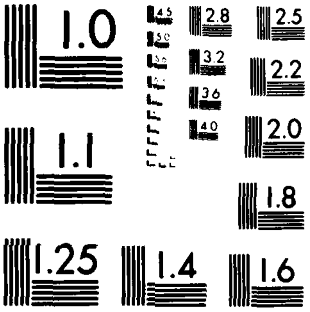
AD-A089 299 CIVIL ENGINEERING LAB (NAVY) PORT HUENEME CA F/G 20/12
SOLID STATE TRANSFORMER CONCEPT DEVELOPMENT.(U)
APR 80 J L BROOKS
UNCLASSIFIED CEL-TN-1575 NL

END
DATE
FILMED
10 80
DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

LEVEL II (12)

Technical Note

CEL

TN no. N-1575

title: SOLID STATE TRANSFORMER CONCEPT DEVELOPMENT

author: James L. Brooks

date: April 1980

sponsor: Naval Material Command

program nos: Z-R000-01-168

CIVIL ENGINEERING LABORATORY
NAVAL CONSTRUCTION BATTALION CENTER
Port Hueneme, California 93043

Approved for public release; distribution unlimited.

(16) ZR00001, WR02103

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER (14) CEL-TN-1575
2. GOVT ACCESSION NO. AD-A089299 ~~DN887100~~
3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) SOLID STATE TRANSFORMER CONCEPT DEVELOPMENT
5. TYPE OF REPORT & PERIOD COVERED (9) Final rept. Oct [illegible]78 – Sep [illegible]79
6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) James L. Brooks
8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS

CIVIL ENGINEERING LABORATORY
Naval Construction Battalion Center
Port Hueneme, California 93043

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS (17) 61152N; R021-03; ZR00001168, WR02103
11. CONTROLLING OFFICE NAME AND ADDRESS

Naval Material Command
Washington, DC 20360

12. REPORT DATE (11) Apr[illegible]80
13. NUMBER OF PAGES 47
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) (12) 51
15. SECURITY CLASS. (of this report) Unclassified
15a. DECLASSIFICATION DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

DTIC ELECTE SEP 19 1980 D

18. SUPPLEMENTARY NOTES

C

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Semiconductor, solid state, power transistor, power system, power converter.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes an effort made to determine the feasibility of developing a circuit using power semiconductor devices to duplicate the function of the power transformer. A circuit concept has been developed which duplicates the primary function of voltage stepup/stepdown but does not demonstrate the DC isolation characteristic of normal transformers. Several characteristics of the circuit appear very attractive, such as increased voltage regulation and relatively high efficiency.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

391111

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(*When Data Entered*)

Library Card

Civil Engineering Laboratory
SOLID STATE TRANSFORMER CONCEPT DEVELOPMENT (Final), by J. L. Brooks
TN-1575 47 pp illus April 1980 Unclassified

1. Solid-state power transformer 2. Semiconductors I. Z-R000-01-168

This report describes an effort made to determine the feasibility of developing a circuit using power semiconductor devices to duplicate the function of the power transformer. A circuit concept has been developed which duplicates the primary function of voltage stepup/stepdown but does not demonstrate the DC isolation characteristic of normal transformers. Several characteristics of the circuit appear very attractive, such as increased voltage regulation and relatively high efficiency.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(*When Data Entered*)

CONTENTS

INTRODUCTION

Electrical power transformers are used primarily as voltage transformation devices in alternating current (AC) systems. That is, the voltage input is either transformed up to a higher level, or down to a lower level. In the distribution of electrical energy, it is customary to transform the voltage up to a high level at the generating source, distribute the energy via transmission lines at the high level, then transform the voltage back down to a lower level for use by the load. This is the most efficient means of distribution over long distances. Over short distances, the transformer is used merely to adapt loads designed for different voltages to the local distribution system.

The power transformers consist of insulated copper wire wound on an iron core and in their simplest form consist of two windings usually referred to as the primary winding and the secondary winding. The turns ratio of these two windings establishes the voltage step-up or step-down capabilities of the device. At the very low power levels a single winding is sometimes used in a configuration referred to as an auto-transformer. In these devices, the input/output voltage ratio is varied by a sliding contactor, making electro-mechanical contact with non-insulated portions of the single winding.

The thrust of this study has been to develop a concept using semiconductor (solid state) devices arranged in a circuit configuration which will have the same functional characteristics as described above but with additional advantages. The hardware is expected to be smaller in size and to weigh less. In addition, the life cycle costs are expected to be less by virtue of increased efficiency and automatic load regulation.

BACKGROUND

The electrical power transformer has been the backbone of the electric utility distribution system for many years. The power transformer has a very high efficiency (98%) and a history of very good reliability. However, in these days of energy consciousness and environmental restrictions, all aspects of electrical hardware engineering - from power generation through distribution to the end use - are subject to question, even the trusted transformer.

There are applications of electrical power, especially in the military, where even the smallest of wave form defects/abnormalities cannot be tolerated, such as communication stations or data processing facilities. In addition, the Navy specifically has a problem in providing power to berthed ships because of the heavy electrical loads represented by ships of all classes. Not only are these loads heavy but they are variable and intermittent, which causes severe voltage regulation problems.

Yet another problem is that the Navy has thousands of Askarel filled transformers, many of which are quite old. Askarel is a liquid formulated from polychlorinated biphenyl (PCB) and is now classified as a highly toxic, nonbiodegradable pollutant under Title 40, Code of Federal regulations [illegible]

Agency will no longer allow the sale of Askarel-filled transformers. Those transformers in the "field" must have the Askarel removed and replaced by a substitute coolant in the near future. Unfortunately, the substitute liquids are more expensive and do not carry the same fireproof rating as Askarel, resulting in yet higher costs for compensating external fire protection provisions in the installations. Even "dry-pack" type transformers are not the answer since they are not considered fireproof by the National Fire Protection Agency either; therefore they cannot be used in certain locations. Indeed, an alternative to the conventional electrical power transformer as we know it today is desirable.

Any large user of electrical power such as the Navy will view even 1/2% increase in efficiency worthwhile because of the rising cost of electrical power. While 98% efficiency sounds extremely good, the 2% loss is a steady, constant loss, 24 hours of every day, which is primarily associated with the core losses of the transformer. This loss occurs whether the transformer is loaded or not. Therefore, a better measure of cost effectiveness is not the classical efficiency of the transformer but one which includes a "use" factor which may be spread over the life of the installation.

Specific Navy shore-to-ship electrical power problems described in this document are a direct result of an engineering workshop which was held at Western Division, Naval Facilities Engineering Command (WESTNAVFAC) on 14 September 1978 (Ref 1).

The Naval shipyards and operating Naval stations have different functions and must provide different types of utility services to the ships. The shipyards will provide long-term service, measured in months and years, for an incomplete ship and generally will not have to support an operational crew. The shipyards also provide separate power services (super shore power) for special equipment testing while the operating Naval stations do not. On the other hand, a larger part of services provided by Naval stations are for complete ships on short-term visits in port in "cold iron" state; i.e. with their power plants completely shutdown.

In many instances, ships will request connections for the amounts of power indicated in the Design Manual (DM-25), then actually use 50 - 75% of these amounts. In other instances, the ship will require much more power than indicated in DM-25, due to ship modifications--especially the addition of air conditioning. A minimum of 5 years' advanced planning is required by NAVFAC, or the home port of the ship, and other locations where ships of the class regularly berth, to provide the revised shore power requirements. The Naval Sea System Command Headquarters must provide data on all changes in shore power requirements as soon as the ship is scheduled for modifications.

The voltage for shipboard power systems as specified in MIL-STD-1399 (Navy) Section 103 is 440 volts, three phase with a tolerance of ± 5% (418-462 volts). The comparable industrial voltage is 480 volts ungrounded (or 480/277 grounded). To supply the proper voltage, the transformer taps must be adjusted or special transformers ordered. At some activities the voltage is higher than specified and has caused problems, especially in shipboard electronic equipment. The transformer taps are adjusted to deliver the required voltage at full load during the day at most activities; but long cable lengths and load changes cause voltage changes. Some utilities do not hold voltage regulation, especially at night. The voltage on the primary side goes up as the load goes down. The primary voltage drop caused by the high load current during the day is greatly reduced at lower load; therefore, the voltage at the ship's terminals frequently exceeds the allowable maximum. The tap changers on the transformers manufactured to the usual specifications are not adequate for the frequent adjustments and become a maintenance problem or fail completely. Automatic voltage regulators for the primary feeders to the piers may be necessary in some instances.

Where the utility voltage is suspected of wide variations, the voltage at the main incoming substation should be measured to determine the actual variations. The voltage problems in the pier area may be partially due to inadequate cable serving the pier area. Voltage regulators must sometimes be installed on the primary feeders at the pier area. In these instances, more rigid specification for transformers are required to provide the manually adjusted tap changers to be built for severe service and for longer contact life.

These specific electrical distribution transformer problems coupled with the rising cost of electrical energy and environmental factors show the need for long range research and development to meet the Navy's electrical energy requirements of the future.

CONCEPT DEVELOPMENT

Based upon a preliminary investigation conducted during FY78, it became clear that by arranging solid state circuit components in certain configurations, it was possible to duplicate some of the characteristics of a conventional transformer. For example, by using high frequency switching techniques, circuits were presented which clearly perform the sinewave voltage step-up or step-down characteristics. However, these circuits required too many components, were not flexible enough to permit feedback and automatic control of the output voltage, and were too inefficient. Further investigation was necessary to specify the desirable characteristics and search for an optimum technology to achieve them.

To place bounds on the concept, specify the desired characteristics, and search for an optimum configuration, the following criteria for additional investigation was formulated; and a study contract was awarded.

The contractor was tasked to perform a study to determine the feasibility of using solid state power devices to duplicate, and improve upon, the performance of a power transformer. The study was confined to a search for an optimum circuit configuration which uses a few bulk power handling solid state devices to obtain the desired high power voltage transformation function. The desired configuration and technical specifications for this approach were outlined as shown in Figure 1. A complete computer simulation of the final circuit configuration was required to accurately specify each solid state component required. In addition, an analysis of the computer waveform printouts of input and output voltages were required to verify performance.

The study has been completed, and the contractor's report is included herein as the Appendix. This report describes two approaches to the problem. The first approach details a circuit which neatly fits the step-down transformation requirements; however, it cannot step-up the voltage and, therefore, has only limited application. The second approach has the sought after step-up/down characteristic and a minimum number of components. The step-up/down solid state transformer described in the contractor's report demonstrates, by computer simulation, that not only can the output voltage be changed at will, but the sought after voltage regulation is readily available. A block diagram of the circuit is shown in Figure 2. The circuit utilizes pulse width modulation in the switching control to accomplish the output voltage wave shape control. The input and output voltages are governed by the relationship:

$$V_o = -\frac{D}{1 - D} V_{in}$$

where V_o = output voltage
V_{in} = input voltage
D = pulse width duty cycle

The pulse width duty cycle normally varies from 0 to 1 in pulse width modulation schemes. Obviously, in this application, it must be limited to less than 1. In addition, the feedback circuit is duty cycle dependent which can lead to stability problems unless carefully controlled.

As stressed in the contractor's report the solid state bidirectional chopper switches are the most critical components in the system. It appears that the chopper switch requirements for a voltage step-up circuit or a voltage step-down circuit are readily met by the present off-the-shelf solid state components. However, the chopper switch requirements for the step-up/down circuit appears to stretch the limits of existing solid state devices, even for the modest 1.2 kVA system studied.

The predicted efficiency of the circuit was given at 95% with indications that this can be increased somewhat. The voltage regulation was given at ±1% for both maximum and minimum load and for both leading and lagging power factor. One interesting characteristic of the step-up/down circuit is the fact that the output voltage is 180 degrees out of phase with the input voltage. This is regarded as neither an asset or a drawback. One final comment on all the circuits considered in the report is that they do not provide the isolation between input and output that is characteristic of conventional transformers with separate windings. This characteristic is probably achievable but at the price of increased complexity.

ECONOMIC ANALYSIS

Forty-eight percent of the total energy demand by the Naval Shore Facilities for FY-76 was for electrical power utilized in four major categories (Ref 2). If it were assumed that consumption patterns are unchanged and if actual FY79 data are used, the projected energy consumption and costs for the four categories are derived (see Table 1).

All of the electrical power utilized was delivered through one or more power transformers. If it were assumed that each distribution leg had only one transformer and that the load was within 80% of the rated load capacity of the transformer, the electrical energy was then delivered at 98% efficiency. Thus, only a 2% loss was incurred, and only $8.68 million were lost.

Unfortunately, the real world is much more complicated. First, there are almost always two or more transformers utilized in distributing the electrical energy to the load. Second, the power transformer maintains its excellent efficiency only at or near full load. The efficiency curve of a typical power transformer is shown in Figure 3. Note that if the load demonstrates a power factor (which most loads do) the efficiency curve drops another 1.5% to 2%. The larger problem, however, is the wide diversity in loading and the inability of the power transformer to maintain its high efficiency over a widely diversified load.

The Navy shore facilities use electrical power in many different ways, and each use has different demand patterns, depending on many variables, such as weather conditions, physical location of the facilities, workday patterns, service to ships or planes, functional requirements (e.g., radio transmitting station), and age of equipment. To assess the impact of all these variables to obtain exact figures on electrical energy usage was beyond the scope of this effort.

Instead, a simplified analysis was undertaken which was to show that the inefficiencies associated with the way electrical equipment is used, rather than the equipment itself, can be very costly. Referring to the domestic electrical power demand curve of Figure 4, the power transformer supplying this load is operating at widely diversified demand levels throughout the 24-hour day. For each demand level, the operating efficiency η is different. Therefore, an effective efficiency η_{eff} must be used to evaluate the performance of the power transformer supplying such a widely diversified load.

An expression for the effective efficiency of the transformer may be written as:

$$\eta_{eff} = \frac{P_1T_1\eta_1 + P_2T_2\eta_2 + \dots P_nT_n\eta_n}{P_1T_1 + P_2T + \dots P_nT_n}$$

where

P_n = Power input to transformer during time period n.

T_n = Time period n.

η_n = Efficiency of transformer during time period n.

For transition periods, a straight line slope may be assumed, such that the average efficiency between start and stop times may be used for the duration of the transition.

If this procedure is followed for the domestic load demand as shown in Figure 4, the effective efficiency of the power transformer is:

$$\eta_{eff} = 93.4\%$$

When this procedure is followed for the (single work shift) industrial load shown in Figure 5, the effective efficiency of the transformer is:

$$\eta_{eff} = 95.9\%$$

It thus becomes obvious that a normally very efficient, but load-dependent, device is delivering less than optimum performance simply because of the way it is used. As a matter of fact, the situation is somewhat worse than stated for the industrial load transformers because not only are they idle for most of each 24-hour work day, but they are usually completely idle for weekends and holidays. A simple calculation of the effective efficiency of the industrial load for a full year are based on the following numbers of days:

336 days total
113 days (weekends + holidays)
253 workdays

This translates into:

6,380.5 hours @ 5% load
2,150.5 hours @ 100% load
253 hours @ 52.5% load

Therefore,

$$\eta_{eff} = \frac{(.05)(6380.5)(.862) + (1)(2150.5)(.97) + (.525)(253)(.916)}{(.05)(6380.5) + 2150.5 + (.525)(253)}$$

$$\eta_{eff} = 95.4\%$$

This means that during 1979, where a total of $265 million were spent supplying both industrial and domestic loads between 93% and 96%, that 4% to 7% ($10.6 to $18.5 million) was wasted due to the normal inefficiencies of the standard distribution equipment we use and the way we use it.

For this reason, technological advances such as the solid state transformer, which appears to be able to operate at 95% efficiency independent of load diversity, seems attractive for certain applications. Unfortunately, at this stage, a true economic analysis is not possible because the cost of the solid state transformer (on a production basis) cannot yet be estimated. In addition, other factors such as the equipment reliability and performance under adverse conditions, (e.g., overload, short circuit, transient line conditions) are not yet fully understood.

DISCUSSION

Conserving electric energy helps to conserve oil, gas, and coal supplies used in the generation of electricity at the fossil-fueled power plants. Power plant (boiler and generator) losses and transmission and distribution losses that occur between the plant and the load account for about 70% of the energy used in generating electricity. Therefore, increasing the efficiency of the distribution and controlling the load losses reduce the consumption of fossil-fuel sources by a factor of more than three.

Exact and detailed figures for the consumption of electrical energy by the Navy Shore Facilities worldwide are not available in the literature; instead, averaged figures, which do appear in the literature, must be relied upon. For example, at certain Naval activities, 45% of the electrical power consumed was for service to berthed ships. In addition, the average utilization was between 65% and 66% of the electrical power available while the ships were connected (Ref 3).

Additional problems become apparent when several ships are nested at one transformer; the feeders to the ship closest to the pier are much shorter than the feeders to the ship farther away. Because of the voltage drop in the feeders, the voltage at the ship closest to the pier will be higher than the voltage at the ship farthest from the pier (Ref 4). Therefore, every time a change occurs in the berthing pattern (nesting) a corresponding change in the voltage output of the pier transformer must be made (tap changing). These changes must be made manually and represent manpower requirements and expenses.

Equipment selection and operating policies can also affect losses in electrical equipment. Energy can be saved by properly selecting transformers based on no-load and load losses and an estimation of the total losses for the expected load cycles. Transformers which are oversized will have needlessly high core losses which are continuous as long as the transformer is energized. For existing equipment, losses can be minimized by selective operation of transformers when the system is partially loaded. For example, net losses may be reduced if a lightly loaded transformer can be de-energized and its load picked up by another transformer. The core-loss savings for the de-energized transformer will sometimes be more than the increased copper losses on the second transformer. Personnel should be made aware of the operating points at which it becomes economical to consolidate transformer and circuit loading. This could also be incorporated into an energy management and control system. It should be noted that it may be necessary to heat some de-energized transformers to prevent condensation, which could reduce their lifetimes (Ref 5).

While the solid state transformer concept, with its promise of high efficiency independent of load diversity and with its promise of superior voltage regulation, appears to answer the future Navy requirements for shore-to-ship power, many other applications where these characteristics may be applied are possible. For example, it appears possible to extend the concept somewhat to effect an excellent motor controller. This motor controller would have the ability to cause the motor to run at maximum efficiency independent of the load.

In addition to concept extension, the voltage regulation characteristics of the solid state transformer may be used to effect energy savings. One example is the ability to trim the load voltage in much the same manner as the power companies do during periods of peak demand.

Another concept which makes use of all the characteristics of the solid state transformer is in direct replacement of fluorescent light transformers. In this application a high voltage is used for initiating tube ionization and a low voltage is used to maintain the tube discharge once it is established. Also, it appears feasible to change the output frequency of the solid state transformer at will, which would enable the fluorescent lamp to operate more efficiently.

In short, it appears that the solid state transformer concept could become the building block of most electrical energy conservation schemes of the future.

CONCLUSIONS

The following conclusions are based on the results of the preliminary feasibility study on the basic concept of a solid state transformer:

1. The output voltage regulation of the solid state transformer far exceeds the obtainable voltage regulation of conventional power transformers (i.e., 1% versus 10%).

2. The operating efficiency of the solid state transformer is basically independent of load diveristy and is relatively high (95%).

3. The practical realization of the solid state transformer is some distance in the future: at normal industrial levels - perhaps as much as 10 years - and at the very high power levels (such as required for shore-to-ship) - power as much as 15 years.

RECOMMENDATIONS

With the realization that an immense amount of research, development, test, and evaluation is yet to be done on the basic concept of the solid state transformer and also that the two technical characteristics of near-perfect voltage regulation and high efficiency independent of load diversity are very desirable features in terms of energy savings and manpower reductions, it is recommended that:

1. The basic concept of the solid state transformer be studied further to the concept demonstration stage.

2. The economics of replacing power transformers with solid state transformers in the future be reassessed, based on measured performance characteristics from the concept demonstration model.

3. Energy conserving schemes that use the solid state transformer concept as a building block be pursued.

REFERENCES

1. Naval Facilities Engineering Command, Western Division. Report on shore power reliability workshop. San Bruno, Calif., Sep 1978.

2. Civil Engineering Laboratory. Naval shore establishment energy research and development, FY-78 Program review. Port Hueneme, Calif., May 1979.

3. Civil Engineering Laboratory. Technical Memorandum M-62-79-14: Analysis of electrical cold iron usage, by D. Shiroma and W. Pierpoint. Port Hueneme, Calif., Aug 1979.

4. Civil Engineering Laboratory. Technical Memorandum M-62-76-20: Investigation of shore-to-shore electrical power demand problems, by W. Pierpoint. Port Hueneme, Calif., Sep 1976.

5. Civil Engineering Laboratory. Technical Memorandum M-62-79-06: Identification of potential electrical conservation concepts for motors and distribution systems, by B. R. Milner. Port Hueneme, Calif., Jan 1979.

6. "An active power bandpass filter," by H. A. Nienhaus, J. C. Bowers, and J. L. Brooks, Power Electronic Specialists Conference (subgroup of the IEEE) '78 Record, pp 307-316.

7. "A general unified approach to modeling switching-converter power stages", by R. D. Middlebrook and S. Cuk, Power Electronics Specialists Conference '76 Record, pp 18-31.

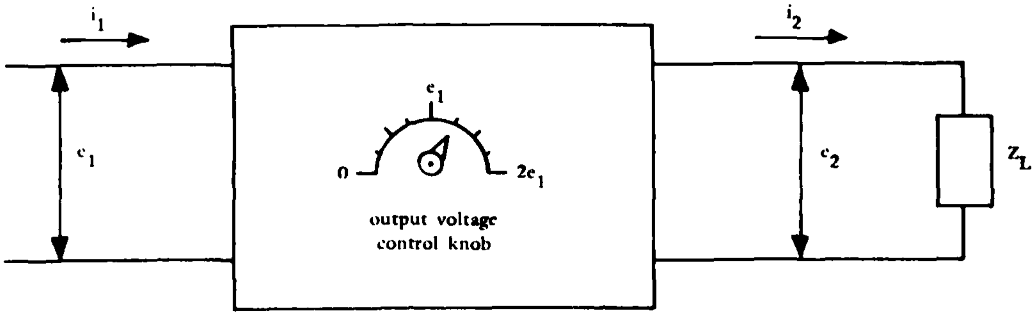
8. "Simulation and analysis methods for sampled power electronics systems", by H. A. Owen, A. Capel, and J. G. Ferrante, Power Electronics Specialists Conference '76, pp 45-55.

9. Department of the Army. SUPER*SCEPTRE user's manual, by J. C. Bowers, et al. May 1975, AD No. A011348.

10. R. Saucedo and E. E. Schiring. Introduction to continuous and digital control systems. New York, N.Y., The MacMillan Co., 1968.

Table 1. Estimated Electrical Energy Consumption and Costs for Navy Shore Facilities

FY79 End Use	Electricity		Cost ($M)
	%	10^9 kWh	
Air Conditioning	25	1.9	66.40
Hot Water	1	0.08	2.66
Lighting	35	2.66	92.96
Industrial Processes	39	2.96	103.6
Totals	100	7.6	265.6



Solid State Transformer

where:

e_1 = 120_{VRMS}, 60 Hz, 1ϕ source voltage

e_2 = E_{VRMS}, 60 Hz, 1ϕ source voltage

E_{VRMS} = n x 120_{VRMS}

n = predetermined (by exterior dial setting) voltage transformation ratio, $0 < n < 2$

Z_L = any impedance (within power rating) with a power factor between 0.8 lagging and 0.8 leading

Power rating = 1.2 KVA

Output voltage regulation = 1%

Notes:

(1) DC isolation between input ports and output ports is desirable but not necessary.
(2) The efficiency and reliability of the circuit must be comparable to those of a conventional transformer.
(3) Temporary energy storage within the circuit will be necessary to effect power flow to and from the load.

Figure 1. Technical specifications for the solid state transformer.

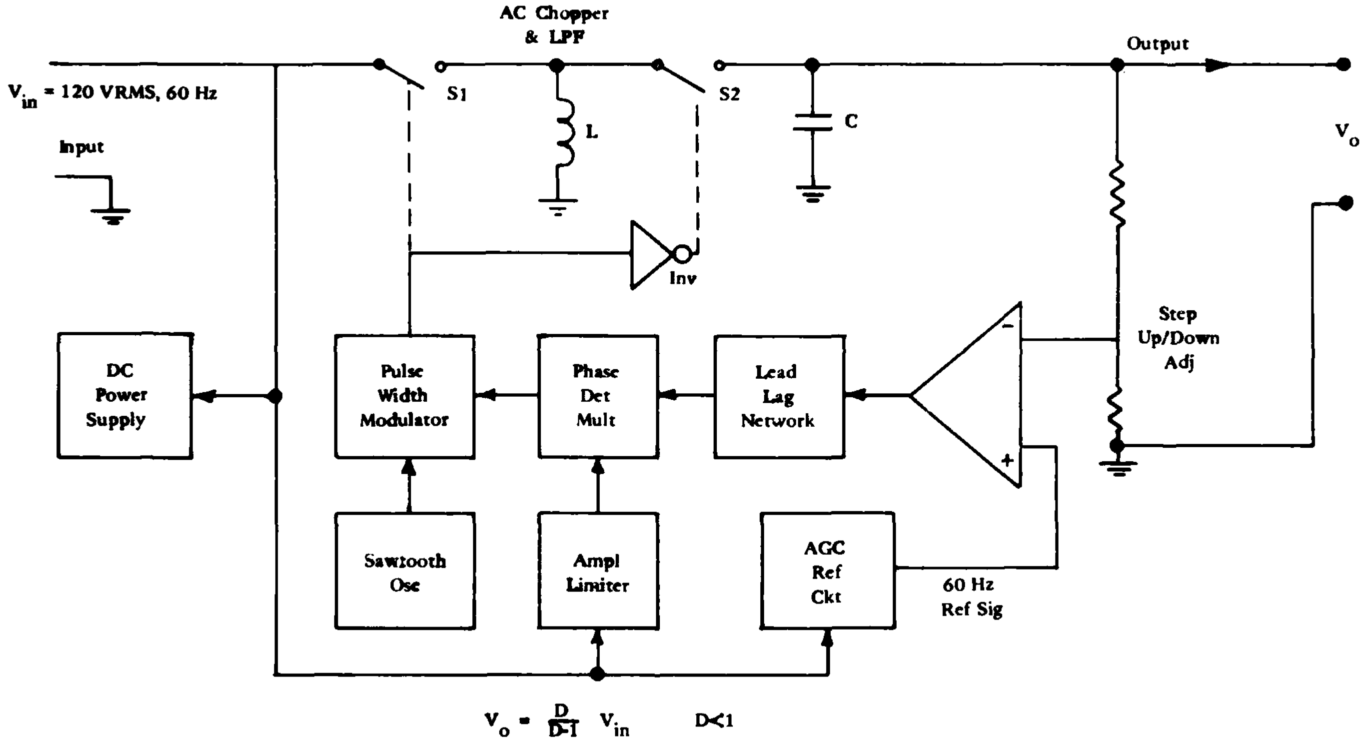


Figure 2. Block diagram of step-up/down solid state transformer.

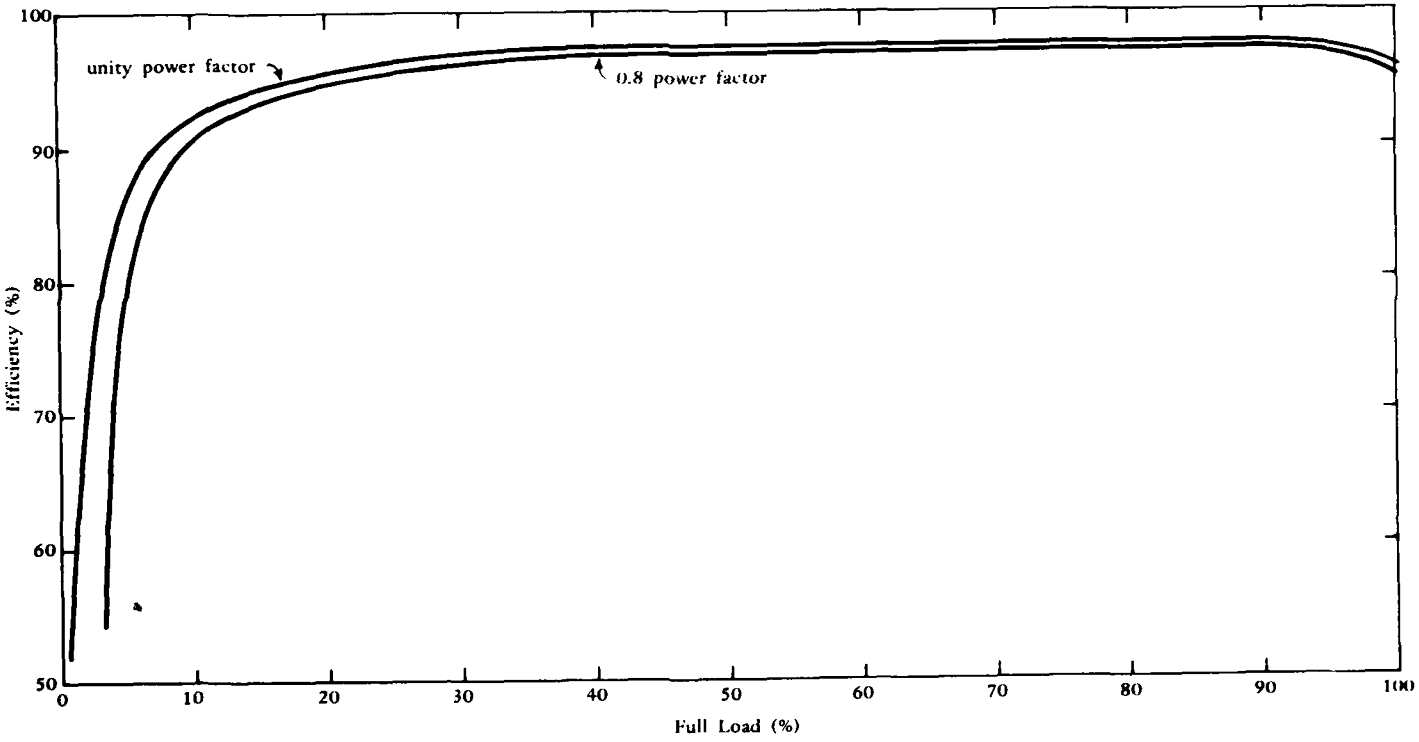


Figure 3. Power transformer efficiency.

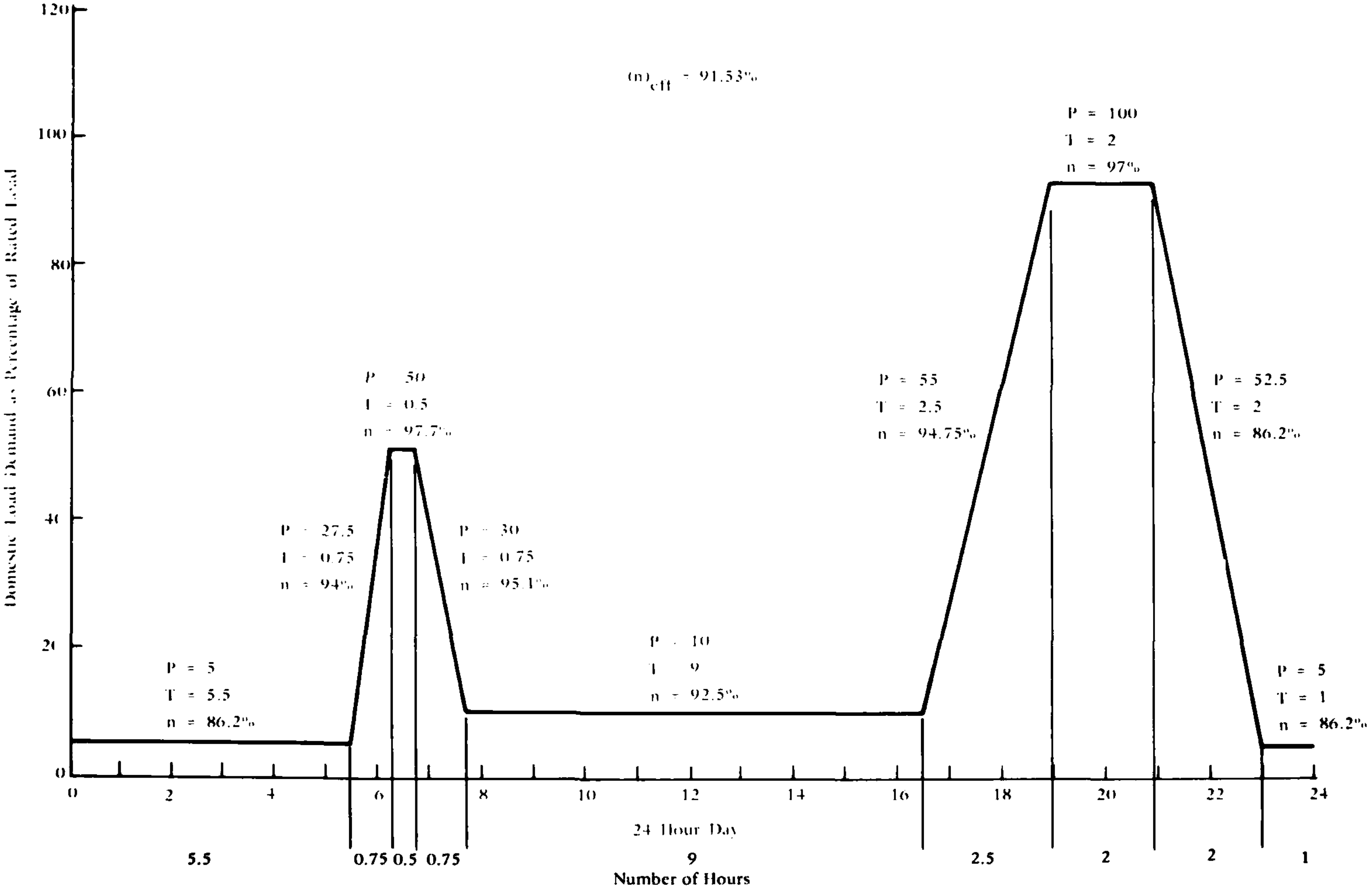


Figure 4. Simplified domestic electrical power demand over a 24-hour day.

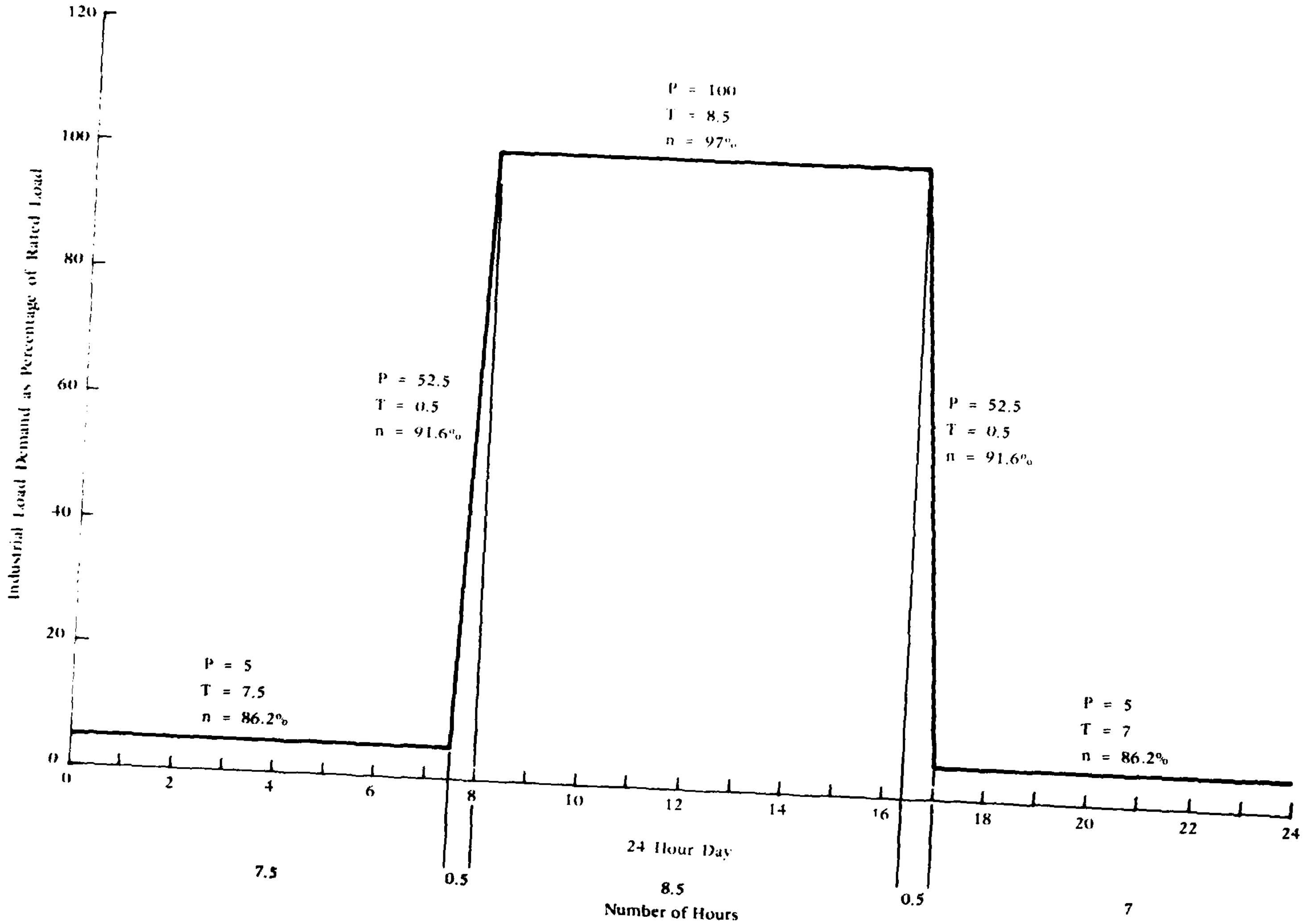


Figure 5. Simplified industrial plant electrical power usage over a 24-hour day.

APPENDIX

PO NO. 79-M-R2331

CIVIL ENGINEERING LABORATORY

NAVAL CONSTRUCTION BATTALION CENTER
Port Hueneme, California 93043

TITLE: SOLID STATE TRANSFORMER

CORPORATE AUTHOR: Dr. James C. Bowers

DATE: May 22, 1979

SPONSOR: Civil Engineering Laboratory

PROGRAM NOS. Z-R000-01-168

Appendix

SOLID STATE TRANSFORMER

INTRODUCTION

This report gives the results of a study to determine the feasibility of replacing electrical power transformers with AC solid state switching regulators (hereafter referred to as solid state transformers). The major advantages of the solid state transformer are smaller size, less weight, environmental considerations, less cost, and the ability to provide output voltage regulation.

Specified performance goals for the solid state transformer are for a 1.2-kVA, single-phase, 60-Hz system capable of transforming 120 Vrms by any preset ratio from 0 to 2. Output voltage regulation is to be ±5%, and output frequency tolerance is to be ±5%. Load power factor can vary from 0.8 lagging to 0.8 leading. Although several system approaches have been considered, the major emphasis in this report is on a step-up/down solid state transformer, which is considered to be the best solution to these performance goals. In addition, a second system is described which is considered to be a better solution for those applications requiring voltage step down only.

Both systems utilize AC solid state power choppers to achieve high efficiencies, and feedback top provide output voltage regulation. The only power inductance required in either system is designed to filter out a 50-kHz chopper frequency. The major differences between the two systems is the type of chopper used and the compensation networks required for system stability.

Feasibility of both systems has been demonstrated by computer simulation. However, neither system is designed to provide output frequency regulation. The output frequency tolerance will be identical to the input frequency tolerance. Although we do not believe that output frequency regulation is feasible, this is not a serious drawback, since conventional transformers cannot provide this feature either.

SOLID STATE VERSUS CONVENTIONAL TRANSFORMERS

Any decision to replace a conventional transformer with a solid state transformer must be based on a comparison of the performance characteristics of the two. The major advantages of a solid state transformer have been mentioned in the INTRODUCTION section. In addition, it will tend to suppress transients and distortion that may be present on the input line. A disadvantage is the fact that the chopper action produces EMI, but this can be removed by filtering.

Although theoretically a solid state switching transformer can achieve the same high efficiencies that a conventional transformer can, we believe that the maximum practical efficiency obtainable with present state-of-the-art switching devices is only about 95%. This will gradually improve as faster power switches become available. By contrast, a conventional transformer can achieve full load efficiencies of 98%, if size and weight limitations are relaxed. This apparent disadvantage of the solid state transformer is offset by the fact that it will maintain its high efficiency at reduced loads. Because of core losses in a conventional transformer, its efficiency will decrease as the load is decreased to the point that the solid state transformer may have a higher efficiency.

One disadvantage of any switching regulator is that it cannot maintain regulation at no-load. Consequently, it may be necessary to include a bleeder resistor on the output of the solid state transformer if no-load operation is required. In practice, no-load would rarely, if ever, exist. The losses in this bleeder resistor could be comparable to the core losses in a conventional transformer at no-load. However, load current sensing could be provided to switch off this bleeder current when the load current is adequate to maintain regulation.

A final disadvantage of the solid state transformer is that it does not provide DC isolation between the input and output terminals, as do conventional transformers. The solid state transformer is more comparable to an autotransformer (or variac) except that output control is obtained with a potentiometer at low power levels, which means less wear and tear on the wiper contact.

At low output voltage levels, the output current must be limited to some maximum rated value. Since this is not specified, a maximum output current rating of 35 A rms is arbitrarily specified. This means that the maximum rating of 1.2 kVA is valid only for output voltages of 35 Vrms or larger. This is equivalent to stating that the minimum load resistance is 1 ohm. This specification is necessary for either type of transformer.

STEP-DOWN SOLID STATE TRANSFORMER

The block diagram of a step-down solid state transformer is shown in Figure 6. This system is identical to the "Active Power Bandpass Filter" described in detail in Reference 5, except for the following.

1. Since the circuit is practical only for step-down voltage applications and is designed to replace a transformer, the input step-up transformer in Reference 5 has been eliminated.

2. Since the input voltage is in phase with the reference voltage at all times, the phase reversal switches in Reference 5 have been eliminated.

3. The phase locked loop used to obtain a 60-Hz reference signal in Reference 5 has been replaced by an automatic gain control (AGC) circuit to obtain a 60-Hz reference with a stable peak amplitude which is in phase with the input voltage.

4. The feedback voltage divider (or the reference circuit) includes a potentiometer so that the step-down voltage ratio can be easily controlled.

The operation of the system shown in Figure 6 is as follows. The 120-Vrms, 60-Hz input is chopped up by a pair of bidirectional power switches, S1 and S2, which are alternately switched on and off by a 50-kHz pulse width modulated oscillator. The 50-kHz chopper frequency is easily removed by the low pass filter. The output of this filter is equal to the instantaneous average value of the chopped input which is equal to the instantaneous 120-Vrms input and the duty cycle of the chopper.

This output is attenuated by a voltage divider and compared to a 60-Hz reference signal which is in phase with the input. The difference between these two is an error signal which is amplified, phase detected, and used to modulate the duty cycle of the pulse width modulator. If the output amplitude is too large, the error signal will cause the duty cycle and the output amplitude to decrease until the error signal is negligibly small. In this manner, the output voltage is forced to follow the 60-Hz reference signal.

As explained in Reference 5, the phase detection multiplier is necessary to maintain negative FB when the 60-Hz reference signal is negative. The lead-lag network is required primarily for system stability in this application.

The computer simulation results described in Reference 5 verify that the output of this system will follow the reference as long as the input and reference signals are in phase. Consequently, there is no doubt about its feasibility.

STEP UP/DOWN SOLID STATE TRANSFORMER

The block diagram of a step-up/down solid state transformer is shown in Figure 7. The major difference between this system and that shown in Figure 6 is the type of AC to AC power converter (AC chopper and low pass filter) used. The system of Figure 7 employs what is commonly referred to in a DC to DC system as a buck-boost converter (Ref 6) to step up or step down in input voltage. On the other hand, the system of Figure 6 employs what is known as a buck converter to step down the input voltage.

The operation of AC to AC power converters is essentially the same as the corresponding DC to DC power converter if the frequency of the AC input is much less than the chopper frequency. Under these conditions, the AC input appears as a slowly varying DC to the chopper. Of course, the AC to AC power converter must employ bidirectional switches to accommodate input voltages of either polarity. Stability compensation is more critical in the AC to AC system since the closed loop bandwidth must be large enough that significant phase shift does not occur at the AC input frequency.

For the buck converter of Figure 6, the output voltage is related to the input voltage and the duty cycle D (fraction of chopper period during which S1 is on and S2 is off) by (Ref 6),

$$V_{out} = D V_{in} \tag{1}$$

This relationship assumes that the current in the filter inductor L is continuous, which may not be valid at no-load unless a bleeder resistor is employed.

For the buck-boost converter of Figure 7, the output voltage is related to the input voltage and the duty cycle D by (Ref 6),

$$V_{out} = -\frac{D}{1 - D} V_{in} \quad (2)$$

Again, this relationship assumes that the current in the inductor is continuous and the duty cycle is not allowed to approach unity. It is apparent from this equation that the converter is capable of either stepping up or stepping down the input voltage, depending on the value of the duty cycle which is determined by the FB attenuator ratio and the amplitude of the reference voltage.

The only other difference, besides the type of power converter used, between the system of Figure 6 and that of Figure 7 is the type of phase compensation used to stabilize the system.

Because the buck-boost power converter has several disadvantages in comparison to the buck converter (Ref 6), the system of Figure 6 is recommended over that of Figure 7 for step-down transformer applications. These disadvantages are:

1. The output voltage is 180 degrees out of phase with the input voltage. This results in added voltage stress on the chopper switches.

2. The open loop gain and low pass filter transfer filter function are functions of the duty cycle, which makes it more difficult to optimize the system performance.

3. The chopper action introduces a small signal zero in the right half plane in the output-to-duty-cycle transfer function which makes it more difficult to stabilize the system.

AGC 60-Hz Reference Circuit

The schematic of the AGC 60-Hz reference circuit is shown in Figure 8. The function of this circuit is to provide a constant amplitude 60-Hz reference signal which is 180 degrees out of phase with the 120 Vrms input and is relatively insensitive to slow variations in the input amplitude. The circuit employs an AGC scheme which is commonly used to stabilize the output amplitude in RC oscillators.

This circuit operates as follows. The 120-Vrms input is inverted and attenuated by op amp 1. High frequency noise on the input is removed by capacitor C1. The transfer function of op amp 1 is,

$$A_1 = -\frac{R_a}{R_b(1 + R_a C_1 S)}$$

The output of op amp 1 is applied to the input of op amp 2 which has a gain,

$$A_z = 1 + \frac{R_f}{R_1}$$

where R_1 includes the drain to source resistance of the JFET.

The output of the AGC amplifier (op amp 2) is sensed by a peak detector (consisting of D2, R2 and C2), and the detector output is compared to a 6.2 V-DC reference. The difference is an error signal which is amplified and used to change the resistance of the JFET and the AGC amplifier gain in such a way that the error signal is driven to zero. In this manner, the peak value of the AGC amplifier output is forced to follow the DC reference.

Because of the forward drop across diode D2, the peak output voltage will be about 0.6 volt above the DC reference voltage. In this system, the reference voltage was selected as 6.8-volt peak which corresponds to 4.8 Vrms. The output of the phase inverter must be considerably less than this since the AGC amplifier gain is limited to a minimum value of one (when the JFET is cut off).

It is possible that the phase inversion and AGC functions can be combined to eliminate one of the op amps used in Figure 8. However, it should be noted that for the step down system of Figure 6 the reference must be in phase with the input, in which case op amp 1 would be replaced by a simple voltage divider. Also for the system of Figure 6, it is preferable to put a potentiometer on the output of the AGC amplifier to adjust the system output voltage, rather than to accomplish this with the FB attenuator as in Figure 7.

Buck-Boost Converter State Averaged Model

A computer model for the buck power converter of Figure 6 (including the AC chopper and low pass filter) can be determined by inspection, and its operation is very easy to understand (Ref 6). This is not the case for the buck-boost converter of Figure 7. Fortunately, modeling and analysis techniques have been developed to handle this problem (Ref 7 and 8). The technique, which has been almost universally adopted by experts in the power electronics field, uses a state averaged model for the power converter circuit. With this method the state equations are averaged over one cycle to obtain average state equations. The model follows directly from (or by manipulating) these average equations. Middlebrook (Ref 7) has shown that the state average model is valid for frequencies well below the chopper frequency. For convenience, a state averaged model for the buck-boost converter of Figure 7 is derived here.

During the interval DT when S1 is on and S2 is off, the buck-boost converter is as shown in Figure 9. The state equations during this interval are,

$$SLI = V_{in} \tag{3a}$$

and

$$SCV_o = -\frac{V_o}{R} \tag{3b}$$

The interval (1-D)T, when S1 is off and S2 is on the buck-boost converter, is as shown in Figure 10. The state equations during this interval are,

$$SLI = V_o \tag{4a}$$

and

$$SCV_o = -\frac{V_o}{R} - I \tag{4b}$$

Averaging these equations over one chopper period T,

$$SLI = D\,V_{in} + (1 - D)\,V_o \tag{5a}$$

and

$$SCV_o = -\frac{V_o}{R} - (1 - D)\,I \tag{5b}$$

Eliminating I from these equations gives,

$$\frac{V_o}{V_{in}} = -\frac{D}{1 - D} \times \frac{1}{1 + \frac{LS}{(1 - D)^2 R} + \frac{LCS^2}{(1 - D)^2}} \tag{6}$$

It is easily shown that this is the transfer function of the circuit shown in Figure 11. Hence, Figure 11 is a state averaged model for the buck-boost converter of Figure 8. This is the model that was used in the computer simulation of the system.

The converter filter must provide a high degree of attenuation to the 50-kHz chopper frequency without providing significant attenuation or phase shift to the 60-Hz input frequency. The filter component values chosen for this study were L = 25 μH and C = 100 μF. We now consider the filter transfer function for two extremes of operation.

First, consider the case where the desired output is 240 Vrms (a 2-to-1 step up). The minimum load resistance for a 1.2-kVA output is R = 48Ω, and a nominal duty cycle, D = 2/3, is required. Thus Equation 6 becomes,

$$\frac{V_o}{V_{in}} = \frac{-2}{1 + 0.0469 \times 10^{-4}\,S + 2.25 \times 10^{-8}\,S^2}$$

Next, consider the case where the desired output is 12 Vrms (a 10-to-1 step down). The minimum load resistance R = 1Ω and a nominal duty cycle D = 1/11 is required. Thus Equation 6 becomes,

$$\frac{V_o}{V_{in}} = \frac{-0.1}{1 + 3.025 \times 10^{-4}\,S + 0.3025 \times 10^{-8}\,S^2}$$

The filter requirements are fulfilled for both of these extreme cases.

Buck-Boost Converter FB Transfer Function

Although the buck-boost converter model of Figure 11 is completely adequate for a computer analysis of the system using the SUPER*SCEPTRE program (Ref 9), the transfer function of Equation 6 is not in a convenient form for feedback system design. This is because insofar as the feedback loop is concerned the input to the buck-boost converter is the duty cycle, D, rather than the input voltage, V_{in}. Thus, we are interested in the converter small signal transfer function, which is the partial derivative of the output voltage, V_o, with respect to the duty cycle, D. An exact solution for this small signal transfer function yields an unintelligible mess. However, Reference 7 shows that this can be closely approximated by,

$$\frac{\partial V_o}{\partial D} \simeq \frac{-V_o}{D(1 - D)} \left(1 - \frac{SDL}{(1 - D)^2 \; R}\right) x \; H(s) \qquad (7)$$

$$\text{where} \quad H(s) = \frac{1}{1 + \frac{LS}{(1 - D)^2 \; R} + \frac{LCS^2}{(1 - D)^2}} \qquad (8)$$

$$\frac{\partial V_o}{\partial D} \simeq \frac{V_{in}}{(1 - D)^2} \; 1 - \left(\frac{SDL}{(1 - D) \; R^2}\right) x \; H(s) \qquad (9)$$

The existence of a zero in the right half plane in this FB transfer function makes it somewhat difficult to stabilize the system.

We now consider this filter transfer function for the two extremes of operation considered in the previous section. First, with V_o = 240 Vrms, R = 48Ω, and D = 2/3,

$$\frac{\partial V_o}{\partial D} = \frac{9 \; V_{in} \; (1 - 0.3125 \times 10^{-5} \; S)}{1 + 0.0469 \times 10^{-4} \; S + 2.25 \times 10^{-8} \; S^2}$$

Second, with V_o = 12 Vrms, R = 1Ω, and D = 1/11,

$$\frac{V_o}{D} = \frac{1.21 \; V_{in} \; (1 - 0.275 \times 10^{-5} \; S)}{1 + 0.3025 \times 10^{-4} \; S + 0.3025 \times 10^{-8} \; S^2}$$

Note that stability problems are also aggravated by the fact that the DC gain of the power converter increases by a factor of 7.45 as the output voltage is increased from 12 to 240 Vrms. This problem can be more than offset by putting the output voltage adjustment in the feedback attenuator rather than in the reference circuit. In this manner, the change in attenuator gain, which is opposite to that of the power converter, minimizes the system open loop gain variations. With a reference voltage of 4.8 Vrms, the attenuator gain $K_A = 0.02$ for $V_o = 240$ Vrms, whereas $K_a = 0.4$ with a 12-volt output, an increase by a factor of 20. The overall system open loop gain change is reduced to 20/7.45 = 2.7 over the output voltage range from 12 to 240 Vrms.

Chopper Switches

The chopper switches are the most critical components in the system. In fact, a 120-volt, 1.2 kVA, 0 to 2 step-up/down solid state transformer is probably not feasible at this time because of the unavailability of suitable solid state switching devices. However, we believe that devices are presently available that can handle the stresses encountered in a 120-volt, 1.2-kVA 0-to-1 step-down transformer or those encountered in a 120-volt, 1.2-kVA, 1-to-2 step-up transformer. The problem is that when the step-up and step-down features are incorporated in a single unit, the phase reversal in the buck-boost converter severely increases the voltage stresses on the power switches. For this reason, a step-up/down solid state transformer is not as practical as either a step-down or a step-up solid state transformer. Table 2 lists the ratings on the power switches for all three systems.

The step-up/down transformer of Figure 7 can be readily converted to a step-up transformer by replacing the buck-boost converter by the boost converter of Figure 12.

Because the primary source of power losses in the system is expected to be chopper switching losses, they must have switching times which are small compared to the chopper period. Although we have assumed a chopper frequency of 50 kHz in this study, this can be decreased somewhat to improve the system efficiency.

The combination of high voltage breakdown, high current, and high-speed switching can probably best be achieved by a high power BJT at the present time. Since the chopper switches must be bidirectional, one possible BJT AC switch configuration is shown in Figure 13.

Computer Simulation Block Diagram

The step-up/down solid state transformer was simulated on the computer using the SUPER*SCEPTRE program (Ref 9) and the block diagram shown in Figure 14. The program listing for a typical simulation is shown in Figure 15. Most of the components shown in the block diagram of Figure 14 are a straightforward implementation of the block diagram of Figure 17 with the following exceptions. The AC buck/boost power converter was simulated by the state averaged model of Figure 11. The pulse width modulator was represented by a limiter whose output is the duty cycle, D. The duty cycle limits were selected as 0 and 0.8 for this system, and the nominal duty cycle was selected as 0.5 (with no error signal). We have also included a single pole approximation to the pulse width modulator time delay, since this can affect the system stability. This is,

$$F_p(S) = E^{-(T/2)S} \simeq 1 - \frac{T}{2} S \simeq \frac{1}{1 + \frac{T}{2} S} \qquad (10)$$

which is valid for values of S such that (T/2) S << 1. T is the period of the pulse width modulator. The pure time delay expression E - (TS/2) for the PWM time delay is commonly used in analyzing power PWM systems (Ref 8). This is also consistent with the results obtained theoretically (Ref 10) for a sample and hold system. In an S & H system, the input is sampled and held for one period; in a PWM system, the pulse is sampled, and the average value is held for one period. Hence, there is a direct analogy between the two systems. With a PWM frequency of 50 kHz, Equation 10 becomes,

$$F_p(S) \simeq \frac{1}{1 + 10^{-5} S}$$

The phase compensation network selected to stabilize the system is,

$$F_c(S) = \frac{(1 + 10^{-5} S)^2}{(1 + 10^{-7} S)^2}$$

The differential amplifier gain K_o was selected as 40. The PWM gain and the phase detection multiplier gains were selected as unity. The FB attenuator gain K_A is adjustable. The rationale for selecting $F_c(s)$ involves complex control theory, hence the details are not included in this report; however, the exceptional results speak for themselves, as the system is completely stable over the complete operating range, including all conditions.

Computer Simulation Results

This section shows graphical results of the system computer simulation for four extreme output and load conditions. For convenience, the inverse of the input voltage is shown in Figure 16 for comparison to the output waveforms in all four cases. Figures 17 and 18 show the output and duty cycle waveforms for the case where the FB attenuator $K_A = 0.02$ and the load $R = 48\Omega$. This represents a step up of 2 to 1 with maximum output power. The output waveform contains no noticeable distortion (except for that introduced by the computer graphics). Since it is difficult to determine the system regulation from this waveform, the following excerpts are included from the computer printout numerical data.

1. The desired peak output voltage for this case is 340 volts which should occur at 4.167 ms. The computer printout peak output voltage was 339.792 volts which occurred at 4.16586 ms.

2. The input and output waveforms passed through zero during the same interval (8.29 to 8.38 ms).

Although these results indicate amazing accuracy, it should be noted that some error will be introduced in the reference circuitry which is not included in the simulation. However, system regulation of ±1% certainly appears to be very feasible.

Figures 19 and 20 show the output and duty cycle waveforms for the case where the feedback attenuator $K_A = 0.5$ and the load $R = 1\Omega$. This represents a step down of 10 to 1 with maximum output current. Again, the output waveform contains no noticeable distortion, and the computer printout data indicates that the output follows the desired output very closely.

Figure 21 shows the output waveform for the case where conditions are the same as those used to obtain Figure 19 except that a 3.53 μf capacitor has been added in shunt with $R = 1\Omega$ to simulate a load with a 0.8 leading power factor. Figure 22 shows the output waveform for the case where conditions are the same as those used to obtain Figure 19 except that a 2-mH inductor has been added in shunt with $R = 1\Omega$ to simulate a load with a 0.8 lagging power factor. Neither the leading nor lagging power factor load has any noticeable effect on the system stability or the output waveform.

The results definitely verify the system feasibility. The solid-state transformer could very well be the approach for the future.

Table 2. Power Switch Ratings for 120-volt, 1.2-kVA System

Rating	0.1 to 2 Step Up/Down	0.1-to-0.1 Step Down	1-to-2 Step Up
Breakdown Voltage, V min.	510	170	340
Current, amp max.	35	35	10
Switching Speed, μsec max.	1	1	1
On Resistance, Ω max.	0.01	0.01	0.25

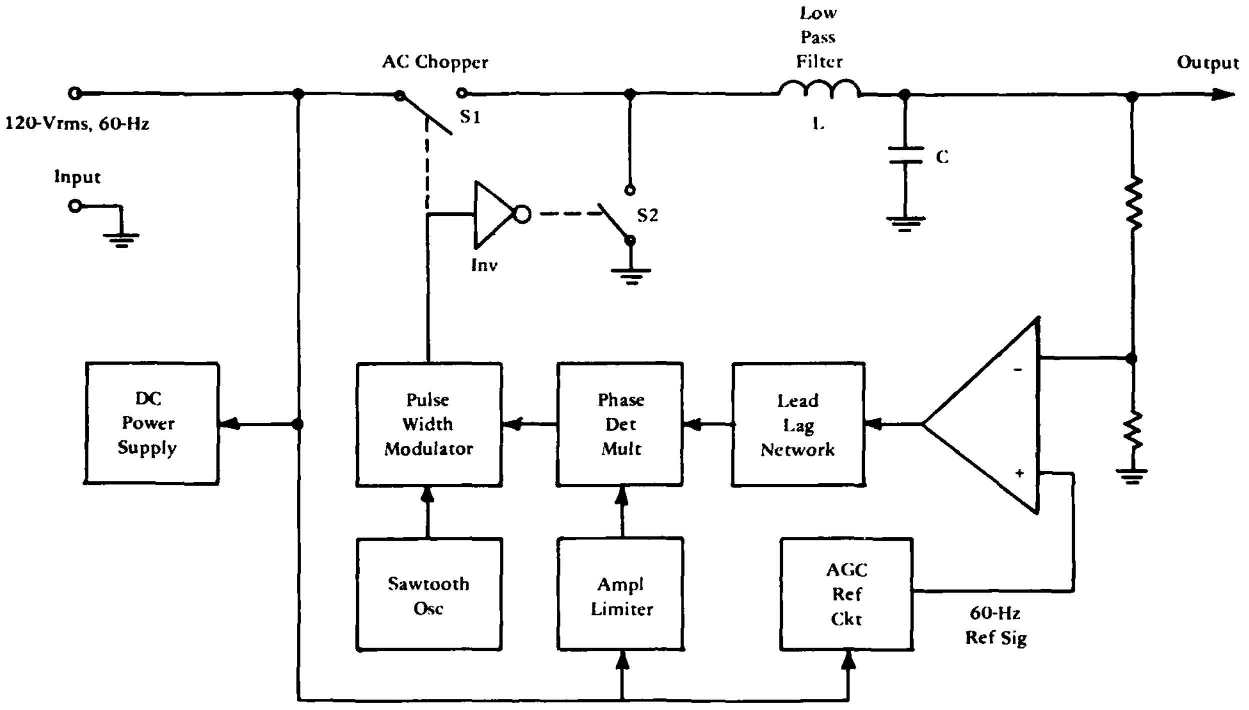


Figure 6. Step-down solid state transformer.

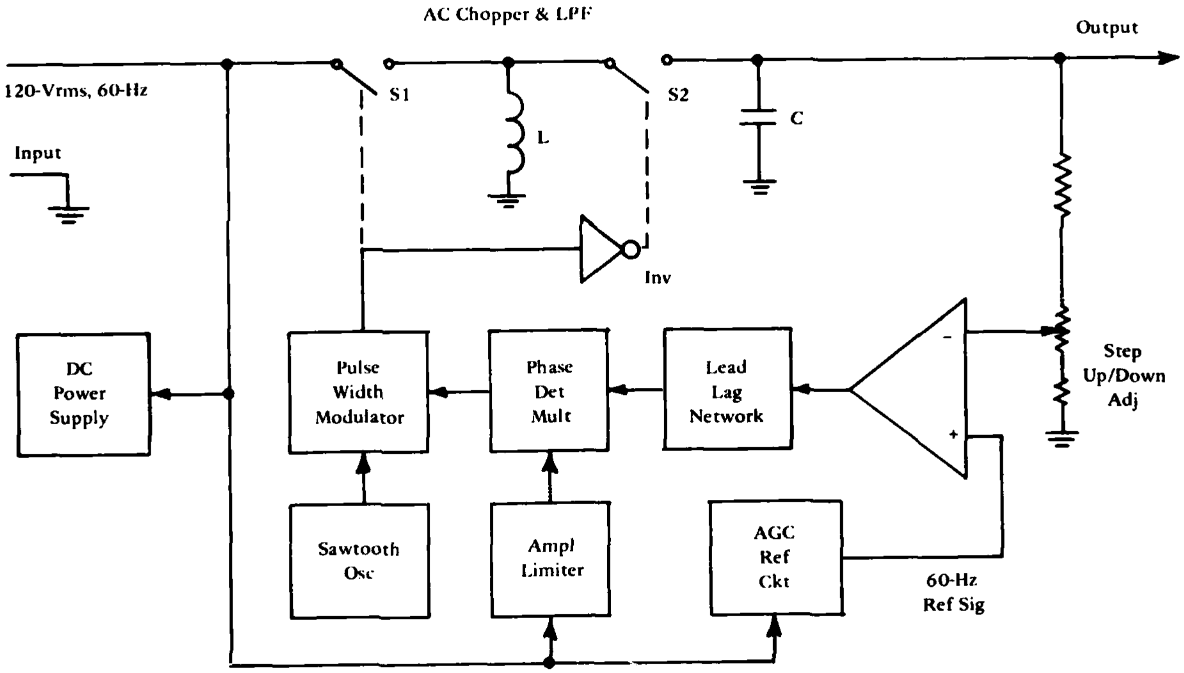


Figure 7. Step-up/down solid state transformer.

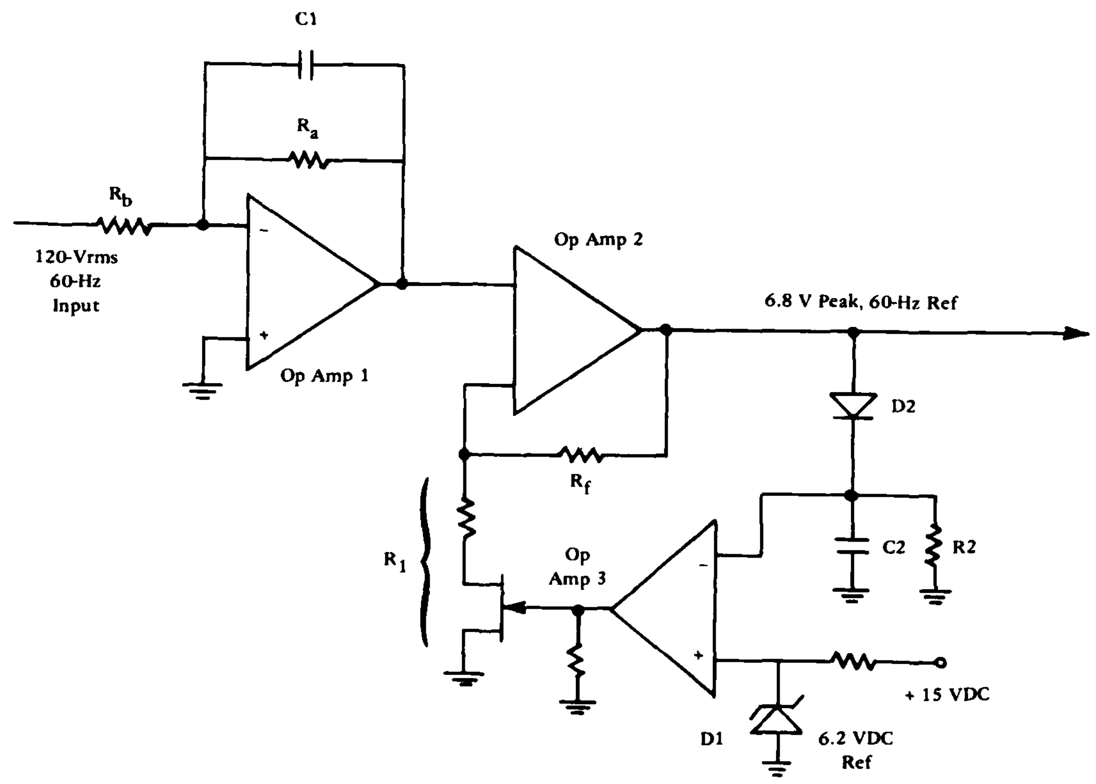


Figure 8. AGC 60 Hz reference circuit.

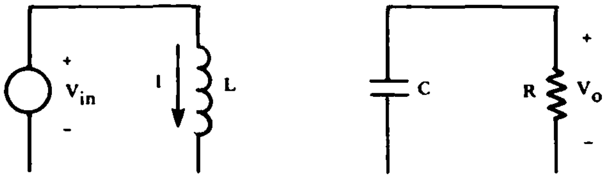


Figure 9. Buck-boost converter during interval DT.

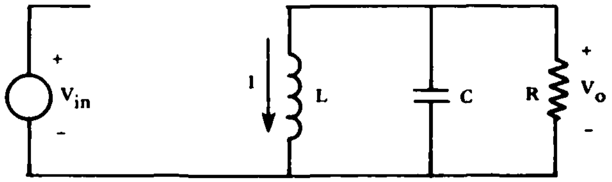


Figure 10. Buck-boost converter during interval (1-D)T.

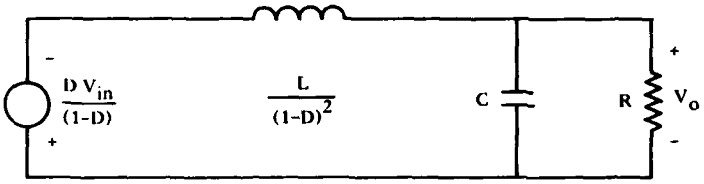


Figure 11. Buck-boost converter state averaged model.

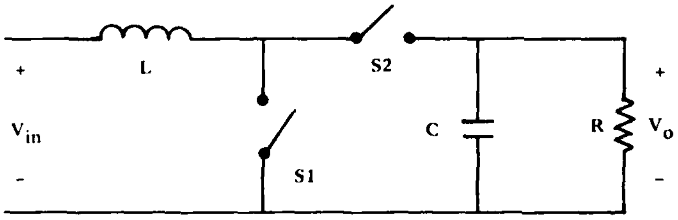


Figure 12. Step up (boost) power converter.

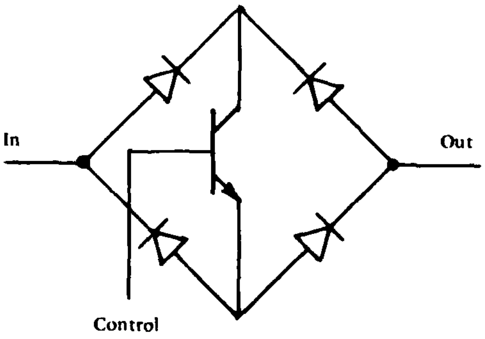


Figure 13. BJT AC switch.

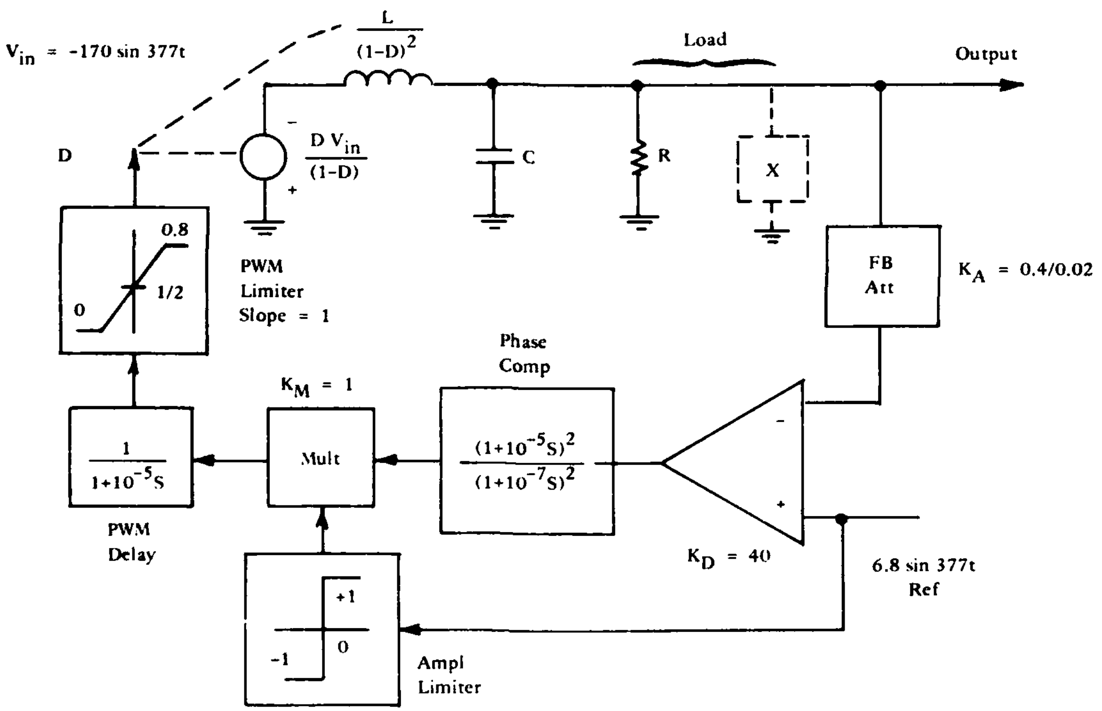


Figure 14. Computer simulation block diagram – step-up/down transformer.

```
TRANSFER FUNCTION DESCRIPTION
MODEL LEADLAG
N=(1E-5,1),(1E-5,1)
D=(1E-7,1),(1E-7,1)
MODEL PWM DELAY
K=1
C=(1E-5,1)
MODEL ATT
K=0.02
MODEL DESCRIPTION
MODEL LIMIT(SATURATION)
Y=1
M=100
MODEL MULT(1-2-3-0)
ELEMENTS
J1,1-0=0
J2,2-0=0
E0,0-3=X1(VJ1*VJ2)
MODEL CHOPPER (1-2-4-0)
ELEMENTS
J1,1-0=0
J2,2-0=0
E1,0-3=P1
L1,3-4=P2
C1,4-0=1E-4
R1,4-0=48
DEFINED PARAMETERS
P1=X1(-VJ1*(VJ2)/(1-VJ1))
P2=X2(25E-6/(1-VJ1)**2)
MODEL DUTYCYCLE (1-2-0)
ELEMENTS
J1,1-0=0
E0,0-2=T1(VJ1)
FUNCTIONS
T1=-1,0, -.5,0, .3,.8, 1,.8
MODEL DIFFAMP (P-N-V-G)
ELEMENTS
JP,P-G=0
JN,N-G=0
E0,G-V=XC(PGN*(VJP-VJN))
DEFINED PARAMETERS
PGN=40
CIRCUIT DESCRIPTION
SOLID-STATE TRANSFORMER MODEL
ELEMENTS
EI,2-0=X1(170*DSIN(377*TIME))
XCH,1-2-4-0=MODEL CHOPPER
ATT,4-0-5-0=MODEL ATT
XDA,6-5-7-0=MODEL DIFFAMP
EREF,0-6=X2(6.8*DSIN(377*TIME))
MU,8-9-10-0=MODEL MULT
XLM,6-0-9-0=MODEL LIMIT
XL,7-0-8-0=MODEL LEADLAG
XP,10-0-11-0=MODEL PWM DELAY
XDC,11-1-0=MODEL DUTYCYCLE
OUTPUTS
EI(INPUT),VR1XCH(OUTPUT),E0XDC(DTY CY),VJ1MU(LEADLG),PLOT
RUN CONTROLS
MINIMUM STEP SIZE = 1E-50
STOP TIME=20E-3
INTEGRATION ROUTINE=XPO
MAXIMUM INTEGRATION PASSES = 1E6
END
```

Figure 15. Typical simulation of SUPER*SCEPTRE program.

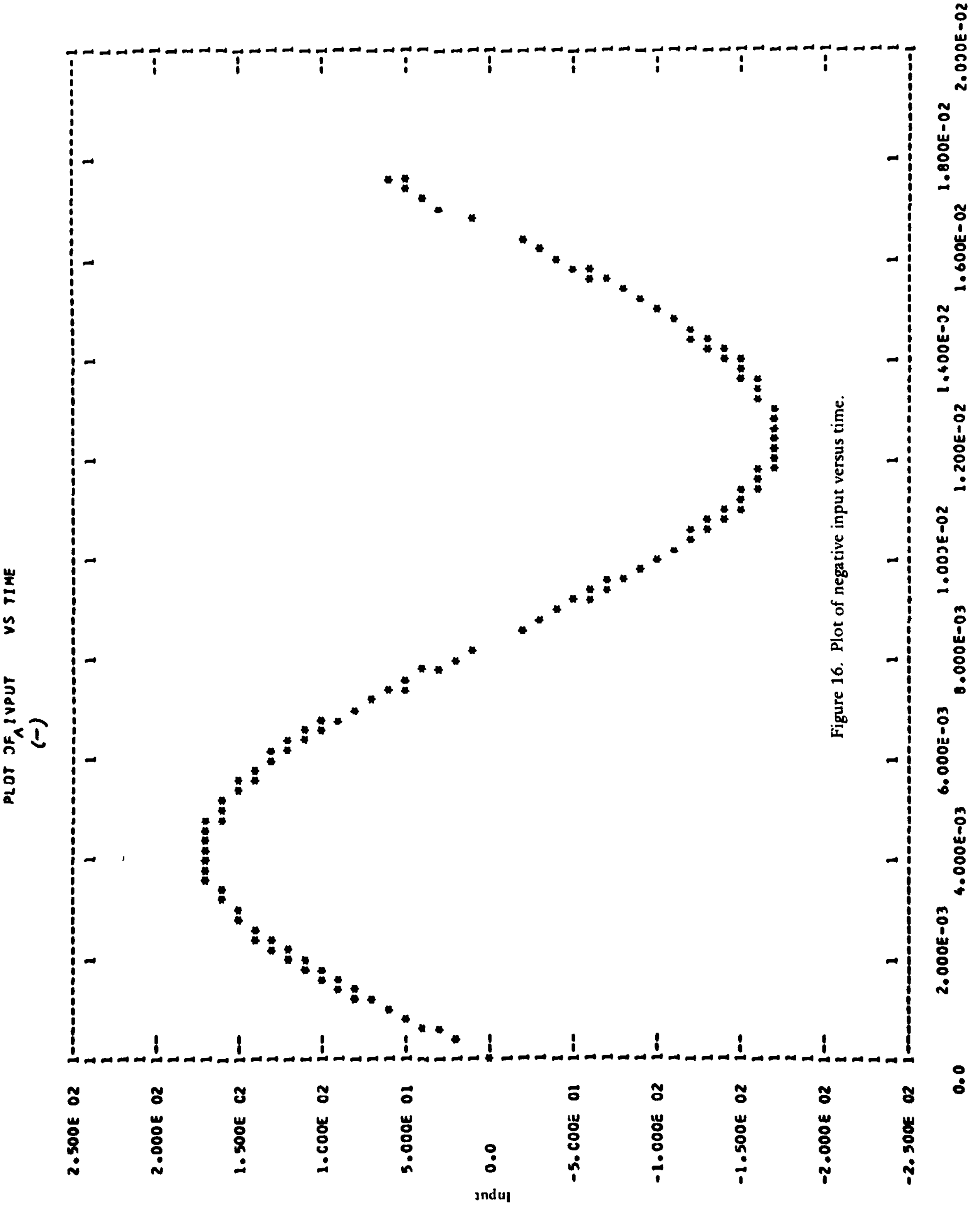


Figure 16. Plot of negative input versus time.

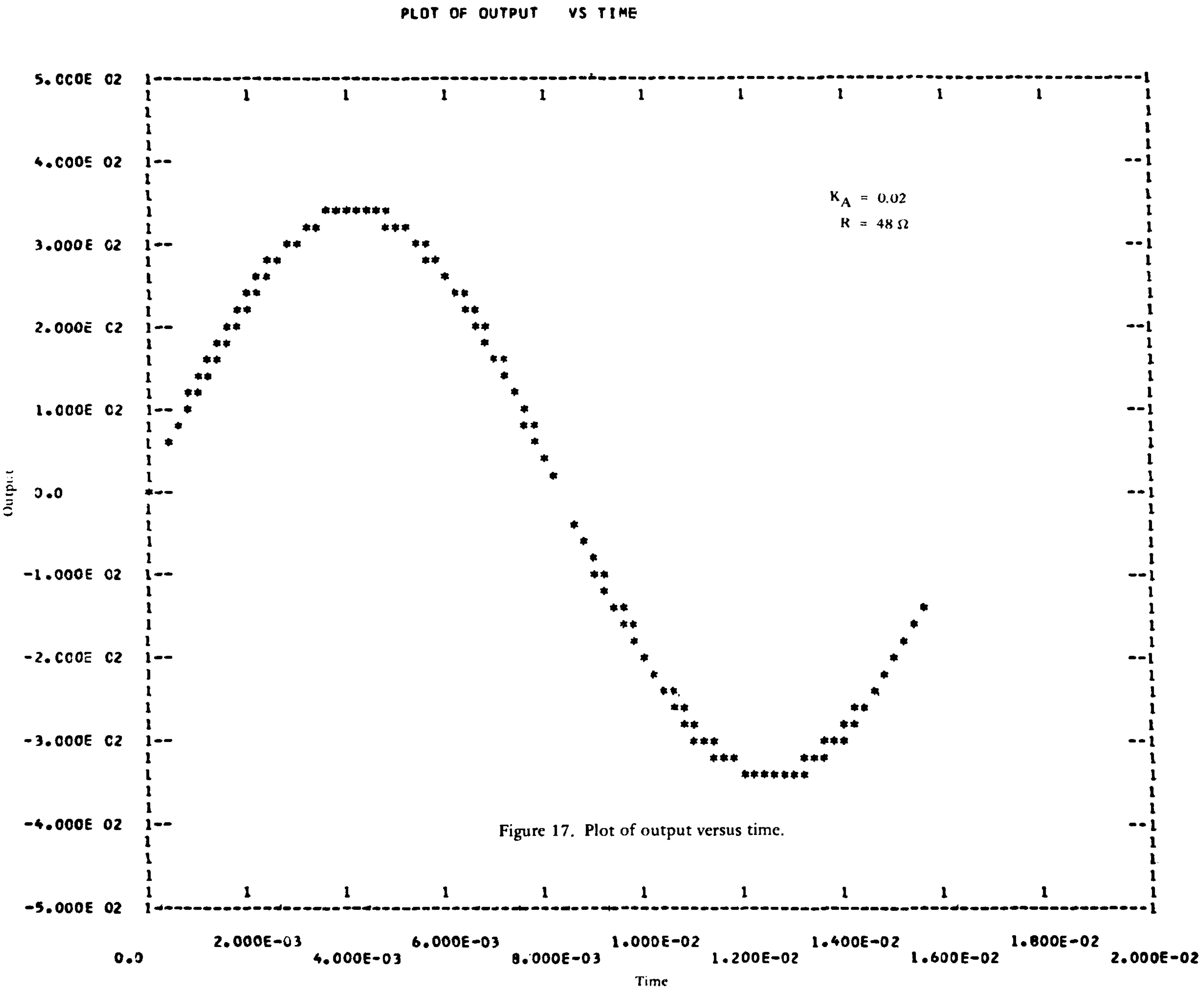


Figure 17. Plot of output versus time.

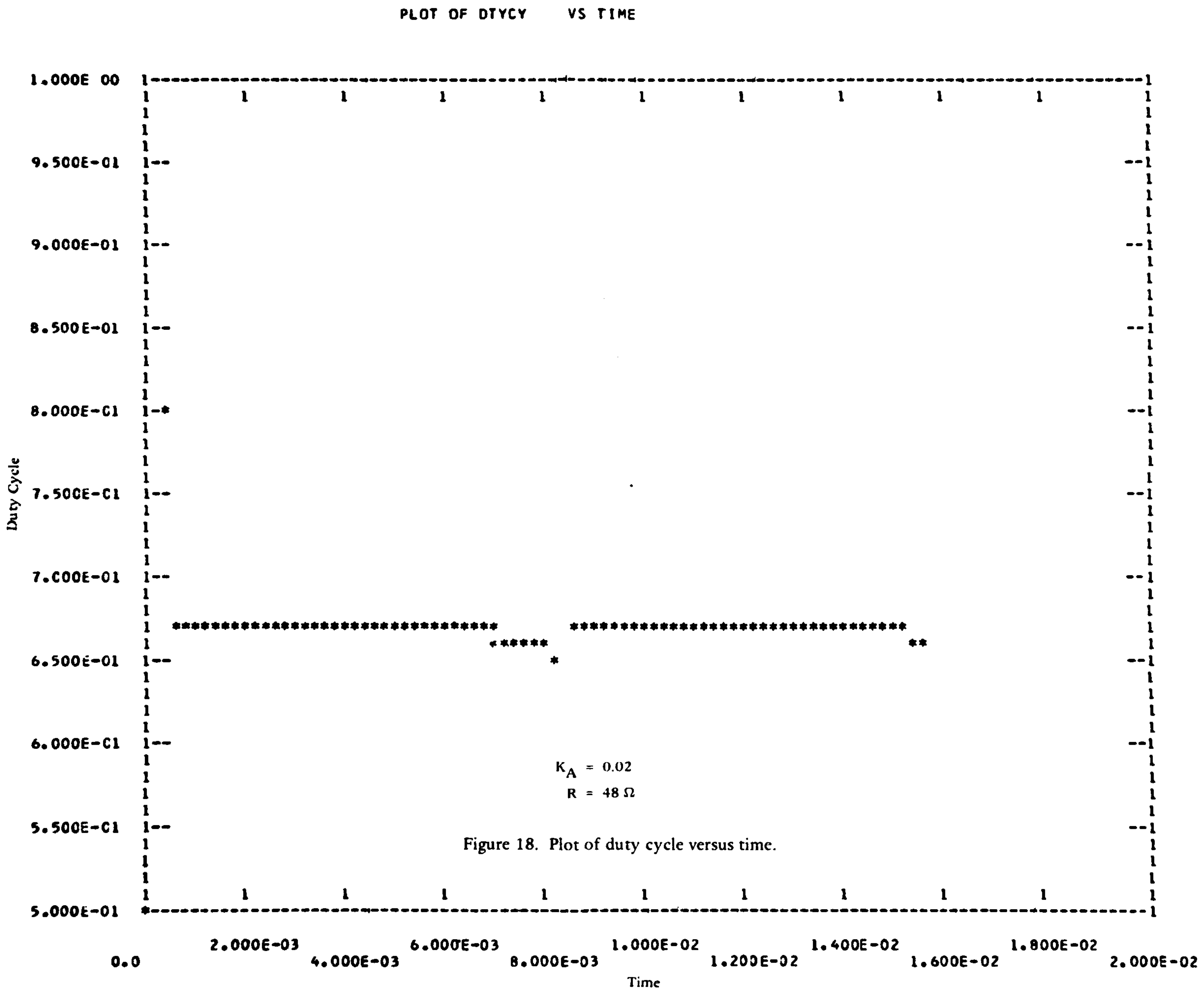


Figure 18. Plot of duty cycle versus time.

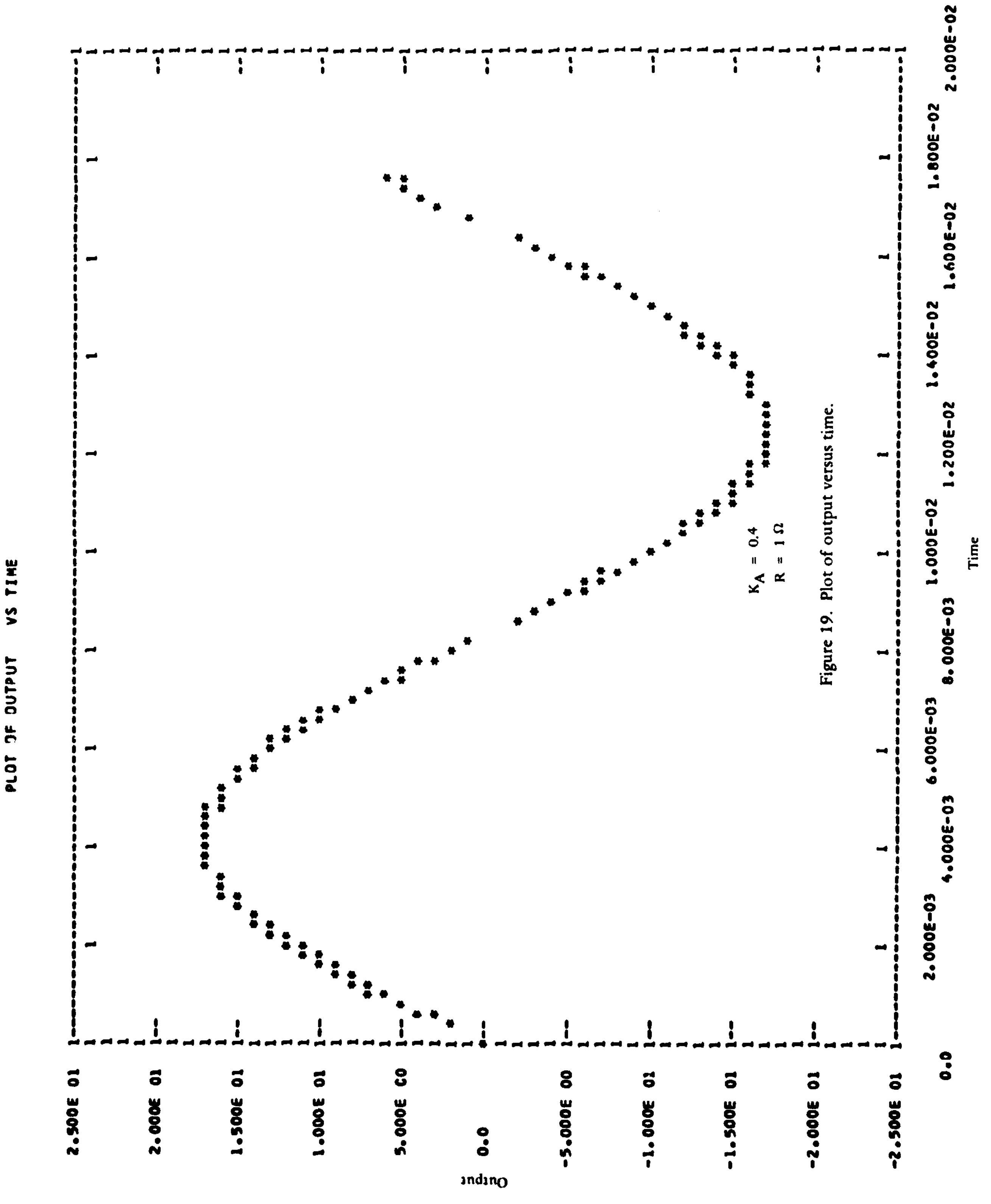
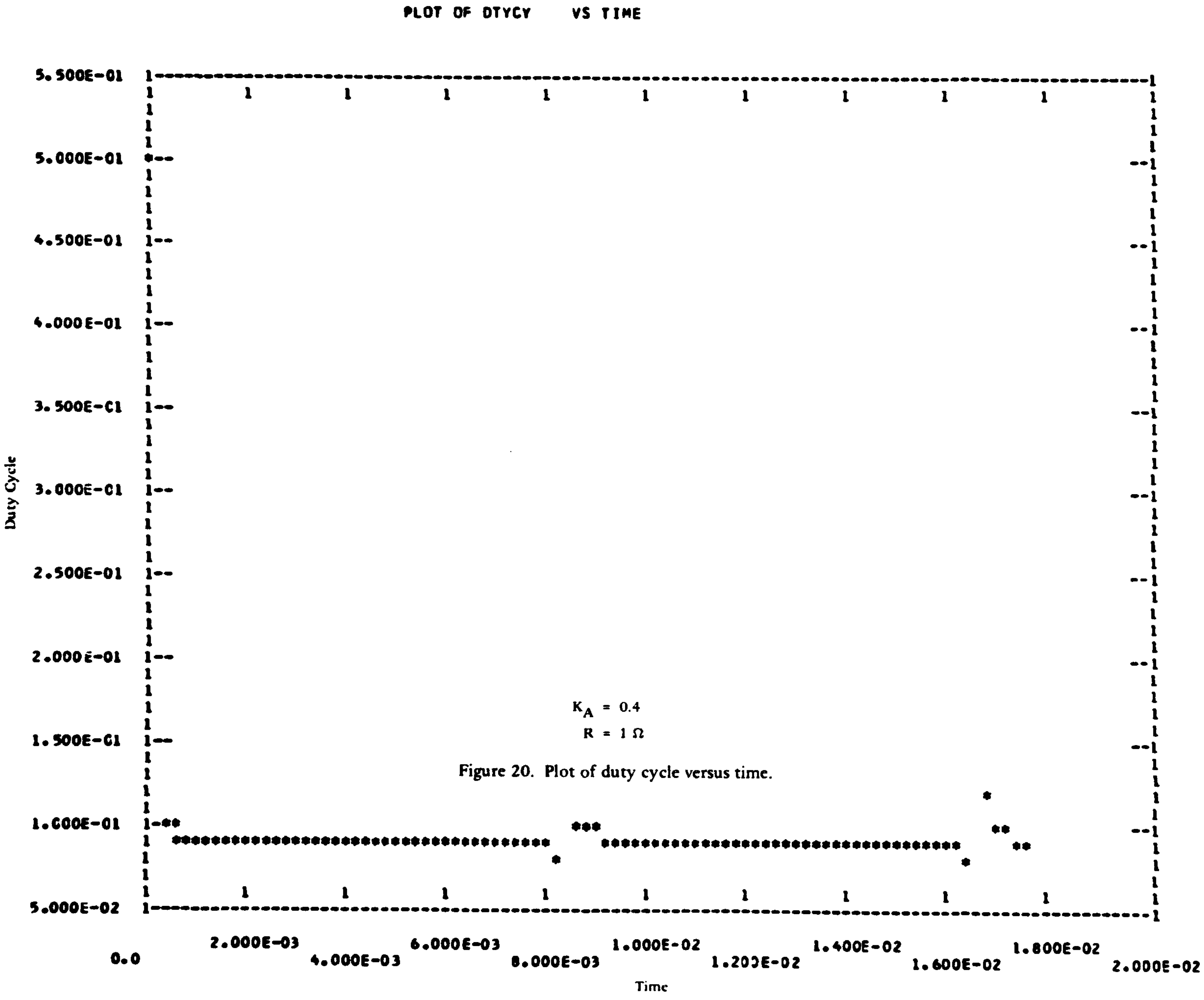


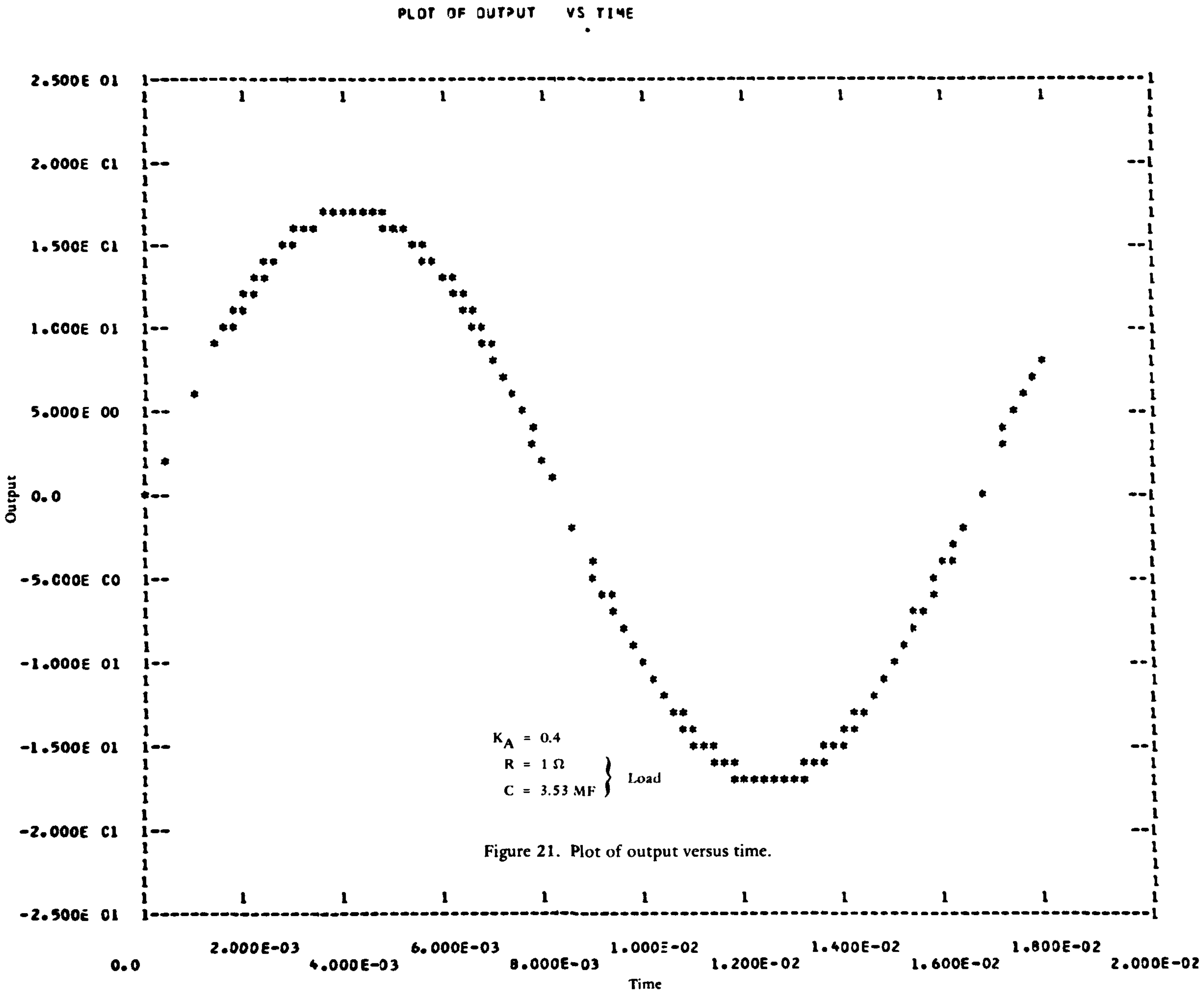
Figure 19. Plot of output versus time.



$K_A = 0.4$

$R = 1\ \Omega$

Figure 20. Plot of duty cycle versus time.



K_A = 0.4
R = 1 Ω } Load
C = 3.53 MF }

Figure 21. Plot of output versus time.

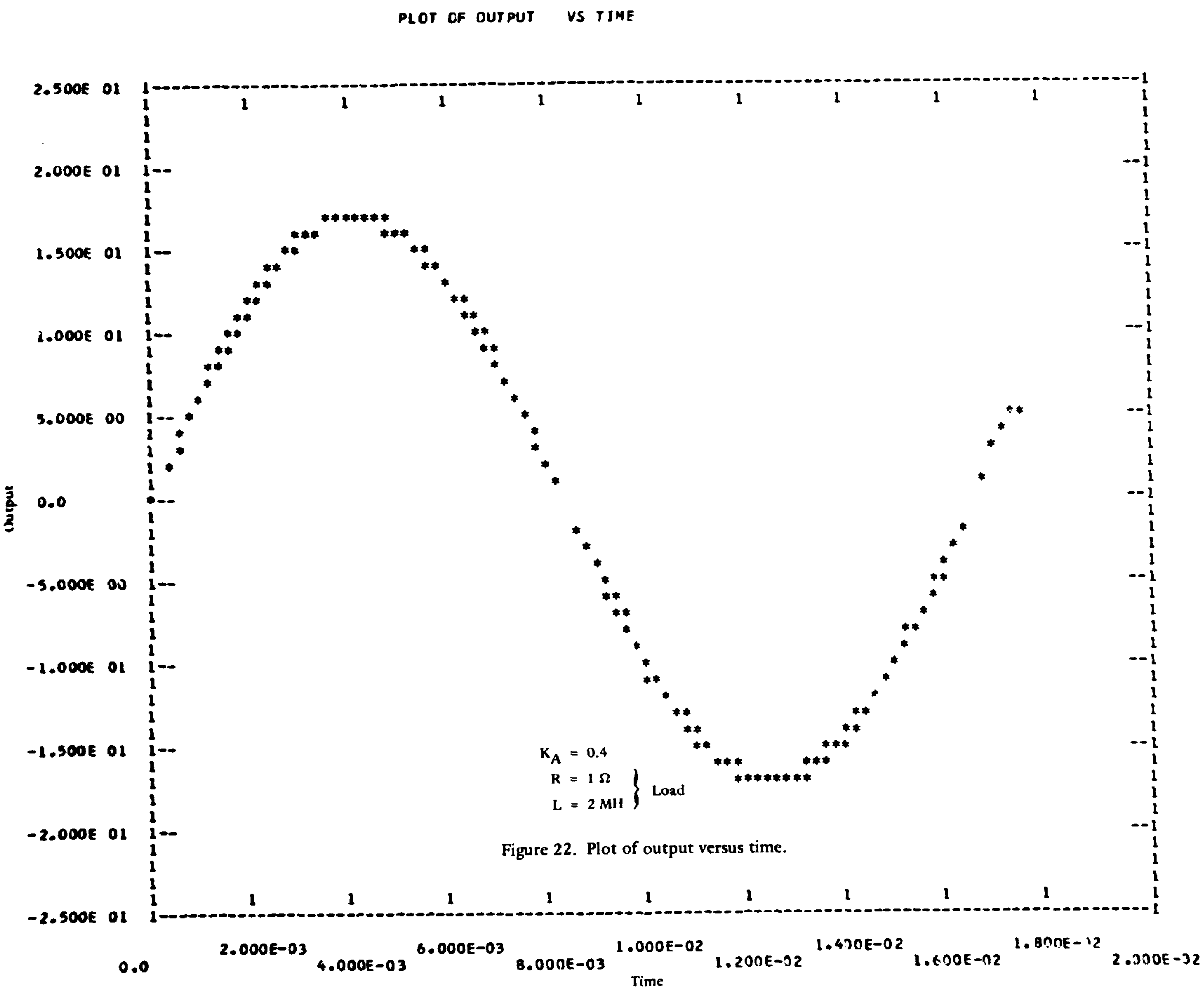


Figure 22. Plot of output versus time.

DISTRIBUTION LIST

AFB AF Tech Office (Mgt & Ops), Tyndall, FL; AFCEC XR.Tyndall FL; CESCH, Wright-Patterson; HQ Tactical Air Cmd (R. E. Fisher), Langley AFB VA; HQAFESC/DEMM, Tyndall AFB, FL; MAC/DET (Col. P. Thompson) Scott, IL; SAMSO/MNND, Norton AFB CA; Stinfo Library, Offutt NE
ARMY BMDSC-RE (H. McClellan) Huntsville AL; DAEN-CWE-M (LT C D Binning), Washington DC; DAEN-FEU-E (J. Ronan), Washington DC; DAEN-MPU, Washington DC; Tech. Ref. Div., Fort Huachuca, AZ
ARMY COE Philadelphia Dist. (LIBRARY) Philadelphia, PA
ARMY CORPS OF ENGINEERS MRD-Eng. Div., Omaha NE; Seattle Dist. Library, Seattle WA
ARMY ENVIRON. HYGIENE AGCY Water Qual Div (Doner), Aberdeen Prov Ground, MD
ASST SECRETARY OF THE NAVY Spec. Assist Energy (Leonard), Washington, DC
BUMED Field Med Svc School, Camp Pendleton, CA
BUREAU OF RECLAMATION Code 1512 (C. Selander) Denver CO
CINCLANT Civil Engr. Supp. Plans. Ofr Norfolk, VA
CINCPAC Fac Engrng Div (J44) Makalapa, HI
CNO Code NOP-964, Washington DC
COMFLEACT, OKINAWA PWO, Kadena, Okinawa
COMNAVMARIANAS Code N4, Guam
COMOCEANSYSPAC SCE, Pearl Harbor HI
DEFENSE DOCUMENTATION CTR Alexandria, VA
DOE Dr. Cohen; FCM (WE UTT) Washington DC
DTNSRDC Code 4111 (R. Gierich), Bethesda MD; Code 42, Bethesda MD
FLTCOMBATTRACENLANT PWO, Virginia Bch VA
FMFLANT CEC Offr, Norfolk VA
KWAJALEIN MISRAN BMDSC-RKL-C
MARINE CORPS BASE Camp Pendleton CA 92055; Code 43-260, Camp Lejeune NC; M & R Division, Camp Lejeune NC; PWO Camp Lejeune NC; PWO, Camp S. D. Butler, Kawasaki Japan
MARINE CORPS HQS Code LFF-2, Washington DC
MCAS Facil. Engr. Div. Cherry Point NC; CO, Kaneohe Bay HI; Code PWE, Kaneohe Bay HI; Code S4, Quantico VA; PWD, Dir. Maint. Control Div., Iwakuni Japan; PWO Kaneohe Bay HI; PWO, Yuma AZ
MCRD PWO, San Diego Ca
NAD Engr. Dir. Hawthorne, NV
NAF PWD - Engr Div. Atsugi, Japan; PWO Sigonella Sicily; PWO, Atsugi Japan
NALF OINC, San Diego, CA
NARF Code 100, Cherry Point, NC
NAS CO, Guantanamo Bay Cuba; Code 114, Alameda CA; Code 183 (Fac. Plan BR MGR); Code 187, Jacksonville FL; Code 18700, Brunswick ME; Code 18U (ENS P.J. Hickey), Corpus Christi TX; Code 6234 (G. Trask), Point Mugu CA; Code 70, Atlanta, Marietta GA; Dir. Util. Div., Bermuda; ENS Buchholz, Pensacola, FL; Lakehurst, NJ; PW (J. Maguire), Corpus Christi TX; PWD Maint. Div., New Orleans, Belle Chasse LA; PWD, Maintenance Control Dir., Bermuda; PWD, Willow Grove PA; PWO Belle Chasse, LA; PWO Chase Field Beeville, TX; PWO Key West FL; PWO Whiting Fld, Milton FL; PWO, Dallas TX; PWO, Glenview IL; PWO, Kingsville TX; PWO, Millington TN; PWO, Miramar, San Diego CA; PWO., Moffett Field CA; SCE Lant Fleet Norfolk, VA; SCE Norfolk, VA; Security Offr, Alameda CA
NATL RESEARCH COUNCIL Naval Studies Board, Washington DC
NATNAVMEDCEN PWO Bethesda, MD
NAVACT PWO, London UK
NAVAEROSPREGMEDCEN SCE, Pensacola FL
NAVAVIONICFAC PWD Deputy Dir. D/701, Indianapolis, IN
NAVCOASTSYSTCTR Code 423 (D. Good), Panama City FL; Code 713 (J. Quirk) Panama City, FL; Library Panama City, FL
NAVCOMMAREAMSTRSTA Code W-602, Honolulu, Wahiawa HI; PWO, Norfolk VA; PWO, Wahiawa HI; SCE Unit 1 Naples Italy
NAVCOMMSTA CO (61E) Puerto Rico; CO, San Miguel, R.P.; Code 401 Nea Makri, Greece; PWO, Exmouth, Australia; PWO, Fort Amador Canal Zone
NAVEDTRAPRODEVCEN Tech. Library

NAVEDUTRACEN Engr Dept (Code 42) Newport, RI

NAVFAC PWO, Brawdy Wales UK; PWO, Cape Hatteras, Buxton NC; PWO, Centerville Bch, Ferndale CA; PWO, Guam

NAVFAC PWO, Lewes DE

NAVFACENGCOM Code 043 Alexandria, VA; Code 044 Alexandria, VA; Code 0451 Alexandria, VA; Code 0454B Alexandria, Va; Code 04B3 Alexandria, VA; Code 04B5 Alexandria, VA; Code 100 Alexandria, VA; Code 1113 (M. Carr) Alexandria, VA; Code 1113 (T. Stevens) Alexandria, VA; Code 1113 Alexandria, VA; Morrison Yap, Caroline Is.; P W Brewer Alexandria, VA

NAVFACENGCOM - CHES DIV. Code 101 Wash, DC; Code 403 (H. DeVoe) Wash, DC; Code 405 Wash, DC

NAVFACENGCOM - LANT DIV. CDR E. Peltier; Code 111, Norfolk, VA; Eur. BR Deputy Dir, Naples Italy; European Branch, New York; RDT&ELO 102, Norfolk VA

NAVFACENGCOM - NORTH DIV. CO; Code 1028, RDT&ELO, Philadelphia PA; Code 111 (Castranovo) Philadelphia, PA; Code 114 (A. Rhoads); Design Div. (R. Masino), Philadelphia PA; ROICC, Contracts, Crane IN

NAVFACENGCOM - PAC DIV. (Kyi) Code 101, Pearl Harbor, HI; Code 2011 Pearl Harbor, HI; Code 402, RDT&E, Pearl Harbor HI; Commander, Pearl Harbor, HI

NAVFACENGCOM - SOUTH DIV. Code 90, RDT&ELO, Charleston SC

NAVFACENGCOM - WEST DIV. 102; 112; AROICC, Contracts, Twentynine Palms CA; Code 04B San Bruno, CA; O9P/20 San Bruno, CA; RDT&ELO Code 2011 San Bruno, CA

NAVFACENGCOM CONTRACT AROICC, Point Mugu CA; AROICC, Quantico, VA; Code 05, TRIDENT, Bremerton WA; Dir. Eng. Div., Exmouth, Australia; Eng Div dir, Southwest Pac, Manila, PI; OICC, Southwest Pac, Manila, PI; OICC/ROICC, Balboa Canal Zone; ROICC AF Guam; ROICC LANT DIV., Norfolk VA; ROICC Off Point Mugu, CA; ROICC, Keflavik, Iceland; ROICC, Pacific, San Bruno CA

NAVHOSP LT R. Elsbernd, Puerto Rico

NAVNUPWRU MUSE DET Code NPU-30 Port Hueneme, CA

NAVOCEANSYSCEN Code 41, San Diego, CA; Code 6700, San Diego, CA; Tech. Library, Code 447

NAVORDSTA PWO, Louisville KY

NAVPETOFF Code 30, Alexandria VA

NAVPHIBASE CO, ACB 2 Norfolk, VA

NAVRADRECFAC PWO, Kami Seya Japan

NAVREGMEDCEN Chief of Police, Camp Pendleton CA; PWO Newport RI; PWO Portsmouth, VA; SCE (D. Kaye); SCE San Diego, CA; SCE, Camp Pendleton CA; SCE, Guam; SCE, Oakland CA

NAVSCOLCECOFF C35 Port Hueneme, CA; CO, Code C44A Port Hueneme, CA

NAVSECGRUACT PWO, Adak AK; PWO, Edzell Scotland; PWO, Puerto Rico; PWO, Torri Sta, Okinawa

NAVSHIPREPFAC SCE Subic Bay

NAVSHIPYD; Code 202.4, Long Beach CA; Code 202.5 (Library) Puget Sound, Bremerton WA; Code 380, (Woodroff) Norfolk, Portsmouth, VA; Code 400, Puget Sound; Code 400.03 Long Beach, CA; Code 404 (LT J. Riccio), Norfolk, Portsmouth VA; Code 410, Mare Is., Vallejo CA; Code 440 Portsmouth NH; Code 440, Norfolk; Code 440, Puget Sound, Bremerton WA; Code 450, Charleston SC; Code 453 (Util. Supr), Vallejo CA; L.D. Vivian; Library, Portsmouth NH; PWD (Code 400), Philadelphia PA; PWO, Mare Is.; PWO, Puget Sound; SCE, Pearl Harbor HI; Tech Library, Vallejo, CA

NAVSTA CO Naval Station, Mayport FL; CO Roosevelt Roads P.R. Puerto Rico; Dir Mech Engr, Gtmo; Engr. Dir., Rota Spain; Long Beach, CA; Maint. Cont. Div., Guantanamo Bay Cuba; Maint. Div. Dir/Code 531, Rodman Canal Zone; PWO Midway Island; PWO, Keflavik Iceland; PWO, Mayport FL; ROICC, Rota Spain; SCE, Guam; SCE, San Diego CA; SCE, Subic Bay, R.P.; Utilities Engr Off. (A.S. Ritchie), Rota Spain

NAVSUBASE ENS S. Dove, Groton, CT; SCE, Pearl Harbor HI

NAVSUPPACT CO, Seattle WA; Code 4, 12 Marine Corps Dist, Treasure Is., San Francisco CA; Code 413, Seattle WA; LTJG McGarrah, SEC, Vallejo, CA; Plan/Engr Div., Naples Italy

NAVSURFWPNCEN PWO, White Oak, Silver Spring, MD

NAVTECHTRACEN SCE, Pensacola FL

NAVWPNCEN Code 2636 (W. Bonner), China Lake CA; PWO (Code 26), China Lake CA; ROICC (Code 702), China Lake CA

NAVWPNSTA (Clebak) Colts Neck, NJ; Code 092, Colts Neck NJ; Code 092A (C. Fredericks) Seal Beach CA; Maint. Control Dir., Yorktown VA

NAVWPNSTA PW Office (Code 09C1) Yorktown, VA

NAVWPNSUPPCEN Code 09 Crane IN

NCBU 405 OIC, San Diego, CA
PWC Code 420, Pensacola, FL
NCBC Code 10 Davisville, RI; Code 155, Port Hueneme CA; Code 156, Port Hueneme, CA; Code 400, Gulfport MS; PW Engrg, Gulfport MS; PWO (Code 80) Port Hueneme, CA; PWO, Davisville RI
NCBU 411 OIC, Norfolk VA
NCR 20, Commander
NCSO BAHRAIN Security Offr, Bahrain
NMCB 5, Operations Dept.; Forty, CO; THREE, Operations Off.
NORDA Code 440 (Ocean Rsch Off) Bay St. Louis MS
NSC Code 54.1 (Wynne), Norfolk VA
NSD SCE, Subic Bay, R.P.
NTC Commander Orlando, FL
NUSC Code 131 New London, CT; Code EA123 (R.S. Munn), New London CT
OCEANSYSLANT LT A.R. Giancola, Norfolk VA
OFFICE SECRETARY OF DEFENSE OASD (MRA&L) Pentagon (T. Casberg), Washington, DC
ONR Code 700F Arlington VA
PHIBCB 1 P&E, Coronado, CA
PMTC Pat. Counsel, Point Mugu CA
PWC ACE Office (LTJG St. Germain) Norfolk VA; CO Norfolk, VA; CO, (Code 10), Oakland, CA; CO, Great Lakes IL; Code 10, Great Lakes, IL; Code 120, Oakland CA; Code 120C, (Library) San Diego, CA; Code 128, Guam; Code 154, Great Lakes, IL; Code 200, Great Lakes IL; Code 220 Oakland, CA; Code 220.1, Norfolk VA; Code 30C, San Diego, CA; Code 400, Great Lakes, IL; Code 400, Oakland, CA; Code 400, Pearl Harbor, HI; Code 400, San Diego, CA; Code 420, Great Lakes, IL; Code 420, Oakland, CA; Code 42B (R. Pascua), Pearl Harbor HI; Code 505A (H. Wheeler); Code 600, Great Lakes, IL; Code 601, Oakland, CA; Code 610, San Diego Ca; LTJG J.L. McClaine, Yokosuka, Japan; Utilities Officer, Guam; XO (Code 20) Oakland, CA
SPCC PWO (Code 120) Mechanicsburg PA
NAF PWO (Code 30) El Centro, CA
U.S. MERCHANT MARINE ACADEMY Kings Point, NY (Reprint Custodian)
USCG (Smith), Washington, DC; G-EOE-4/61 (T. Dowd), Washington DC
USNA Ch. Mech. Engr. Dept Annapolis MD; PWD Engr. Div. (C. Bradford) Annapolis MD
CORNELL UNIVERSITY Ithaca NY (Serials Dept, Engr Lib.)
DAMES & MOORE LIBRARY LOS ANGELES, CA
ILLINOIS STATE GEO. SURVEY Urbana IL
LEHIGH UNIVERSITY Bethlehem PA (Linderman Lib. No.30, Flecksteiner)
LIBRARY OF CONGRESS WASHINGTON, DC (SCIENCES & TECH DIV)
MIT Cambridge MA; Cambridge MA (Rm 10-500, Tech. Reports, Engr. Lib.)
NEW MEXICO SOLAR ENERGY INST. Dr. Zwibel Las Cruces NM
NY CITY COMMUNITY COLLEGE BROOKLYN, NY (LIBRARY)
PURDUE UNIVERSITY Lafayette, IN (CE Engr. Lib)
CONNECTICUT Hartford CT (Dept of Plan. & Energy Policy)
UNIVERSITY OF CALIFORNIA Berkeley CA (E. Pearson)
UNIVERSITY OF DELAWARE Newark, DE (Dept of Civil Engineering, Chesson)
UNIVERSITY OF ILLINOIS URBANA, IL (LIBRARY)
UNIVERSITY OF MASSACHUSETTS (Heronemus), Amherst MA CE Dept
UNIVERSITY OF NEBRASKA-LINCOLN Lincoln, NE (Ross Ice Shelf Proj.)
UNIVERSITY OF TEXAS Inst. Marine Sci (Library), Port Arkansas TX
UNIVERSITY OF WISCONSIN Milwaukee WI (Ctr of Great Lakes Studies)
URS RESEARCH CO. LIBRARY SAN MATEO, CA
BECHTEL CORP. SAN FRANCISCO, CA (PHELPS)
BROWN & CALDWELL E M Saunders Walnut Creek, CA
CANADA Trans-Mnt Oil Pipe Lone Corp. Vancouver, BC Canada
COLUMBIA GULF TRANSMISSION CO. HOUSTON, TX (ENG. LIB.)
DURLACH, O'NEAL, JENKINS & ASSOC. Columbia SC
FORD, BACON & DAVIS, INC. New York (Library)
GLIDDEN CO. STRONGSVILLE, OH (RSCH LIB)
LOCKHEED MISSILES & SPACE CO. INC. Sunnyvale, CA (K.L. Krug)

MCDONNEL AIRCRAFT CO. Dept 501 (R.H. Fayman), St Louis MO
RAYMOND INTERNATIONAL INC. E Colle Soil Tech Dept, Pennsauken, NJ
SANDIA LABORATORIES Seabed Progress Div 4536 (D. Talbert) Albuquerque NM
WISS, JANNEY, ELSTNER, & ASSOC Northbrook, IL (D.W. Pfeifer)
BRAHTZ La Jolla, CA
BRYANT ROSE Johnson Div. UOP, Glendora CA
R.F. BESIER Old Saybrook CT
T.W. MERMEL Washington DC