Optimum Power Conditioning and Motor Combination for Locomotive Traction

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16. Abstract

This is the interim report describing the results of the research on Phase I, the first year, of this contract. The object of the research is to study alternate power conditioning-motor combinations for single axle locomotive traction drives applicable to both freight and passenger use. Candidate systems are defined and analyzed on the basis of costs, reliability, size, efficiency and performance. The three preferred candidate systems are a McMurray commutated voltage source inverter, an auto-sequentially commutated current source inverter and a GTO voltage source inverter, each supplying a variable frequency squirrel cage induction motor. The GTO inverter-induction motor system is recommended as the most compact system with at least equal or better reliability, performance, efficiency and cost than the other two candidate systems.

During Phase II of the research (the second year, June 1, 1982 - May 31, 1983) the GTO inverter system will be designed and a digital simulation devised to demonstrate the performance of the system. It is also recommended that a low power model GTO inverter be designed, constructed and evaluated during Phase II.

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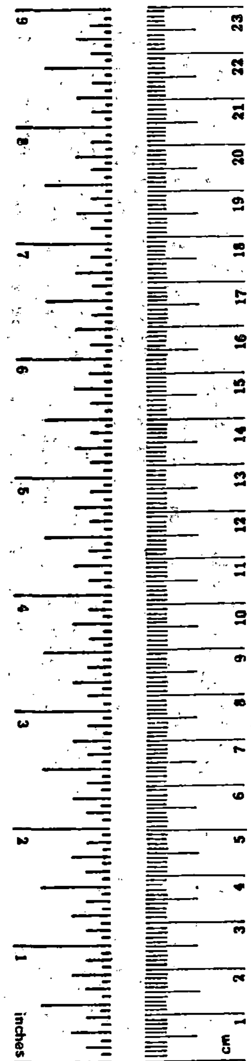
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

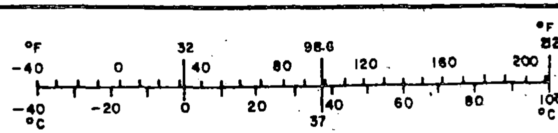
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1.0 INTRODUCTION

The purpose of this research is to analyze alternative power conditioning units and traction motor combinations for locomotive propulsion. At the conclusion of the first year of the work (Phase I), the goal is to identify the optimum system on the basis of cost, reliability, size and performance. During Phase II (the second year), the optimum system will be designed, and digital computer simulation studies will be completed to establish important design parameters and to verify system performance.

Since the first thyristor became available in late 1957, there has been extensive development and application of solid state power converters. One of the most important applications of such converters is in adjustable speed motor drives. Presently, the phase controlled rectifier adjustable speed dc motor drive is widely used in industrial motor position, speed and torque controls. Both phase controlled rectifier and thyristor chopper dc motor drives are also applied in a wide range of traction applications, particularly in the USA, Japan and Europe. However, the most attractive adjustable speed drive for traction applications is the variable frequency controlled ac motor. This approach permits independent speed and torque control over a wide speed range, and makes it possible to utilize the squirrel cage induction motor which is the lowest cost, most rugged and reliable motor to manufacture.

The variable frequency ac motor drive can be produced using either synchronous motors or induction motors. With the squirrel cage induction machine the commutator and slip rings are eliminated. Thus, the variable frequency-squirrel cage induction motor shows great promise for reliable, high performance and competitive cost traction motor drive systems.

At present, the variable frequency squirrel cage induction motor drive is being used for locomotive traction applications in West Germany. However, it is reported that the cost of these systems is quite high. The power electronic converter to supply variable frequency power to the traction motor is presently quite complex and expensive. With the continued development of variable frequency ac drive systems, including the application of modern power semiconductor devices and microprocessors, it appears that very sophisticated systems will be produced at reasonable cost.

The research began on June 1, 1981. This is the interim report for Phase I. The systems considered are described and analyzed, a rather detailed comparison of the candidate systems is presented, and the GTO inverter-induction motor is selected as the preferred locomotive propulsion system. In the final section of this report, recommendations are included regarding a possible revision of the scope of Phase II to include the design, construction and evaluation of a low power model power conditioning unit.

2.0 OBJECT AND SCOPE

The object of this research is to

- Study alternate power conditioning-motor combinations for single axle locomotive traction drives applicable to both freight and passenger use.
- Compare candidate systems on basis of projected life cycle costs, reliability and maintainability, size and performance
- Select preferred system and verify performance using digital computer simulation

The work plan is included in Appendix A.

At the conclusion of the research, the goal is to define an optimum power conditioning-motor combination applicable to both freight and passenger use and adaptable for both all electric and diesel electric locomotives. The results of the research shall include a detailed system design, specifications for major components and digital computer simulation results to demonstrate performance.

In the context of this research, the features of an optimum locomotive propulsion system are considered to be as follows

- Independent torque and speed control
- Minimum torque pulsations and smooth speed control
- Rapid response
- Minimum degradation in performance with variations in wheel diameter and track condition
- Improved braking, including regenerative braking
- Reasonable production cost
- High reliability and low maintenance
- Minimum size
- Minimum fuel consumption

Appendix B and Appendix C include summaries of visits with two locomotive manufacturers to provide base line information for our work. Appendix D is the Directory of Potential Users of the results of this research.

3.0 CANDIDATE SYSTEMS

The procedure for the identification of candidate systems leading to the selection of the system considered optimum can best be described with reference to the milestones included in the Work Plan (Appendix A).

Milestone #1 - Visit two locomotive manufacturers

The visits to General Motors and General Electric provided an excellent orientation to the nature of the power conditioning-traction motor combinations on present locomotives.

Milestone #2 - Define space and mechanical limitations

As a result of our discussions with locomotive manufacturers, it was concluded that a new propulsion system cannot occupy significantly more space than occupied by systems in locomotives currently manufactured. It was also concluded that, particularly with the use of variable frequency induction motors for traction, space and mechanical limitations are not limiting factors in the selection of an optimum system.

Milestone #3 - Define maximum horsepower per axle

Generally, it was concluded that space is available to provide more horsepower/axle than is necessary for fully satisfactory performance with existing power conditioning-motor technology. This is especially true assuming that a variable frequency polyphase induction motor is used as the traction motor.

Milestone #4 - List and describe candidate systems

At the beginning of the work we concluded that there were four viable candidate systems -

Voltage Source Inverter - Induction Motor (VSI-IM)

Current Source Inverter - Induction Motor (CSI-IM)

Cycloconverter - Synchronous Motor (CY-SM)

Chopper - DC Motor (CH-DCM)

Systems with three phase ac traction motors have several significant advantages - 1) Higher torque and output rating for the same motor size and weight; 2) No commutator or brushes, which means less motor maintenance; 3) Greater immunity from adverse environmental conditions - moisture, dust, etc.; and 4) Lower motor manufacturing cost.

The major disadvantage of three phase ac traction motor propulsion systems is that a complicated power electronic equipment is required for the PCU, which results in high cost and possible reliability problems.

We concluded that it is best to consider only three phase ac traction motor systems because they show the greatest potential performance advantages, and it is possible to manufacture very sophisticated power electronic equipment with high reliability and reasonable cost in production. HVDC equipment is one example of this.

We also concluded that the squirrel cage induction motor is much preferable to a synchronous motor due to its lower production cost and somewhat smaller size and greater reliability because of the absence of slip rings, rotary transformers and/or shaft position sensors.

Thus, it was concluded that either a VSI-squirrel cage induction motor or a CSI-squirrel cage induction motor traction system was preferred. As a result of a visit to Japan in November, 1981, it was determined that a variation of the VSI using GTO thyristors was also a viable alternative.*

The selection of the optimum system is based on the following

1. Freight and passenger application
2. Diesel electric or all electric locomotives
3. Three phase squirrel cage induction machines for the traction motors
4. Space and mechanical limitations of present systems
5. Horsepower/axle of 600-1200 hp

The remainder of this section includes a more detailed description of the candidate systems.

3.1 Thyristor Voltage Source Inverter - Induction Motor (VSI-IM)

The preferred candidate VSI-IM system is a three phase McMurray inverter as shown in Figure 1. This is an efficient and reliable variable frequency inverter which is quite widely used. Pulse width modulation (PWM) is assumed to reduce harmonic currents in the motor, which is necessary for maximum efficiency and minimum motor size for a given rating. The system of Figure 1 is discussed and analyzed in detail in Appendix E.

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* 1) Proceedings of US-Japan Cooperative Science Seminar on Analysis and Design in Power Electronics, November 25-28, 1981, Kobe, Japan.

* 2) Japan Trip Report, R. G. Hoft, December, 1981.

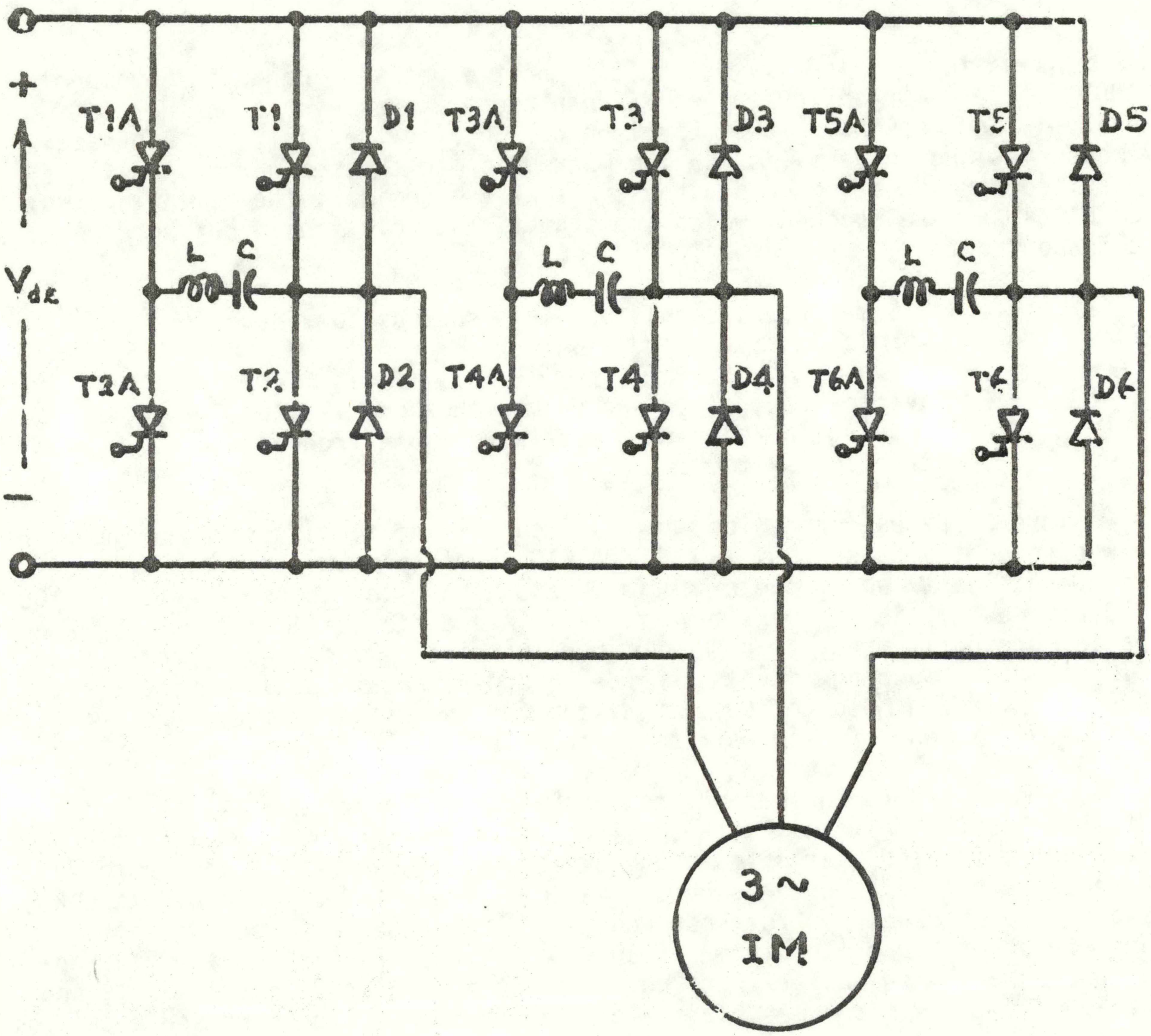


Figure 1
Three Phase McMurray VSI - IM

3.2 Current Source Inverter - Induction Motor (CSI-IM)

The preferred CSI-IM system is shown in Figure 2. This is the most commonly used version of the CSI. Assuming no commutation overlap, there are 18 distinct modes of operation in one complete cycle. A detailed discussion and analysis of the circuit of Figure 2 is presented in Appendix F. When a CSI is used in conjunction with inductive load, an inevitable high voltage spike across the load terminals occurs during the commutation intervals. Therefore, the analysis concentrates on the intervals of commutation, or the transfer modes.

3.3 Gate Turn Off VSI - Induction Motor (GTO-IM)

As stated previously, Dr. Hoft spent two weeks in Japan in November, 1981 as the US Organizer for a US-Japan Cooperative Science Seminar on Analysis and Design in Power Electronics. During the visits to Japanese industries and universities in the week prior to the seminar and as a result of presentations and discussions at the seminar, the following two conclusions were reached, which are significant relative to our work on this contract

1. GTO inverters should be given serious consideration for locomotive propulsion.

2. "Vector controlled" ac drives show promise for improving the performance of a variable frequency ac traction system.

Three Japanese companies were visited - Toshiba, Hitachi and Mitsubishi - who presently have 2500V, 800-1000A GTO thyristors in commercial production. At least two of these manufacturers have plans to produce 5000V, 1600A GTO devices within the next five years. In addition, all of these three companies presently produce, and have in commercial service, equipments using GTO devices. Such equipments include an experimental 600kVA variable frequency induction motor propulsion system for the Osaka Railways and much larger GTO equipments for industrial purposes.

With regard to the second item, four manufacturers were visited in Japan - Toshiba, Hitachi, Mitsubishi and Yaskawa Electric - who now produce "vector controlled" variable frequency ac drives. These all appear to be based somewhat on a German scheme developed about 15 years ago by Blaschke, and further pursued by Professor Leonhard (Braunschweig - West Germany) and Professor Nabae (Toshiba - Japan). The vector controlled ac motor appears to have much faster transient response in a closed loop control, and it appears to be more amenable to fully independent torque and speed control.

The major advantage of the GTO system is that commutating circuit components are not required, since the GTO can be turned off with the application of a negative gate current pulse. The negative gate current is required

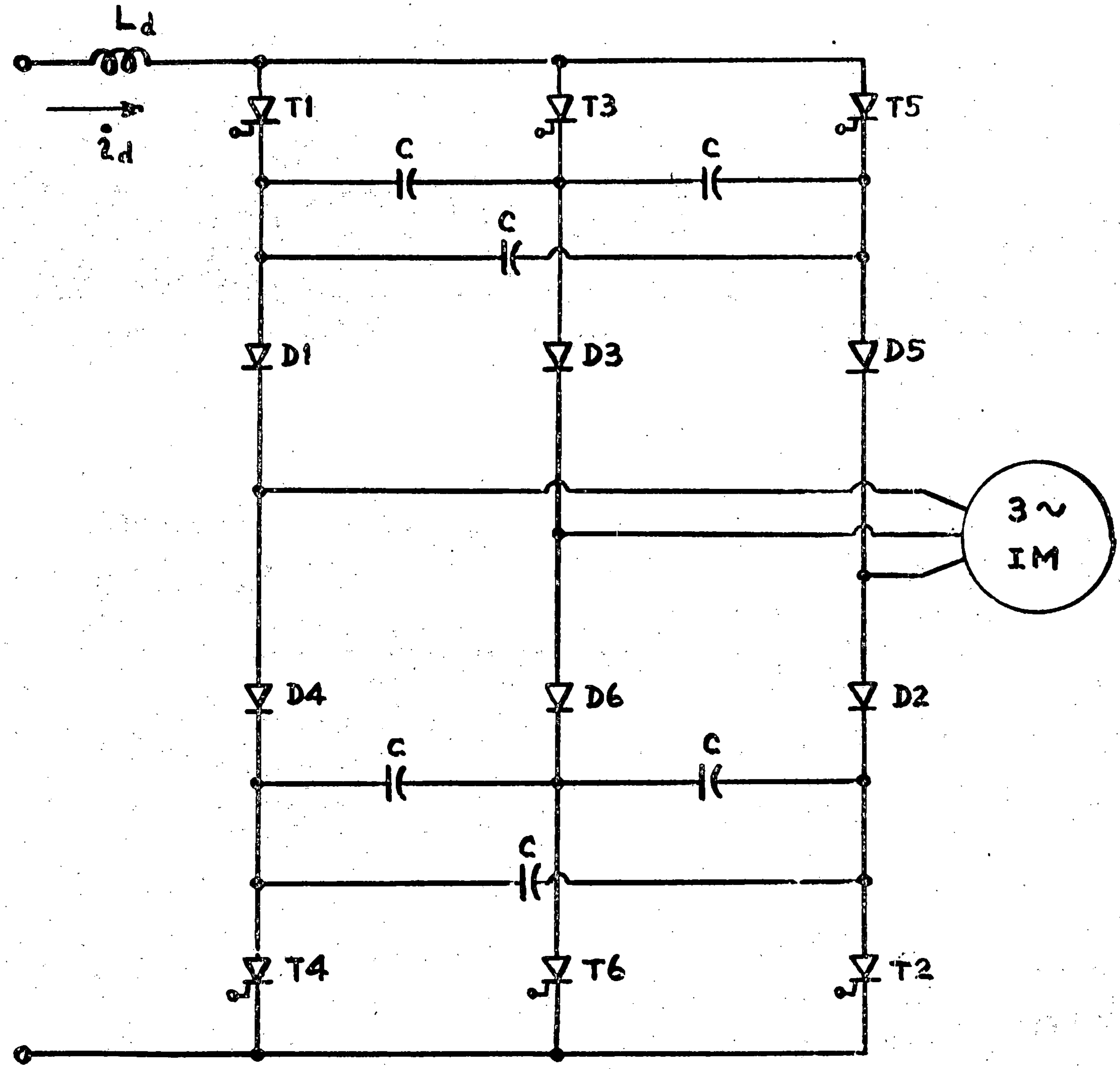


Figure 2
Current Source Inverter - IM

for about 10μs. Thus, the gate drive circuits are somewhat more complicated than for conventional thyristors, but the added complexity is not great as long as the PWM switching frequency is not greater than a few kHz.

Figure 3 shows the power circuit configuration for the GTO-IM. This is very similar to the VSI-IM except that commutating components are not required. It again would be necessary to use PWM to reduce the harmonic currents supplied to the induction motor.

Appendix G includes a discussion of the GTO voltage source inverter.

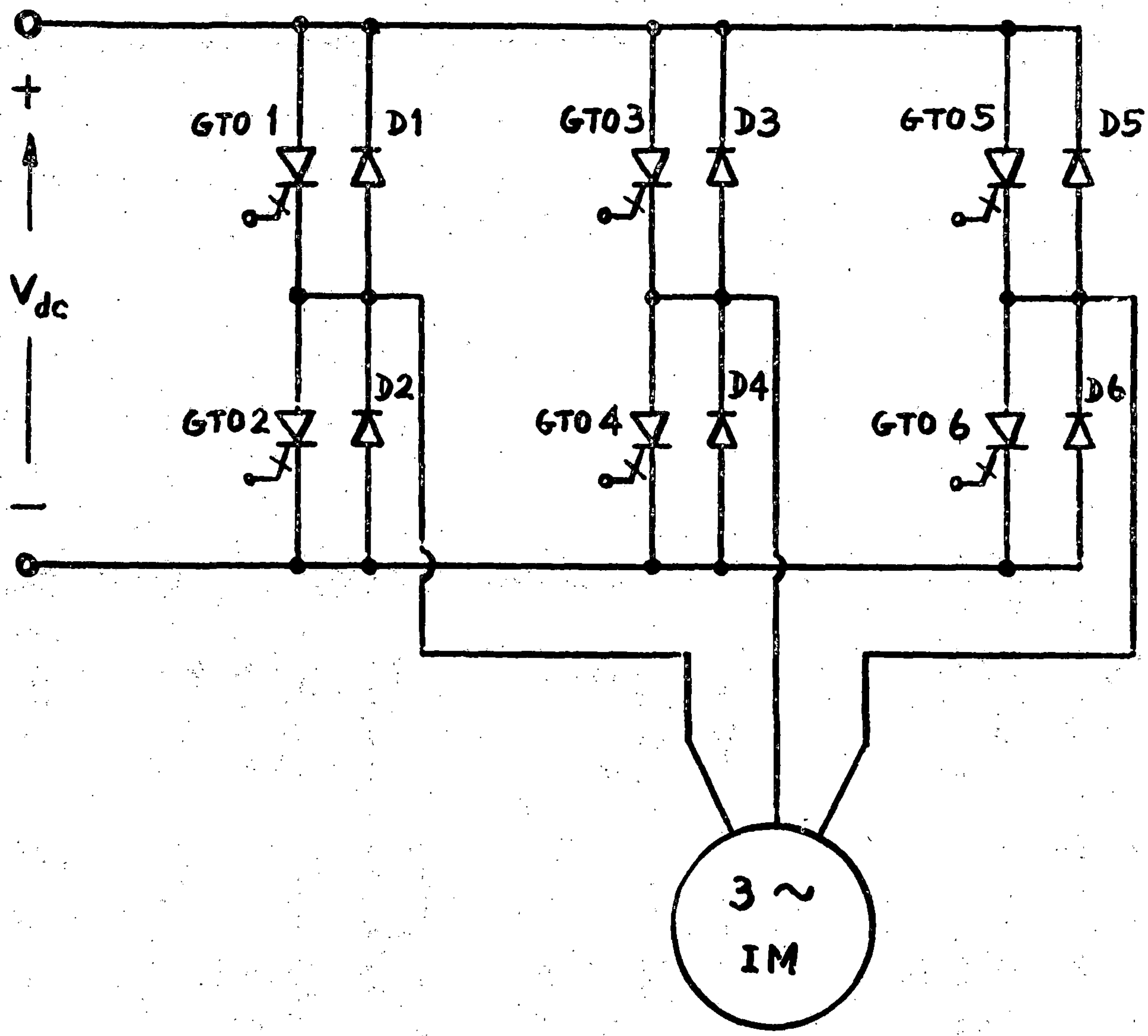


Figure 3
Voltage Source Inverter with GTO-IM

4.0 SYSTEM COMPARISON

Each of the three contenders as the optimum single axle PCU-motor combination utilize a three phase, squirrel cage induction motor for traction. The three PCU's which are compared in this section are as follows:

1) Voltage source thyristor inverter

2) Current source thyristor inverter

3) Voltage source thyristor inverter using gate turn-off devices

The primary thrust of this comparison is to provide an estimate of the relative power handling capability, physical size and cost of the PCU components necessary to supply a given power level to the traction motor. The detailed development of this comparison is given in Appendix H.

The normalized total component rating is designed to indicate the distribution of power handling capability among the various PCU components. All ratings are normalized with respect to the total component rating (TCR) of the main thyristors in the McMurray VSI. The value of this rating is found from

$$R_{Tm} = \frac{K_I N P_m}{\eta \cos \theta}$$

where $K_I = 7.92 \times 10^3$

N = Number of ideal switches = 6

P_m = Output power of the traction motor in horsepower

η = Efficiency of the traction motor

$\cos \theta$ = Power factor of the traction motor

Table 4.1 shows this comparison.

The ratings of the dc filter components dominate the total PCU rating, as would be expected. However, the apparent disproportionate size of the CSI commutating capacitors and the dc filter reactor deserve some discussion.

One of the main difficulties encountered in the implementation of the CSI is the large magnitude voltage spikes which occur during commutation. It is these spikes which determine the peak and RMS rating of the commutating capacitors. Also, the value of capacitance used in the CSI simulation was about 300 times that of the McMurray VSI.

Because of the voltage spikes, it is necessary to use a lower motor RMS voltage with the CSI than for the VSI, and this means that the current through the CSI components is significantly increased over that of the VSI at the same power level. The dc bus current at 600hp for the CSI is just under 22 amps, and the dc filter reactor is 27.39mH. The ac variation of the input terminal

TABLE 4.1

NORMALIZED TOTAL COMPONENT RATINGS

(For rating definitions, see TABLE H1, APPENDIX H)

	VSI	CSI	GTO
Main Thyristors	1.0	1.038	0.75
Commutating Thyristors	0.335	0	0
Diodes	1.0	1.038	0.75
Commutating Capacitors	0.0883	0.902	0
Commutating Inductors	0.0318	0	0
Total Inverter Rating	2.455	2.978	1.50
DC Bus Filter Capacitor	29.38	0	29.38
DC Bus Filter Inductor	0	69.73	0
Total PCU Rating	31.835	72.71	30.88

voltage is six times that of the inverter output frequency. All of these factors contribute to the large rating of the dc filter reactor.

The total component rating alone does not specify the peak voltage and RMS current ratings of the inverter components. This information is provided in Table 4.2.

Notice the reduced peak voltage rating of the GTO-VSI thyristors compared to that of the main thyristors in the McMurray VSI. Although there is a voltage spike present during commutation (see Appendix G, Figure G4), the magnitude of this peak voltage is only about 25% above the dc bus voltage. In the McMurray circuit, the series LC commutating circuit generates a peak voltage which is $(1 + K_z)$ times the dc bus voltage ($K_z = 0.667$).

This reduced voltage rating will reduce the cost of the GTO thyristors. This is important because the cost of GTO's is now several times that of comparably rated thyristors without gate turn off capability. However, it is estimated that the ultimate production cost of the GTO should be only about 1.5 times the cost of the comparably rated conventional thyristor.

The size advantage of the GTO system is immediately obvious due to the absence of the commutating components.

The peak voltage and RMS current ratings of the dc filter components are as follows:

<u>VSI/GTO-VSI DC Filter Capacitor</u>

$$V_{peak} = (1 + \tfrac{1}{2}K_r)\, V_{DC}$$

$$I_{RMS} = I_{dc} = 0.06\, I_m$$

<u>CSI DC Filter Capacitor</u>

$$I_{RMS} \simeq (1 + \tfrac{1}{2}K_r)\, I_{DC}$$

$$= 1.3\, (1 + \tfrac{1}{2}K_r)\, I_m$$

In the remainder of this section of the report, a qualitative comparison of cost, size, efficiency, reliability and control complexity for the alternative systems is presented. The total component rating information in Table 4.1 is the basis for most of the qualitative comparisons presented.

A detailed design of each system component assuming the best commercial manufacturing techniques and methods is required to obtain quantitative size and cost information. However, the following statements can be made from the TCR information.

TABLE 4.2

PEAK VOLTAGE AND RMS CURRENT RATINGS
SHOWN FOR P_m = 600/1200 HORSEPOWER

V_{DC} = DC bus voltage — K_z = 0.667

V_m = RMS IM terminal voltage — I_m = RMS IM line current

a) McMurray VSI	V_{peak}	I_{RMS}
Main Thyristors	$(1+K_z)\ V_{DC}$ = 4.33kV	$(\sqrt{2}/2)\ I_m$ = 104.75/209.5 amps
Commutating Thyristors	"	$(1/\sqrt{10}\ K_z)\ I_m$ = 70.27/140.54 amps
Diodes	"	"
Commutating Capacitors	"	"
Commutating Inductors	"	"
b) CSI	V_{peak}	I_{RMS}
Main Thyristors and Diodes	$(1.5)\ \sqrt{2}\ V_m$ = 2.83kV	$I_{DC}/\sqrt{3} = 0.75\ I_m$ = 167/334 amps
Commutating Capacitors	2.83kV	0/288 I_{DC} = 83/166 amps = 0.374 I_m
c) GTO-VSI	V_{peak}	I_{RMS}
Main Thyristors and Diodes	$(1.25)\ V_{DC}$ = 3.25kV	$(\sqrt{2}/2)\ I_m$ = 104.75/209.5 amps

1. The size and cost of the power semiconductors with their required heat sinks will not be greatly different for the three alternative systems. However, the GTO system is expected to involve the highest total power semiconductor cost, and the CSI system would have the lowest total semiconductor cost. At present it is estimated that the total parts cost of the power semiconductors and their heat sink assemblies would be less than 50% greater for the GTO systen than for the CSI system in production.

2. The commutating components required by the McMurray commutated VSI will add to the size and cost of this approach. The GTO system is best from this standpoint, but the commutating components required by the McMurray VSI are not believed to be an extremely significant factor in total cost and size. The fact that the GTO system requires the largest snubber components and more complex gate drives reduces the advantage gained by this system due to the absence of commutating components.

3. The largest components in all three systems are the dc bus filters. The dc bus filter capacitors are the largest single component in the VSI systems. These capacitors will probably be polypropylene-paper ac capacitors due to the high voltage involved and the large RMS currents. The dc bus reactor for the CSI is expected to be considerably larger than the dc filter capacitors for the VSI systems. The cost differential will not be great for the dc filters, but this is expected to result in roughly 25% more volume for the CSI than for the GTO system, which is expected to be the most compact system.

4. The commutating capacitor and snubber capacitors for all systems must be those designed for high pulse currents, such as General Electric 97F8500 components, or equal.

5. The snubber network, including diodes, capacitors and reactors, must be carefully designed to minimize the power loss from these components, while still effectively limiting peak voltages and switching losses in the power semiconductor devices.

In summary, the GTO system is expected to provide the most compact system. The cost, reliability, efficiency and control complexity of all three systems are expected to be close enough to each other such that these factors will not be the bases for the choice of the preferred system. The use of modern digital techniques and microprocessors in production systems can greatly simplify and reduce the cost of control components. It is also expected that the performance of all three systems would be comparable.

Table 4.3 presents our best judgment of the qualitative comparison of the three candidate systems.

TABLE 4.3 QUALITATIVE SYSTEM COMPARISON

	VSI	CSI	GTO
COST	Highest	Lowest	Intermediate
SIZE	Intermediate	Largest	Smallest
RELIABILITY	Lowest	Highest	Intermediate
EFFICIENCY	Lowest	Intermediate	Highest
CONTROL COMPLEXITY	Slightly Greater	Slightly Lower	Intermediate

5.0 CONCLUSIONS AND RECOMMENDATIONS

As a result of a study and analysis of the candidate power conditioning-motor combinations for single axle locomotive traction drives, a GTO voltage source inverter-squirrel cage induction motor is recommended. We believe that this system is applicable to both freight and passenger use and that it is adaptable for both all electric and diesel electric locomotives. The GTO inverter supplying a variable frequency traction motor is believed to provide the most compact system which will also be at least equal and slightly better than other possible systems from the standpoints of cost, reliability, efficiency and performance.

During Phase II (the second year) of this research, the GTO inverter-squirrel cage induction motor system will be designed to specify all significant parameters, and a digital simulation will be developed to demonstrate system performance. It is also recommended that a low power model GTO inverter be designed, constructed and evaluated during Phase II of this research. This would be very valuable in assessing the losses in an ultimate system, potential problems with using GTO devices in series and optimum gate drive circuits.

APPENDIX A WORK PLAN

OPTIMUM POWER CONDITIONING AND MOTOR COMBINATION FOR LOCOMOTIVE TRACTION

(Department of Transportation Grant DTRS 5681-C-00035)

1.0 Object

The specific object of this research is to select and analyze an integrated single-axle drive for modern locomotives. The optimum system will include a power conditioning and motor combination which has independent torque and speed control, rapid response, high reliability, minimum size and reasonable cost.

2.0 Organization

The research will be carried out under the direction of Dr. Richard G. Hoft, Professor of Electrical Engineering, University of Missouri-Columbia, who will serve as the project director and principal investigator. The following graduate students will contribute to the study:

T. Khuwatsamrit (PhD Candidate in Electrical Engineering)

J. Leonard (MSEE Candidate)

D. Williams (MSEE Candidate)

Mr. Khuwatsamrit will work full-time on the project for two months each summer and half-time on the project during each academic year. Mr. Leonard will work half-time for two months on the research during the summer of 1981. Mr. Williams will work half-time on the project for two months during the summer of 1981, full-time for two months in the summer of 1982 and half-time during each academic year. Dr. Hoft will devote half-time for three months each summer and quarter-time during each academic year to the research.

3.0 Description of Work

A schedule for the study is attached. The specific tasks and milestones are described below:

PHASE I - Select Best Candidate System

The overall object of this phase is to identify the most attractive candidate systems, analyze each of these systems in sufficient detail to compare them, and then select the traction system which is considered optimum for a single-axle locomotive drive.

Task 1 - Define Space and Mechanical Limitations

During this task, locomotive manufacturers and users will be contacted to obtain information on space and mechanical constraints.

Milestone #1 - Visit two locomotive manufacturers.

Milestone #2 - Define space available, power input, output shaft requirements and other key mechanical limitations for power conditioning and traction motor.

Task 2 - Estimate Maximum Horsepower per Axle

Using the space and mechanical constraints and basic design relationships for the power conditioning and traction motor, the maximum horsepower per axle will be determined.

Milestone #3 - Define maximum horsepower which can be delivered per axle.

Task 3 - Identify Candidate Systems

This task will involve the determination of all systems which presently appear feasible to meet the requirements.

Milestone #4 - List and describe the candidate systems.

Task 4 - Select Optimum System

As a result of an overall analysis of each candidate system and a detailed comparison of the relative merits of each, the single system considered optimum will be selected.

Milestone #5 - Define the optimum system, including a block diagram and rating information on major components.

Task 5 - Prepare Phase I Report

Milestone #6 - Complete Phase I report.

PHASE II - Develop Digital Computer Simulation and Analyze Optimum System

During this second phase, the system selected will be designed on paper to define all significant parameters, and then a digital computer simulation will be devised and run to aid in design refinements and to demonstrate performance.

Task 6 - Develop Mathematical Model for Digital Simulation

A mathematical model will be devised which accurately represents the system and which does not require excessive computer time.

Milestone #7 - Complete block diagram and program listings for simulation.

Task 7 - Design Motor and Power Conditioning Unit

This task will require the basic design of the motor and PCU - including torque and speed requirements, ratings, overall circuit diagrams and a possible packaging scheme.

Milestone #8 - Complete motor design.

Milestone #9 - Complete PCU design.

Task 8 - Analyze the Integrated Single-Axle Drive System

The computer simulation will be used to verify and refine design parameters and to demonstrate system performance.

Milestone #10 - Complete simulation runs to demonstrate performance.

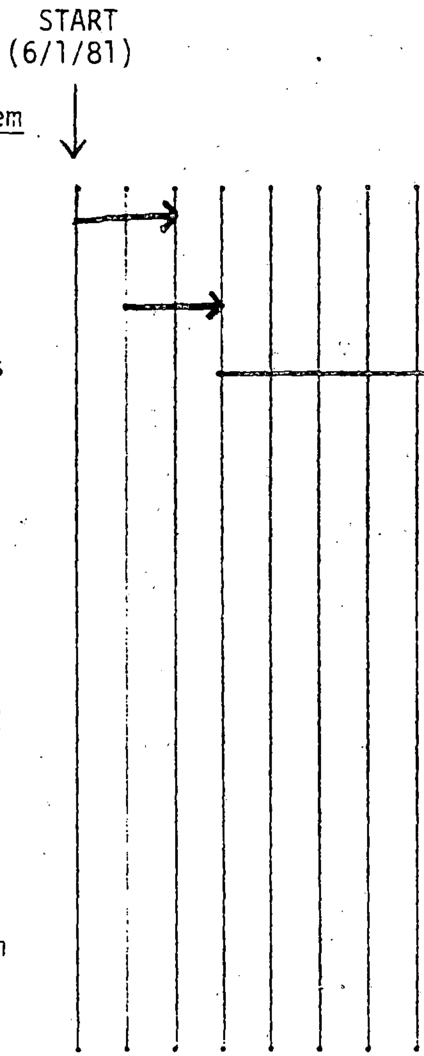
Task 9 - Prepare Final Report

Milestone #11 - Complete final report.

The expected results of the research will be the definition of an optimum power conditioning and motor combination, including a detailed system design and specification of major components, and simulation results to show the performance possible with the optimum system.

Richard G. Hoft
Principal Investigator
June 29, 1981

SCHEDULE



PHASE I - Select Best Candidate System

Task 1 Define Space & Mechanical Limitations

Task 2 Estimate Maximum Horse-power per Axle

Task 3 Identify Candidate Systems

Task 4 Select the Optimum System

Task 5 Prepare Phase I Report

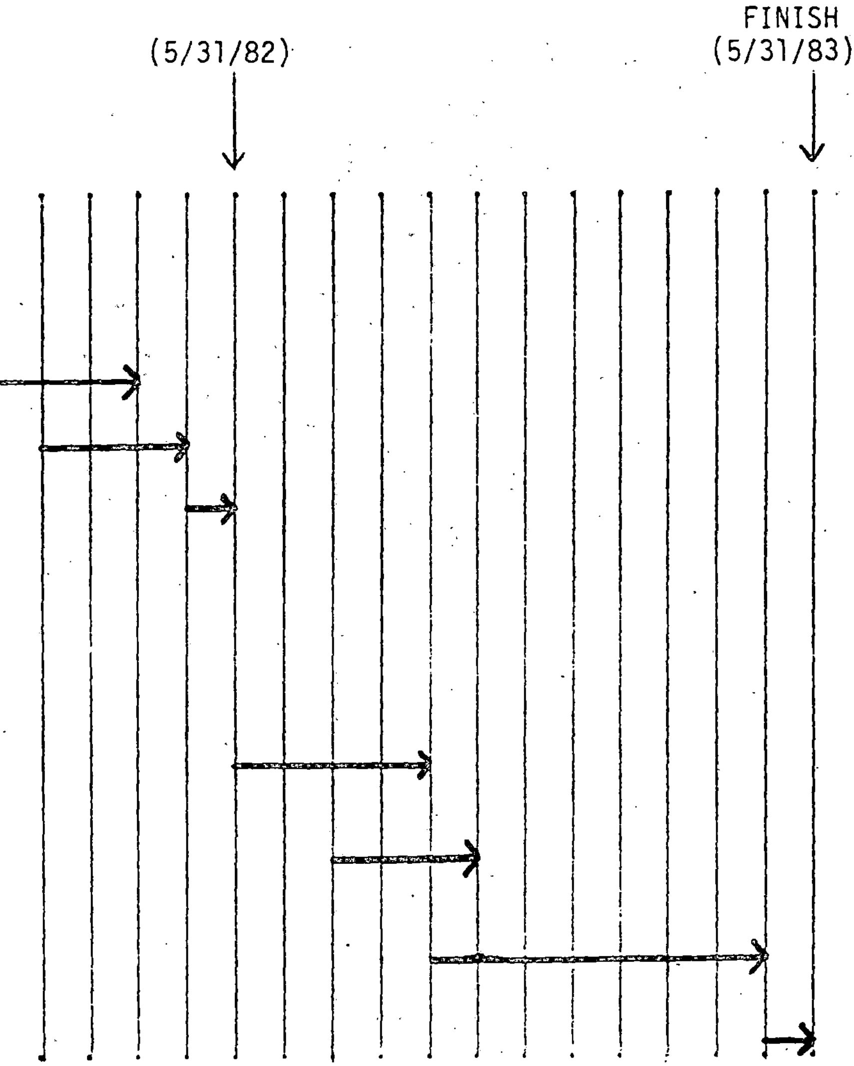
PHASE II - Develop Digital Computer Simulation and Analyze Candidate System

Task 6 Develop Mathematical Model for Digital Simulation

Task 7 Design Motor and Power Conditioning Unit

Task 8 Analyze the Integrated Single-Axle Drive System

Task 9 Prepare Comprehensive Final Report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APPENDIX B SUMMARY OF VISIT TO GM-EMD, LAGRANGE, ILLINOIS

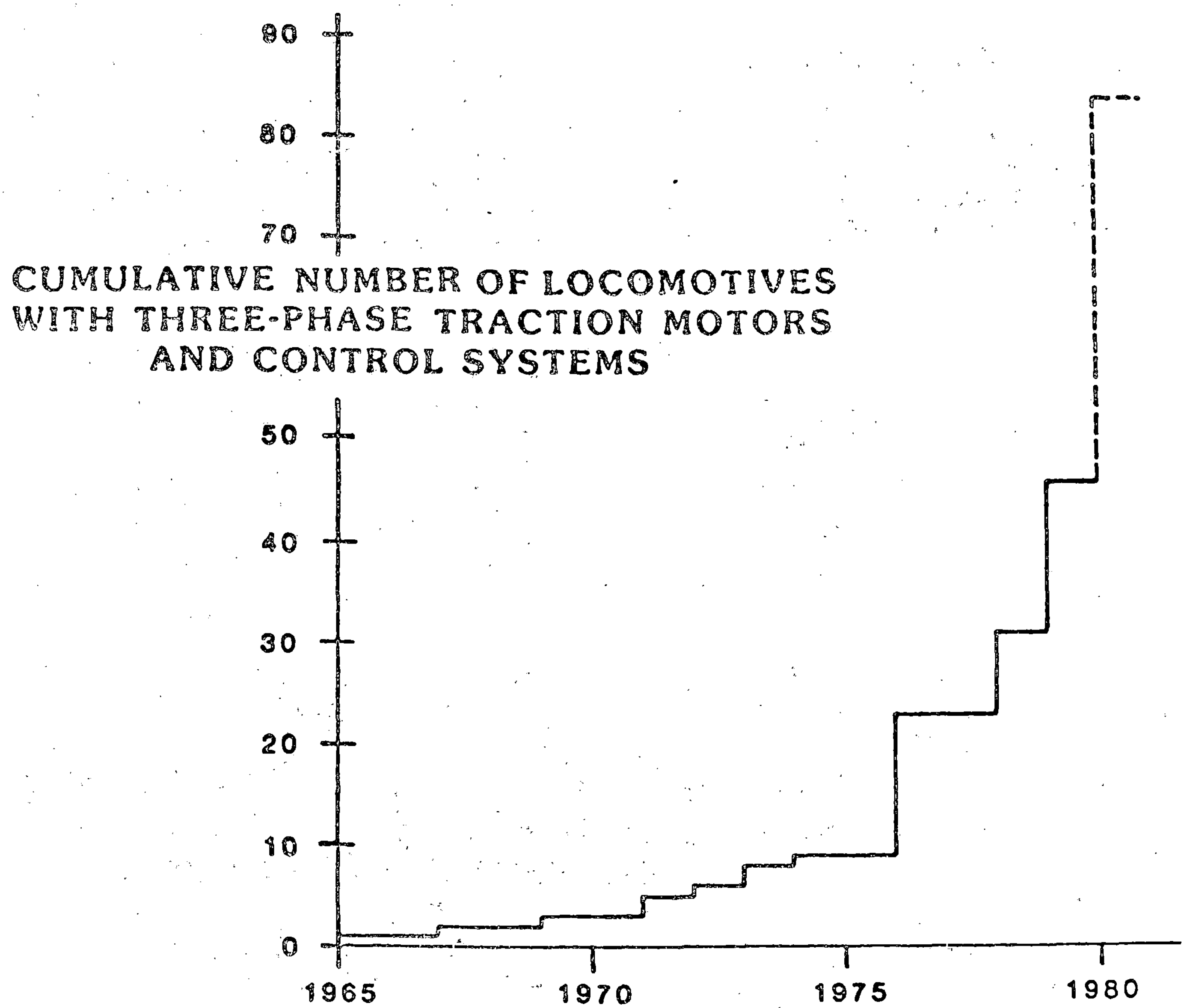
JULY 22, 1981

The following is a brief summary of the visit by R. Hoft, T. Khuwatsamrit, J. Leonard and D. Williams to GM-EMD on July 22, 1981. We were the guests of Eric Sjokvist, arriving in his office about 9:00 AM and completing our visit about 4:00 PM. The visit included a very informative slide presentation by Mr. Sjokvist, a tour of the manufacturing building and a conference with Mr. Sjokvist's staff.

1. The first locomotive propulsion systems using three phase traction motors were constructed in the early 1900's. However, these were not of much practical interest. As a result of the availability of large thyristors, considerable research and development activity began in the 1960's on power electronic ac drive systems for locomotives and urban transit cars. Experimental three phase, variable frequency thyristor ac propulsion systems for locomotives have been built by Brush Electric (England), WABCO-Reliance (Cleveland), Russia, France and Germany. The graph labeled slide 3 shows the worldwide increase in the number of three phase thyristor traction systems for locomotives since they first appeared in about 1965.* Currently there are nearly 90 such locomotives in existence. Approximately half of these have been built by the Brown Boveri Company (BBC) in Mannheim, Germany. In addition to these locomotives, there are about 200 rapid transit cars in operation using three phase thyristor ac propulsion systems.

2. There are significant differences in manufacturing philosophies in Europe and the US. The reproduction of Slide 13 summarizes these. Two additional very important points are - (1) In general, the railways in Europe are nationalized so that equipment cost is not quite as important as in the US; (2) At least at present,

*Most of the figures included in this report are copies of slides which were provided to us by GM-EMD. We very much appreciate receipt of this information as well as all of the other articles and reports which they graciously provided to us.


CUMULATIVE NUMBER OF LOCOMOTIVES
WITH THREE-PHASE TRACTION MOTORS
AND CONTROL SYSTEMS
90
80
70
50
40
30
20
10
0
1965
1970
1975
1980

Slide 13

COMPARISON OF RAILROADING PHILOSOPHIES

	U.S. CONCEPT	EUROPEAN CONCEPT
LOCOMOTIVE SPEED	FREIGHT TO 75 MPH	FREIGHT & PASSENGER WITH SPEEDS TO 100 MPH
AXLE LOAD	65000 LBS(TYPICAL)	43000-48000 LBS
WHEEL DIAMETER	40-42 INCHES	43.3 DE 49.2 EL
MECHANICAL DRIVE	RIGID GEAR	FLEXIBLE DRIVE
MOTOR SUSPENSION	AXLE HUNG	PREDOMINANTLY FRAME HUNG

locomotive manufacturers in Europe put a greater percentage of their total sales into R&D than US companies.

3. The main advantages of three phase thyristor propulsion systems are

   a. Higher torque and output rating for the same size and weight.

   b. No commutator or brushes.

   c. Less susceptibility to adverse environments.

   The major disadvantage of such propulsion systems is that a complicated power electronic system is required which results in a higher locomotive cost.

4. A summary of three phase thyristor variable frequency ac traction developments in Europe is as follows:

Brown Boveri	Locomotives since 1971 Rapid Transit since 1979	Voltage Source Inverter (VSI)
Siemens	Rapid Transit since 1975	Current Source Inverter (CSI)
AEG	Rapid Transit since 1976 Locomotive Prototype 1980	CSI
ASEA	Locomotive Prototype 1980	VSI

   Mr. Sjokvist pointed out that although the current production capability of Brown Boveri is entirely VSI, most of this company's R&D expenditures in recent years have been devoted to the CSI technology.

5. Slide 11 summarizes GM-EMD three phase variable frequency thyristor traction development.

6. There may be limited applications for three phase ac traction during the next few years, but widespread demand is likely in future years, particularly when electrification is adopted. The bar graph (page 20) shows the current amount of electrified rail miles, the number of which is increasing at the rate of approximately 8 miles per day.

THREE-PHASE TRACTION TRANSMISSION DEVELOPMENT WITHIN ELECTRO-MOTIVE

1968-1974 EMD Investigated a Three-Phase Drive for Diesel Electric Locomotives:

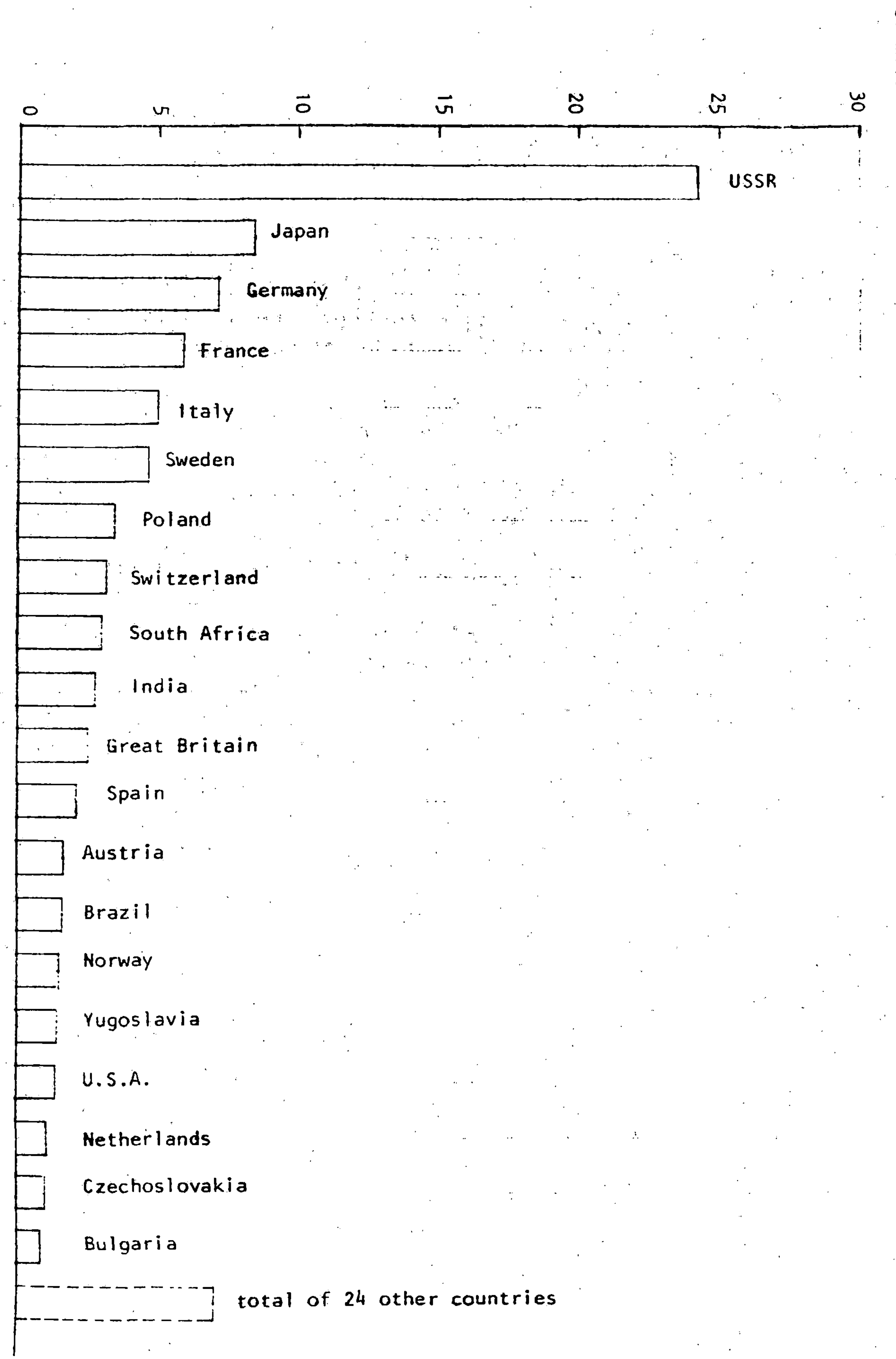
Engine---High Frequency Alternator---
Cycloconverter---Induction Motor

1976 EMD Evaluated Various Three Phase Systems for Locomotive Propulsion

1978-1979 EMD Designed and Developed a Cycloconverter Self-Synchronous Drive System

Successfully Demonstrated System Operation in all Four Modes

Shipped Completed System to Department of Energy for further Evaluation



ELECTRIFIED ROUTE MILES IN VARIOUS COUNTRIES

Source: "Railway Electrification Systems" by J. C. Grant
Boletin de la ACPF No. 262 (October-December 1979)

7. There are three practical alternatives for three phase ac traction:

   VSI - Induction Motor

   CSI - Induction Motor

   Cycloconverter - Synchronous Motor

   The synchronous motor system is disadvantageous because of the need for slip rings, or a rotary transformer, and a shaft position sensor. A comparison of the VSI-IM and CSI-IM is shown on Slide 31. GM presently prefers a CSI-IM system.

8. The following comments and suggestions were made during the final discussions with Mr. Sjokvist and his staff:

   a. In order for the project to be "realistic", the scope should be limited somewhat or at least more precisely defined than the stated purpose in the DOT contract.

   b. Since our project is a "paper" study, all system performance will be based on the results of computer simulation. Therefore, the selection of the models representing physical components will be crucial.

   c. A single axle study must not overlook the critical interactions inherent in a multi-axle locomotive.

   d. The control system and motor must be considered as a single design problem. This is due to the fact that the peak ratings of the electronic switching devices in the power conditioning unit depend upon motor parameters. The motor leakage inductance is particularly important for motors rated at 200 horsepower or higher. Typical thyristor device ratings are 4,000 Volts, 1,000 Amps.

   e. We should begin with a specific Tractive Effort (TE) curve and then select the following types of specifications:

Slide 31

ADVANTAGES AND DISADVANTAGES WITH DIFFERENT INVERTER SYSTEMS

	VSI VOLTAGE SOURCE INVERTER	CSI CURRENT SOURCE INVERTER
EFFICIENCY	GOOD	*SLIGHTLY BETTER (DIFFERENCE <1%)
POWER FACTOR	ADJUSTABLE BY INPUT SYSTEM	ADJUSTABLE BY INPUT SYSTEM
TORQUE PULSATIONS	*MINIMAL (PROVEN)	CAN BE REDUCED (DEGREE NOT YET DEMONSTRATED)
POWER ELECTRONICS	MORE ELECTRONICS	*BASE
TYPE OF SEMICONDUCTOR	SPECIAL (SHORT TURN OFF TIME)	*STANDARD HIGH VOLTAGE
FAILURE MODE	REQUIRES PROTECTIVE CIRCUITS FOR OVERLOAD	*INHERENT PROTECTION
APPLICATION TO DIESEL ELECTRIC LOCOMOTIVES	*PROVEN	FEASIBLE (UNPROVEN)
WEIGHT AND VOLUME OF ELECTRICAL EQUIPMENT	GREATER THAN FOR THE CSI	*BASE
PRESENT EXPERIENCE	*MORE EXTENSIVE FOR LOCOMOTIVES	MORE EXTENSIVE FOR RAPID TRANSIT
LOCOMOTIVE COST	APPROXIMATELY 5% MORE EXPENSIVE	*BASE

*FAVORED BY PRESENT EXPERIENCE

Wheel Base	4 ft. 8 in.
Wheel Diameter	40 to 42 in.
Axle Load	65,000 lbs.
Maximum Speed	75 mph
Maximum Horsepower	3,000 to 4,000 hp
Number of Axles	4 or 6

f. Individual motor control is absolutely necessary, because without such control as little as a 1% variation in wheel diameter may cause an induction motor to be totally unloaded. Also, as much as a 10% variation is possible with 5% or 6% being a common figure. Due to this variation, care must be taken to ensure that the motor housing rides 4-1/2 inches above the track, with no wear on the wheels, so that the minimum Association of American Railroads (AAR) profile of 2-1/2 inches can be maintained with the wheels fully worn.

D. Williams/R. Hoft

September 5, 1981

APPENDIX C SUMMARY OF VISIT TO GE, ERIE, PA, AUGUST 20, 1981

The following is a summary of the visit to General Electric, Erie, PA, by R. Hoft, T. Khuwatsamrit and D. Williams. Hal Henderson made all of the arrangements for our visit. We arrived in his office about 9:00 AM and left about 3:00 PM. Most of our time was spent in conference with Hal Henderson, Bob Weeks, Dave Plette and Ron Bailey. We also toured their manufacturing building. Many of our discussions were similar to those that we had with GM-EMD. This summary will not repeat items contained in the GM Trip Report Summary.

1. The general consensus of opinion was that we should carefully limit the scope of our project. Initially, choices must be made concerning the specific application of the locomotive (freight or passenger service), the type of locomotive (diesel electric or totally electric) and the basic type of traction motor (ac or dc).

2. It is our intent that the results of the research have the widest possible impact, affecting a large segment of the rail industry within the United States. Given this intention, the initial choices must be based on the following type of general information:

   a. The overwhelming majority of locomotives in service in the US are used in freight applications. Locomotives used in freight service generally experience less acceleration and operate over a lower speed range than those used in passenger service. They also may operate for extended periods at each operating condition.

   b. The number of diesel electric locomotives in this country far outweighs the number of totally electric locomotives. However, the diesel electric locomotives have less space available for power conditioning and control circuitry and the associated cooling equipment. Even though the worldwide trend towards total electrification should be considered, that trend in the US is not as significant at the present time.

c. DC traction technology has been developed extensively. It appears that the development of ac traction offers the greatest potential for improvement of locomotive propulsion systems. The possibility also exists that even if the complete changeover to ac traction is not economically feasible, there may still be a sufficient incentive to utilize the new technology for special purpose vehicles (drilling rigs, cranes, etc.).

Based on these facts, we feel that the initial focus of the project should be limited to diesel electric locomotives employing ac traction propulsion systems to be used in freight applications. As our study progresses, the basis for selection between alternatives will be more technical in nature. The choice between four or six axles on the locomotive is a good example. At first glance, this choice appears to have been implied when choosing the type of locomotive. But even at this early stage, this particular choice demands the consideration of a number of interdependent selection criteria.

3. Certainly the economic cost benefit analysis will be the ultimate criteria for the adoption of any new technology. Along these lines, the efficiency of the propulsion system is of prime importance. According to Mr. Henderson, one additional percentage point of efficiency equates with a present worth of $30,000.

4. The size and weight of the propulsion system components are both important, size usually being the overriding restriction. Although maximum weight is usually not a limiting factor, minimum weight certainly could be due to the effects of weight on the coefficient of adhesion of the locomotive. Typically, this coefficient is approximately 0.25.

5. The continuous horsepower rating of the locomotive is limited by the diesel engine. The minimum continuous speed is a function of the type of traction motor. At the same traction motor horsepower rating, the six axle locomotive provides 50% additional tractive effort over the four axle locomotive.

6. In terms of size and weight, both proved to be limiting factors in the propulsion system design of the four axle locomotive. However, the six axle locomotive required additional ballast weight to maintain acceptable adhesion. Of course, these were conventional dc propulsion systems, and the same comparison may not be valid for ac traction.

7. In terms of efficiency, assuming individual axle motor control, the loss of traction to a single axle results in a less severe efficiency reduction for the six axle locomotive compared to that of the four axle locomotive (17% vs. 25%). This is a failure mode comparison which may have more impact on the design of inherent redundancy than on the overall efficiency of the locomotive. Discounting the failure mode, it may turn out that the four axle locomotive is the more efficient machine, particularly when used in freight applications where three or four locomotives are connected to the same train.

8. We do not believe that the choice between a four or six axle locomotive can be made at this early stage of our project. Our primary concern is with a single axle propulsion system, the characteristics of which will obviously depend on the basic locomotive parameters previously outlined. It would be presumptuous to make this decision until we have identified and compared the alternative propulsion systems.

9. A discussion of design strategies led to some practical ideas to aid in the comparison of propulsion systems. These ideas included the use of modular design of subsystem components; the use of a normalized, per unit scheme to describe the variation of the propulsion system parameters; the interdependence of critical subsystem parameters preventing the separation of individual subsystem designs; and some practical guidelines to implement safety margin by the proper selection of electronic switching device ratings.

   The use of modular design of subsystem components offers two principle advantages. First, easily accessible component modules greatly facilitate maintenance. This is particularly important because it is almost a certainty that the ac traction system control and power conditioning circuitry will be more complicated than that required for the conventional dc traction system. Secondly, modular design lends itself to the use of common technology, which is desirable for the modification of an existing product line. Both of these factors should reduce the economic impact resulting from the changeover to the new system.

Another valuable suggestion concerns the use of a normalized, per unit description of the propulsion system parameters. Using this type of scheme allows more flexibility in terms of space and mechanical limitations. Instead of rigid requirements, a range of values could be more useful. For example, a certain amount of horsepower requires a certain amount of packaging space for the power conditioning equipment. The main problem with this approach is that the scaling will probably not be linear.

It has been stated repeatedly that the interdependence of the propulsion subsystem parameters prohibits the separate design of those subsystems. The most obvious example is the effect of the traction motor leakage inductance on the inverter characteristics. In the case of the current source inverter, there may be a severe load (weight) penalty in order to obtain the small leakage inductance required for high speed operation.

The thyristor ratings are important to ensure a margin of safety in the PCU operation. The following suggestions outline the selection of the voltage, current and temperature ratings and the required turn off time of the devices.

To select the voltage ratings, two cases must be considered. If the voltage is a well controlled dc voltage, then the rating should be 1-1/4 to 1-1/2 times the maximum voltage across the device. If the source is an ac line voltage, then the rating should be 2-1/2 times the maximum voltage across the device. For current and temperature ratings, calculate the requirements for all the possible worst case conditions and select the rating to meet these requirements with no additional margin. To select the proper turn off time, calculate the worst case condition and then add 10%.

It is true that the power handling capability of thyristors has improved dramatically in recent years. However, too much dependence on continuing capability may not be wise. It seems that the power semiconductor industry has reached a plateau. Barring a significant breakthrough in the fabrication technology, it is not likely that any jumps in the power handling capability will occur. This brings to mind the fact that electrification has been "just around the corner" for quite some time.

10. There was some discussion of high capability gate turn off (GTO) thyristors. Hitachi has reported a device with ratings of 1600V and 600A, and Toshiba has reported one with ratings of 2500V and 600A. Even with significantly higher capability, the switching losses increase with the square of the current handling capability. The resulting loss in efficiency may be significant, possibly even prohibitive in terms of adopting this new technology.

11. During the course of our visit, Mr. Henderson provided us with a large quantity of literature that will be very helpful in determining the space and mechanical limitations of the locomotive. It may be the wisest course of action to simply select maximum space limitations based on the existing mechanical framework.

12. At this stage of our study, it seems that the most likely area for improvement will be the circuit design of the power conditioning equipment. Certainly the work already done in this area is extensive, but we feel that it is far from exhaustive.

13. Several additional items mentioned during our discussions included:

    a. The Southern Pacific Railroad appears to have an interest in three phase ac traction.

    b. The VSI and CSI are quite close competitors.

    c. A VSI system is preferred for rapid transit application, since dc input power is used.

    d. For an all electric locomotive, it may be feasible to use 1500HP/traction motor.

    e. The General Electric C712 and C713 thyristors are quite standard for transportation applications.

D. Williams/R. Hoft

September 5, 1981

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APPENDIX E ANALYSIS OF MCMURRAY VSI-IM

The analysis of the system in Figure 1 is done in two parts

Selection of commutation components

Induction motor steady-state performance with PWM voltage source

E.1 Selection of Commutation Components

The commutation circuit is one of the main considerations in evaluating the voltage source inverter. It is an important factor in the efficiency, volume and weight of a power conditioning unit (PCU). Optimization of the McMurray inverter cannot be done without considering the commutation circuit.

The commutation operation of a single phase McMurray inverter is described in the following section. Peak commutation current, peak commutation capacitor voltage and turn-off time are main concerns in commutation circuit design.

E.1.1 Derivation of Equations for McMurray Commutation Circuit

General Equations for RLC Circuit (Series)

$$i_L(t) = \frac{E-V_C(0)}{\omega L} e^{-\frac{R}{2L}t} \sin(\omega t) - \frac{\omega_o}{\omega} i_L(0) e^{-\frac{R}{2L}t} \sin(\omega t-\phi)$$

$$v_C(t) = E - \frac{\omega_o}{\omega} [E-v_C(0)] e^{-\frac{R}{2L}t} \sin(\omega t+\phi) + \frac{i_L(0)}{\omega C} e^{-\frac{R}{2L}t} \sin(\omega t)$$

where $\omega_o = \frac{1}{\sqrt{LC}}$

$$\omega = \sqrt{\omega_o^2 - (R/2L)^2}$$

$$= \omega_o/\sqrt{1+(1/2Q)^2}$$

and $\phi = \tan^{-1} (2\omega L/R)$

Interval $\rightarrow t_0^-$

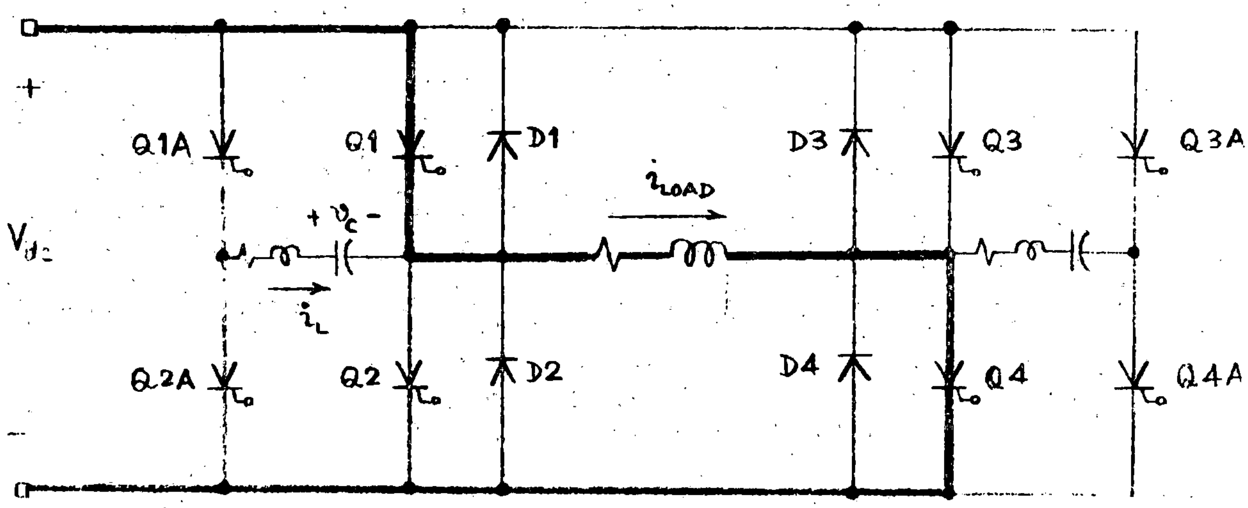


Fig. E1: Initial condition at t_0^-

Q1 and Q4 are conducting.

Interval $t_0 \rightarrow t_1$

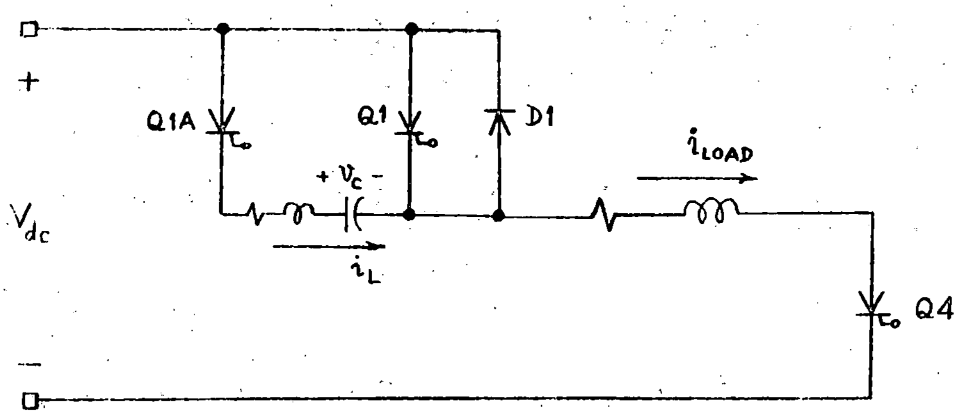


Fig. E2: Equivalent circuit for interval $t_0 \rightarrow t_1$

Initial conditions for commutation circuit:

$E = 0\ (V); \quad v_C(0) = -V_{dc}\ (v), \quad i_L(0) = 0 \quad (A)$

implies $$i_L(t) = \frac{V_{dc}}{\omega L}\, e^{-\frac{R}{2L}t} \sin(\omega t)$$

and $$v_C(t) = \frac{\omega_o}{\omega} V_{dc}\, e^{-\frac{R}{2L}t} \sin(\omega t+\phi)$$

for $0 < t < (t_1 - t_0)$

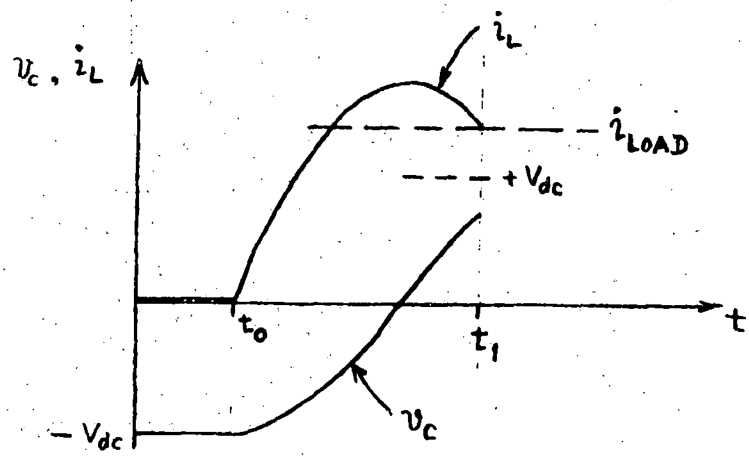


Fig. E3: Waveforms of v_C and i_L for interval t_o-t_1

Assume negligible ripple in i_{load} and high Q.

Interval $t_1 \rightarrow t_2$

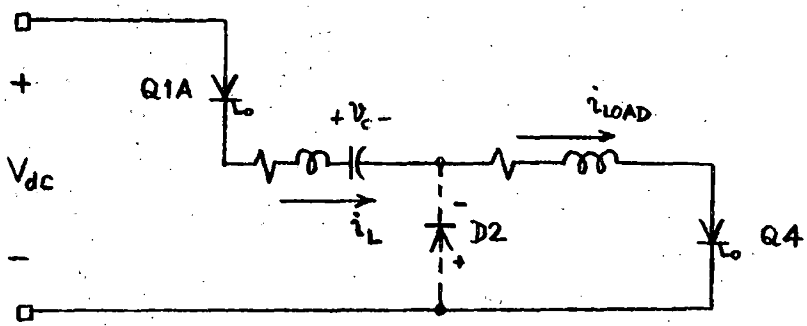


Fig. E4: Equivalent circuit for interval t_1-t_2

Initial conditions: $i_L(0) = i_{load}$

assume negligible ripple in i_{load}

implies $i_L(t) = i_L(0) = i_{load}$

and $v_C(t) = v_C(0) + \frac{i_{load}(t)}{C}$

for $0<t<(t_2-t_1)$

where $v_C(0) = v_C(t_1)$

Termination condition: $v_{D2}>0$

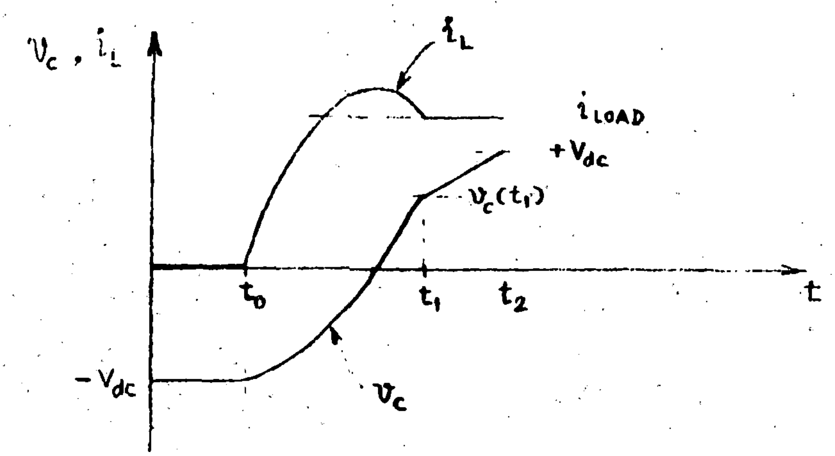


Fig. E5: Waveform of v_c and i_L for interval t_o-t_2

Interval $t_2 \rightarrow t_3$

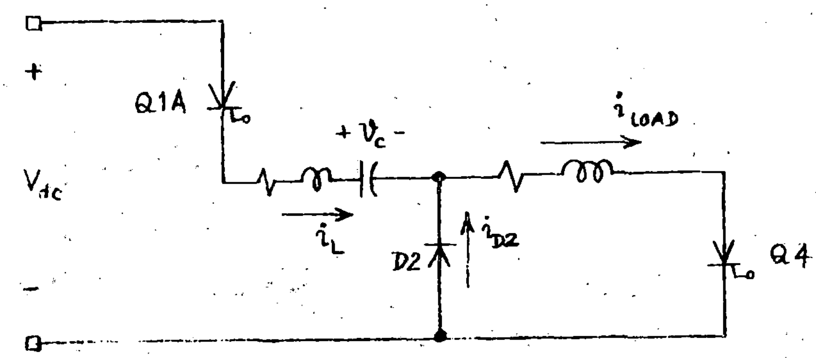


Fig. E6: Equivalent circuit for interval t_2-t_3

Initial conditions for commutation circuit:

$E = V_{dc}$, $i_L(0) = i_L(t_2)$, $v_C(0) = v_C(t_2)$

implies $$i_L(t) = \frac{E-V_C(0)}{\omega L} e^{-\frac{R}{2L}t} \sin(\omega t) - \frac{\omega_o}{\omega} i_L(0) e^{-\frac{R}{2L}t} \sin(\omega t-\phi)$$

and $$v_C(t) = E - \frac{\omega_o}{\omega} [E-v_C(0)] e^{-\frac{R}{2L}t} \sin(\omega t+\phi) + \frac{i_L(0)}{\omega C} e^{-\frac{R}{2L}t} \sin(\omega t)$$

for $0<t<(t_3-t_2)$

Termination condition:

$i_L(t_3) = 0$

Commutation process is completed.

E.1.2 Design Information

With the following assumptions

- Negligible ripple in load current during commutation interval
- Commutation capacitor voltage is initially at dc bus voltage
- Negligible resistance in commutation circuit

the peak voltage, peak current and turn-off time can be written as

$$v_{C,peak} = V_{dc} + \frac{i\ load}{\omega_0 C} \tag{1}$$

$$i_{L,peak} = \frac{Vdc}{\sqrt{L/C}} \tag{2}$$

$$t_q = \frac{2}{\omega_0}\left[\frac{\pi}{2} - \sin^{-1}\left(\sqrt{\frac{L}{C}}\ \frac{i_{load}}{V_{dc}}\right)\right] \tag{3}$$

where

V_{dc} = dc bus voltage (V) minimum

i_{load} = load current (A) maximum

L = commutation inductance (H)

C = commutation capacitance (F)

ω_0 = $1/\sqrt{LC}$ (rad/sec)

If two parameters are defined as

$$K_o = \frac{i_{L,peak}}{i_{load}}$$

and

$$K_1 = \frac{V_{dc}}{i_{L,peak}} \quad (\Omega)$$

then (1), (2) and (3) become

$$K_o\left[\frac{v_{C,peak}}{v_{dc}} - 1\right] = 1 \tag{4}$$

$$\sqrt{\frac{L}{C}} = K_1 \tag{5}$$

and

$$\frac{t_q}{\frac{\pi}{2} - \sin^{-1}\left(\frac{1}{K_o}\right)} = \frac{2}{K_1} \cdot L \tag{6}$$

Equations (4), (5) and (6) are plotted using a log-log scale, from the modified equations

$$\log\left[\frac{v_{C,peak}}{V_{dc}} - 1\right] = -\log K_o \tag{7}$$

$$\log L = 2 \log K_1 + \log C \tag{8}$$

$$\log t_q - \{\log [\tfrac{\pi}{2} - \sin^{-1}(\tfrac{1}{K_o})] + \log 2\} = -\log K_1 + \log L \tag{9}$$

The graphs of (7), (8) and (9) are shown in Fig. E7. These are families of straight line curves which are easy to produce and can be used as a first guide in selecting the commutation circuit components.

In order to determine how well the approximations used to develop Fig. E7 compare to the actual situation, a detailed simulation was done with the only assumption that there is no ripple in the load current. The results are shown in Tables E1 through E5. The program listings for the simulation are shown in the next section. It is noted that if the initial voltage across the commutation capacitor is equal to the dc bus voltage, which is valid for the modified McMurray inverter, with Q factor higher than 10, the differences between the approximate results and those obtained from more detailed simulation stay within 10% for either peak voltage, peak current or t_q. The approximation is inaccurate for the cases where the initial voltage is greater than $1.25V_{dc}$.

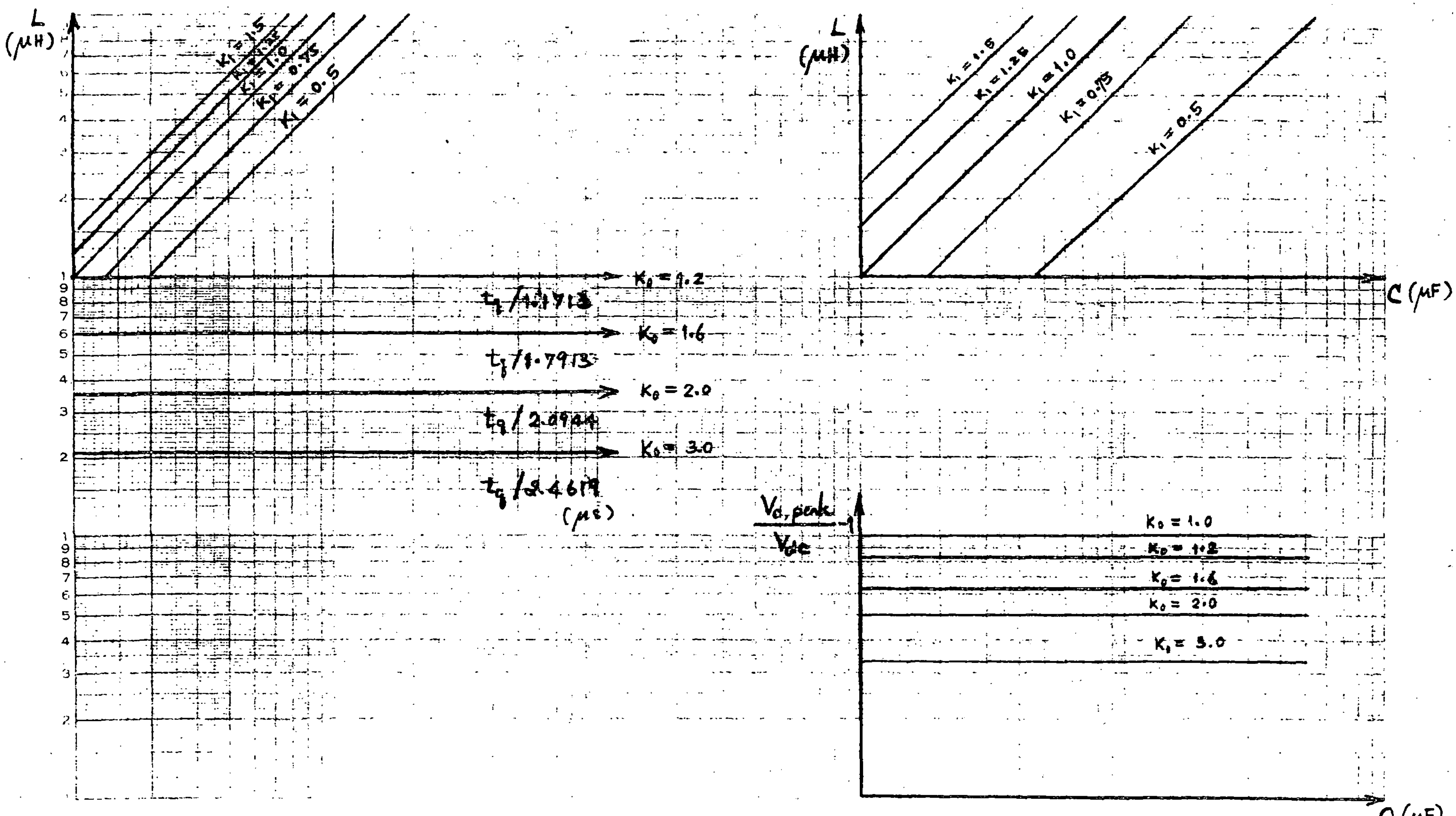


Fig. E7: PLOT OF $V_{C,PEAK}$, t_q VS L AND C WITH K_0 AND K_1 AS PARAMETERS

Q = 10 VCI = 1.0V_{dc}		$V_{C,peak}$(V)			$I_{L,peak}$(A)			t_q(μsec)		
L(μH)	C(μF)	More Detail Simulation	Approximate Result	% Difference	More Detail Simulat.	Approx. Result	% Diff.	More Detail Simulat.	Approx. Result	% Diff.
100	100	1830	1900	-3.82	926	1000	-7.99	48.0	90.2	-8.79
100	200	1585	1636	-3.22	1310	1414	-7.94	230.5	249.2	-8.11
100	300	1480	1520	-2.70	1605	1732	-7.91	338.0	354.9	-5.00
100	400	1414	1450	-2.54	1852	2000	-7.99	425.9	441.6	-3.69
75	400	1359	1390	-2.28	2140	2309	-7.90	393.9	405.5	-2.94
50	400	1295	1318	-1.78	2620	2828	-7.94	345.0	352.7	-2.23
25	400	1208	1225	-1.41	3706	4000	-7.93	265.5	268.8	-1.24

Table E1

Q = 50 VCI = 1.0V_{dc}		$V_{C,peak}$(V)			$I_{L,peak}$(A)			t_q(μsec)		
L(μH)	C(μF)	Detail Simu-lation	Approx. Result	% Diff.	Detail Simu-lation	Approx. Result	% Diff.	Detail Simu-lation	Approx. Result	% Diff.
100	100	1886	1900	-0.74	984	1000	-1.63	83.5	90.2	-8.02
100	200	1628	1636	-0.49	1392	1414	-1.58	245.0	249.0	-1.71
100	300	1512	1520	-0.53	1705	1732	-1.58	351.5	354.9	-0.97
100	400	1443	1450	-0.48	1968	2000	-1.63	438.4	441.6	-0.73
75	400	1382	1390	-0.58	2272	2309	-1.63	402.9	405.5	-0.64
50	400	1313	1318	-0.38	2784	2828	-1.58	351.5	352.7	-0.34
25	400	1222	1225	-0.24	3934	4000	-1.68	268.0	268.8	-0.30

Table E2

Q = 100, VCI = 1.0V_{dc}		$V_{C,peak}$(V)			$I_{L,peak}$(A)			t_q(μsec)		
L(μH)	C(μF)	Detail Simu-lation	Approx. Result	% Diff.	Detail Simu-lation	Approx. Result	% Diff.	Detail Simu-lation	Approx. Result	% Diff.
100	100	1895	1900	-0.26	991	1000	-0.91	87.0	90.2	-3.68
100	200	1629	1636	-0.43	1403	1414	-0.78	247.5	249.2	-0.69
100	300	1514	1520	-0.40	1718	1732	-0.81	353.5	354.9	-0.40
100	400	1446	1450	-0.28	1983	2000	-0.86	439.9	441.6	-0.39
75	400	1388	1390	-0.14	2290	2309	-0.83	404.4	405.5	-0.27
50	400	1316	1318	-0.15	2806	2828	-0.96	352.0	352.7	-0.20
25	400	1222	1225	-0.24	3964	4000	-0.91	268.5	268.8	-0.11

Table E3

Q = 100 VCI = 1.25V_{dc}		$V_{C,peak}$(V)			$I_{L,peak}$(A)			t_q(μsec)		
L(μH)	C(μF)	Detail Simu-lation	Approx. Result	% Diff.	Detail Simu-lation	Approx. Result	% Diff.	Detail Simu-lation	Approx. Result	% Diff.
100	100	1893	1900	-0.37	1240	1000	19.35	152.0	90.2	40.66
100	200	1632	1636	-0.37	1754	1414	19.38	292.0	249.2	14.66
100	300	1527	1520	0.46	2146	1732	19.29	394.4	354.9	10.02
100	400	1468	1450	1.23	2480	2000	19.35	479.9	441.6	7.98
75	400	1419	1390	2.04	2864	2309	19.38	432.9	405.5	6.33
50	400	1363	1318	3.30	3504	2828	19.29	371.0	352.7	4.93
25	400	1300	1225	5.77	4959	4000	19.34	277.5	268.8	3.14

Table E4

Q = 100 VCI = 1.50V_{dc}		$V_{C,peak}$(V)			$I_{L,peak}$(A)			t_q(μsec)		
L(μH)	C(μF)	Detail Simu-lation	Approx. Result	% Diff.	Detail Simu-lation	Approx. Result	% Diff.	Detail Simu-lation	Approx. Result	% Diff.
100	100	1910	1900	0.52	1488	1000	32.80	184.0	90.2	50.98
100	200	1709	1636	4.27	2102	1414	32.73	319.0	249.2	21.88
100	300	1638	1520	7.20	2578	1732	32.81	420.9	354.9	15.68
100	400	1599	1450	9.32	2976	2000	32.80	505.4	441.6	12.62
75	400	1569	1390	11.41	3433	2309	32.74	452.4	405.5	10.37
50	400	1536	1318	14.19	4206	2828	32.76	383.5	352.7	8.03
25	400	1502	1225	18.44	5953	4000	32.81	283.5	268.8	5.18

Table E5

E.1.3 McMurray Commutation Circuit Simulation Program

```
$JOB
      REAL L,ILOAD,IL,IL1,IPEAK
      REAL TIME(200),CURR(200),VC(200)
      INTEGER PMAX
      DO 2000 KK=1,7
C    READ CIRCUIT PARAMETERS
      READ(5,10) C,L,Q
   10 FORMAT(4(5X,E15.4))
      READ(5,20) VDC,ILOAD
   20 FORMAT(8F10.0)
C    CALCULATE MODIFIED PARAMETERS
      PMAX=25
      W0=1.0/SQRT(L*C)
      WTEMP=1.0+(0.5/Q)**2
      W=W0/SQRT(WTEMP)
      PHI=ATAN(2.0*Q)
      ALPHA=0.5*W/Q
      R=2.0*ALPHA*L
      VCI= 1.00*VDC
C    INTERVAL  T0 - T1
C    COMPUTE T1
      CALL CMPT1(T1,VCI,ILOAD,W,L,ALPHA,T10)
      TQ0=T1-T10
C    COMPUTE DELT1
      DELT1=T1/PMAX
C    START COMPUTE CURR AND VOLTAGE
      T=0.0
      DO 100 I=1,PMAX
      TIME(I)=T
      CURR(I)=VCI*EXP(-ALPHA*T)*SIN(W*T)/(W*L)
      VC(I)=-W0*VCI*EXP(-ALPHA*T)*SIN(W*T+PHI)/W
  100 T=T+DELT1
C    INTERVAL  T1 - T2
      VC0=VC(PMAX)
      IL=CURR(PMAX)
      INDEX=PMAX
      DF=-VC0*ALPHA*EXP(-ALPHA*T)*SIN(W*T)/(W*L)
      DF=DF+VC0*EXP(-ALPHA*T)*COS(W*T)/L
      VD0=VDC-IL*R-L*DF-VC0
  200 IF(VD0.LE.0.0) GO TO 300
      IF(INDEX.GT.1000) GO TO 999
      INDEX=INDEX+1
      CURR(INDEX)=ILOAD
      TIME(INDEX)=INDEX*DELT1
      VC1=VC0+ILOAD*DELT1/C
      VC(INDEX)=VC1
      VC0=VC1
      IL=CURR(INDEX)
      VD0=VDC-IL*R-VC0
      GO TO 200
C    INTERVAL  T2 -T3
  300 T=0.0
      T0=TIME(INDEX)
      IL=CURR(INDEX)
      IL1=IL
      VTEMP=VDC-VC0
  310 IF(IL1.LE.0.0) GO TO 400
      IF(INDEX.GT.1000) GO TO 9999
      INDEX=INDEX+1
      T=T+DELT1
```

```
      CTEMP1=EXP(-ALPHA*T)
      CTEMP2=CTEMP1*SIN(W*T)
      CTEMP3=CTEMP1*SIN(W*T-PHI)
      CTEMP4=CTEMP1*SIN(W*T+PHI)
      CURR(INDEX)=VTEMP*CTEMP2/(W*L)-W0*IL*CTEMP3/W
      VC(INDEX)=VDC-W0*VTEMP*CTEMP4/W+IL*CTEMP2/(W*C)
      TIME(INDEX)=T+T0
      IL1=CURR(INDEX)
      GO TO 310
C   OUTPUT THE RESULTS
  400 CONTINUE
      IF(KK.GT.3) GO TO 1000
      CALL PLOT(TIME,CURR,INDEX)
      WRITE(6,410)
  410 FORMAT('0',/'   PLOT OF COMMUTATION CURRENT VS. TIME')
      CALL PLOT(TIME,VC,INDEX)
      WRITE(6,420)
  420 FORMAT('0',/'   PLOT OF CAPACITOR VOLTAGE VS. TIME')
      GO TO 1000
  999 WRITE(6,500)
  500 FORMAT('0',' ***  INDEX EXCEEDS 1000 IN 200   ***')
      GO TO 1000
 9999 WRITE(6,600)
  600 FORMAT('0',' ***  INDEX EXCEEDS 1000 IN 300   ***')
 1000 CONTINUE
      CTEMP5=SQRT(L/C)
      VCPEAK=VDC+ILOAD/(W0*C)
      IPEAK=VDC/CTEMP5
      TQ=2.0*(1.5708-ARSIN(CTEMP5*ILOAD/VDC))/W0
      WRITE(6,1001)
 1001 FORMAT('1','  APPOX. VALUES')
      WRITE(6,1010)
 1010 FORMAT('0',10X,'VCPEAK(V)',5X,' IPEAK(A)',9X,'TQ')
      WRITE(6,1020) VCPEAK,IPEAK,TQ
 1020 FORMAT('0',10X,F9.2,5X,F9.2,5X,E11.4)
      VCPEAK=VC(INDEX)
      CALL CMAX(CURR,INDEX,IPEAK)
      WRITE(6,1030)
 1030 FORMAT('0',/'  TRUE VALUES')
      WRITE(6,1010)
      WRITE(6,1020) VCPEAK,IPEAK,TQ0
      WRITE(6,11) C,L,Q
   11 FORMAT('0',//' C = ',E15.4,'  L = ',E15.4,'  Q = ',F6.1)
      WRITE(6,21) VDC,ILOAD,VCI
   21 FORMAT('0',/' VDC = ',F10.2,'  ILOAD = ',F10.2,'  VCI = ',F10
 2000 CONTINUE
      STOP
      END
```

```
      SUBROUTINE CMPT1(T1,VCI,ILOAD,W,L,ALPHA,T10)
      REAL ILOAD,L
      XMAX=1.0E-2
      DELX=0.5E-6
      X0=1.0E-6
      F0=VCI*EXP(-ALPHA*X0)*SIN(W*X0)/(W*L)-ILOAD
    5 X1=X0+DELX
      F1=VCI*EXP(-ALPHA*X1)*SIN(W*X1)/(W*L)-ILOAD
      IF(X1.GT.XMAX) GO TO 99
      IF(F0*F1) 20,20,10
   10 X0=X1
      F0=F1
      GO TO 5
   20 DF=-VCI*ALPHA*EXP(-ALPHA*X1)*SIN(W*X1)/(W*L)
      DF=DF+VCI*EXP(-ALPHA*X1)*COS(W*X1)/L
      IF(DF.LT.0.0) GO TO 30
      T10=X1
      GO TO 10
   30 T1=X1
      GO TO 1000
   99 WRITE(6,100)
  100 FORMAT('0',' ***  XMAX EXCEEDED, NO ROOT FOUND')
 1000 CONTINUE
      RETURN
      END

      SUBROUTINE CMAX(X,NMAX,XMAX)
      DIMENSION X(NMAX)
      XMAX=0.0
      DO 10 I=1,NMAX
      IF(XMAX.LT.X(I)) XMAX=X(I)
   10 CONTINUE
      RETURN
      END
```

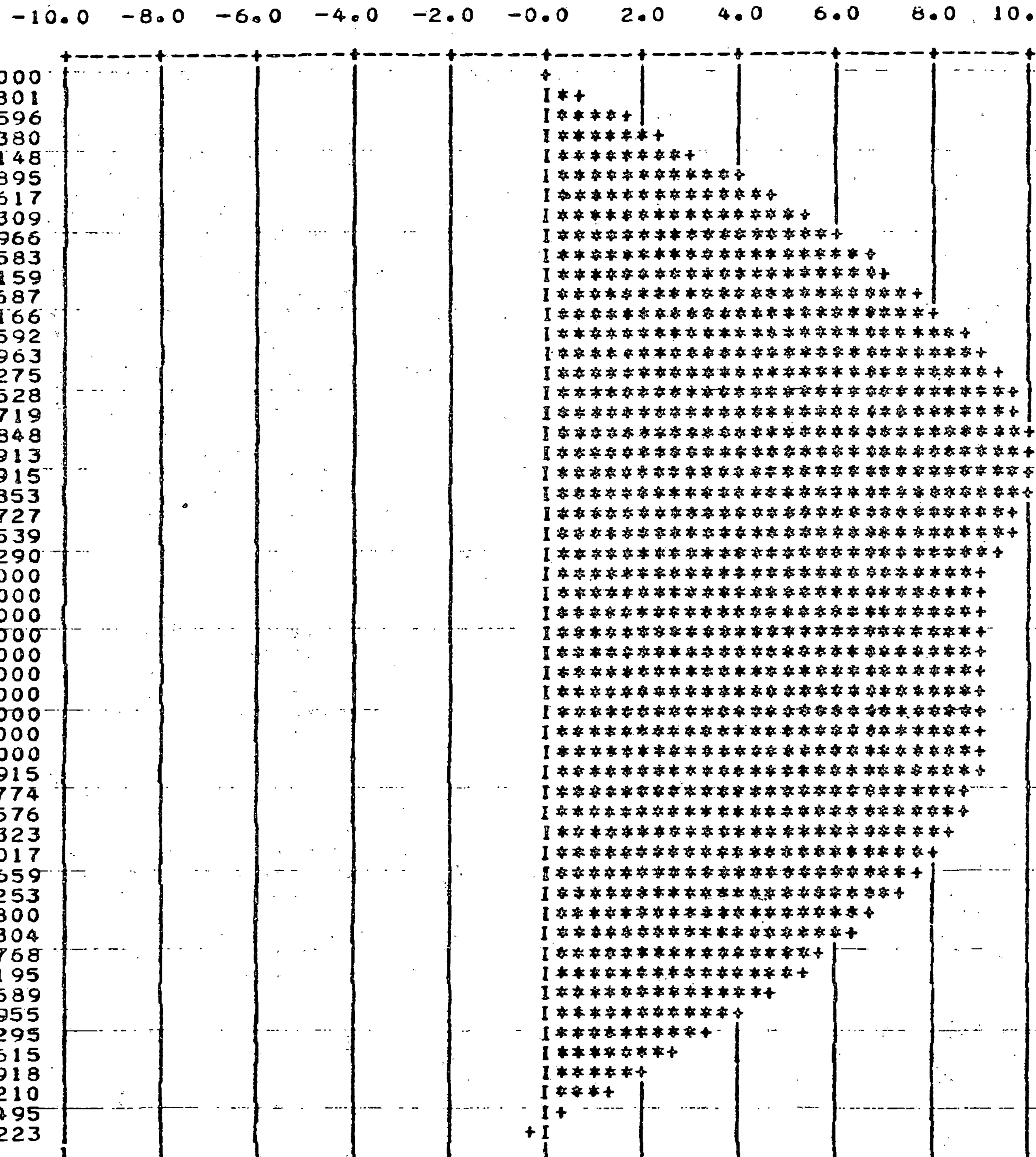
```
      SUBROUTINE PLOT(T,F,N)
      INTEGER PLINE(61),ASTRX,AXIS,BLANK,PLUS,VDASH
      DIMENSION T(N),F(N),DISP(3),DY(11),SCALE(3),SFRCT(5)
      DATA ASTRX,AXIS,BLANK,PLUS,VDASH/'*','I',' ','+','|'/
      DATA SFRCT/1.,2.5,5.,7.5,10./,DISP/1.5,61.5,31.5/,SCALE/2*60.
      FMAX = F(1)
      FMIN = F(1)
      DO 4 I = 1,N
      IF(F(I)-FMAX)2,2,1
    1 FMAX = F(I)
    2 IF(F(I)-FMIN)3, 4,4
    3 FMIN = F(I)
    4 CONTINUE
      IF(ABS(FMAX)-ABS(FMIN))6,5,5
    5 DIV= ABS(FMAX)
      GO TO 7
    6 DIV = ABS(FMIN)
    7 NEXP = IFIX(ALOG(DIV)/ALOG(10.))
      IF(DIV.LT.1.)NEXP = NEXP - 1
      PP = 10.**NEXP
      P = 10.**(-NEXP)
      FRACT = DIV*P
      DO 8 I =1,5
      DIV=SFRCT(I)*PP
      IF(FRACT-SFRCT(I))9,9,8
    8 CONTINUE
    9 CONTINUE
      WRITE(6,11)PP
   11 FORMAT('1TO GET THE TRUE VALUES, MULTIPLY THOSE IN THE 2ND COL
     1BY ',1PE7.1/)
      IF(FMIN)12,20,20
   12 IF(FMAX)25,25,30
   20 INDEX = 1
      DY(1) = 0.
      YINC = DIV/10.
      GO TO 100
   25 INDEX = 2
      DY(1) = -DIV*P
      YINC = DIV/10.
      GO TO 100
   30 INDEX = 3
      DY(1) = -DIV*P
      YINC = DIV/5.
  100 DO 110 I = 2,11
  110 DY(I) = DY(I-1) + YINC*P
      WRITE(6,120) DY
  120 FORMAT(16X,11F6.1)
      WRITE(6,125)
  125 FORMAT('0',2X,'T',11X,'F',T21,'+',10('-----+'))
      DO 190 J = 1,N
      I = IFIX((F(J)/DIV)*SCALE(INDEX)+DISP(INDEX))
      DO 135 L = 1,60,6
      DO 130 K = 1,5
  130 PLINE(L+K) = BLANK
  135 PLINE(L) = VDASH
      PLINE(61) = VDASH
      GO TO (140,150,160), INDEX
  140 DO 145 L= 1,I
  145 PLINE(L) = ASTRX
```

```
      PLINE(I) = AXIS
      GO TO 170
  150 DO 155 L=1,I
  155 PLINE(L) = ASTRX
      PLINE(61) = AXIS
      GO TO 170
  160 IF(I-31)165,169,167
  165 DO 166 L = I,30
  166 PLINE(L)  = ASTRX
      GO TO 169
  167 DO 168 L = 32,I
  168 PLINE(L) = ASTRX
  169 PLINE(31) = AXIS
  170 PLINE(I) = PLUS
      FP = F(J)*P
      WRITE(6,180) T(J),FP,PLINE
  180 FORMAT(' ',G10.3,1X,F7.3,1X,61A1)
  190 CONTINUE
      WRITE(6,195)
  195 FORMAT(20X,'I',10('_____|'))
      RETURN
      END

 $ENTRY
```

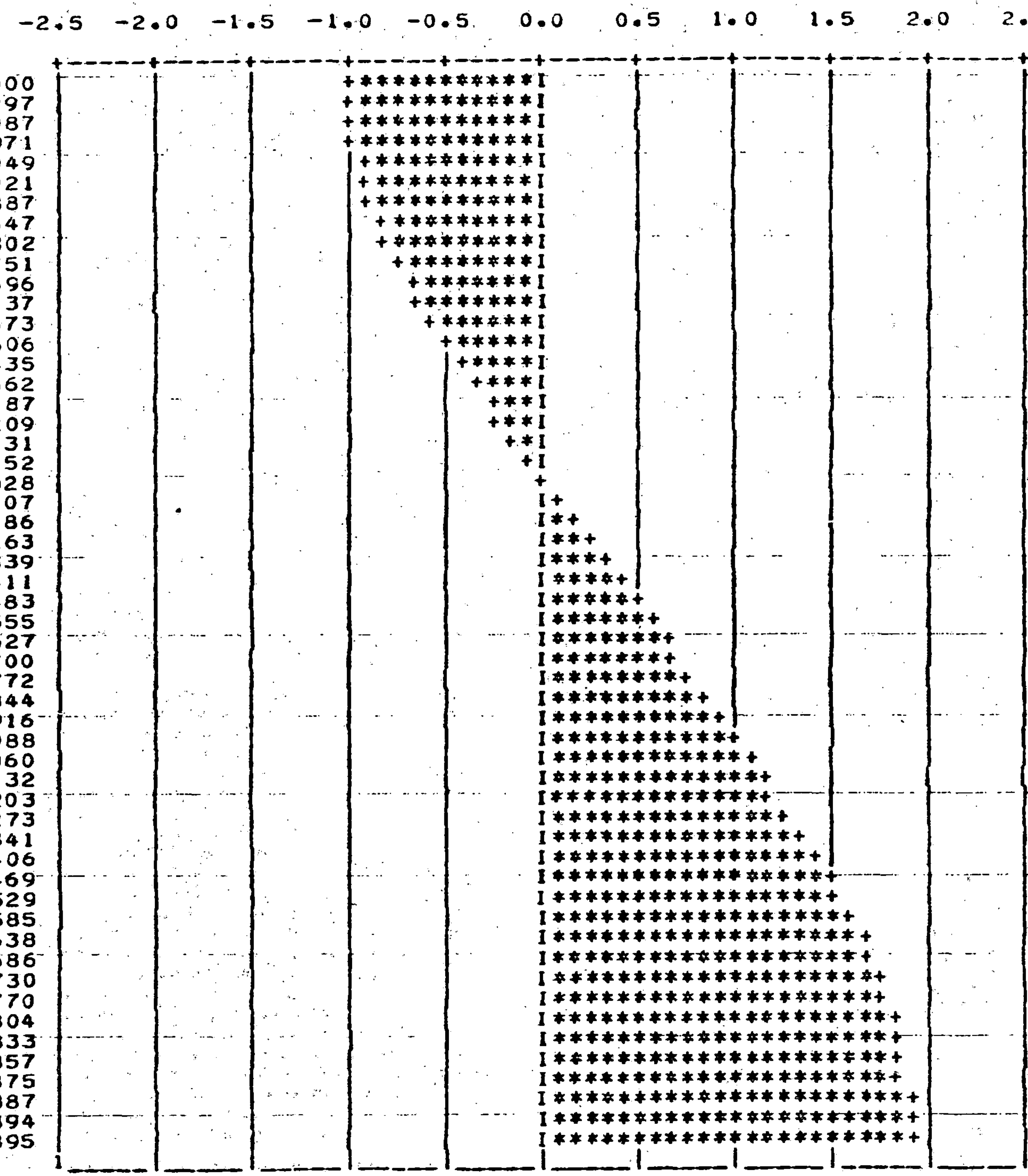
TO GET THE TRUE VALUES, MULTIPLY THOSE IN THE 2ND COLUMN BY 1.0E 02

T	F
0.000	0.000
0.802E-05	0.801
0.160E-04	1.596
0.241E-04	2.380
0.321E-04	3.148
0.401E-04	3.895
0.481E-04	4.617
0.561E-04	5.309
0.642E-04	5.966
0.722E-04	6.583
0.802E-04	7.159
0.882E-04	7.687
0.962E-04	8.166
0.104E-03	8.592
0.112E-03	8.963
0.120E-03	9.275
0.128E-03	9.528
0.136E-03	9.719
0.144E-03	9.848
0.152E-03	9.913
0.160E-03	9.915
0.168E-03	9.853
0.176E-03	9.727
0.184E-03	9.539
0.192E-03	9.290
0.209E-03	9.000
0.217E-03	9.000
0.225E-03	9.000
0.233E-03	9.000
0.241E-03	9.000
0.249E-03	9.000
0.257E-03	9.000
0.265E-03	9.000
0.273E-03	9.000
0.281E-03	9.000
0.289E-03	8.915
0.297E-03	8.774
0.305E-03	8.576
0.313E-03	8.323
0.321E-03	8.017
0.329E-03	7.659
0.337E-03	7.253
0.345E-03	6.800
0.353E-03	6.304
0.361E-03	5.768
0.369E-03	5.195
0.377E-03	4.589
0.385E-03	3.955
0.393E-03	3.295
0.401E-03	2.615
0.409E-03	1.918
0.417E-03	1.210
0.425E-03	0.495
0.433E-03	-0.223



TO GET THE TRUE VALUES, MULTIPLY THOSE IN THE 2ND COLUMN BY 1.0E 03

T	F
0.000	-1.000
0.802E-05	-0.997
0.160E-04	-0.987
0.241E-04	-0.971
0.321E-04	-0.949
0.401E-04	-0.921
0.481E-04	-0.887
0.561E-04	-0.847
0.642E-04	-0.802
0.722E-04	-0.751
0.802E-04	-0.696
0.882E-04	-0.637
0.962E-04	-0.573
0.104E-03	-0.506
0.112E-03	-0.435
0.120E-03	-0.362
0.128E-03	-0.287
0.136E-03	-0.209
0.144E-03	-0.131
0.152E-03	-0.052
0.160E-03	0.028
0.168E-03	0.107
0.176E-03	0.186
0.184E-03	0.263
0.192E-03	0.339
0.209E-03	0.411
0.217E-03	0.483
0.225E-03	0.555
0.233E-03	0.627
0.241E-03	0.700
0.249E-03	0.772
0.257E-03	0.844
0.265E-03	0.916
0.273E-03	0.988
0.281E-03	1.060
0.289E-03	1.132
0.297E-03	1.203
0.305E-03	1.273
0.313E-03	1.341
0.321E-03	1.406
0.329E-03	1.469
0.337E-03	1.529
0.345E-03	1.585
0.353E-03	1.638
0.361E-03	1.686
0.369E-03	1.730
0.377E-03	1.770
0.385E-03	1.804
0.393E-03	1.833
0.401E-03	1.857
0.409E-03	1.875
0.417E-03	1.887
0.425E-03	1.894
0.433E-03	1.895



APPOX. VALUES

VCPEAK(V)	IPEAK(A)	TQ
1900.00	1000.00	0.9021E-04

TRUE VALUES

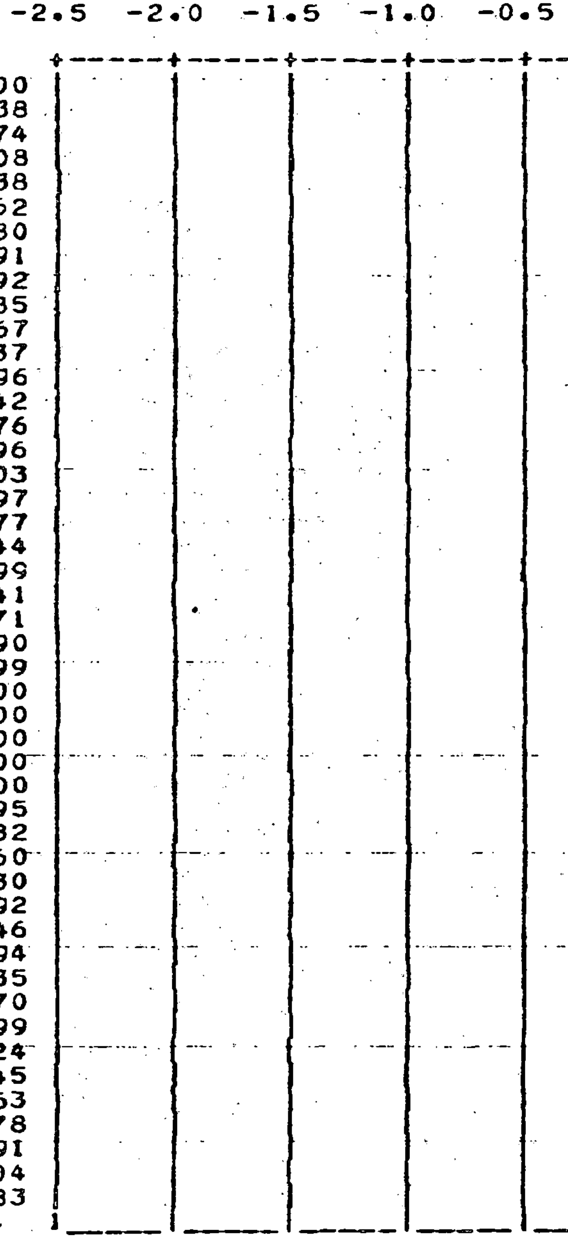
VCPEAK(V)	IPEAK(A)	TQ
1895.31	991.48	0.8700E-04

C = 0.1000E-03 L = 0.1000E-03 Q = 100.0

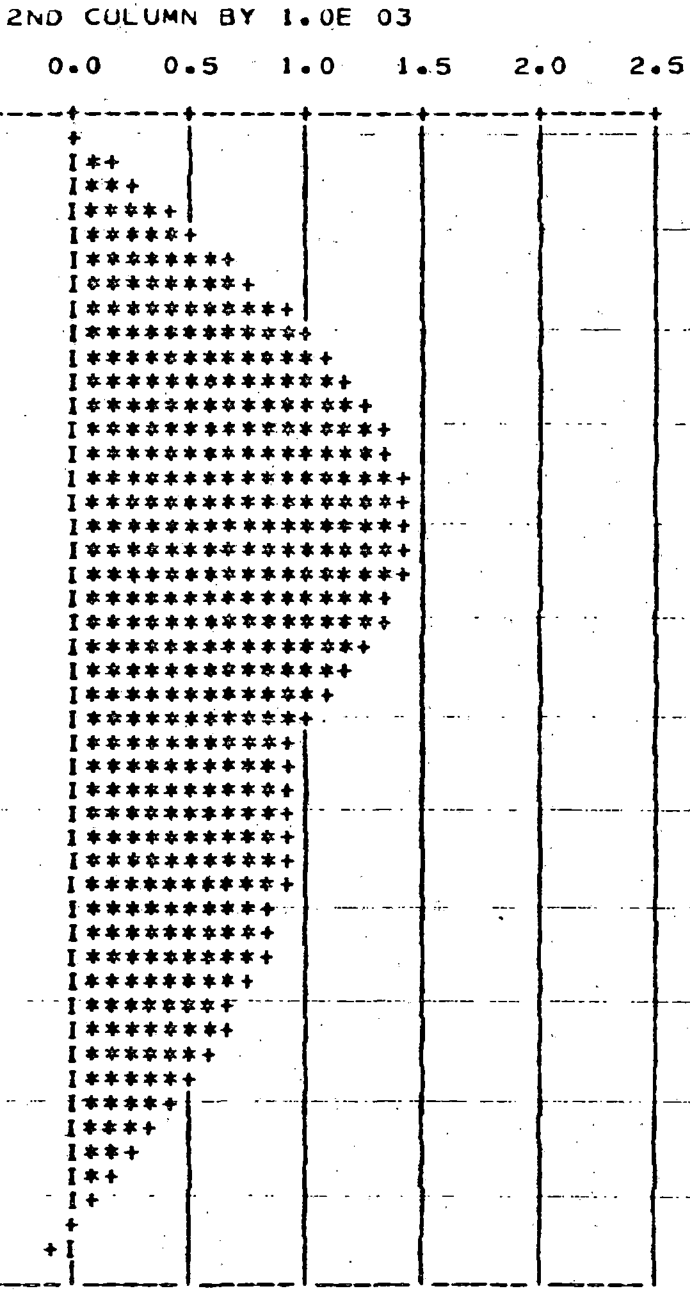
VDC = 1000.00 ILOAD = 900.00 VCI = 1000.00

TO GET THE TRUE VALUES. MULTIPLY THOSE IN THE

T	F
0.000	0.000
0.138E-04	0.138
0.276E-04	0.274
0.415E-04	0.408
0.553E-04	0.538
0.691E-04	0.662
0.829E-04	0.780
0.967E-04	0.891
0.111E-03	0.992
0.124E-03	1.085
0.138E-03	1.167
0.152E-03	1.237
0.166E-03	1.296
0.180E-03	1.342
0.193E-03	1.376
0.207E-03	1.396
0.221E-03	1.403
0.235E-03	1.397
0.249E-03	1.377
0.263E-03	1.344
0.276E-03	1.299
0.290E-03	1.241
0.304E-03	1.171
0.318E-03	1.090
0.332E-03	0.999
0.359E-03	0.900
0.373E-03	0.900
0.387E-03	0.900
0.401E-03	0.900
0.415E-03	0.900
0.428E-03	0.895
0.442E-03	0.882
0.456E-03	0.860
0.470E-03	0.830
0.484E-03	0.792
0.497E-03	0.746
0.511E-03	0.694
0.525E-03	0.635
0.539E-03	0.570
0.553E-03	0.499
0.567E-03	0.424
0.580E-03	0.345
0.594E-03	0.263
0.608E-03	0.178
0.622E-03	0.091
0.636E-03	0.004
0.649E-03	-0.083

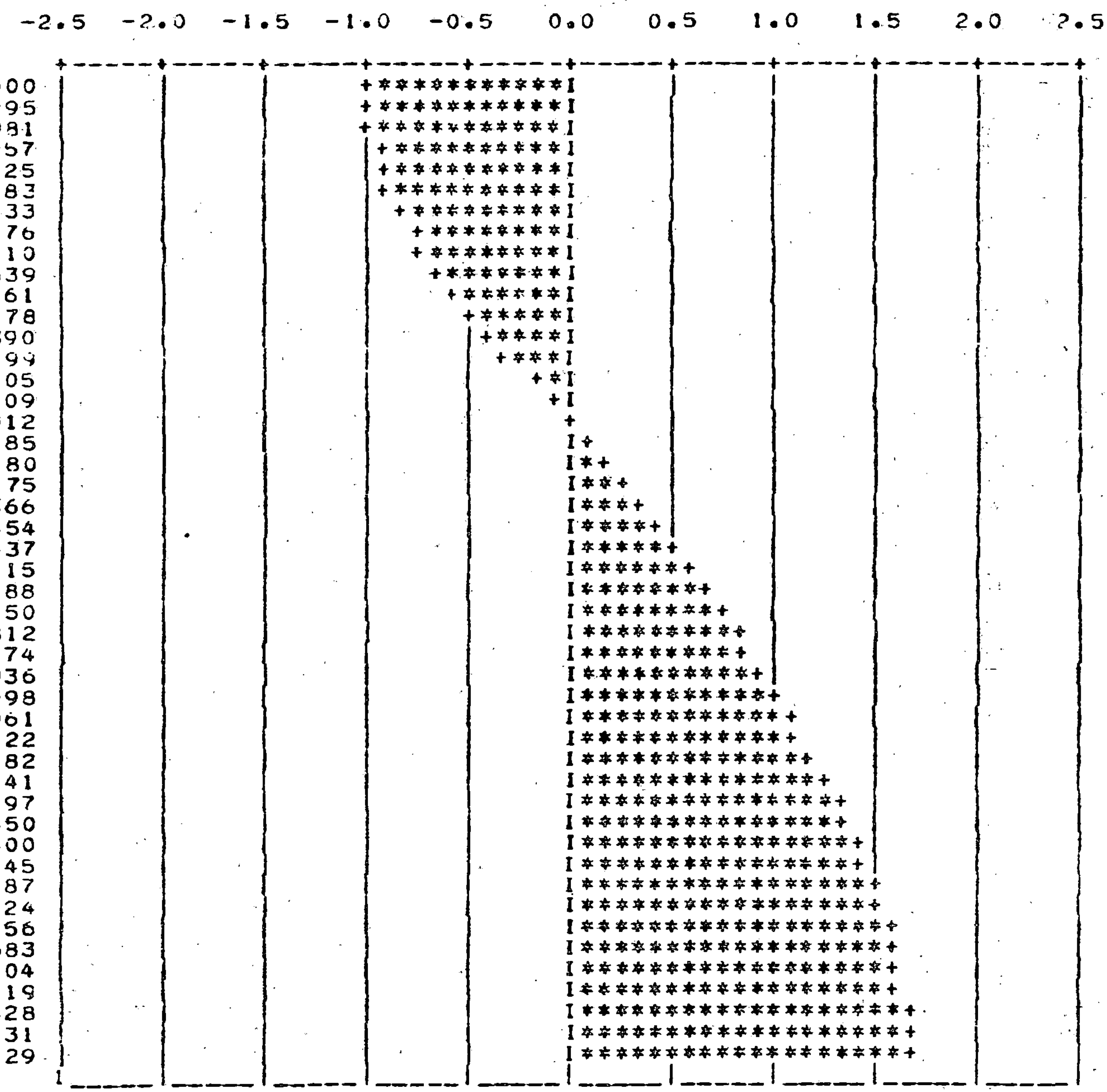


PLOT OF COMMUTATION CURRENT VS. TIME


2ND COLUMN BY 1.0E 03
0.0 0.5 1.0 1.5 2.0 2.5

TO GET THE TRUE VALUES, MULTIPLY THOSE IN THE 2ND COLUMN BY 1.0E 03

T	F
0.000	-1.000
0.138E-04	-0.995
0.276E-04	-0.981
0.415E-04	-0.957
0.553E-04	-0.925
0.691E-04	-0.883
0.829E-04	-0.833
0.967E-04	-0.776
0.111E-03	-0.710
0.124E-03	-0.639
0.138E-03	-0.561
0.152E-03	-0.478
0.166E-03	-0.390
0.180E-03	-0.299
0.193E-03	-0.205
0.207E-03	-0.109
0.221E-03	-0.012
0.235E-03	0.085
0.249E-03	0.180
0.263E-03	0.275
0.276E-03	0.366
0.290E-03	0.454
0.304E-03	0.537
0.318E-03	0.615
0.332E-03	0.688
0.359E-03	0.750
0.373E-03	0.812
0.387E-03	0.874
0.401E-03	0.936
0.415E-03	0.998
0.428E-03	1.061
0.442E-03	1.122
0.456E-03	1.182
0.470E-03	1.241
0.484E-03	1.297
0.497E-03	1.350
0.511E-03	1.400
0.525E-03	1.445
0.539E-03	1.487
0.553E-03	1.524
0.567E-03	1.556
0.580E-03	1.583
0.594E-03	1.604
0.608E-03	1.619
0.622E-03	1.628
0.636E-03	1.631
0.649E-03	1.629



PLOT OF CAPACITOR VOLTAGE VS. TIME

APPOX. VALUES

VCPEAK(V)	IPEAK(A)	TQ
1636.40	1414.21	0.2492E-03

TRUE VALUES

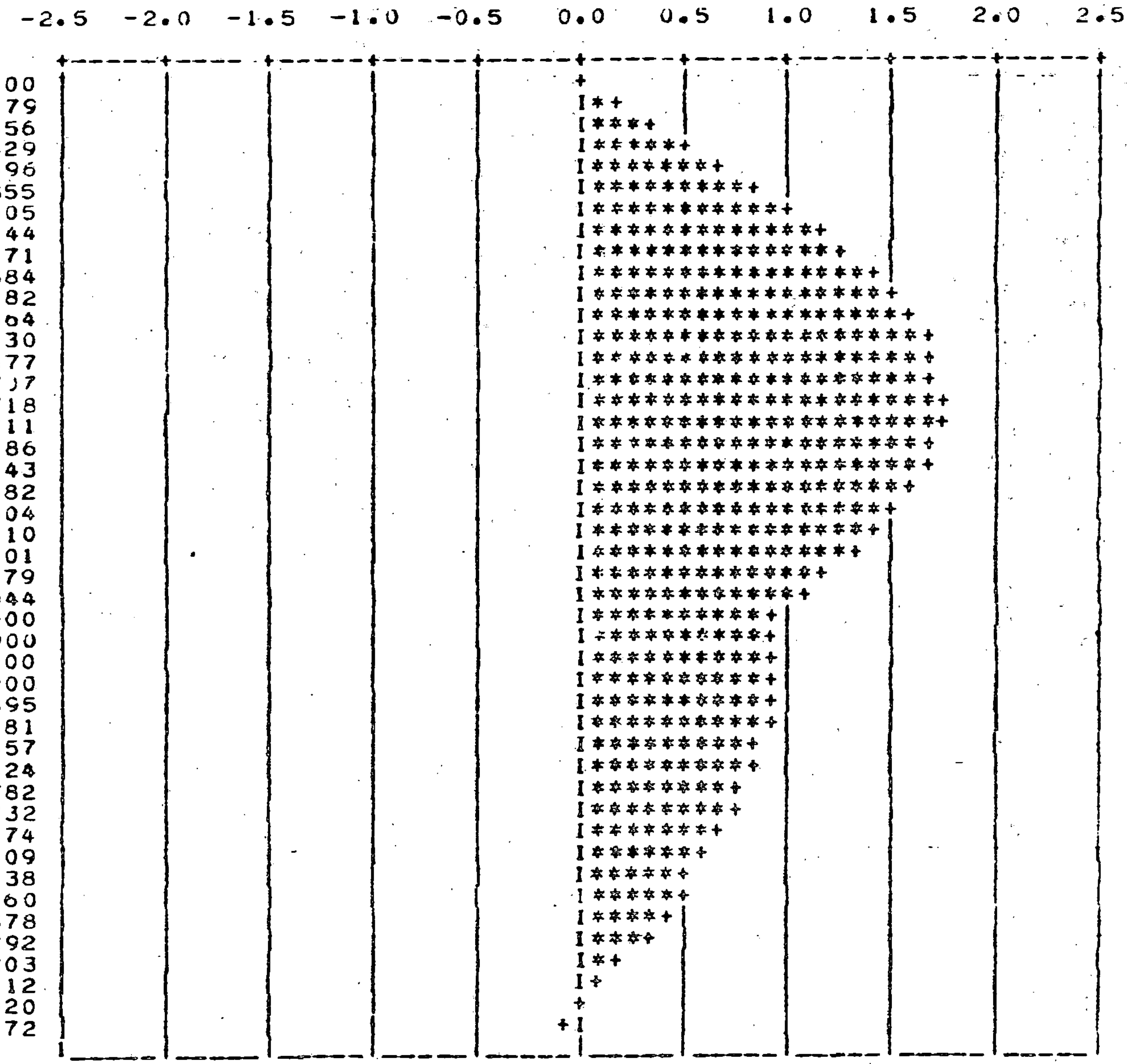
VCPEAK(V)	IPEAK(A)	TQ
1628.70	1403.18	0.2475E-03

C = 0.2000E-03 L = 0.1000E-03 Q = 100.0

VDC = 1000.00 ILOAD = 900.00 VCI = 1000.00

TO [illegible] THE TRUE VALUES, MULTIPLY THOSE [illegible] THE 2ND COLUMN BY [illegible]

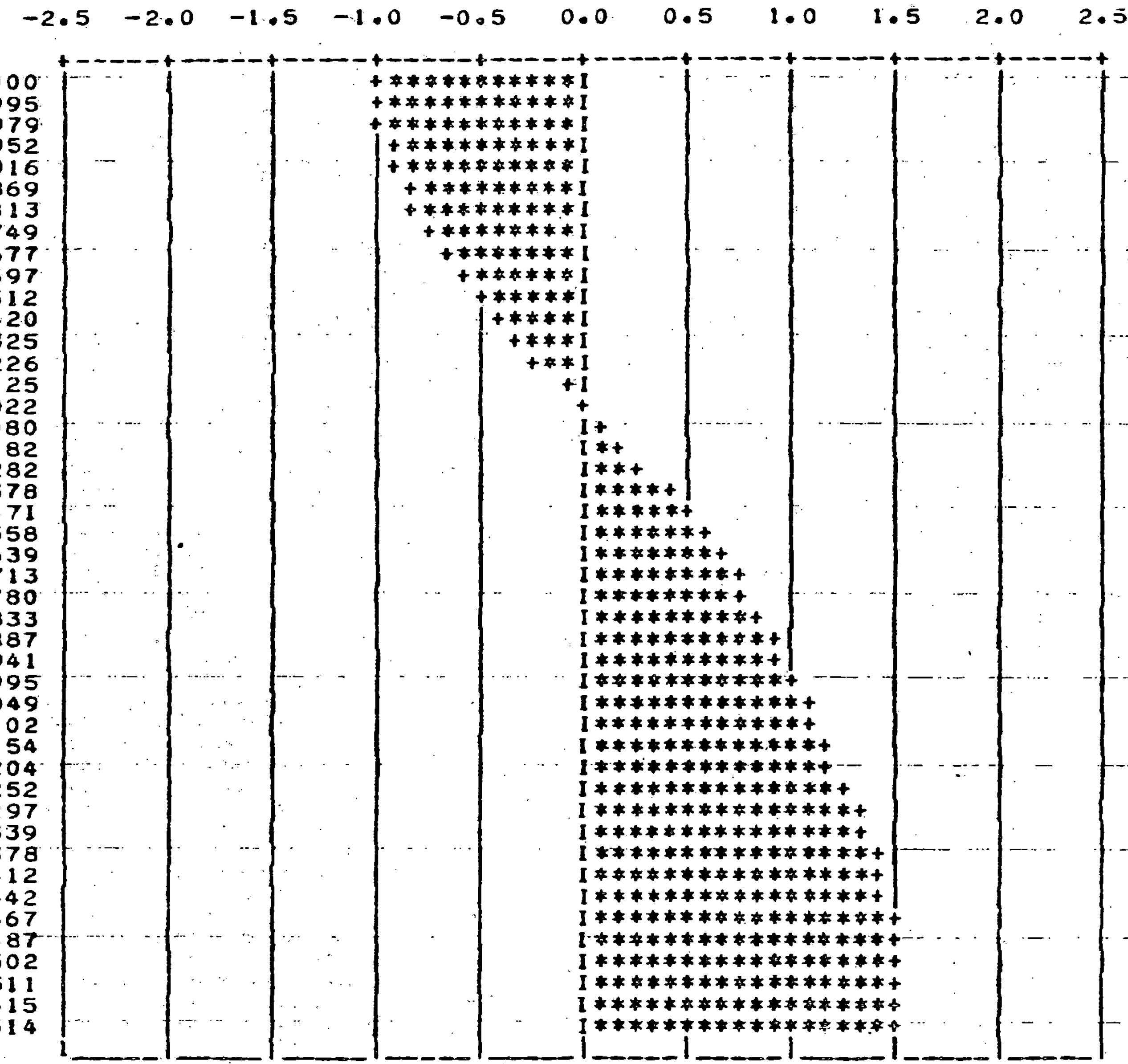
T	F
0.000	0.000
0.179E-04	0.179
0.359E-04	0.356
0.538E-04	0.529
0.718E-04	0.696
0.897E-04	0.855
0.108E-03	1.005
0.126E-03	1.144
0.144E-03	1.271
0.161E-03	1.384
0.179E-03	1.482
0.197E-03	1.564
0.215E-03	1.630
0.233E-03	1.677
0.251E-03	1.707
0.269E-03	1.718
0.287E-03	1.711
0.305E-03	1.686
0.323E-03	1.643
0.341E-03	1.582
0.359E-03	1.504
0.377E-03	1.410
0.395E-03	1.301
0.413E-03	1.179
0.431E-03	1.044
0.466E-03	0.900
0.484E-03	0.900
0.502E-03	0.900
0.520E-03	0.900
0.538E-03	0.895
0.556E-03	0.881
0.574E-03	0.857
0.592E-03	0.824
0.610E-03	0.782
0.628E-03	0.732
0.646E-03	0.674
0.664E-03	0.609
0.682E-03	0.538
0.700E-03	0.460
0.718E-03	0.378
0.735E-03	0.292
0.753E-03	0.203
0.771E-03	0.112
0.789E-03	0.020
0.807E-03	-0.072



PLOT OF COMMUTATION CURRENT VS. TIME

TO GET THE TRUE VALUES, MULTIPLY THOSE IN THE 2ND COLUMN BY 1.0E 03

T	F
0.000	-1.000
0.179E-04	-0.995
0.359E-04	-0.979
0.538E-04	-0.952
0.718E-04	-0.916
0.897E-04	-0.869
0.108E-03	-0.813
0.126E-03	-0.749
0.144E-03	-0.677
0.161E-03	-0.597
0.179E-03	-0.512
0.197E-03	-0.420
0.215E-03	-0.325
0.233E-03	-0.226
0.251E-03	-0.125
0.269E-03	-0.022
0.287E-03	0.080
0.305E-03	0.182
0.323E-03	0.282
0.341E-03	0.378
0.359E-03	0.471
0.377E-03	0.558
0.395E-03	0.639
0.413E-03	0.713
0.431E-03	0.780
0.466E-03	0.833
0.484E-03	0.887
0.502E-03	0.941
0.520E-03	0.995
0.538E-03	1.049
0.556E-03	1.102
0.574E-03	1.154
0.592E-03	1.204
0.610E-03	1.252
0.628E-03	1.297
0.646E-03	1.339
0.664E-03	1.378
0.682E-03	1.412
0.700E-03	1.442
0.718E-03	1.467
0.735E-03	1.487
0.753E-03	1.502
0.771E-03	1.511
0.789E-03	1.515
0.807E-03	1.514



PLOT OF CAPACITOR VOLTAGE VS. TIME

APPOX. VALUES

VCPEAK(V)	IPEAK(A)	TQ
1519.62	1732.05	0.3549E-03

TRUE VALUES

VCPEAK(V)	IPEAK(A)	TQ
1513.83	1718.41	0.3535E-03

C = 0.3000E-03 L = 0.1000E-03 Q = 100.0

VDC = 1000.00 ILOAD = 900.00 VCI = 1000.00

E.2 Induction-Motor Steady-State Performance with PWM Voltage Source

The performance discussed in this section means the line currents and the developed torque. The method of multiple reference frames is used with balanced PWM voltage sources. The step-by-step analysis and a program to perform the calculations are shown in the next section. With the PWM input, the resultant line currents and developed torques at different slips are shown in Table E6.

Slip	Line Current Fundamental = 100%	Developed Torque dc torque = 100%
0.0	5th Harmonic = 24.0% 7th Harmonic = 8.6%	6th Harmonic Pulsation Torque
0.02	5th Harmonic = 8.4% 7th Harmonic = 3.0%	6th Harmonic = 2.9%
0.05	5th Harmonic = 3.8% 7th Harmonic = 1.4%	6th Harmonic = 1.3%
0.10	5th Harmonic = 2.2% 7th Harmonic = 0.8%	6th Harmonic = 0.8%

Table E6: The table shows harmonic contents of line current and developed torque for a particular PWM voltage source.

E.2.1 Method of Multiple Reference Frame Analysis

The following step-by-step procedure is developed according to [4]. With the connection shown in Fig. E8 -

Step 1: Determine the Fourier Series representation of voltage sources v_{ga}, v_{gb} and v_{gc}.

$$v_{ga} = V \sum_{k=1}^{\infty} [a_{ka} \cos k\omega_e t + b_{ka} \sin k\omega_e t]$$

$$v_{gb} = V \sum_{k=1}^{\infty} [a_{kb} \cos k(\omega_e t - \tfrac{2\pi}{3}) + b_{kb} \sin k(\omega_e t - \tfrac{2\pi}{3})]$$

$$v_{gc} = V \sum_{k=1}^{\infty} [a_{kc} \cos k(\omega_e t + \tfrac{2\pi}{3}) + b_{kc} \sin k(\omega_e t + \tfrac{2\pi}{3})]$$

With PWM waveform shown in Fig. E9 -

$$v_{ga} \simeq \frac{4V}{\pi} (0.95 \sin \omega_e t - 0.22 \sin 3\omega_e t + 0.04 \sin 5\omega_e t - 0.02 \sin 7\omega_e t)$$

$$v_{gb} = \frac{4V}{\pi} [0.95 \sin (\omega_e t - \tfrac{2\pi}{3}) - 0.22 \sin 3(\omega_e t - \tfrac{2\pi}{3}) + 0.04 \sin 5(\omega_e t - \tfrac{2\pi}{3}) - 0.02 \sin 7(\omega_e t - \tfrac{2\pi}{3})]$$

$$v_{gc} = \frac{4V}{\pi} [0.95 \sin (\omega_e t + \tfrac{2\pi}{3}) - 0.22 \sin 3(\omega_e t + \tfrac{2\pi}{3}) + 0.04 \sin 5(\omega_e t + \tfrac{2\pi}{3}) - 0.02 \sin 7(\omega_e t + \tfrac{2\pi}{3})]$$

For more detail about the Fourier Series Coefficients, see pp. 406-409 in [1].

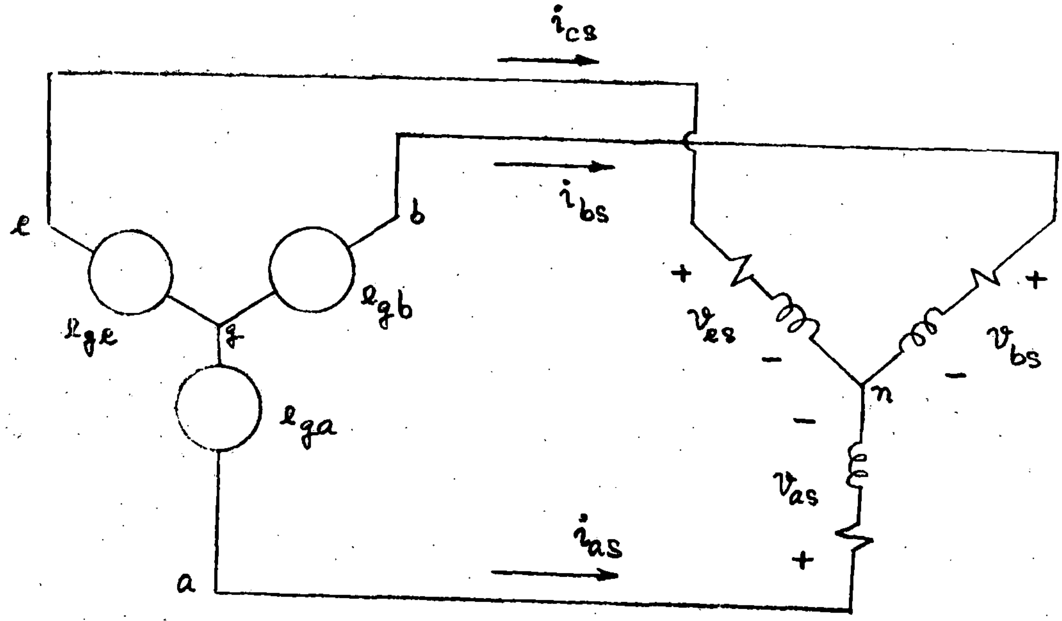


FIG E8 : 3 - WIRE CONNECTION

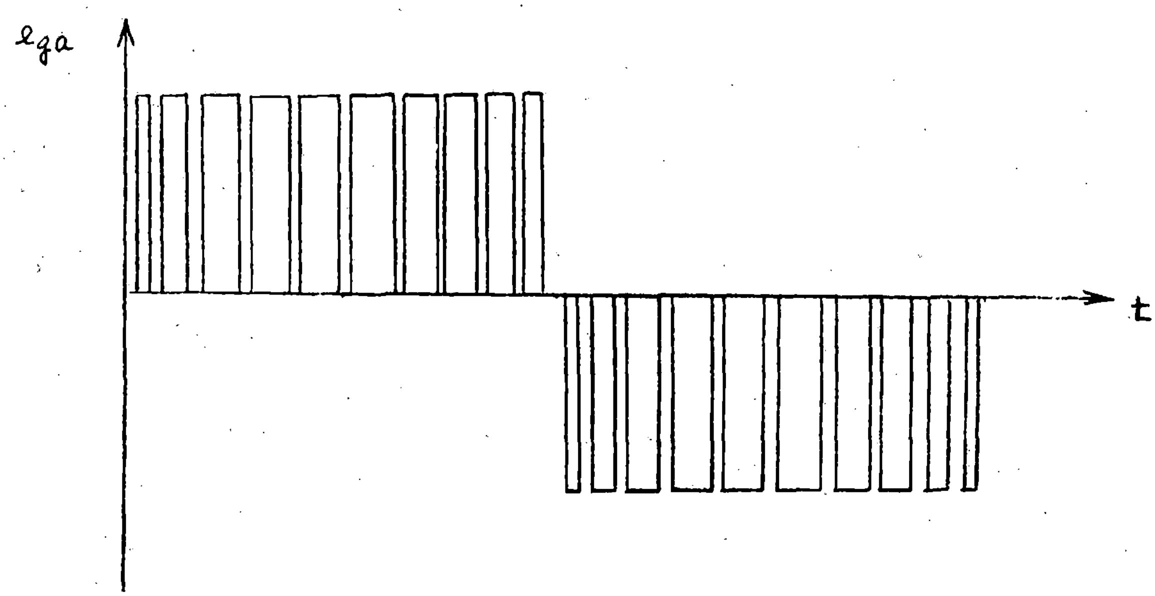


FIG E9 : PWM WAVEFORM WITH N = 10

Step 2: Determine corresponding voltages, v_{qs}^{s} and v_{ds}^{s}, in d-q reference frame which is fixed in the stator as shown in Fig. E10.

$$v_{qs}^{s} = \frac{2}{3}\left[v_{as} - \frac{1}{2}(v_{bs} + v_{cs})\right]$$

$$v_{ds}^{s} = \frac{2}{3}\left(-\frac{\sqrt{3}}{2} v_{bs} + \frac{\sqrt{3}}{2} v_{cs}\right)$$

$$= \frac{1}{\sqrt{3}}(-v_{bs} + v_{cs})$$

For the example set in Step 1 -

$$v_{qs}^{s} = \frac{2}{3}\left[\frac{4V}{\pi}\{0.95\,(1-\cos\tfrac{2\pi}{3})\sin\omega_e t - 0.22\,(1-\cos 3x\tfrac{2\pi}{3})\sin 3\omega_e t\right.$$

$$\left. + 0.04\,(1-\cos 5x\tfrac{2\pi}{3})\sin 5\omega_e t - 0.02(1-\cos 7x\tfrac{2\pi}{3})\sin 7\omega_e t\}\right]$$

and
$$v_{ds}^{s} = \frac{1}{\sqrt{3}}\left[\frac{4V}{\pi}\{0.95 \times 2\sin(\tfrac{2\pi}{3})\cos(\omega_e t)\right.$$

$$-0.22 \times 2\sin(3x\tfrac{2\pi}{3})\cos(3\omega_e t)$$

$$+0.04 \times 2\sin(5x\tfrac{2\pi}{3})\cos(5\omega_e t)$$

$$\left.-0.02 \times 2\sin(7x\tfrac{2\pi}{3})\cos(7\omega_e t)\}\right]$$

Step 3: Determine the amplitudes of harmonics components of v_{qs}^{s} and v_{ds}^{s} as shown in Fig. E11.

$$v_{qs}^{s} = \sum_{k=1}^{\infty}(V_{kq\alpha}\cos k\omega_e t + V_{kq\gamma}\sin k\omega_e t)$$

and
$$v_{ds}^{s} = \sum_{k=1}^{\infty}(V_{kd\alpha}\cos k\omega_e t + V_{kd\gamma}\sin k\omega_e t)$$

By equating the coefficients of v_{qs}^{s} and v_{ds}^{s} with those obtained in Step 2, $V_{kq\alpha}$, $V_{kq\gamma}$, $V_{kd\alpha}$ and $V_{kd\gamma}$ can be determined.

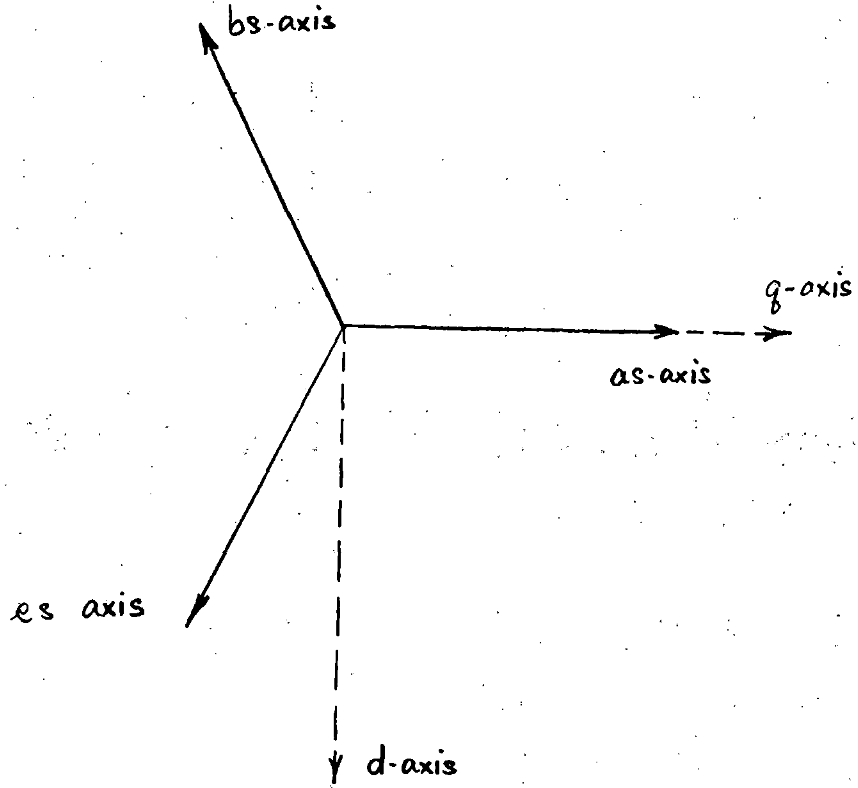


FIG E10: PHASOR DIAGRAM SHOWING d-q REFERENCE FRAME

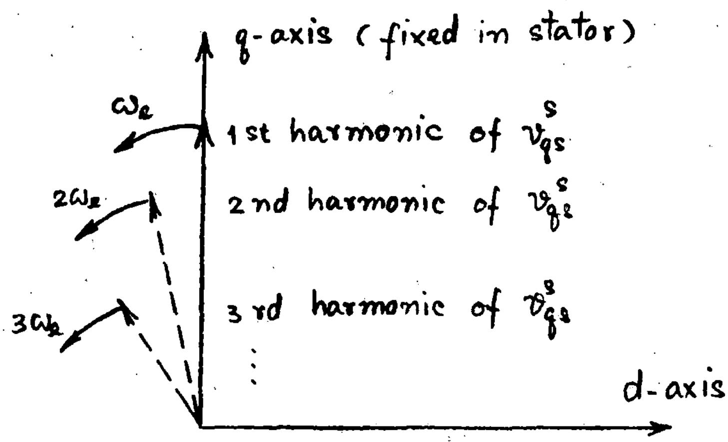


FIG E11: PHASOR ON d-q REFERENCE FRAME SHOWING HARMONIC COMPONENTS.

As an example, from Step 2 -

$$v_{qs}^{s} = \sum_{k=1}^{\infty} (V_{kq\alpha} \cos k\omega_e t + V_{kq\gamma} \sin k\omega_e t)$$

and $$v_{ds}^{s} = \sum_{k=1}^{\infty} (V_{kd\alpha} \cos k\omega_e t + V_{kd\gamma} \sin k\omega_e t)$$

By equating the coefficients of v_{qs}^{s} and v_{ds}^{s} with those obtained in Step 2, $V_{kq\alpha}$, $V_{kq\gamma}$, $V_{kd\alpha}$ and $V_{kd\gamma}$ can be determined.

As an example, from Step 2 -

$$v_{qs}^{s} = \frac{2}{3} [\frac{4V}{\pi} \{0.95 \, (1-\cos \frac{2\pi}{3}) \sin \omega_e t$$

$$-0.22(1-\cos 3x\frac{2\pi}{3}) \sin 3 \, \omega_e t$$

$$+0.04(1-\cos 5x\frac{2\pi}{3}) \sin 5 \, \omega_e t$$

$$-0.02(1-\cos 7x\frac{2\pi}{3}) \sin 7 \, \omega_e t\}]$$

implies $V_{1q\alpha} = 0$; $V_{1q\gamma} = \frac{4V}{\pi} \times (0.95) \times \frac{2(1-\cos\frac{2\pi}{3})}{3}$

$$V_{3q\alpha} = 0; \quad V_{3q\gamma} = \frac{4V}{\pi} \times (-0.22) \times \frac{2(1-\cos 3\frac{2\pi}{3})}{3}$$

$$V_{5q\alpha} = 0; \quad V_{5q\gamma} = \frac{4V}{\pi} \times (0.04) \times \frac{2(1-\cos 5\frac{2\pi}{3})}{3}$$

$$V_{7q\alpha} = 0; \quad V_{7q\gamma} = \frac{4V}{\pi} \times (-0.02) \times \frac{2(1-\cos 7\frac{2\pi}{3})}{3}$$

also implies

$$V_{1d\alpha} = \frac{4V}{\pi} \times (0.95) \times \frac{2\sin(\frac{2\pi}{3})}{3} \; ; \quad V_{1d\gamma} = 0$$

$$V_{3d\alpha} = \frac{4V}{\pi} \times (-0.22) \times \frac{2\sin(3\frac{2\pi}{3})}{\sqrt{3}} ; \quad V_{3d\gamma} = 0$$

$$V_{5d\alpha} = \frac{4V}{\pi} \times (0.04) \times \frac{2\sin(5\frac{2\pi}{3})}{\sqrt{3}} \; ; \quad V_{5d\gamma} = 0$$

$$V_{7d\alpha} = \frac{4V}{\pi} \times (-0.02) \times \frac{2\sin(7\frac{2\pi}{3})}{\sqrt{3}} ; \quad V_{7d\gamma} = 0$$

<u>Step 4</u>: Compute the constant forcing functions, v_{qs}^{+ke}, v_{ds}^{+ke}, v_{qs}^{-ke}, v_{ds}^{-ke}, in multiple reference from +ke and -ke, using

$$v_{qs}^{+ke} = \frac{1}{2}\,(V_{kq\alpha} - V_{kd\gamma}), \; k=1,2,3,\ldots\ldots\ldots$$

$$v_{ds}^{+ke} = \frac{1}{2}\,(V_{kq\alpha} - V_{kd\gamma})$$

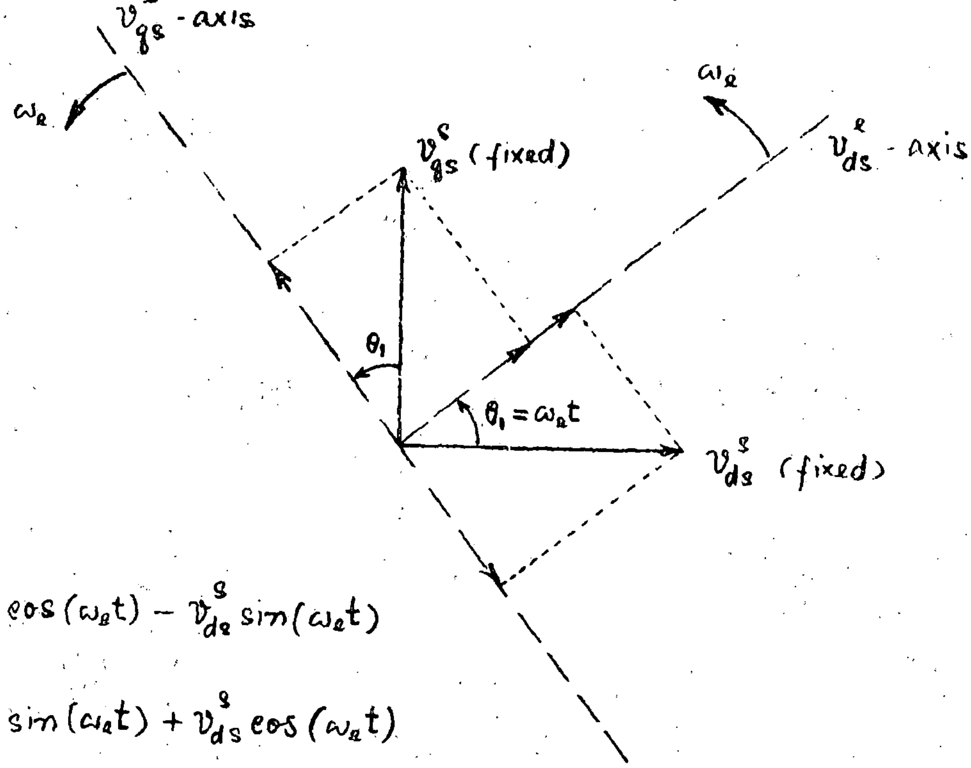
$$v_{qs}^{-ke} = \frac{1}{2}\,(V_{kq\alpha} + V_{kd\gamma})$$

and $$v_{ds}^{-ke} = \frac{1}{2}\,(V_{kq\alpha} - V_{kd\gamma})$$

Together with $V_{kq\alpha}$, $V_{kd\alpha}$, $V_{kq\gamma}$, and $V_{kd\gamma}$ from Step 3, the constant forcing functions can be computed.

The following sequences of phasor diagrams (Fig.E12-E15) show how the multiple reference frames, +ke and -ke, are set up such that the forcing functions on those reference frames are constant. With constant forcing functions, linear analysis can be applied in each reference frame.

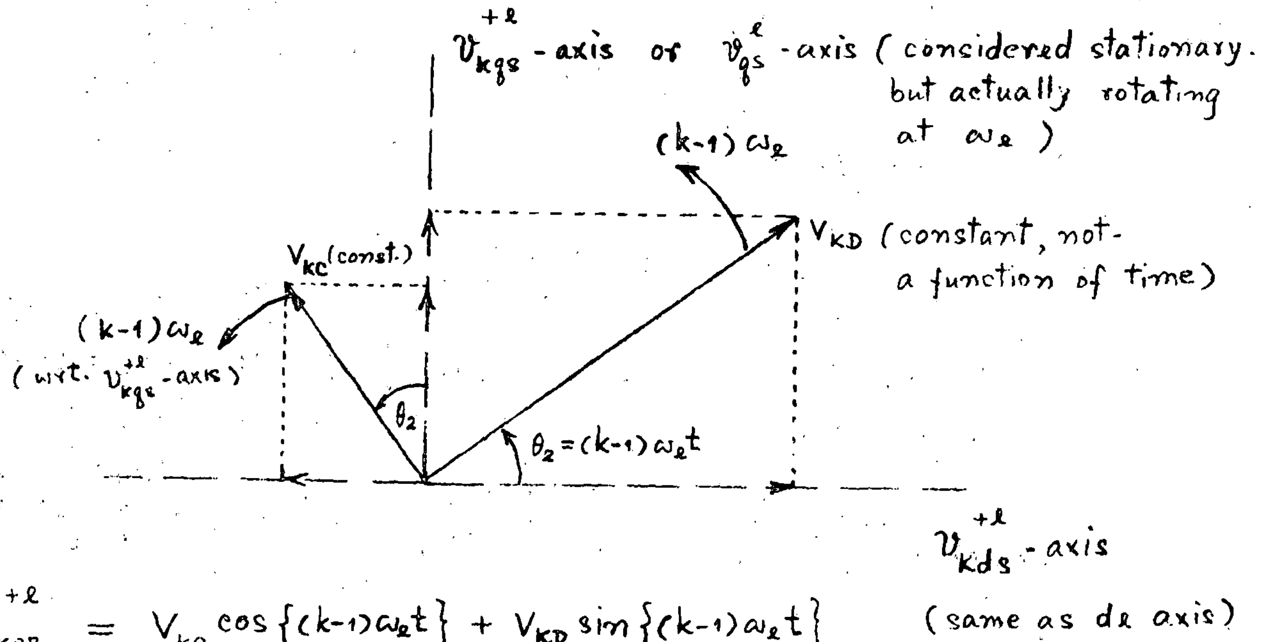
Finally, in each reference frame, +ke and -ke, a set of constant forcing functions can be written as



$$v_{qs}^{e} = v_{qs}^{s}\cos(\omega_e t) - v_{ds}^{s}\sin(\omega_e t)$$

$$v_{ds}^{e} = v_{qs}^{s}\sin(\omega_e t) + v_{ds}^{s}\cos(\omega_e t)$$

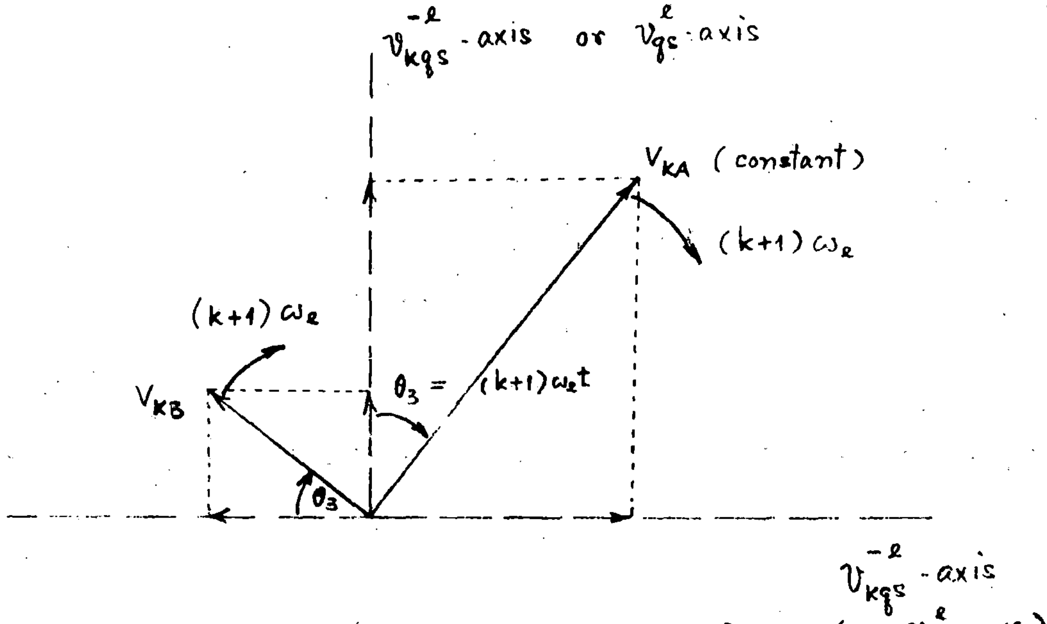
FIG. E12 : PHASOR DIAGRAM SHOWING de - qe frame



$$v_{kqs}^{+e} = V_{kC}\cos\{(k-1)\omega_e t\} + V_{KD}\sin\{(k-1)\omega_e t\}$$

$$v_{kds}^{+e} = -V_{kC}\sin\{(k-1)\omega_e t\} + V_{KD}\cos\{(k-1)\omega_e t\}$$

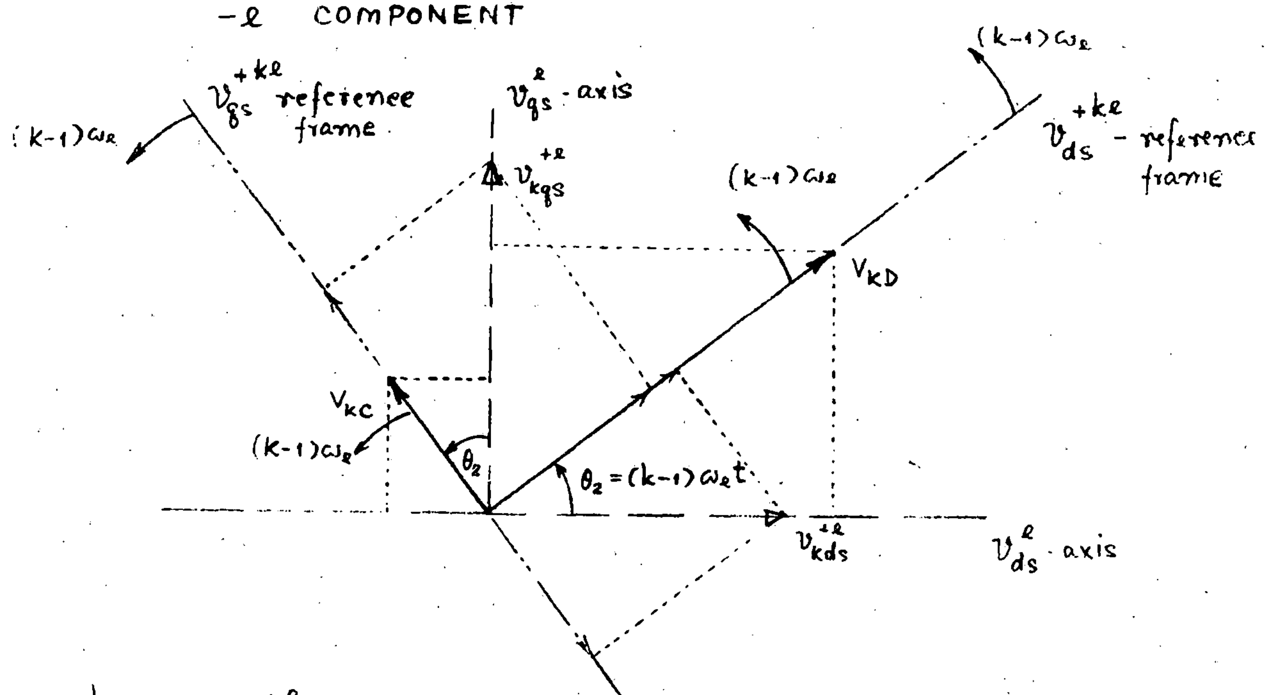
FIG. E13 : PHASOR DIAGRAM SHOWING K^{th} HARMONIC OF +e COMPONENT



$$v_{kqs}^{-\ell} = V_{KA} \cos\{(k+1)\omega_\ell t\} + V_{KB} \sin\{(k+1)\omega_\ell t\}$$

$$v_{kds}^{-\ell} = V_{KA} \sin\{(k+1)\omega_\ell t\} - V_{KB} \cos\{(k+1)\omega_\ell t\}$$

FIG. E14 : PHASOR DIAGRAM SHOWING Kth HARMONIC OF $-\ell$ COMPONENT



$$v_{qs}^{+k\ell} = v_{kqs}^{+\ell} \cos\{(k-1)\omega_\ell t\} - v_{kds}^{+\ell} \sin\{(k-1)\omega_\ell t\}$$

$$v_{ds}^{+k\ell} = v_{kqs}^{+\ell} \sin\{(k-1)\omega_\ell t\} + v_{kds}^{+\ell} \cos\{(k-1)\omega_\ell t\}$$

FIG. E15 : PHASOR DIAGRAM SHOWING $+k\ell$ OF MULTIPLE REFERENCE FRAME

$$v_{qs}^{+ke} = \frac{1}{2} V_{KC} = \frac{1}{2} (V_{kq\alpha} - V_{kd\gamma})$$

$$v_{ds}^{+ke} = \frac{1}{2} V_{KD} = \frac{1}{2} (V_{kq\gamma} + V_{kd\alpha})$$

$$v_{qs}^{-ke} = \frac{1}{2} V_{KA} = \frac{1}{2} (V_{kq\alpha} + V_{kd\gamma})$$

$$v_{ds}^{-ke} = \frac{1}{2} V_{KB} = \frac{1}{2} (V_{kq\gamma} - V_{kd\alpha})$$

<u>Step 5</u>: Solve for $i_{qs}^{\pm ke}$, $i_{qr}^{\pm ke}$, $i_{ds}^{\pm ke}$ and $i_{dr}^{\pm ke}$, currents in multiple reference frames +ke and -ke, using the relation

$$\begin{bmatrix} v_{qs}^{\pm ke} \\ v_{ds}^{\pm ke} \\ v_{qr}^{\pm ke} \\ v_{dr}^{\pm ke} \end{bmatrix} = \begin{bmatrix} (r_s+L_{ss}p) & \pm k\omega_e L_{ss} & Mp & \pm k\omega_e M \\ -(\pm k\omega_e L_{ss}) & r_s+L_{ss}p & -(\pm k\omega_e M) & Mp \\ Mp & (\pm k\omega_e-\omega_r)M & (r_r+L_{rr}p) & (\pm k\omega_e-\omega_r)L_{rr} \\ -(\pm k\omega_e-\omega_r)M & Mp & -(\pm k\omega_e-\omega_r)L_{rr} & (r_r+L_{rr}p) \end{bmatrix} \text{X} \begin{bmatrix} i_{qs}^{\pm ke} \\ i_{ds}^{\pm ke} \\ i_{qr}^{\pm ke} \\ i_{dr}^{\pm ke} \end{bmatrix}$$

where operator p = d/dt

ω_e = synchronous angular velocity (rad/s)

ω_r = rotor angular frequency (rad/s)

r_s = stator resistance (Ω)

r_r = rotor resistance referred to stator

L_{ss} = $L_s - L_{sm}$

L_s = stator phase inductance

L_{sm} = mutual inductance between stator phase

L_{rr} = $L_r - L_{rm}$

L_r = rotor inductance referred to stator

L_{rm} = mutual inductance between rotor phase (referred to stator)

$M = \frac{3}{2} L_{ms}$

The preceding system of equations can be solved with some modifications. However, with the following assumptions -

- constant speed (which is a necessary assumption for preceding analysis)
- steady state condition (p=0)
- short circuit rotor

the system of equations becomes a set of simultaneous algebraic equations from which $i_{qs}^{\pm ke}$, $i_{ds}^{\pm ke}$, $i_{qr}^{\pm ke}$ and $i_{dr}^{\pm ke}$ can be solved with $v_{qr}^{\pm ke} = v_{dr}^{\pm ke} = 0$.

<u>Step 6</u>: Work backwards to find i_{qs}^{s}, i_{ds}^{s}, i_{qr}^{s} and i_{dr}^{s} using

$$i_{qs}^{s} = \sum_{k=1}^{\infty} [(i_{qs}^{+ke} + i_{qs}^{-ke}) \cos k\omega_e t + (i_{ds}^{+ke} - i_{ds}^{-ke}) \sin k\omega_e t]$$

$$i_{ds}^{s} = \sum_{k=1}^{\infty} [(i_{ds}^{+ke} + i_{ds}^{-ke}) \cos k\omega_e t - (i_{qs}^{+ke} - i_{qs}^{-ke}) \sin k\omega_e t]$$

$$i_{qr}^{s} = \sum_{k=1}^{\infty} [(i_{qr}^{+ke} + i_{qr}^{-ke}) \cos k\omega_e t + (i_{dr}^{+ke} - i_{dr}^{-ke}) \sin k\omega_e t]$$

$$i_{dr}^{s} = \sum_{k=1}^{\infty} [(i_{dr}^{+ke} + i_{dr}^{-ke}) \cos k\omega_e t - (i_{qr}^{+ke} - i_{qr}^{-ke}) \sin k\omega_e t]$$

<u>Step 7</u>: Compute i_{as}, i_{bs} and i_{cs} using

$$i_{as} = i_{qs}^{s}$$

$$i_{bs} = -\frac{1}{2} i_{qs}^{s} - \frac{\sqrt{3}}{2} i_{ds}^{s}$$

and

$$i_{cs} = -\frac{1}{2} i_{qs}^{s} + \frac{\sqrt{3}}{2} i_{ds}^{s}$$

At this step, the harmonic contents of line currents i_{as}, i_{bs} and i_{cs} can be determined using Fast Fourier Transform for one complete cycle of the sampled version of i_{as}, which is readily available if i_{as} is solved by using a digital computer.

Step 8: Find the developed torque using

$$T = M(\frac{m}{2})(\frac{P}{2})(i_{qs}^{s} \; i_{dr}^{s} - i_{ds}^{s} \; i_{qr}^{s})$$

where m = number of phases

P = number of poles

Similarly, FFT can be applied to find the harmonics of pulsation torque.

The listings of the program which handle these step-by-step computations are shown in section E.2.2.

```
$JOB
      REAL FREQ(128),XX(50),TX(50)
      REAL IQRS(128),IDRS(128),TORQUE(128),TIME(128),XA(128),MAG(128)
      REAL A(20),B(20),IQSS(128),IDSS(128),IAS(128),IBS(128),ICS(128)
      REAL IQSPE(20),IDSPE(20),IQSNE(20),IDSNE(20)
      REAL IQRPE(20),IDRPE(20),IQRNE(20),IDRNE(20)
      REAL VQSPE(20),VDSPE(20),VQSNE(20),VDSNE(20)
      REAL VQA(20),VDA(20),VQB(20),VDB(20)
      REAL APE(20),ANE(20),BPE(20),BNE(20),CPE(20),CNE(20)
      REAL DPE(20),DNE(20),EPE(20),ENF(20)
      COMPLEX XSMALL(128),CMPLX
C     ENTER CKT PARAMETERS
      RS=0.0453
      RR=0.0222
      XMS=2.0420
      XLS=0.0775
      XLR=0.0322
      FB=60.0
      FE=60.0
      SLIP=0.05
      NPHASE=3
      NPOLE=4
C     CALCULATE OTHER DEPENDENT PARAMETERS
      KMAX=13
      PI=3.14159
      WB=2.0*PI*FB
      WE=2.0*PI*FE
      FR=WE/WB
      WR=(1.0-SLIP)*WE
      XM=1.5*XMS
      XSS=XLS+XM
      XRR=XLR+XM
C     READ COEFS OF FOURIER SERIES REPRESENTING THE I/P VOLTAGE SOUCE
      READ(5,10) (A(I),I=1,20)
      READ(5,10) (B(I),I=1,20)
   10 FORMAT(10F8.3)
      B1MAX=8.0/(3.0*PI)
      ARGU=2.0*PI/3.0
      B2MAX=8.0/(1.73205*PI)
      TC=(1.0/60.0)/128.0
C     CALCULATE VQA,VDA,VQB,VDB
      WRITE(6,20)
   20 FORMAT('0',///,5X,'K',8X,'VQA(K)',8X,'VQB(K)',8X,'VDA(K)',
     *        8X,'VDB(K)')
      DO 100 K=1,KMAX,2
      VQA(K)=0.0
      VQB(K)=B1MAX*B(K)*(1.0-COS(K*ARGU))
      VDA(K)=B2MAX*B(K)*SIN(K*ARGU)
      VDB(K)=0.0
      WRITE(6,21) K,VQA(K),VQB(K),VDA(K),VDB(K)
   21 FORMAT('0',4X,I2,4(6X,F8.4))
  100 CONTINUE
C     CALCULATE VQSPE,VDSPE,VQSNE,VDSNE
      WRITE(6,110)
  110 FORMAT('0',///,5X,'K',5X,'VQSE+(K)',5X,'VDSE+(K)',5X,'VQSE-(K)',
     *        5X,'VDSE-(K)')
      DO 200 K=1,KMAX,2
      VQSPE(K)=0.5*(VQA(K)-VDB(K))
      VDSPE(K)=0.5*(VQB(K)+VDA(K))
      VQSNE(K)=0.5*(VQA(K)+VDB(K))
```

```
      VDSNE(K)=0.5*(VQB(K)-VDA(K))
      WRITE(6,111) K,VQSPE(K),VDSPE(K),VQSNE(K),VDSNE(K)
  111 FORMAT('0',4X,I2,4(5X,F8.4))
  200 CONTINUE
C   COMPUTE AE,BE,CE,DE,EE
      DO 300 K=1,KMAX,2
      KN=-K
      APE(K)=RS*(RR**2+((K-WR/WE)*FR*XRR)**2)+
     *       K*(K-WR/WE)*RR*(FR*XM)**2
      ANE(K)=RS*(RR**2+((KN-WR/WE)*FR*XRR)**2)+
     *       KN*(KN-WR/WE)*RR*(FR*XM)**2
      BPE(K)=K*(K-WR/WE)**2*FR**3*XRR*(XM**2-XSS*XRR)-K*RR**2*FR*XSS
      BNE(K)=KN*(KN-WR/WE)**2*FR**3*XRR*(XM**2-XSS*XRR)-
     *       KN*RR**2*FR*XSS
      CPE(K)=-(K-WR/WE)*FR**2*XM*(K*RR*XSS+(K-WR/WE)*RS*XRR)
      CNE(K)=-(KN-WR/WE)*FR**2*XM*(KN*RR*XSS+(KN-WR/WE)*RS*XRR)
      DPE(K)=-(K-WR/WE)*FR*XM*(RS*RR+K*(K-WR/WE)*FR**2*(XM**2-XSS*XRR))
      DNE(K)=-(KN-WR/WE)*FR*XM*(RS*RR+KN*(KN-WR/WE)*
     *       FR**2*(XM**2-XSS*XRR))
      EPE(K)=(RS*RR+K*(K-WR/WE)*FR**2*(XM**2-XSS*XRR))**2+
     *       (K*RR*FR*XSS+(K-WR/WE)*RS*FR*XRR)**2
      ENE(K)=(RS*RR+KN*(KN-WR/WE)*FR**2*(XM**2-XSS*XRR))**2+
     *       (KN*RR*FR*XSS+(KN-WR/WE)*RS*FR*XRR)**2
  300 CONTINUE
C   COMPUTE CURRENTS
      WRITE(6,310)
  310 FORMAT('0',///,3X,'K',3X,'IQSE+(K)',3X,'IQSE-(K)',3X,'IDSE+(K)',
     *       3X,'IDSE-(K)',3X,'IQRE+(K)',3X,'IQRE-(K)',3X,'IDRE+(K)',
     *       3X,'IDRE-(K)')
      DO 400 K=1,KMAX,2
      IQSPE(K)=(APE(K)*VQSPE(K)+BPE(K)*VDSPE(K))/EPE(K)
      IQSNE(K)=(ANE(K)*VQSNE(K)+BNE(K)*VDSNE(K))/ENE(K)
      IDSPE(K)=(-BPE(K)*VQSPE(K)+APE(K)*VDSPE(K))/EPE(K)
      IDSNE(K)=(-BNE(K)*VQSNE(K)+ANE(K)*VDSNE(K))/ENE(K)
      IQRPE(K)=(CPE(K)*VQSPE(K)+DPE(K)*VDSPE(K))/EPE(K)
      IQRNE(K)=(CNE(K)*VQSNE(K)+DNE(K)*VDSNE(K))/ENE(K)
      IDRPE(K)=(-DPE(K)*VQSPE(K)+CPE(K)*VDSPE(K))/EPE(K)
      IDRNE(K)=(-DNE(K)*VQSNE(K)+CNE(K)*VDSNE(K))/ENE(K)
      XA(1)=IQSPE(K)
      XA(2)=IQSNE(K)
      XA(3)=IDSPE(K)
      XA(4)=IDSNE(K)
      XA(5)=IQRPE(K)
      XA(6)=IQRNE(K)
      XA(7)=IDRPE(K)
      XA(8)=IDRNE(K)
      WRITE(6,311) K,(XA(I),I=1,8)
  311 FORMAT('0',2X,I2,8(3X,F8.4))
  400 CONTINUE
C   COMPUTE IQSS,IDSS,IQRS,IDRS
      DO 510 I=1,128
      T=(I-1)*TC
      ARGU=WE*T
      IQSS(I)=0.0
      IDSS(I)=0.0
      IQRS(I)=0.0
      IDRS(I)=0.0
      DO 500 K=1,KMAX,2
      IQSS(I)=IQSS(I)+(IQSPE(K)+IQSNE(K))*COS(K*ARGU)
     *                +(IDSPE(K)-IDSNE(K))*SIN(K*ARGU)
```

```
      IDSS(I)=IDSS(I)+(IDSPE(K)+IDSNE(K))*COS(K*ARGU)
     *                  -(IQSPE(K)-IQSNE(K))*SIN(K*ARGU)
      IQRS(I)=IQRS(I)+(IQRPE(K)+IQRNE(K))*COS(K*ARGU)
     *                  +(IDRPE(K)-IDRNE(K))*SIN(K*ARGU)
      IDRS(I)=IDRS(I)+(IDRPE(K)+IDRNE(K))*COS(K*ARGU)
     *                  -(IQRPE(K)-IQRNE(K))*SIN(K*ARGU)
  500 CONTINUE
      TIME(I)=T
      IAS(I)=IQSS(I)
      IBS(I)=-0.5*IQSS(I)-0.866*IDSS(I)
      ICS(I)=-0.5*IQSS(I)+0.866*IDSS(I)
      TORQUE(I)=0.25*XM/WE*NPHASE*NPOLE*
     *          (IQSS(I)*IDRS(I)-IDSS(I)*IQRS(I))
  510 CONTINUE
      DO 520 JJ=1,42
      KK=3*JJ
      XX(JJ)=IAS(KK)
      TX(JJ)=TIME(KK)
  520 CONTINUE
      CALL PLOT(TX,XX,42)
      WRITE(6,600)
  600 FORMAT('0',/'  PLOT OF IAS VS. TIME')
      DO 75 I=1,128
   75 XSMALL(I)=CMPLX(IAS(I),0.0)
      CALL FFT(XSMALL,7,128)
      DO 76 I=1,128
      MAG(I)=CABS(XSMALL(I))
   76 FREQ(I)=(1.0/TC)*(I-1)/128.0
      CALL PLOT(FREQ,MAG,42)
      WRITE(6,700)
  700 FORMAT('0',/'  PLOT OF FREQUENCY SPECTRUM OF IAS')
      DO 620 JJ=1,42
      KK=3*JJ
      XX(JJ)=TORQUE(KK)
      TX(JJ)=TIME(KK)
  620 CONTINUE
      CALL PLOT(TX,XX,42)
      WRITE(6,630)
  630 FORMAT('0',/'  PLOT OF TORQUE VS. TIME')
      DO 77 I=1,128
   77 XSMALL(I)=CMPLX(TORQUE(I),0.0)
      CALL FFT(XSMALL,7,128)
      DO 78 I=1,128
      MAG(I)=CABS(XSMALL(I))
   78 FREQ(I)=(1.0/TC)*(I-1)/128.0
      CALL PLOT(FREQ,MAG,42)
      WRITE(6,710)
  710 FORMAT('0',/'  PLOT OF FREQUENCY SPECTRUM OF TORQUE',9(/))
      STOP
      END

      SUBROUTINE FFT(X,M,NUMDAT)
      COMPLEX X(NUMDAT),U,W,T,CMPLX
      N = 2**M
      NV2 = N/2
      NM1 = N-1
      J = 1
      DO 7 I = 1, NM1
      IF(I.GE.J) GO TO 5
```

```
      T = X(J)
      X(J) = X(I)
      X(I) = T
    5 K = NV2
    6 IF(K.GE.J) GO TO 7
      J = J-K
      K = K/2
      GO TO 6
    7 J = J + K
      PI = 3.1415927
      DO 20 L = 1, M
      LE = 2**L
      LE1 = LE/2
      U = (1.0,0.0)
      W = CMPLX(COS(PI/FLOAT(LE1)),-SIN(PI/FLOAT(LE1)))
      DO 20 J = 1, LE1
      DO 10 I = J,N,LE
      IP = I + LE1
      T = X(IP)*U
      X(IP) = X(I) - T
   10 X(I) = X(I) + T
   20 U = U*W
      RETURN
      END


      SUBROUTINE PLOT(T,F,N)
C
C     ******************************************************************
C     *                                                                *
C     *  SUBROUTINE NAME : PLOT                                        *
C     *  ARGUMENT LIST : N = NO. OF POINTS TO BE PLOTTED.              *
C     *                  T = TIME, A ONE DIMENSIONAL ARRAY OF SIZE N.  *
C     *                  F = FUNCTION VALUE, A ONE DIMANTIONAL ARRAY   *
C     *                      OF SIZE N.                                *
C     *  DESCRIPTION : THIS ROUTINE PLOT FF VS T FOR N POINTS.         *
C     *                T, F AND N MUST BE SUPPLIED BY THE CALLING PROG *
C     *                                                                *
C     ******************************************************************
      INTEGER PLINE(61),ASTRX,AXIS,BLANK,PLUS,VDASH
      DIMENSION T(N),F(N),DISP(3),DY(11),SCALE(3),SFRCT(5)
      DATA ASTRX,AXIS,BLANK,PLUS,VDASH/'*','I',' ','+','|'/
      DATA SFRCT/1.,2.5,5.,7.5,10./,DISP/1.5,61.5,31.5/,SCALE/2*60.,30./
      FMAX = F(1)
      FMIN = F(1)
      DO 4 I = 1,N
      IF(F(I)-FMAX)2,2,1
    1 FMAX = F(I)
    2 IF(F(I)-FMIN)3, 4,4
    3 FMIN = F(I)
    4 CONTINUE
      IF(ABS(FMAX)-ABS(FMIN))6,5,5
    5 DIV= ABS(FMAX)
      GO TO 7
    6 DIV = ABS(FMIN)
    7 NEXP = IFIX(ALOG(DIV)/ALOG(10.))
      IF(DIV.LT.1.)NEXP = NEXP - 1
      PP = 10.**NEXP
      P = 10.**(-NEXP)
      FRACT = DIV*P
```

```
      DO 8 I =1,3
      DIV=SFRCT(I)*PP
      IF(FRACT-SFRCT(I))9,9,8
    8 CONTINUE
    9 CONTINUE
      WRITE(6,11)PP
   11 FORMAT('1TO GET THE TRUE VALUES. MULTIPLY THOSE IN THE 2ND COLUMN
     1BY ',1PE7.1/)
      IF(FMIN)12,20,20
   12 IF(FMAX)25,25,30
   20 INDEX = 1
      DY(1) = 0.
      YINC = DIV/10.
      GO TO 100
   25 INDEX = 2
      DY(1) = -DIV*P
      YINC = DIV/10.
      GO TO 100
   30 INDEX = 3
      DY(1) = -DIV*P
      YINC = DIV/5.
  100 DO 110 I = 2,11
  110 DY(I) = DY(I-1) + YINC*P
      WRITE(6,120) DY
  120 FORMAT(16X,11F6.1)
      WRITE(6,125)
  125 FORMAT('0',2X,'T',11X,'F',T21,'+',10('-----+'))
      DO 190 J = 1,N
      I = IFIX((F(J)/DIV)*SCALE(INDEX)+DISP(INDEX))
      DO 135 L = 1,60,6
      DO 130 K = 1,5
  130 PLINE(L+K) = BLANK
  135 PLINE(L) = VDASH
      PLINE(61) = VDASH
      GO TO (140,150,160), INDEX
  140 DO 145 L= 1,I
  145 PLINE(L) = ASTRX
      PLINE(1) = AXIS
      GO TO 170
  150 DO 155 L=1,I
  155 PLINE(L) = ASTRX
      PLINE(61) = AXIS
      GO TO 170
  160 IF(I-31)165,169,167
  165 DO 166 L = I,30
  166 PLINE(L)  = ASTRX
      GO TO 169
  167 DO 168 L = 32,I
  168 PLINE(L) = ASTRX
  169 PLINE(31) = AXIS
  170 PLINE(I) = PLUS
      FP = F(J)*P
      WRITE(6,180) T(J),FP,PLINE
  180 FORMAT(' ',G10.3,1X,F7.3,1X,61A1)
  190 CONTINUE
      WRITE(6,195)
  195 FORMAT(20X,'I',10('_____|'))
      RETURN
      END
```

$ENTRY

K	VQA(K)	VQB(K)	VDA(K)
1	0.0000	1.2096	1.2096
3	0.0000	-0.0000	0.0000
5	0.0000	0.0509	-0.0509
7	0.0000	-0.0255	-0.0255
9	0.0000	0.0000	0.0000
11	0.0000	0.0000	0.0000
13	0.0000	0.0000	0.0000

K	VQSE+(K)	VDSE+(K)	VQSE-(K)
1	0.0000	1.2096	0.0000
3	0.0000	0.0000	0.0000
5	0.0000	0.0000	0.0000
7	0.0000	-0.0255	0.0000
9	0.0000	0.0000	0.0000
11	0.0000	0.0000	0.0000
13	0.0000	0.0000	0.0000

K	IQSE+(K)	IQSE-(K)	IDSE+(K)	IDSE-(K)
1	-0.8208	-0.0000	2.2694	-0.0000
3	-0.0000	-0.0000	0.0000	-0.0000
5	-0.0000	0.0919	0.0000	0.0107
7	0.0330	0.0000	-0.0030	0.0000
9	0.0000	0.0000	0.0000	0.0000
11	0.0000	0.0000	0.0000	0.0000
13	0.0000	0.0000	0.0000	0.0000

VDB(K)

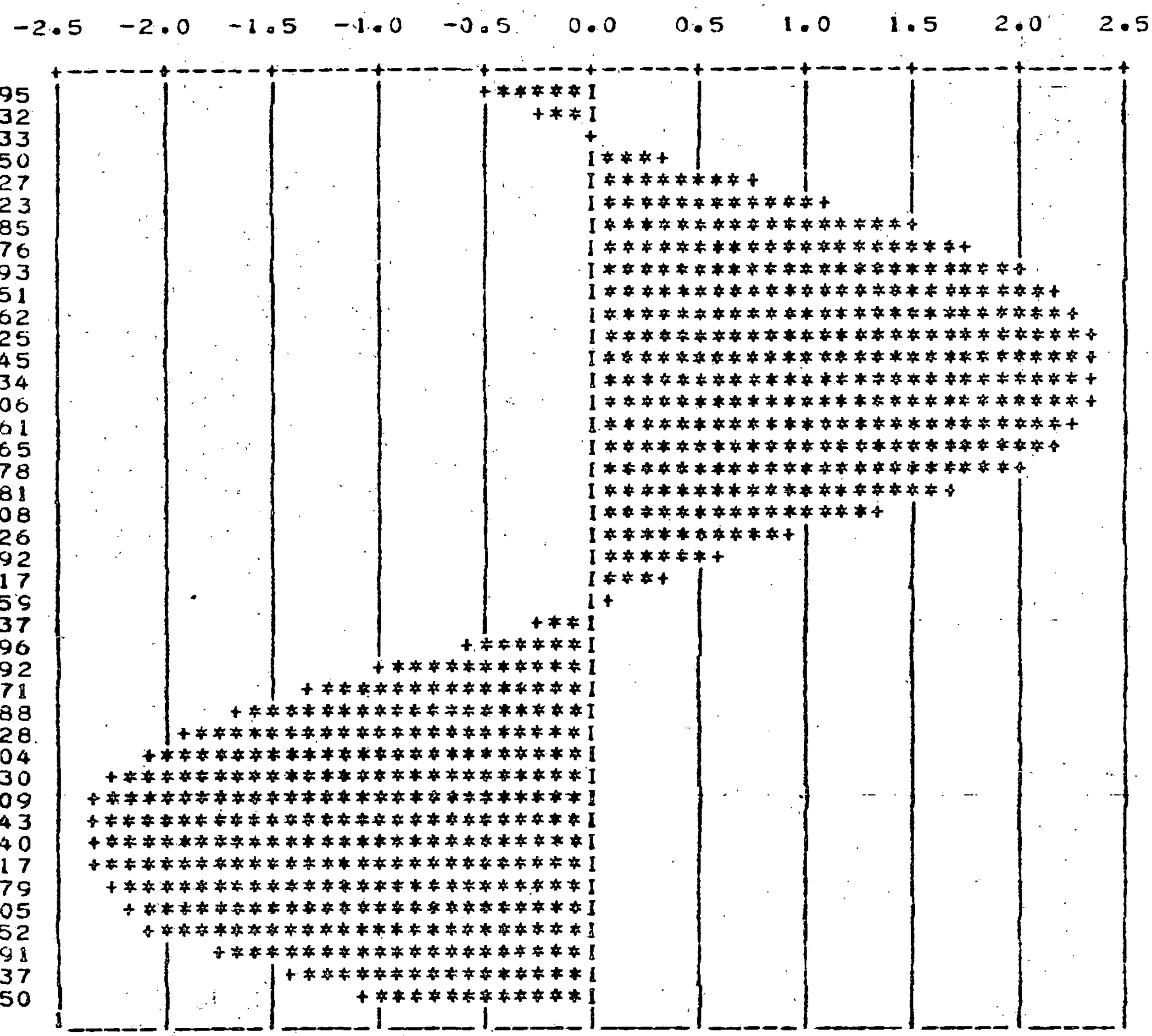
0.0000
0.0000
0.0000
0.0000
0.0000
0.0000
0.0000

VDSE-(K)

-0.0000
-0.0000
0.0509
0.0000
0.0000
0.0000
0.0000

IQRE+(K)	IQRE-(K)	IDRE+(K)	IDRE-(K)
0.4802	0.0000	-2.3147	0.0000
0.0000	0.0000	-0.0000	0.0000
0.0000	-0.0909	-0.0000	-0.0107
-0.0326	-0.0000	0.0030	-0.0000
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000

T	
0.260E-03	-0.495
0.651E-03	-0.232
0.104E-02	0.033
0.143E-02	0.350
0.182E-02	0.727
0.221E-02	1.123
0.260E-02	1.485
0.299E-02	1.776
0.339E-02	1.993
0.378E-02	2.151
0.417E-02	2.262
0.456E-02	2.325
0.495E-02	2.345
0.534E-02	2.334
0.573E-02	2.306
0.612E-02	2.261
0.651E-02	2.165
0.690E-02	1.978
0.729E-02	1.681
0.768E-02	1.308
0.807E-02	0.926
0.846E-02	0.592
0.885E-02	0.317
0.924E-02	0.059
0.964E-02	-0.237
0.100E-01	-0.596
0.104E-01	-0.992
0.108E-01	-1.371
0.112E-01	-1.688
0.116E-01	-1.928
0.120E-01	-2.104
0.124E-01	-2.230
0.128E-01	-2.309
0.132E-01	-2.343
0.135E-01	-2.340
0.139E-01	-2.317
0.143E-01	-2.279
0.147E-01	-2.205
0.151E-01	-2.052
0.155E-01	-1.791
0.159E-01	-1.437
0.163E-01	-1.050

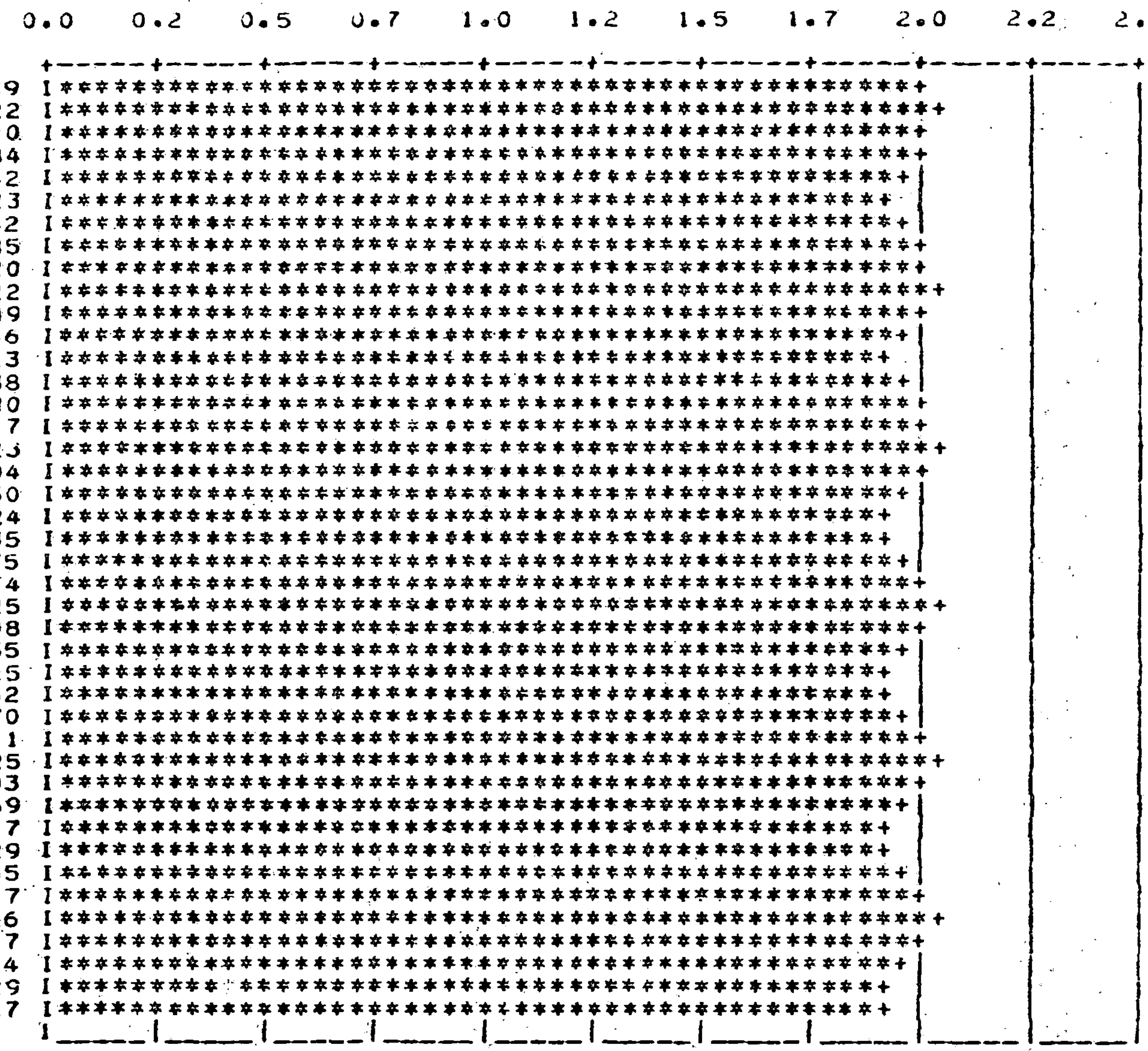


PLOT OF IAS VS. TIME

```
TO GET THE TRUE VALUES, MULTIPLY THOSE IN THE 2ND COLUMN BY 1.0E 02
                          0.0   0.2   0.5   0.7   1.0   1.2   1.5   1.7   2.0   2.2   2.5
      T             F     +-----+-----+-----+-----+-----+-----+-----+-----+-----+-----+
    0.000         0.000   +
     60.0         1.544   I************************************+
    120.          0.000   +
    180.          0.000   +
    240.          0.000   +
    300.          0.059   I+
    360.          0.000   +
    420.          0.021   I+
    480.          0.000   +
    540.          0.000   +
    600.          0.000   +
    660.          0.000   +
    720.          0.000   +
    780.          0.000   +
    840.          0.000   +
    900.          0.000   +
    960.          0.000   +
    0.102E 04     0.000   +
    0.108E 04     0.000   +
    0.114E 04     0.000   +
    0.120E 04     0.000   +
    0.126E 04     0.000   +
    0.132E 04     0.000   +
    0.138E 04     0.000   +
    0.144E 04     0.000   +
    0.150E 04     0.000   +
    0.156E 04     0.000   +
    0.162E 04     0.000   +
    0.168E 04     0.000   +
    0.174E 04     0.000   +
    0.180E 04     0.000   +
    0.186E 04     0.000   +
    0.192E 04     0.000   +
    0.198E 04     0.000   +
    0.204E 04     0.000   +
    0.210E 04     0.000   +
    0.216E 04     0.000   +
    0.222E 04     0.000   +
    0.228E 04     0.000   +
    0.234E 04     0.000   +
    0.240E 04     0.000   +
    0.246E 04     0.000   +
                          I

PLOT OF FREQUENCY SPECTRUM OF IAS
```

T	F
0.260E-03	1.989
0.651E-03	2.022
0.104E-02	2.020
0.143E-02	1.984
0.182E-02	1.942
0.221E-02	1.923
0.260E-02	1.942
0.299E-02	1.985
0.339E-02	2.020
0.378E-02	2.022
0.417E-02	1.989
0.456E-02	1.946
0.495E-02	1.923
0.534E-02	1.938
0.573E-02	1.980
0.612E-02	2.017
0.651E-02	2.023
0.690E-02	1.994
0.729E-02	1.950
0.768E-02	1.924
0.807E-02	1.935
0.846E-02	1.975
0.885E-02	2.014
0.924E-02	2.025
0.964E-02	1.998
0.100E-01	1.955
0.104E-01	1.925
0.108E-01	1.932
0.112E-01	1.970
0.116E-01	2.011
0.120E-01	2.025
0.124E-01	2.003
0.128E-01	1.959
0.132E-01	1.927
0.135E-01	1.929
0.139E-01	1.965
0.143E-01	2.007
0.147E-01	2.026
0.151E-01	2.007
0.155E-01	1.964
0.159E-01	1.929
0.163E-01	1.927



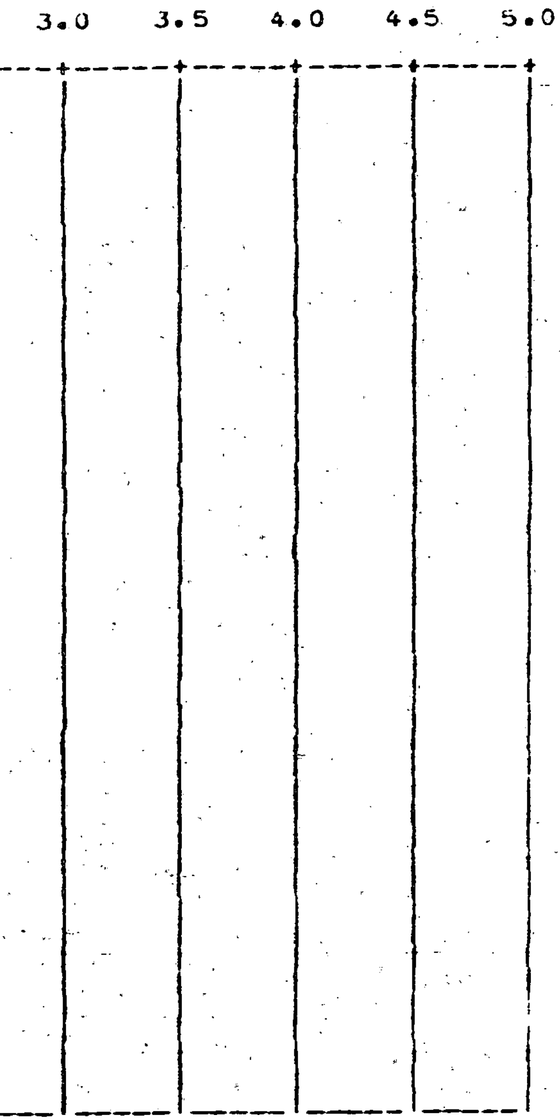
PLCT OF TORQUE VS. TIME

```
TO GET THE TRUE VALUES, MULTIPLY THOSE IN THE 2ND

                                      0.0   0.5   1.0   1.5   2.0   2.5

   T                   F        +-----+-----+-----+-----+-----+---
 0.000               2.527      I*****************************+
  60.0               0.000      +
  120.               0.000      +
  180.               0.000      +
  240.               0.000      +
  300.               0.000      +
  360.               0.033      +
  420.               0.000      +
  480.               0.000      +
  540.               0.000      +
  600.               0.000      +
  660.               0.000      +
  720.               0.000      +
  780.               0.000      +
  840.               0.000      +
  900.               0.000      +
  960.               0.000      +
 0.102E 04           0.000      +
 0.108E 04           0.000      +
 0.114E 04           0.000      +
 0.120E 04           0.000      +
 0.126E 04           0.000      +
 0.132E 04           0.000      +
 0.138E 04           0.000      +
 0.144E 04           0.000      +
 0.150E 04           0.000      +
 0.156E 04           0.000      +
 0.162E 04           0.000      +
 0.168E 04           0.000      +
 0.174E 04           0.000      +
 0.180E 04           0.000      +
 0.186E 04           0.000      +
 0.192E 04           0.000      +
 0.198E 04           0.000      +
 0.204E 04           0.000      +
 0.210E 04           0.000      +
 0.216E 04           0.000      +
 0.222E 04           0.000      +
 0.228E 04           0.000      +
 0.234E 04           0.000      +
 0.240E 04           0.000      +
 0.246E 04           0.000      +
                                I

PLOT OF FREQUENCY SPECTRUM OF TORQUE
```


3.0 3.5 4.0 4.5 5.0

APPENDIX F ANALYSIS OF CSI-IM

A somewhat more detailed circuit diagram of the preferred CSI-IM, called the auto-sequential commutated inverter (ASCI) is shown in Fig. F1. The circuit configurations for each of the 18 operating modes are shown in Fig. F2 through Fig. F19.

Assuming steady state, the operation during each commutation interval is similar. Hence, only the operation of modes 1-3 will be discussed. The simplified equivalent circuits of operating modes 1-3 are shown in Fig. F20 through Fig. F22 respectively.

Define

$$A1 = RF + RC + RB$$
$$A2 = RC + RB$$
$$A3 = RF + RB + RC + RC(LF + LB)/LA$$
$$A4 = RF + RB - RA(LF + LB)/LA$$
$$A5 = RA + RB$$
$$A6 = RF + RA + RB$$
$$B1 = LF + LC + LB$$
$$B2 = LC + LB$$
$$B3 = LF + LB + LC + LC(LF + LB)/LA$$
$$B4 = LA + LB$$
$$B5 = LF + LA + LB$$
$$D1 = (LF + LB)/LA$$
$$D2 = 1 + D1$$

The corresponding equations for the circuit shown in Fig. F20 can be written as

$$v_{ab} = v_{as} - v_{bs} + LB \cdot x \frac{di_c}{dt} + RB \ x \ i_c$$

$$v_{bc} = -A2 \ x \ i_c - B2 \ x \frac{di_c}{dt} + v_{bs} - v_{cs}$$

$$v_{ca} = RC \ x \ i_c + LC \ x \frac{di_c}{dt} + v_{cs} - v_{as}$$

$$v_i = v_c - v_{bc}$$

$$i_d = i_c$$

$$\frac{di_c}{dt} = (V_d - v_c - v_{cs} + v_{bs} - A1 \ x \ i_c)/B1$$

$$\frac{dv_c}{dt} = \frac{2}{3C} \ x \ i_c$$

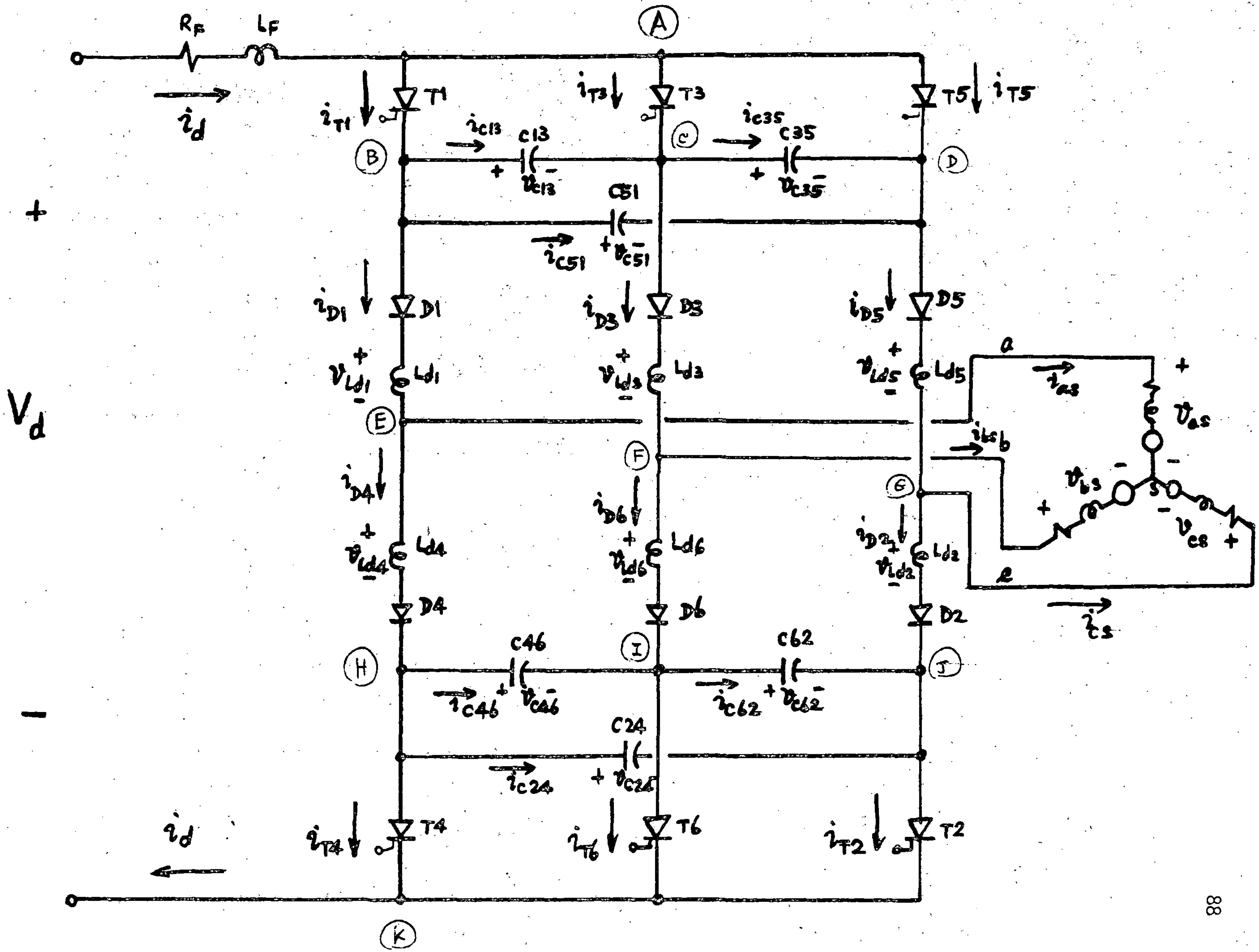
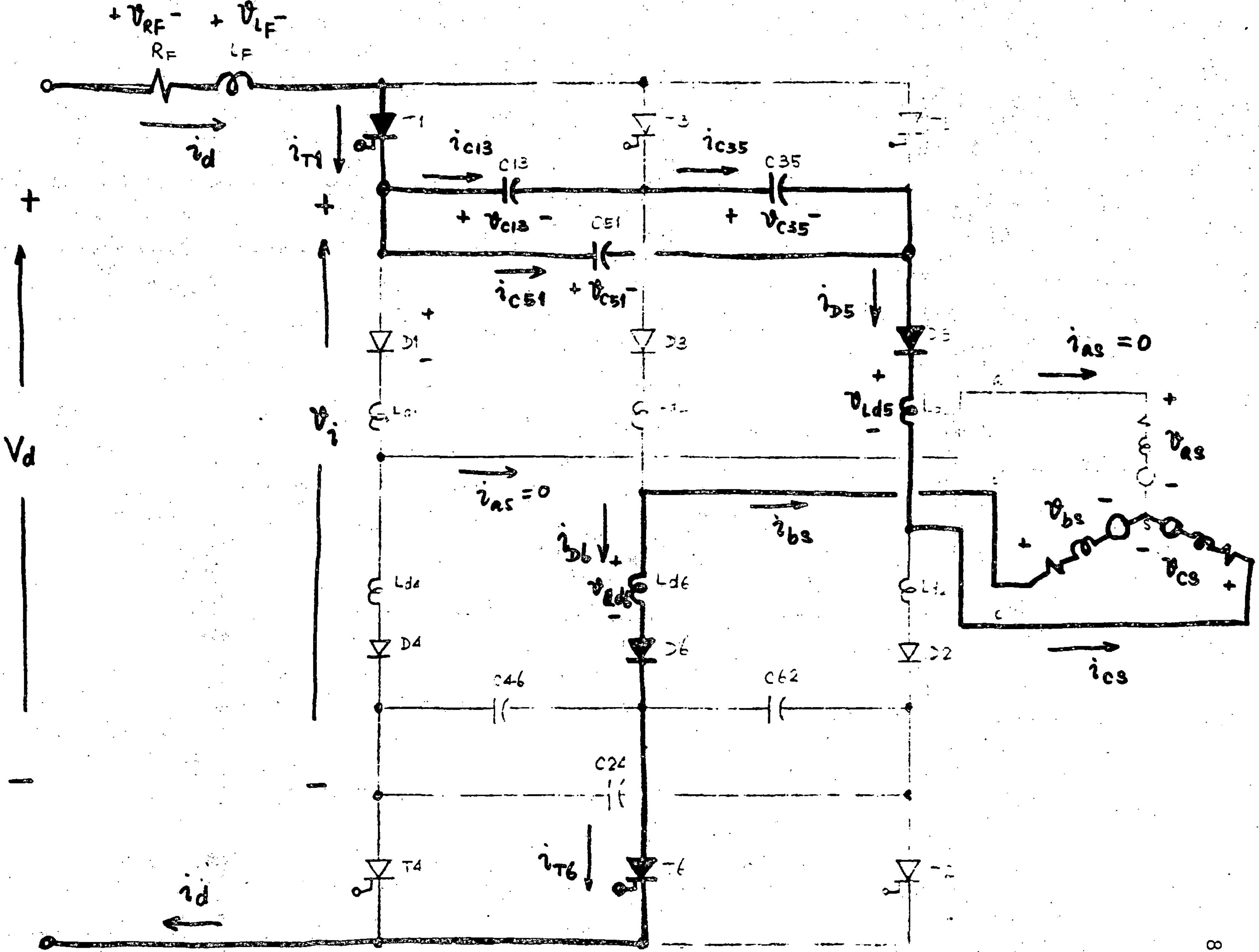


Fig. F1 The circuit configuration of ASCI with motor load.

mode 1



$+ v_{RF} -$
$+ v_{LF} -$
R_F
L_F
i_d
i_{T1}
i_{C13}
C13
$+ v_{C13} -$
C51
i_{C51}
$+ v_{C51} -$
i_{C35}
C35
$+ v_{C35} -$
i_{D5}
D1
D3
D4
D6
D2
T4
i_{T6}
$i_{as} = 0$
i_{bs}
i_{cs}
i_{D6}
v_{Ld6}
v_{Ld5}
Ld4
Ld6
C46
C62
C24
v_{as}
v_{bs}
v_{cs}
V_d
v_i

Fig. F2

mode 2

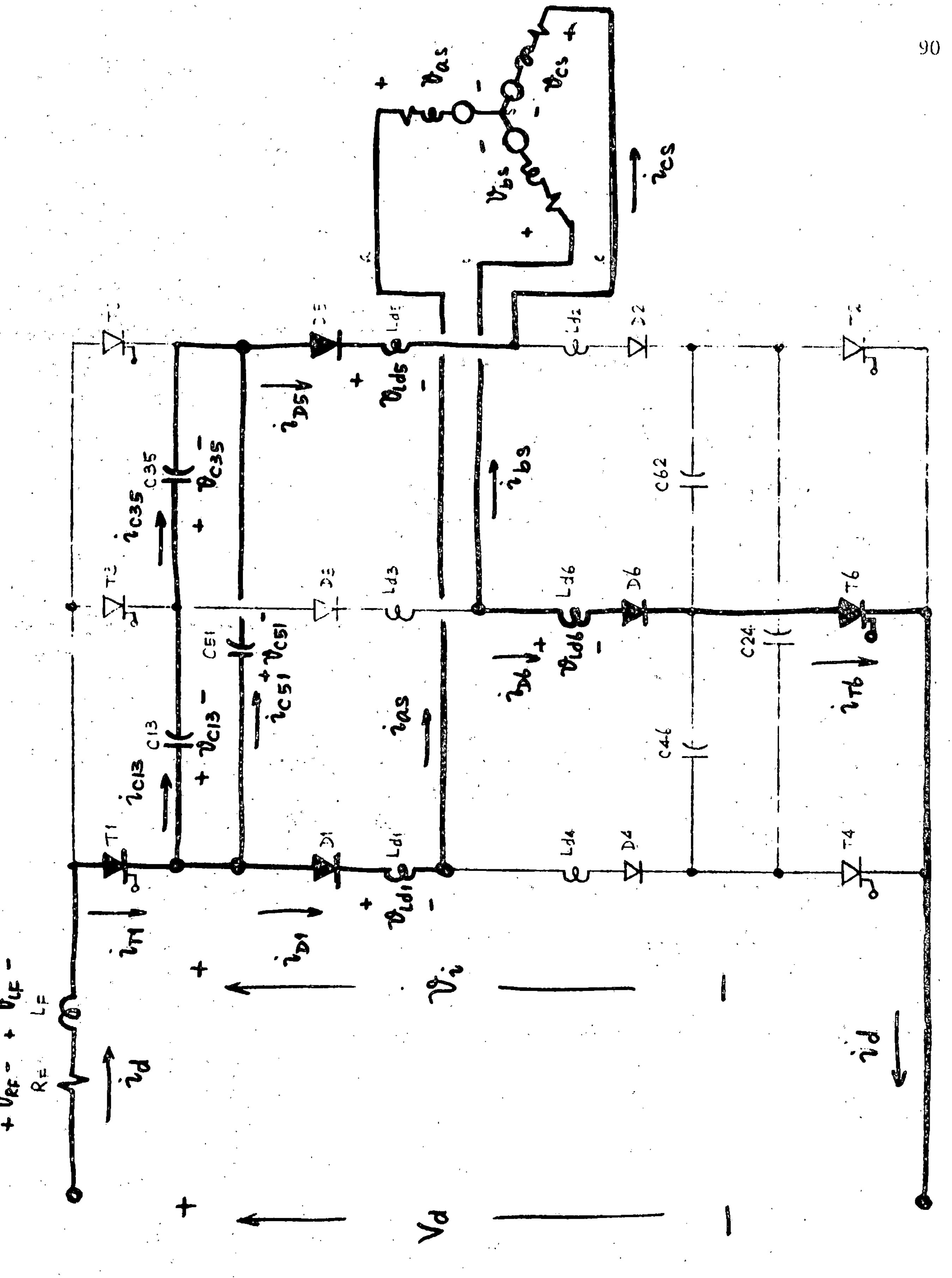
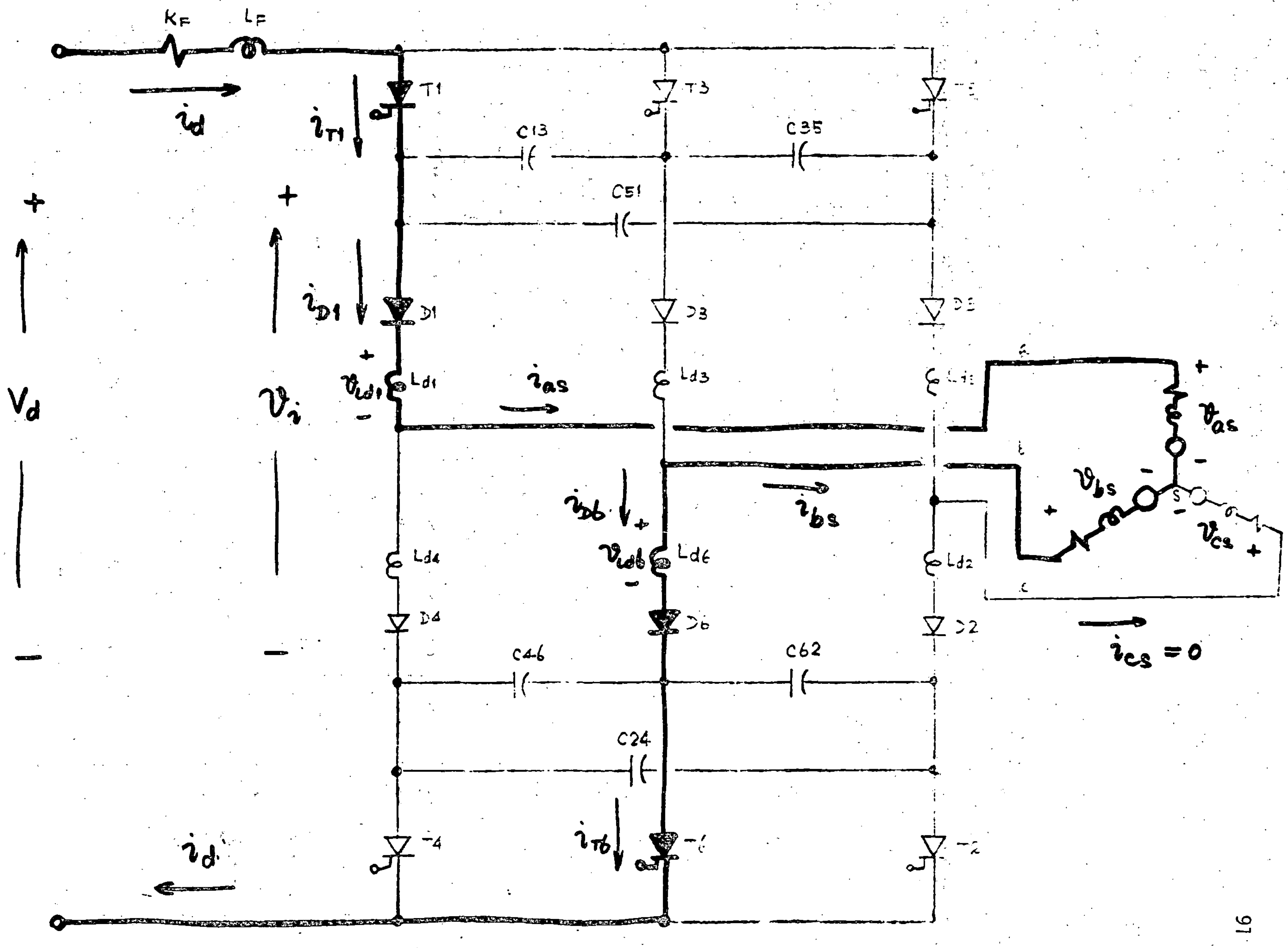


Fig. F3

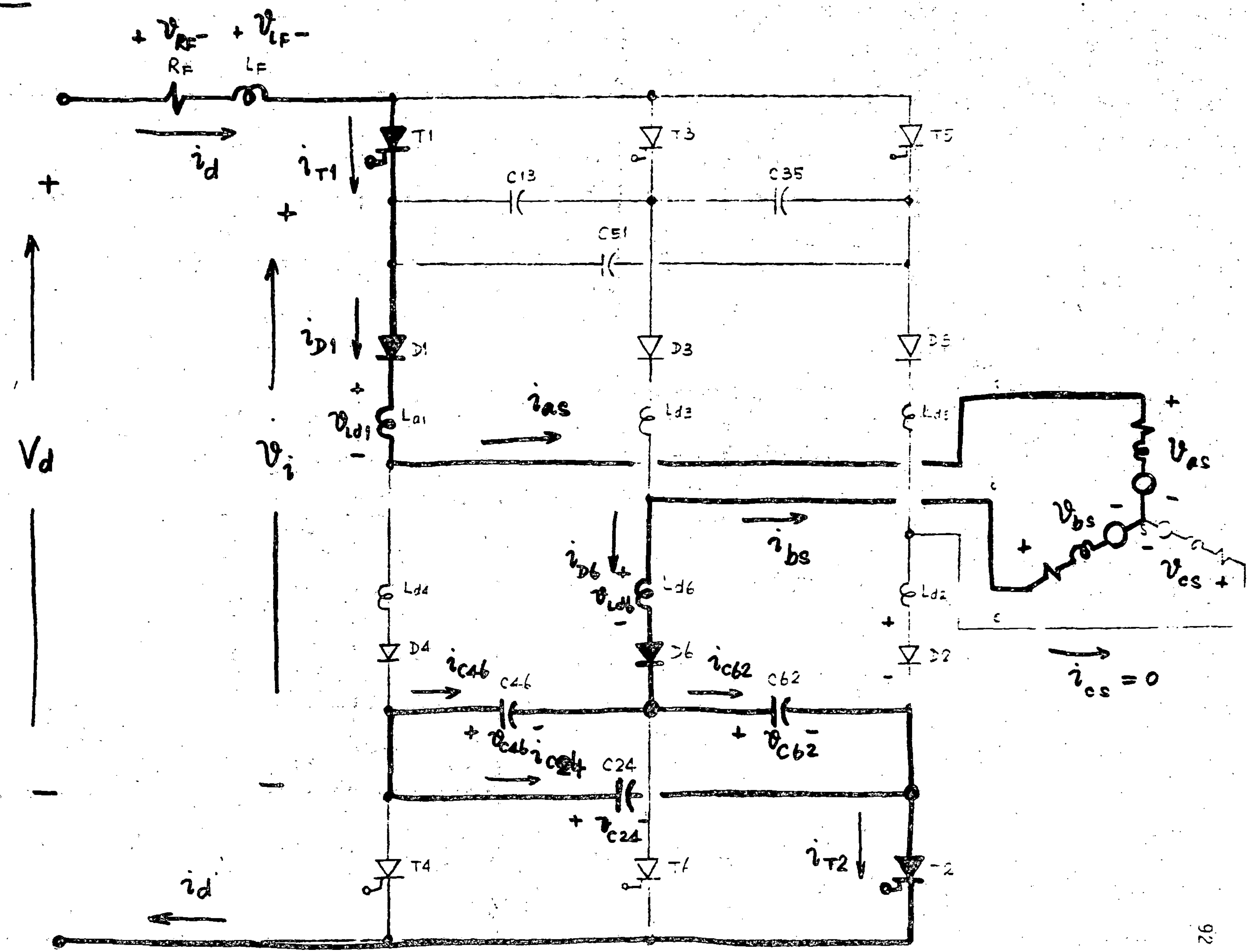
mode 3



K_F
L_F
i_d
i_{T1}
T1
T3
C13
C35
C51
i_{D1}
D1
D3
V_d
v_i
v_{Ld1}
Ld1
Ld3
i_{as}
v_{as}
v_{bs}
i_{bs}
v_{cs}
i_{D6}
v_{Ld6}
Ld4
Ld6
Ld2
D4
D6
C46
C62
$i_{cs} = 0$
C24
i_d
i_{T6}

Fig.F4

mode 4



+ v_{RF} -
+ v_{LF} -
RF
LF
i_d
i_{T1}
T1
T3
T5
C13
C35
C51
i_{D1}
D1
D3
D5
+
V_d
v_i
v_{Ld1}
Ld1
Ld3
Ld5
i_{as}
v_{as}
v_{bs}
i_{bs}
v_{cs}
i_{D6}
v_{Ld6}
Ld4
Ld6
Ld2
D4
D6
D2
i_{c46}
C46
i_{c62}
C62
$i_{cs} = 0$
v_{c46}
i_{c24}
C24
v_{c62}
v_{c24}
i_{T2}
T4
T6
T2

Fig. F5

mode 5

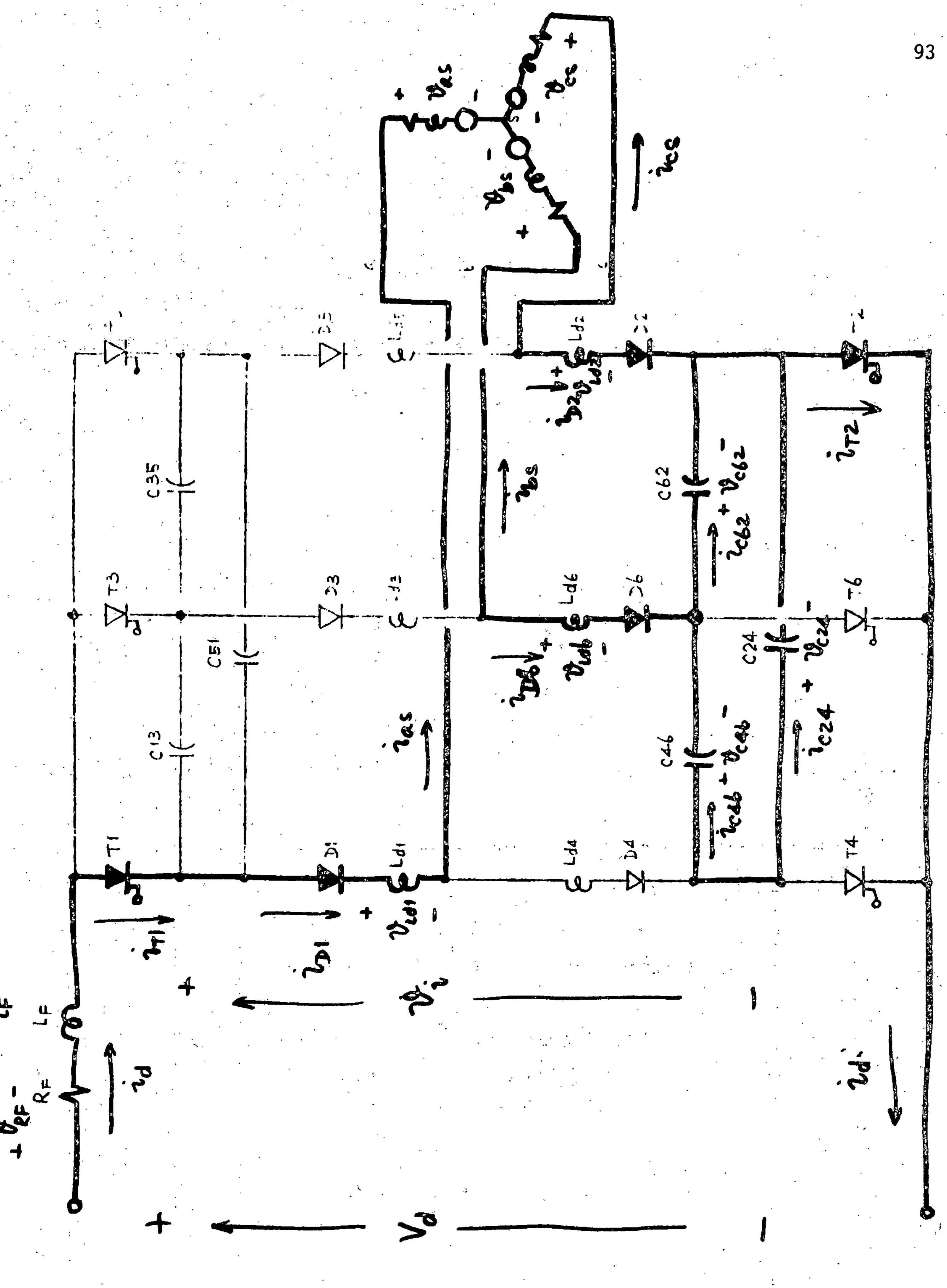

T1
D1
Ld1
C13
C51
C35
T3
D3
Ld6
D6
C46
C24
C62
Ld4
D4
T4
T6
Ld2
LF
RF

Fig. F6

mode 6

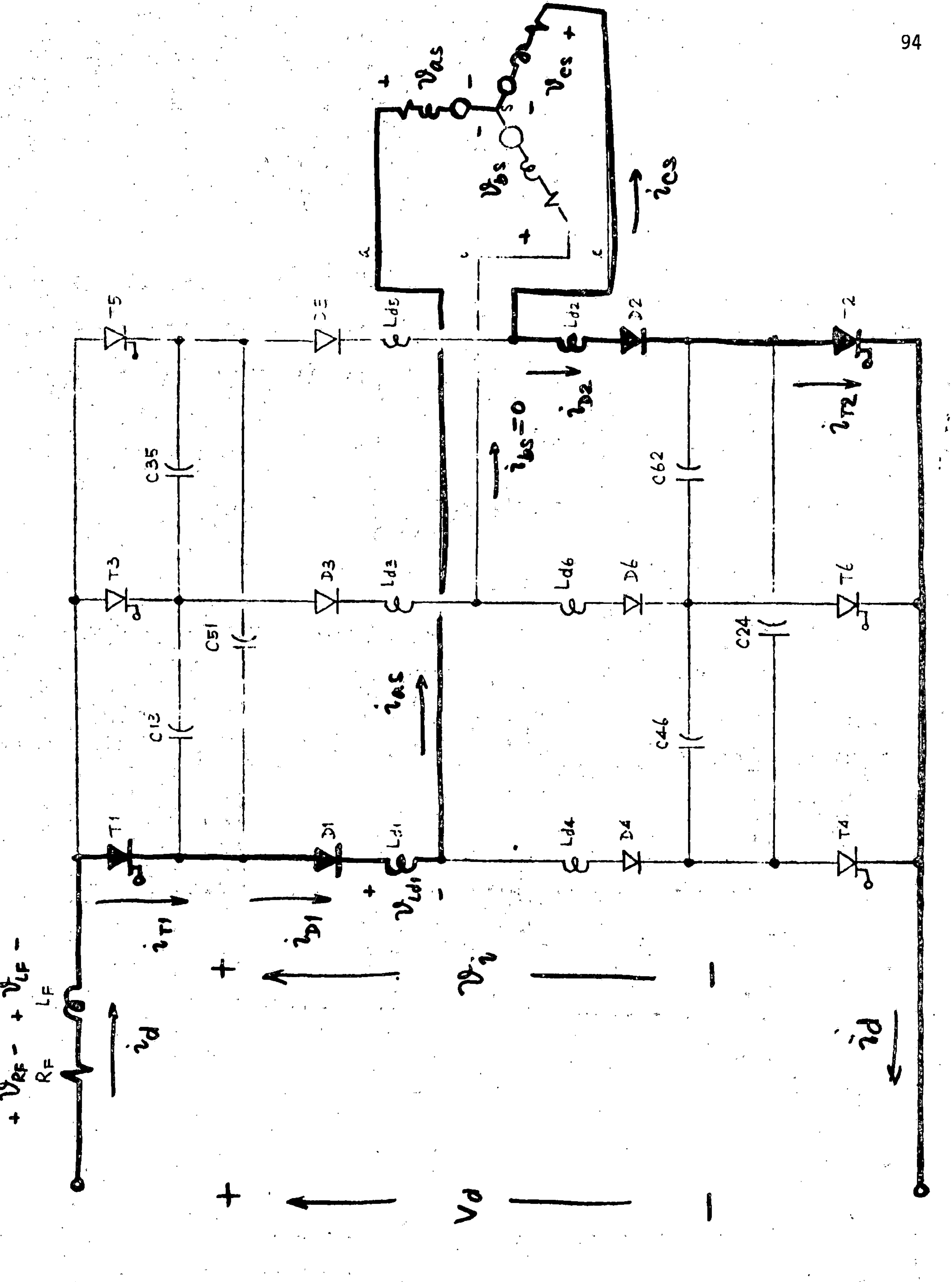

T1
T3
T4
T6
D1
D2
D3
D4
D6
C13
C35
C51
C46
C62
C24
Ld1
Ld2
Ld3
Ld4
Ld5
Ld6
R F
L F
Vd

Fig. F7

mode 7

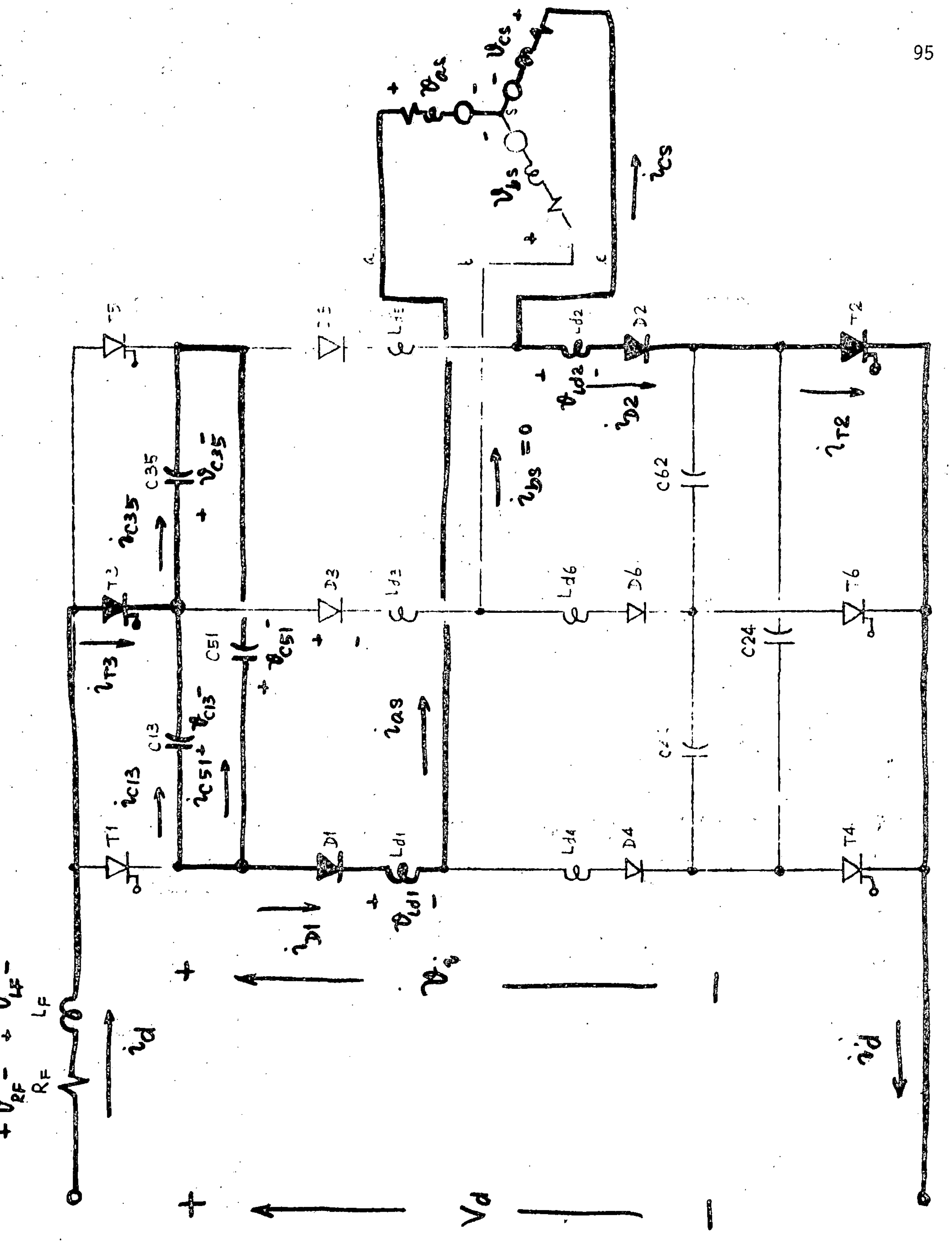
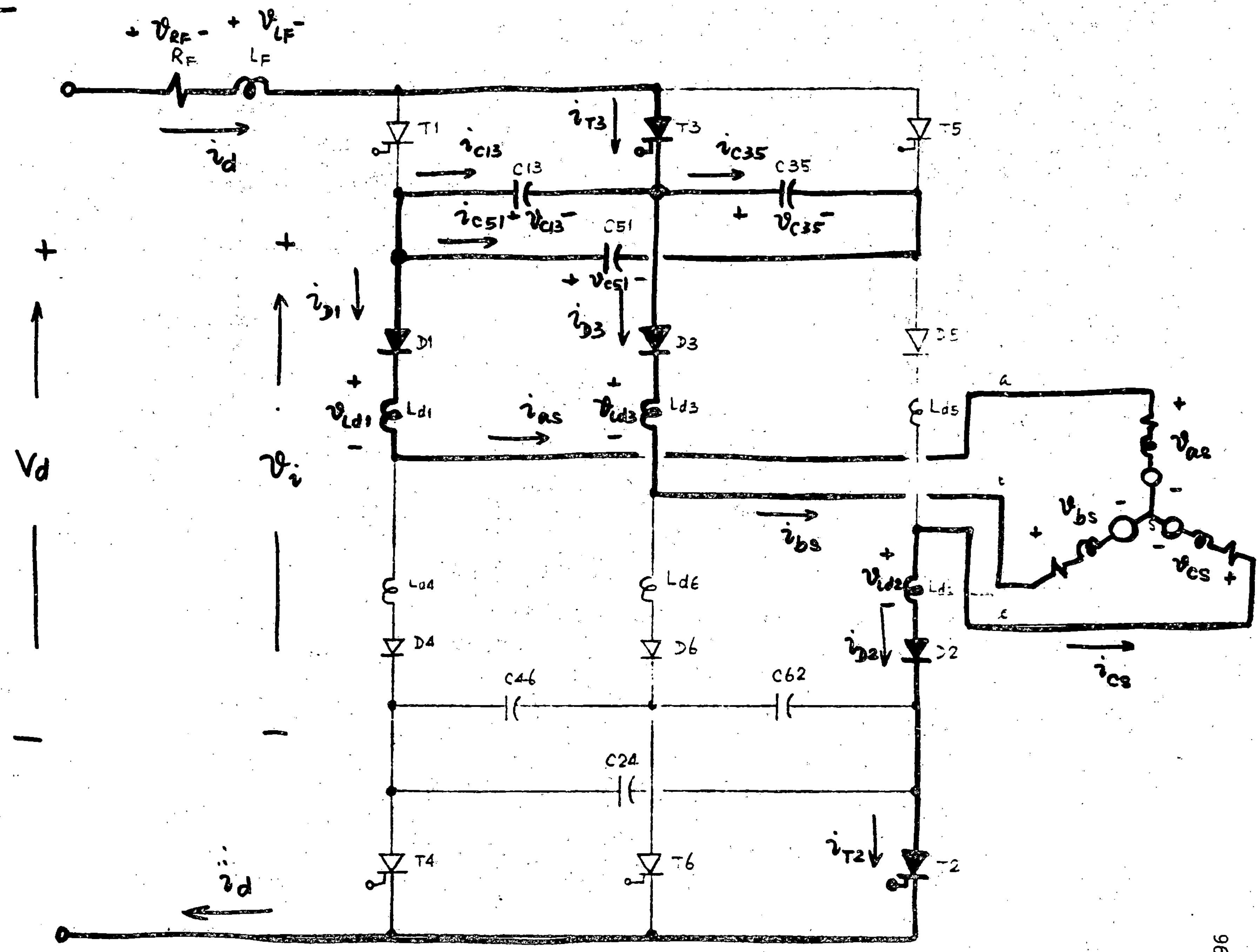

T1
T3
T5
D1
D3
D4
D6
D2
T4
T6
T2
C13
C51
C35
C24
C62
Ld1
Ld4
Ld6
Ld3
Ld2
L_F
R_F
i_d
V_d
v_i
i_{D1}
i_{T3}
i_{C13}
i_{C35}
i_{C51}
i_{as}
$i_{bs} = 0$
i_{cs}
i_{D2}
i_{T2}
v_{as}
v_{bs}
v_{cs}
v_{Ld1}
v_{Ld2}
v_{C13}
v_{C35}
v_{C51}
v_{RF}
v_{LF}

Fig. F8

mode 8



+ v_{RF} -
+ v_{LF} -
R_F
L_F
i_d
T1
T3
T5
i_{T3}
i_{C13}
C13
i_{C35}
C35
i_{C51}
+ v_{C13} -
+ v_{C35} -
C51
+ v_{C51} -
i_{D1}
i_{D3}
D1
D3
D5
+ v_{Ld1} -
Ld1
i_{as}
+ v_{Ld3} -
Ld3
Ld5
a
+ v_{as} -
V_d
v_i
+
-
t
v_{bs}
i_{bs}
s
- v_{cs} +
+ v_{Ld2}
Ld4
Ld6
D4
D6
i_{D2}
D2
c
i_{cs}
C46
C62
C24
i_{T2}
T4
T6
T2
i_d

Fig. F9

mode 9

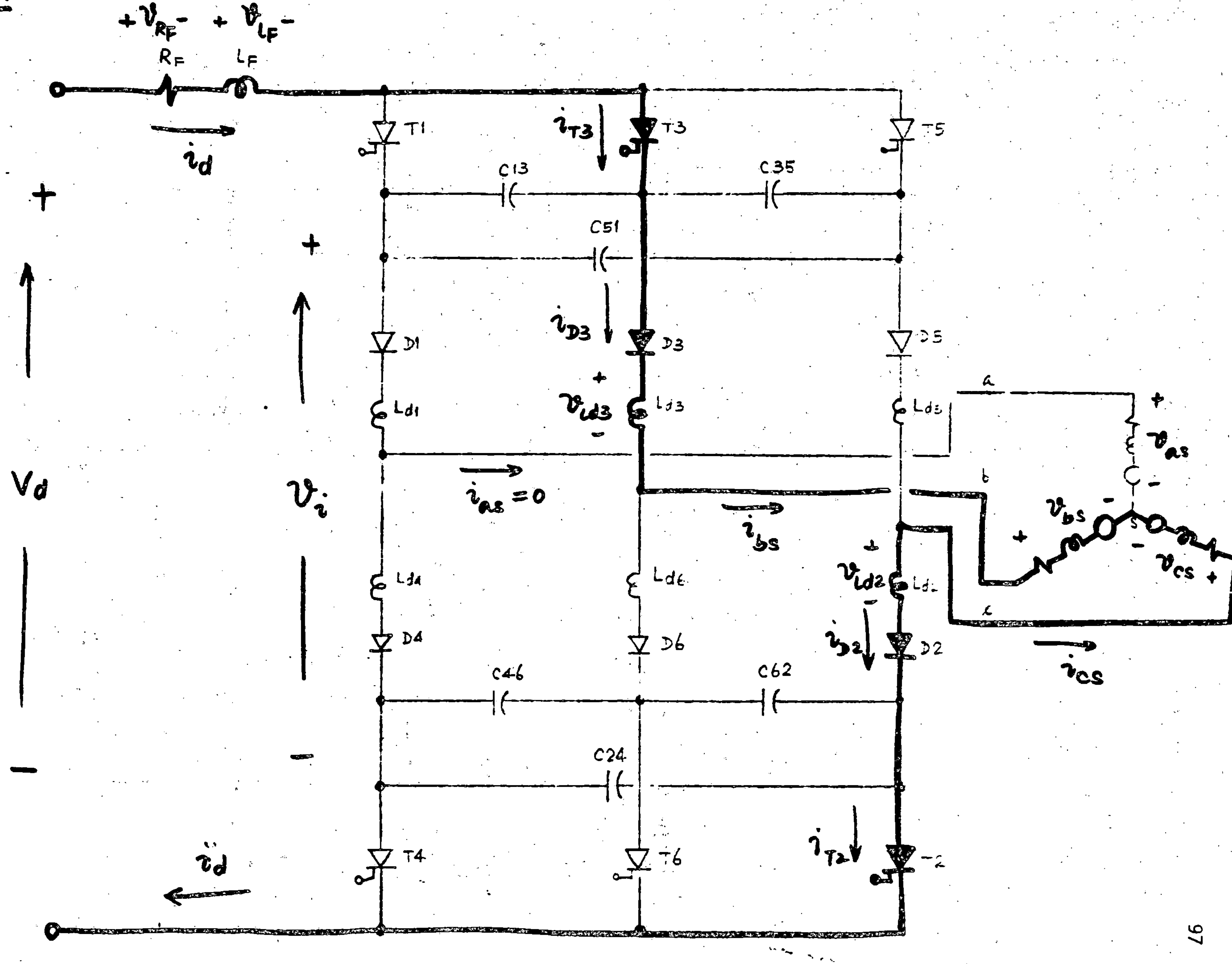


Fig F10

mode 10

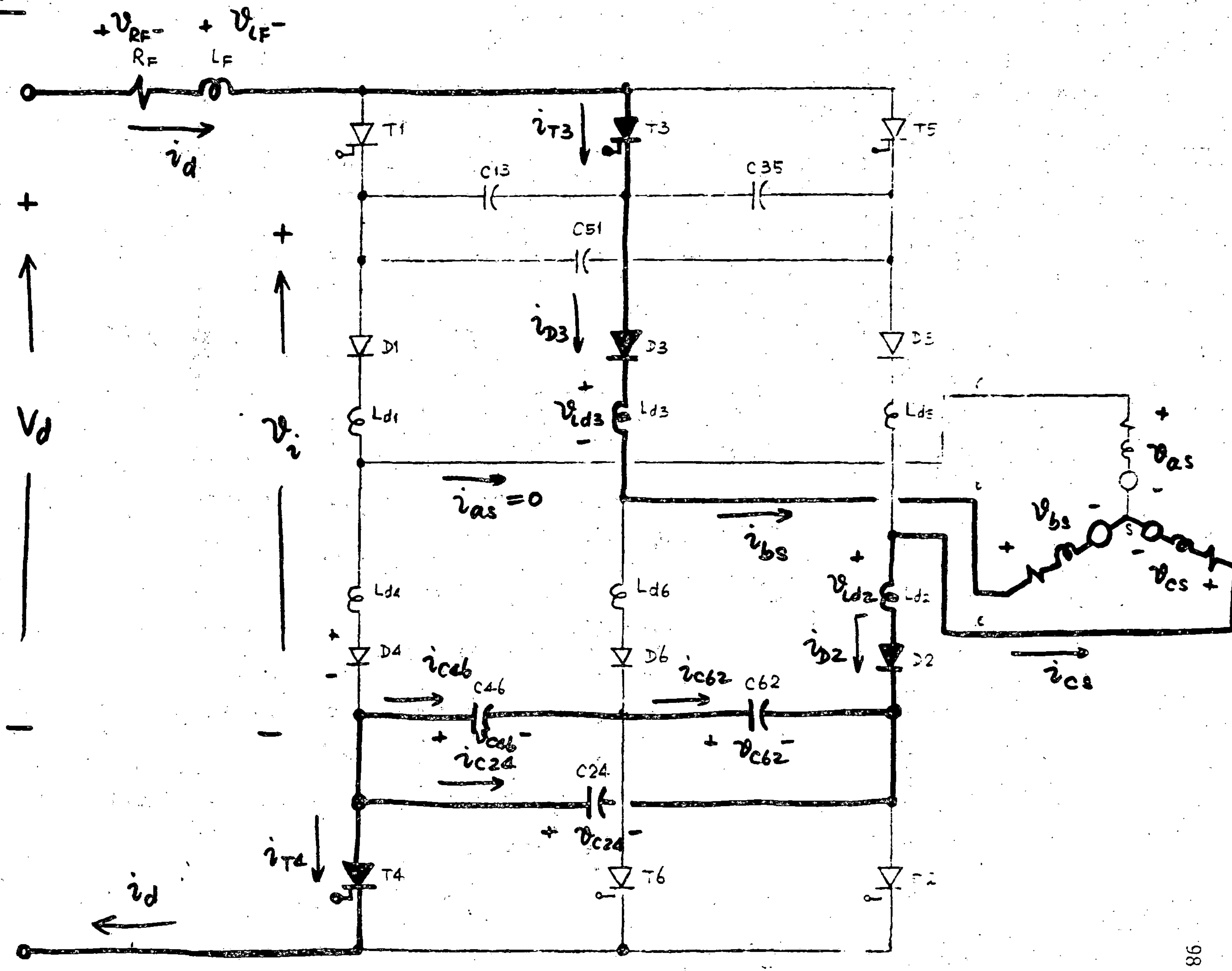


Fig. F11

mode 11

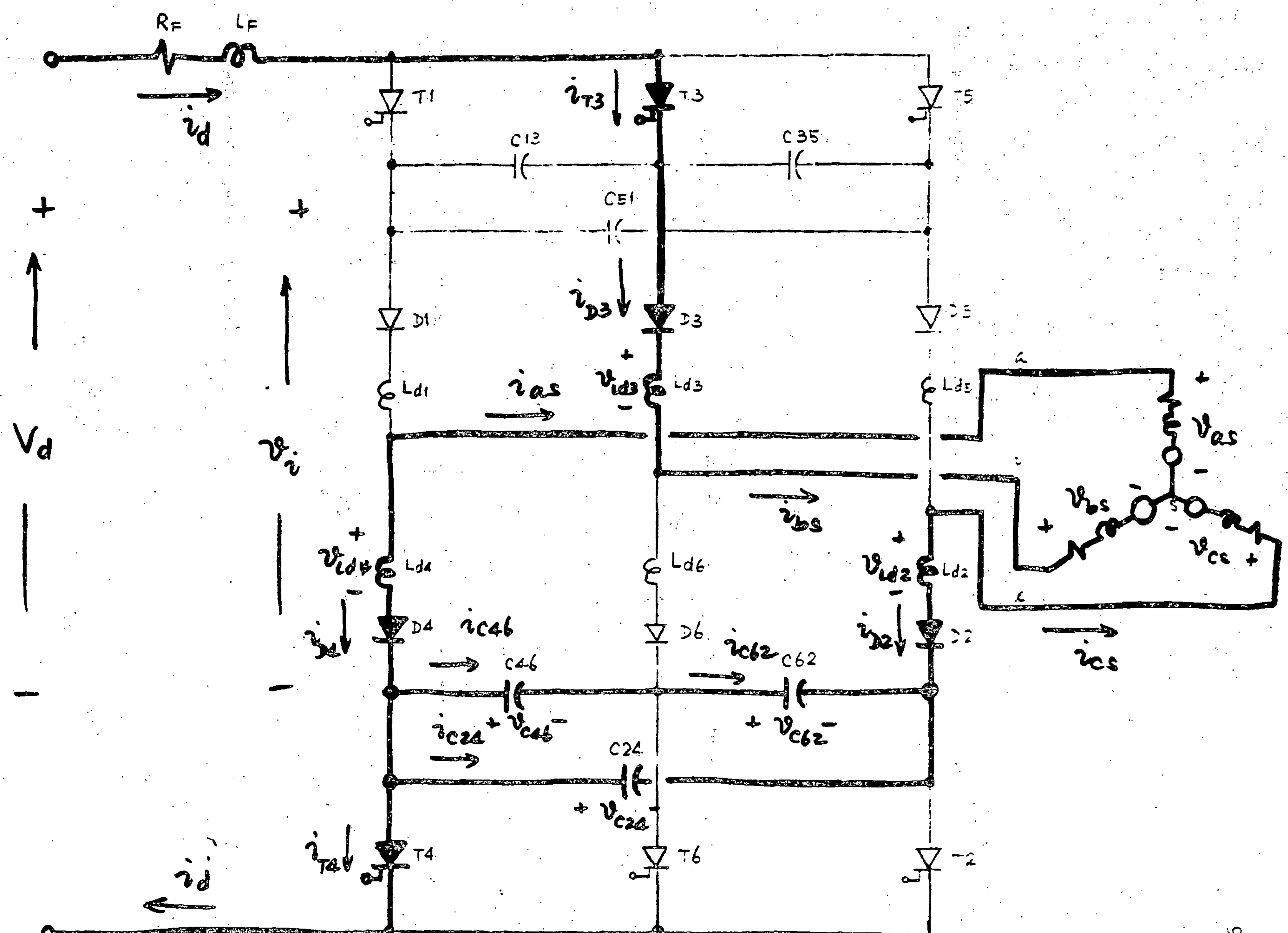


Fig. F12

mode 12

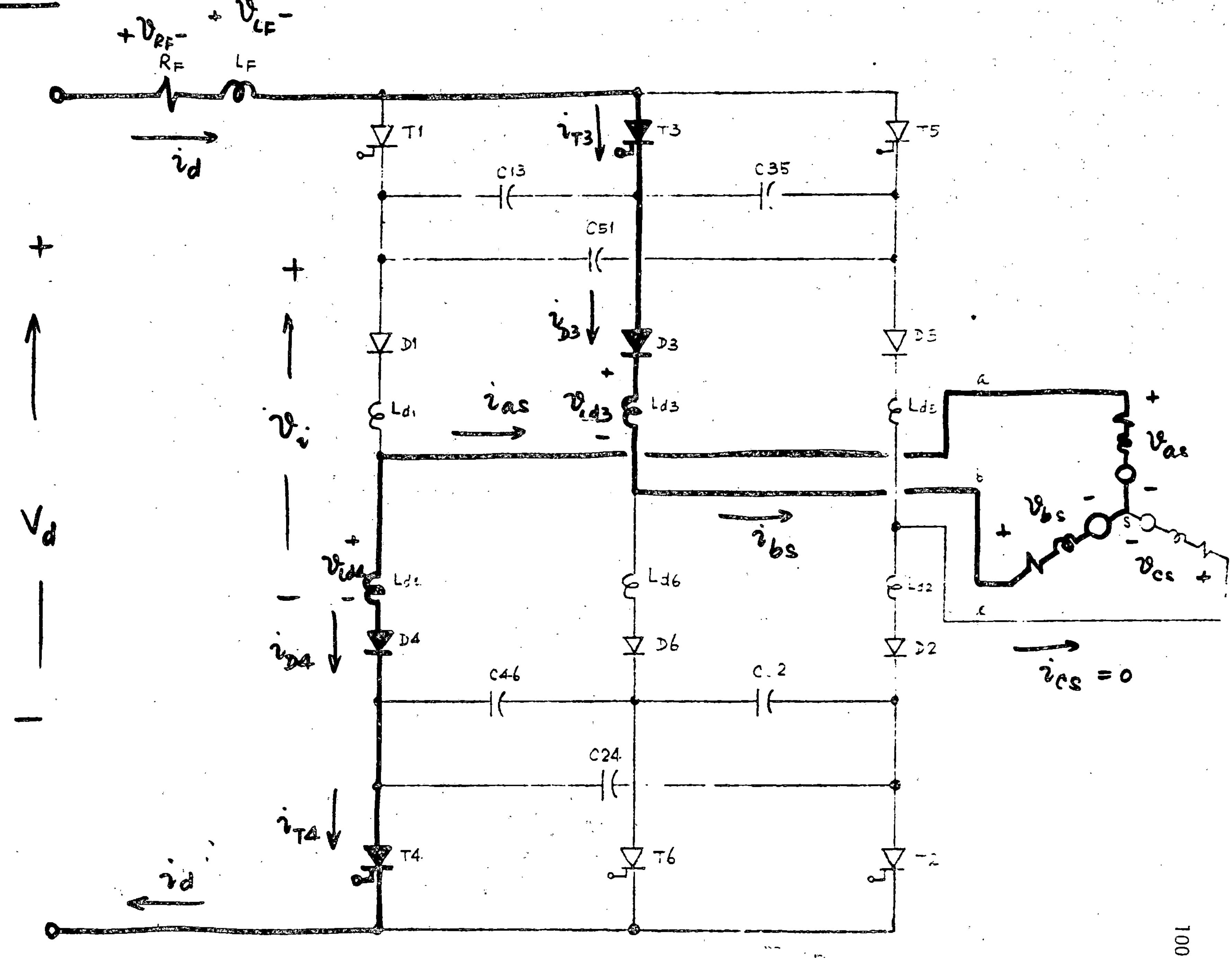


Fig.F13

mode 13

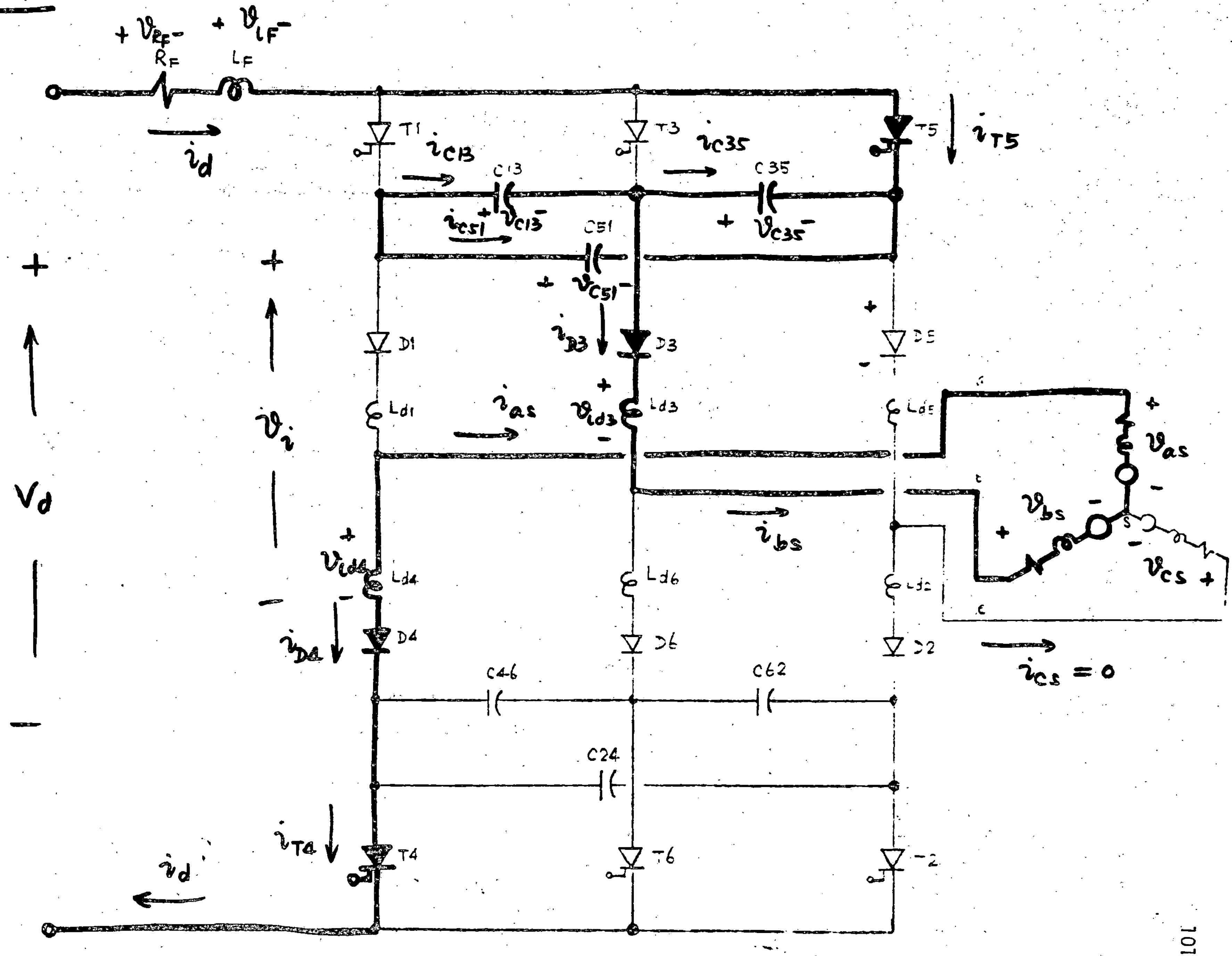


Fig. F14

mode 14

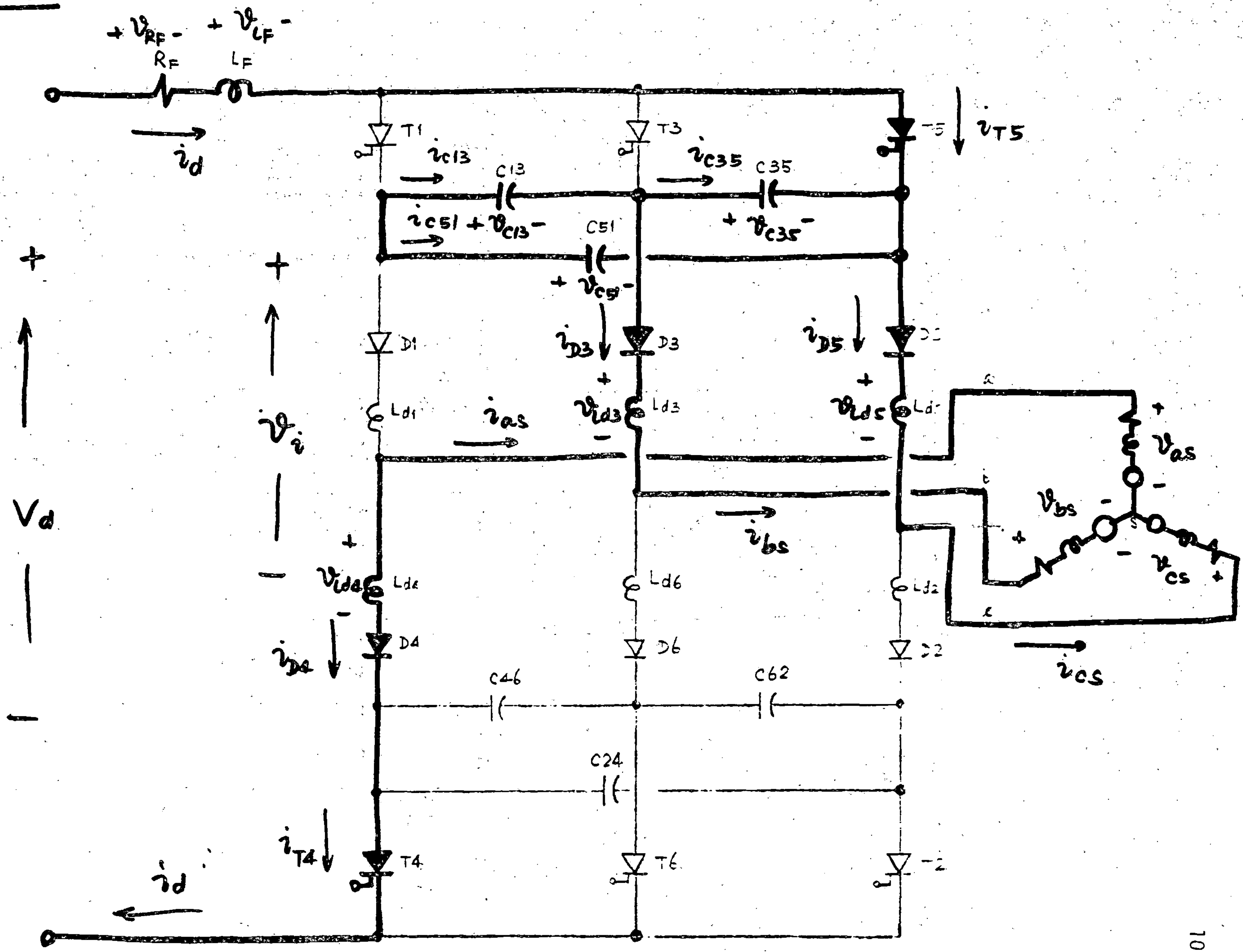


Fig.F15

mode 15

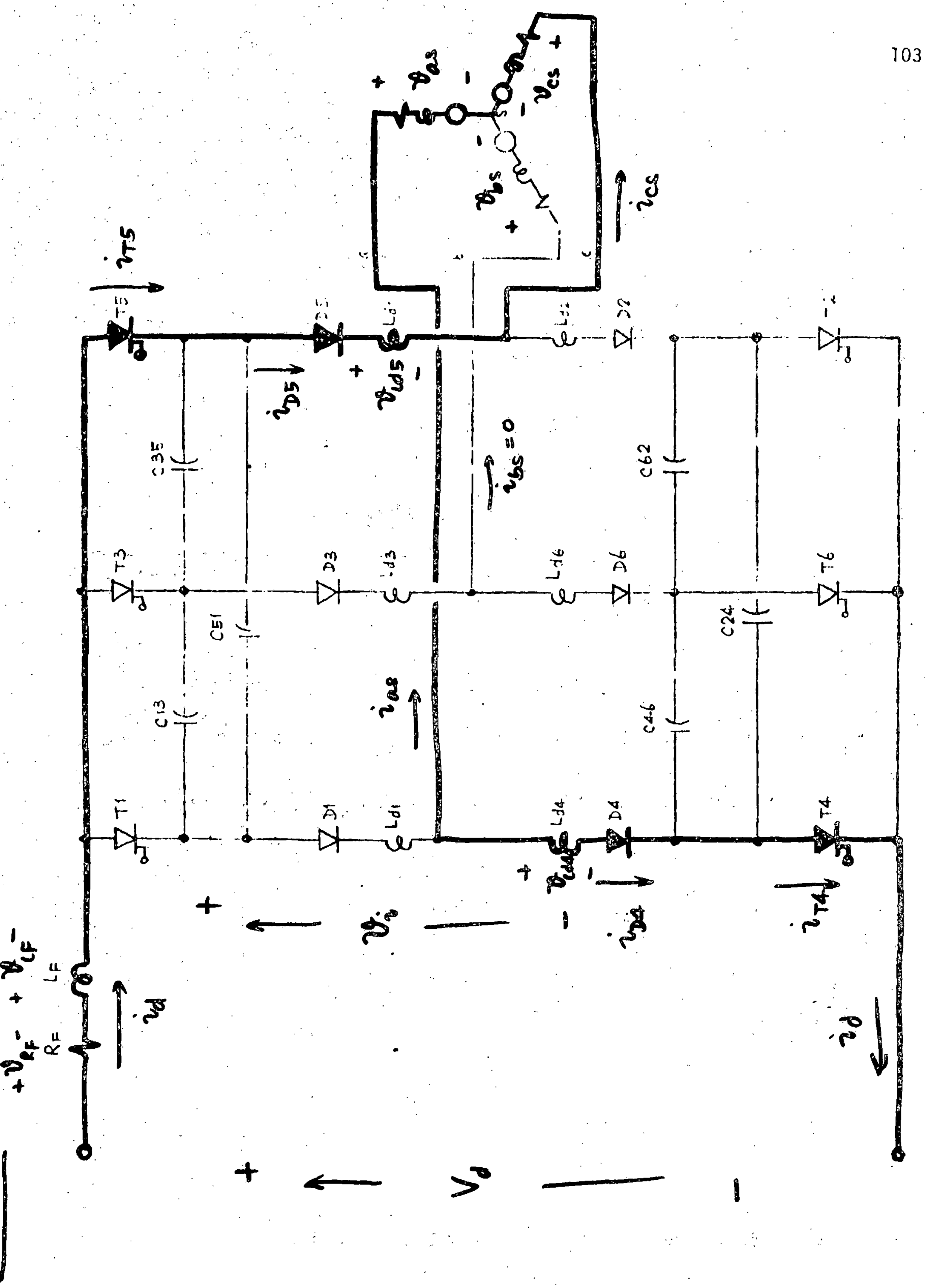


Fig. F16

mode 16

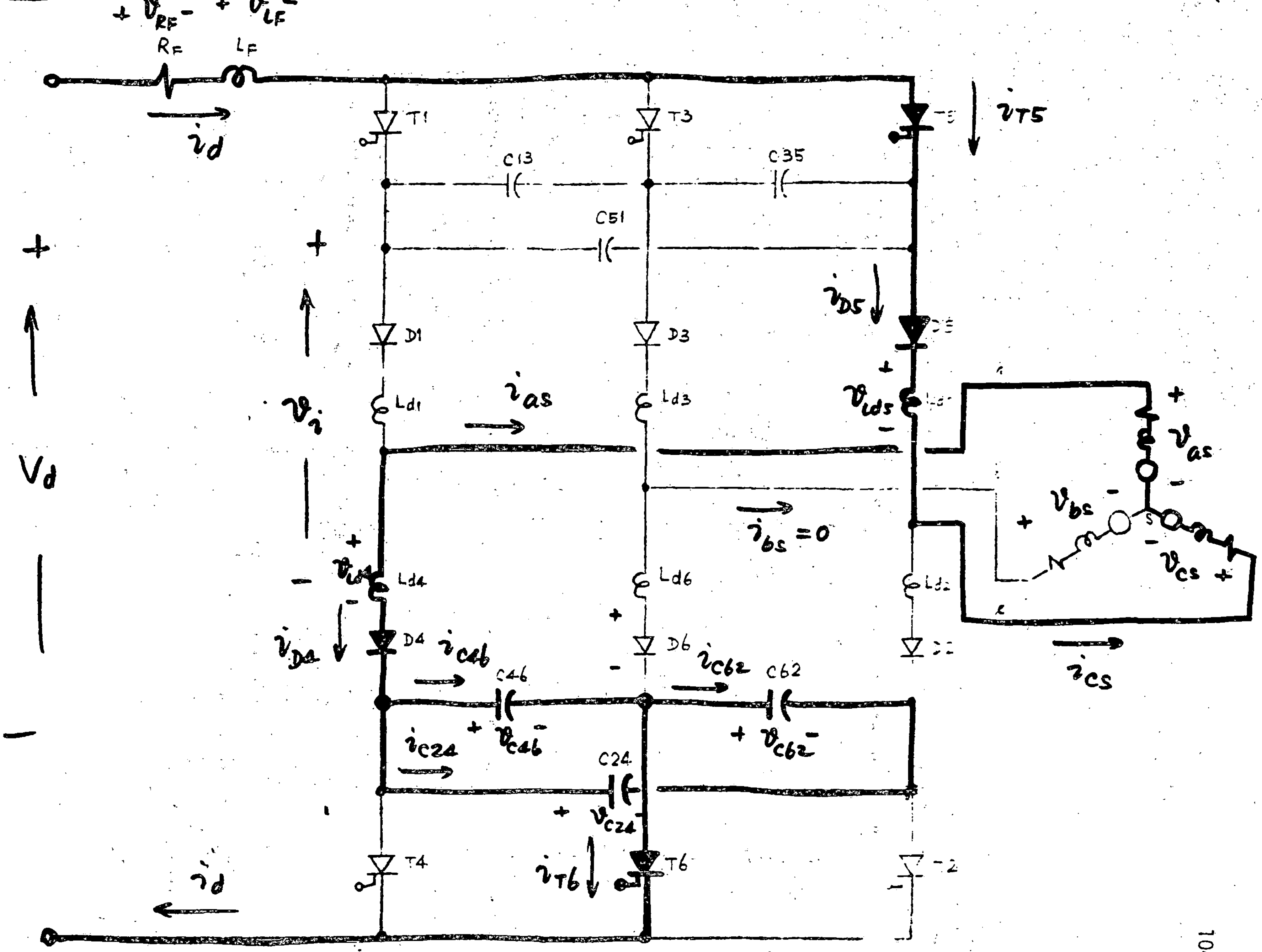


Fig. FL 7

mode 17

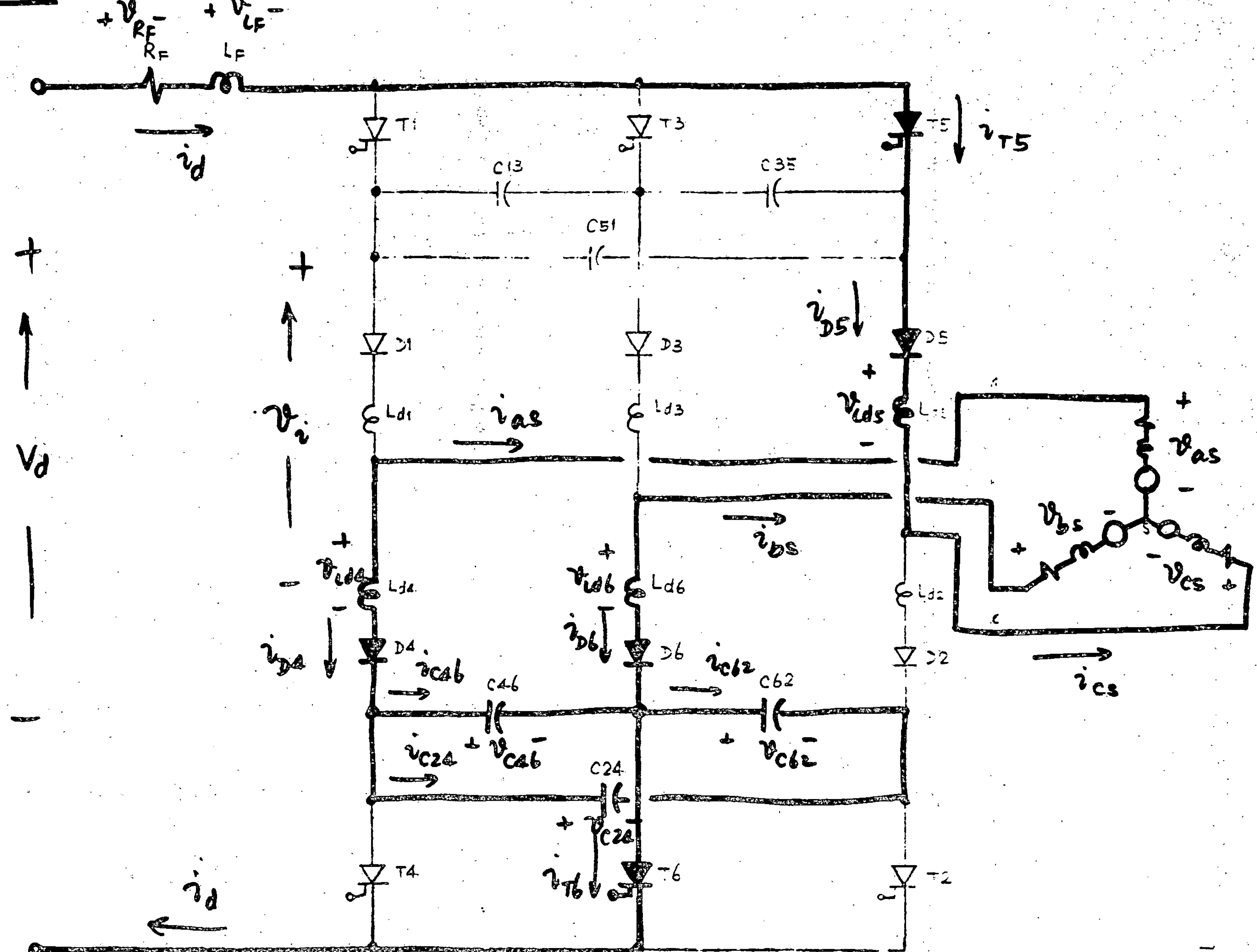


Fig. F18

mode 18

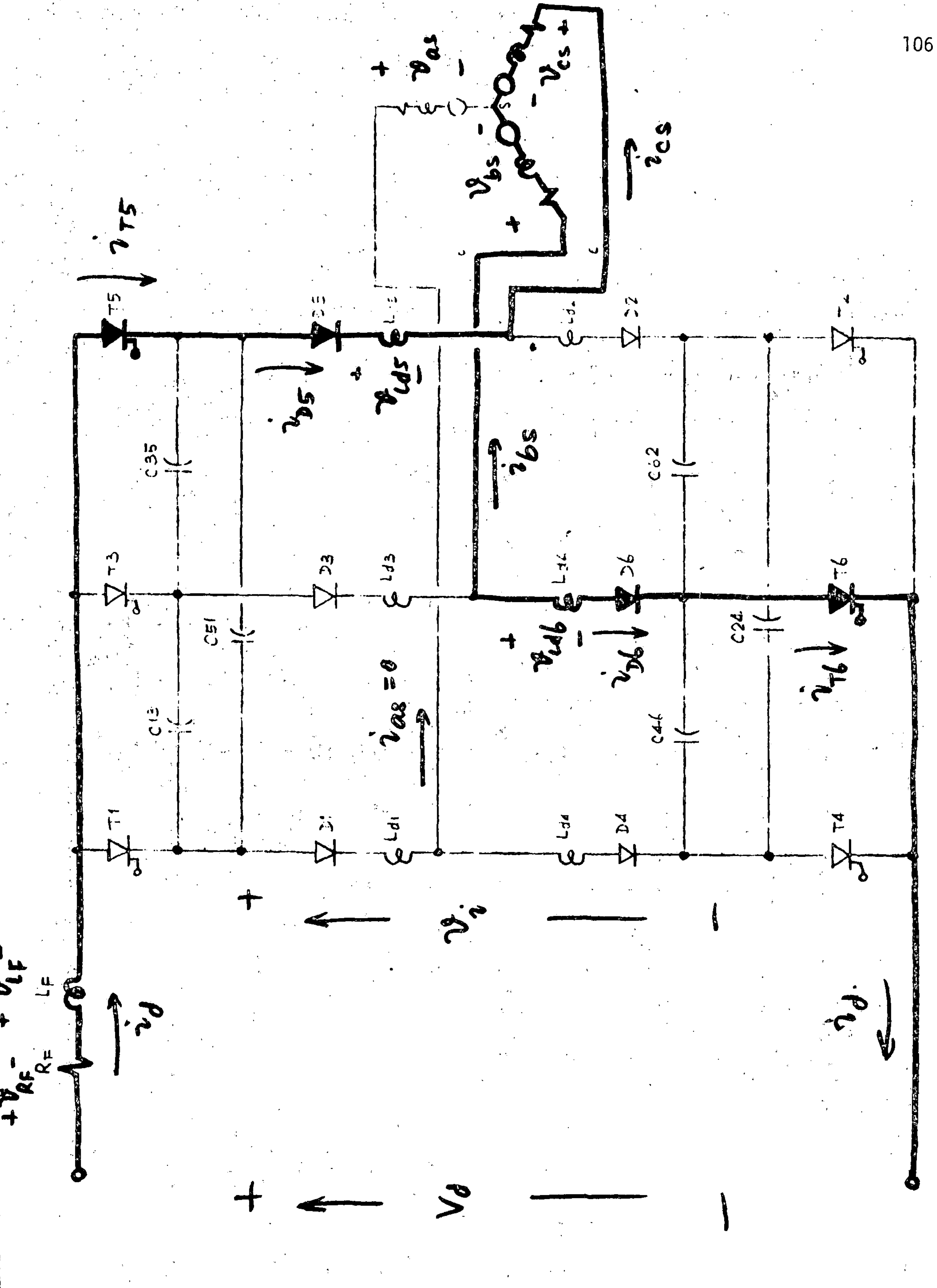


Fig. F1.9

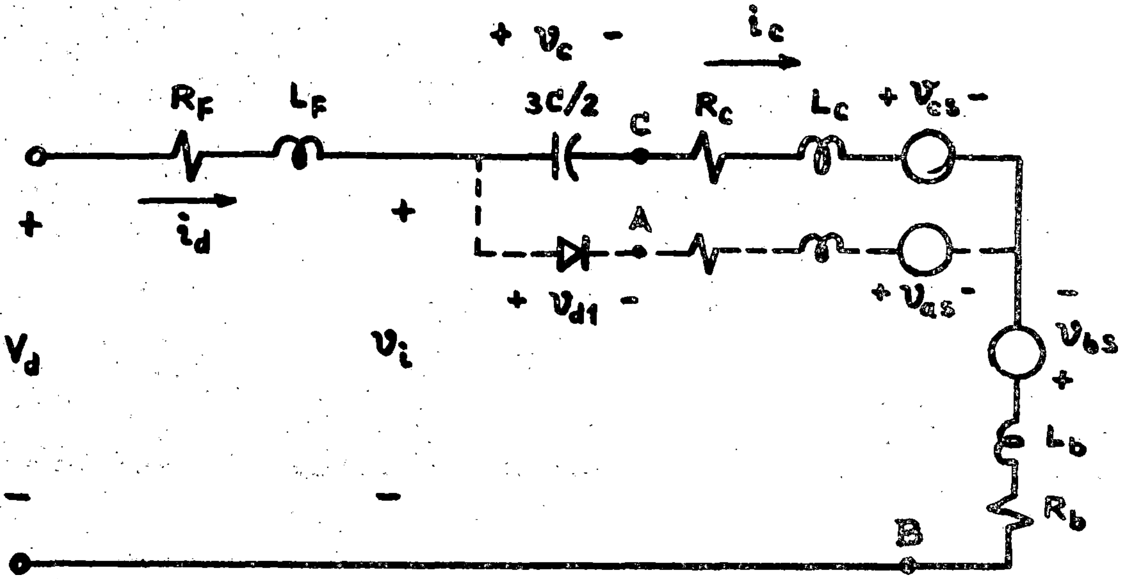


Fig.F20 : The equivalent circuit of mode 1.

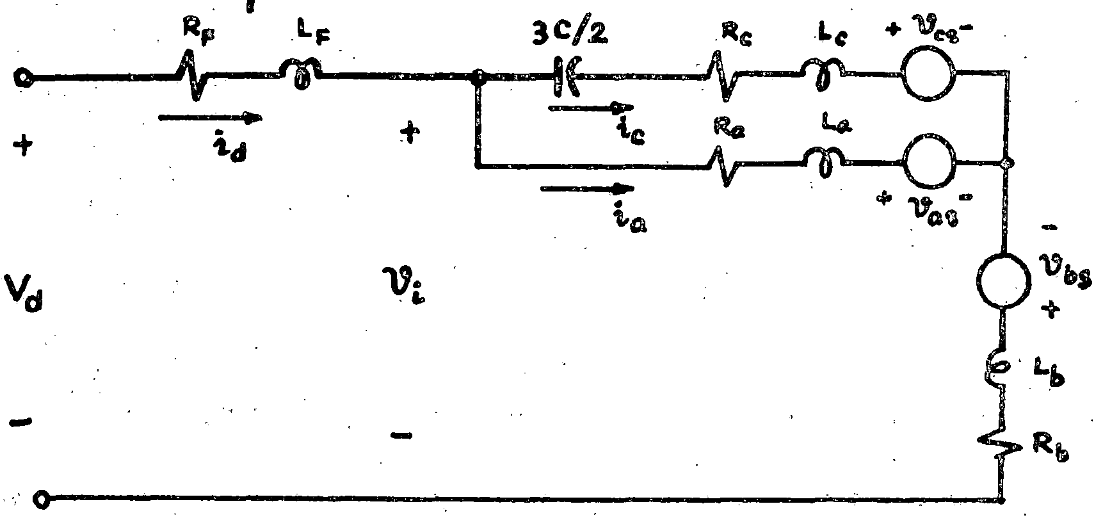


Fig. F21 : The equivalent circuit of mode 2.

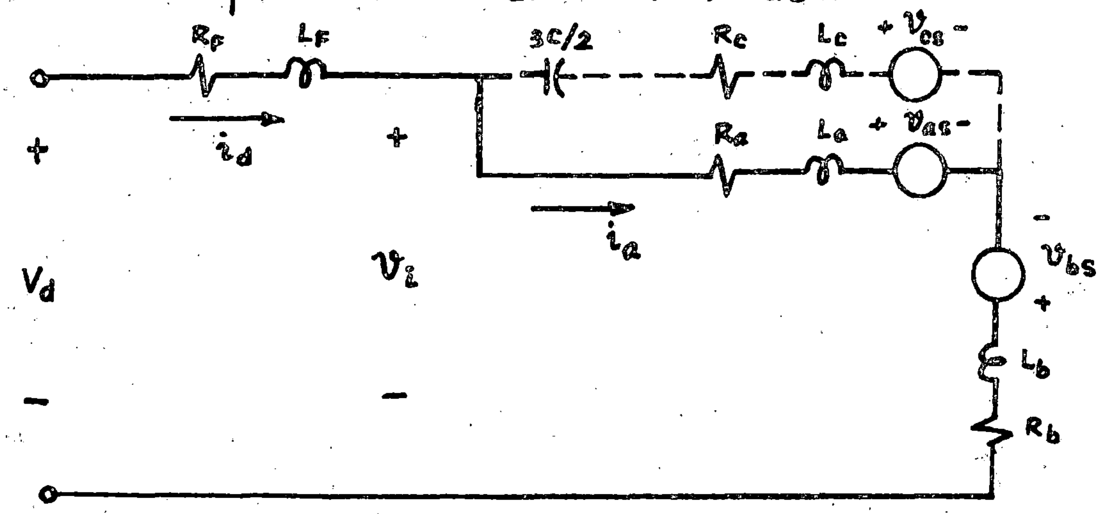


Fig. F22 : The equivalent circuit of mode 3.

The corresponding equations for the circuit shown in Fig. F21 can be written as

$$v_{ab} = A5 \times i_a + B4 \times \frac{di_a}{dt} + RB \times i_c + LB \times \frac{di_c}{dt} + v_{as} - v_{bs}$$

$$v_{bc} = -A2 \times i_c - B2 \times \frac{di_c}{dt} - RB \times i_a - LB \times \frac{di_a}{dt} + v_{bs} - v_{cs}$$

$$v_{ca} = -v_c$$

$$v_i = v_{ab}$$

$$i_d = i_c + i_a$$

$$\frac{di_c}{dt} = (V_d - D2 \times (v_c + v_{cs}) + D1 \times v_{as} + v_{bs} - A3 \times i_c - A4 \times i_a)/B3$$

$$\frac{di_a}{dt} = (v_c + v_{cs} - v_{as} + RC \times i_c - RA \times i_a + LC \times \frac{di_c}{dt})/LA$$

$$\frac{dv_c}{dt} = \frac{2}{3C} \times i_c$$

Finally, the equations for the circuit shown in Fig. F22 can be written as

$$v_{ab} = A5 \times i_a + B4 \times \frac{di_a}{dt} + v_{as} - v_{bs}$$

$$v_{bc} = -RB \times i_a - LB \times \frac{di_a}{dt} + v_{bs} - v_{cs}$$

$$v_{ca} = v_{cs} - v_{as} - LA \times \frac{di_a}{dt} - RA \times i_a$$

$$v_i = v_{ab}$$

$$i_d = i_a$$

$$\frac{di_a}{dt} = (V_d - v_{as} + v_{bs} - A6 \times i_a)/B5$$

The preceding derivation is based on the following assumptions:

1. No commutation overlap.
2. The motor CEMF's (v_{as}, v_{bs}, v_{cs}) are pure sinusoidal voltage sources caused by the fundamental components of the input currents i_a, i_b and i_c respectively.
3. The SCR's are considered as ideal switches.

The remaining problem is to determine the magnitude of the motor CEMF's. Based on assumption 3, v_{as}, v_{bs} and v_{cs} can be written as

$$v_{as} = v_{pk} \sin (\omega t + \theta_A - 2\pi/3)$$

$$v_{bs} = v_{pk} \sin (\omega t + \theta_A + 2\pi/3)$$

$$\text{and} \quad v_{cs} = v_{pk} \sin (\omega t + \theta_A)$$

The derivations of v_{pk} and θ_A are shown in the sequence of figures starting from Fig. F23 through Fig. F25.

A CSMP program has been developed to simulate the operation of modes 1-3 in order to study the peak voltage and time to complete commutation with a given set of circuit parameters. The program listing and results of this simulation are shown at the end of this appendix.

Since steady state is assumed, initial condition and final states have to be compared before a meaningful simulation can be judged. Some of the problems concerning the digital simulation are discussed in the following paragraph.

Since the operation of the CSI is highly dependent on load conditions, the simulation of the system cannot be separated into an inverter part and a motor part as was done in the VSI analysis. The complexity of the system creates problems for a straightforward simulation approach. It is desirable to study the effects of power circuit parameters without worrying about the closed-loop control. However, since the CSI has a self-feedback characteristic, it has a high tendency of becoming unstable with open-loop simulation. Since the objective of the analysis in this phase is to study the response of the power circuit for a set of parameters and load conditions, the closed-loop system will be avoided. The problem of instability is solved by selecting a proper set of initial conditions for a few cycles of simulation.

Developed torque is a direct function of currents. With the current source inverter, more direct control of the torque can be achieved. However, the six-step current waveform is generally employed. Thus, the currents contain larger harmonics than those of a PWM voltage source.

Regenerative capability can be achieved without much additional effort for the CSI together with a phase controlled rectifier. However, this advantage will be nullified if it is applied to the diesel electric system, where it is not possible to feed power back into the ac source.

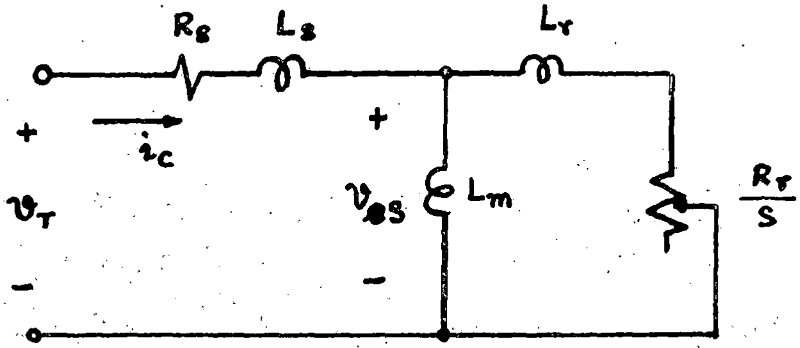


Fig. F23 : Equivalent circuit of an induction motor.

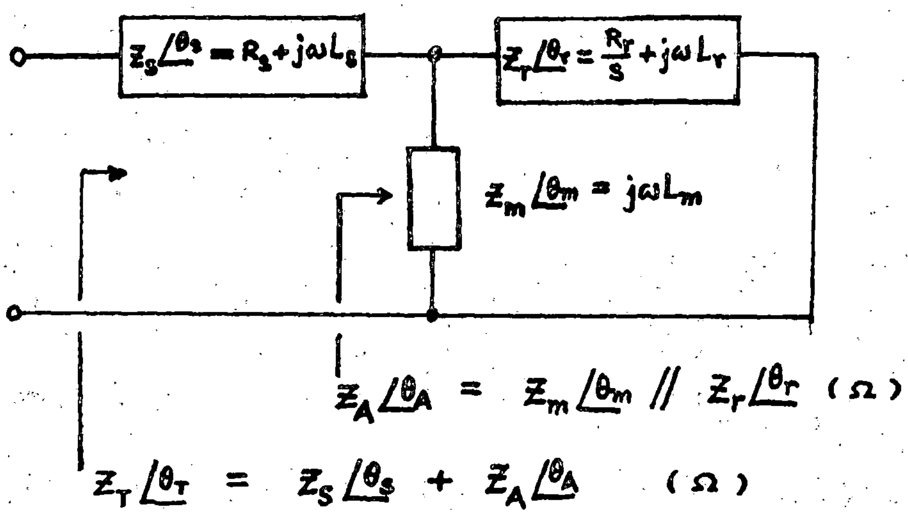


Fig. F24 : The equivalent ckt in impedance form.

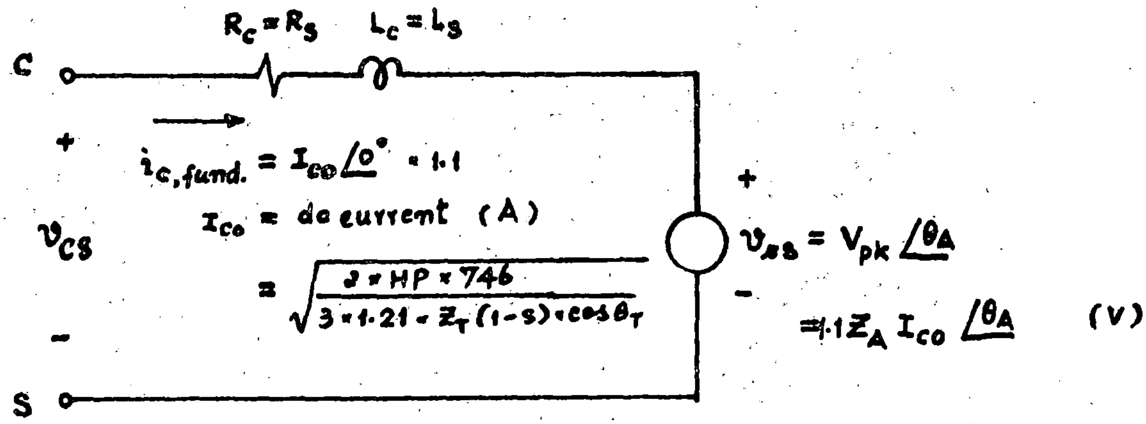


Fig. F25 : The equivalent ckt of phase C of an induction motor as seen from the inverter output.

Due to the auto-sequential commutation characteristic of the ASCI, the control circuit will be simpler than that of a PWM VSI. This consideration does not include the increased difficulty in the design of a stable control policy.

```
****CONTINUOUS SYSTEM MODELING PROGRAM****

*** VERSION 1.3 ***

TITLE COMMUTATION CHARACTERISTIC OF CSI-IM
INITIAL
    PARAMETER RR=0.1732,RS=0.3523,XMS=15.9276,XLS=0.6045,...
              KK=(0.2,0.25,0.3,0.35,0.4,0.45),...
              XLR=0.2512,FB=60.0,FE=60.0,VD=1500.0,RF=0.01,LF=500.0
    CONSTANT  PI=3.1415927,PI2=6.2831853,SQRT2=1.415927,...
              SQRT3=1.7320508
    INCON     M1=1,M2=0,M3=0,IA0=0,VC0=-2800.0
*  COMPUTE LM,LS,LR
        LM=XMS/(PI2*FB)
        LS=XLS/(PI2*FB)
        LR=XLR/(PI2*FB)
*  ASSIGN MORE PARAMETERS
        W=PI2*FE
        ONE6=1.0/(6.0*FE)
        S=0.05
        HP=600.0
        PHI=PI2/3.0
        K=1.11
        RA=RS
        RB=RS
        RC=RS
        LA=LS
        LB=LS
        LC=LS
*  COMPUTE VAS0,VBS0,VCS0
        ZS=SQRT((RR/S)**2+(W*LR+W*LM)**2)
        THETAS=ATAN(W*(LR+LM)*S/RS)
        ZM=W*LM
        THETAM=PI/2.0
        ZR=SQRT((RR/S)**2+(W*LR)**2)
        THETAR=ATAN(W*LR*S/RR)
        ZA=ZM*ZR/ZS
        THETAA=THETAM+THETAR-THETAS
        RAA=ZA*COS(THETAA)
        WLA=ZA*SIN(THETAA)
        ZT=SQRT((RAA+RS)**2+(W*LS+WLA)**2)
        THETAT=ATAN((W*LS+WLA)/(RAA+RS))
        IC0=SQRT(HP*746.0/(3.0*ZT*(1.0-S)*COS(THETAT)))*SQRT2/K
        VPK=ZA*IC0
        VAS0=VPK*SIN(PHI-PI2/3.0+THETAA)
        VBS0=VPK*SIN(PHI+PI2/3.0+THETAA)
        VCS0=VPK*SIN(PHI+THETAA)
        A1=RF+RC+RB
        A2=RC+RB
        A3=(RF+RB+RC+RC*(LF+LB)/LA)
        A4=(RF+RB-RA*(LF+LB)/LA)
        A5=RA+RB
        A6=RF+RA+RB
        B1=LF+LC+LB
        B2=LC+LB
        B3=(LF+LB+LC+LC*(LF+LB)/LA)
        B4=LA+LB
        B5=LF+LA+LB
        D1=(LF+LB)/LA
        D2=1.0+D1
```

E-3

```
*  DETERMINE C
      C=-PI*ICO/(12.0*W*VCO)*KK
      VD1=VCO+RC*ICO+VCSO-VASO
      IC=ICO
      M1=1
      M2=0
      M3=0
*
*
DYNAMIC
    NOSORT
      IF(VD1.GT.1.0) GO TO 102
      IF(IC.LT.0.0) GO TO 103
      GO TO 101
  102 M1=0
      M2=1
      M3=0
      GO TO 101
  103 M1=0
      M2=0
      M3=1
  101 CONTINUE
    SORT
      VAS=VPK*SIN(W*TIME+PHI-PI2/3.0+THETAA)
      VBS=VPK*SIN(W*TIME+PHI+PI2/3.0+THETAA)
      VCS=VPK*SIN(W*TIME+PHI+THETAA)
      VDC=M1*(A1*IC+B1*ICDOT+VC+VCS-VBS)...
         +M2*(A3*IC+B3*ICDOT+A4*IA+D2*(VC+VCS)-D1*VAS-VBS)...
         +M3*(A6*IA+B5*IADOT+VAS-VBS)
      VAB=M1*(VAS-VBS+LB*ICDOT+RB*IC)...
         +M2*(A5*IA+B4*IADOT+RB*IC+LB*ICDOT+VAS-VBS)...
         +M3*(A5*IA+B4*IADOT+VAS-VBS)
      VBC=M1*(-A2*IC-B2*ICDOT+VBS-VCS)...
         +M2*(-A2*IC-B2*ICDOT-RB*IA-LB*IADOT+VBS-VCS)...
         +M3*(-RB*IA-LB*IADOT+VBS-VCS)
      VCA=M1*(RC*IC+LC*ICDOT+VCS-VAS)...
         +M2*(-VC)+M3*(VCS-VAS-LA*IADOT-RA*IA)
      VI=M1*(VC-VBC)+M2*VAB+M3*VAB
      VD1=M1*(VC+RC*IC+LC*ICDOT+VCS-VAS)
      ID=M1*IC+M2*(IC+IA)+M3*IA
      IADOT=M2*((VC+VCS-VAS+RC*IC-RA*IA+LC*ICDOT)/LA)...
           +M3*((VD-VAS+VBS-A6*IA)/B5)
      ICDOT=M1*(VD-VC-VCS+VBS-A1*IC)/B1...
           +M2*(VD-D2*(VC+VCS)+D1*VAS+VBS-A3*IC-A4*IA)/B3
      VCDOT=2.0*IC/(3.0*C)
      IC=INTGRL(ICO,ICDOT)
      IA=INTGRL(IAO,IADOT)
      VC=INTGRL(VCO,VCDOT)
*
*
TERMINAL
    METHOD RKSFX
    TIMER DELT=1.0E-6,FINTIM=2.78E-3,OUTDEL=60.0E-6
    PRTPLOT VBC(M1,M2,M3)
    PRTPLOT VAB(VAS,VBS,VCS)
    PRTPLOT VI(ID,VDC,M2)
    PRTPLOT VC(IC,IA,M2)
    PRTPLOT IC(ICDOT,IADOT,M2)
    PRTPLOT VCA(VD1,KK)
    END
```

*** CSMP/360 SIMULATION DATA ***

```
TITLE COMMUTATION CHARACTERISTIC OF CSI-IM

    PARAMETER RR=0.1732,RS=0.3523,XMS=15.9276,XLS=0.6045,...

              KK=(0.2,0.25,0.3,0.35,0.4,0.45),...

              XLR=0.2512,FB=60.0,FE=60.0,VD=1500.0,RF=0.01,LF=500.0E-3

    CONSTANT  PI=3.1415927,PI2=6.2831853,SQRT2=1.415927,...

              SQRT3=1.7320508

    INCON     M1=1,M2=0,M3=0,IA0=0,VC0=-2800.0

    METHOD RKSFX

    TIMER DELT=1.0E-6,FINTIM=2.78E-3,OUTDEL=60.0E-6

    PRTPLOT VBC(M1,M2,M3)

    PRTPLOT VAB(VAS,VBS,VCS)

    PRTPLOT VI(ID,VDC,M2)

    PRTPLOT VC(IC,IA,M2)

    PRTPLOT IC(ICDOT,IADOT,M2)

    PRTPLOT VCA(VD1,KK)

    END


TIMER VARIABLES
 DELT   = 1.0000E-06
 DELMIN= 2.7800E-10
 FINTIM= 2.7600E-03
 PRDEL = 0.0
 OUTDEL= 6.0000E-05
```

PROBLEM DURATION 0.0 TO 2.7600E-03

VARIABLE	MINIMUM	TIME	MAXIMUM	TIME
VBC	-1.6370E+03	0.0	2.7714E+02	6.2900E-04
VAB	1.4656E+03	0.0	3.2852E+03	6.2500E-04
VI	-1.1630E+03	0.0	3.2852E+03	6.2500E-04
VC	-2.8000E+03	0.0	3.5736E+03	2.7600E-03
IC	1.1262E-01	6.3000E-04	2.7825E+02	1.9400E-04
VCA	-3.5621E+03	6.2900E-04	1.7145E+02	0.0

```
                         MINIMUM                  VBC     VERSUS TIME
                        -1.6370E+03               KK     = 2.0000E-01
 TIME          VBC          I
0.0           -1.6370E+03   +
6.0000E-05    -1.6149E+03   +
1.2000E-04    -1.5920E+03   -+
1.8000E-04    -1.5683E+03   -+
2.4000E-04    -1.3226E+03   --------+
3.0000E-04    -9.2783E+02   ------------------+
3.6000E-04    -5.6438E+02   ----------------------------+
4.2000E-04    -2.5030E+02   ------------------------------------+
4.8000E-04    -6.7480E-01   ----------------------------------------
5.4000E-04     1.7311E+02   ----------------------------------------
6.0000E-04     2.6392E+02   ----------------------------------------
6.6000E-04    -1.2933E+03   --------+
7.2000E-04    -1.2686E+03   ---------+
7.8000E-04    -1.2434E+03   ----------+
8.4000E-04    -1.2175E+03   ----------+
9.0000E-04    -1.1911E+03   -----------+
9.6000E-04    -1.1641E+03   ------------+
1.0200E-03    -1.1366E+03   -------------+
1.0800E-03    -1.1086E+03   -------------+
1.1400E-03    -1.0800E+03   --------------+
1.2000E-03    -1.0509E+03   ---------------+
1.2600E-03    -1.0214E+03   ----------------+
1.3200E-03    -9.9138E+02   ----------------+
1.3800E-03    -9.6090E+02   -----------------+
1.4400E-03    -9.2999E+02   ------------------+
1.5000E-03    -8.9864E+02   -------------------+
1.5600E-03    -8.6690E+02   --------------------+
1.6200E-03    -8.3476E+02   --------------------+
1.6800E-03    -8.0224E+02   ---------------------+
1.7400E-03    -7.6937E+02   ----------------------+
1.8000E-03    -7.3616E+02   -----------------------+
1.8600E-03    -7.0262E+02   ------------------------+
1.9200E-03    -6.6877E+02   -------------------------+
1.9800E-03    -6.3463E+02   --------------------------+
2.0400E-03    -6.0022E+02   ---------------------------+
2.1000E-03    -5.6556E+02   ---------------------------+
2.1600E-03    -5.3065E+02   ----------------------------+
2.2200E-03    -4.9554E+02   -----------------------------+
2.2800E-03    -4.6022E+02   ------------------------------+
2.3400E-03    -4.2471E+02   -------------------------------+
2.4000E-03    -3.8905E+02   --------------------------------+
2.4600E-03    -3.5323E+02   ---------------------------------+
2.5200E-03    -3.1729E+02   ----------------------------------+
2.5800E-03    -2.8124E+02   -----------------------------------+
2.6400E-03    -2.4509E+02   ------------------------------------+
2.7000E-03    -2.0837E+02   -------------------------------------+
2.7600E-03    -1.7259E+02   --------------------------------------+
```

MAXIMUM
2.7714E+02

I	M1	M2	M3
	1.0000E+00	0.0	0.0
	1.0000E+00	0.0	0.0
	1.0000E+00	0.0	0.0
	1.0000E+00	0.0	0.0
	0.0	1.0000E+00	0.0
	0.0	1.0000E+00	0.0
	0.0	1.0000E+00	0.0
	0.0	1.0000E+00	0.0
---+	0.0	1.0000E+00	0.0
---------+	0.0	1.0000E+00	0.0
-----------+	0.0	1.0000E+00	0.0
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00

```
                              MINIMUM                  VBC     VERSUS TIME
                            -1.6370E+03                KK      = 3.0000E-01
 TIME             VBC           I
0.0           -1.6370E+03    +
6.0000E-05    -1.6166E+03    +
1.2000E-04    -1.5955E+03    -+
1.8000E-04    -1.5736E+03    -+
2.4000E-04    -1.5509E+03    --+
3.0000E-04    -1.5276E+03    --+
3.6000E-04    -1.3171E+03    --------+
4.2000E-04    -1.0503E+03    ---------------+
4.8000E-04    -7.9839E+02    ---------------------+
5.4000E-04    -5.6930E+02    ---------------------------+
6.0000E-04    -3.7017E+02    ---------------------------------+
6.6000E-04    -2.0691E+02    -------------------------------------+
7.2000E-04    -8.4041E+01    ---------------------------------------
7.8000E-04    -4.5645E+00    ---------------------------------------
8.4000E-04     3.0148E+01    ---------------------------------------
9.0000E-04    -1.1913E+03    -----------+
9.6000E-04    -1.1643E+03    ------------+
1.0200E-03    -1.1368E+03    -------------+
1.0800E-03    -1.1087E+03    -------------+
1.1400E-03    -1.0802E+03    --------------+
1.2000E-03    -1.0511E+03    ---------------+
1.2600E-03    -1.0215E+03    ----------------+
1.3200E-03    -9.9153E+02    ----------------+
1.3800E-03    -9.6105E+02    -----------------+
1.4400E-03    -9.3014E+02    ------------------+
1.5000E-03    -8.9879E+02    -------------------+
1.5600E-03    -8.6705E+02    --------------------+
1.6200E-03    -8.3491E+02    --------------------+
1.6800E-03    -8.0239E+02    ---------------------+
1.7400E-03    -7.6952E+02    ----------------------+
1.8000E-03    -7.3631E+02    -----------------------+
1.8600E-03    -7.0277E+02    ------------------------+
1.9200E-03    -6.6892E+02    -------------------------+
1.9800E-03    -6.3478E+02    --------------------------+
2.0400E-03    -6.0037E+02    ---------------------------+
2.1000E-03    -5.6571E+02    ---------------------------+
2.1600E-03    -5.3080E+02    ----------------------------+
2.2200E-03    -4.9569E+02    -----------------------------+
2.2800E-03    -4.6037E+02    ------------------------------+
2.3400E-03    -4.2486E+02    -------------------------------+
2.4000E-03    -3.8920E+02    --------------------------------+
2.4600E-03    -3.5338E+02    ---------------------------------+
2.5200E-03    -3.1744E+02    ----------------------------------+
2.5800E-03    -2.8139E+02    -----------------------------------+
2.6400E-03    -2.4524E+02    ------------------------------------+
2.7000E-03    -2.0902E+02    -------------------------------------+
2.7600E-03    -1.7274E+02    --------------------------------------+
```

MAXIMUM
2.7714E+02

I	M1	M2	M3
	1.0000E+00	0.0	0.0
	1.0000E+00	0.0	0.0
	1.0000E+00	0.0	0.0
	1.0000E+00	0.0	0.0
	1.0000E+00	0.0	0.0
	1.0000E+00	0.0	0.0
	0.0	1.0000E+00	0.0
	0.0	1.0000E+00	0.0
	0.0	1.0000E+00	0.0
	0.0	1.0000E+00	0.0
	0.0	1.0000E+00	0.0
	0.0	1.0000E+00	0.0
-+	0.0	1.0000E+00	0.0
---+	0.0	1.0000E+00	0.0
----+	0.0	1.0000E+00	0.0
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00
	0.0	0.0	1.0000E+00

```
                                                                                     PAGE    1

                                    MINIMUM              VBC     VERSUS TIME            MAXIMUM
                                  -1.6370E+03            KK    = 4.0000E-01           2.7714E+02
   TIME          VBC               I                                                    I         M1          M2          M3
 0.0           -1.6370E+03         +                                                           1.0000E+00  0.0         0.0
 6.0000E-05    -1.6175E+03         +                                                           1.0000E+00  0.0         0.0
 1.2000E-04    -1.5972E+03         -+                                                          1.0000E+00  0.0         0.0
 1.8000E-04    -1.5762E+03         -+                                                          1.0000E+00  0.0         0.0
 2.4000E-04    -1.5545E+03         --+                                                         1.0000E+00  0.0         0.0
 3.0000E-04    -1.5320E+03         --+                                                         1.0000E+00  0.0         0.0
 3.6000E-04    -1.5068E+03         ---+                                                        1.0000E+00  0.0         0.0
 4.2000E-04    -1.4850E+03         ---+                                                        1.0000E+00  0.0         0.0
 4.8000E-04    -1.3085E+03         --------+                                                   0.0         1.0000E+00  0.0
 5.4000E-04    -1.1051E+03         -------------+                                              0.0         1.0000E+00  0.0
 6.0000E-04    -9.0991E+02         ------------------+                                         0.0         1.0000E+00  0.0
 6.6000E-04    -7.2751E+02         -----------------------+                                    0.0         1.0000E+00  0.0
 7.2000E-04    -5.6199E+02         ----------------------------+                               0.0         1.0000E+00  0.0
 7.8000E-04    -4.1691E+02         -------------------------------+                            0.0         1.0000E+00  0.0
 8.4000E-04    -2.9524E+02         -----------------------------------+                        0.0         1.0000E+00  0.0
 9.0000E-04    -1.9924E+02         -------------------------------------+                      0.0         1.0000E+00  0.0
 9.6000E-04    -1.3046E+02         ---------------------------------------+                    0.0         1.0000E+00  0.0
 1.0200E-03    -8.9657E+01         ----------------------------------------+                   0.0         1.0000E+00  0.0
 1.0800E-03    -1.1089E+03         -------------+                                              0.0         0.0         1.0000E+00
 1.1400E-03    -1.0803E+03         --------------+                                             0.0         0.0         1.0000E+00
 1.2000E-03    -1.0512E+03         ---------------+                                            0.0         0.0         1.0000E+00
 1.2600E-03    -1.0217E+03         ----------------+                                           0.0         0.0         1.0000E+00
 1.3200E-03    -9.9165E+02         ----------------+                                           0.0         0.0         1.0000E+00
 1.3800E-03    -9.6118E+02         -----------------+                                          0.0         0.0         1.0000E+00
 1.4400E-03    -9.3026E+02         ------------------+                                         0.0         0.0         1.0000E+00
 1.5000E-03    -8.9892E+02         -------------------+                                        0.0         0.0         1.0000E+00
 1.5600E-03    -8.6717E+02         --------------------+                                       0.0         0.0         1.0000E+00
 1.6200E-03    -8.3503E+02         --------------------+                                       0.0         0.0         1.0000E+00
 1.6800E-03    -8.0252E+02         ---------------------+                                      0.0         0.0         1.0000E+00
 1.7400E-03    -7.6965E+02         ----------------------+                                     0.0         0.0         1.0000E+00
 1.8000E-03    -7.3643E+02         -----------------------+                                    0.0         0.0         1.0000E+00
 1.8600E-03    -7.0289E+02         ------------------------+                                   0.0         0.0         1.0000E+00
 1.9200E-03    -6.6904E+02         -------------------------+                                  0.0         0.0         1.0000E+00
 1.9800E-03    -6.3491E+02         --------------------------+                                 0.0         0.0         1.0000E+00
 2.0400E-03    -6.0050E+02         ---------------------------+                                0.0         0.0         1.0000E+00
 2.1000E-03    -5.6583E+02         ---------------------------+                                0.0         0.0         1.0000E+00
 2.1600E-03    -5.3093E+02         ----------------------------+                               0.0         0.0         1.0000E+00
 2.2200E-03    -4.9581E+02         -----------------------------+                              0.0         0.0         1.0000E+00
 2.2800E-03    -4.6049E+02         ------------------------------+                             0.0         0.0         1.0000E+00
 2.3400E-03    -4.2499E+02         -------------------------------+                            0.0         0.0         1.0000E+00
 2.4000E-03    -3.8932E+02         --------------------------------+                           0.0         0.0         1.0000E+00
 2.4600E-03    -3.5351E+02         ---------------------------------+                          0.0         0.0         1.0000E+00
 2.5200E-03    -3.1756E+02         ----------------------------------+                         0.0         0.0         1.0000E+00
 2.5800E-03    -2.8151E+02         -----------------------------------+                        0.0         0.0         1.0000E+00
 2.6400E-03    -2.4536E+02         ------------------------------------+                       0.0         0.0         1.0000E+00
 2.7000E-03    -2.0914E+02         -------------------------------------+                      0.0         0.0         1.0000E+00
 2.7600E-03    -1.7287E+02         --------------------------------------+                     0.0         0.0         1.0000E+00
```

```
                                    MINIMUM                   VAB    VERSUS TIME
                                   1.4656E+03                 KK     = 2.0000E-01
 TIME            VAB               I
0.0             1.4656E+03         +
6.0000E-05      1.4822E+03         +
1.2000E-04      1.4982E+03         +
1.8000E-04      1.5134E+03         -+
2.4000E-04      1.7512E+03         -------+
3.0000E-04      2.1384E+03         ------------------+
3.6000E-04      2.4930E+03         ----------------------------+
4.2000E-04      2.7973E+03         -------------------------------------+
4.8000E-04      3.0364E+03         --------------------------------------
5.4000E-04      3.1988E+03         --------------------------------------
6.0000E-04      3.2777E+03         --------------------------------------
6.6000E-04      1.7229E+03         -------+
7.2000E-04      1.7337E+03         -------+
7.8000E-04      1.7437E+03         -------+
8.4000E-04      1.7529E+03         -------+
9.0000E-04      1.7613E+03         --------+
9.6000E-04      1.7690E+03         --------+
1.0200E-03      1.7758E+03         --------+
1.0800E-03      1.7818E+03         --------+
1.1400E-03      1.7870E+03         --------+
1.2000E-03      1.7914E+03         --------+
1.2600E-03      1.7950E+03         ---------+
1.3200E-03      1.7978E+03         ---------+
1.3800E-03      1.7998E+03         ---------+
1.4400E-03      1.8009E+03         ---------+
1.5000E-03      1.8012E+03         ---------+
1.5600E-03      1.8007E+03         ---------+
1.6200E-03      1.7994E+03         ---------+
1.6800E-03      1.7973E+03         ---------+
1.7400E-03      1.7944E+03         ---------+
1.8000E-03      1.7906E+03         --------+
1.8600E-03      1.7860E+03         --------+
1.9200E-03      1.7807E+03         --------+
1.9800E-03      1.7745E+03         --------+
2.0400E-03      1.7675E+03         --------+
2.1000E-03      1.7597E+03         --------+
2.1600E-03      1.7511E+03         -------+
2.2200E-03      1.7418E+03         -------+
2.2800E-03      1.7316E+03         -------+
2.3400E-03      1.7207E+03         -------+
2.4000E-03      1.7090E+03         ------+
2.4600E-03      1.6965E+03         ------+
2.5200E-03      1.6832E+03         -----+
2.5800E-03      1.6692E+03         -----+
2.6400E-03      1.6545E+03         -----+
2.7000E-03      1.6390E+03         ----+
2.7600E-03      1.6227E+03         ----+
```

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MAXIMUM
3.2852E+03
I

+
--------+
------------+
--------------+

VAS	VBS	VCS
4.3137E+02	-9.2781E+02	4.9644E+02
4.4986E+02	-9.2842E+02	4.7857E+02
4.6811E+02	-9.2856E+02	4.6045E+02
4.8613E+02	-9.2822E+02	4.4209E+02
5.0390E+02	-9.2741E+02	4.2351E+02
5.2141E+02	-9.2612E+02	4.0471E+02
5.3866E+02	-9.2436E+02	3.8570E+02
5.5563E+02	-9.2213E+02	3.6650E+02
5.7231E+02	-9.1942E+02	3.4711E+02
5.8871E+02	-9.1625E+02	3.2754E+02
6.0480E+02	-9.1260E+02	3.0781E+02
6.2058E+02	-9.0849E+02	2.8791E+02
6.3604E+02	-9.0391E+02	2.6787E+02
6.5118E+02	-8.9888E+02	2.4769E+02
6.6599E+02	-8.9338E+02	2.2739E+02
6.8045E+02	-8.8742E+02	2.0697E+02
6.9457E+02	-8.8101E+02	1.8644E+02
7.0833E+02	-8.7415E+02	1.6582E+02
7.2173E+02	-8.6684E+02	1.4511E+02
7.3476E+02	-8.5909E+02	1.2433E+02
7.4741E+02	-8.5090E+02	1.0349E+02
7.5968E+02	-8.4227E+02	8.2591E+01
7.7157E+02	-8.3322E+02	6.1651E+01
7.8305E+02	-8.2373E+02	4.0680E+01
7.9414E+02	-8.1383E+02	1.9688E+01
8.0482E+02	-8.0351E+02	-1.3154E+00
8.1509E+02	-7.9278E+02	-2.2317E+01
8.2494E+02	-7.8164E+02	-4.3307E+01
8.3437E+02	-7.7010E+02	-6.4275E+01
8.4338E+02	-7.5817E+02	-8.5210E+01
8.5195E+02	-7.4585E+02	-1.0610E+02
8.6009E+02	-7.3315E+02	-1.2694E+02
8.6778E+02	-7.2007E+02	-1.4771E+02
8.7503E+02	-7.0663E+02	-1.6841E+02
8.8184E+02	-6.9282E+02	-1.8902E+02
8.8819E+02	-6.7866E+02	-2.0953E+02
8.9409E+02	-6.6415E+02	-2.2994E+02
8.9953E+02	-6.4930E+02	-2.5023E+02
9.0451E+02	-6.3412E+02	-2.7039E+02
9.0903E+02	-6.1862E+02	-2.9041E+02
9.1308E+02	-6.0280E+02	-3.1029E+02
9.1667E+02	-5.8667E+02	-3.3000E+02
9.1979E+02	-5.7024E+02	-3.4955E+02
9.2243E+02	-5.5352E+02	-3.6892E+02
9.2461E+02	-5.3651E+02	-3.8809E+02
9.2631E+02	-5.1924E+02	-4.0708E+02
9.2754E+02	-5.0169E+02	-4.2585E+02

```
                                  MINIMUM                    VAB     VERSUS TIME
                                 1.4656E+03                  KK      = 3.0000E-01
 TIME            VAB             I
0.0            1.4656E+03       +
6.0000E-05     1.4831E+03       +
1.2000E-04     1.4999E+03       +
1.8000E-04     1.5160E+03       -+
2.4000E-04     1.5313E+03       -+
3.0000E-04     1.5459E+03       --+
3.6000E-04     1.7480E+03       -------+
4.2000E-04     2.0055E+03       ---------------+
4.8000E-04     2.2469E+03       ----------------------+
5.4000E-04     2.4642E+03       ----------------------------+
6.0000E-04     2.6505E+03       ---------------------------------+
6.6000E-04     2.7998E+03       -------------------------------------+
7.2000E-04     2.9078E+03       ----------------------------------------+
7.8000E-04     2.9713E+03       -----------------------------------------
8.4000E-04     2.9892E+03       -----------------------------------------
9.0000E-04     1.7616E+03       --------+
9.6000E-04     1.7693E+03       --------+
1.0200E-03     1.7761E+03       --------+
1.0800E-03     1.7821E+03       --------+
1.1400E-03     1.7873E+03       --------+
1.2000E-03     1.7917E+03       --------+
1.2600E-03     1.7953E+03       ---------+
1.3200E-03     1.7981E+03       ---------+
1.3800E-03     1.8001E+03       ---------+
1.4400E-03     1.8012E+03       ---------+
1.5000E-03     1.8015E+03       ---------+
1.5600E-03     1.8010E+03       ---------+
1.6200E-03     1.7997E+03       ---------+
1.6800E-03     1.7976E+03       ---------+
1.7400E-03     1.7947E+03       ---------+
1.8000E-03     1.7909E+03       --------+
1.8600E-03     1.7863E+03       --------+
1.9200E-03     1.7810E+03       --------+
1.9800E-03     1.7748E+03       --------+
2.0400E-03     1.7678E+03       --------+
2.1000E-03     1.7600E+03       --------+
2.1600E-03     1.7514E+03       -------+
2.2200E-03     1.7421E+03       -------+
2.2800E-03     1.7319E+03       -------+
2.3400E-03     1.7210E+03       -------+
2.4000E-03     1.7093E+03       ------+
2.4600E-03     1.6968E+03       ------+
2.5200E-03     1.6835E+03       -----+
2.5800E-03     1.6695E+03       -----+
2.6400E-03     1.6548E+03       -----+
2.7000E-03     1.6393E+03       ----+
2.7600E-03     1.6230E+03       ----+
```

PAGE 1

MAXIMUM
3.2852E+03

I	VAS	VBS	VCS
	4.3137E+02	-9.2781E+02	4.9644E+02
	4.4986E+02	-9.2842E+02	4.7857E+02
	4.6811E+02	-9.2856E+02	4.6045E+02
	4.8613E+02	-9.2822E+02	4.4209E+02
	5.0390E+02	-9.2741E+02	4.2351E+02
	5.2141E+02	-9.2612E+02	4.0471E+02
	5.3866E+02	-9.2436E+02	3.8570E+02
	5.5563E+02	-9.2213E+02	3.6650E+02
	5.7231E+02	-9.1942E+02	3.4711E+02
	5.8871E+02	-9.1625E+02	3.2754E+02
	6.0480E+02	-9.1260E+02	3.0781E+02
	6.2058E+02	-9.0849E+02	2.8791E+02
	6.3604E+02	-9.0391E+02	2.6787E+02
	6.5118E+02	-8.9838E+02	2.4769E+02
	6.6599E+02	-8.9338E+02	2.2739E+02
	6.8045E+02	-8.8742E+02	2.0697E+02
	6.9457E+02	-8.8101E+02	1.8644E+02
	7.0833E+02	-8.7415E+02	1.6582E+02
	7.2173E+02	-8.6684E+02	1.4511E+02
	7.3476E+02	-8.5909E+02	1.2433E+02
	7.4741E+02	-8.5090E+02	1.0349E+02
	7.5968E+02	-8.4227E+02	8.2591E+01
	7.7157E+02	-8.3322E+02	6.1651E+01
	7.8305E+02	-8.2373E+02	4.0680E+01
	7.9414E+02	-8.1383E+02	1.9688E+01
	8.0482E+02	-8.0351E+02	-1.3154E+00
	8.1509E+02	-7.9278E+02	-2.2317E+01
	8.2494E+02	-7.8164E+02	-4.3307E+01
	8.3437E+02	-7.7010E+02	-6.4275E+01
	8.4338E+02	-7.5817E+02	-8.5210E+01
	8.5195E+02	-7.4585E+02	-1.0610E+02
	8.6009E+02	-7.3315E+02	-1.2694E+02
	8.6778E+02	-7.2007E+02	-1.4771E+02
	8.7503E+02	-7.0663E+02	-1.6841E+02
	8.8184E+02	-6.9282E+02	-1.8902E+02
	8.8819E+02	-6.7866E+02	-2.0953E+02
	8.9409E+02	-6.6415E+02	-2.2994E+02
	8.9953E+02	-6.4930E+02	-2.5023E+02
	9.0451E+02	-6.3412E+02	-2.7039E+02
	9.0903E+02	-6.1862E+02	-2.9041E+02
	9.1308E+02	-6.0280E+02	-3.1029E+02
	9.1667E+02	-5.8667E+02	-3.3000E+02
	9.1979E+02	-5.7024E+02	-3.4955E+02
	9.2243E+02	-5.5352E+02	-3.6892E+02
	9.2461E+02	-5.3651E+02	-3.8809E+02
	9.2631E+02	-5.1924E+02	-4.0708E+02
	9.2754E+02	-5.0169E+02	-4.2585E+02

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                                                          PAGE    1
                       MINIMUM            VAB    VERSUS TIME         MAXIMUM
                      1.4656E+03          KK     = 4.0000E-01        3.2852E+03
 TIME           VAB           I                                         I          VAS         VBS         VCS
0.0            1.4656E+03    +                                                   4.3137E+02 -9.2781E+02  4.9644E+02
6.0000E-05     1.4835E+03    +                                                   4.4986E+02 -9.2842E+02  4.7657E+02
1.2000E-04     1.5008E+03    +                                                   4.6611E+02 -9.2856E+02  4.6045E+02
1.8000E-04     1.5173E+03    -+                                                  4.8613E+02 -9.2822E+02  4.4209E+02
2.4000E-04     1.5331E+03    -+                                                  5.0390E+02 -9.2741E+02  4.2351E+02
3.0000E-04     1.5481E+03    --+                                                 5.2141E+02 -9.2612E+02  4.0471E+02
3.6000E-04     1.5624E+03    --+                                                 5.3866E+02 -9.2436E+02  3.8570E+02
4.2000E-04     1.5759E+03    ---+                                                5.5563E+02 -9.2213E+02  3.6650E+02
4.8000E-04     1.7420E+03    -------+                                            5.7231E+02 -9.1942E+02  3.4711E+02
5.4000E-04     1.9340E+03    ------------+                                       5.8871E+02 -9.1625E+02  3.2754E+02
6.0000E-04     2.1164E+03    -----------------+                                  6.0480E+02 -9.1260E+02  3.0781E+02
6.6000E-04     2.2848E+03    ----------------------+                             6.2058E+02 -9.0849E+02  2.8791E+02
7.2000E-04     2.4350E+03    --------------------------+                         6.3604E+02 -9.0391E+02  2.6787E+02
7.8000E-04     2.5636E+03    ------------------------------+                     6.5118E+02 -8.9885E+02  2.4769E+02
8.4000E-04     2.6677E+03    ---------------------------------+                  6.6599E+02 -8.9338E+02  2.2739E+02
9.0000E-04     2.7449E+03    -----------------------------------+                6.8045E+02 -8.8742E+02  2.0697E+02
9.6000E-04     2.7938E+03    ------------------------------------+               6.9457E+02 -8.8101E+02  1.8644E+02
1.0200E-03     2.8137E+03    -------------------------------------+              7.0833E+02 -8.7415E+02  1.6582E+02
1.0800E-03     1.7824E+03    --------+                                           7.2173E+02 -8.6684E+02  1.4511E+02
1.1400E-03     1.7876E+03    --------+                                           7.3476E+02 -8.5909E+02  1.2433E+02
1.2000E-03     1.7920E+03    --------+                                           7.4741E+02 -8.5090E+02  1.0349E+02
1.2600E-03     1.7956E+03    ---------+                                          7.5968E+02 -8.4227E+02  8.2591E+01
1.3200E-03     1.7984E+03    ---------+                                          7.7157E+02 -8.3322E+02  6.1651E+01
1.3800E-03     1.8003E+03    ---------+                                          7.8305E+02 -8.2373E+02  4.0680E+01
1.4400E-03     1.8015E+03    ---------+                                          7.9414E+02 -8.1383E+02  1.9688E+01
1.5000E-03     1.8018E+03    ---------+                                          8.0482E+02 -8.0351E+02 -1.3154E+00
1.5600E-03     1.8013E+03    ---------+                                          8.1509E+02 -7.9278E+02 -2.2317E+01
1.6200E-03     1.8000E+03    ---------+                                          8.2494E+02 -7.8164E+02 -4.3307E+01
1.6800E-03     1.7979E+03    ---------+                                          8.3437E+02 -7.7010E+02 -6.4275E+01
1.7400E-03     1.7949E+03    ---------+                                          8.4338E+02 -7.5817E+02 -8.5210E+01
1.8000E-03     1.7912E+03    --------+                                           8.5195E+02 -7.4585E+02 -1.0610E+02
1.8600E-03     1.7866E+03    --------+                                           8.6009E+02 -7.3315E+02 -1.2694E+02
1.9200E-03     1.7812E+03    --------+                                           8.6778E+02 -7.2007E+02 -1.4771E+02
1.9800E-03     1.7750E+03    --------+                                           8.7503E+02 -7.0663E+02 -1.6841E+02
2.0400E-03     1.7681E+03    --------+                                           8.8184E+02 -6.9282E+02 -1.8902E+02
2.1000E-03     1.7603E+03    --------+                                           8.8819E+02 -6.7866E+02 -2.0953E+02
2.1600E-03     1.7517E+03    -------+                                            8.9409E+02 -6.6415E+02 -2.2994E+02
2.2200E-03     1.7423E+03    -------+                                            8.9953E+02 -6.4930E+02 -2.5023E+02
2.2800E-03     1.7322E+03    -------+                                            9.0451E+02 -6.3412E+02 -2.7039E+02
2.3400E-03     1.7212E+03    -------+                                            9.0903E+02 -6.1862E+02 -2.9041E+02
2.4000E-03     1.7095E+03    ------+                                             9.1308E+02 -6.0280E+02 -3.1029E+02
2.4600E-03     1.6970E+03    ------+                                             9.1667E+02 -5.8667E+02 -3.3000E+02
2.5200E-03     1.6838E+03    -----+                                              9.1979E+02 -5.7024E+02 -3.4955E+02
2.5800E-03     1.6698E+03    -----+                                              9.2243E+02 -5.5352E+02 -3.6892E+02
2.6400E-03     1.6550E+03    -----+                                              9.2461E+02 -5.3651E+02 -3.8809E+02
2.7000E-03     1.6395E+03    ----+                                               9.2631E+02 -5.1924E+02 -4.0708E+02
2.7600E-03     1.6233E+03    ----+                                               9.2754E+02 -5.0169E+02 -4.2585E+02
```

MINIMUM -1.1630E+03 | VI VERSUS TIME | KK = 2.0000E-01 | MAXIMUM 3.2852E+03

TIME	VI	ID	VDC	M2
0.0	-1.1630E+03	2.7773E+02	1.5000E+03	0.0
6.0000E-05	-3.7829E+02	2.7800E+02	1.5000E+03	0.0
1.2000E-04	4.0626E+02	2.7817E+02	1.5000E+03	0.0
1.8000E-04	1.1904E+03	2.7824E+02	1.5000E+03	0.0
2.4000E-04	1.7512E+03	2.7824E+02	1.5002E+03	1.0000E+00
3.0000E-04	2.1384E+03	2.7818E+02	1.5002E+03	1.0000E+00
3.6000E-04	2.4930E+03	2.7807E+02	1.5002E+03	1.0000E+00
4.2000E-04	2.7973E+03	2.7794E+02	1.5002E+03	1.0000E+00
4.8000E-04	3.0364E+03	2.7776E+02	1.5002E+03	1.0000E+00
5.4000E-04	3.1986E+03	2.7757E+02	1.5002E+03	1.0000E+00
6.0000E-04	3.2777E+03	2.7736E+02	1.5002E+03	1.0000E+00
6.6000E-04	1.7229E+03	2.7712E+02	1.5000E+03	0.0
7.2000E-04	1.7337E+03	2.7709E+02	1.5000E+03	0.0
7.8000E-04	1.7437E+03	2.7706E+02	1.5000E+03	0.0
8.4000E-04	1.7529E+03	2.7703E+02	1.5000E+03	0.0
9.0000E-04	1.7613E+03	2.7698E+02	1.5000E+03	0.0
9.6000E-04	1.7690E+03	2.7694E+02	1.5000E+03	0.0
1.0200E-03	1.7758E+03	2.7690E+02	1.5000E+03	0.0
1.0800E-03	1.7818E+03	2.7685E+02	1.5000E+03	0.0
1.1400E-03	1.7870E+03	2.7681E+02	1.5000E+03	0.0
1.2000E-03	1.7914E+03	2.7676E+02	1.5000E+03	0.0
1.2600E-03	1.7950E+03	2.7672E+02	1.5000E+03	0.0
1.3200E-03	1.7978E+03	2.7668E+02	1.5000E+03	0.0
1.3800E-03	1.7998E+03	2.7663E+02	1.5000E+03	0.0
1.4400E-03	1.8009E+03	2.7659E+02	1.5000E+03	0.0
1.5000E-03	1.8012E+03	2.7654E+02	1.5000E+03	0.0
1.5600E-03	1.8007E+03	2.7650E+02	1.5000E+03	0.0
1.6200E-03	1.7994E+03	2.7646E+02	1.5000E+03	0.0
1.6800E-03	1.7973E+03	2.7641E+02	1.5000E+03	0.0
1.7400E-03	1.7944E+03	2.7637E+02	1.5000E+03	0.0
1.8000E-03	1.7906E+03	2.7633E+02	1.5000E+03	0.0
1.8600E-03	1.7860E+03	2.7628E+02	1.5000E+03	0.0
1.9200E-03	1.7807E+03	2.7624E+02	1.5000E+03	0.0
1.9800E-03	1.7745E+03	2.7619E+02	1.5000E+03	0.0
2.0400E-03	1.7675E+03	2.7615E+02	1.5000E+03	0.0
2.1000E-03	1.7597E+03	2.7611E+02	1.5000E+03	0.0
2.1600E-03	1.7511E+03	2.7606E+02	1.5000E+03	0.0
2.2200E-03	1.7418E+03	2.7603E+02	1.5000E+03	0.0
2.2800E-03	1.7316E+03	2.7600E+02	1.5000E+03	0.0
2.3400E-03	1.7207E+03	2.7597E+02	1.5000E+03	0.0
2.4000E-03	1.7090E+03	2.7594E+02	1.5000E+03	0.0
2.4600E-03	1.6965E+03	2.7591E+02	1.5000E+03	0.0
2.5200E-03	1.6832E+03	2.7588E+02	1.5000E+03	0.0
2.5800E-03	1.6692E+03	2.7585E+02	1.5000E+03	0.0
2.6400E-03	1.6545E+03	2.7582E+02	1.5000E+03	0.0
2.7000E-03	1.6390E+03	2.7579E+02	1.5000E+03	0.0
2.7600E-03	1.6227E+03	2.7577E+02	1.5000E+03	0.0

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MINIMUM -1.1630E+03 | VI VERSUS TIME, KK = 3.0000E-01 | MAXIMUM 3.2652E+03

TIME	VI	I ... I	ID	VDC	M2
0.0	-1.1630E+03	+	2.7773E+02	1.5000E+03	0.0
6.0000E-05	-6.4549E+02	-----+	2.7601E+02	1.5000E+03	0.0
1.2000E-04	-1.2827E+02	-----------+	2.7823E+02	1.5000E+03	0.0
1.8000E-04	3.8857E+02	-----------------+	2.7839E+02	1.5000E+03	0.0
2.4000E-04	9.0491E+02	-----------------------+	2.7848E+02	1.5000E+03	0.0
3.0000E-04	1.4206E+03	-----------------------------+	2.7852E+02	1.5000E+03	0.0
3.6000E-04	1.7480E+03	--------------------------------+	2.7850E+02	1.5002E+03	1.0000E+00
4.2000E-04	2.0055E+03	-----------------------------------+	2.7844E+02	1.5002E+03	1.0000E+00
4.8000E-04	2.2469E+03	--------------------------------------+	2.7836E+02	1.5002E+03	1.0000E+00
5.4000E-04	2.4642E+03	--+	2.7826E+02	1.5002E+03	1.0000E+00
6.0000E-04	2.6505E+03	--+	2.7813E+02	1.5002E+03	1.0000E+00
6.6000E-04	2.7998E+03	--+	2.7798E+02	1.5002E+03	1.0000E+00
7.2000E-04	2.9078E+03	---+	2.7782E+02	1.5002E+03	1.0000E+00
7.8000E-04	2.9713E+03	--+	2.7764E+02	1.5002E+03	1.0000E+00
8.4000E-04	2.9892E+03	--+	2.7746E+02	1.5001E+03	1.0000E+00
9.0000E-04	1.7616E+03	--------------------------------+	2.7741E+02	1.5000E+03	0.0
9.6000E-04	1.7693E+03	--------------------------------+	2.7737E+02	1.5000E+03	0.0
1.0200E-03	1.7761E+03	---------------------------------+	2.7733E+02	1.5000E+03	0.0
1.0800E-03	1.7821E+03	---------------------------------+	2.7728E+02	1.5000E+03	0.0
1.1400E-03	1.7873E+03	---------------------------------+	2.7724E+02	1.5000E+03	0.0
1.2000E-03	1.7917E+03	---------------------------------+	2.7719E+02	1.5000E+03	0.0
1.2600E-03	1.7953E+03	---------------------------------+	2.7715E+02	1.5000E+03	0.0
1.3200E-03	1.7981E+03	---------------------------------+	2.7711E+02	1.5000E+03	0.0
1.3800E-03	1.8001E+03	---------------------------------+	2.7706E+02	1.5000E+03	0.0
1.4400E-03	1.8012E+03	---------------------------------+	2.7702E+02	1.5000E+03	0.0
1.5000E-03	1.8015E+03	---------------------------------+	2.7697E+02	1.5000E+03	0.0
1.5600E-03	1.8010E+03	---------------------------------+	2.7693E+02	1.5000E+03	0.0
1.6200E-03	1.7997E+03	---------------------------------+	2.7689E+02	1.5000E+03	0.0
1.6800E-03	1.7976E+03	---------------------------------+	2.7684E+02	1.5000E+03	0.0
1.7400E-03	1.7947E+03	---------------------------------+	2.7680E+02	1.5000E+03	0.0
1.8000E-03	1.7909E+03	---------------------------------+	2.7675E+02	1.5000E+03	0.0
1.8600E-03	1.7863E+03	---------------------------------+	2.7671E+02	1.5000E+03	0.0
1.9200E-03	1.7810E+03	---------------------------------+	2.7667E+02	1.5000E+03	0.0
1.9800E-03	1.7748E+03	---------------------------------+	2.7662E+02	1.5000E+03	0.0
2.0400E-03	1.7678E+03	--------------------------------+	2.7658E+02	1.5000E+03	0.0
2.1000E-03	1.7600E+03	--------------------------------+	2.7653E+02	1.5000E+03	0.0
2.1600E-03	1.7514E+03	--------------------------------+	2.7649E+02	1.5000E+03	0.0
2.2200E-03	1.7421E+03	--------------------------------+	2.7646E+02	1.5000E+03	0.0
2.2800E-03	1.7319E+03	--------------------------------+	2.7643E+02	1.5000E+03	0.0
2.3400E-03	1.7210E+03	--------------------------------+	2.7640E+02	1.5000E+03	0.0
2.4000E-03	1.7093E+03	--------------------------------+	2.7637E+02	1.5000E+03	0.0
2.4600E-03	1.6968E+03	--------------------------------+	2.7634E+02	1.5000E+03	0.0
2.5200E-03	1.6835E+03	-------------------------------+	2.7631E+02	1.5000E+03	0.0
2.5800E-03	1.6695E+03	-------------------------------+	2.7628E+02	1.5000E+03	0.0
2.6400E-03	1.6548E+03	-------------------------------+	2.7625E+02	1.5000E+03	0.0
2.7000E-03	1.6393E+03	-------------------------------+	2.7622E+02	1.5000E+03	0.0
2.7600E-03	1.6230E+03	-------------------------------+	2.7620E+02	1.5000E+03	0.0

PAGE 1

MINIMUM -1.1630E+03   VI VERSUS TIME   MAXIMUM 3.2852E+03

KK = 4.0000E-01

TIME	VI	I ... I	ID	VDC	M2
0.0	-1.1630E+03	+	2.7773E+02	1.5000E+03	0.0
6.0000E-05	-7.7910E+02	----+	2.7802E+02	1.5000E+03	0.0
1.2000E-04	-3.9556E+02	--------+	2.7826E+02	1.5000E+03	0.0
1.8000E-04	-1.2447E+01	------------+	2.7846E+02	1.5000E+03	0.0
2.4000E-04	3.7019E+02	-----------------+	2.7861E+02	1.5000E+03	0.0
3.0000E-04	7.5229E+02	---------------------+	2.7872E+02	1.5000E+03	0.0
3.6000E-04	1.1338E+03	-------------------------+	2.7878E+02	1.5000E+03	0.0
4.2000E-04	1.5147E+03	------------------------------+	2.7879E+02	1.5000E+03	0.0
4.8000E-04	1.7420E+03	--------------------------------+	2.7877E+02	1.5001E+03	1.0000E+00
5.4000E-04	1.9340E+03	----------------------------------+	2.7872E+02	1.5002E+03	1.0000E+00
6.0000E-04	2.1164E+03	------------------------------------+	2.7865E+02	1.5002E+03	1.0000E+00
6.6000E-04	2.2848E+03	--------------------------------------+	2.7856E+02	1.5002E+03	1.0000E+00
7.2000E-04	2.4350E+03	--+	2.7846E+02	1.5002E+03	1.0000E+00
7.8000E-04	2.5636E+03	---+	2.7834E+02	1.5002E+03	1.0000E+00
8.4000E-04	2.6677E+03	---+	2.7820E+02	1.5002E+03	1.0000E+00
9.0000E-04	2.7449E+03	---+	2.7806E+02	1.5002E+03	1.0000E+00
9.6000E-04	2.7938E+03	--+	2.7790E+02	1.5001E+03	1.0000E+00
1.0200E-03	2.8137E+03	--+	2.7774E+02	1.5002E+03	1.0000E+00
1.0800E-03	1.7824E+03	---------------------------------+	2.7764E+02	1.5000E+03	0.0
1.1400E-03	1.7876E+03	---------------------------------+	2.7760E+02	1.5000E+03	0.0
1.2000E-03	1.7920E+03	---------------------------------+	2.7755E+02	1.5000E+03	0.0
1.2600E-03	1.7956E+03	---------------------------------+	2.7751E+02	1.5000E+03	0.0
1.3200E-03	1.7984E+03	---------------------------------+	2.7746E+02	1.5000E+03	0.0
1.3800E-03	1.8003E+03	---------------------------------+	2.7742E+02	1.5000E+03	0.0
1.4400E-03	1.8015E+03	---------------------------------+	2.7738E+02	1.5000E+03	0.0
1.5000E-03	1.8018E+03	---------------------------------+	2.7733E+02	1.5000E+03	0.0
1.5600E-03	1.8013E+03	---------------------------------+	2.7729E+02	1.5000E+03	0.0
1.6200E-03	1.8000E+03	---------------------------------+	2.7724E+02	1.5000E+03	0.0
1.6800E-03	1.7979E+03	---------------------------------+	2.7720E+02	1.5000E+03	0.0
1.7400E-03	1.7949E+03	---------------------------------+	2.7716E+02	1.5000E+03	0.0
1.8000E-03	1.7912E+03	---------------------------------+	2.7711E+02	1.5000E+03	0.0
1.8600E-03	1.7866E+03	---------------------------------+	2.7707E+02	1.5000E+03	0.0
1.9200E-03	1.7812E+03	---------------------------------+	2.7702E+02	1.5000E+03	0.0
1.9800E-03	1.7750E+03	---------------------------------+	2.7698E+02	1.5000E+03	0.0
2.0400E-03	1.7681E+03	--------------------------------+	2.7694E+02	1.5000E+03	0.0
2.1000E-03	1.7603E+03	--------------------------------+	2.7689E+02	1.5000E+03	0.0
2.1600E-03	1.7517E+03	--------------------------------+	2.7685E+02	1.5000E+03	0.0
2.2200E-03	1.7423E+03	--------------------------------+	2.7681E+02	1.5000E+03	0.0
2.2800E-03	1.7322E+03	--------------------------------+	2.7679E+02	1.5000E+03	0.0
2.3400E-03	1.7212E+03	--------------------------------+	2.7676E+02	1.5000E+03	0.0
2.4000E-03	1.7095E+03	--------------------------------+	2.7673E+02	1.5000E+03	0.0
2.4600E-03	1.6970E+03	--------------------------------+	2.7670E+02	1.5000E+03	0.0
2.5200E-03	1.6838E+03	-------------------------------+	2.7667E+02	1.5000E+03	0.0
2.5800E-03	1.6698E+03	-------------------------------+	2.7664E+02	1.5000E+03	0.0
2.6400E-03	1.6550E+03	-------------------------------+	2.7661E+02	1.5000E+03	0.0
2.7000E-03	1.6395E+03	-------------------------------+	2.7658E+02	1.5000E+03	0.0
2.7600E-03	1.6233E+03	-------------------------------+	2.7655E+02	1.5000E+03	0.0

```
                              MINIMUM            VC     VERSUS TIME            MAXIMUM
                            -2.8000E+03          KK     = 2.0000E-01           3.5736E+03
 TIME          VC          I                                                  I        IC          IA          M2
0.0          -2.8000E+03   +                                                          2.7773E+02  0.0         0.0
6.0000E-05   -1.9932E+03   ------+                                                    2.7800E+02  0.0         0.0
1.2000E-04   -1.1857E+03   ------------+                                              2.7817E+02  0.0         0.0
1.8000E-04   -3.7794E+02   -------------------+                                       2.7824E+02  0.0         0.0
2.4000E-04    4.2859E+02   -------------------------+                                 2.7582E+02  2.4139E+00  1.0000E+00
3.0000E-04    1.2105E+03   -------------------------------+                           2.6051E+02  1.7662E+01  1.0000E+00
3.6000E-04    1.9286E+03   -------------------------------------+                     2.3206E+02  4.6012E+01  1.0000E+00
4.2000E-04    2.5470E+03   -----------------------------------------+                 1.9217E+02  8.5766E+01  1.0000E+00
4.8000E-04    3.0357E+03   ---------------------------------------------+             1.4313E+02  1.3464E+02  1.0000E+00
5.4000E-04    3.3720E+03   ------------------------------------------------+          8.7689E+01  1.8988E+02  1.0000E+00
6.0000E-04    3.5417E+03   -------------------------------------------------+         2.8924E+01  2.4843E+02  1.0000E+00
6.6000E-04    3.5623E+03   -------------------------------------------------+         1.1262E-01  2.7712E+02  0.0
7.2000E-04    3.5626E+03   -------------------------------------------------+         1.1262E-01  2.7709E+02  0.0
7.8000E-04    3.5629E+03   -------------------------------------------------+         1.1262E-01  2.7706E+02  0.0
8.4000E-04    3.5633E+03   -------------------------------------------------+         1.1262E-01  2.7703E+02  0.0
9.0000E-04    3.5636E+03   -------------------------------------------------+         1.1262E-01  2.7698E+02  0.0
9.6000E-04    3.5639E+03   -------------------------------------------------+         1.1262E-01  2.7694E+02  0.0
1.0200E-03    3.5642E+03   -------------------------------------------------+         1.1262E-01  2.7690E+02  0.0
1.0800E-03    3.5645E+03   -------------------------------------------------+         1.1262E-01  2.7685E+02  0.0
1.1400E-03    3.5649E+03   -------------------------------------------------+         1.1262E-01  2.7681E+02  0.0
1.2000E-03    3.5652E+03   -------------------------------------------------+         1.1262E-01  2.7676E+02  0.0
1.2600E-03    3.5655E+03   -------------------------------------------------+         1.1262E-01  2.7672E+02  0.0
1.3200E-03    3.5658E+03   -------------------------------------------------+         1.1262E-01  2.7668E+02  0.0
1.3800E-03    3.5662E+03   -------------------------------------------------+         1.1262E-01  2.7663E+02  0.0
1.4400E-03    3.5665E+03   -------------------------------------------------+         1.1262E-01  2.7659E+02  0.0
1.5000E-03    3.5668E+03   -------------------------------------------------+         1.1262E-01  2.7654E+02  0.0
1.5600E-03    3.5671E+03   -------------------------------------------------+         1.1262E-01  2.7650E+02  0.0
1.6200E-03    3.5674E+03   -------------------------------------------------+         1.1262E-01  2.7646E+02  0.0
1.6800E-03    3.5678E+03   -------------------------------------------------+         1.1262E-01  2.7641E+02  0.0
1.7400E-03    3.5681E+03   -------------------------------------------------+         1.1262E-01  2.7637E+02  0.0
1.8000E-03    3.5684E+03   -------------------------------------------------+         1.1262E-01  2.7633E+02  0.0
1.8600E-03    3.5687E+03   -------------------------------------------------+         1.1262E-01  2.7628E+02  0.0
1.9200E-03    3.5691E+03   -------------------------------------------------+         1.1262E-01  2.7624E+02  0.0
1.9800E-03    3.5694E+03   -------------------------------------------------+         1.1262E-01  2.7619E+02  0.0
2.0400E-03    3.5697E+03   -------------------------------------------------+         1.1262E-01  2.7615E+02  0.0
2.1000E-03    3.5700E+03   -------------------------------------------------+         1.1262E-01  2.7611E+02  0.0
2.1600E-03    3.5703E+03   -------------------------------------------------+         1.1262E-01  2.7606E+02  0.0
2.2200E-03    3.5707E+03   -------------------------------------------------+         1.1262E-01  2.7603E+02  0.0
2.2800E-03    3.5710E+03   -------------------------------------------------+         1.1262E-01  2.7600E+02  0.0
2.3400E-03    3.5713E+03   -------------------------------------------------+         1.1262E-01  2.7597E+02  0.0
2.4000E-03    3.5716E+03   -------------------------------------------------+         1.1262E-01  2.7594E+02  0.0
2.4600E-03    3.5720E+03   -------------------------------------------------+         1.1262E-01  2.7591E+02  0.0
2.5200E-03    3.5723E+03   -------------------------------------------------+         1.1262E-01  2.7588E+02  0.0
2.5800E-03    3.5726E+03   -------------------------------------------------+         1.1262E-01  2.7585E+02  0.0
2.6400E-03    3.5729E+03   -------------------------------------------------+         1.1262E-01  2.7582E+02  0.0
2.7000E-03    3.5732E+03   -------------------------------------------------+         1.1262E-01  2.7579E+02  0.0
2.7600E-03    3.5736E+03   -------------------------------------------------+         1.1262E-01  2.7577E+02  0.0
```

MINIMUM VC VERSUS TIME MAXIMUM

-2.8000E+03 KK = 3.0000E-01 3.5736E+03

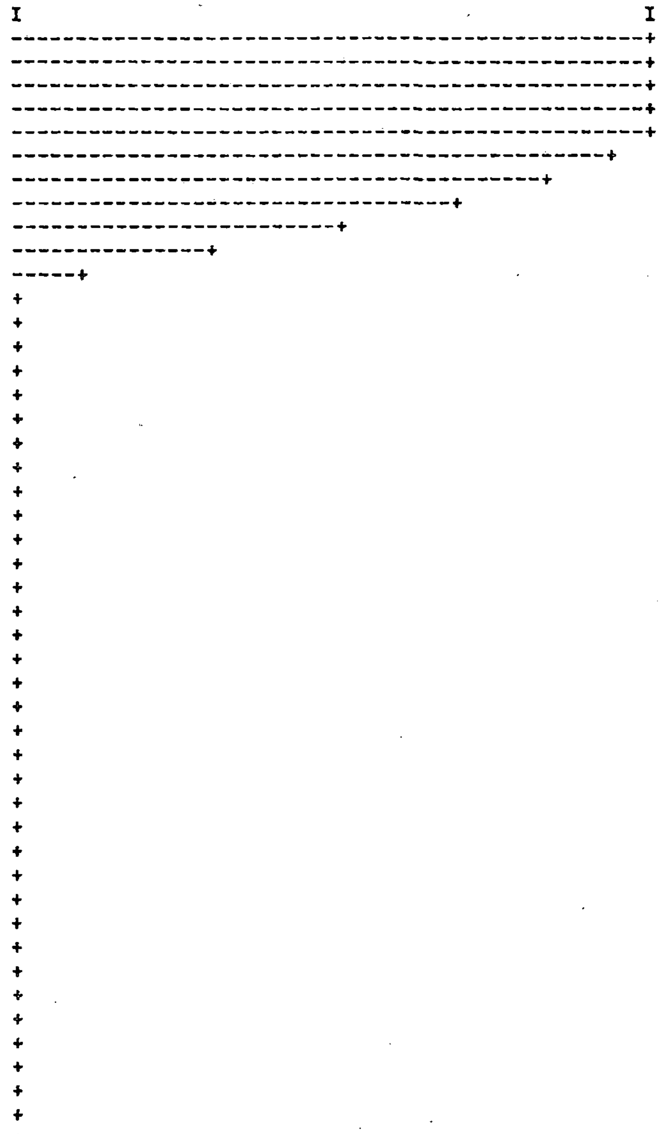
TIME	VC	I (plot) I	IC	IA	M2
0.0	-2.8000E+03	+	2.7773E+02	0.0	0.0
6.0000E-05	-2.2621E+03	----+	2.7801E+02	0.0	0.0
1.2000E-04	-1.7237E+03	--------+	2.7823E+02	0.0	0.0
1.8000E-04	-1.1850E+03	------------+	2.7839E+02	0.0	0.0
2.4000E-04	-6.4603E+02	----------------+	2.7848E+02	0.0	0.0
3.0000E-04	-1.0693E+02	---------------------+	2.7852E+02	0.0	0.0
3.6000E-04	4.3090E+02	-------------------------+	2.7587E+02	2.6283E+00	1.0000E+00
4.2000E-04	9.5514E+02	-----------------------------+	2.6430E+02	1.4141E+01	1.0000E+00
4.8000E-04	1.4485E+03	---------------------------------+	2.4407E+02	3.4297E+01	1.0000E+00
5.4000E-04	1.8949E+03	------------------------------------+	2.1600E+02	6.2263E+01	1.0000E+00
6.0000E-04	2.2803E+03	---------------------------------------+	1.8120E+02	9.6931E+01	1.0000E+00
6.6000E-04	2.5929E+03	--+	1.4101E+02	1.3697E+02	1.0000E+00
7.2000E-04	2.8237E+03	--+	9.6943E+01	1.8080E+02	1.0000E+00
7.8000E-04	2.9668E+03	---+	5.0624E+01	2.2702E+02	1.0000E+00
8.4000E-04	3.0193E+03	---+	3.7442E+00	2.7372E+02	1.0000E+00
9.0000E-04	3.0196E+03	---+	-5.3638E-03	2.7741E+02	0.0
9.6000E-04	3.0196E+03	---+	-5.3638E-03	2.7737E+02	0.0
1.0200E-03	3.0196E+03	---+	-5.3638E-03	2.7733E+02	0.0
1.0800E-03	3.0196E+03	---+	-5.3638E-03	2.7728E+02	0.0
1.1400E-03	3.0195E+03	---+	-5.3638E-03	2.7724E+02	0.0
1.2000E-03	3.0195E+03	---+	-5.3638E-03	2.7719E+02	0.0
1.2600E-03	3.0195E+03	---+	-5.3638E-03	2.7715E+02	0.0
1.3200E-03	3.0195E+03	---+	-5.3638E-03	2.7711E+02	0.0
1.3800E-03	3.0195E+03	---+	-5.3638E-03	2.7706E+02	0.0
1.4400E-03	3.0195E+03	---+	-5.3638E-03	2.7702E+02	0.0
1.5000E-03	3.0195E+03	---+	-5.3638E-03	2.7697E+02	0.0
1.5600E-03	3.0194E+03	---+	-5.3638E-03	2.7693E+02	0.0
1.6200E-03	3.0194E+03	---+	-5.3638E-03	2.7689E+02	0.0
1.6800E-03	3.0194E+03	---+	-5.3638E-03	2.7684E+02	0.0
1.7400E-03	3.0194E+03	---+	-5.3638E-03	2.7680E+02	0.0
1.8000E-03	3.0194E+03	---+	-5.3638E-03	2.7675E+02	0.0
1.8600E-03	3.0194E+03	---+	-5.3638E-03	2.7671E+02	0.0
1.9200E-03	3.0194E+03	---+	-5.3638E-03	2.7667E+02	0.0
1.9800E-03	3.0193E+03	---+	-5.3638E-03	2.7662E+02	0.0
2.0400E-03	3.0193E+03	---+	-5.3638E-03	2.7658E+02	0.0
2.1000E-03	3.0193E+03	---+	-5.3638E-03	2.7653E+02	0.0
2.1600E-03	3.0193E+03	---+	-5.3638E-03	2.7649E+02	0.0
2.2200E-03	3.0193E+03	---+	-5.3638E-03	2.7646E+02	0.0
2.2800E-03	3.0193E+03	---+	-5.3638E-03	2.7643E+02	0.0
2.3400E-03	3.0192E+03	---+	-5.3638E-03	2.7640E+02	0.0
2.4000E-03	3.0192E+03	---+	-5.3638E-03	2.7637E+02	0.0
2.4600E-03	3.0192E+03	---+	-5.3638E-03	2.7634E+02	0.0
2.5200E-03	3.0192E+03	---+	-5.3638E-03	2.7631E+02	0.0
2.5800E-03	3.0192E+03	---+	-5.3638E-03	2.7628E+02	0.0
2.6400E-03	3.0192E+03	---+	-5.3638E-03	2.7625E+02	0.0
2.7000E-03	3.0192E+03	---+	-5.3638E-03	2.7622E+02	0.0
2.7600E-03	3.0191E+03	---+	-5.3638E-03	2.7620E+02	0.0

MINIMUM -2.8000E+03 — VC VERSUS TIME — MAXIMUM 3.5736E+03

KK = 4.0000E-01

TIME	VC	I I	IC	IA	M2
0.0	-2.8000E+03	+	2.7773E+02	0.0	0.0
6.0000E-05	-2.3966E+03	---+	2.7802E+02	0.0	0.0
1.2000E-04	-1.9928E+03	------+	2.7826E+02	0.0	0.0
1.8000E-04	-1.5886E+03	---------+	2.7846E+02	0.0	0.0
2.4000E-04	-1.1643E+03	------------+	2.7861E+02	0.0	0.0
3.0000E-04	-7.7970E+02	---------------+	2.7872E+02	0.0	0.0
3.6000E-04	-3.7502E+02	-------------------+	2.7878E+02	0.0	0.0
4.2000E-04	2.9711E+01	----------------------+	2.7879E+02	0.0	0.0
4.8000E-04	4.3347E+02	-------------------------+	2.7639E+02	2.3774E+00	1.0000E+00
5.4000E-04	8.2893E+02	----------------------------+	2.6733E+02	1.1390E+01	1.0000E+00
6.0000E-04	1.2065E+03	-------------------------------+	2.5184E+02	2.6805E+01	1.0000E+00
6.6000E-04	1.5573E+03	----------------------------------+	2.3044E+02	4.8123E+01	1.0000E+00
7.2000E-04	1.8730E+03	------------------------------------+	2.0376E+02	7.4696E+01	1.0000E+00
7.8000E-04	2.1467E+03	--------------------------------------+	1.7260E+02	1.0574E+02	1.0000E+00
8.4000E-04	2.3724E+03	--+	1.3784E+02	1.4036E+02	1.0000E+00
9.0000E-04	2.5457E+03	---+	1.0047E+02	1.7759E+02	1.0000E+00
9.6000E-04	2.6634E+03	--+	6.1520E+01	2.1638E+02	1.0000E+00
1.0200E-03	2.7240E+03	---+	2.2064E+01	2.5568E+02	1.0000E+00
1.0800E-03	2.7330E+03	---+	-6.8308E-03	2.7764E+02	0.0
1.1400E-03	2.7330E+03	---+	-6.8308E-03	2.7760E+02	0.0
1.2000E-03	2.7330E+03	---+	-6.8308E-03	2.7755E+02	0.0
1.2600E-03	2.7330E+03	---+	-6.8308E-03	2.7751E+02	0.0
1.3200E-03	2.7330E+03	---+	-6.8308E-03	2.7746E+02	0.0
1.3800E-03	2.7329E+03	---+	-6.8308E-03	2.7742E+02	0.0
1.4400E-03	2.7329E+03	---+	-6.8308E-03	2.7738E+02	0.0
1.5000E-03	2.7329E+03	---+	-6.8308E-03	2.7733E+02	0.0
1.5600E-03	2.7329E+03	---+	-6.8308E-03	2.7729E+02	0.0
1.6200E-03	2.7329E+03	---+	-6.8308E-03	2.7724E+02	0.0
1.6800E-03	2.7329E+03	---+	-6.8308E-03	2.7720E+02	0.0
1.7400E-03	2.7329E+03	---+	-6.8308E-03	2.7716E+02	0.0
1.8000E-03	2.7328E+03	---+	-6.8308E-03	2.7711E+02	0.0
1.8600E-03	2.7328E+03	---+	-6.8308E-03	2.7707E+02	0.0
1.9200E-03	2.7328E+03	---+	-6.8308E-03	2.7702E+02	0.0
1.9800E-03	2.7328E+03	---+	-6.8308E-03	2.7698E+02	0.0
2.0400E-03	2.7328E+03	---+	-6.8308E-03	2.7694E+02	0.0
2.1000E-03	2.7328E+03	---+	-6.8308E-03	2.7689E+02	0.0
2.1600E-03	2.7328E+03	---+	-6.8308E-03	2.7685E+02	0.0
2.2200E-03	2.7327E+03	---+	-6.8308E-03	2.7681E+02	0.0
2.2800E-03	2.7327E+03	---+	-6.8308E-03	2.7679E+02	0.0
2.3400E-03	2.7327E+03	---+	-6.8308E-03	2.7676E+02	0.0
2.4000E-03	2.7327E+03	---+	-6.8308E-03	2.7673E+02	0.0
2.4600E-03	2.7327E+03	---+	-6.8308E-03	2.7670E+02	0.0
2.5200E-03	2.7327E+03	---+	-6.8308E-03	2.7667E+02	0.0
2.5800E-03	2.7327E+03	---+	-6.8308E-03	2.7664E+02	0.0
2.6400E-03	2.7326E+03	---+	-6.8308E-03	2.7661E+02	0.0
2.7000E-03	2.7326E+03	---+	-6.8308E-03	2.7658E+02	0.0
2.7600E-03	2.7326E+03	---+	-6.8308E-03	2.7655E+02	0.0

MINIMUM -1.4758E-01   IC VERSUS TIME   KK = 2.0000E-01   MAXIMUM 2.7893E+02



TIME	IC	ICDOT	IADOT	M2
0.0	2.7773E+02	5.3204E+03	0.0	0.0
6.0000E-05	2.7800E+02	3.7510E+03	0.0	0.0
1.2000E-04	2.7817E+02	2.1819E+03	0.0	0.0
1.8000E-04	2.7824E+02	6.1365E+02	0.0	0.0
2.4000E-04	2.7582E+02	-1.3886E+05	1.3836E+05	1.0000E+00
3.0000E-04	2.6051E+02	-3.6840E+05	3.6712E+05	1.0000E+00
3.6000E-04	2.3206E+02	-5.7513E+05	5.7314E+05	1.0000E+00
4.2000E-04	1.9217E+02	-7.4823E+05	7.4563E+05	1.0000E+00
4.8000E-04	1.4313E+02	-8.7884E+05	8.7576E+05	1.0000E+00
5.4000E-04	8.7689E+01	-9.6048E+05	9.5708E+05	1.0000E+00
6.0000E-04	2.8924E+01	-9.8942E+05	9.8586E+05	1.0000E+00
6.6000E-04	1.1262E-01	0.0	-4.5131E+02	0.0
7.2000E-04	1.1262E-01	0.0	-4.7290E+02	0.0
7.8000E-04	1.1262E-01	0.0	-4.9293E+02	0.0
8.4000E-04	1.1262E-01	0.0	-5.1138E+02	0.0
9.0000E-04	1.1262E-01	0.0	-5.2822E+02	0.0
9.6000E-04	1.1262E-01	0.0	-5.4348E+02	0.0
1.0200E-03	1.1262E-01	0.0	-5.5713E+02	0.0
1.0800E-03	1.1262E-01	0.0	-5.6917E+02	0.0
1.1400E-03	1.1262E-01	0.0	-5.7960E+02	0.0
1.2000E-03	1.1262E-01	0.0	-5.8841E+02	0.0
1.2600E-03	1.1262E-01	0.0	-5.9559E+02	0.0
1.3200E-03	1.1262E-01	0.0	-6.0114E+02	0.0
1.3800E-03	1.1262E-01	0.0	-6.0506E+02	0.0
1.4400E-03	1.1262E-01	0.0	-6.0735E+02	0.0
1.5000E-03	1.1262E-01	0.0	-6.0800E+02	0.0
1.5600E-03	1.1262E-01	0.0	-6.0702E+02	0.0
1.6200E-03	1.1262E-01	0.0	-6.0440E+02	0.0
1.6800E-03	1.1262E-01	0.0	-6.0015E+02	0.0
1.7400E-03	1.1262E-01	0.0	-5.9427E+02	0.0
1.8000E-03	1.1262E-01	0.0	-5.8676E+02	0.0
1.8600E-03	1.1262E-01	0.0	-5.7762E+02	0.0
1.9200E-03	1.1262E-01	0.0	-5.6687E+02	0.0
1.9800E-03	1.1262E-01	0.0	-5.5450E+02	0.0
2.0400E-03	1.1262E-01	0.0	-5.4052E+02	0.0
2.1000E-03	1.1262E-01	0.0	-5.2495E+02	0.0
2.1600E-03	1.1262E-01	0.0	-5.0778E+02	0.0
2.2200E-03	1.1262E-01	0.0	-4.8904E+02	0.0
2.2800E-03	1.1262E-01	0.0	-4.6873E+02	0.0
2.3400E-03	1.1262E-01	0.0	-4.4685E+02	0.0
2.4000E-03	1.1262E-01	0.0	-4.2343E+02	0.0
2.4600E-03	1.1262E-01	0.0	-3.9846E+02	0.0
2.5200E-03	1.1262E-01	0.0	-3.7196E+02	0.0
2.5800E-03	1.1262E-01	0.0	-3.4395E+02	0.0
2.6400E-03	1.1262E-01	0.0	-3.1444E+02	0.0
2.7000E-03	1.1262E-01	0.0	-2.8344E+02	0.0
2.7600E-03	1.1262E-01	0.0	-2.5098E+02	0.0

MINIMUM IC VERSUS TIME MAXIMUM
-1.4758E-01 KK = 3.0000E-01 2.7893E+02

TIME	IC	I ... I	ICDOT	IADOT	M2
0.0	2.7773E+02	--+	5.3204E+03	0.0	0.0
6.0000E-05	2.7801E+02	--+	4.2854E+03	0.0	0.0
1.2000E-04	2.7823E+02	--+	3.2510E+03	0.0	0.0
1.8000E-04	2.7839E+02	--+	2.2173E+03	0.0	0.0
2.4000E-04	2.7848E+02	--+	1.1846E+03	0.0	0.0
3.0000E-04	2.7852E+02	--+	1.5315E+02	0.0	0.0
3.6000E-04	2.7587E+02	--+	-1.1694E+05	1.1643E+05	1.0000E+00
4.2000E-04	2.6430E+02	--+	-2.6685E+05	2.6583E+05	1.0000E+00
4.8000E-04	2.4407E+02	--+	-4.0524E+05	4.0374E+05	1.0000E+00
5.4000E-04	2.1600E+02	---------------------------------------+	-5.2730E+05	5.2536E+05	1.0000E+00
6.0000E-04	1.8120E+02	---------------------------------+	-6.2886E+05	6.2655E+05	1.0000E+00
6.6000E-04	1.4101E+02	--------------------------+	-7.0654E+05	7.0394E+05	1.0000E+00
7.2000E-04	9.6943E+01	------------------+	-7.5788E+05	7.5506E+05	1.0000E+00
7.8000E-04	5.0624E+01	---------+	-7.8138E+05	7.7843E+05	1.0000E+00
8.4000E-04	3.7442E+00	+	-7.7656E+05	7.7357E+05	1.0000E+00
9.0000E-04	-5.3638E-03	+	0.0	-5.2883E+02	0.0
9.6000E-04	-5.3638E-03	+	0.0	-5.4409E+02	0.0
1.0200E-03	-5.3638E-03	+	0.0	-5.5774E+02	0.0
1.0800E-03	-5.3638E-03	+	0.0	-5.6978E+02	0.0
1.1400E-03	-5.3638E-03	+	0.0	-5.8021E+02	0.0
1.2000E-03	-5.3638E-03	+	0.0	-5.8901E+02	0.0
1.2600E-03	-5.3638E-03	+	0.0	-5.9620E+02	0.0
1.3200E-03	-5.3638E-03	+	0.0	-6.0175E+02	0.0
1.3800E-03	-5.3638E-03	+	0.0	-6.0567E+02	0.0
1.4400E-03	-5.3638E-03	+	0.0	-6.0796E+02	0.0
1.5000E-03	-5.3638E-03	+	0.0	-6.0861E+02	0.0
1.5600E-03	-5.3638E-03	+	0.0	-6.0763E+02	0.0
1.6200E-03	-5.3638E-03	+	0.0	-6.0501E+02	0.0
1.6800E-03	-5.3638E-03	+	0.0	-6.0076E+02	0.0
1.7400E-03	-5.3638E-03	+	0.0	-5.9488E+02	0.0
1.8000E-03	-5.3638E-03	+	0.0	-5.8737E+02	0.0
1.8600E-03	-5.3638E-03	+	0.0	-5.7823E+02	0.0
1.9200E-03	-5.3638E-03	+	0.0	-5.6748E+02	0.0
1.9800E-03	-5.3638E-03	+	0.0	-5.5511E+02	0.0
2.0400E-03	-5.3638E-03	+	0.0	-5.4113E+02	0.0
2.1000E-03	-5.3638E-03	+	0.0	-5.2555E+02	0.0
2.1600E-03	-5.3638E-03	+	0.0	-5.0838E+02	0.0
2.2200E-03	-5.3638E-03	+	0.0	-4.8964E+02	0.0
2.2800E-03	-5.3638E-03	+	0.0	-4.6934E+02	0.0
2.3400E-03	-5.3638E-03	+	0.0	-4.4746E+02	0.0
2.4000E-03	-5.3638E-03	+	0.0	-4.2403E+02	0.0
2.4600E-03	-5.3638E-03	+	0.0	-3.9907E+02	0.0
2.5200E-03	-5.3638E-03	+	0.0	-3.7257E+02	0.0
2.5800E-03	-5.3638E-03	+	0.0	-3.4456E+02	0.0
2.6400E-03	-5.3638E-03	+	0.0	-3.1505E+02	0.0
2.7000E-03	-5.3638E-03	+	0.0	-2.8405E+02	0.0
2.7600E-03	-5.3638E-03	+	0.0	-2.5159E+02	0.0

	MINIMUM	IC	VERSUS TIME	MAXIMUM
	-1.4758E-01	KK	= 4.0000E-01	2.7893E+02

TIME	IC	I I	ICDOT	IADOT	M2
0.0	2.7773E+02	--+	5.3204E+03	0.0	0.0
6.0000E-05	2.7802E+02	--+	4.5526E+03	0.0	0.0
1.2000E-04	2.7826E+02	--+	3.7856E+03	0.0	0.0
1.8000E-04	2.7846E+02	--+	3.0193E+03	0.0	0.0
2.4000E-04	2.7861E+02	--+	2.2540E+03	0.0	0.0
3.0000E-04	2.7872E+02	--+	1.4898E+03	0.0	0.0
3.6000E-04	2.7878E+02	--+	7.2682E+02	0.0	0.0
4.2000E-04	2.7879E+02	--+	-3.4903E+01	0.0	0.0
4.8000E-04	2.7639E+02	--+	-9.5287E+04	9.4797E+04	1.0000E+00
5.4000E-04	2.6733E+02	--+	-2.0559E+05	2.0472E+05	1.0000E+00
6.0000E-04	2.5184E+02	--+	-3.0895E+05	3.0772E+05	1.0000E+00
6.6000E-04	2.3044E+02	--+	-4.0268E+05	4.0110E+05	1.0000E+00
7.2000E-04	2.0376E+02	-------------------------------------+	-4.8437E+05	4.8249E+05	1.0000E+00
7.8000E-04	1.7260E+02	-------------------------------+	-5.5199E+05	5.4985E+05	1.0000E+00
8.4000E-04	1.3784E+02	-------------------------+	-6.0390E+05	6.0156E+05	1.0000E+00
9.0000E-04	1.0047E+02	-------------------+	-6.3892E+05	6.3643E+05	1.0000E+00
9.6000E-04	6.1520E+01	-----------+	-6.5633E+05	6.5374E+05	1.0000E+00
1.0200E-03	2.2064E+01	---+	-6.5589E+05	6.5326E+05	1.0000E+00
1.0800E-03	-6.8308E-03	+	0.0	-5.7029E+02	0.0
1.1400E-03	-6.8308E-03	+	0.0	-5.8072E+02	0.0
1.2000E-03	-6.8308E-03	+	0.0	-5.8952E+02	0.0
1.2600E-03	-6.8308E-03	+	0.0	-5.9670E+02	0.0
1.3200E-03	-6.8308E-03	+	0.0	-6.0226E+02	0.0
1.3800E-03	-6.8308E-03	+	0.0	-6.0618E+02	0.0
1.4400E-03	-6.8308E-03	+	0.0	-6.0847E+02	0.0
1.5000E-03	-6.8308E-03	+	0.0	-6.0912E+02	0.0
1.5600E-03	-6.8308E-03	+	0.0	-6.0814E+02	0.0
1.6200E-03	-6.8308E-03	+	0.0	-6.0552E+02	0.0
1.6800E-03	-6.8308E-03	+	0.0	-6.0127E+02	0.0
1.7400E-03	-6.8308E-03	+	0.0	-5.9539E+02	0.0
1.8000E-03	-6.8308E-03	+	0.0	-5.8788E+02	0.0
1.8600E-03	-6.8308E-03	+	0.0	-5.7874E+02	0.0
1.9200E-03	-6.8308E-03	+	0.0	-5.6799E+02	0.0
1.9800E-03	-6.8308E-03	+	0.0	-5.5562E+02	0.0
2.0400E-03	-6.8308E-03	+	0.0	-5.4164E+02	0.0
2.1000E-03	-6.8308E-03	+	0.0	-5.2606E+02	0.0
2.1600E-03	-6.8308E-03	+	0.0	-5.0889E+02	0.0
2.2200E-03	-6.8308E-03	+	0.0	-4.9015E+02	0.0
2.2800E-03	-6.8308E-03	+	0.0	-4.6984E+02	0.0
2.3400E-03	-6.8308E-03	+	0.0	-4.4797E+02	0.0
2.4000E-03	-6.8308E-03	+	0.0	-4.2454E+02	0.0
2.4600E-03	-6.8308E-03	+	0.0	-3.9957E+02	0.0
2.5200E-03	-6.8308E-03	+	0.0	-3.7308E+02	0.0
2.5800E-03	-6.8308E-03	+	0.0	-3.4507E+02	0.0
2.6400E-03	-6.8308E-03	+	0.0	-3.1555E+02	0.0
2.7000E-03	-6.8308E-03	+	0.0	-2.8456E+02	0.0
2.7600E-03	-6.8308E-03	+	0.0	-2.5209E+02	0.0

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                                                                             PAGE   1

                         MINIMUM              VCA    VERSUS TIME             MAXIMUM
                       -3.5621E+03            KK     = 2.0000E-01          1.7145E+02
 TIME          VCA        I                                                  I      VD1          KK
0.0           1.7145E+02  --------------------------------------------------+  -2.6286E+03  2.0000E-01
6.0000E-05    1.3266E+02  --------------------------------------------------+  -1.8605E+03  2.0000E-01
1.2000E-04    9.3829E+01  -------------------------------------------------+   -1.0919E+03  2.0000E-01
1.8000E-04    5.4967E+01  -------------------------------------------------+   -3.2297E+02  2.0000E-01
2.4000E-04   -4.2859E+02  ------------------------------------------+           0.0         2.0000E-01
3.0000E-04   -1.2105E+03  --------------------------------+                     0.0         2.0000E-01
3.6000E-04   -1.9286E+03  ----------------------+                               0.0         2.0000E-01
4.2000E-04   -2.5470E+03  --------------+                                       0.0         2.0000E-01
4.8000E-04   -3.0357E+03  -------+                                              0.0         2.0000E-01
5.4000E-04   -3.3720E+03  --+                                                   0.0         2.0000E-01
6.0000E-04   -3.5417E+03  +                                                     0.0         2.0000E-01
6.6000E-04   -4.2957E+02  ------------------------------------------+           0.0         2.0000E-01
7.2000E-04   -4.6503E+02  ------------------------------------------+           0.0         2.0000E-01
7.8000E-04   -5.0031E+02  ------------------------------------------+           0.0         2.0000E-01
8.4000E-04   -5.3537E+02  -----------------------------------------+            0.0         2.0000E-01
9.0000E-04   -5.7022E+02  -----------------------------------------+            0.0         2.0000E-01
9.6000E-04   -6.0482E+02  ----------------------------------------+             0.0         2.0000E-01
1.0200E-03   -6.3917E+02  ----------------------------------------+             0.0         2.0000E-01
1.0800E-03   -6.7324E+02  ---------------------------------------+              0.0         2.0000E-01
1.1400E-03   -7.0702E+02  ---------------------------------------+              0.0         2.0000E-01
1.2000E-03   -7.4049E+02  --------------------------------------+               0.0         2.0000E-01
1.2600E-03   -7.7363E+02  --------------------------------------+               0.0         2.0000E-01
1.3200E-03   -8.0643E+02  -------------------------------------+                0.0         2.0000E-01
1.3800E-03   -8.3886E+02  -------------------------------------+                0.0         2.0000E-01
1.4400E-03   -8.7092E+02  -------------------------------------+                0.0         2.0000E-01
1.5000E-03   -9.0259E+02  ------------------------------------+                 0.0         2.0000E-01
1.5600E-03   -9.3385E+02  ------------------------------------+                 0.0         2.0000E-01
1.6200E-03   -9.6468E+02  -----------------------------------+                  0.0         2.0000E-01
1.6800E-03   -9.9507E+02  -----------------------------------+                  0.0         2.0000E-01
1.7400E-03   -1.0250E+03  ----------------------------------+                   0.0         2.0000E-01
1.8000E-03   -1.0545E+03  ----------------------------------+                   0.0         2.0000E-01
1.8600E-03   -1.0834E+03  ----------------------------------+                   0.0         2.0000E-01
1.9200E-03   -1.1119E+03  ---------------------------------+                    0.0         2.0000E-01
1.9800E-03   -1.1399E+03  ---------------------------------+                    0.0         2.0000E-01
2.0400E-03   -1.1673E+03  ---------------------------------+                    0.0         2.0000E-01
2.1000E-03   -1.1942E+03  --------------------------------+                     0.0         2.0000E-01
2.1600E-03   -1.2205E+03  --------------------------------+                     0.0         2.0000E-01
2.2200E-03   -1.2462E+03  --------------------------------+                     0.0         2.0000E-01
2.2800E-03   -1.2714E+03  -------------------------------+                      0.0         2.0000E-01
2.3400E-03   -1.2960E+03  -------------------------------+                      0.0         2.0000E-01
2.4000E-03   -1.3199E+03  -------------------------------+                      0.0         2.0000E-01
2.4600E-03   -1.3432E+03  ------------------------------+                       0.0         2.0000E-01
2.5200E-03   -1.3659E+03  ------------------------------+                       0.0         2.0000E-01
2.5800E-03   -1.3880E+03  ------------------------------+                       0.0         2.0000E-01
2.6400E-03   -1.4094E+03  -----------------------------+                        0.0         2.0000E-01
2.7000E-03   -1.4301E+03  -----------------------------+                        0.0         2.0000E-01
2.7600E-03   -1.4501E+03  -----------------------------+                        0.0         2.0000E-01
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MINIMUM VCA VERSUS TIME MAXIMUM
-3.5621E+03 KK = 3.0000E-01 1.7145E+02

TIME	VCA	VDI	KK
0.0	1.7145E+02	-2.6286E+03	3.0000E-01
6.0000E-05	1.3352E+02	-2.1286E+03	3.0000E-01
1.2000E-04	9.5566E+01	-1.6282E+03	3.0000E-01
1.8000E-04	5.7589E+01	-1.1274E+03	3.0000E-01
2.4000E-04	1.9616E+01	-6.2641E+02	3.0000E-01
3.0000E-04	-1.8337E+01	-1.2527E+02	3.0000E-01
3.6000E-04	-4.3090E+02	0.0	3.0000E-01
4.2000E-04	-9.5514E+02	0.0	3.0000E-01
4.8000E-04	-1.4485E+03	0.0	3.0000E-01
5.4000E-04	-1.8949E+03	0.0	3.0000E-01
6.0000E-04	-2.2803E+03	0.0	3.0000E-01
6.6000E-04	-2.5929E+03	0.0	3.0000E-01
7.2000E-04	-2.8237E+03	0.0	3.0000E-01
7.8000E-04	-2.9668E+03	0.0	3.0000E-01
8.4000E-04	-3.0193E+03	0.0	3.0000E-01
9.0000E-04	-5.7037E+02	0.0	3.0000E-01
9.6000E-04	-6.0497E+02	0.0	3.0000E-01
1.0200E-03	-6.3932E+02	0.0	3.0000E-01
1.0800E-03	-6.7339E+02	0.0	3.0000E-01
1.1400E-03	-7.0717E+02	0.0	3.0000E-01
1.2000E-03	-7.4064E+02	0.0	3.0000E-01
1.2600E-03	-7.7378E+02	0.0	3.0000E-01
1.3200E-03	-8.0658E+02	0.0	3.0000E-01
1.3800E-03	-8.3901E+02	0.0	3.0000E-01
1.4400E-03	-8.7107E+02	0.0	3.0000E-01
1.5000E-03	-9.0274E+02	0.0	3.0000E-01
1.5600E-03	-9.3400E+02	0.0	3.0000E-01
1.6200E-03	-9.6483E+02	0.0	3.0000E-01
1.6800E-03	-9.9522E+02	0.0	3.0000E-01
1.7400E-03	-1.0251E+03	0.0	3.0000E-01
1.8000E-03	-1.0546E+03	0.0	3.0000E-01
1.8600E-03	-1.0836E+03	0.0	3.0000E-01
1.9200E-03	-1.1121E+03	0.0	3.0000E-01
1.9800E-03	-1.1400E+03	0.0	3.0000E-01
2.0400E-03	-1.1674E+03	0.0	3.0000E-01
2.1000E-03	-1.1943E+03	0.0	3.0000E-01
2.1600E-03	-1.2206E+03	0.0	3.0000E-01
2.2200E-03	-1.2464E+03	0.0	3.0000E-01
2.2800E-03	-1.2715E+03	0.0	3.0000E-01
2.3400E-03	-1.2961E+03	0.0	3.0000E-01
2.4000E-03	-1.3201E+03	0.0	3.0000E-01
2.4600E-03	-1.3434E+03	0.0	3.0000E-01
2.5200E-03	-1.3661E+03	0.0	3.0000E-01
2.5800E-03	-1.3881E+03	0.0	3.0000E-01
2.6400E-03	-1.4095E+03	0.0	3.0000E-01
2.7000E-03	-1.4302E+03	0.0	3.0000E-01
2.7600E-03	-1.4503E+03	0.0	3.0000E-01

MINIMUM -3.5621E+03 | VCA VERSUS TIME | KK = 4.0000E-01 | MAXIMUM 1.7145E+02

TIME	VCA	VD1	KK
0.0	1.7145E+02	-2.6286E+03	4.0000E-01
6.0000E-05	1.3396E+02	-2.2626E+03	4.0000E-01
1.2000E-04	9.6434E+01	-1.8963E+03	4.0000E-01
1.8000E-04	5.8901E+01	-1.5297E+03	4.0000E-01
2.4000E-04	2.1376E+01	-1.1629E+03	4.0000E-01
3.0000E-04	-1.6123E+01	-7.9583E+02	4.0000E-01
3.6000E-04	-5.3577E+01	-4.2860E+02	4.0000E-01
4.2000E-04	-9.0966E+01	-6.1256E+01	4.0000E-01
4.8000E-04	-4.3347E+02	0.0	4.0000E-01
5.4000E-04	-8.2893E+02	0.0	4.0000E-01
6.0000E-04	-1.2065E+03	0.0	4.0000E-01
6.6000E-04	-1.5573E+03	0.0	4.0000E-01
7.2000E-04	-1.8730E+03	0.0	4.0000E-01
7.8000E-04	-2.1467E+03	0.0	4.0000E-01
8.4000E-04	-2.3724E+03	0.0	4.0000E-01
9.0000E-04	-2.5457E+03	0.0	4.0000E-01
9.6000E-04	-2.6634E+03	0.0	4.0000E-01
1.0200E-03	-2.7240E+03	0.0	4.0000E-01
1.0800E-03	-6.7351E+02	0.0	4.0000E-01
1.1400E-03	-7.0729E+02	0.0	4.0000E-01
1.2000E-03	-7.4076E+02	0.0	4.0000E-01
1.2600E-03	-7.7390E+02	0.0	4.0000E-01
1.3200E-03	-8.0670E+02	0.0	4.0000E-01
1.3800E-03	-8.3914E+02	0.0	4.0000E-01
1.4400E-03	-8.7120E+02	0.0	4.0000E-01
1.5000E-03	-9.0287E+02	0.0	4.0000E-01
1.5600E-03	-9.3412E+02	0.0	4.0000E-01
1.6200E-03	-9.6495E+02	0.0	4.0000E-01
1.6800E-03	-9.9534E+02	0.0	4.0000E-01
1.7400E-03	-1.0253E+03	0.0	4.0000E-01
1.8000E-03	-1.0547E+03	0.0	4.0000E-01
1.8600E-03	-1.0837E+03	0.0	4.0000E-01
1.9200E-03	-1.1122E+03	0.0	4.0000E-01
1.9800E-03	-1.1401E+03	0.0	4.0000E-01
2.0400E-03	-1.1676E+03	0.0	4.0000E-01
2.1000E-03	-1.1944E+03	0.0	4.0000E-01
2.1600E-03	-1.2207E+03	0.0	4.0000E-01
2.2200E-03	-1.2465E+03	0.0	4.0000E-01
2.2800E-03	-1.2717E+03	0.0	4.0000E-01
2.3400E-03	-1.2962E+03	0.0	4.0000E-01
2.4000E-03	-1.3202E+03	0.0	4.0000E-01
2.4600E-03	-1.3435E+03	0.0	4.0000E-01
2.5200E-03	-1.3662E+03	0.0	4.0000E-01
2.5800E-03	-1.3883E+03	0.0	4.0000E-01
2.6400E-03	-1.4096E+03	0.0	4.0000E-01
2.7000E-03	-1.4304E+03	0.0	4.0000E-01
2.7600E-03	-1.4504E+03	0.0	4.0000E-01

APPENDIX G DISCUSSION OF GTO VSI

The discussion of the GTO VSI is separated into two parts

- device characteristics
- circuit performance

G.1 Device Characteristics [11]

A GTO thyristor is a power device which combines the good features of a thyristor and those of a transistor. Table G1 shows a comparison of these devices. Table G2 shows some specifications of three particular GTO's from different vendors.

G.1.1 Turn-On Operation

The turn-on operation of a GTO is similar to that of a thyristor. The operation can be described by using the two-transistor equivalent circuit as shown in Fig. G1.

G.1.2 Turn-Off Operation

The turn-off operation is shown in Fig. G2. The principle involved is to bypass the base current of the npn transistor via the gate turn-off circuit. The turn-off gain of a GTO is about three. This means that a reverse gate current in the order of one-third of the anode current is required to turn off a conducting GTO. The gate turn-off current is very high. However, the duration of this high current pulse is in the order of only ten microseconds. Therefore, the average power ratings for turn-on and turn-off circuits are approximately the same [12].

G.2 Circuit Performance

Since a GTO thyristor is a self-extinguishing device, no commutation circuit is required. However, normal operation creates the circumstance that the device may be turned off while it is conducting high current. This condition is similar to that which occurs in high power transistor switching and may result in very high turn-off losses. Care must be taken to operate the device within its safe operating condition specified by the device manufacturer.

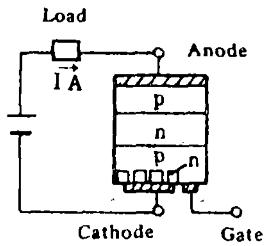
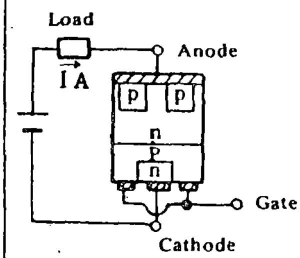
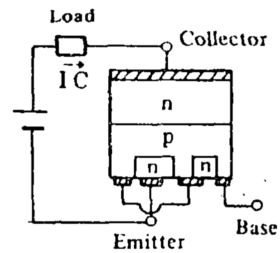
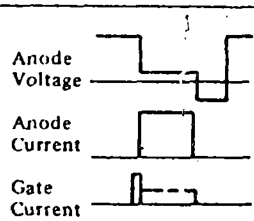
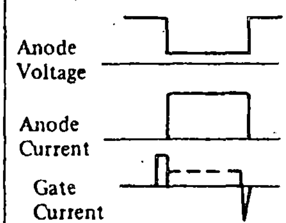
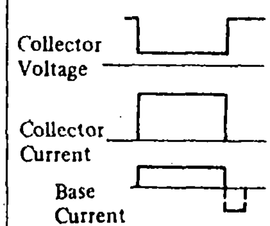
Fig. G3 shows a comparison of the application ranges of switching devices.

G.2.1 Switching Characteristics [14]

Some of the voltage and current waveforms of a GTO switching circuit are shown in Fig. G4. During the turn-on interval, the following aspects should be considered

- The GTO has a relatively high latching current, and the gate pulse must be maintained long enough such that the anode current exceeds this latching level [15].
- The feedback diodes must be the fast recovery type in order to minimize the short circuit recovery current.

TABLE 61: Comparison of Switching Devices with Each Other [11]

Devices / Characteristics, etc.		Thyristor (High-speed Type)	GTO Thyristor (Anode Shorted Emitter Construction)	Transistor (Darlington Type)
Device Construction				
Waveforms of Voltages and Currents				
Switching Operation	Turn-on	Feeds a trigger current to the gate.	Feeds a trigger current to the gate.	Feeds a base current.
	ON holding	If the anode current is greater than the holding current, the gate current is unnecessary	If the anode current is greater than the holding current, the gate current is unnecessary.	Continues to feed the base current.
	Turn-off	Breaks the anode current externally or applies a reverse voltage by a forced commutation circuit.	Feeds a reverse current to the gate.	Makes the base current zero.
Turn-off Time (Maximum value)		15 to 50μs	10μs	10μs (when the base is reversely biased.)
On-state Voltage (Maximum value)		1.5 to 2.5V	2 to 2.6V	2 to 2.5V
Drive Power		High because turn-off requires the forced commutation circuit.	Very low because both turn-on and turn-off requires only a pulse.	High because the base current is fed during the on period.
Over-current protection		Protection bv fuse	Turn-off with the gate reversely biased within a non-repetitive controllable on-state current limit or protection by fuse	Turn-off of the base current within an ASO region.
Features		1) Easily available high blocking voltage and large current capability 2) Medium-speed switching 3) No self turn-off function	1) Turned on and off by a polarity of the gate current. 2) High-speed switching and low loss 3) Available high blocking voltage and large current capability	1) Turned on and off by the control of the base current. 2) High-speed switching 3) Unavailable high blocking voltage and large current capability 4) Weak to an overload

	SYMBOLS	UNIT	Hitachi GFP 1000B25 [8]	IR 160PFT120 [9]	TOSHIBA SG800R21 [10]
off voltage	V_{DRM}	V	2,500	1,200	1,300
max current	I_{TGQ}	A	1,000	600	800
on-effective curr.	$I_{T(RMS)}$	A	400	250	400
surge current	I_{TSM}	A	7,000	1,800	6,600
gate rev. voltage	V_{GRM}	V	16	18	10
gate trigger curr.	I_{GT}	A	0.6 (TYP.)	4	0.12 (TYP.)
on voltage	V_{TM}	V	1.8 (TYP.)	3.44 (max.)	2.0 (max.)
dv/dt	dv/dt	V/μs	-	1,000	500 (min.)
di/dt	di/dt	A/μs	-	NO LIMIT	100
turn-on time	t_{gt}	μs	10	5	7.5 (TYP.)
turn-off time	t_{gq}	μs	25	8	13 (TYP.)
Junction Temp	T_j	°C	-40 to 125	-10 to 125	-40 to 115
Thermal res.	$R_{\theta JC}$	°c/w	0.05	0.075	0.04

Table G2 : Specifications of some particular GTO's
(for more details, consult manufacturers' data sheets indicated in references [8], [9] and [10])

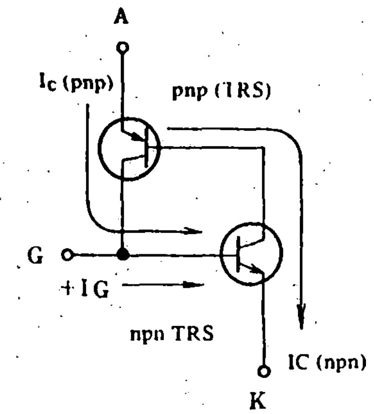


Fig. G1: Turn-on Operation [11]

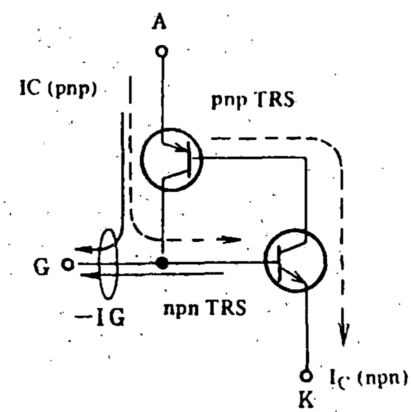


Fig. G2: Turn-off Operation [11]

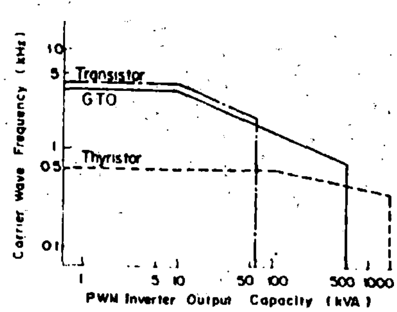


Fig.G3: Application Field of Switching Devices to PWM Inverter [13]

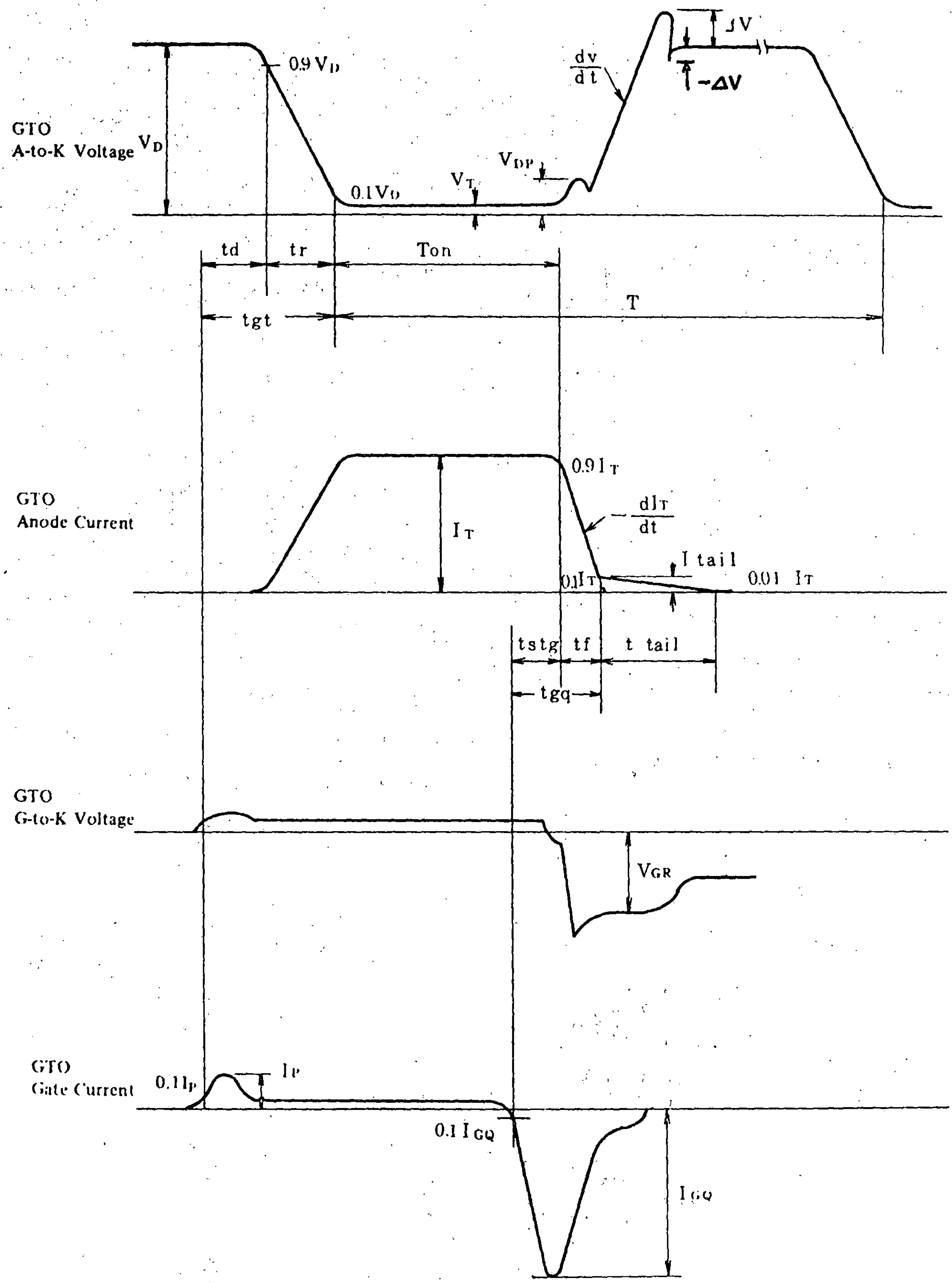


Fig. 64: Waveforms of Voltages and Currents [14]

During the turn-off interval, the following aspects should be considered

- A high negative gate current in the order of one-third of the anode current must be maintained for about 10μs (storage time plus turn-off time).

- The locus of anode voltage vs. anode current must stay inside the safe operating range.

G.2.2 Snubber Circuit

The snubber circuit for GTO thyristors is as important as that for the transistor switching circuit. Although the snubber circuit is larger than that required for a conventional thyristor, the GTO requires neither L-C components nor auxiliary thyristors for commutation.

To design the snubber circuit, the following aspects must be carefully considered

- The value of the snubber capacitor must be chosen such that it is large enough to absorb energy stored in the wiring inductance or to limit the dv/dt for safe operating conditions. At the same time, the capacitor should not be too large because the energy stored in this capacitor must be totally dissipated in the snubber resistor during the on interval. The essence of this aspect is shown in Fig. G5.

- The wiring of the snubber circuit must be made as short as possible.

- A special snubber capacitor with extremely low inductance is required.

- The snubber diode must be a fast recovery type.

G.2.3 Motor Performance

The motor performance for a GTO VSI is similar to that described in Appendix E2. Since the turn-off time of a GTO VSI is less than that of the McMurray commutated VSI, the PWM waveform can be improved.

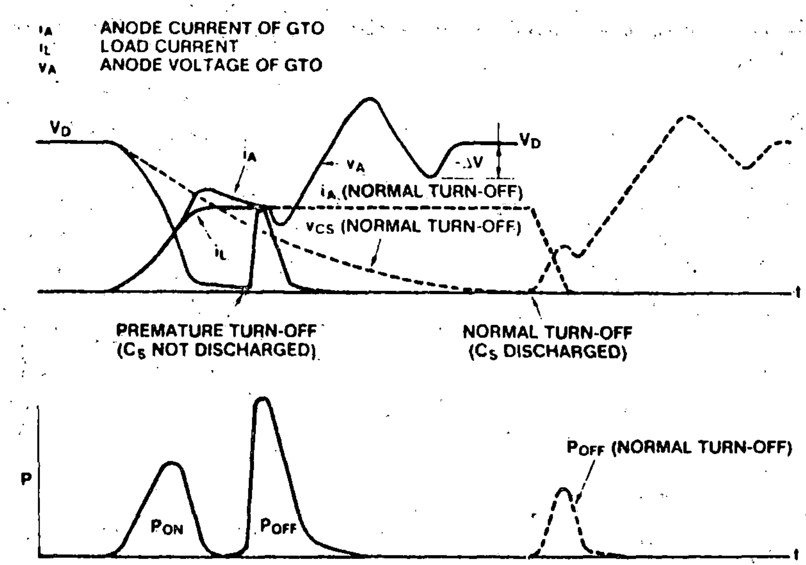


Fig. G-5: Waveforms Illustrating Operation When the Snubber Capacitor C_S is Not Able to Fully Discharge During the On-Time of the GTO. [15]

APPENDIX H COMPARISON OF CANDIDATE SYSTEMS

List of Symbols

P_m	Induction Motor (IM) Power Output
V_m	RMS Line to Line IM Terminal Voltage
I_m	RMS IM Line Current Per Phase
n	IM Efficiency
$\cos \theta$	IM Power Factor
V_{DC}	VSI DC Bus Voltage
v_{DC}	CSI Input Terminal Voltage
I_{DC}	CSI DC Bus Current
i_{DC}	VSI Input Terminal Current
V_{cp}	Peak Commutating Capacitor Voltage
V_c	RMS Commutating Capacitor Voltage (Partial)
I_{cp}	Peak Commutating Current
I_c	RMS Commutating Current
V_{peak}	Peak Voltage across a Device
I_{RMS}	RMS Current through a Device

Note: These last two symbols will be used to define the Total Component Rating (TCR) of a device.

R_{Tm}	TCR of Main Thyristors
R_{Tc}	TCR of Commutating Thyristors
R_D	TCR of Diodes
R_{Cc}	TCR of Commutating Capacitors
R_{Lc}	TCR of Commutating Inductors
R_{INV}	TCR of Inverter
R_{CB}	TCR of DC Bus Filter Capacitor
R_{LB}	TCR of DC Bus Filter Inductor
R_{TOT}	TCR of Inverter plus DC Filter
t_q	Turn Off Time of Thyristors

List of Symbols (continued)

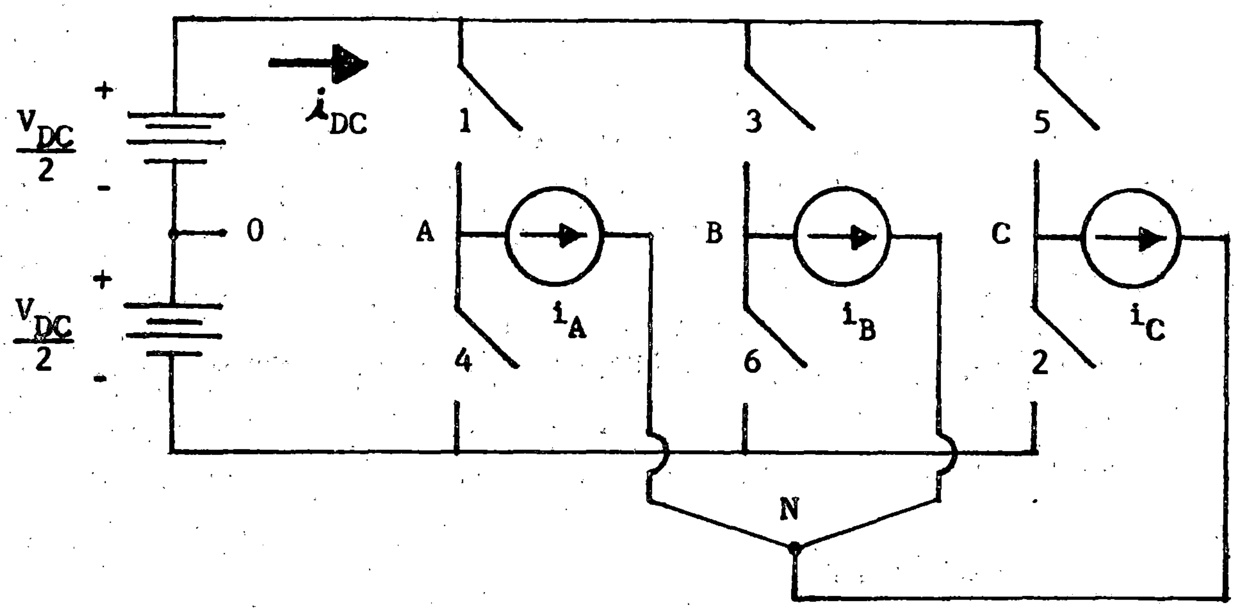
K_z	Impedance constant = 0.667
K_r	% ripple expressed as a decimal
K_I	Inverter constant used to calculate the TCR of the main thyristors in the McMurray VSI $K_I = 7.92 \times 10^3$ VA/horsepower
V_{dc}	RMS value of the ac component of the inverter input terminal voltage
I_{dc}	RMS value of the ac component of the inverter input terminal current
w_c	Commutating angular frequency
w_I	Maximum inverter output angular frequency
Z_c	Characteristic impedance of series LC circuit $Z_c = \sqrt{L/C}$

H.1 General

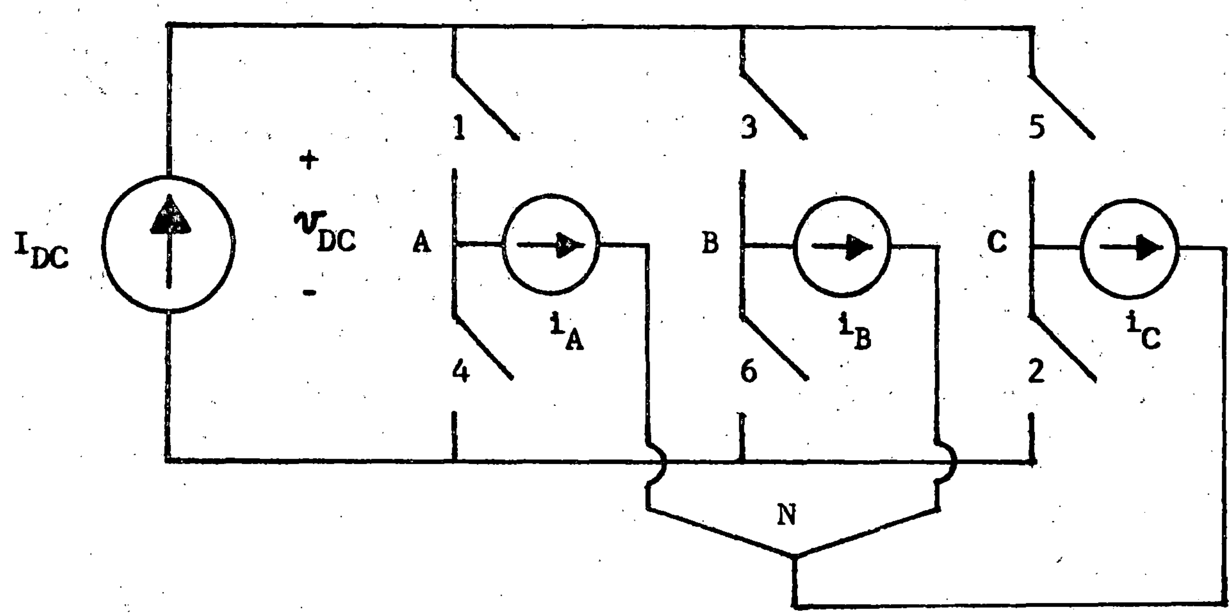
The comparison of the propulsion systems begins with the development of the total component rating (TCR). This rating is designed to indicate the power handling capability of each PCU. It is desirable to be able to compare the systems both horizontally (by internal component groups) and vertically (by total PCU component ratings).

Figure H1 shows the circuit models and Figures H2 and H3 respectively display important waveforms for the voltage and current source inverters. The calculation of the TCR for the PCU components follows from the basic assumptions listed below.

	VSI / GTO	CSI
1)	180^{o} conduction of thyristors	120^{o} conduction of thyristors
2)	Line current is sinusoidal (See Figure H2(d))	Line current is pulsed (See Figure H3(c))
3)	The dc bus voltage has an average value $V_{DC} = 1.3\ V_m$ with 10% pure sinusoidal ripple.	The inverter input terminal voltage v_{DC} has an average value $V_{DC} = (3\sqrt{3}/\sqrt{2}\pi)\ V_m$ with an ac component whose RMS value is $V_{dc} = 0.214\ V_m$. (See Figure H3(d))
4)	The inverter input current i_{DC} has an average value $I_{DC} = (3\sqrt{2}/\pi)\ I_m$ with an ac component whose RMS value is $I_{dc} = 0.06\ I_m$. (See Figure H2(e))	The dc bus current has an average value $I_{DC} = 1.3\ I_m$ with 10% pure sinusoidal ripple.

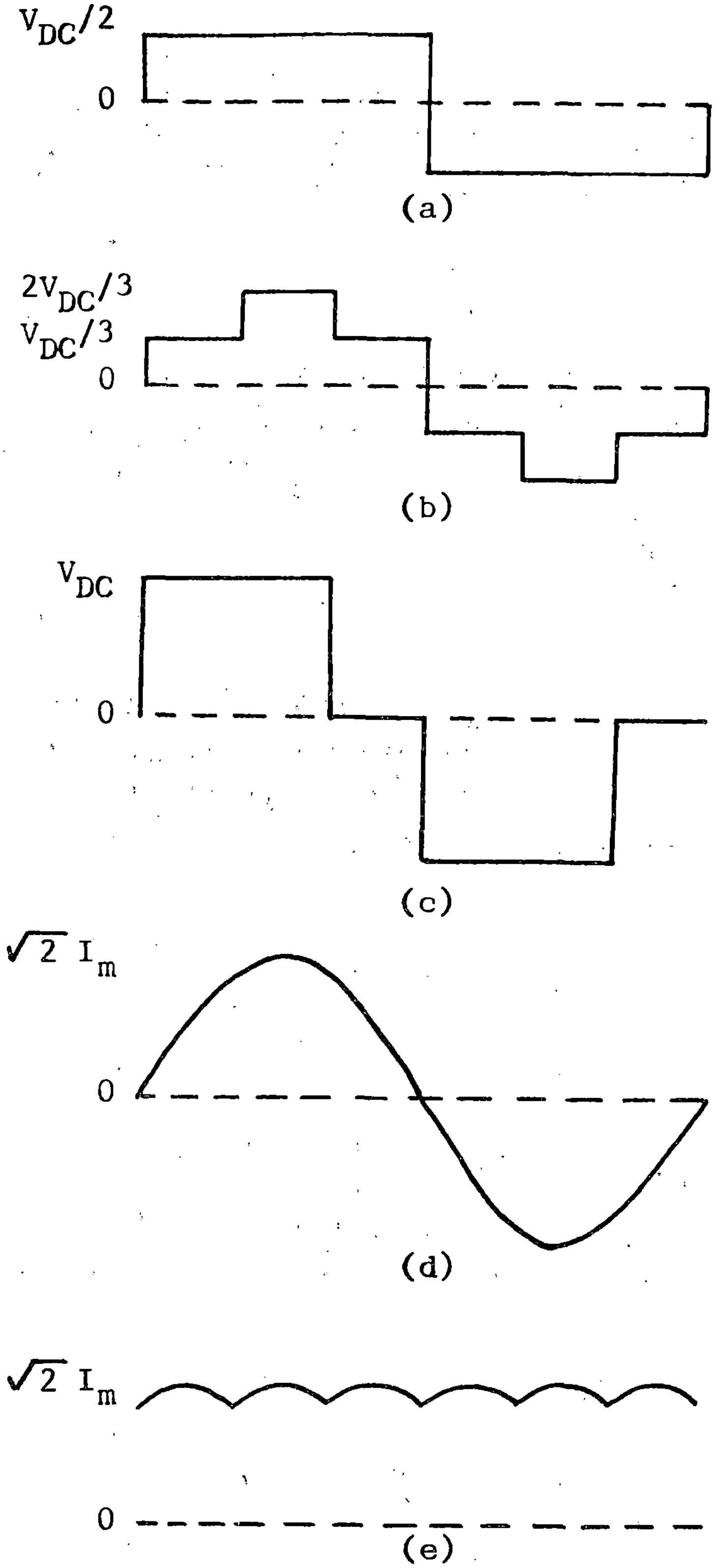


a) Voltage Source Inverter



b) Current Source Inverter

Figure H1



(a) v_{A0} Voltage from output nodes to fictitious center tap of battery. Shown to emphasize 180 degree conduction of thyristors.

(b) v_{AN} Phase voltage of standard six-step inverter.

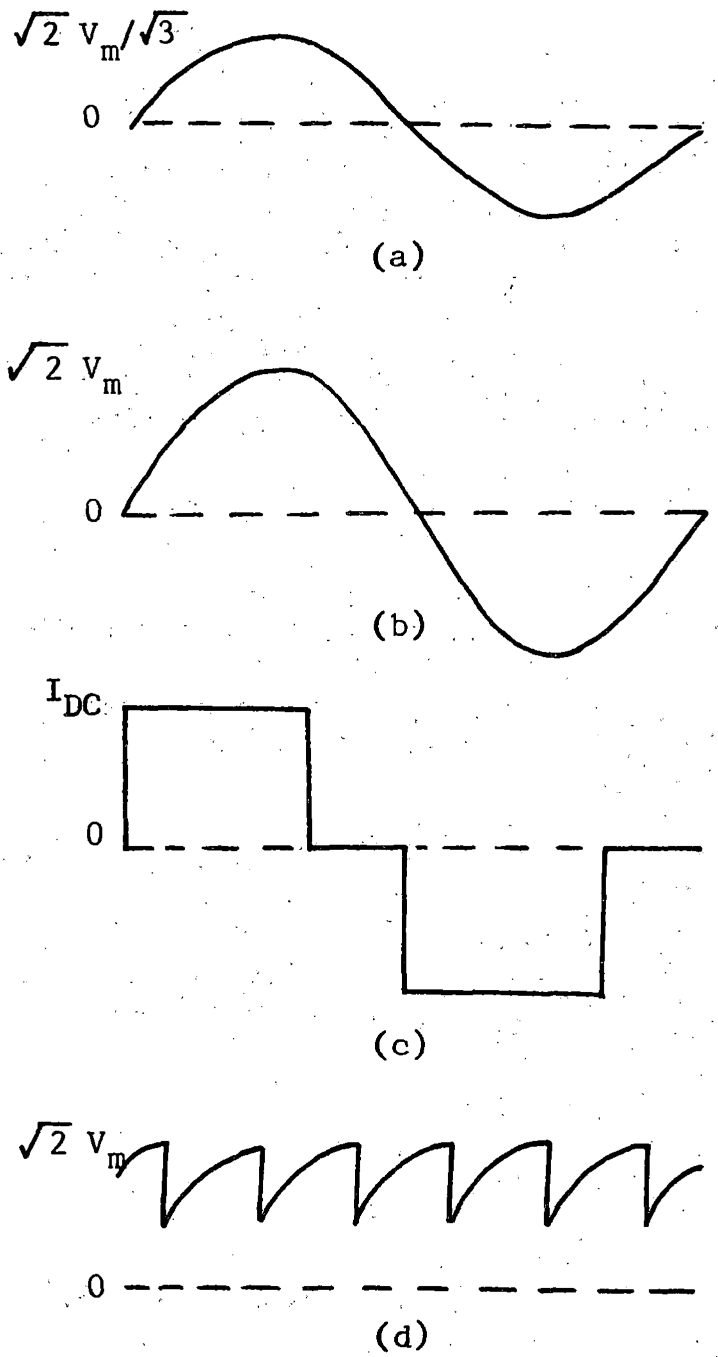
(c) v_{AB} Line to line voltage at IM terminals. RMS value of fundamental component is $V_m = \sqrt{6}/\pi \; V_{DC}$ so that $V_{DC} \cong 1.3 \; V_m$

(d) i_A The load current is assumed to be purely sinusoidal.

(e) i_{DC} The source must supply one phase of load current during each 60 degree interval. RMS value of AC component: $I_{dc} \cong 0.06 \; I_m$ $\quad I_{DC} = (3\sqrt{2}/\pi) \; I_m$

Figure H2

Ideal Voltage Source Inverter Waveforms



v_{AN} The phase voltage is assumed to be purely sinusoidal, neglecting the voltage spikes during commutation.

v_{AB} The line to line IM terminal voltage is also sinusoidal, neglecting the voltage spikes.

i_A The RMS value of the fundamental component is: $I_m = \sqrt{6}/\pi \, I_{DC}$ so that

$I_{DC} \cong 1.3 \, I_m$

v_{DC} The RMS value of the AC component of the inverter input voltage is:

$V_{dc} \cong 0.214 V_m \quad V_{DC} = (3\sqrt{3}/\sqrt{2}\pi) V_m$

Figure H3

Ideal Current Source Inverter Waveforms

The average value of the VSI inverter input current i_{DC} shown in Figure H2(e) is

$$I_{DC} = \frac{3}{\pi} \int_{(\pi/3)}^{(2\pi/3)} \sqrt{2}\, I_m \sin(wt)\, dwt \qquad = (3\sqrt{2}\, I_m) / \pi$$

The RMS value of the ac component of the VSI inverter input current i_{DC} shown in Figure H2(e) is

$$I_{dc} = \sqrt{\frac{3}{\pi} \int_{(\pi/3)}^{(2\pi/3)} (i_{DC} - I_{DC})^2\, dwt} \qquad = \sqrt{\frac{3}{\pi} \int_{(\pi/3)}^{(2\pi/3)} (\sqrt{2}\, I_m \sin(wt) - 3\sqrt{2} I_m/\pi)^2\, dwt}$$

$$I_{dc} = 0.056675\ I_m = 0.06\ I_m$$

where I_m is the RMS value of the induction motor line current.

The average value of the CSI inverter input terminal voltage v_{DC} shown in Figure H3(d) is

$$V_{DC} = \frac{3}{\pi} \int_{\pi/6}^{\pi/2} \sqrt{2}\, V_m \sin(wt)\, dwt = \frac{3\sqrt{3}}{\sqrt{2}\,\pi} V_m = 1.169\ V_m$$

The RMS value of the ac component of the CSI inverter input terminal voltage v_{DC} shown in Figure H3(d) is

$$V_{dc} = \sqrt{\frac{3}{\pi} \int_{\pi/6}^{\pi/2} (\, v_{DC} - V_{DC}\,)^2\, dwt}$$

$$V_{dc} = \sqrt{\frac{3}{\pi} \int_{\pi/6}^{\pi/2} (\, \sqrt{2}\, V_m \sin(wt) - 1.169\ V_m\,)^2\, dwt}$$

$$V_{dc} = 0.213695\ V_m = 0.214\ V_m$$

where V_m is the RMS value of the induction motor line to line terminal voltage.

The ripple frequency of the VSI dc bus voltage and the CSI dc bus current is not specified. This eliminates the restriction to a particular type of input power source. The ripple frequency would be twice the line frequency for a rectified single phase catenary input on a totally electric locomotive; or it would be six times the line frequency for a rectified three phase alternator input on a diesel powered locomotive.

The ripple frequency of the VSI input current and the CSI input voltage is six times the inverter output frequency. It is this frequency, shown in Figures H2(e) and H3(d), which determines the values of the dc filter components.

The general expressions defining the total component ratings and those applicable to a particular inverter are listed in Table H1. Each TCR has dimensions of power so that both horizontal and vertical comparison in Table 4.1 is possible.

Device	TCR	General	VSI	CSI	GTO
Thyristors (Main)	R_{Tm}	$N(2V_{peak})I_{RMS}$	$6\sqrt{2}V_{cp}I_m$	$12V_{cp}(0.75\ I_m)$	$6\sqrt{2}(1.25\ V_{DC})I_m$
Thyristors (Commutating)	R_{Tc}	$N(2V_{peak})I_{RMS}$	$6\sqrt{2}V_{cp}I_c$	-	-
Diodes	R_D	R_{Tm}	$6\sqrt{2}V_{cp}I_m$	$12V_{cp}(0.75\ I_m)$	$6\sqrt{2}(1.25\ V_{DC})I_m$
Capacitors (Commutating)	R_{Cc}	$Nw_cC(V_{RMS})^2$	$3(V_c)^2/Z_c$	$6w_IC(V_{RMS})^2$	-
Inductors (Commutating)	R_{Lc}	$Nw_cL(I_{RMS})^2$	$3(I_c)^2Z_c$	-	-
Total Inverter Rating	R_{INV}	$(R_{Tm} + R_{Tc} + R_D + R_{Cc} + R_{Lc})$			
Capacitor (DC Filter)	R_{CB}	$6w_IC_B(V_{peak})^2$	$6w_IC_B((1+\frac{1}{2}K_r)V_{DC})^2$		$6w_IC_B((1+\frac{1}{2}K_r)V_{DC})^2$
Inductor (DC Filter)	R_{LB}	$6w_IL_B(I_{RMS})^2$	-	$6w_IL_B((1+\frac{1}{2}K_r)I_{DC})^2$	-
Total PCU Rating	R_{TOT}	$(R_{INV} + R_{CB} + R_{LB})$			

Table H1

Expressions for Total Component Ratings TCR

w_c = Fundamental commutating frequency $1/\sqrt{LC}$

w_I = Maximum fundamental inverter output frequency $2\pi/(10\ t_q)$

Z_c = Equivalent characteristic impedance of LC commutating circuit $\sqrt{L/C}$

N = Number of devices

K_r = % ripple

H.2 Voltage Source Inverter TCR Calculations

The base value for the traction motor output is 600 horsepower. The IM terminal voltage, as suggested by Levi [16], is $V_m = 2$ kV. The motor power factor is selected to correspond with the motor parameters of Appendix F. The result is $\cos\theta = 0.918$ when calculated at a motor efficiency of 95%. Summarizing these results:

$P_m = 600$ hp $\qquad n = 0.95$

$V_m = 2$ kV $\qquad \cos\theta = 0.918$

The RMS value of the motor line current is

$$I_m = \frac{746\ P_m}{\sqrt{3}\ V_m\ n\ \cos\theta} = 148.16 \text{ Amperes}$$

The value of the dc bus voltage is found by equating V_m to the RMS value of the fundamental component in the Fourier series representation of the line to line IM terminal voltage. (See Figure H2(c)) This procedure leads to

$$V_{DC} = 1.3\ V_m = 2.6 \text{ kV}$$

The turn off time required by the thyristors is arbitrarily chosen to be $t_q = 25$ microseconds. As suggested by McMurray [17], the optimum values of commutating components are given by

$$L = 0.397\ (V_{DC}\ /\ I_m)\ t_q = 174.2 \text{ uH}$$

$$C = 0.893\ (I_m\ /\ V_{DC})\ t_q = 1.272 \text{ uF}$$

It is convenient to consider the commutating series LC circuit in the McMurray inverter as a lossless transmission line with a characteristic impedance given by

$$Z_c = \sqrt{L/C} = K_z\,(V_{DC} / I_m) = 11.7 \text{ Ohms}$$

where

$$K_z = \sqrt{(0.397 / 0.893)} = 0.667$$

The peak commutating current available to turn off the thyristors and the peak voltage across the commutating capacitor are given by

$$I_{cp} = V_{DC} / Z_c = 222.2 \text{ Amperes} = (I_m / K_z)$$

$$V_{cp} = (I_{cp} + I_m)\, Z_c = 4.33 \text{ kV} = (1 + K_z)\, V_{DC}$$

The RMS value of the commutating current is calculated at the highest inverter operating frequency given by

$$w_I = (2\pi/10\, t_q) = 25.13 \times 10^3 \text{ rad / second}$$

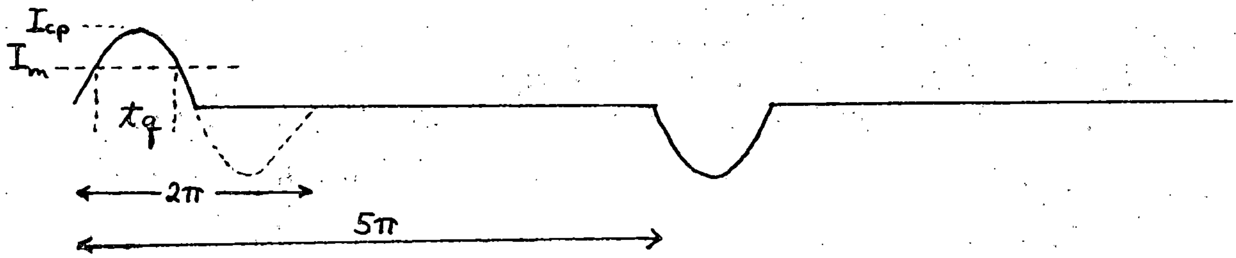


Figure H4
Commutating Current

$$I_c = \sqrt{\frac{1}{5\pi}\int_0^{\pi} (I_{cp}\sin(wt))^2\, dwt} = (I_{cp} / \sqrt{10})$$

Similarly, neglecting periods of zero current,

$$V_c = \sqrt{\frac{1}{5\pi}\int_0^{\pi} (V_{cp}\cos(wt))^2\, dwt} = (V_{cp} / \sqrt{10})$$

It is very important to note that the RMS value of voltage given by V_c is not the total RMS voltage across the capacitor. V_c is the portion of the RMS voltage due to the component waveforms which occur during periods of nonzero current. It is this partial RMS value which is used to calculate the TCR of the commutation capacitors. The same argument will be used during the calculation of the TCR for the CSI commutation capacitors.

To evaluate the TCR expressions given in Table H1, the appropriate peak and RMS voltages and RMS currents must be specified. For the McMurray VSI, the peak voltage appearing across the main thyristors, auxiliary commutating thyristors, and the reverse parallel protection diodes is equal to the peak commutating capacitor voltage.

$$V_{peak} = V_{cp}$$

The RMS current through the main thyristors is one half the peak motor current.

$$I_{RMS} = (\sqrt{2}\ I_m) / 2$$

The RMS current through the auxiliary commutating thyristors is equal to I_c. The RMS voltage across the commutating capacitors for the purpose of the TCR calculation is V_c.

The diodes carry the excess commutation current above the load current, which is assumed to be constant during commutation. Besides the excess commutation current, the diodes may carry the full load current for as much as one quarter cycle in the case of a purely inductive load. For these reasons, and to allow for light loading conditions, the TCR of the reverse parallel protection diodes is conservatively chosen to be the same as the main thyristors.

Proceeding with the calculations:

			Normalized
$R_{Tm} = R_D =$	$6\sqrt{2}\, V_{cp} I_m$	$= 5.448 \times 10^6$ VA	1.0
$R_{Tc} =$	$6\sqrt{2}\, V_{cp} I_c$	$= 1.827 \times 10^6$ VA	0.335
$R_{Cc} =$	$3\,(V_c)^2 / Z_c$	$= 0.482 \times 10^6$ VA	0.0883
$R_{Lc} =$	$3\,(I_c)^2 Z_c$	$= 0.1733 \times 10^6$ VA	0.0318

The above normalized values appear in the VSI column of table 4.1.

H.2.1 Development of Main Thyristor Rating in VSI For use with Table 4.1

$$R_{Tm} = \frac{K_I P_M}{n \cos\theta}$$

Beginning with the definition of R_{Tm} given in Table H1

$R_{Tm} = 6\,(2\, V_{peak})\, I_{RMS}$

Substitute $V_{peak} = V_{cp} = (1 + K_z)\, V_{DC}$

and $V_{DC} = 1.3\, V_m$ so that $V_{peak} = (1 + K_z)(1.3)\, V_m$

Also substitute for $I_{RMS} = \frac{1}{2}(\,2\, I_m)$

And finally substitute for $I_m = \dfrac{746\, P_m}{\sqrt{3}\, V_m\, n \cos\theta}$

$$R_{Tm} = \frac{(6)(2\,(1+K_z)(1.3))(746\, P_m)}{\sqrt{3}\, n \cos\theta}$$

Define $K_I = 6 \times 2 \times (1+0.667) \times 1.3 \times 746 / \sqrt{3} = 7.92 \times 10^3$ VA/horsepower

H.2.2 Selection of VSI DC Filter Capacitance & TCR Calculation

The dc filter capacitor is chosen both to maintain the dc bus voltage within the maximum percent ripple and to provide the ac component of inverter input terminal current. Beginning with the volt-ampere relationship C dv/dt = i, the value of the dc filter capacitance may be estimated as follows

$$C_B = (\Delta t / \Delta V)\, I_{dc} = 142.44 \text{ uF}$$

where

Δt = period of the ac variation of the inverter input current evaluated at the lowest inverter output frequency, 60 Hz. The frequency of the ac variation is 6 x 60 Hz.

$$\Delta t = 1 / (360 \text{ Hz}) = 2.78 \text{ milliseconds}$$

ΔV = % ripple times the dc bus voltage

$$\Delta V = K_r V_{DC} = (0.1) V_{DC} = 260 \text{ Volts}$$

I_{dc} = RMS value of the ac component of the inverter input current shown in Figure H2(e)

$$I_{dc} = 0.06 I_m$$

The TCR of the dc filter capacitor is given by

$$R_{CB} = 6w_I C_B (V_{peak})^2 = 160.1 \times 10^6 \text{ VA} = 29.384 \text{ Normalized}$$

where

$$V_{peak} = (1 + \tfrac{1}{2} K_r) V_{DC} = (1.05) V_{DC} = 2.73 \text{ kV}$$

H.3 Current Source Inverter TCR Calculations

The base horsepower and induction motor characteristics are the same as those used for the VSI calculations, with one important exception. The IM terminal RMS line to line voltage is no longer fixed at 2 kV.

One of the major problems encountered with the implementation of the current source inverter is the presence of large magnitude voltage spikes which appear across the IM terminals during commutation. Certainly the induction motor would be designed specifically to operate with a CSI drive. However for the purpose of the TCR calculations we assume the same motor parameters and restrict the peak magnitude of the IM terminal voltage to be the same as that for the VSI system.

Going one step further, we choose a specific commutating capacitance value from the simulation in Appendix F so that the magnitude of the voltage spike will be 50% above that of the fundamental sinusoid magnitude. This procedure gives a value for the line to line RMS IM terminal voltage of

$$V_m = 2 \text{ kV} / (1.5) = 1.33 \text{ kV}$$

with a commutating capacitance of (See Appendix F)

$$C_c = \frac{(0.4)\ I_{C0}}{(12)(377)\ V_{C0}} = 27.48 \text{ uF} \quad \text{with } I_{C0} = 277 \text{ Amperes}, \quad V_{C0} = 2800 \text{ Volts}$$

The RMS IM line current is found in the same way as before.

$$I_m = \frac{746\ P_m}{\sqrt{3}\ V_m\ n \cos\theta} = 222.24 \text{ Amperes}$$

In the ideal current source inverter, the line current is assumed to have the pulsed waveform shown in Figure H3(c). The value of the dc bus current is found by equating I_m to the RMS value of the fundamental component in the Fourier series representation of this waveform. The resulting dc bus current is

$$I_{DC} = 1.3\ I_m = 288.9 \text{ Amperes}$$

Again, to calculate the TCR's for the CSI components, peak and RMS voltages and currents must be specified. The peak voltage across the commutation capacitors is the same as the peak IM line to line voltage.

$$V_{cp} = 2\sqrt{2}\ \text{kV} = 2.83\ \text{kV}$$

This is the same voltage which must be supported by the main thyristors and diodes. The RMS value of the current through the thyristors and diodes is given by

$$I_{RMS} = I_{DC} / \sqrt{3} = 0.75\ I_m = 166.68 \text{ Amperes}$$

The TCR of the main thyristors and diodes as given in Table H1 is

$$R_{Tm} = R_D = 12\ V_{cp}\ (0.75)\ I_m = 5.657 \times 10^6\ \text{VA}$$

The normalized value is 1.038.

The TCR of the commutating capacitors presents the same type of difficulty with the RMS voltage as was encountered with the VSI system. Periods of zero capacitor current are discounted in the partial RMS calculation. The change in voltage during capacitor charge and discharge is approximated as linear. The time interval of nonzero current, which occurs three times per cycle, is approximately (π/ 9) radians.

The approximate partial RMS voltage V_c is calculated from the waveforms shown in Figure H5 on the following page.

$$V_c = \sqrt{\frac{9}{\pi} \int_0^{\pi/9} \left(\left(2\ V_{cp} / (\pi/9)\right) (wt) \right)^2 dwt}$$

$$V_c = 0.385\ V_{cp} = 1.089\ \text{kV}$$

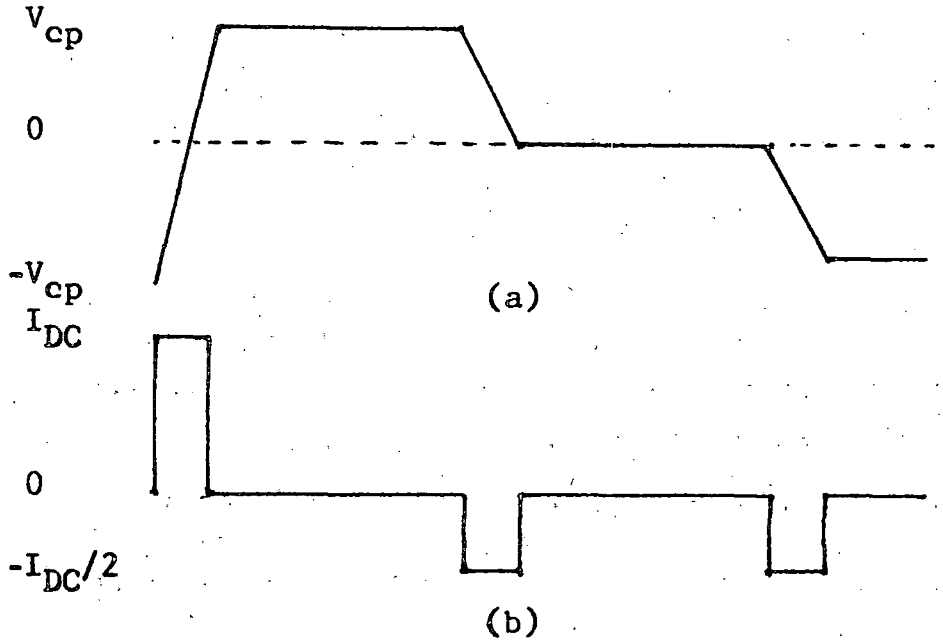


Figure H5
Approximate CSI Commutating Capacitor Waveforms
(a) Voltage
(b) Current

The TCR of the commutating capacitors is given by

$$R_{Cc} = 6w_I\, C\, (V_c)^2 = 4.914 \times 10^6 \text{ VA}$$

The normalized value is 0.902 which turns out to be about twice the rating of the commutation components in the VSI system (including the auxiliary thyristors).

The RMS value of the above current waveform, Figure H5(b) is

$$I_c = \sqrt{\frac{1}{2\pi}\left[\int_0^{\pi/9}(I_{DC})^2\, dwt + \int_0^{\pi/9}(I_{DC}/2)^2\, dwt + \int_0^{\pi/9}(I_{DC}/2)^2\, dwt\right]}$$

$$I_c = 0.288\, I_{DC} = 0.374\, I_m$$

H.3.1 Selection of CSI DC Filter Inductance & TCR Calculation

The dc filter inductor is chosen to maintain the dc bus current within the maximum specified percent ripple while supporting the inverter input terminal ac voltage. Beginning with the volt-ampere relationship L di/dt = v, the value of dc filter inductance may be estimated as follows

$$L_B = (\Delta t / \Delta I)\, V_{dc} = 27.39 \text{ mH}$$

where

Δt = period of the ac variation of the inverter input voltage evaluated at the lowest inverter output frequency, 60 Hz. The frequency of the ac variation is 6 x 60 Hz.

$$\Delta t = 1 / (360 \text{ Hz}) = 2.78 \text{ milliseconds}$$

ΔI = % ripple times the dc bus current

$$\Delta I = K_r I_{DC} = (0.1) I_{DC} = 28.89 \text{ Amperes}$$

V_{dc} = RMS value of the ac component of the inverter input terminal voltage shown in Figure H3(d)

$$V_{dc} = 0.214\, V_m$$

The TCR of the dc filter inductor is given by

$$R_{LB} = 6w_I L_B (I_{RMS})^2 = 380.04 \times 10^6 \text{ VA} = 69.73 \text{ Normalized}$$

where

$$I_{RMS} \cong (1 + \tfrac{1}{2} K_r) I_{DC} = (1.05) I_{DC} = 303.35 \text{ Amperes}$$

H.4 GTO Voltage Source Inverter TCR Calculations

Since the basic inverter circuit topology is the same for the GTO VSI and the McMurray VSI, the basic waveforms are also the same. The important exception is the absence of the series LC commutating circuit.

The major advantage here, besides the obvious reduction in size, is the smaller voltage rating and hence TCR of both the main thyristors and reverse parallel diodes. Figure G4 in Appendix G shows that there is about a 25% increase in voltage above the dc bus level during commutation. This compares with a 66.7% increase in the McMurray VSI. The resulting reduction in the TCR is about 25%.

$$R_{Tm} = R_D = 6\sqrt{2}\,(1.25\ V_{DC})\ I_m = 3.066 \times 10^6\ \text{VA}$$

The normalized value is 0.75. Of course, the dc bus filter capacitor and its TCR are the same as for the McMurray VSI.

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