinic1)
PROCEDURAL(pvcapin1=iLin1,vcapin1,isw1,Cin1,Rin1,cb1)
IF (cb1) THEN
    pvcapin1 = (iLin1-vcapin1/Rin1-isw1)/Cin1
ELSE
    pvcapin1 = (iLin1)/Cin1
    "pvcapin1 = (iLin1-vcapin1/Rin1)/Cin1"
ENDIF
END!"of procedural"
vcapin1 = INTEG(pvcapin1, vcapini1)
iout1 = Vc/Rout1
SCHEDULE fullbuck .XP. t-tbuckon-tacc
PROCEDURAL(pduty=cb1,buckup)
IF ((cb1) .AND. (buckup)) THEN
    pduty = ramprate
ELSE
    pduty = 0.0
ENDIF
END
duty = INTEG(pduty, 0.0)
SCHEDULE final1B .xz. WT - D*WW    !"needed to initiate TSC1 to TSO1 at D"
SCHEDULE final2B .xz. WT - WW
!"needed to initiate TSO1 to TSC1 at new cycle"
! Multiloop controller
R= Rout1
E= Vcapin1    !"voltage source for Buck"
E1 = 875.0

```

```

a1 = 3600.0
b2 = 1.93e6
c3 = 3.9e8
hI = (a1*(L*R*C) - L)/(E1*R*C)
hN = c3*(L*C)/E1
hV = (b2*(L*R*C) - E1*hI - R)/(E1*R)
PROCEDURAL(delILd,delVc = VcD,Rout1,IL,VC)
! " determines change in current"
IF ((cb1).and. (Ibuckup)) THEN      ! " voltage while converter is on"
    delILd = (IL - VcD/Rout1)
    delVc = (Vc - VcD)
    else
delILd = 0.0
    delVc = 0.0
ENDIF
END
Vcx = INTEG(delVc,0.0)
!"more buck equations"
PROCEDURAL(DD = E,VcD,delD,Duty) ! " determines d"
IF (Buckup) THEN
    DD=Duty
delD= 0.0
ELSEIF ((Ibuckup) .and. (Multiloop)) THEN
    delD= -hV*delVc - hI*delILd - hN*Vcx
DD= VcD/E + delD
ELSE
delD=0.0
DD= 0.6
ENDIF
END
D = BOUND(1.0e-5,1.0, DD)
WT = INTEG(slope, 0.0)
PROCEDURAL(pIL,isw1 = E,Vc,L,TSC1,TSO1,IL,cb1,Ibase)
! "finds slope of IL"
IF ((TSC1) .and. (cb1)) THEN
    pIL = (E-Vc)/L
isw1 = IL/Ibase
ELSEIF ((TSO1) .and. (cb1)) THEN
pIL = -Vc/L
isw1 = 0.0
else
pIL = 0.0
isw1 = 0.0

```

```

ENDIF
END
IL= BOUND(0.0,1000.0, LIMINT(pIL,0.0,0.0,1000.0)) ! "finds IL"
ic= IL- (Vc/Rout1)
Vc= (1/c)*INTEG(ic,0.0)
END ! "of derivative"
"----schedule end of up ramp for the duty cycle"
DISCRETE fullbuck
buckup = .false.
Ibuckup =.true.
pduty = 0.0
duty = dutymax
END!"of fullbuck"
DISCRETE final1B
TSC1 = (.false.)
TSO1 = (.true.)
WTX = 0.0
END
DISCRETE final2B
TSC1 = (.true.)
TSO1 = (.false.)
WT = 0.0
END
END ! "of dynamic"
END ! "of program"

```

## 2) Lncomconv3

```

"*****"
"*****"
"Author: John G. Ciezki"
"Last Revised: 26 Apr 94"
"Developed For: Personal Use"
" MACRO Title: Lncomconv3
"
"DESCRIPTION:"
"ASSUMPTIONS:"
"VARIABLE DEFINITION"
"
CONCATENATION"
"z-3-phase line-commutated converter identifier"
" INPUTS"
"ia-a-phase current referenced positive into"
"the converter (A)"
"ib-b-phase current referenced positive into"
"the converter (A)"

```

"ic-c-phase current referenced positive into"  
 "the converter (A)"  
 "Idc-dc-side current referenced positive out of"  
 "the converter (A)"  
 "vg1-gate signal for thyristor 1 ( T or F )"  
 "vg2-gate signal for thyristor 2 ( T or F )"  
 "vg3-gate signal for thyristor 3 ( T or F )"  
 "vg4-gate signal for thyristor 4 ( T or F )"  
 "vg5-gate signal for thyristor 5 ( T or F )"  
 "vg6-gate signal for thyristor 6 ( T or F )"  
 "    OUTPUTS"  
 "vdc-dc-side voltage positive node on top (V)"  
 "va-a-phase line-to-neutral voltage (V)"  
 "vb-b-phase line-to-neutral voltage (V)"  
 "vc-c-phase line-to-neutral voltage (V)"  
 "    PARAMETERS"  
 "rlo&z-the value of the bimodal thyristor resistance"  
 "during conduction (ohms)"  
 "rhi&z-the value of the bimodal thyristor resistance"  
 "during blocking (ohms)  "  
 "INTERNAL (STATE OR STATE RELATED)"  
 "none"  
 "    INTERNAL (NOT STATE RELATED)"  
 "j&z-index for going through all possible conv states"  
 "index&z -records index of proper conduction configuration"  
 "c1&z-possible thyristor 1 conduction states        "  
 "0 = blocking, 1 = conducting"  
 "c2&z-possible thyristor 2 conduction states        "  
 "0 = blocking, 1 = conducting"  
 "c2&z-possible thyristor 2 conduction states        "  
 "0 = blocking, 1 = conducting"  
 "c3&z-possible thyristor 3 conduction states        "  
 "0 = blocking, 1 = conducting"  
 "c4&z-possible thyristor 4 conduction states        "  
 "0 = blocking, 1 = conducting"  
 "c5&z-possible thyristor 5 conduction states        "  
 "0 = blocking, 1 = conducting"  
 "c6&z-possible thyristor 6 conduction states        "  
 "0 = blocking, 1 = conducting"  
 " c1&z 0000000000 0 0 0 0 0 0 etc"  
 " c2&z 0000000000 0 0 0 0 0 0 etc"  
 " c3&z 000000001 1 1 1 1 1 1 etc"  
 " c4&z 000011110 0 0 0 1 1 1 etc"

" c5&z 001100110011001 etc"  
 " c6&z 01010101010101010 etc"  
 "index 123456789101112131415"  
 "v1&z-logical conduction status of thyristor 1"  
 "F = not conducting, T = conducting"  
 "v2&z-logical conduction status of thyristor 2"  
 "F = not conducting, T = conducting"  
 "v3&z-logical conduction status of thyristor 3"  
 "F = not conducting, T = conducting"  
 "v4&z-logical conduction status of thyristor 4"  
 "F = not conducting, T = conducting"  
 "v5&z-logical conduction status of thyristor 5"  
 "F = not conducting, T = conducting"  
 "v6&z-logical conduction status of thyristor 6"  
 "F = not conducting, T = conducting"  
 "vallow1&z -logical status of whether thyristor 1 can be"  
 "conducting current, F = no, T = yes"  
 "vallow2&z -logical status of whether thyristor 2 can be"  
 "conducting current, F = no, T = yes"  
 "vallow3&z -logical status of whether thyristor 3 can be"  
 "conducting current, F = no, T = yes"  
 "vallow4&z -logical status of whether thyristor 4 can be"  
 "conducting current, F = no, T = yes"  
 "vallow5&z -logical status of whether thyristor 5 can be"  
 "conducting current, F = no, T = yes"  
 "vallow6&z -logical status of whether thyristor 6 can be"  
 "conducting current, F = no, T = yes"  
 "VALVE1&z(64) -matrix of the possible conduction states for"  
 "thyristor 1 for the 64 possible conv configs."  
 "VALVE2&z(64) -matrix of the possible conduction states for"  
 "thyristor 2 for the 64 possible conv configs."  
 "VALVE3&z(64) -matrix of the possible conduction states for"  
 "thyristor 3 for the 64 possible conv configs."  
 "VALVE4&z(64) -matrix of the possible conduction states for"  
 "thyristor 4 for the 64 possible conv configs."  
 "VALVE5&z(64) -matrix of the possible conduction states for"  
 "thyristor 6 for the 64 possible conv configs."  
 "CIDC&z(64) -matrix of impedance values which when multiplied"  
 "by I<sub>dc</sub> yields a component of v<sub>dc</sub> (ohms)  
 CIA&z(64) -matrix of impedance values which when multiplied"  
 "by i<sub>a</sub> yields a component of v<sub>dc</sub> (ohms)"  
 "CIB&z(64) -matrix of impedance values which when multiplied"  
 "by i<sub>b</sub> yields a component of v<sub>dc</sub> (ohms)"

```

"vdc = CIDC&z()*Idc + CIA&z()*ia + CIB&z()*ib"
"r1&z-the bimodal resistance representing thyristor 1 "
"r2&z-the bimodal resistance representing thyristor 2 "
"r3&z-the bimodal resistance representing thyristor 3 "
"r4&z-the bimodal resistance representing thyristor 4 "
"r5&z-the bimodal resistance representing thyristor 5 "
"r6&z-the bimodal resistance representing thyristor 6 "
"all in (ohms)"
" Idc --->"
"-----"
"||| +"
"|||"
"r1&zr3&zr5&z "
" ia --->| ib --->| ic --->|"
"||| vdc"
"r4&zr6&zr2&z "
"|||"
"|||"
"-----"
" g"
"vdcmax&z -initially set to alrge negative number, it will "
"be the largest possible dc voltage for the "
"given currents ia, ib, ic and Idc (V)"
"vag&z-the a-phase to ground (- terminal) voltage (V)"
"vbg&z-the b-phase to ground (- terminal) voltage (V)"
"vcg&z-the c-phase to ground (- terminal) voltage (V)"
"vng&z-the neutral-to-ground voltage for the wye-conn."
"ac system (V)"
"*****"
"*****"
"!!!!!!!!!!!!!!! MACRO DEFINITION BEGINS HERE !!!!!!!!!!!!!!!"

MACRO Lncomconv(z,ia,ib,ic,Idc,vg1,vg2,vg3,vg4,vg5,vg6,vdc,va,vb,vc, &
prlo, prhi)

INITIAL

CONSTANT prlo
CONSTANT prhi

"Define indexing integers"
INTEGER j&z, index&z
INTEGER c1&z, c2&z, c3&z, c4&z, c5&z, c6&z

```

```

"Define conduction logical variables"
LOGICAL v1&z, v2&z, v3&z, v4&z, v5&z, v6&z
"Define future conduction logical variables"
LOGICAL vallow1&z, vallow2&z, vallow3&z
LOGICAL vallow4&z, vallow5&z, vallow6&z
"Define matrices of logic states for 64 possible conv. configs"
LOGICAL VALVE1&z(64)
LOGICAL VALVE2&z(64)
LOGICAL VALVE3&z(64)
LOGICAL VALVE4&z(64)
LOGICAL VALVE5&z(64)
LOGICAL VALVE6&z(64)
"Dimension impedance vectors needed to represent impedance seen"
" by currents ia, ib and Idc through to vdc"
DIMENSION CIA&z(64)
DIMENSION CIB&z(64)
DIMENSION CIDC&z(64)
"Loop through all 64 possible conduction states"
DO 10&z c1&z = 0,1
DO 10&z c2&z = 0,1
DO 10&z c3&z = 0,1
DO 10&z c4&z = 0,1
DO 10&z c5&z = 0,1
DO 10&z c6&z = 0,1
"If the state is = 1 then set the conduction logic T "
v1&z = c1&z .EQ. 1
v2&z = c2&z .EQ. 1
v3&z = c3&z .EQ. 1
v4&z = c4&z .EQ. 1
v5&z = c5&z .EQ. 1
v6&z = c6&z .EQ. 1
"If conducting, set bimodal resistance to rlo&z"
" otherwise set it to rhi&z"
r1&z = RSW(v1&z, rlo&z, rhi&z)
r2&z = RSW(v2&z, rlo&z, rhi&z)
r3&z = RSW(v3&z, rlo&z, rhi&z)
r4&z = RSW(v4&z, rlo&z, rhi&z)
r5&z = RSW(v5&z, rlo&z, rhi&z)
r6&z = RSW(v6&z, rlo&z, rhi&z)
"Keep running index of possible configs -> 1 to 64"
index&z = 1 + c6&z + 2*(c5&z + 2*(c4&z + 2*(c3&z + &
2*(c2&z + 2*c1&z))))
"If the thyristor is conducting at a particular value"

```

```

"of index, then set the vector location to T"
VALVE1&z(index&z) = v1&z
VALVE2&z(index&z) = v2&z
VALVE3&z(index&z) = v3&z
VALVE4&z(index&z) = v4&z
VALVE5&z(index&z) = v5&z
VALVE6&z(index&z) = v6&z
"Compute the impedance needed to compute the Idc"
"contribution to the dc voltage vdc"
"-1"
"-----"
" 1   1   1"
"   ----- + ----- + -----"
"r1 + r4  r3 + r6  r2 + r5"

CIDC&z(index&z) = -1.0/(1.0/(r1&z+r4&z)+1.0/(r3&z+r6&z) &
+ 1.0/(r2&z+r5&z))
"Compute the impedance needed to compute the ia "
"contribution to the dc voltage vdc"
CIA&z(index&z) = (r4&z/(r2&z+r4&z)-r1&z/(r1&z+r5&z))* &
((r1&z+r5&z)*(r2&z+r4&z)/ &
(r1&z+r2&z+r4&z+r5&z))* &
(r3&z+r6&z)/ &
(r3&z+r6&z+(r2&z+r5&z)*(r1&z+r4&z)/ &
(r2&z+r5&z+r1&z+r4&z))
"Compute the impedance needed to compute the ib "
"contribution to the dc voltage vdc"
CIB&z(index&z) = (r6&z/(r2&z+r6&z)-r3&z/(r3&z+r5&z))* &
((r3&z+r5&z)*(r2&z+r6&z)/ &
(r3&z+r5&z+r2&z+r6&z))* &
(r1&z+r4&z)/ &
(r1&z+r4&z+(r2&z+r5&z)*(r3&z+r6&z)/ &
(r2&z+r5&z+r3&z+r6&z))
10&z.. CONTINUE
"Initialize valve conduction to no valves conducting"
v1&z = .FALSE.
v2&z = .FALSE.
v3&z = .FALSE.
v4&z = .FALSE.
v5&z = .FALSE.
v6&z = .FALSE.
END! "OF INITIAL"
"Establish the vdc by evaluating it for each of the 64"

```

```

"converter configurations with ia, ib, ic, and Idc and using"
"the maximum value found"
PROCEDURAL(vdc, r1&z, r2&z, r3&z, r4&z, r5&z, r6&z = &
  v1&z, v2&z, v3&z, v4&z, v5&z, v6&z, &
  vg1, vg2, vg3, vg4, vg5, vg6, &
  ia, ib, Idc)
"A switch may conduct if it has been conducting or"
" if a gate signal is applied"
vallow1&z = v1&z .OR. vg1
vallow2&z = v2&z .OR. vg2
vallow3&z = v3&z .OR. vg3
vallow4&z = v4&z .OR. vg4
vallow5&z = v5&z .OR. vg5
vallow6&z = v6&z .OR. vg6
"very small value to begin iteration of comparisons"
vdcmax&z = -1.0e30
index&z = 0
"cycle through the 64 possible configurations"
DO 20&z j&z = 1,64
  "Check if the assumed configuration is a "
  "conduction configuration or whether the valve"
  "could be clamped on"
  IF (((.NOT. VALVE1&z&(j&z)) .OR. vallow1&z) .AND. &
    ((.NOT. VALVE2&z&(j&z)) .OR. vallow2&z) .AND. &
    ((.NOT. VALVE3&z&(j&z)) .OR. vallow3&z) .AND. &
    ((.NOT. VALVE4&z&(j&z)) .OR. vallow4&z) .AND. &
    ((.NOT. VALVE5&z&(j&z)) .OR. vallow5&z) .AND. &
    ((.NOT. VALVE6&z&(j&z)) .OR. vallow6&z)) THEN
    "If the configuration is valid, then"
    "compute the dc voltage"
      vdc = CIA&z(j&z)*ia + CIB&z(j&z)*ib + &
        CIDC&z(j&z)*Idc
    "compare the new value of the dc voltage with"
    "the previous maximum"
    IF (vdc .GT. vdcmax&z) THEN
      "If the new value is greater set it"
      "equal to the maximum, and store the"
      "index indicating that configuration"
      vdcmax&z = vdc
      index&z = j&z
    END IF
  END DO

```

```

END IF
20&z.. CONTINUE
"the dc voltage equals the maximum voltage found among"
"the valid conduction configurations"
vdc = vdcmax&z
"set the valve conduction thyristor according to the"
"desired configuration index"
v1&z = VALVE1&z&(index&z)
v2&z = VALVE2&z&(index&z)
v3&z = VALVE3&z&(index&z)
v4&z = VALVE4&z&(index&z)
v5&z = VALVE5&z&(index&z)
v6&z = VALVE6&z&(index&z)
"set the actual value of the bimodal resistors"
r1&z = RSW(v1&z, rlo&z, rhi&z)
r2&z = RSW(v2&z, rlo&z, rhi&z)
r3&z = RSW(v3&z, rlo&z, rhi&z)
r4&z = RSW(v4&z, rlo&z, rhi&z)
r5&z = RSW(v5&z, rlo&z, rhi&z)
r6&z = RSW(v6&z, rlo&z, rhi&z)
END ! "OF PROCEDURAL"
"given the desired resistor values and dc voltage,"
"determine the phase to ground voltages"
vag&z = r4&z*(vdc+r1&z*ia)/(r1&z+r4&z)
vbg&z = r6&z*(vdc+r3&z*ib)/(r3&z+r6&z)
vcg&z = r2&z*(vdc+r5&z*ic)/(r2&z+r5&z)
"establish the neutral-to-ground voltage"
vng&z = (vag&z + vbg&z + vcg&z)/3.0
"calculate the phase voltages"
va = vag&z - vng&z
vb = vbg&z - vng&z
vc = vcg&z - vng&z
MACRO END

```

### 3) Sm31kq Macro

```

"*****"
"*****"
"Author: John G. Ciezki"
"Last Revised: 26 Apr 94"
"Developed For: Personal Use"
" MACRO Title: sm31kq.mac"
"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-l idsr | | ad11&z ad12&z ad13&z | | sidsr&z | "
"ad12&z-l ifdr | = | ad12&z ad22&z ad23&z | | sifdr&z | "
"ad13&z-l 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-l iqsr | | bq11&z bq12&z bq13&z | | siqsr&z | "
"bq12&z-l ikq1r | = | bq12&z bq22&z bq23&z | | sikq1r&z | "
"bq13&z-l ikq2r | | bq13&z bq23&z bq33&z | | sikq2r&z | "
"bq22&z-"
"bq23&z-"
"bq33&z-"
"siqsr&z -q-axis flux linkage/sec initial condition (V)"
"sidsr&z -d-axis flux linkage/sec initial condition (V)"
"si0sr&z -zero seq. flux linkage/sec initial condition (V)"
"sikq1r&z -#1 q-axis referred damper flux linkage/s i.c.(V)"
"sikq2r&z -#2 q-axis referred damper flux linkage/s i.c.(V)"
"sikdr&z -d-axis referred damper flux linkage/sec i.c. (V)"
"sifdr&z -d-axis referred field flux linkage/sec i.c. (V)"
"wr&z-rotor electrical angular velocity (rad/sec)"
"*****

```

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

```

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"

$Xls\&z = Xq\&z - Xm\&z$

"A convenient constant for determining q-axis currents"

$Xq2\&z = Xq\&z * Xk\&z - Xm\&z * Xm\&z$

"determine the array elements for relating q-axis flux"

"linkage per sec vars to q-axis currents"

$bq11\&z = Xk\&z / Xq2\&z$

$bq12\&z = -Xm\&z / Xq2\&z$

$bq21\&z = -Xm\&z / Xq2\&z$

$bq22\&z = Xq\&z / Xq2\&z$

"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
"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, siqsr&z)
sidsr&z = INTEG(psidsr&z, sidsr&z)
si0sr&z = INTEG(psi0sr&z, si0sr&z)
sikqr&z = INTEG(psikqr&z, sikqr&z)
sifdr&z = INTEG(psifdr&z, sifdr&z)
sikdr&z = INTEG(psikdr&z, sikdr&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

```



## INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center 2  
Cameron Station  
Alexandria, VA 22304-6145
2. Dudley Knox Library, Code 013 2  
Naval Postgraduate School  
Monterey, CA 93943-5101
3. Chairman, Code EC 1  
Department of Electrical and Computer Engineering  
Naval Postgraduate School  
Monterey, CA 93943-5121
4. Prof. John G. Ciezki, Code EC/Cy 1  
Department of Electrical and Computer Engineering  
Naval Postgraduate School  
Monterey, CA 93943-5121
5. Prof. Robert W. Ashton, Code EC/Ah 1  
Department of Electrical and Computer Engineering  
Naval Postgraduate School  
Monterey, CA 93943-5121
6. Lt. Kenneth D. Filor 1  
NAVSECGRUCOM DET POTOMAC WASH  
Building 92 Anacostia NDW  
Washington, DC 20371-0922