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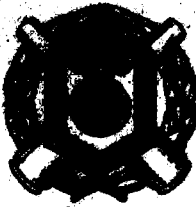
**TECHNICAL REPORT ARPSD-TR-87010**

**DETERMINATION OF THE COMMUTATION ANGLE AND LOAD  
RESPONSE FOR A CONTINUOUS-CURRENT, SINGLE PHASE  
CONTROLLED RECTIFIER**

**JOHN A. PAPPAS  
MAJ JOSEPH E. BENO**

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# CONTENTS

	Page
Introduction	1
Description of Model and Boundary Conditions	1
Development of Equations for Load Current and Constants	3
Determination of Minimum Phase Control Angle	5
Determination of Continuity of Current	6
Results	7
Appendixes	
A FORTRAN Source Code	15
B Instructions for Running the FORTRAN Program	27
Distribution List	31



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## FIGURES

	Page
1 Bridge rectifier	9
2 Two-phase rectifier	9
3 Conduction circuit	10
4 Commutation circuit	10
5 Expected load response	11
6 Load response for transformer inductance of 50 mH and load inductance of 326 mH	11
7 Load response for transformer inductance increased to 250 mH	12
8 Load response for back EMF of 10V	12
9 Load response for back EMF increased to 30V	13
10 Flat response for large load inductance	13
11 Invalid response showing negative current swing	14

## INTRODUCTION

Controlled rectifiers employing power semiconductors are used to vary the average power supplied by a constant voltage a.c. source to a load circuit. One of the problems inherent in the design of such a system is the determination of the commutation or overlap angle. Knowledge of the commutation angle gives the designer information about the rate of change of current in the power semiconductor and allows him to accurately model the load current.

A short review of the literature failed to produce a rigorous determination of the commutation angle. Common methods of analysis either ignore the commutation reactance contained in any rectifier circuit or assume constant load current.

The model developed here represents the circuits depicted in figures 1 and 2. A full wave rectifier employing a transformer connected across the single-phase source and a bridge-rectifier circuit are shown in figure 1. The circuit shown in figure 2 also gives full wave rectification and consists of a center-tapped transformer and controlled rectifiers. While the center-tapped transformer has the effect of transforming the single-phase source into a two-phase source, the circuit is commonly referred to as a single-phase transformer.<sup>1</sup>

The load current obtained from either circuit is the same; the choice of which circuit should be employed is application dependant. *Factors to be considered in such a selection include cost, required load voltage, and the available voltage supply.*<sup>1</sup>

## DESCRIPTION OF MODEL AND BOUNDARY CONDITIONS

The method used to calculate the commutation angle and load current is dictated by the fact that no a priori knowledge of the magnitude of the current at the boundaries exists. The current at the boundary points depends on the firing and commutation angles as well as the circuit parameters. As a result, the conventional Laplace transformation approach is not applicable.

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<sup>1</sup>Dewan, S. B. and Straughen, A., Power Semiconductor Circuits, John Wiley and Sons, New York, 1975, p 216.

To solve the problem, a set of equations with undetermined constants of integration were developed. The equations represent the current in the load during commutation and conduction and the phase "a" current during commutation. Through successive application of the boundary conditions, four independent transcendental equations containing the constants of integration and commutation angle were generated. The equations were then solved simultaneously through an iterative process resulting in numerical values valid for the input circuit values and firing angle.

Continuity of load current was assumed. The method of application of the boundary conditions forces continuous load current and cases resulting in a discontinuous response will not lead to accurate results. Fortunately, it is not difficult to determine if a discontinuous current situation exists. The procedure to determine continuity of current is discussed later.

During the conduction phase of operation, either circuit may be represented by the single phase equivalent shown in figure 3. Since the response of both "phases" to the load is symmetrical, it is only required to calculate the phase "a" response for one half cycle. The response during the second half cycle is simply a time shifted duplication of the phase "a" current.

The commutation circuit (fig. 4) represents the circuit while SCR 1 is coming on and SCR 2 is going off. The voltage sources are sinusoidal so  $v_a = V\sin\omega t$  and  $v_b = V\sin\omega t$ . The time reference is established so that  $t = 0$  when the phase "a" voltage becomes positive. SCR 1 is fired at  $\omega t = \alpha$ . It is assumed that SCR 1 is forward biased at this point. During commutation, both phases conduct simultaneously and the load current,  $i_d$ , is the sum of the phase currents  $i_a$  and  $i_b$ .

The expected load response is illustrated in figure 5. The following boundary conditions used in the formulation of the load current equations are readily apparent from reference to the figure:

$$i_a(\alpha) = 0$$

$$i_d(\alpha + \mu) = i_a(\alpha + \mu)$$

$$i_d(\alpha + \mu) = i_{ac}(\alpha + \mu)$$

$$i_{ac}(\alpha + \pi) - i_d(\alpha)$$

## DEVELOPMENT OF EQUATIONS FOR LOAD CURRENT AND CONSTANTS

Beginning with the method described by Hoff<sup>2</sup>, the voltage balance around the outside and lower paths in figure 4 is written

$$-V \sin \omega t + L_t \frac{di_a}{dt} + L \frac{d(i_a + i_b)}{dt} + R(i_a + i_b) + V_c = 0$$

$$V \sin \omega t + L_t \frac{di_b}{dt} + L \frac{d(i_a + i_b)}{dt} + R(i_a + i_b) + V_c = 0$$

Adding these two equations and defining a load current during commutation,  $i_d = i_a + i_b$ , leads to an equation without a forcing term

$$\frac{di_d}{dt} + \frac{2R i_d}{L_t + 2L} + \frac{2V_c}{L_t + 2L} = 0 \quad (1)$$

Equation 1 is a linear first order differential equation and has the solution

$$i_d = k_1 e^{-(t(\omega) - \alpha)/\omega\tau_1} - \frac{V_c}{R} \quad (2)$$

where

$$\tau_1 = \frac{L_t + 2L}{2R}$$

and  $k_1$  is to be determined from the boundary conditions.  $\tau_1$  is the time constant of the circuit during commutation.

In order to obtain an independent expression for the phase "a" current during commutation, consider the voltage balance around the outer loop of figure 4

$$-V \sin \omega t + L_t \frac{di_a}{dt} + V_0 = 0 \quad (3)$$

where

$$V_0 = L \frac{di_d}{dt} + R i_d + V_c$$

<sup>2</sup>Hoff, R.G., Semiconductor Power Electronics, Van Nostrand Reinhold Co., New York, 1986, p 126.

Taking the derivative of equation 2 and substituting for  $V_0$  and  $i_d$  in equation 3 yields a separable differential equation for  $i_a$  which can be integrated as

$$\begin{aligned} i_a \int \left\{ \frac{V}{L_t} \sin \omega t - \frac{k_1}{2\tau_1} e^{-(t\omega - \alpha)/\omega\tau_1} \right\} dt \\ = -\frac{V}{\omega L_t} \cos \omega t + \frac{k_1}{2} e^{-(t\omega - \alpha)/\omega\tau_1} + k_2 \end{aligned} \quad (4)$$

To determine the constant  $k_2$ , apply the first boundary condition ( $i_a(\alpha) = 0$ ) to equation 4. Then,

$$k_2 = \frac{V}{\omega L_t} \cos \alpha - \frac{k_1}{2} \quad (5)$$

Applying the second boundary condition [ $i_d(\alpha + \mu) = i_a(\alpha + \mu)$ ] in equations 2 and 4 and substituting for  $k_2$  from above results in an expression for  $k_1$

$$k_1 = \frac{2}{1 + e^{-\mu/\omega\tau_1}} \left\{ \frac{V}{\omega L_t} [\cos \alpha - \cos(\alpha + \mu)] + \frac{V_c}{R} \right\} \quad (6)$$

Now consider the conduction period for phase "a" ( $\alpha + \mu < \omega t < \alpha + \pi$ ). Referring to figure 3, the voltage around the circuit can be expressed as

$$-V \sin \omega t + (L_t + L) \frac{di_{ac}}{dt} + R i_{ac} + V_c = 0$$

The solution for the conduction current is

$$i_{ac} = \frac{V}{Z} \sin(\omega t - \Phi) + k_3 e^{-(\omega t - \alpha - \mu)/\omega\tau_2} - \frac{V_c}{R} \quad (7)$$

where

$$Z = \sqrt{(\omega L)^2 + R^2}, \quad \Phi = \tan^{-1} \frac{\omega(L_t + L)}{R}$$

and

$$\tau_2 = \frac{L_t + L}{R}$$

$\tau_2$  is referred to as the conduction time constant and  $k_3$  is to be determined from the third boundary condition.

The third boundary condition deserves some explanation. Note that  $i_d(\alpha + \mu) = i_a(\alpha + \mu) + i_b(\alpha + \mu)$  and  $i_b(\alpha + \mu) = 0$ . In addition,  $i_a(\alpha + \mu) = i_{ac}(\alpha + \mu)$ ; therefore,  $i_d(\alpha + \mu) = i_{ac}(\alpha + \mu)$ . Substituting this condition into equations 7 and 2 leads to an expression for  $k_3$

$$k_3 = k_1 e^{-\mu/\omega\tau_1} - \frac{V}{Z} \sin(\alpha + \mu - \Phi) \quad (8)$$

One more independent equation is required to completely specify the four unknowns ( $k_1$ ,  $k_2$ ,  $k_3$ , and  $\mu$ ). To obtain the last equation, the remaining boundary condition is used. Note first that for steady state operation,  $i_{ac}(\alpha + \pi) = i_b(\alpha)$ . Using reasoning similar to that above, since  $i_a(\alpha) = 0$ ,  $i_{ac}(\alpha + \pi) = i_d(\alpha)$ . Using this information in equations 2 and 4 yields

$$k_1 = -\frac{V}{Z} \sin(\alpha - \Phi) + k_3 e^{-(\pi - \mu)/\omega\tau_2} \quad (9)$$

Equations 5, 6, 8, and 9 are four independent equations defining  $k_1$ ,  $k_2$ ,  $k_3$ , and  $\mu$ . Substituting equations 6 and 8 into equation 9 yields a single (albeit cumbersome) transcendental equation for  $\mu$  in terms of circuit parameters. Numerical solution to this equation then allows calculation of  $k_1$ ,  $k_2$ , and  $k_3$ . Once these constants are known,  $i_{ac}$ ,  $i_d$ , and  $i_a$  can be readily calculated.

### DETERMINATION OF MINIMUM PHASE CONTROL ANGLE

As mentioned previously, it is assumed that SCR 1 is forward biased at  $\omega t = \alpha$ . Once  $\mu$  is numerically determined, it is a simple matter to check this assumption. Just prior to the instant SCR 1 is fired, Kirchoff's voltage law can be written for the top loop in figure 4

$$-2V \sin \omega t + V_{AK1} - L_1 \frac{di_b}{dt} = 0$$

Since  $i_a = 0$ ,  $i_b = i_d$  and, using equation 2, the voltage on the SCR is

$$V_{AK1} = -\frac{L_T k_1}{\tau_1} + 2V \sin \omega t$$

If  $V_{AK1}$  is less than zero, then the assumption was violated and the SCR could not be forward biased at  $\omega t = \alpha$ .<sup>3</sup>

### DETERMINATION OF CONTINUITY OF CURRENT

In the previous derivations, it was presumed that operation was under steady-state continuous-current conditions (i.e.,  $i_d$  is never zero). There are two indicators which can be examined to determine if this assumption is violated.

Some combinations of circuit parameters and firing angle always produce a discontinuous current. These can be determined by assuming a discontinuous current (so there is no commutation) and writing Kirchoff's law for phase "a" conduction

$$V \sin \omega t = (L_T + L) \frac{di_a}{dt} + R i_a + V_c$$

This equation applies for  $\alpha < \omega t < \beta$  where  $\beta$  is the electrical angle at which  $i_a$  returns to zero. Solving the voltage equation for  $i_a$  and writing  $i_a(\omega t = \beta)$  produces a transcendental equation for  $\beta$ .<sup>4</sup>

$$\left\{ \frac{E}{R} - \frac{V}{Z} \sin(\alpha - \Phi) \right\} e^{-R(\alpha - \beta)/\omega L} + \frac{V}{Z} \sin(\beta - \Phi) - \frac{E}{R} = 0$$

<sup>3</sup>Hoft, R.G., Semiconductor Power Electronics, Van Nostrand Reinhold Co., New York, 1986, p 126.

<sup>4</sup>Dewan, S.B. and Straughen, A., Power Semiconductor Circuits, John Wiley and Sons, New York, 1975, chap. 3.

Since  $i_a$  is always positive while SCR 1 conducts, it is not necessary to solve this equation. Substitution of values for  $\beta$  which are less than the true value will produce a positive number from the above equation, while substitution of values for  $\beta$  which are greater than the true value will produce a negative number. If substitution of the value  $\beta = \alpha + \pi$  results in a negative value, then the true  $\beta$  is less than  $\alpha + \pi$  and the circuit shuts off completely prior to firing SCR 2. In this case, the current is discontinuous.

The above criterion for discontinuity is not sufficient in all cases. Some cases which pass that test still result in negative values for phase "a" current (indicating a discontinuous case) for some value of  $\omega t$  between  $\alpha$  and  $\alpha + \pi$ . These cases can only be found by calculating  $\mu$  and the circuit response for the range of values  $\alpha \leq \omega t \leq \alpha + \pi$ .

## RESULTS

The transcendental equation for  $\mu$  was solved numerically on a CDC Dual Cyber 170/750. The program (Appendices A and B) allowed input of all circuit parameters and a firing angle,  $\alpha$ . The commutation angle,  $\mu$ , was then calculated using a straightforward method of bisections. If the input  $\alpha$  failed the check, as discussed previously,  $\alpha$  was incremented by 1 degree and  $\mu$  was recalculated. This continued until an acceptable  $\alpha$  was found (to within 1 degree). The current values were then calculated and plotted. In spite of the unsophisticated method of bisections, run times were relatively short.

The plots from several runs are included which show some trends as various parameters are varied (figs. 6 through 11). The input  $\alpha$  for all runs was zero so that the  $\alpha$  indicated was the minimum  $\alpha$  determined iteratively. In general, large values of inductances were selected to clearly display various trends.

Most runs provided current plots with the expected shapes, even for the flat response expected from a very large load inductance (fig. 10). One run in which the load electromotive force is 50 volts (fig. 11) shows a negative phase "a" current indicating the discontinuous case, which violate our initial assumptions. Therefore, these results are invalid. This case is interesting because it did not have a value of  $\beta$  greater than  $\alpha + \pi$ .

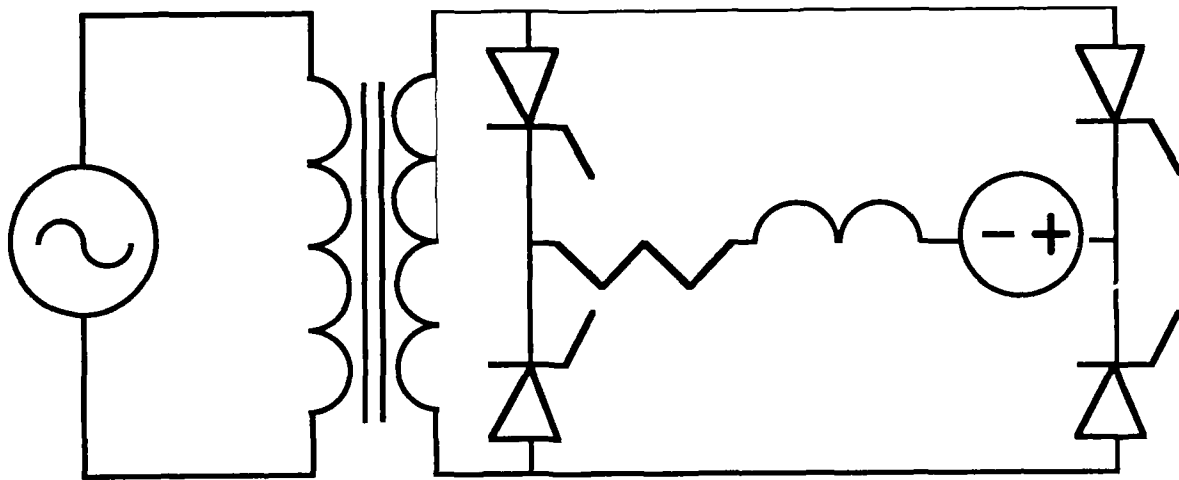


Figure 1. Bridge rectifier

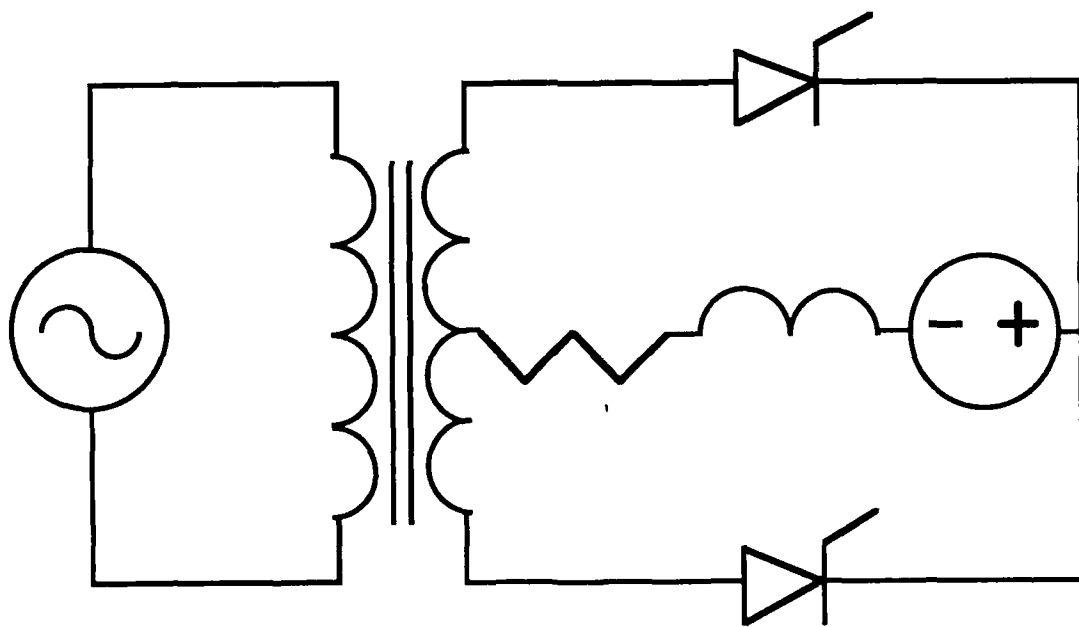


Figure 2. Two-phase rectifier

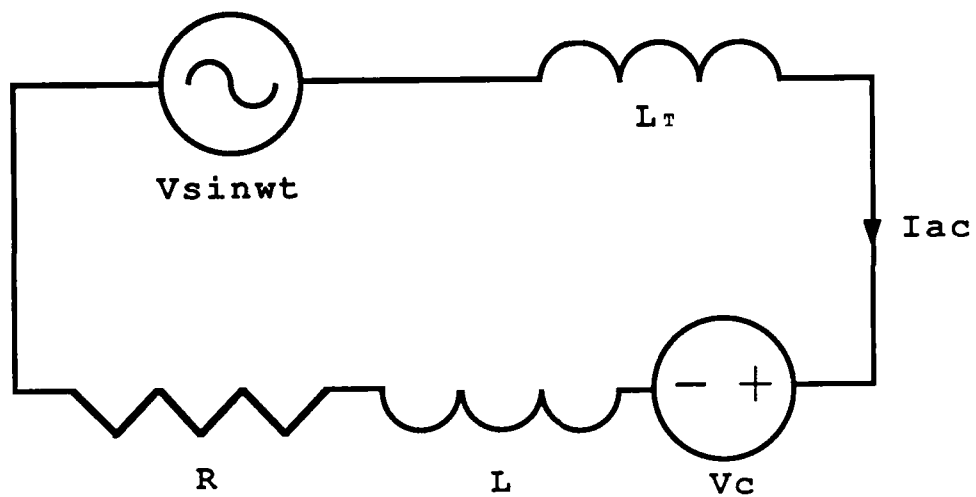


Figure 3. Conduction circuit

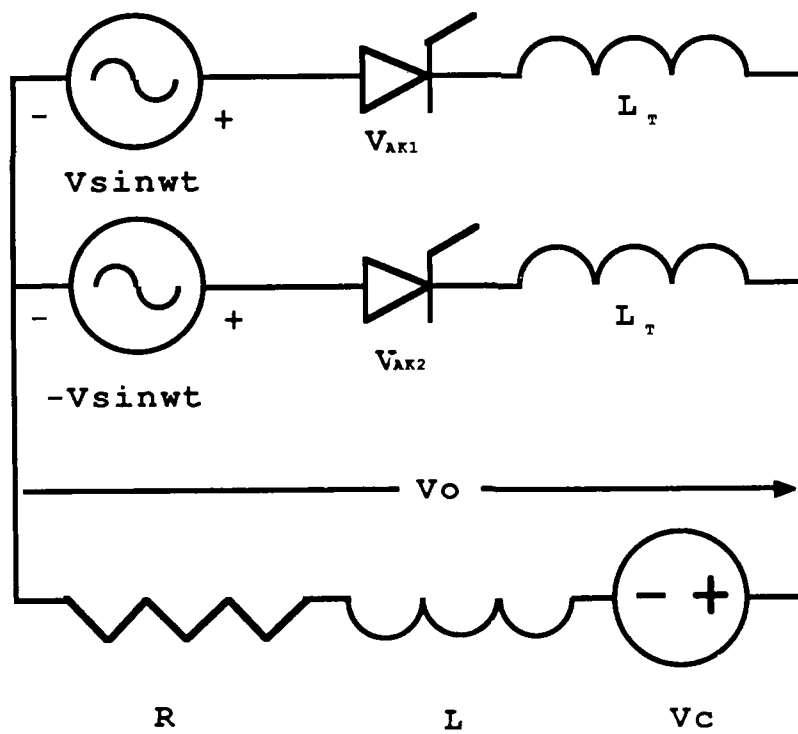


Figure 4. Commutation circuit

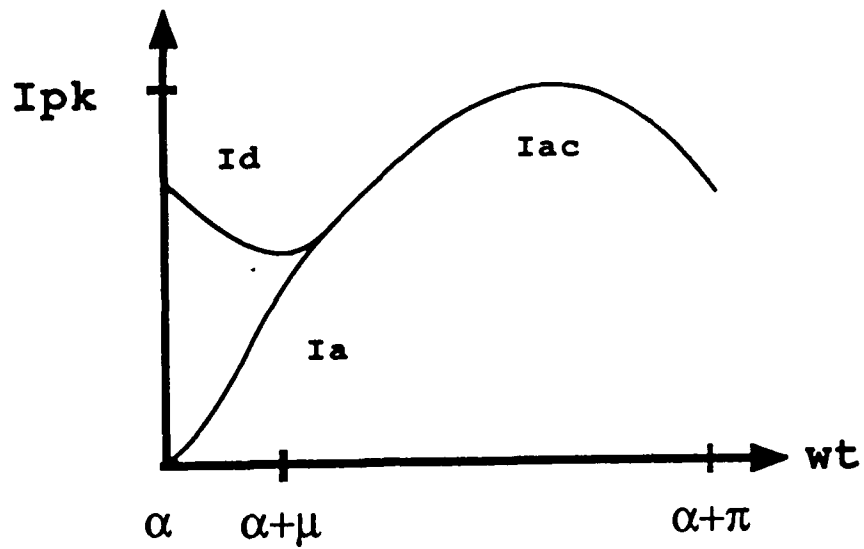
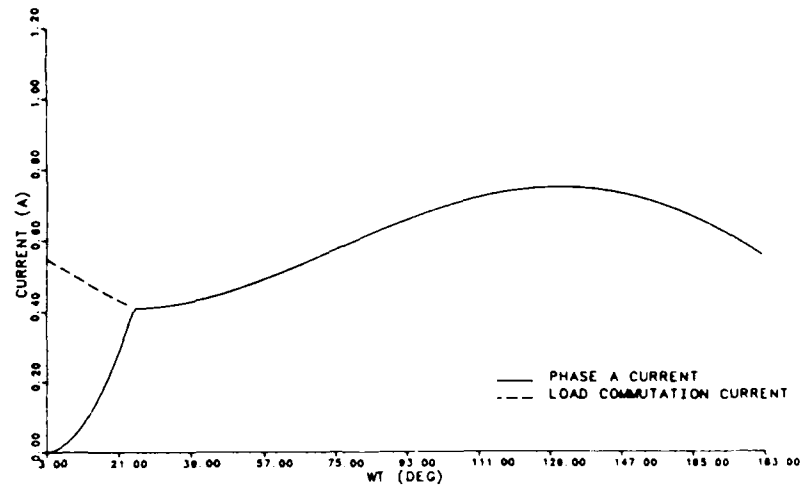
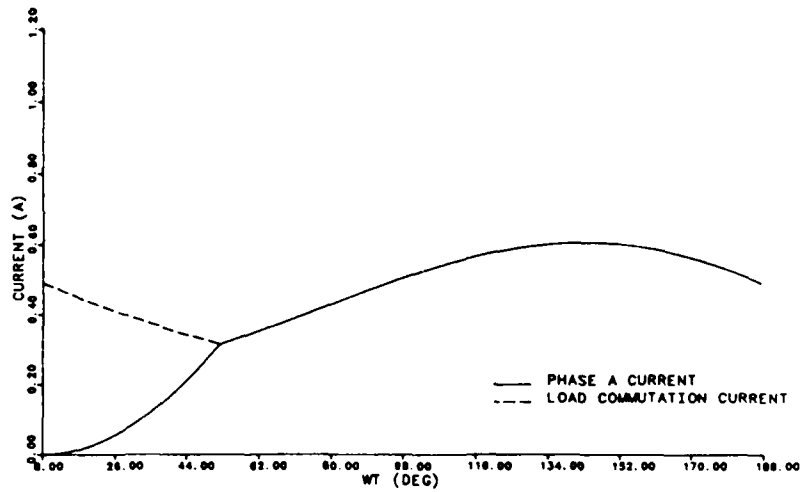


Figure 5. Expected load response



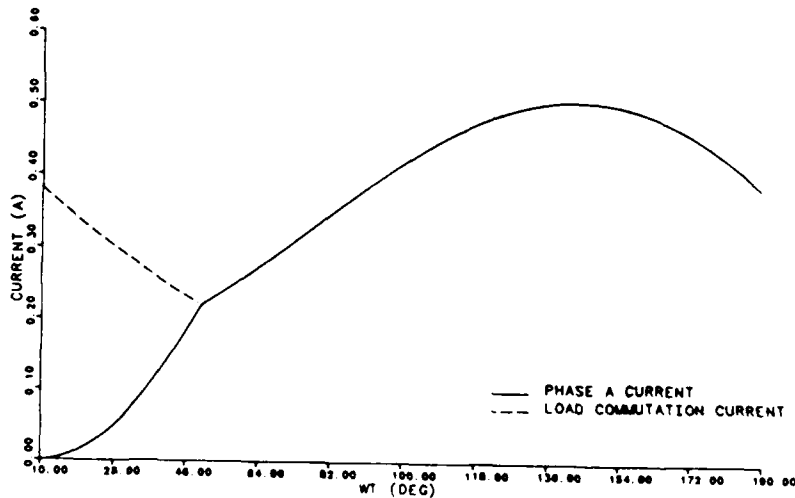
PK SOURCE VOLTAGE (V)	100.00	LOAD RESISTANCE (OHM)	100.00
SOURCE FREQUENCY (HZ)	60.00	LOAD EMF (V)	0.00
FIRING ANGLE (DEG)	3.00	CONDUCTION TAU (S)	0.0038
TRANS INDUCTANCE (H)	0.0500000	COMMUTATION TAU (S)	0.0035
LOAD INDUCTANCE (H)	0.3260000	COMMUTATION ANG (DEG)	21.7505

Figure 6. Load response for transformer inductance of 50 mH and load inductance of 326 mH



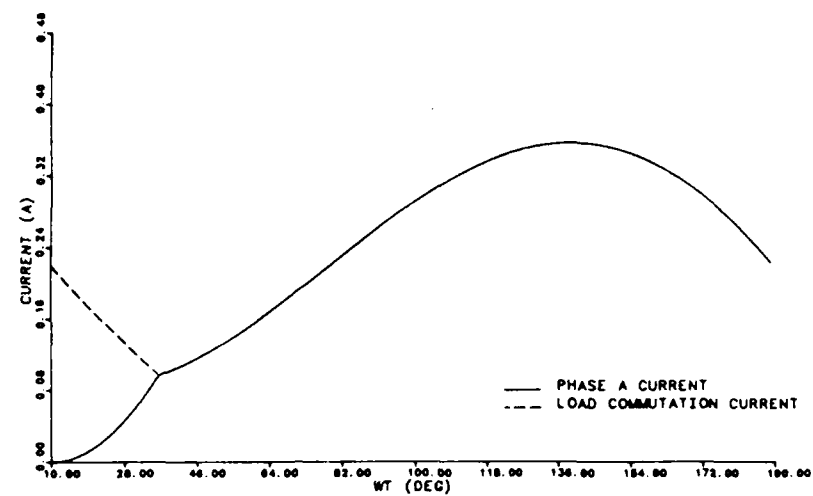
PK SOURCE VOLTAGE (V)	100.00	LOAD RESISTANCE (OHM)	100.00
SOURCE FREQUENCY (HZ)	60.00	LOAD EMF (V)	0.00
FIRING ANGLE (DEG)	8.00	CONDUCTION TAU (S)	0.0058
TRANS INDUCTANCE (H)	0.2500000	COMMUTATION TAU (S)	0.0045
LOAD INDUCTANCE (H)	0.3260000	COMMUTATION ANG (DEG)	44.3335

Figure 7. Load response for transformer inductance increased to 250 mH



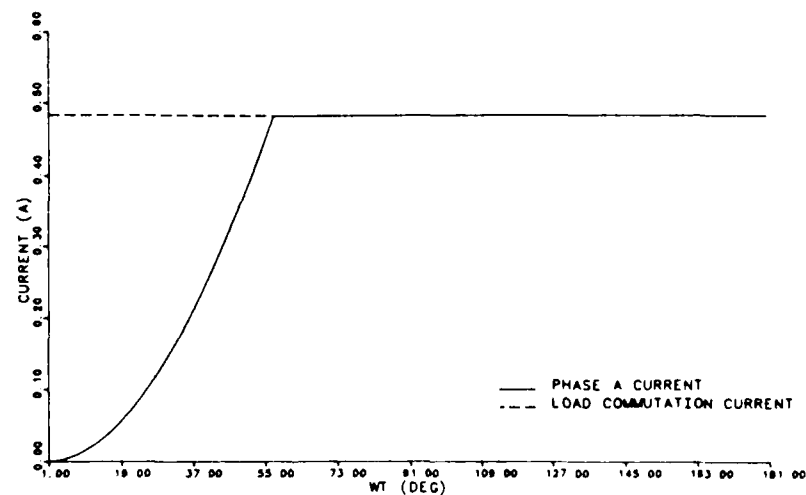
PK SOURCE VOLTAGE (V)	100.00	LOAD RESISTANCE (OHM)	100.00
SOURCE FREQUENCY (HZ)	60.00	LOAD EMF (V)	10.00
FIRING ANGLE (DEG)	10.00	CONDUCTION TAU (S)	0.0060
TRANS INDUCTANCE (H)	0.3000000	COMMUTATION TAU (S)	0.0045
LOAD INDUCTANCE (H)	0.3000000	COMMUTATION ANG (DEG)	39.8755

Figure 8. Load response for back EMF of 10 V



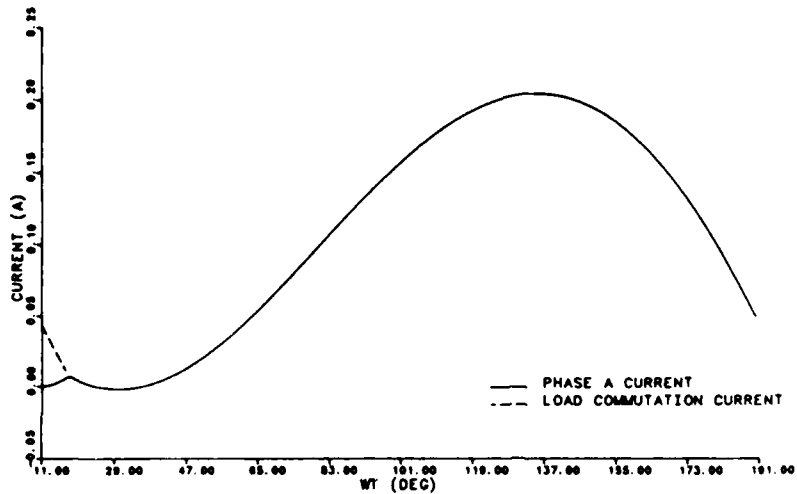
PK SOURCE VOLTAGE (V)	100.00	LOAD RESISTANCE (OHM)	100.00
SOURCE FREQUENCY (HZ)	60.00	LOAD EMF (V)	30.00
FIRING ANGLE (DEG)	10.00	CONDUCTION TAU (S)	0.0060
TRANS INDUCTANCE (H)	0.3000000	COMMUTATION TAU (S)	0.0045
LOAD INDUCTANCE (H)	0.3000000	COMMUTATION ANG (DEG)	26.3335

Figure 9. Load response for back EMF increased to 30 V



PK SOURCE VOLTAGE (V)	100.00	LOAD RESISTANCE (OHM)	100.00
SOURCE FREQUENCY (HZ)	60.00	LOAD EMF (V)	0.00
FIRING ANGLE (DEG)	1.00	CONDUCTION TAU (S)	1.0025
TRANS INDUCTANCE (H)	0.2500000	COMMUTATION TAU (S)	1.0013
LOAD INDUCTANCE (H)	100.000000	COMMUTATION ANG (DEG)	56.0005

Figure 10. Flat response for large load inductance



PK SOURCE VOLTAGE (V)	100.00	LOAD RESISTANCE (OHM)	100.00
SOURCE FREQUENCY (HZ)	60.00	LOAD EMF (V)	50.00
FIRING ANGLE (DEG)	11.00	CONDUCTION TAU (S)	0.0060
TRANS INDUCTANCE (H)	0.3000000	COMMUTATION TAU (S)	0.0045
LOAD INDUCTANCE (H)	0.3000000	COMMUTATION ANG (DEG)	6.7505

Figure 11. Invalid response showing negative current swing  
(Current in this case is discontinuous and is not correctly calculated with this model.)

APPENDIX A  
FORTRAN SOURCE CODE

PROGRAM SGLFAZ (INPUT, OUTPUT, TAPE5=INPUT, TAPE6=OUTPUT, TAPE7)

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\*

FORTRAN PROGRAM SINGLE PHASE

\*

JOHN PAPPAS & JOSEPH BENO  
UNIVERSITY OF TEXAS AT AUSTIN  
DEPARTMENT OF COMPUTER AND ELECTRICAL ENGINEERING

\*

20 APRIL 1987

\*

COMPUTES THE COMMUTATION ANGLE AND LOAD RESPONSE  
FOR A SINGLE PHASE FULL-WAVE RECTIFIER. USER  
INPUTS ARE LOAD AND SOURCE CHARACTERISTICS, FIRING  
ANGLE AND TRANSFORMER INDUCTANCE.

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VARIABLE DICTIONARY

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A        FIRING ANGLE IN RADIANS  
ALPHA    FIRING ANGLE IN DEGREES  
DELTA    TIME-ANGLE INCREMENT IN CURRENT  
          CALCULATION  
ESIGN    DETERMINES ZERO CROSSING  
          IN MU ESTIMATION ROUTINE  
EFACT    ACCURACY FACTOR IN METHOD OF  
          BISECTION  
ENEW    VALUE OF FUNCTION DRIVEN TO ZERO  
          IN MU ESTIMATION  
EOLD    VALUE OF FUNCTION DRIVEN TO ZERO  
          IN MU ESTIMATION  
ERROR    NEARNESS TO ZERO REQUIREMENT FOR  
          FUNCTION OF MU IN BISECTION  
F        SOURCE FREQUENCY IN HERTZ  
FX       SUBSCRIPTED F (IE. F1, ETC.).  
          HOLDS VALUES GENERATED IN KX  
          ROUTINE  
ID       LOAD CURRENT DURING COMMUTATION  
IA       SCR#1 CURRENT DURING COMMUTATION  
IAC      SCR#1 AND LOAD CURRENT DURING  
          CONDUCTION  
IAP      ARRAY HOLDING PHASE A CURRENT VALUES  
          FOR ZETA PLOT ROUTINE  
IDP      ARRAY HOLDING LOAD CURRENT DURING COMMUTATION  
          FOR ZETA PLOT ROUTINE  
J        COUNTER  
KX       SINGLE SUBSCRIPTED K. FUNCTION  
          CONTAINING CONSTANTS OF INTEGRATION  
          IN CURRENT EQUATIONS  
KXX      DOUBLE SUBSCRIPTED K. INTERMEDIATE

```

*          RESULT
*  L        LOAD INDUCTANCE IN HENRIES
*  LL       TRANSFORMER INDUCTANCE IN HENRIES
*  MU       COMMUTATION ANGLE IN DEGREES
*  MUST     START ESTIMATE OF MU FOR BISECTION
*  MUSTP   STOP ESTIMATE OF MU FOR BISECTION
*  MUOLD   INTERMEDIATE RESULT IN BISECTION
*          USED IN ACCURACY CHECK
*  MUNEW   INTERMEDIATE RESULT IN BISECTION
*          USED IN ACCURACY CHECK
*  PHI     LOAD IMPEDANCE ANGLE IN RADIANS
*  PI      PI
*  R       LOAD RESISTANCE IN OHMS
*  T1     TIME CONSTANT OF COMMUTATION CIRCUIT
*  T2     TIME CONSTANT OF CONDUCTION CIRCUIT
*  TEST1  SIGN DETERMINES SIDE OF ZERO CROSSING
*          IN BISECTION
*  U       COMMUTATION ANGLE IN RADIANS
*  V       PEAK VALUE OF SOURCE IN VOLTS
*  VC     LOAD EMF
*  W       SOURCE FREQUENCY IN R/S
*  WT     INCREMENT ANGLE OF HALF CYCLE
*  WTP    ARRAY HOLDING TIME-ANGLE INFORMATION
*          FOR ZETA PLOT ROUTINE
*  Z       LOAD IMPEDANCE MAGNITUDE IN OHMS

```

```

*****
*
*  HOUSEKEEPING
*
*****

```

```

REAL L,LL,K11,K12,K13,K1,K41,K42,K43,K44,K4
REAL MU,K2,K3,MUST,MUSTP,MUOLD,MUNEW,ID,IA,IAC
REAL IA1,IA2,IA3
REAL IAP(182),IDP(182),WTP(182)

```

```

*****
*
*  INTERACTIVE DATA ENTRY
*
*****

```

```

399 FORMAT(//)
400 FORMAT('INPUT DATA(1) OR USE INTERNAL(0)')
401 FORMAT('DATA MAY BE INPUT IN REAL, INTEGER OR
EXPONENTIAL (XX.XE XX) FORM')
402 FORMAT('PEAK SOURCE VOLTAGE (V)')
403 FORMAT('SOURCE FREQUENCY (HZ)')
404 FORMAT('TRANSFORMER INDUCTANCE (H)')
405 FORMAT('LOAD INDUCTANCE (H)')
406 FORMAT('LOAD EMF, VC (V)')
407 FORMAT('LOAD RESISTANCE (OHM)')
408 FORMAT('FIRING ANGLE (DEG)')

```

```

409 FORMAT('CONVERGENCE FACTOR (START WITH ABOUT 0.1)')
398 FORMAT('RUN IDENTIFICATION NUMBER')
440 FORMAT('200 ITERATIONS AND STILL THE FUNCTION DOES
& NOT CONVERGE!')
441 FORMAT('THE ERROR FACTOR CURRENTLY IN USE IS: ',G18.8)
442 FORMAT('THE "ZERO" YOU ARE TRYING TO MATCH IS: ',G18.8)
443 FORMAT('THE CLOSEST YOU HAVE COME SO FAR IS: ',G18.8)
444 FORMAT('INPUT A LARGER ERROR FACTOR')
445 FORMAT('MINIMUM ALPHA REQUIREMENT VIOLATED.')
446 FORMAT('ALPHA INCREASED BY 1 DEGREE TO:',F7.3,'DEGREES')

```

```

WRITE(9,400)
ACCEPT J
IF(J.EQ.0)GOTO 10
WRITE(9,401)
WRITE(9,399)
WRITE(9,402)
ACCEPT V
WRITE(9,399)
WRITE(9,403)
ACCEPT F
WRITE(9,399)
WRITE(9,404)
ACCEPT LL
WRITE(9,399)
WRITE(9,405)
ACCEPT L
WRITE(9,399)
WRITE(9,406)
ACCEPT VC
WRITE(9,399)
WRITE(9,407)
ACCEPT R
WRITE(9,399)
WRITE(9,408)
ACCEPT ALPHA
WRITE(9,399)
WRITE(9,409)
ACCEPT EFAC
WRITE(9,399)
WRITE(9,398)
ACCEPT RUN
GOTO 20

```

```

.....
*
*   INITIALIZATION AND IDENTIFICATION OF CONSTANTS
*
*
.....

```

```

1  EFAC=0.1
   R=100.
   LL=.3
   L=.326
   V=100.

```

```

VC=0.
ALPHA=0.
F=60.
RUN=100.
20 WT=0.
   I=1
   ENEW=0.
   MUSTP=0.
   J=0
   T1=(LL+2.*L)/(2.*R)
   T2=(LL+L)/R
   PI=ACOS(-1.)
   W=2*PI*F
   Z=(R**2.+((LL+L)**2.)*(W**2.))**.5
   PHI=ATAN2(W*(LL+L),R)
30 A=(2.*PI/360.)*ALPHA
   U=0

```

```

*****
*
*   ITERATIVE CALCULATION TO ESTIMATE THE VALUE OF THE
*   COMMUTATION ANGLE
*
*****

```

```

110 F1=K1(A,U,T1,W,V,LL,VC,R)
    F3=K3(A,U,T1,W,V,VC,F1,PHI,Z,R)
    E1=2.*VC*T1
    E2=V/Z*SIN(A-PHI)
    E3=F3*EXP(-(PI-U)/(W*T2))
    E4=VC/R
    EOLD=ENEW
    ENEW=E1-F1-E2+E3-E4
    MUST=MUSTP
    MUSTP=U*180./PI
    E=ENEW*EOLD
    ERROR=ABS(ENEW-EOLD)*EFACT
    IF(E.LT.0) GOTO 100
    U=U+PI/180.
    GOTO 110

```

```

*****
*
*   METHOD OF BISECTION TO CALCULATE
*   COMMUTATION ANGLE
*
*****

```

```

100 MUOLD=MUST
    MU=(MUST+MUSTP)/2.

120 IF(J.EQ.200)THEN
    J=0
    WRITE(9,399)

```

```

WRITE (9, 440)
WRITE (9, 399)
WRITE (9, 441) EFACT
WRITE (9, 399)
WRITE (9, 442) ERROR
WRITE (9, 399)
WRITE (9, 443) ABS (E)
WRITE (9, 399)
WRITE (9, 444)
ACCEPT EFACT
ERROR=ABS (ENEW-EOLD) *EFACT

```

```

ENDIF

```

```

J=J+1
U=MU*PI/180.
F1=K1 (A, U, T1, W, V, LL, VC, R)
F3=K3 (A, U, T1, W, V, VC, F1, PHI, Z, R)
E3=F3*EXP (- (PI-U) / (W*T2))
E=E1-F1-E2+E3-E4

```

```

IF (ABS (E) . LE. ERROR) THEN
  GOTO 130
ENDIF

```

```

TEST1=EOLD*E

```

```

IF (TEST1.LT.0) THEN:
  MUNEW=(MU-MUOLD) /2.+MUOLD
  MUOLD=MU
  MU=MUNEW
  GOTO 120
ENDIF

```

```

MUNEW=(MU-MUOLD) *1.5+MUOLD
MUOLD=MU
MU=MUNEW

```

```

GOTO 120

```

```

130 U=MU*PI/180.
F1=K1 (A, U, T1, W, V, LL, VC, R)
F2=K2 (A, T1, W, V, LL, VC, R, F1)
F3=K3 (A, U, T1, W, V, VC, F1, PHI, Z, R)

```

```

.....
.
. CHECK FOR MINIMUM FIRING ANGLE
.
.....

```

```

ACHECK=2*V*SIN(A) - (LL*F1) /T1

```

```

IF (ACHECK.LT.0.) THEN
  ALPHA=ALPHA+1

```

```

WRITE(9,445)
WRITE(9,446) ALPHA
GOTO 30
ENDIF

```

```

CALL OUTPUT(F1,F2,F3,T1,T2,V,VC,LL,L,R,ALPHA
&,MU,F,EFACT,RUN)

```

```

*****
*
*   CALCULATE CURRENT RESPONSE THROUGH COMMUTATION AND
*   ONE CONDUCTION PERIOD (WT=PI+ALPHA)
*
*****

```

```

WT=A
DELTA=PI/180.

```

```

140 IDP(I)=F1*EXP(-(WT-A)/(W*T1))-2.*VC*T1
    IA1=V/(W*LL)*COS(WT)
    IA2=(F1/2)*EXP(-(WT-A)/(W*T1))
    IA3=(VC/LL)*(1.-2.*R*T1)*(WT/W)
    IAP(I)=-IA1+IA2-IA3+F2
    WTP(I)=WT
    I=I+1
    WT=WT+DELTA

```

```

IF(WT.LE.A+U)GOTO 140

```

```

150 IAP(I)=(V/Z)*SIN(WT-PHI)+F3*EXP(-(WT-A-U)/
&(W*T2))-VC/R
    WTP(I)=WT
    I=I+1
    WT=WT+DELTA

```

```

IF(WT.LE.A+PI)GOTO 150

```

```

*****
*
*   CREATE PLOT FILE COMPATIBLE WITH ZETA PLOTTER
*
*****

```

```

WTP(181)=A
WTP(182)=18.
NPTS=1/DELTA
NPTS2=180.
CALL PLOTS(0,0,L"PLOTS")
CALL PIGIN(1.0,4.0,0)
CALL SCALE(IAP,6.,180,1)
IDP(181)=IAP(181)
IDP(182)=IAP(182)
CALL AXIS(0.,0.,'wt',-2,10.,0.,WTP(181),WTP(182))
CALL AXIS(0.,0.,'Current (A)',11,6.,90.,IAP(181))

```

```

&, IAP(182))
CALL LINE(WTP, IAP, NPTS2, 1, 0, 2)
CALL LINE(WTP, IDP, NPTS, 1, 0, 2)
CALL PLOT(0., 0., 999)
STOP
END

```

```

*****
*
*   DEFINED FUNCTIONS FOR CONSTANTS OF INTEGRATION
*   IN MU AND CURRENT EQUATIONS
*
*****

```

```

REAL FUNCTION K1(A, U, T1, W, V, LL, VC, R)
REAL K11, K12, K13, A, U, T1, W, V, LL, VC, R

```

```

K11=2. / (1.+EXP(-U/(W*T1)))
K12=V/(W*LL) * (COS(A)-COS(A+U))
K13=VC/(W*LL) * U * (1.-2.*R*T1)
K1=K11*(K12-K13+2.*VC*T1)

```

```

RETURN
END

```

```

REAL FUNCTION K2(A, T1, W, V, LL, VC, R, F1)
REAL A, T1, W, V, LL, VC, R, F1, K21, K22, K23

```

```

K21=V/(W*LL) * COS(A)
K22=F1/2.
K23=(VC*A)/(W*LL) * (1.-2.*R*T1)
K2=K21-K22+K23

```

```

RETURN
END

```

```

REAL FUNCTION K3(A, U, T1, W, V, VC, F1, PHI, Z, R)
REAL A, U, T1, W, V, VC, F1, K31, K32, K34, Z, R, K33

```

```

K31=F1*EXP(-U/(W*T1))
K32=2.*VC*T1
K33=VC/R
K34=V/Z*SIN(A+U-PHI)
K3=K31-K32+K33-K34

```

```

RETURN
END

```

```

*****
*
*   SUBROUTINE TO PRINT INPUT DATA AND CALCULATED
*   CONSTANTS TO OUTPUT FILE
*
*****

```

```

SUBROUTINE OUTPUT (F1, F2, F3, T1, T2, V, VC, LL, L, R, ALPHA
&, MU, F, EFACT, RUN)
410 FORMAT (/)
399 FORMAT (//)
411 FORMAT (10X, 'INPUT DATA & CALCULATED CONSTANTS FOR
& PROGRAM SINGLE PHASE')
412 FORMAT (34X, 'RUN #', F6.2)
413 FORMAT (10X, 'PEAK SOURCE VOLTAGE      ', G18.8, ' VOLTS')
414 FORMAT (10X, 'SOURCE FREQUENCY        ', G18.8, ' HERTZ')
415 FORMAT (10X, 'TRANSFORMER INDUCTANCE  ', G18.8, ' HENRIES')
416 FORMAT (10X, 'FIRING ANGLE            ', G18.8, ' DEGREES')
417 FORMAT (10X, 'LOAD INDUCTANCE        ', G18.8, ' HENRIES')
418 FORMAT (10X, 'LOAD RESTANCE           ', G18.8, ' OHMS')
419 FORMAT (10X, 'LOAD EMF                ', G18.8, ' VOLTS')
420 FORMAT (10X, 'COMMUTATION ANGLE       ', G18.8, ' DEGREES')
421 FORMAT (10X, 'ACCURACY FACTOR          ', G18.8)
422 FORMAT (10X, 'COMMUTATION TAU         ', G18.8, ' SECONDS')
423 FORMAT (10X, 'CONDUCTION TAU         ', G18.8, ' SECONDS')
424 FORMAT (10X, 'CONSTANTS IN CURRENT EQUATIONS')
425 FORMAT (15X, 'K1=', G18.8)
426 FORMAT (15X, 'K2=', G18.8)
427 FORMAT (15X, 'K3=', G18.8)

```

```

WRITE (7, 410)
WRITE (7, 411)
WRITE (7, 412) RUN
WRITE (7, 399)
WRITE (7, 413) V
WRITE (7, 410)
WRITE (7, 414) F
WRITE (7, 410)
WRITE (7, 416) ALPHA
WRITE (7, 410)
WRITE (7, 415) LL
WRITE (7, 410)
WRITE (7, 417) L
WRITE (7, 410)
WRITE (7, 418) R
WRITE (7, 410)
WRITE (7, 419) VC
WRITE (7, 410)
WRITE (7, 422) T1
WRITE (7, 410)
WRITE (7, 423) T2
WRITE (7, 410)
WRITE (7, 420) MU
WRITE (7, 410)
WRITE (7, 421) EFACT
WRITE (7, 399)
WRITE (7, 424)
WRITE (7, 410)
WRITE (7, 425) F1
WRITE (7, 410)
WRITE (7, 426) F2
WRITE (7, 410)

```

WRITE (7, 427) F3

RETURN  
END

APPENDIX B  
INSTRUCTIONS FOR RUNNING THE FORTRAN PROGRAM

INSTRUCTIONS FOR RUNNING PROGRAM SGLFAZ ON THE UT CDC DUAL  
CYBER 170/750

Log into your account, then type the commands listed below at the appropriate prompt. User inputs are in **boldface** type.

```
.READ PF **** ** SGLFAZ  
.FTN5 I=SGLFAZ  
.REWALLX  
.LDSET LIB=ZETLIBF/  
.LGO
```

\*\*\*\* \*\* is the access code for the permanent file where the program is stored.

At this point, you will be presented with a choice of using input data contained in the source file or entering your own. If you choose the internal data, the program will run and create the plot and output data files.

If you choose to input your own data, the program will prompt you from the screen. Correct units for the data are indicated with each prompt.

After the program has run, the load response can be plotted. At the prompt type:

```
.DISPOSE PLOT ID=**
```

\*\* is the unit identifier for the plotter you are using.

In order to view the input data used and the constants calculated in the program ( $\mu$ ,  $k_1$ ,  $k_2$ ,  $k_3$ ,  $\alpha$ ,  $\tau_1$ , and  $\tau_2$ ) on the screen, type:

```
.SHOW TAPE7
```

If you want to print the data on a line printer type:

```
.PRINT TAPE7 ID=**
```

\*\* is the unit identifier of the line printer you are using.

The file "OUTPUT" contains a compiled listing of the FORTRAN source code.

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