NASA

National Aeronautics and Space Administration

Lyndon B. Johnson Space Center
Houston, Texas 77058

JSC-16517

MARCH 1980

(NASA-TM-80795) STEADY-STATE ANALYSIS OF A FAULTED THREE-PHASE FOUR-WIRE SYSTEM SUPPLYING INDUCTION MOTORS WITH NEUTRALS CONNECTED AND OTHER SINGLE-PHASE LINE-TO-NEUTRAL LOADS (NASA) 67 p

N80-22596

Unclas

G3/33 18484

AVIONICS SYSTEMS DIVISION

INTERNAL NOTE EH-80-03

STEADY-STATE ANALYSIS OF A FAULTED THREE-PHASE FOUR-WIRE SYSTEM SUPPLYING INDUCTION MOTORS WITH NEUTRALS CONNECTED AND OTHER SINGLE-PHASE LINE-TO-NEUTRAL LOADS

JSC-16517

AVIONICS SYSTEMS DIVISION

INTERNAL NOTE EH-80-03

STEADY-STATE ANALYSIS OF A FAULTED THREE-PHASE FOUR-WIRE SYSTEM SUPPLYING INDUCTION MOTORS WITH NEUTRALS CONNECTED AND OTHER SINGLE-PHASE LINE-TO-NEUTRAL LOADS

PREPARED BY

Marion E. Wood

Marion E. Wood

APPROVED BY

R E Wilson

R. E. Wilson, Chief
Power Distribution and Control Branch

John F. Hanaway

John F. Hanaway, Chief
Avionics Systems Division

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
Houston, Texas

March 1980

CONTENTS

Section		Page
TITLE		i
SIGNATURE PAGE		ii
TABLE OF CONTENTS		iii
LIST OF FIGURES		v
LIST OF IMPORTANT SYMBOLS		vii
ABSTRACT		ix
1.0	INTRODUCTION	1
1.1	BACKGROUND OF PROBLEM	1
1.2	STATEMENT OF PROBLEM	1
1.3	REVIEW OF THE LITERATURE	5
2.0	THEORETICAL DEVELOPMENT	7
2.1	SYMMETRICAL COMPONENTS	7
2.2	EQUIVALENT CIRCUIT OF MOTORS	11
2.3	ANALYSIS OF SERIES FAULT	15
2.4	ANALYSIS OF SHUNT FAULT	22
2.5	TWO-PHASE STARTING	25
3.0	COMPUTER ANALYSIS	26
3.1	PROGRAM DESCRIPTION (SOPSFS)	26
3.2	FLOW DIAGRAM FOR "SOPSFS"	28
3.3	PROGRAM DESCRIPTION (SOTPMS)	31
3.4	COMPUTER RESULTS	32

Section	Page
4.0 CONCLUSIONS AND RECOMMENDATIONS	42
4.1 CONCLUSIONS	42
4.2 RECOMMENDATIONS	43
REFERENCES	44
APPENDIX A - FORTRAN LISTING - "SOPSFS"	A-1
APPENDIX B - FORTRAN LISTING - "SOTPMS"	B-1

LIST OF FIGURES

Number	Title	Page
1	SIMPLIFIED SCHEMATIC DIAGRAM OF AC SYSTEM SHOWING SIMULATED SERIES FAULT	3
2	SIMPLIFIED SCHEMATIC DIAGRAM OF AC SYSTEM SHOWING SHUNT FAULT	4
3	SCHEMATIC DIAGRAM OF 3-PHASE INDUCTION MOTOR STATOR WINDING SHOWING COUPLING AND BACK EMF . .	10
4	ZERO SEQUENCE EQUIVALENT CIRCUIT	12
5	POSITIVE SEQUENCE EQUIVALENT CIRCUIT	12
6	NEGATIVE SEQUENCE EQUIVALENT CIRCUIT	12
7	SERIES FAULT	16
8	CONNECTION DIAGRAM FOR SERIES FAULT	16
9	NETWORK REDUCTION OF POSITIVE SEQ. CIRCUIT . . .	17
10	NEG. SEQ. CKT. (REDUCED)	17
11	ZERO SEQ. CKT. (REDUCED)	17
12	SYSTEM INTERCONNECTION DIAGRAM - SERIES FAULT .	19
13	REDUCED INTERCONNECTION DIAGRAM - SERIES FAULT	19
14	SIMPLIFIED SCHEMATIC OF SHUNT FAULT	23
15	SIMPLIFIED DIAGRAM OF AC SYSTEM SHOWING TEST MOTOR STARTING ON TWO PHASES	27
16	SYSTEM CURRENT VS. NON-MOTOR LOAD FOR 0.1 HP MOTOR LOAD	34
17	SYSTEM CURRENT VS. NON-MOTOR LOAD FOR 0.25 HP MOTOR LOAD	35
18	SYSTEM CURRENT VS. NON-MOTOR LOAD FOR 0.5 HP MOTOR LOAD	36
19	SYSTEM CURRENT VS. NON-MOTOR LOAD FOR 0.75 HP MOTOR LOAD	37

Number	Title	Page
20	SYSTEM CURRENT VS. NON-MOTOR LOAD FOR 1.0 HP MOTOR LOAD	38
21	GENERATED MOTOR CURRENTS DURING SERIES FAULT . .	39
22	GENERATED MOTOR CURRENTS DURING SHUNT FAULT . .	40
23	GENERATED VOLTAGE ON PHASE A DURING SERIES FAULT	41

LIST OF IMPORTANT SYMBOLS

a	-	Vector Operator Equal $\cos\left(\frac{2\pi}{3}\right) + j\sin\left(\frac{2\pi}{3}\right)$
V_a, V_b, V_c	-	"ABC" Applied Voltages (Phase-to-Neutral)
I_a, I_b, I_c	-	"ABC" System Currents
X_c	-	Mutual Reactance Between Stator Phases
R_s, R_1	-	Stator Resistance of Motor
X_s	-	Self Reactance of Stator
E'_a, E'_b, E'_c	-	"ABC" Back EMF Voltages
$\triangleq$	-	Defined As
V_{abc}	-	"ABC" Applied Voltages (Matrix Form)
V_{zpn}	-	"ZPN" Applied Voltages (Matrix Form)
Z_p	-	Primitive Impedance Matrix
E'_{abc}	-	"ABC" Back EMF Voltages (Matrix Form)
Z_s	-	$R_s + jX_s$
Z_c	-	$0 + jX_c$
V_z, V_p, V_n	-	"ZPN" Applied Voltages
E'_z, E'_p, E'_n	-	"ZPN" Back EMF Voltages
Z_{zp}	-	Rotor Impedance to Positive Sequence Current
Z_{zn}	-	Rotor Impedance to Negative Sequence Current
P_{br}	-	Blocked Rotor Input Power (Motor)
I_{br}	-	Blocked Rotor Line Current (Motor)
V_{br}	-	Blocked Rotor Line Voltage (Motor)
I_{nl}	-	No Load Line Current (Motor)
V_{nl}	-	No Load Line Voltage (Motor)
R_2	-	Rotor Resistance of Motor
X_1	-	Stator Reactance of Motor

LIST OF IMPORTANT SYMBOLS (CONT.)

X_2	-	Rotor Reactance of Motor
X_m	-	Mutual Reactance of Motor
Z_z	-	Impedance to Zero Sequence Current
PU	-	Per Unit Values
CHP	-	Connected Horsepower
Z_1	-	Impedance of Non-Motor Loads
R	-	Resistance of Non-Motor Loads
VAC	-	Volt-Amperes Connected
Z_{ps}	-	System Impedance to Positive Sequence Currents
Z_{ns}	-	System Impedance to Negative Sequence Currents
Z_{zs}	-	System Impedance to Zero Sequence Currents
E_{ap}	-	Positive Sequence Input Voltage to Phase "A" of the Equivalent Circuit
S	-	Motor Slip
$A // B$	-	Circuit "A" in Parallel with Circuit "B"
E_{aa}', E_{bb}', E_{cc}'	-	Voltage Drops Across Series Fault
I_{zm}, I_{pm}, I_{mm}	-	"ZPN" Motor Currents
I_{am}, I_{bm}, I_{cm}	-	"ABC" Motor Currents
I_{a1}, I_{b1}, I_{c1}	-	"ABC" Currents into Non-Motor Load
V_{am}, V_{bm}, V_{cm}	-	"ABC" Voltages at Motor Terminals

ABSTRACT

Four-wire Wye connected a.c. power systems exhibit peculiar steady-state fault characteristics when the fourth wire of three-phase induction motors is connected. This type of system is used to provide additional motor redundancy on power systems of spacecraft such as the Space Shuttle Orbiter. In the event of the loss of one phase of power source due to a series or shunt fault, currents higher than anticipated will result on the remaining two phases. This is due to the magnetic coupling between phases of the motors. This report develops a theoretical approach to compute the fault currents and voltages. A FORTRAN program is also developed and is included in the appendix.

1.0 INTRODUCTION

1.1 BACKGROUND OF PROBLEM

The a.c. power systems on spacecraft differ in many respects from those of aircraft systems. Whereas aircraft generally use engine-driven alternators as the prime power source, spacecraft generally use d.c. sources such as fuel cells or solar cells. The a.c. power is then derived from some form of static inversion device. As an example, the Shuttle Orbiter spacecraft utilizes three single-phase static inverters phased together to provide a 115-volt, 400 Hz, 4-wire Wye power system. This 4-wire system has the advantage that it provides a capability to operate polyphase induction motors after the loss of any one phase. Certain precautions must be observed, however, in the application of a system of this type, and an understanding of its fault characteristics is essential. The Orbiter system will be used as an example throughout the remainder of this thesis.

1.2 STATEMENT OF PROBLEM

The purpose of this investigation is to develop a model, using both analytical and empirical methods, to determine performance characteristics of the system during series and shunt faults. It is not intended as an exact or generalized model since several simplifying assumptions are made. The model is expected to be sufficiently accurate to permit a system designer or operations engineer to perform load and redundancy management studies.

Figure 1 shows a simplified schematic of one string of an a.c. system. This diagram depicts a series fault simulated with an open switch. One example of the series fault is the loss of one of the three single-phase inverters. A shunt fault is shown in figure 2. A phase-to-neutral short circuit is shown on phase A of sub-bus 3. The single-phase circuit breaker protecting this phase has opened. For the purpose of this analysis, the circuit breaker is assumed to trip properly and clear the fault from the source. This type of fault is of concern only on those sub-buses using single-phase breakers as opposed to three-phase breakers, since a three-phase breaker would clear all three phases.

Both of these faults are of concern for a system of this type because of the magnetic coupling between phases of the three-phase induction motors. In case of a series fault, the motors will continue to run on two phases and, through generator action, will supply power to the non-motor loads connected to the various sub-buses. This will add additional load to the two remaining phases and possibly overload the inverters or trip the circuit breakers. As stated previously, the shunt fault is of no concern on those sub-buses using three-phase circuit breakers. For sub-buses using single-phase breakers, the situation is similar to the series fault. Due to the magnetic coupling between phases, the two remaining phases will continue to supply current to the phase-to-neutral fault. Depending on the number and size of motors connected,

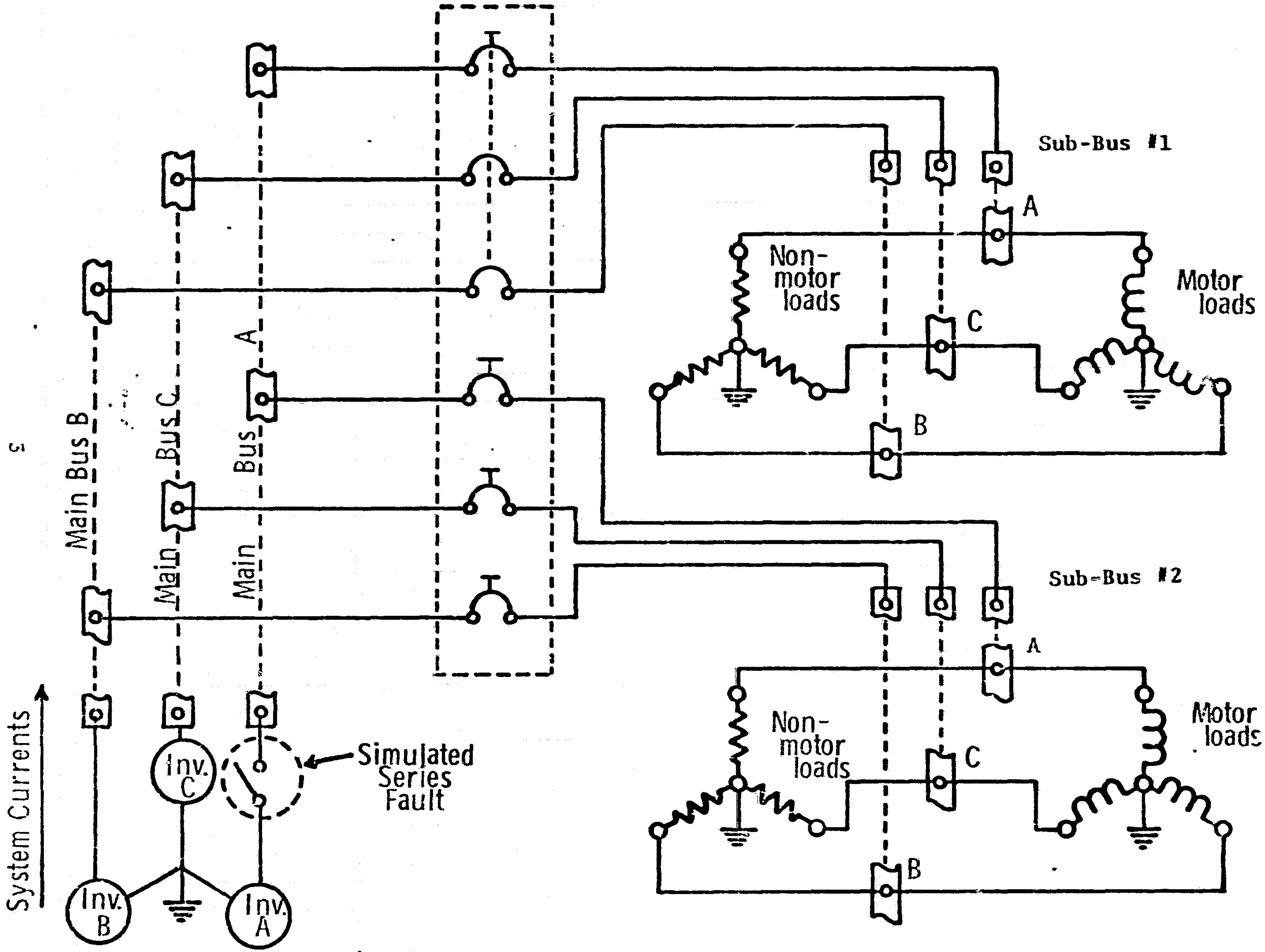


FIGURE 1. SIMPLIFIED SCHEMATIC DIAGRAM OF AC SYSTEM SHOWING SIMULATED SERIES FAULT

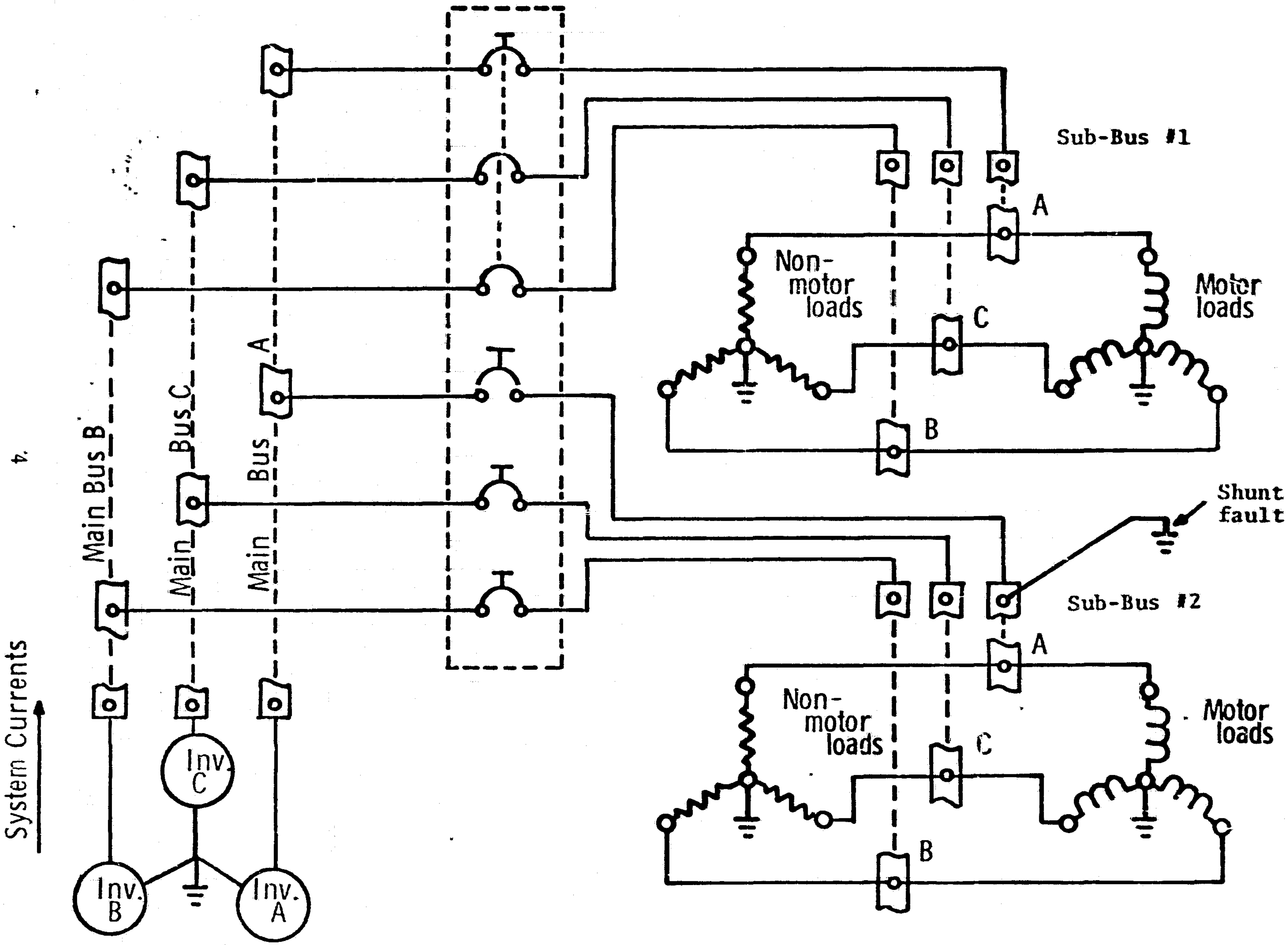


FIGURE 2. SIMPLIFIED SCHEMATIC DIAGRAM OF AC SYSTEM SHOWING SHUNT FAULT

the two remaining phases could be overloaded and trip circuit breakers. A secondary concern of the series fault is the magnitude and phase of the voltage on the faulted bus. This is a concern if the equipment connected to this bus could be damaged by low voltage. The model to be developed will enable one to compute these voltage and current parameters for various loading conditions. It will also permit isolation of one motor of varying horsepower and computation of its starting current with and without other motors running.

1.3 REVIEW OF THE LITERATURE

Methods for the analysis of unbalanced polyphase systems have been known for many years. In 1918, C. L. Fortescue[1] showed that any three phasors, Q_a, Q_b, and Q_c, which are unsymmetrical in phase and/or magnitude, can be resolved into two sets of balanced (symmetrical) three-phase phasors and one set of three equal phasors. The set of three equal phasors, Q_{ao}, Q_{bo}, and Q_{co}, is commonly referred to as the "Zero Phase Sequence" set. The two balanced three-phase phasors are commonly referred to as the "Positive Phase Sequence" set and the "Negative Phase Sequence" set. The positive phase sequence set rotates in the counter-clockwise sense and the negative phase sequence set rotates in the reverse (clockwise) sense. For the remainder of this report, phase quantities will be referred to as "ABC" quantities or as the "ABC" domain. Sequence quantities will be referred to as "ZPN" quantities or as the "ZPN" domain. Fortescue defined an operator "a" where:

$$a \triangleq \cos\left(\frac{2\pi}{3}\right) + j\sin\left(\frac{2\pi}{3}\right) \text{ and } a^2 \triangleq \cos\left(\frac{4\pi}{3}\right) + j\sin\left(\frac{4\pi}{3}\right)$$

Two useful properties of the phasor operator "a" are:

$$1 + a + a^2 = 0$$

$$a \cdot a^2 = 1$$

He then developed a transformation matrix [C] where:

$$[C] = \left(\frac{1}{3}\right) \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}$$

which when applied to the "ABC" quantities, transforms them into "ZPN" quantities as follows:

$$\begin{bmatrix} Q_z \\ Q_p \\ Q_n \end{bmatrix} = [C] \cdot \begin{bmatrix} Q_a \\ Q_b \\ Q_c \end{bmatrix}$$

Similarly, the inverse of the [C] matrix,

$$[C^{-1}] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}$$

could be applied to "ZPN" quantities to transform back into the "ABC" quantities:

$$\begin{bmatrix} Q_a \\ Q_b \\ Q_c \end{bmatrix} = [C^{-1}] \cdot \begin{bmatrix} Q_z \\ Q_p \\ Q_n \end{bmatrix}$$

The factor $\left(\frac{1}{3}\right)$ in the [C] matrix permits working with single-phase quantities in the "ZPN" domain; however, recent authors such as P. L. Alger[2] have suggested that the transformation should maintain power invariance in both domains and they suggest using a factor $(1/\sqrt{3})$ in both the [C] matrix and its inverse $[C^{-1}]$. Either approach is acceptable if properly used; however, the earlier version as suggested by Fortescue is used in this report. Numerous other techniques have been proposed and used successfully for the analysis of unbalanced systems. The symmetrical component method, however, is the most widely used technique.

2.0 THEORETICAL DEVELOPMENT

2.1 SYMMETRICAL COMPONENTS

The first step will be to show that the positive, negative, and zero sequence components are uncoupled and therefore can be represented by three single-phase equivalent circuits. This is frequently done in the literature for the positive and negative sequence. The zero-sequence is generally omitted because of the fact that induction motors are usually operated "3-wire" and zero-sequence currents cannot flow.

Figure 3 is a schematic diagram of an induction motor showing back EMF terms and coupling between stator phases. Kirchoff's voltage equations will now be applied to this circuit:

$$\left.\begin{aligned} V_a &= (R_s + jX_s)I_a - (jX_c)I_b - (jX_c)I_c + E'_a \\ V_b &= -(jX_c)I_a + (R_s + jX_s)I_b - (jX_c)I_c + E'_b \\ V_c &= -(jX_c)I_a - (jX_c)I_b + (R_s + jX_s)I_c + E'_c \end{aligned}\right\} \text{EQ. 1}$$

or in matrix form:

$$\left.\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} (R_s + jX_s) & -jX_c & -jX_c \\ -jX_c & (R_s + jX_s) & -jX_c \\ -jX_c & -jX_c & (R_s + jX_s) \end{bmatrix} \cdot \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} E'_a \\ E'_b \\ E'_c \end{bmatrix}\right\} \text{EQ. 2}$$

where:

$|E'_a| = |E'_b| = |E'_c| \triangleq$ Magnitude of back EMF's

$jX_c \triangleq$ Mutual reactance between stator phases

$Z_s = (R_s + jX_s)$; $Z_c = (0 + jX_c)$

The primitive impedance matrix can be written as follows:

$$[Z_p] = \begin{bmatrix} Z_s & -Z_c & -Z_c \\ -Z_c & Z_s & -Z_c \\ -Z_c & -Z_c & Z_s \end{bmatrix} \qquad \text{EQ. 3}$$

The symmetrical component transformation is now applied to equation 2. The transformation matrix [C] was defined in section 1 and is shown below for convenience to the reader:

$$[C] = \left(\frac{1}{3}\right)\cdot\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \qquad [C^{-1}] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}$$

Equation 2 in simplified form is written as follows:

$$[V_{abc}] = [Z_p] \cdot [I_{abc}] + [E'_{abc}] \qquad \text{EQ. 4}$$

The transformation of a set of voltages or currents from the "ZPN" domain to the "ABC" domain has been shown to be as follows:

$$[V_{abc}] = [C^{-1}] \cdot [V_{zpn}]$$

Substituting for the "ABC" terms in equation 4 gives the following system of equations in the "ZPN" domain:

$$[C^{-1}]\cdot[V_{zpn}] = [Z_p]\cdot[C^{-1}]\cdot[I_{zpn}]+[C^{-1}]\cdot[E'_{zpn}] \qquad \text{EQ. 5}$$

Multiplying both sides of this equation by [C] gives:

$$[V_{zpn}] = [C]\cdot[Z_p]\cdot[C^{-1}]\cdot[I_{zpn}]+[E'_{zpn}] \qquad \text{EQ. 6}$$

Now the expression $[C]\cdot[Z_p]\cdot[C^{-1}]$ can be evaluated:

$$\left(\frac{1}{3}\right)\cdot\begin{bmatrix}1 & 1 & 1\\ 1 & a & a^2\\ 1 & a^2 & a\end{bmatrix}\cdot\begin{bmatrix}Z_s & -Z_c & -Z_c\\ -Z_c & Z_s & -Z_c\\ -Z_c & -Z_c & Z_s\end{bmatrix}\cdot\begin{bmatrix}1 & 1 & 1\\ 1 & a^2 & a\\ 1 & a & a^2\end{bmatrix} =$$

$$\begin{bmatrix}1 & 1 & 1\\ 1 & a & a^2\\ 1 & a^2 & a\end{bmatrix}\cdot\begin{bmatrix}(Z_s-2Z_c) & (a^2+a)\cdot(Z_s-Z_c) & (a^2+a)\cdot(Z_s-Z_c)\\ (Z_s-2Z_c) & a^2Z_s-(1+a)Z_c & aZ_s-(1+a^2)Z_c\\ (Z_s-2Z_c) & aZ_s-(1+a^2)Z_c & a^2Z_s-(1+a)Z_c\end{bmatrix} =$$

$$\begin{bmatrix}Z_s-2Z_c & 0 & 0\\ 0 & (Z_s+Z_c) & 0\\ 0 & 0 & (Z_s+Z_c)\end{bmatrix}$$

Equation 6 can now be written as follows:

$$\begin{bmatrix}V_z\\ V_p\\ V_n\end{bmatrix} = \begin{bmatrix}Z_z & 0 & 0\\ 0 & Z_1 & 0\\ 0 & 0 & Z_1\end{bmatrix}\cdot\begin{bmatrix}I_z\\ I_p\\ I_n\end{bmatrix} + \begin{bmatrix}E'_z\\ E'_p\\ E'_n\end{bmatrix} \qquad \text{EQ. 7}$$

where: Z_z = zero sequence impedance

Z_1 = stator impedance for positive and negative equivalent circuits. (See figures 5 and 6.)

Since the impedance matrix in equation 7 is diagonal, it can be concluded that the sequence circuits are uncoupled and can therefore be represented as three separate single-phase circuits. Textbooks on classical induction motor theory[2,5] show that the back EMF terms E'_p and E'_n can be represented as fictional rotor impedances multiplied by the positive and negative sequence rotor currents:

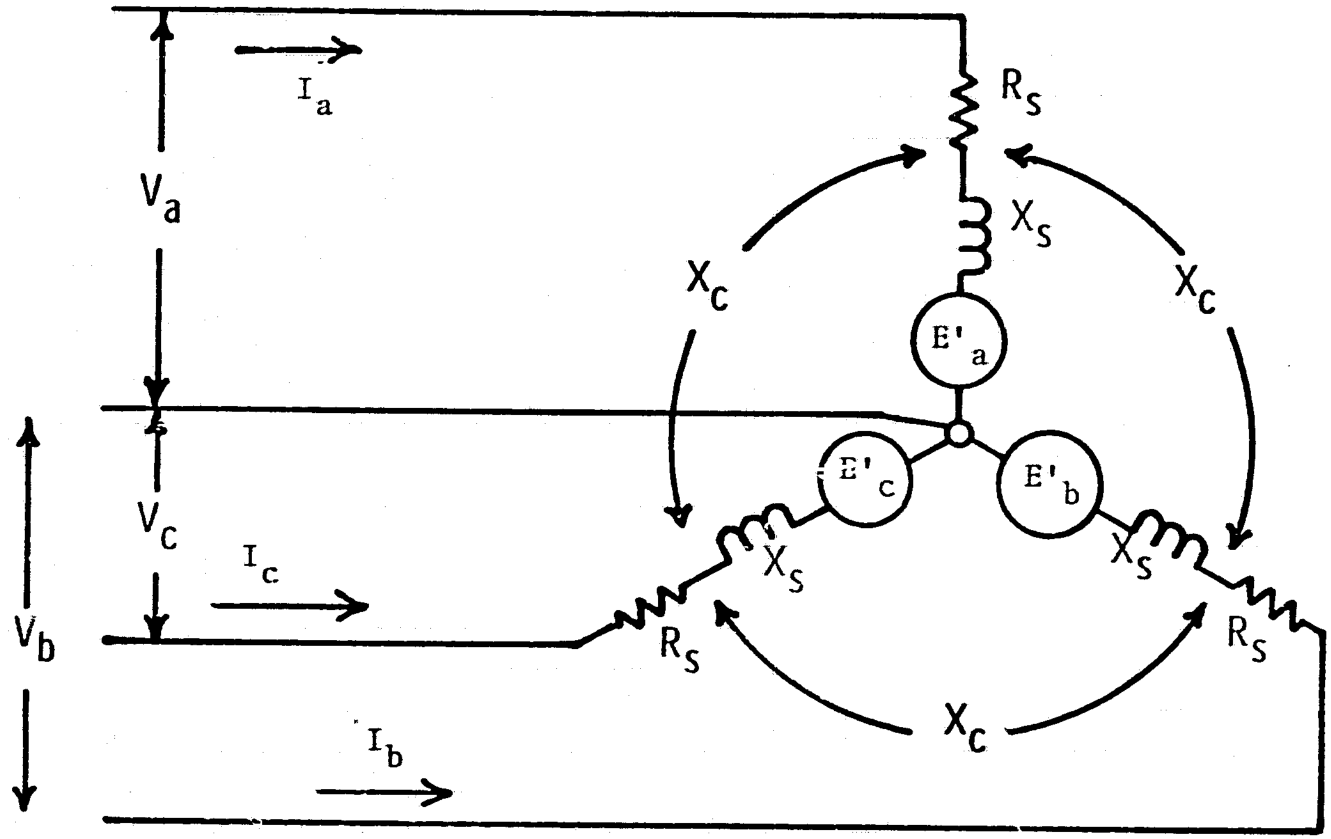


FIGURE 3 - SCHEMATIC DIAGRAM OF 3-PHASE INDUCTION MOTOR STATOR WINDING SHOWING COUPLING AND BACK EMF.

$$E'_p = (Z_{2p})\cdot(I_{2p})$$

$$E'_n = (Z_{2n})\cdot(I_{2n})$$

where:

$Z_{2p} \triangleq$ Rotor impedance to positive sequence current

$Z_{2n} \triangleq$ Rotor impedance to negative sequence current

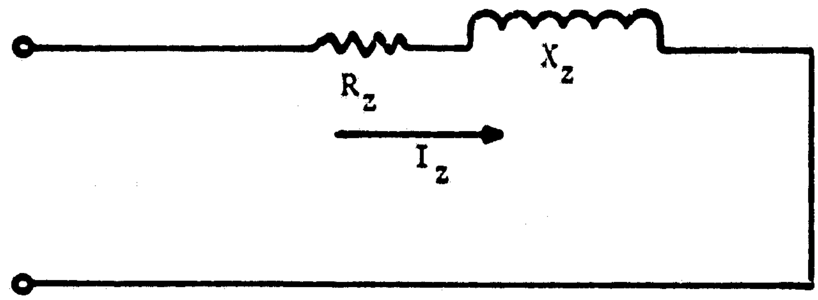
Furthermore, since zero sequence currents are all in phase, they do not contribute to the rotating air gap flux and therefore $E'_z = 0$. Also, since the power source generates only balanced positive sequence voltages, V_z and V_n are zero. After substitution, matrix equation 7 can be written in the following form:

$$\begin{aligned} 0 &= (Z_z)\cdot(I_z) + 0 \\ V_p &= (Z_1)\cdot(I_p) + (Z_{2p})\cdot(I_{2p}) \\ 0 &= (Z_1)\cdot(I_n) + (Z_{2n})\cdot(I_{2n}) \end{aligned} \qquad \text{EQ. 8}$$

From inspection of equation 8, the zero sequence equivalent circuit can be drawn. This is shown in figure 4. Equivalent circuits for the positive and negative sequences are available throughout the literature and simplified versions shown in figures 5 and 6 are generally accepted as adequate.[2,5]

2.2 EQUIVALENT CIRCUIT OF MOTORS

For convenience of input to the computer, the non-motor loads will be expressed as volt-amperes and the computer will compute the equivalent resistance value. The motor loads will be expressed as total connected horsepower. The computer will



Note: This circuit is not required for 3-wire motors since Zero sequence currents cannot flow.

FIGURE 4 - ZERO SEQUENCE EQUIVALENT CIRCUIT

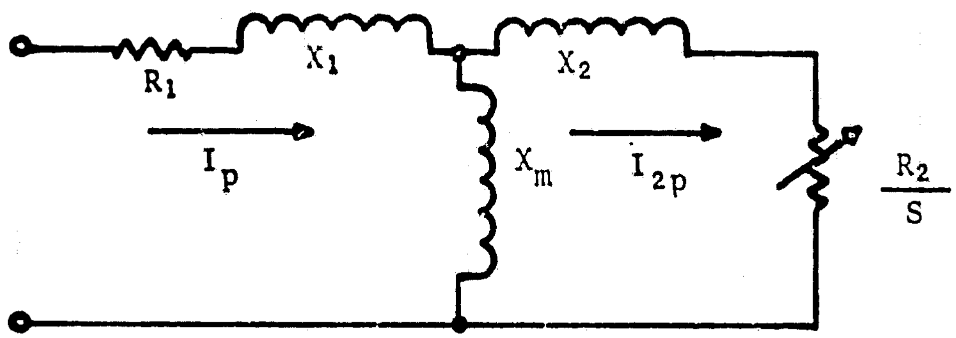


FIGURE 5 - POSITIVE SEQUENCE EQUIVALENT CIRCUIT

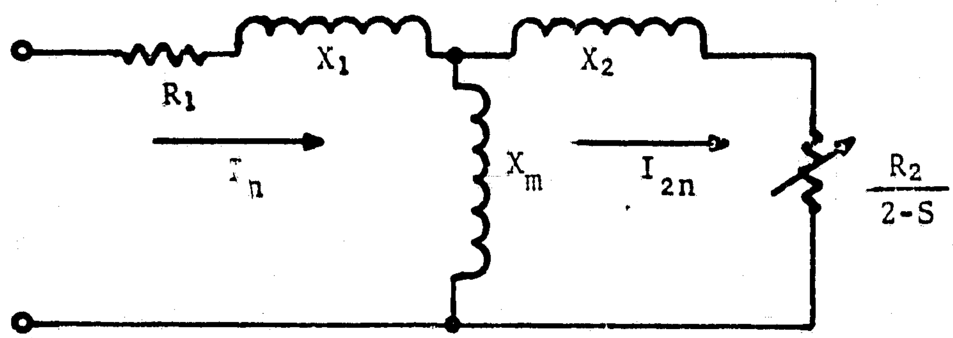


FIGURE 6 - NEGATIVE SEQUENCE EQUIVALENT CIRCUIT

then compute the equivalent circuit parameters for this motor load. This is an approximation, and assumes that the equivalent circuit parameters are inversely proportional to motor horsepower. This is assumed to be adequate for purposes of this analysis and is supported by Clarke[3] for motors up to 5 horsepower.

The circuit parameters for the equivalent circuits shown in figures 5 and 6 can be computed from blocked rotor and no-load test data plus d.c. resistance measurements:

R_1 = Measured d.c. resistance in ohms

$$R_2 = \left(\frac{P_{br}}{3\cdot(I_{br})^2} - R_1\right) \text{ ohms}$$

$$X_1+X_2 = \sqrt{\left(\frac{V_{br}}{\sqrt{3}I_{br}}\right)^2 - \left(\frac{P_{br}}{3I^2_{br}}\right)^2}$$

X_1 = X_2 for class "A" motors[3]

$$X_m = \left(\frac{V_{nl}}{\sqrt{3}I_{nl}} - X_1\right) \text{ ohms}$$

where: P_{br}, I_{br}, and V_{br} are, respectively, the total power input, line current, and line voltage measured with the rotor blocked.

I_{nl} and V_{nl} are the line current and the line voltage at no load.

Zero sequence parameters can be measured by connecting the three-phase windings in parallel and applying single-phase voltage from line-to-neutral, in which case we have

$$Z_z' = \frac{3\cdot(V \underline{/\phi°})}{I \underline{/\theta°}}$$

An alternate method is to connect the three-phase windings in series and apply a single-phase voltage, in which case we have

$$Z_z = \frac{V \angle \phi^\circ}{3 \cdot (I \angle \theta^\circ)}$$

An empirical method is used to obtain the equivalent circuit parameters used for this study. Several 400 Hz aircraft-type motors were tested to obtain a typical set of equivalent circuit parameters. These included a Sawyer motor (.125 hp), three IMC motors (.125 hp, .25 hp, and .5 hp), and a Westinghouse motor (.67 hp). These motors are assumed to be typical of other motors in this general size and class category. The parameters for these motors were measured in the laboratory and average values are listed below: (Note: The following values are normalized to a common base of 0.75 hp.)

R_1 = 1.86 ohms; R_2 = 3.34 ohms; $X_1 = X_2$ = 4.9 ohms

X_m = 50 ohms; R_z = 3.2 ohms; X_z = 3.22 ohms

These parameters will now be expressed in per unit (PU) values (i.e., normalized with respect to some base value). A single string of the Orbiter a.c. system will be used as the base value.[6]

Base volt-amperes = 750 VA (single-phase inverter rating)

Base volts = 120 volts (phase-to-neutral)

Base amps = 750/120 = 6.25 amps

Base impedance = 120/6.25 = 19.2 ohms

Per unit values for this motor are as follows:

$R_1 = 1.86/19.2 = .097$ PU; $R_2 = 3.34/19.2 = .174$ PU

$X_1 = X_2 = 4.9/19.2 = .256$ PU; $X_m = 50/19.2 = 2.605$ PU;

$R_z = 3.2/19.2 = .165$ PU; $X_z = 3.22/19.2 = .168$ PU

The computer will calculate these parameters for every set of input values of connected horsepower (CHP). As an example:

Primary resistance for any size motor = $R_1(.75/CHP)$

Where: $R_1 \triangleq$ Stator resistance in PU

.75 = Horsepower of test motor

CHP $\triangleq$ Connected horsepower

2.3 ANALYSIS OF SERIES FAULT

The series fault previously shown in figure 1 can be analyzed using methods outlined in the Westinghouse Transmission and Distribution Reference Book.[4] For purposes of this study, the series fault condition shown in figure 7 is adequate since line impedance is less than 3% and can be neglected. Westinghouse shows that the positive, negative, and zero sequence equivalent circuits can be interconnected as shown in figure 8 to analyzo the series fault in the "ZPN" domain.

It will be more convenient to analyze this interconnected network if the motor equivalent circuits are reduced to their simplest form. Figure 9 shows how the positive sequence circuit can be reduced. Figures 10 and 11 show the negative and zero sequence circuits in reduced form.

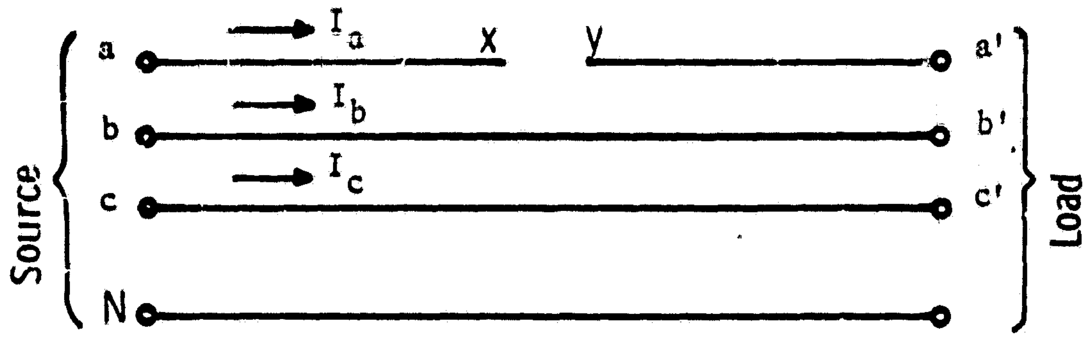


FIGURE 7 - SERIES FAULT

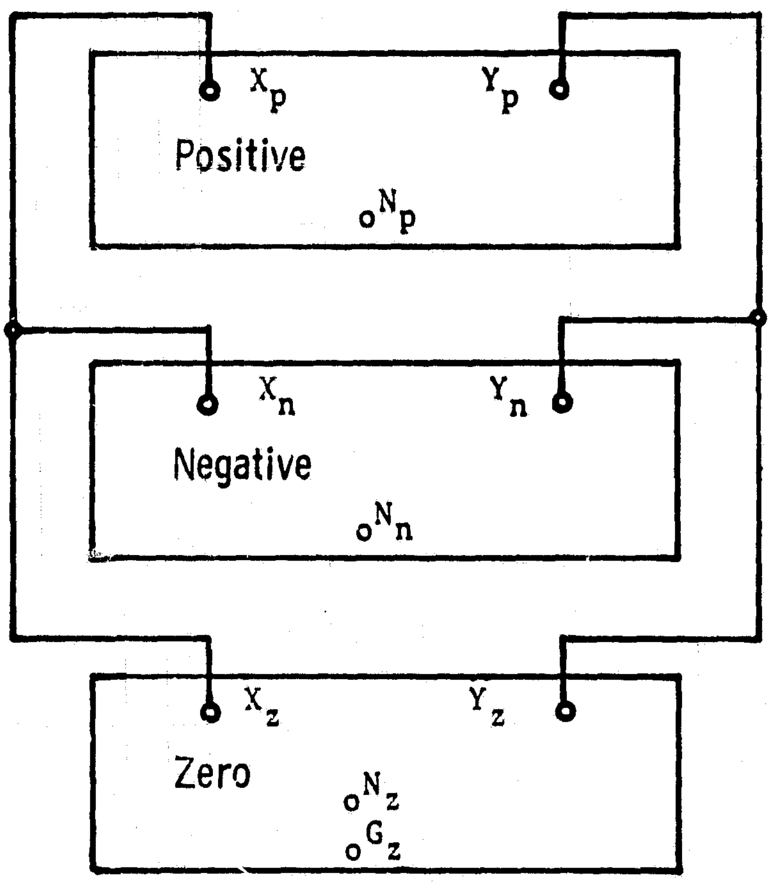


FIGURE 8 - CONNECTION DIAGRAM FOR SERIES FAULT

Note: From Westinghouse Transmission and Distribution Handbook, Ref. 4.

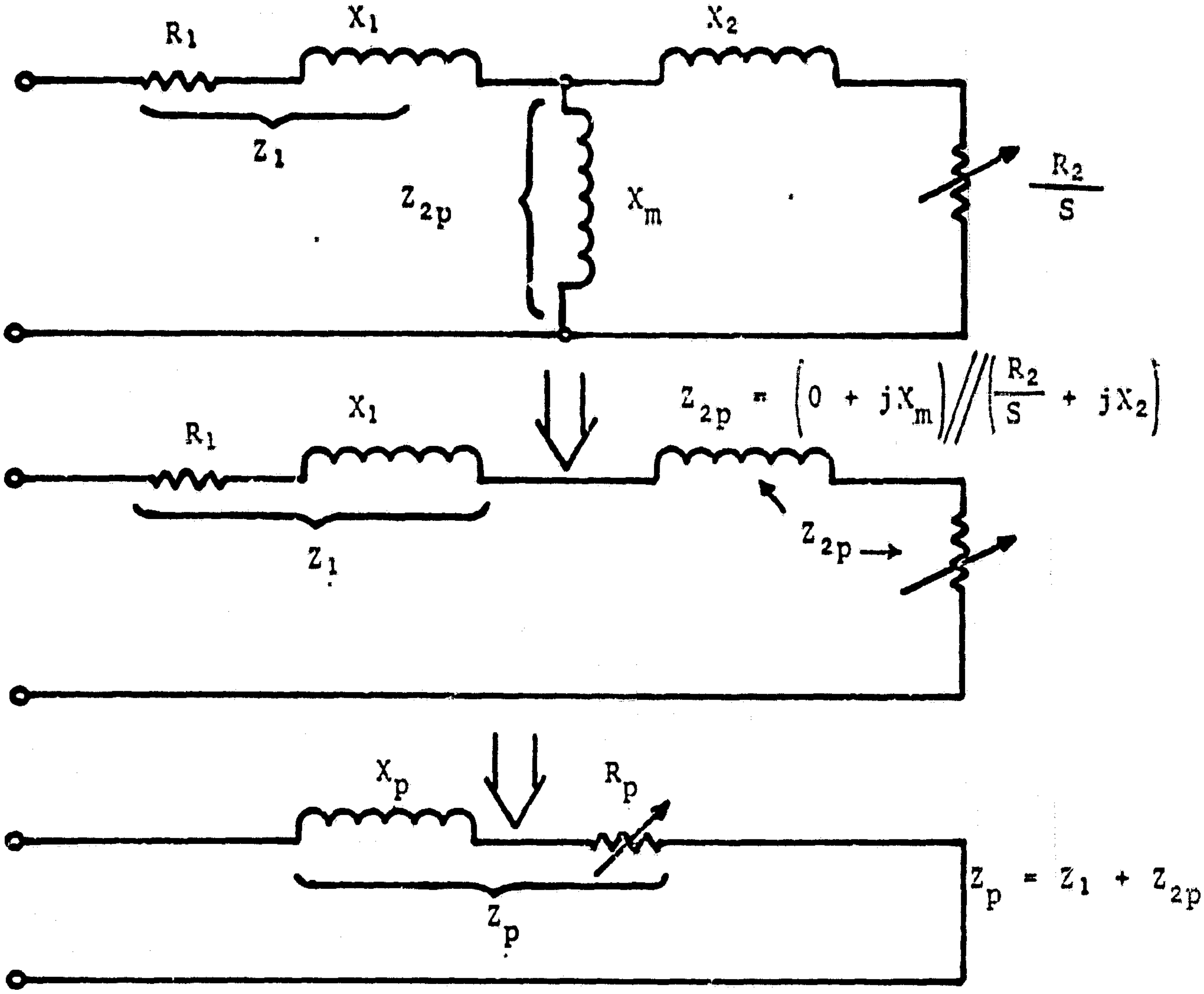


FIGURE 9 - NETWORK REDUCTION OF POSITIVE SEQ. CIRCUIT

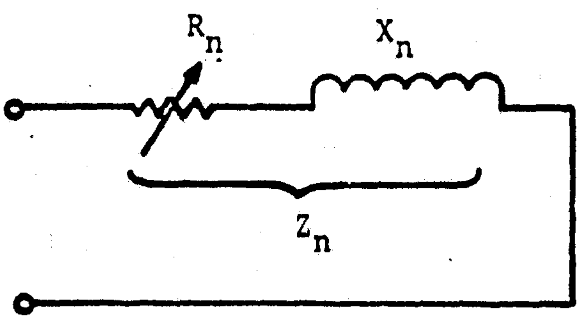


FIGURE 10 - NEG. SEQ. CKT (REDUCED)

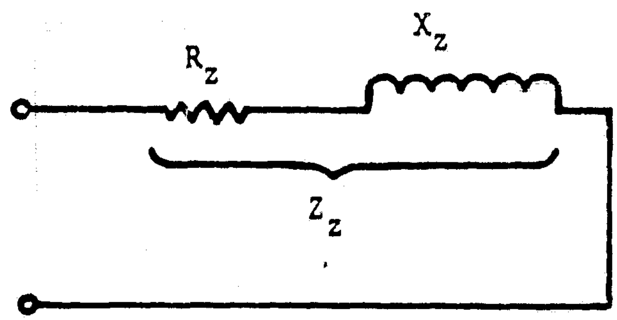


FIGURE 11 - ZERO SEQ. CKT (REDUCED)

Positive Sequence Circuit Reduction Equation:

$$Z_{2p} \triangleq (0 + jX_m) \mathbin{//} \left(\frac{R_2}{S} + jX_2\right)$$

$$Z_p = Z_1 + Z_{2p} \qquad \text{EQ. 9}$$

Negative Sequence Circuit Reduction Equation:

$$Z_{2n} \triangleq (0 + jX_m) \mathbin{//} \left(\frac{R_2}{(2-S)} + jX_2\right)$$

$$Z_n = Z_1 + Z_{2n} \qquad \text{EQ. 10}$$

Zero Sequence Circuit Reduction Equation:

$$Z_z = R_z + jX_z \qquad \text{EQ. 11}$$

Since the non-motor loads are resistive with no coupling between phases, the positive, negative, and zero sequence equivalent circuits are identical and the impedance of the single-phase equivalent circuit is:

$$Z_1 = R + j0 \qquad \text{EQ. 12}$$

where: $R = (\text{Base Volts})^2/\text{VAC}/\text{Base Impedance}$

VAC $\triangleq$ Volts-Amperes-Connected

Figure 12 shows the simplified "ZPN" equivalent circuits for the motor and non-motor loads interconnected for the series fault. This circuit can be reduced further as shown in figure 13, where impedances are defined as the following parallel combinations.

$$Z_{ps} \triangleq Z_1 // Z_p$$

$$Z_{ns} \triangleq Z_1 // Z_n$$

$$Z_{zs} \triangleq Z_1 // Z_z$$

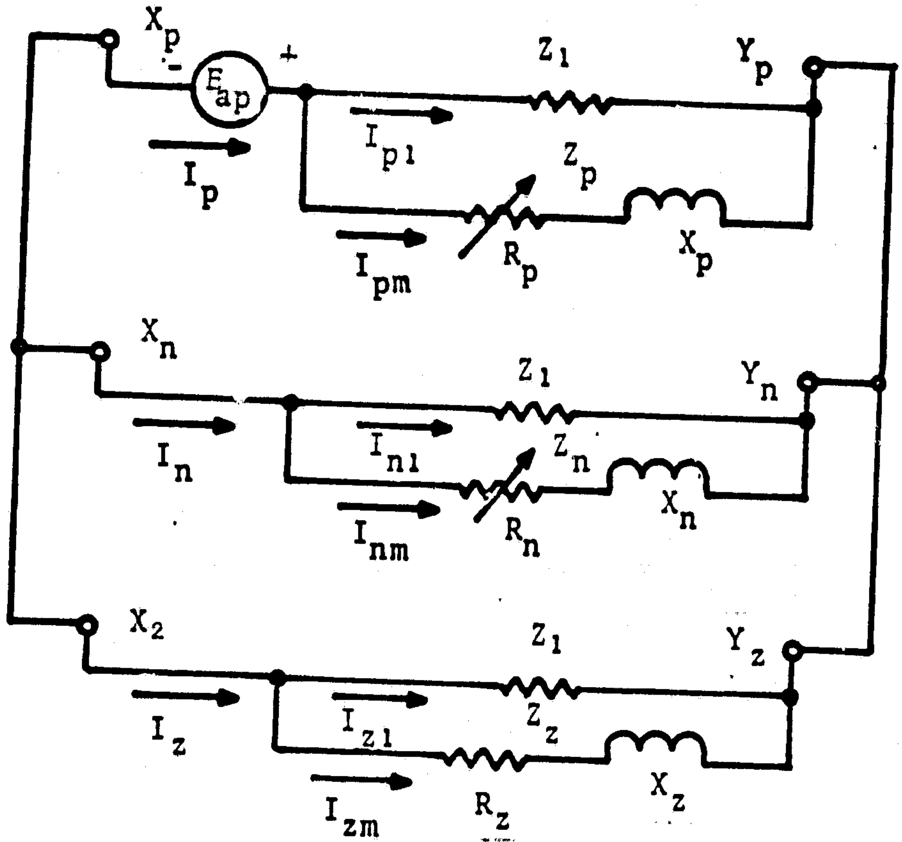


FIGURE 12 - SYSTEM INTERCONNECTION DIAGRAM - SERIES FAULT

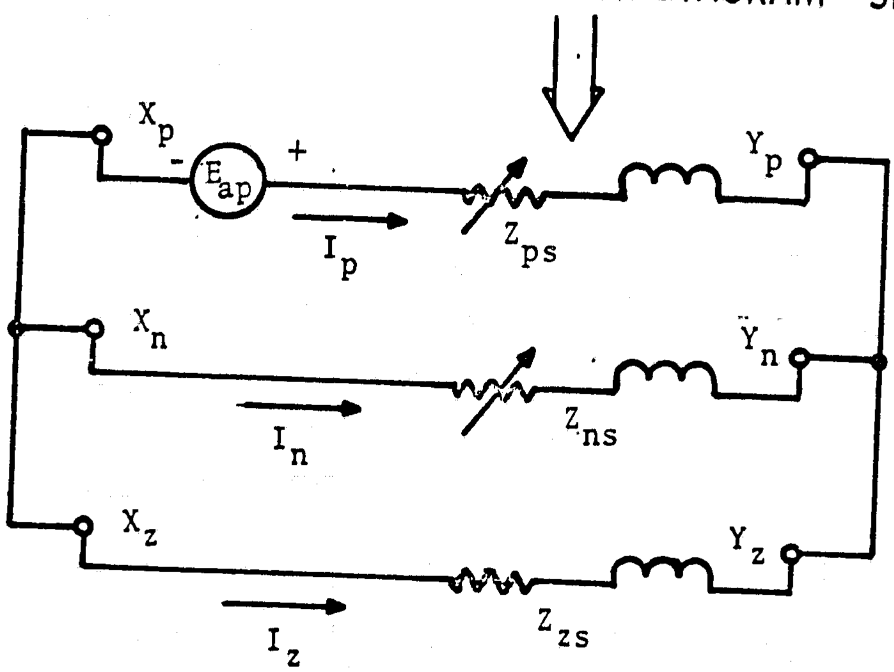


FIGURE 13 - REDUCED INTERCONNECTION DIAGRAM - SERIES FAULT

This is the circuit which will be analyzed to obtain fault currents in the "ZPN" domain for the series fault:

$$I_p = \frac{E_{ap} \cdot (Z_{ns} + Z_{zs})}{(Z_{ps} \cdot Z_{ns}) + (Z_{ps} \cdot Z_{zs}) + (Z_{ns} \cdot Z_{zs})} \qquad \text{EQ. 13}$$

$$I_n = \frac{-(E_{ap} \cdot Z_{zs})}{(Z_{ps} \cdot Z_{ns}) + (Z_{ps} \cdot Z_{zs}) + (Z_{ns} \cdot Z_{zs})} \qquad \text{EQ. 14}$$

$$I_z = \frac{-(E_{ap} \cdot Z_{ns})}{(Z_{ps} \cdot Z_{ns}) + (Z_{ps} \cdot Z_{zs}) + (Z_{ns} \cdot Z_{zs})} \qquad \text{EQ. 15}$$

ZPN voltages across the fault are as follows:

$$V_p = V_{xp} - V_{yp} = E_{ap} - I_p \cdot Z_{ps} \qquad \text{EQ. 16}$$

$$V_n = V_{xn} - V_{yn} = -I_n \cdot Z_{ns} \qquad \text{EQ. 17}$$

$$V_z = V_{xz} - V_{yz} = -I_z \cdot Z_{zs} \qquad \text{EQ. 18}$$

E_{ap} is defined as the positive sequence input voltage to phase "A" of the equivalent circuit. This voltage is obtained by applying the [C] transform to the balanced input voltages:

$$\begin{bmatrix} E_z \\ E_p \\ E_n \end{bmatrix} = \left(\frac{1}{3}\right) \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \qquad \text{EQ. 19}$$

where: $E_a = 1\underline{/0^\circ}$ PU; $E_b = 1\underline{/240^\circ}$ PU; $E_c = 1\underline{/120^\circ}$ PU

Therefore:

$$\begin{bmatrix} E_z \\ E_p \\ E_n \end{bmatrix} = \left(\frac{1}{3}\right) \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} 1\underline{/0^\circ} \\ 1\underline{/240^\circ} \\ 1\underline{/120^\circ} \end{bmatrix}$$

$$= \left(\frac{1}{3}\right) \cdot \begin{bmatrix} 1\underline{/0^\circ} + 1\underline{/240^\circ} + 1\underline{/120^\circ} \\ 1\underline{/0^\circ} + 1\underline{/360^\circ} + 1\underline{/360^\circ} \\ 1\underline{/0^\circ} + 1\underline{/120^\circ} + 1\underline{/240^\circ} \end{bmatrix} = \begin{bmatrix} 0 \\ 1\underline{/0^\circ} \\ 0 \end{bmatrix}$$

It can be seen that the single phase value for $E_p = 1\underline{/0^\circ}$ PU. This is the value to be assigned to E_{ap}. As could be expected, E_z and E_n equal zero since the input voltages are balanced.

The ZPN voltages and currents will now be transformed back into the "ABC" reference frame. Using the inverse transformation $[C^{-1}]$:

$$\left.\begin{bmatrix} E_{aa'} \\ E_{bb'} \\ E_{cc'} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \cdot \begin{bmatrix} V_z \\ V_p \\ V_n \end{bmatrix}\right\}$$ Voltage drops across series fault. EQ. 20

$$\left.\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \cdot \begin{bmatrix} I_z \\ I_p \\ I_n \end{bmatrix}\right\}$$ System currents from source. EQ. 21

$$I_{zm} = \frac{(I_z \cdot Z_1)}{(Z_z + Z_1)} \qquad \text{EQ. 22}$$

$$I_{pm} = \frac{(I_p \cdot Z_1)}{(Z_p + Z_1)} \qquad \text{EQ. 23}$$

$$I_{nm} = \frac{(I_n \cdot Z_1)}{(Z_n + Z_1)} \qquad \text{EQ. 24}$$

"ZPN" motor currents.

$$\left.\begin{bmatrix} I_{am} \\ I_{bm} \\ I_{cm} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \cdot \begin{bmatrix} I_{zm} \\ I_{pm} \\ I_{nm} \end{bmatrix}\right\}$$ "ABC" motor currents EQ. 25

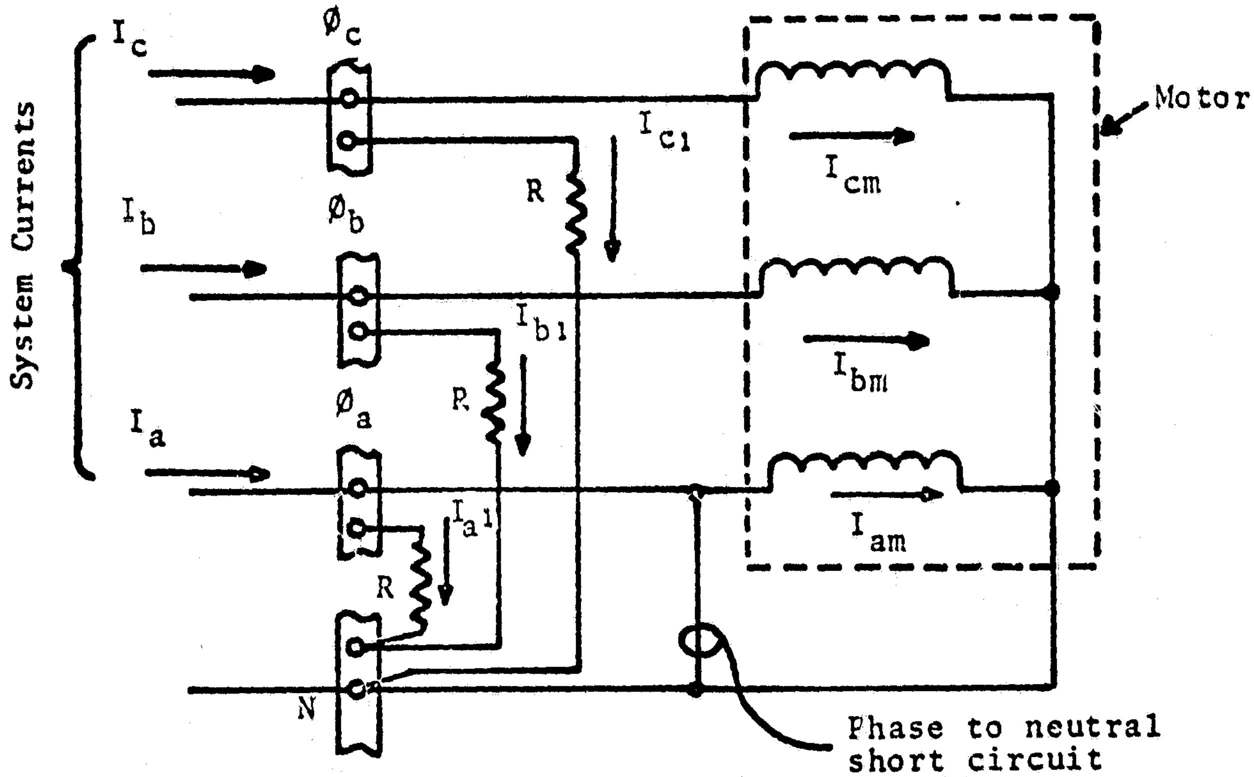
$$\left.\begin{bmatrix} I_{a1} \\ I_{b1} \\ I_{c1} \end{bmatrix} = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} - \begin{bmatrix} I_{am} \\ I_{bm} \\ I_{cm} \end{bmatrix}\right\}$$ "ABC" resistive load currents. EQ. 26

$$\begin{bmatrix} V_{am} \\ V_{bm} \\ V_{cm} \end{bmatrix} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} - \begin{bmatrix} E_{aa}' \\ E_{bb}' \\ E_{cc}' \end{bmatrix} \quad \left.\right\} \text{"ABC" voltages at motor and load terminals.} \qquad \text{EQ. 27}$$

This completes the analysis of the series fault. A FORTRAN program is shown later to solve the above equations on the computer.

2.4 ANALYSIS OF SHUNT FAULT

The method of solution for the shunt fault (figure 2) will be different from the one for the series fault since the terminal voltage on the faulted phase will be zero. The shunt fault is actually a simultaneous series/shunt fault since the circuit breaker on the faulted phase is assumed to have been tripped. The period of interest for this fault is after the single-phase circuit breaker has tripped. The fault is assumed to be a zero impedance short circuit to neutral; therefore, no current induced in the phase "A" motor winding will flow in the resistive load. This simplifies the problem by permitting separate computation of motor and load currents and then superimposing these to obtain system currents. Figure 14 is a simplified diagram showing terminal voltage and current flow for the shunt fault. It has been shown that the motor can be represented by three independent equivalent circuits in the "ZPN" domain. These are shown in figures 9, 10, and 11. If the applied voltages to each of these equivalent circuits are known, the "ZPN" and the "ABC" currents can be computed. The "ZPN" voltages are computed as follows:



$I_c = I_{c1} + I_{cm}$ $V_a = 0$

$I_b = I_{b1} + I_{bm}$ $V_b = 1\angle{-120°}$

$I_a = 0$ $V_c = 1\angle{120°}$

FIGURE 14 - SIMPLIFIED SCHEMATIC OF SHUNT FAULT

$$\begin{bmatrix} V_z \\ V_p \\ V_n \end{bmatrix} = \left(\frac{1}{3}\right) \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad \text{EQ. 28}$$

Sample Calculation:

$$\begin{bmatrix} V_z \\ V_p \\ V_n \end{bmatrix} = \left(\frac{1}{3}\right) \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a \\ 1 & a & a \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 1\underline{/-120^\circ} \\ 1\underline{/120^\circ} \end{bmatrix}$$

$$= \left(\frac{1}{3}\right) \cdot \begin{bmatrix} 1\underline{/-120^\circ} & + & 1/120^\circ \\ 1\underline{/0^\circ} & + & 1\underline{/0^\circ} \\ 2\underline{/-120^\circ} & + & 1\underline{/120^\circ} \end{bmatrix} = \left(\frac{1}{3}\right) \cdot \begin{bmatrix} 1\underline{/180^\circ} \\ 2\underline{/0^\circ} \\ 2\underline{/180^\circ} \end{bmatrix}$$

Therefore:

$$V_z = \left(\frac{-1}{3}\right) + j0$$

$$V_p = \left(\frac{2}{3}\right) + j0$$

$$V_n = \left(\frac{-2}{3}\right) + j0$$

The "ZPN" currents are computed as follows:

$$I_z = \frac{V_z}{Z_z} \qquad \text{EQ. 29}$$

$$I_p = \frac{V_p}{Z_p} \qquad \text{EQ. 30}$$

$$I_n = \frac{V_n}{Z_n} \qquad \text{EQ. 31}$$

NOTE: Z_p, Z_n, and Z_z are computed using equations 9 through 11.

ABC motor currents are computed as follows:

$$\begin{bmatrix} I_{am} \\ I_{bm} \\ I_{cm} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \cdot \begin{bmatrix} I_z \\ I_p \\ I_n \end{bmatrix} \qquad \text{EQ. 32}$$

Since the resistive loads are not sensitive to voltage unbalance, load currents can be computed in the ABC domain.

$$I_{a1} = \frac{V_a}{Z_1} = 0 \qquad \text{EQ. 33}$$

$$I_{b1} = \frac{V_b}{Z_1} \qquad \text{EQ. 34}$$

$$I_{c1} = \frac{V_c}{Z_1} \qquad \text{EQ. 35}$$

The system currents are as follows:

$$I_a = 0 \qquad \text{EQ. 36}$$

$$I_b = I_{bm} + I_{b1} \qquad \text{EQ. 37}$$

$$I_c = I_{cm} + I_{c1} \qquad \text{EQ. 38}$$

This completes the computations for the shunt fault condition.

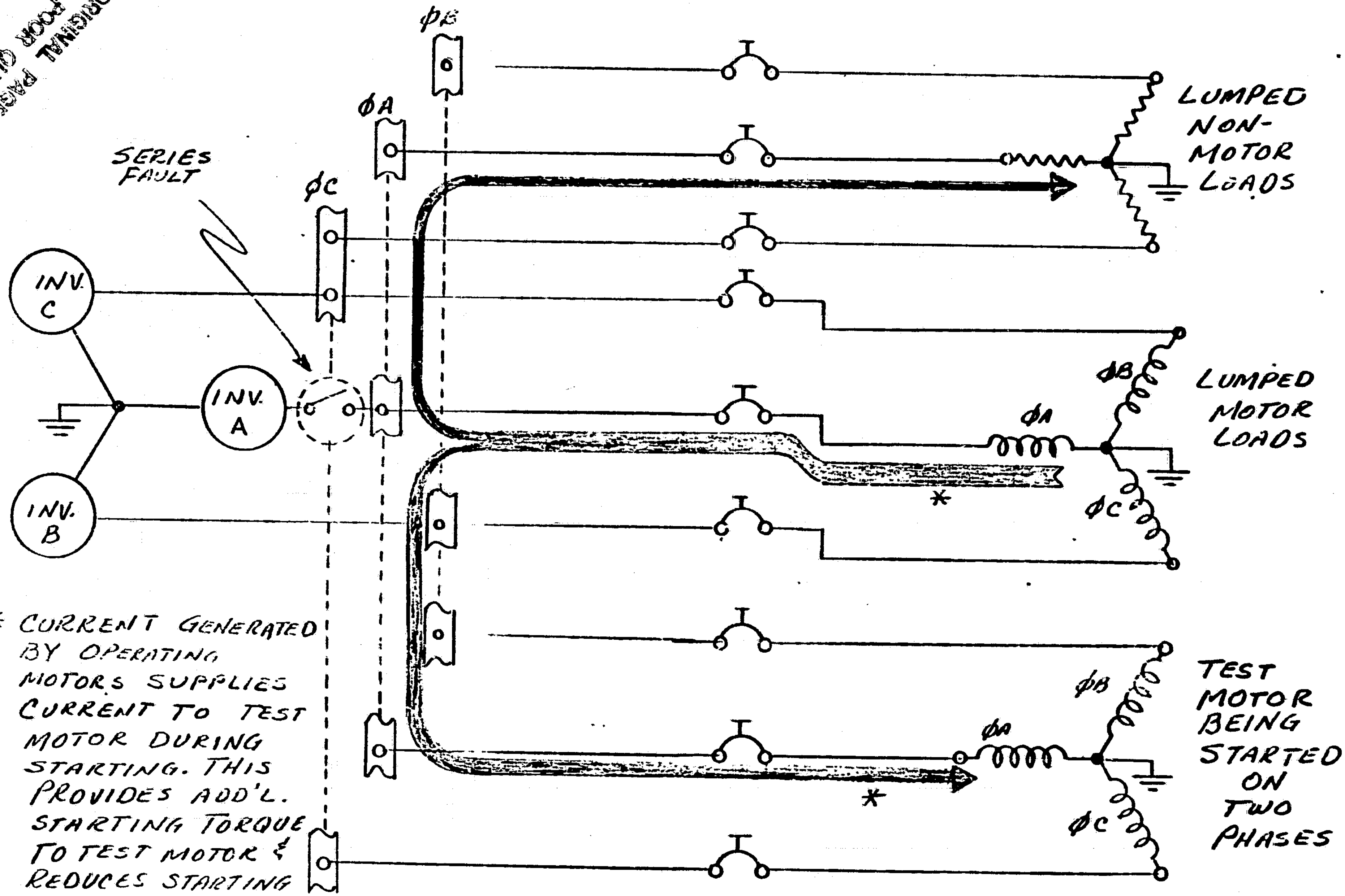
2.5 TWO-PHASE STARTING

The series fault analysis assumed all the motors on the system were lumped together and running at the same slip. This did not permit the separate computation of starting current for one motor when other motor and non-motor loads were operating. A minor change in the circuit equations for the series fault was accomplished to permit separate computation. An analysis of this sort is of particular interest since the operating motors supply current, through generator action, to the dead phase of the motor being started. Since this current is in the proper time phase relative to the other two phases, it assists in the starting of the motor. In generating this current, however, the other motors demand more current from the bus. The computer program to be described later computes bus currents and voltages, currents to the motor being started, currents to the other operating motors, and currents being generated on the dead phase by the other operating motors. Figure 15 shows the current generated in the dead phase of the operating motors and being supplied to the test motor being started and to the non-motor loads. As the size of the non-motor increases, its current demand increases leaving less current available to start the test motor.

3.0 COMPUTER ANALYSIS

3.1 PROGRAM DESCRIPTION (SOPSFS)

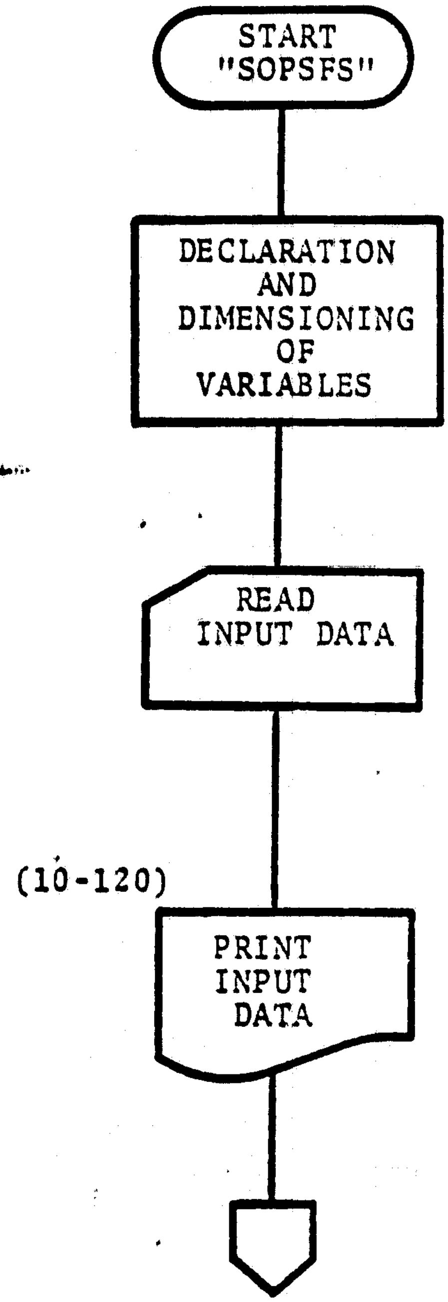
A FORTRAN program is developed to calculate system currents, motor currents, non-motor currents, and bus voltages. The program is set up to permit computation of up to 10 values of slip, 10 values of connected horsepower, and 10 values of non-motor loads. It is only necessary for the user to put in values for slip, connected horsepower, and connected volt-amperes of non-motor loads. It is written in FORTRAN IV language. The computations, which basically involve the solution of equations 1-38, take place within three nested do-loops. A listing of the FORTRAN program is included in the appendix. The program is designated SOPSFS (Shuttle Orbiter power system fault simulation).

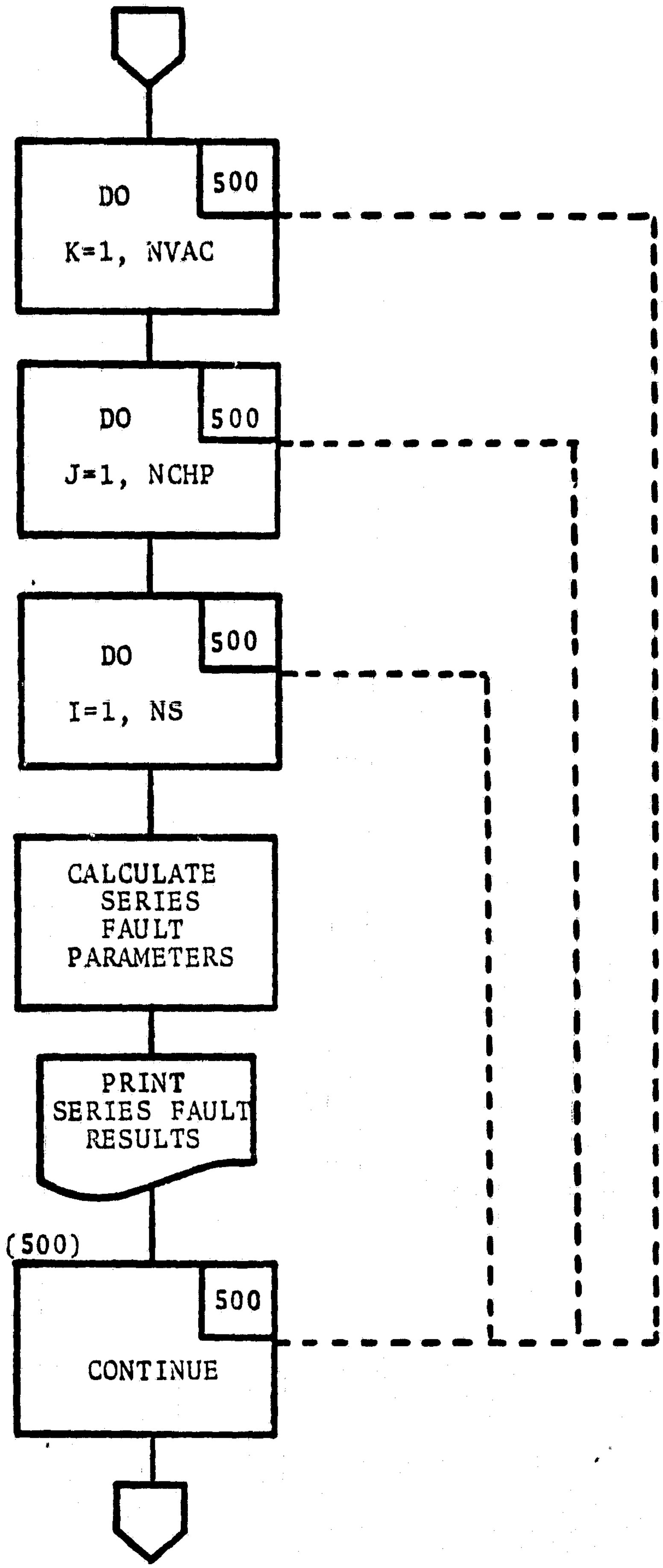


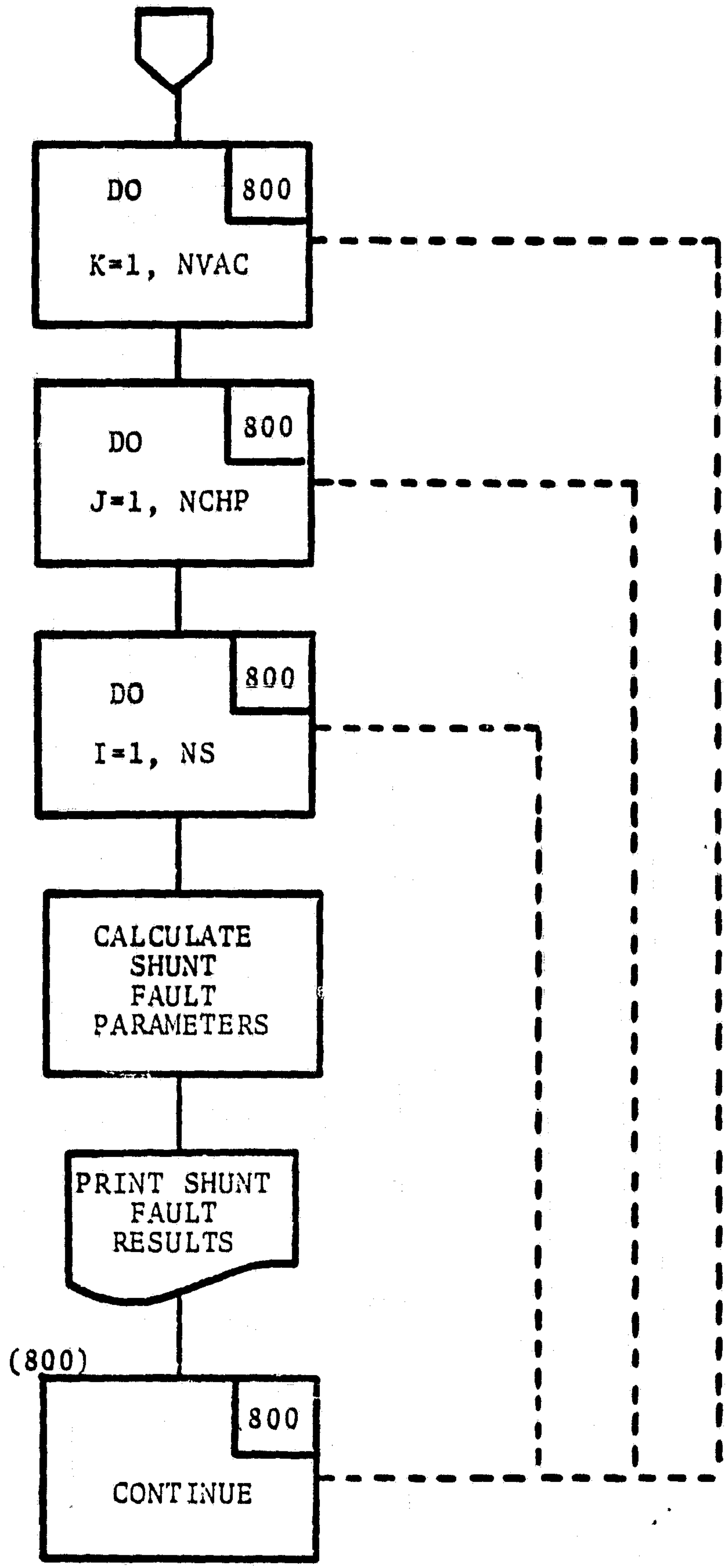
* CURRENT GENERATED BY OPERATING MOTORS SUPPLIES CURRENT TO TEST MOTOR DURING STARTING. THIS PROVIDES ADD'L. STARTING TORQUE TO TEST MOTOR & REDUCES STARTING TIME.

FIG 15- SIMPLIFIED DIAGRAM OF AC SYSTEM SHOWING TEST MOTOR STARTING ON TWO PHASES.

3.2 FLOW DIAGRAM FOR "SOPSFS"




DO
500
K=1, NVAC
DO
500
J=1, NCHP
DO
500
I=1, NS
CALCULATE SERIES FAULT PARAMETERS
PRINT SERIES FAULT RESULTS
(500)
500
CONTINUE


DO
800
K=1, NVAC
DO
800
J=1, NCHP
DO
800
I=1, NS
CALCULATE SHUNT FAULT PARAMETERS
PRINT SHUNT FAULT RESULTS
(800)
800
CONTINUE

3.3 PROGRAM DESCRIPTION (SOTPMS)

The SOTPMS (Shuttle Orbiter two-phase motor starting) program is an extension of SOPSFS and permits separation of one motor (test motor) from the group of lumped motors. This permits the test motor to be operated at values of slip different from the other motors. As a result, calculations can be made with the test motor at zero speed while the other motors are operating at full speed. Operation of this program requires the user to put in values for horsepower and slip for the test motor, horsepower and slip for the other lumped motors, and volt-amperes of the non-motor loads. As presently configured, the outputs are bus currents, test motor currents, lumped motor currents, non-motor load currents, and bus voltages. These currents and voltages are complex and are printed out in rectangular coordinate form. The following example illustrates the use of the program.

Assume the loss of phase "A" inverter on AC-2. Calculate the starting and running current of a 0.5 horsepower motor when no other loads are connected to the system and when other motor and non-motor loads are connected. This example simulates the starting current of a cabin fan under various conditions of system load. It shows how the generated current from other operating motors on the bus can provide starting current to phase "A" of the cabin fan and thereby improve its starting performance.

STARTING & RUNNING CURRENTS FOR SERIES FAULT

NON-MOTOR LOAD (VA)	MOTOR LOAD (HP)	INVERTER AMPS (ØB)	TEST MOTOR AMPS (ØB)	TEST MOTOR AMPS (ØA)	REMARKS
0	0	9.7	9.7	0	Starting
0	0.5	13.4	9.0	2.4*	Starting
200	0	10.5	9.7	.5	Starting
200	0.5	14.3	9.1	2.3*	Starting
0	0	3.2	3.2	0	Running
0	0.5	6.25	3.1	0	Running
200	0	4.9	3.8	1.1	Running
200	0.5	7.8	3.4	.6	Running

Of particular interest here is the test motor phase "A" current. Values marked "*" are supplied to the test motor from the other motors running on the bus. This current assists the test motor in starting. When the test motor gets up to speed, it is acting as a generator, along with the other motors, in supplying current to the non-motor load.

3.4 COMPUTER RESULTS

Figures 16 through 20 are graphs, plotted from computer data, of system current in phase "B" versus non-motor load in volt-amperes for various motor loads. The fault is placed on phase "A" and the phase "B" system current is plotted. Phase "B" was chosen to plot since it is consistently higher in magnitude than phase "C" and therefore represents the worse case condition. Since the ordinate of these curves is in per unit current, a horizontal line at the 1.0 point represents the full load line for phase "B." The dotted line represents the current anticipated on phase "B" during a series fault if the magnetic coupling between motor phases is neglected. It takes into account the additional current required to supply the mechanical load from two rather than three phases, plus the additional current due to the higher slip. Examination of the curves shows that a significant error could result if one does not consider the coupling when making a load analysis. For example, figure 18 shows that the system, under balanced conditions, can handle 0.5 horsepower motor load plus an additional 600 volt-amperes of non-motor loads per phase. If coupling is neglected (dotted curve) during a series fault, one would erroneously expect the system to handle the 0.5 horsepower motor plus 415 volt-amperes of other loads when in fact it could handle only 347 volt-amperes of other loads. Families of curves for other motor loads are shown in the other figures.

Figure 21 gives a family of curves for various motor loads showing the current generated by phase "A" of the motor during a series fault. The current is again plotted versus volt-amperes of non-motor loads and shows current increasing as load increases. This is what would be expected since increasing load represents decreasing impedance. This plot vividly illustrates the problem addressed by this analysis; that is, the non-motor loads connected to the bus represent an additional load to the remaining two phases because of the generating action of the motors. Figure 22 shows the generated current in phase "A" as a function of motor horsepower during a shunt fault. This could be considered the limiting case of the series fault since the shunt fault really represents a zero impedance

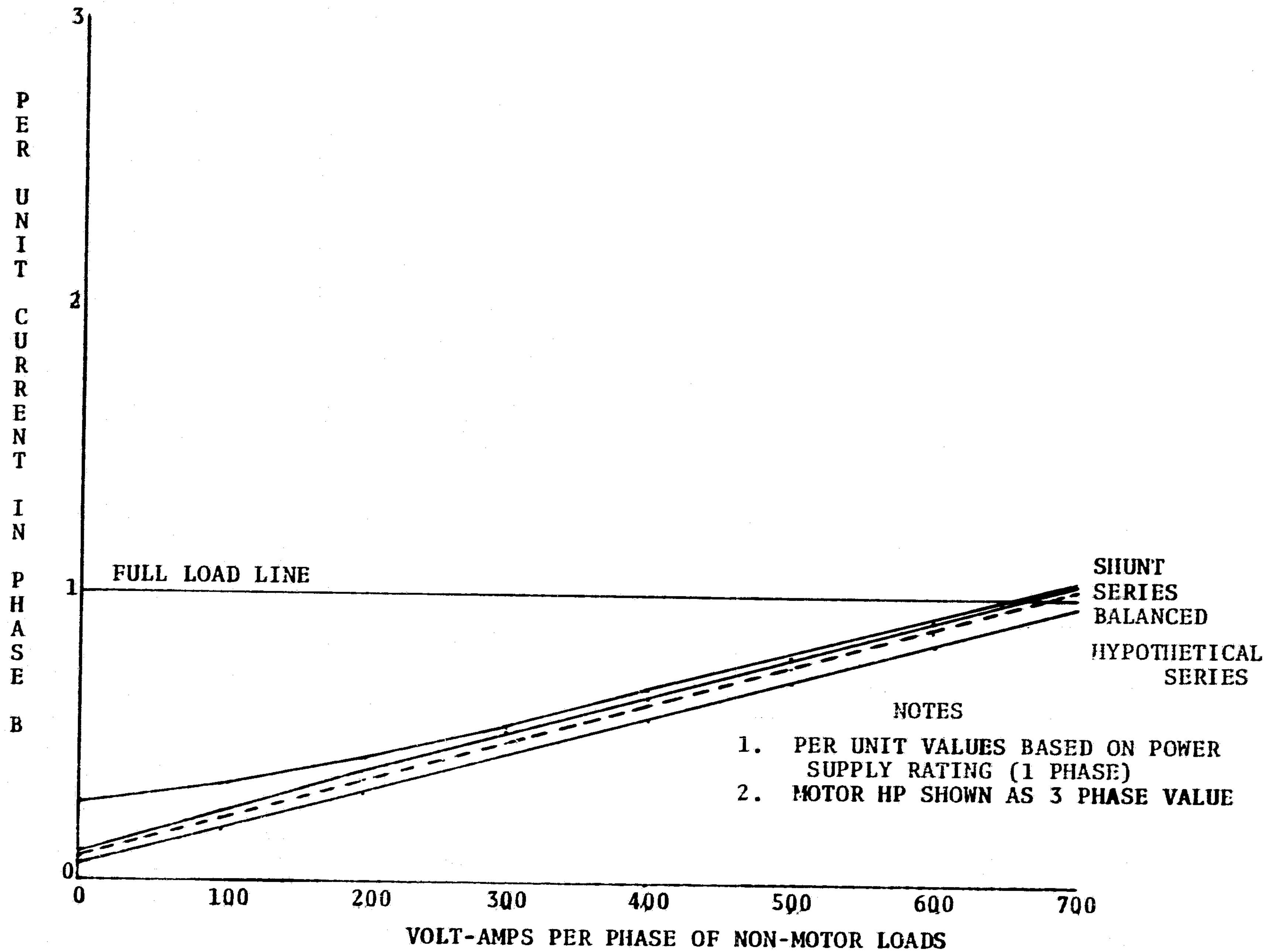


FIGURE 16 - SYSTEM CURRENT VS. NON-MOTOR LOAD FOR 0.1 HP MOTOR LOAD

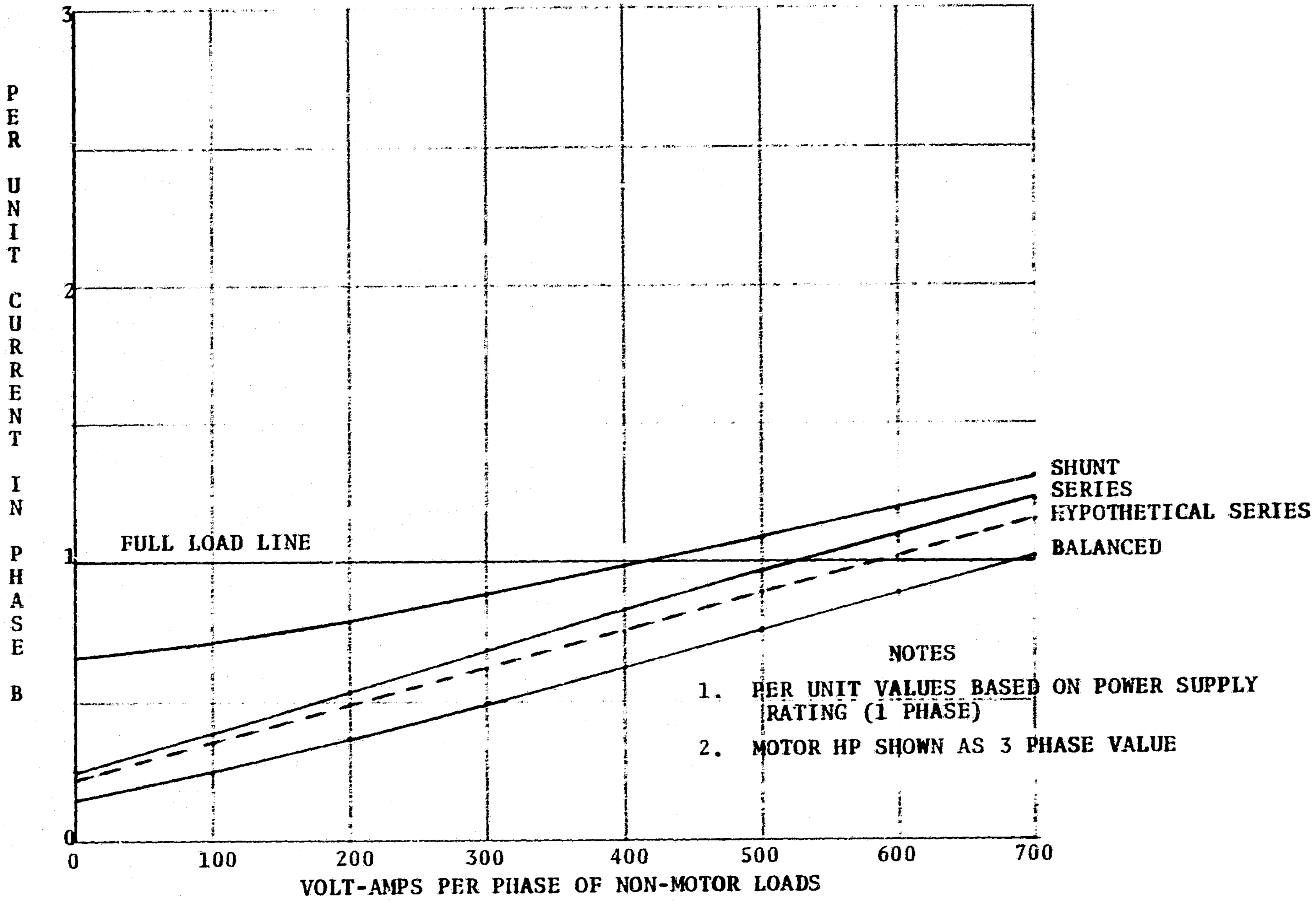


FIGURE 17 - SYSTEM CURRENT VS. NON-MOTOR LOAD FOR 0.25 HP MOTOR LOAD

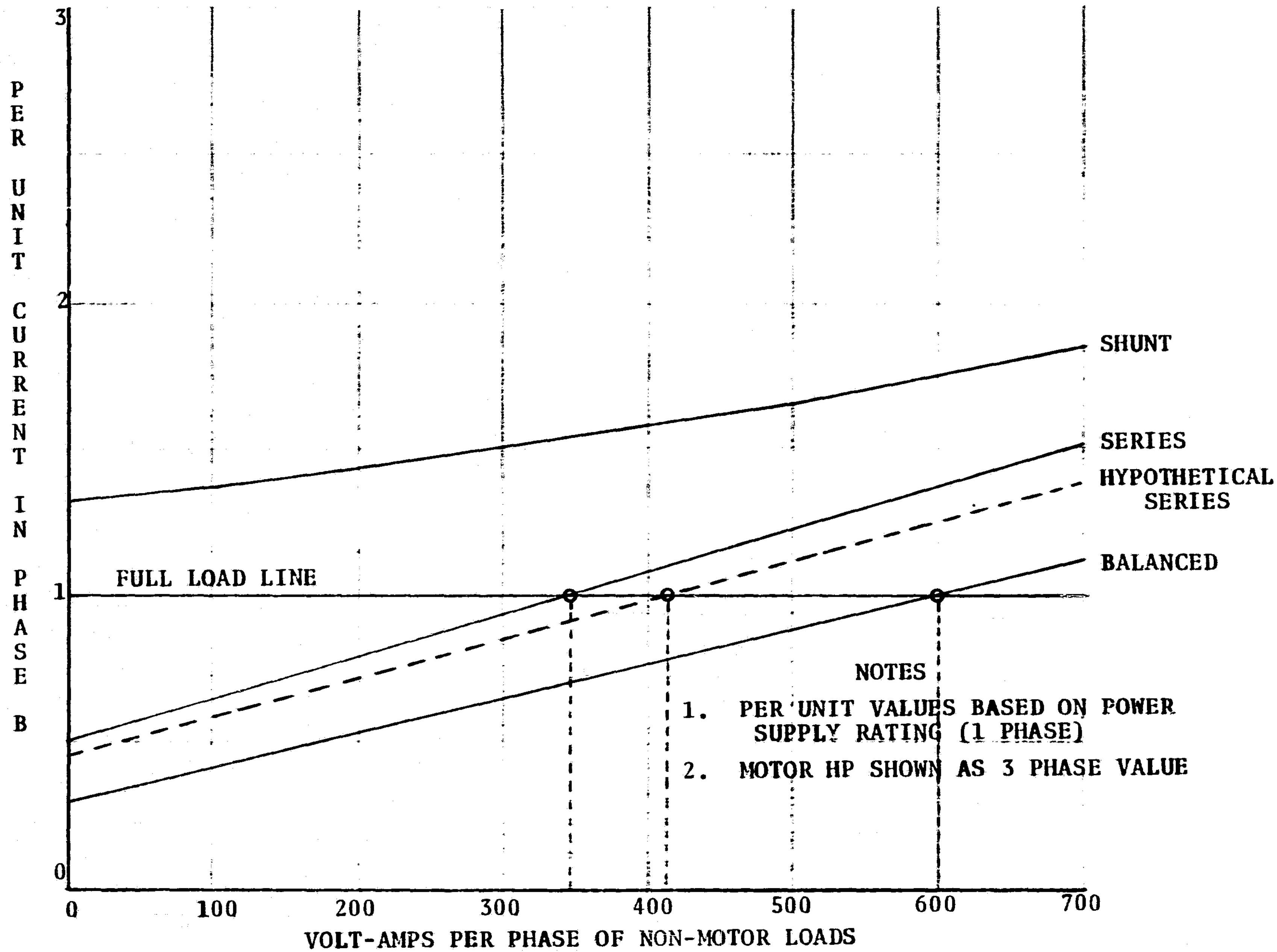


FIGURE 18 - SYSTEM CURRENT VS. NON-MOTOR LOAD FOR 0.5 HP MOTOR LOAD

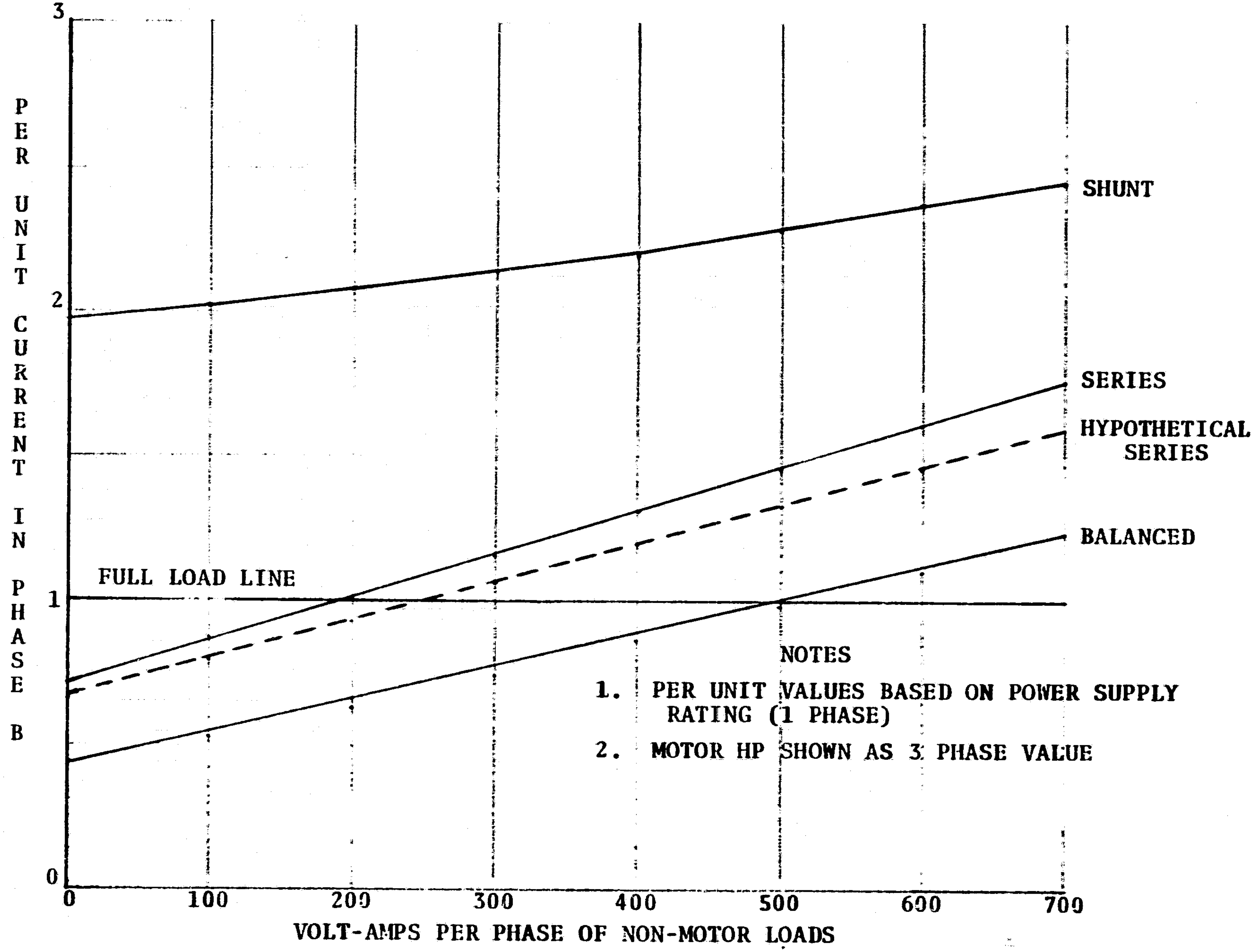


FIGURE 19 - SYSTEM CURRENT VS. NON-MOTOR LOAD FOR 0.75 HP MOTOR LOAD

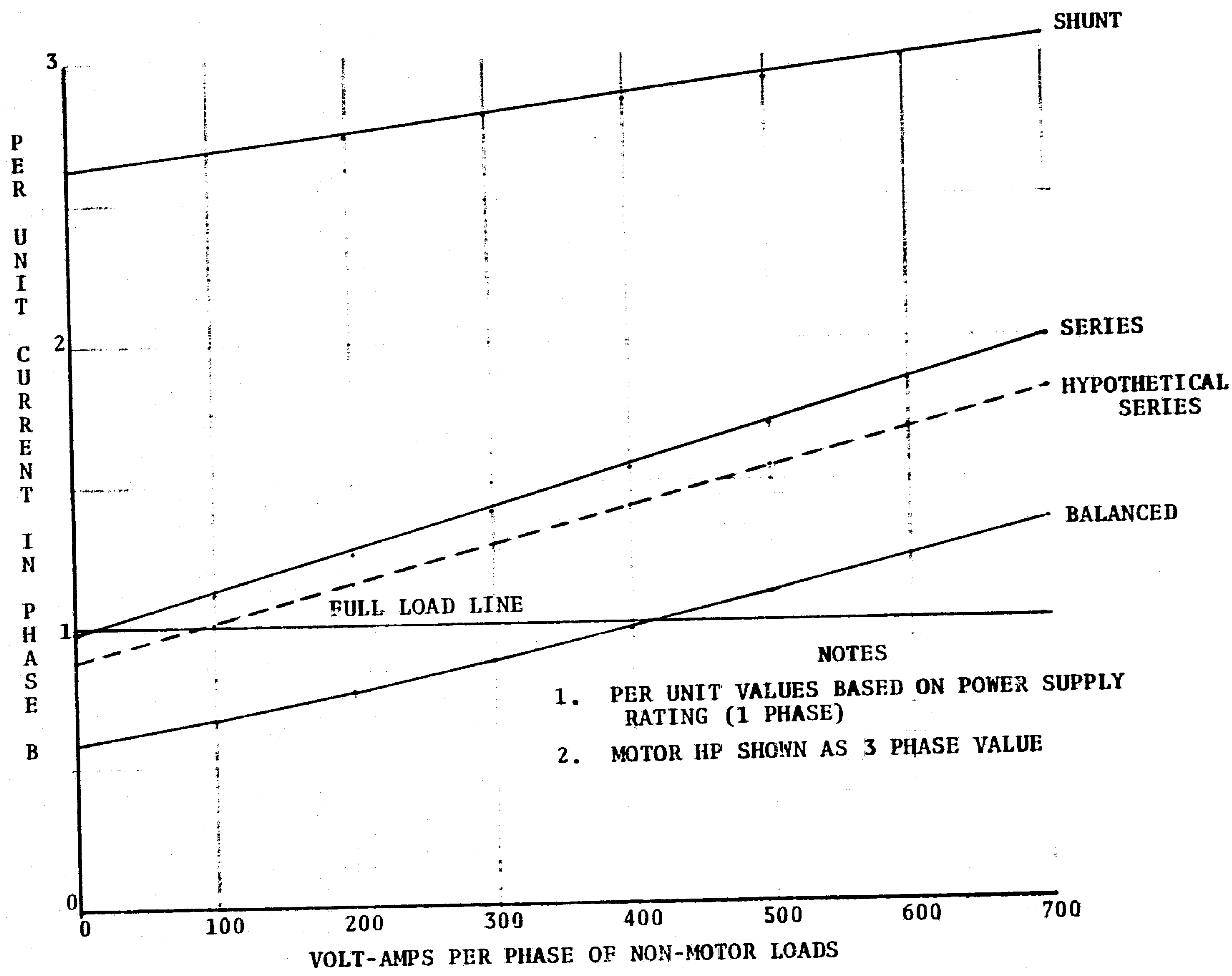


FIGURE 20 - SYSTEM CURRENT VS. NON-MOTOR LOAD FOR 1.0 HP MOTOR LOAD

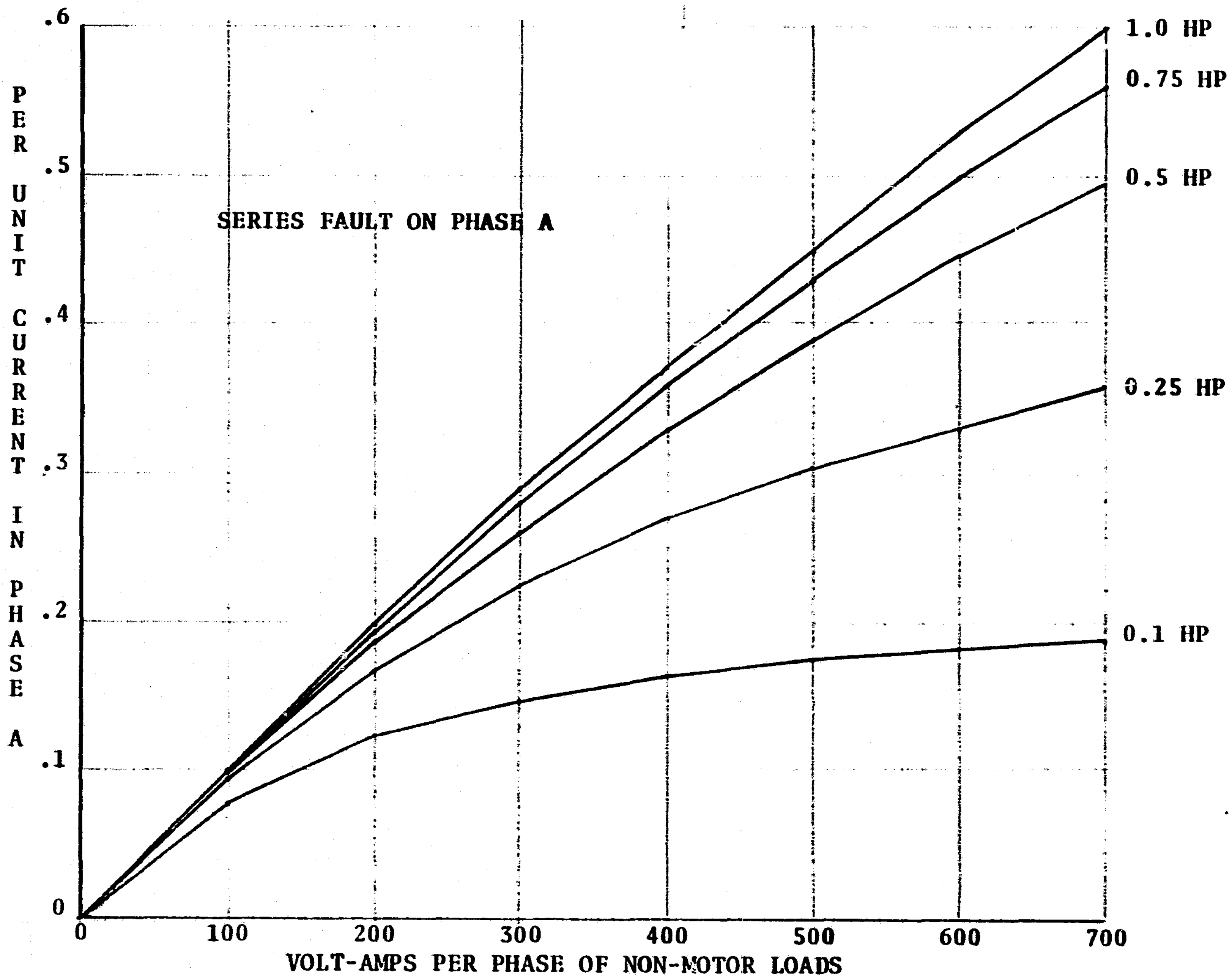


FIGURE 21 - GENERATED MOTOR CURRENTS DURING SERIES FAULT

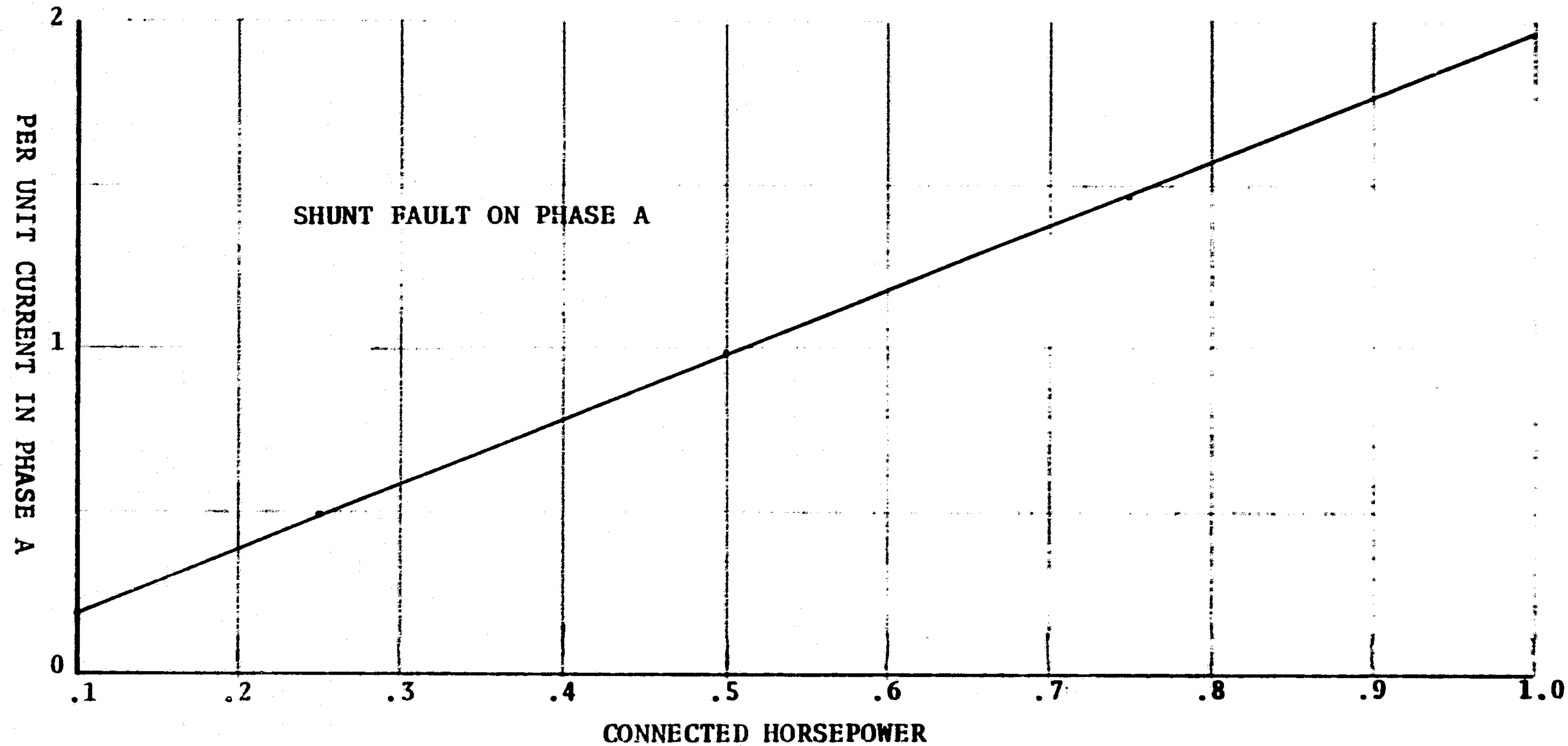


FIGURE 22 - GENERATED MOTOR CURRENTS DURING SHUNT FAULT

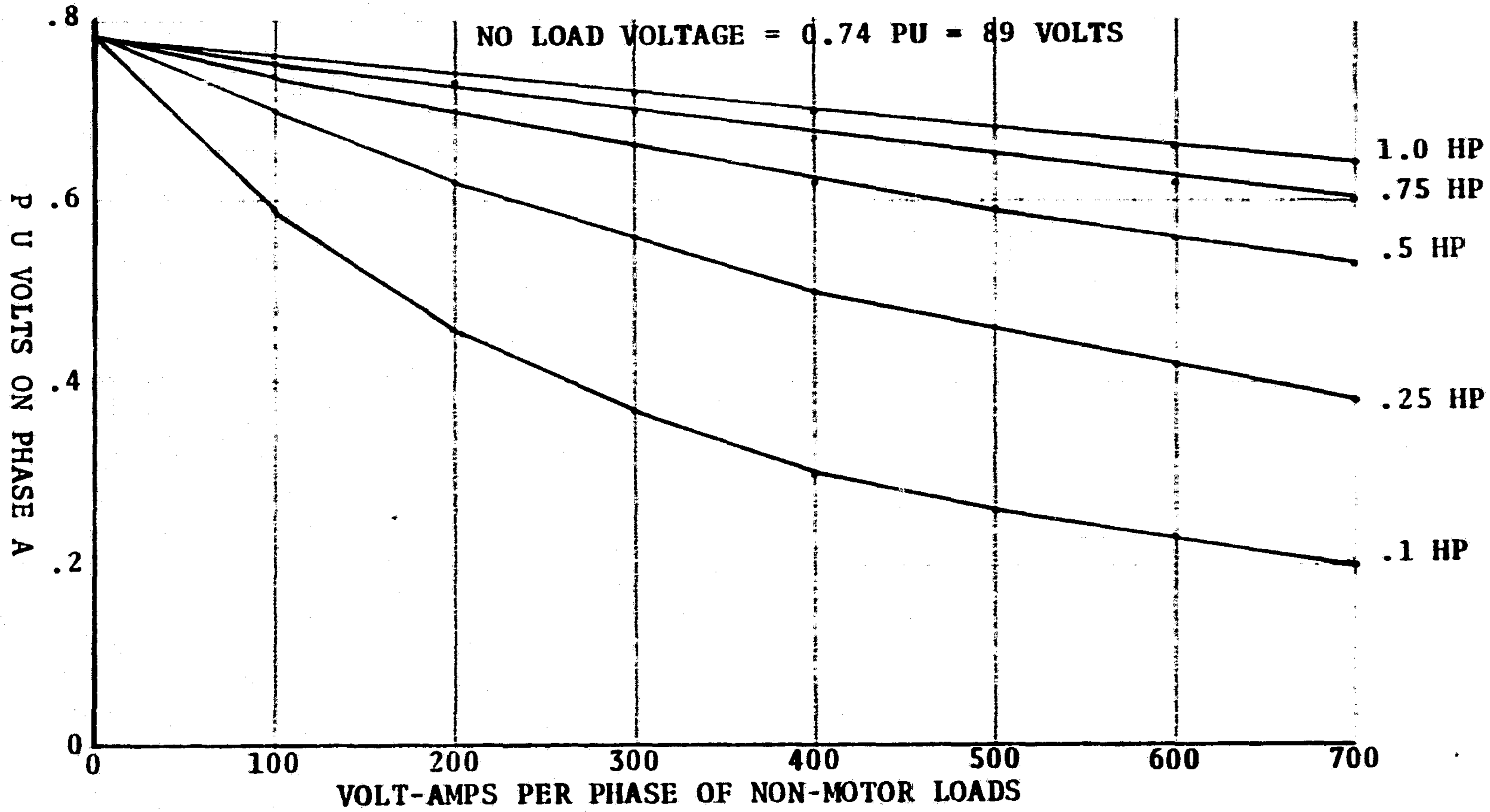


FIGURE 23 - GENERATED VOLTAGE ON PHASE A DURING SERIES FAULT

load. Another parameter of interest is the voltage on bus "A" during a series fault. This represents the voltage, generated by the connected motors, impressed on the non-motor loads connected to bus "A" and could be a problem if these loads are sensitive to low voltage. A plot showing the magnitude of this voltage as a function of volt-amperes connected is shown in figure 23.

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

Whereas 4-wire a.c. systems offer the advantage that 3-phase induction motors will start on two phases, their performance during fault conditions must be taken into account. In order to predict this performance, one must take into account the magnetic coupling between phases of the motors. This coupling can result in overloads on the system as well as undesirable voltages on the faulted phase. A method has been presented to estimate the magnitude of these voltages and currents quickly and easily for series and shunt faults. For example, it has been shown that the non-motor-load capacity of the Space Shuttle Orbiter system is approximately 16% lower than would be anticipated if coupling were not considered. It has also been shown that there exists a practical upper limit on the size of motor loads that will tolerate a shunt fault. For example, on the Orbiter this upper limit is less than 0.5 horsepower.

4.2 RECOMMENDATIONS

The program as developed does not permit reactive non-motor loads nor does it permit impedance-to-neutral type shunt faults. These features should be incorporated in later versions of the program. The addition of distribution system (source) impedance would be a useful feature also. It was not included in this version since the distribution impedance for most spacecraft is very low (3% or less voltage drop at full load).

REFERENCES

1. Fortescue, C. L., "Method of Symmetrical Coordinates Applied to the Solution of Polyphase Networks," Trans. AIEE 37: 1027-1140, 1918.

2. Alger, P. L., Induction Machines, Gordon and Breach Science Publishers, New York, 1969.

3. Clark, Edith, Circuit Analysis of AC Power Systems, General Electric Co., Schenectady, New York, 1950.

4. Westinghouse Electric Corporation, Electrical Transmission and Distribution Reference Book, 4th Edition, East Pittsburgh, Pennsylvania, 1964.

5. Lawrence, R. R., and Richards, H. E., Principles of Alternating-Current Machinery, McGraw-Hill Co., New York, 1953.

6. Lyndon B. Johnson Space Center, Shuttle Operational Data Book (JSC 08934, Volume 1, Revision A), Houston, Texas, October 1976.

APPENDIX A

FORTRAN LISTING - "SOPSFS"

```
****  THIS PROGRAM IS WRITTEN IN FORTRAN AND SIMULATES SERIES AND SHUNT       0001
       FAULTS ON THE SHUTTLE ORBITER AC POWER SYSTEM. THE SERIES FAULT       0002
       IS DEFINED AS A TOTAL OF ONE PHASE OF THE AC SYSTEM. AN EXAMPLE       0003
       OF THIS IS THE LOSS OF ONE OF THE THREE SINGLE PHASE INVERTERS.       0004
       THE SHUNT FAULT IS DEFINED AS A PHASE TO NEUTRAL SHORT CIRCUIT        0005
       AFTER THE CIRCUIT BREAKER OR FUSE HAS DISCONNECTED THE SOURCE         0006
       FROM THE FAULT.                                                       0007
***   THE SIMULATED SYSTEM INCLUDES TWO TYPES OF LOADS, MOTOR AND NON-       0008
       MOTOR LOADS. THE MOTOR LOADS ARE REPRESENTED BY A COMPOSITE           0009
       EQUIVALENT CIRCUIT. THE EQUIVALENT CIRCUIT PARAMETERS ARE             0010
       CALCULATED BY THE COMPUTER BASED ON TOTAL CONNECTED HORSEPOWER        0011
       WHICH IS INPUTTED BY THE OPERATOR. THE NON-MOTOR LOADS ARE            0012
       REPRESENTED BY A 3-PHASE, WYE CONNECTED RESISTIVE LOAD BANK. THE      0013
       SIZE OF THE LOAD IN VOLT-AMPERES IS INPUTTED BY THE OPERATOR.         0014
***   THE ANALYTICAL METHOD USED IS COMMONLY REFERRED TO AS THE"METHOD       0015
       OF SYMMETRICAL COMPONENTS". BRIEFLY THIS METHOD TRANSFORMS THE        0016
       PHASE QUANTITIES FROM THE "ABC" REFERENCE FRAME INTO A "ZPN"          0017
       REFERENCE FRAME (ZERO,POSITIVE, AND NEGATIVE SEQUENCE). CALCU-        0018
       LATIONS ARE MADE WHILE IN THE "ZPN" REFERENCE FRAME AND THEN          0019
       TRANSFORMED BACK INTO THE "ABC" REF. FRAME.                           0020
***   DEFINITIONS                                                            0026
      R1,R2,X1,X2,AND XM - TRADITIONAL INDUCTION MOTOR EQUIVALENT            0027
        CIRCUIT PARAMETERS EXPRESSED IN PER UNIT VALUES PER PHASE.           0028
      ZZ = RZ+JXZ - ZERO SEQUENCE IMPEDANCE IN PU PER PHASE.                 0029
      BASE VOLT-AMPERES=750 VA (SINGLE PHASE INVERTER RATING)                0030
      BASE VOLTAGE = 120 VOLTS (PHASE TO NEUTRAL)                            0031
      BASE CURRENT = 6.25 AMPS; BASE IMPEDANCE = 19.2 OHMS                   0032
      CHP - SUM TOTAL OF ALL MOTORS CONNECTED TO BUS (EXPRESSED IN HP)       0033
        CHP IS ONE OF THE REQUIRED INPUTS.                                   0034
      VAC - SUM TOTAL OF ALL NON-MOTOR LOADS CONNECTED TO BUS (EXPRES-       0035
        SED IN VOLT-AMPS PER PHASE). VAC IS ALSO A REQUIRED INPUT.           0036
      S- MOTOR SLIP. THIS IS ALSO A REQUIRED INPUT.                          0037
      A - COMPLEX OPERATOR = COS(120)+JSIN(120)                              0038
      AA - COMPLEX OPERATOR = COS(240)+JSIN(240)                             0039
      Z1 - COMPLEX IMPEDANCE OF MOTOR STATOR WINDING = R1+JX1 (SAME FOR      0040
        POSITIVE AND NEGATIVE SEQUENCE).                                     0041
      Z2P - POSITIVE SEQUENCE IMPEDANCE OF ROTOR WHICH IS A FUNCTION         0042
        OF S.                                                                0043
      Z2N - NEGATIVE SEQUENCE IMPEDANCE OF ROTOR WHICH IS A FUNCTION         0044
        OF S.                                                                0045
      ZP=RP+JXP; ZN=RN+JXN - POSITIVE AND NEGATIVE SEQUENCE IMPEDANCES       0046
        OF MOTOR. BOTH ARE FUNCTIONS OF S.                                   0047
      ZZ=RZ+JXZ - ZERO SEQUENCE IMPEDANCE OF MOTOR.                          0048
      ZL=R+J0 - IMPEDANCE OF NON-MOTOR LOADS.                                0049
      CIPL,CINL,CIZL - POSITIVE,NEGATIVE, AND ZERO SEQUENCE CURRENTS         0051
        IN NON-MOTOR LOAD.                                                   0052
      CIPM,CINM,CIZM - P,N,Z CURRENTS IN MOTOR.                              0053
      CIP,CIN,CIZ - P,N,Z CURRENTS FROM SOURCE.                              0054
      ZPS,ZNS,ZZS - TOTAL SYSTEM IMPEDANCES IN PNZ REF. FRAME.               0055
      EAP - PHASE A POSITIVE SEQUENCE VOLTAGE.                               0056
      VP,VN,VZ                  - PNZ FAULT VOLTAGES FOR SERIES FAULT.       0057
      EAAP,EBBP,ECCP - ABC VOLTAGES ACROSS SERIES FAULT.                     0058
      CIA,CIB,CIC - ABC CURRENTS FROM SOURCE.                                0059
      CIAM,CIBM,CICM - ABC CURRENTS INTO MOTOR.                              0060
      CIAL,CIBL,CICL - ABC CURRENTS INTO NON-MOTOR LOADS.                    0061
      VA,VB,VC - ABC APPLIED VOLTAGES (PHASE TO NEUTRAL).                    0062
      VAM,VBM,VCM - ABC PHASE VOLTAGES ACROSS MOTOR AND LOAD TERMINALS.      0063
      NS - COUNTER OF NUMBER OF SLIP POINTS. REQUIRED INPUT.                 0064
      NCHP - COUNTER OF NUMBER OF HP VALVES. REQUIRED INPUT.                 0065
      NVAC - COUNTER OF NUMBER OF LOAD VALVES. REQUIRED INPUT.               0066
```

```
      Z2PP,Z2NP - PARALLEL COMBINATION OF ROTOR IMPEDANCES AND MUTUAL.-      0067
      INTEGER LP,ITI,CDR,TTO
      COMPLEX A,AA,ZP,ZL,Z2,ZN,ZM,CIPL,CINL,CIZL,CIPM,CINM,CIZM,CIP,
     + CIN,CIZ,EAP,VP,VN,VZ,EAAP,EBBP,ECCP,CIA,CIB,CIC,CIAM,CIBM,CICM,
     + CIAL,CIBL,CICL,VA,VB,VC,VAM,VCM,Z2PP,Z2NP,Z1,Z2P,Z2N,ZPS,ZNS,
     + Z2S,VBM,ZA,ZB,ZC
      DIMENSION S(10),CHP(10),VAC(10)
      LP=6
      CDR=5
***   READ INPUT DATA
      READ(CDR,10) NS,NCHP,NVAC
      READ(CDR,20)(S(I),I=1,NS)
      READ(CDR,20)(CHP(I),I=1,NCHP)
      READ(CDR,30)(VAC(I),I=1,NVAC)
10    FORMAT(3I5)
20    FORMAT(10F5.2)
30    FORMAT(10F7.2)
40    FORMAT(1H1,5X,'FAULT SIMULATION OF ORBITER POWER SYSTEM'/)
50    FORMAT(1H0,5X,'SLIP PTS.=',I2,5X,'CHP PTS.=',I2,5X,'VAC PTS.=',I2
     +)
      WRITE(LP,40)
      WRITE(LP,50)NS,NCHP,NVAC
60    FORMAT(1H0,5X,'VALUES OF SLIP, CONNECTED HP, AND CONNECTED LOAD A
     +S FOLLOWS:')
      WRITE(LP,60)
70    FORMAT(1H0,5X,'VALUES OF SLIP (S) ARE:'/)
      WRITE(LP,70)
80    FORMAT(1H ,5X,10F6.2)
      WRITE(LP,80) (S(I),I=1,NS)
90    FORMAT(1H0,5X,'VALUES OF CONNECTED HORSEPOWER ARE:'/)
      WRITE(LP,90)
100   FORMAT(1H , 5X,10F6.2)
      WRITE(LP,100) (CHP(I),I=1,NCHP)
110   FORMAT(1H0,5X,'VALUES OF CONNECTED LOAD (VAC) ARE:'/)
      WRITE(LP,110)
120   FORMAT(1H , 5X,10F6.2)
      WRITE(LP,120) (VAC(I),I=1,NVAC)
***   WE WILL COMPUTE CURRENTS AND VOLTAGES FOR BALANCED CONDITIONS
        USING THE SAME TRANSFORMATION EQUATIONS AS WILL BE USED FOR
        FAULT CONDITIONS. THIS IS BEING DONE PRIMARILY AS A CHECK ON
        THE ARITHMETIC.
**    COMPUTATIONS FOR BALANCED CONDITIONS. TO BE MADE WITHIN 3 DO LOOPS.
      WRITE(LP,125)
125   FORMAT(1H0,5X,'PARAMETERS OF INTEREST FOR THE   BALANCED   CONDIT
     +ION ARE AS FOLLOWS:'/)
      WRITE(LP,140)
      WRITE(LP,150)
      WRITE(LP,160)
      WRITE(LP,170)
406   FORMAT(1H ,1X,'S= ',F4.2,51X,'BALANCED')
***   ALL PARAMETERS ARE CONVERTED TO PER UNIT VALUES AND ALL RESULTS    0350
        ARE PRINTED AS PER UNIT VALUES.                                  0355
**    BEGIN CALCULATIONS                                                 0360
      PI=3.14159
      A=CMPLX(COS(2.*PI/3.),SIN(2.*PI/3.))
      AA=CMPLX(COS(4.*PI/3.),SIN(4.*PI/3.))
      VA=CMPLX(1.,0.)
      VB=CMPLX(-.5,-.866)
      VC=CMPLX(-.5,.866)
      EAP=VA
```

```
      DO 400 K=1,NVAC
      DO 400 J=1,NCHP
      DO 400 I=1,NS
      WRITE(LP,406) S(I)
      WRITE(LP,410) CHP(J)
      WRITE(LP,420) VAC(K)
      R1=.229*(.75/CHP(J))
      X1=.135*(.75/CHP(J))
      X2=X1
      R2=.156*((.75/CHP(J))/S(I))
      XM=1.72*(.75/CHP(J))
      RZ=.247*(.75/CHP(J))
      XZ=.137*(.75/CHP(J))
      R=750./VAC(K)
      ZL=CMPLX(R,0.)
      Z1=CMPLX(R1,X1)
      R2P=R2
      Z2P=CMPLX(R2P,X2)
      R2N=.156*((.75/CHP(J))/(2-S(I)))
      Z2N=CMPLX(R2N,X2)
      ZZ=CMPLX(RZ,XZ)
      ZM=CMPLX(0.,XM)
**    WE WILL NOW COMPUTE "ZPN" VOLTAGES
      VZ=(1./SQRT(3.))*(VA+VB+VC)
      VP=(1./SQRT(3.))*(VA+A*VB+AA*VC)
      VN=(1./SQRT(3.))*(VA+AA*VB+A*VC)
**    BEGIN REDUCTION OF MOTOR EQUIVALENT CIRCUIT.
      Z2PP=ZM*Z2P/(ZM+Z2P)
      Z2NP=ZM*Z2N/(ZM+Z2N)
      ZP=Z1+Z2PP
      ZN=Z1+Z2NP
      CIZ=VZ/ZZ
      CIP=VP/ZP
      CIN=VN/ZN
**    WE WILL NOW COMPUTE ABC MOTOR CURRENTS.
      CIAM=(1./SQRT(3.))*(CIZ+CIP+CIN)
      CIBM=(1./SQRT(3.))*(CIZ+AA*CIP+A*CIN)
      CICM=(1./SQRT(3.))*(CIZ+A*CIP+AA*CIN)
**    WE WILL NOW COMPUTE CURRENTS (ABC) IN RESISTIVE LOAD.
      CIAL=VA/ZL
      CIBL=VB/ZL
      CICL=VC/ZL
**    WE WILL NOW COMPUTE PHASE VOLTAGE ON MOTOR TERMINALS.
      VAM=(1./SQRT(3.))*(VZ+VP+VN)
      VBM=(1./SQRT(3.))*(VZ+AA*VP+A*VN)
      VCM=(1./SQRT(3.))*(VZ+A*VP+AA*VN)
**    AND FINALLY WE WILL COMPUTE SYSTEM CURRENTS.
      CIA=CIAM+CIAL
      CIB=CIBM+CIBL
      CIC=CICM+CICL
***   THIS COMPLETES COMPUTATION OF VOLTAGES AND CURRENTS FOR THE
        BALANCED      CONDITION. WE WILL NOW PRINT CURRENTS AND VOLTAGES
        OF INTEREST.
      WRITE(LP,430)CIA,CIAM,CIAL,VAM
      WRITE(LP,440)CIB,CIBM,CIBL,VBM
      WRITE(LP,450)CIC,CICM,CICL,VCM
**    WE WILL NOW CLOSE THE DO LOOP.
400   CONTINUE
130   FORMAT(1H0,5X,'PARAMETERS OF INTEREST FOR THE SERIES FAULT CONDIT
     +ION ARE AS FOLLOWS:'/)
```

```
135   FORMAT(1H0,5X,'PARAMETERS OF INTEREST FOR THE SHORT  FAULT CONDI
     +ION ARE AS FOLLOWS:'/)
      WRITE(LP,130)
140   FORMAT(1H0,10X,'COMPLEX',7X,'COMPLEX',7X,'COMPLEX',7X,'COMPLEX')
150   FORMAT(1H ,10X, 'SYSTEM',9X,'MOTOR',9X,'LOAD',8X,'MOTOR TERM.')
160   FORMAT(1H ,10X,'CURRENTS',6X,    'CURRENTS',6X,'CURRENTS',6X,'VOL
     +TAGE')
170   FORMAT(1H ,12X,'(PU)'10X,'(PU)',10X,'(PU)',10X,'(PU)')
      WRITE(LP,140)
      WRITE(LP,150)
      WRITE(LP,160)
      WRITE(LP,170)
**    COMPUTATIONS FOR SERIES FAULT. (TO BE MADE WITHIN 3 DO LOOPS)        0400
**    THE VALUE OF SLIP IS NOW ADJUSTED TO COMPENSATE FOR THE SLOWDOWN
        CAUSED BY THE SERIES FAULT.
      DO 499 I=1,NS
      S(I)=S(I)+.01
499   CONTINUE
      DO 500 K=1,NVAC
      DO 500 J=1,NCHP
      DO 500 I=1,NS
      R1=.229*(.75/CHP(J))
      X1=.135*(.75/CHP(J))
      X2=X1
      R2=.156*((.75/CHP(J))/S(I))
      XM=1.72*(.75/CHP(J))
      RZ=.247*(.75/CHP(J))
      XZ=.137*(.75/CHP(J))
      R=750./VAC(K)
      ZL=CMPLX(R,0.)
      Z1=CMPLX(R1,X1)
      R2P=R2
      Z2P=CMPLX(R2P,X2)
      R2N=.156*((.75/CHP(J))/(2-S(I)))
      Z2N=CMPLX(R2N,X2)
      ZZ=CMPLX(RZ,XZ)
      ZM=CMPLX(0.,XM)
**    BEGIN REDUCTION OF MOTOR EQUIVALENT CIRCUIT.                         0500
      Z2PP=ZM*Z2P/(ZM+Z2P)
      Z2NP=ZM*Z2N/(ZM+Z2N)
      ZP=Z1+Z2PP
      ZN=Z1+Z2NP
**    WE NOW HAVE COMPUTED ZP,ZN, AND ZZ. WE WILL NOW COMPUTE THE          0525
        SYSTEM IMPEDANCES WHICH WILL BE THE PARALLEL COMBINATION OF ZL     0530
        AND THE MOTOR SEQUENCE IMPEDANCES.                                 0535
      ZPS=ZL*ZP/(ZL+ZP)
      ZNS=ZL*ZN/(ZL+ZN)
      ZZS=ZL*ZZ/(ZL+ZZ)
**    WE WILL NOW COMPUTE POSITIVE, NEGATIVE, AND ZERO SEQUENCE            0555
        CURRENTS (CIP,CIN,CIZ) FOR THE INTERCONNECTED SYSTEM.              0560
      CIP=(EAP*(ZNS+ZZS)/((ZPS*ZNS)+(ZPS*ZZS)+(ZNS*ZZS)))
      CIN=-(EAP*ZZS)/((ZPS*ZNS)+(ZPS*ZZS)+(ZNS*ZZS))
      CIZ=-(EAP*ZNS)/((ZPS*ZNS)+(ZPS*ZZS)+(ZNS*ZZS))
**    WE WILL NOW COMPUTE FAULT VOLTAGES FOR SERIES FAULT IN THE ZPN       0580
        REFERENCE FRAME.                                                   0585
      VP= EAP-(CIP*ZPS)
      VN=-(CIN*ZNS)
      VZ=-(CIZ*ZZS)
**    WE WILL NOW COMPUTE THE VOLTAGE DROP ACROSS THE FAULT IN THE ARC     0605
        REFERENCE FRAME USING THE TRANSFORMATION.                          0610
```

```
      EAAP= VP+VZ+VN
      EBBP= VZ+AA*VP+A*VN
      ECCP=VZ+A*VP+AA*VN
**    WE WILL NOW COMPUTE SYSTEM CURRENTS IN ABC REFERENCE FRAME.              0630
      CIA=CIZ+CIP+CIN
      CIB=CIZ+AA*CIP+A*CIN
      CIC=CIZ+A*CIP+AA*CIN
**    WE WILL NOW COMPUTE MOTOR CURRENTS IN THE ZPN REFERENCE FRAME.           0650
      CIZM=(CIZ*ZL)/(ZZ+ZL)
      CIPM=(CIP*ZL)/(ZP+ZL)
      CINM=(CIN*ZL)/(ZN+ZL)
**    WE WILL NOW COMPUTE MOTOR CURRENTS IN THE ABC REFERENCE FRAME.           0670
      CIAM=CIZM+CIPM+CINM
      CIBM=CIZM+AA*CIPM+A*CINM
      CICM=CIZM+A*CIPM+AA*CINM
**    WE WILL NOW COMPUTE CURRENTS INTO RESISTIVE LOAD.(ABC REF.FRAME)         0690
      CIAL=CIA-CIAM
      CIBL=CIB-CIBM
      CICL=CIC-CICM
**    WE WILL NOW COMPUTE PHASE VOLTAGE ON MOTOR AND LOAD TERMINALS.           0710
      VAM=VA-EAAP
      VBM=VB-EBBP
      VCM=VC-ECCP
***   THIS COMPLETES COMPUTATION OF VOLTAGES AND CURRENTS FOR THE              0730
        SERIES FAULT CONDITION. WE WILL NOW PRINT CURRENTS AND VOLTAGES        0735
        OF INTEREST.                                                           0740
      WRITE(LP,404) S(I)
404   FORMAT(1H ,1X,'S= ',F4.2,51X,'SERIES')
405   FORMAT(1H ,1X,'S=',F4.2,51X,'SHUNT')
410   FORMAT(1H ,1X,'CHP=',F4.2)
      WRITE(LP,410) CHP(J)
420   FORMAT(1H ,1X,'VAC=',F4.0)
      WRITE(LP,420) VAC(K)
430   FORMAT(1H ,2X,'PH A',2X,2F6.3,2X,2F6.3,2X,2F6.3,3X,2F6.3)
      WRITE(LP,430)CIA,CIAM,CIAL,VAM
440   FORMAT(1H ,2X,'PH B',2X,2F6.3,2X,2F6.3,2X,2F6.3,3X,2F6.3)
      WRITE(LP,440)CIB,CIBM,CIBL,VBM
450   FORMAT(1H ,2X,'PH C',2X,2F6.3,2X,2F6.3,2X,2F6.3,3X,2F6.3)
      WRITE(LP,450)CIC,CICM,CICL,VCM
**    WE WILL NOW CLOSE THE DO LOOP.                                           0805
500   CONTINUE
****  WE WILL NOW BEGIN SETTING UP CONDITIONS FOR THE SHUNT FAULT. HERE        0815
        AGAIN WE WILL PLACE FAULT ON PHASE A. THE SOLUTION METHOD FOR          0820
        THE SHUNT FAULT WILL BE DIFFERENT FROM THE SERIES FAULT SINCE          0825
        THE TERMINAL VOLTAGE ON THE FAULTED PHASE OF THE MOTOR/LOAD            0830
        WILL BE ZERO. ALSO NONE OF THE CURRENT INDUCED IN THE PHASE A          0835
        MOTOR WINDING WILL FLOW IN THE RESISTIVE LOAD. THIS SIMPLIFIES         0840
        THE PROBLEM BY PERMITTING SEPARATE COMPUTATION OF MOTOR AND            0845
        LOAD CURRENTS AND THEN SUPERIMPOSING THESE TO OBTAIN SYSTEM            0850
        CURRENTS.                                                              0855
**    SET UP INPUT VOLTAGES FOR THE SHUNT FAULT.                               0860
      WRITE(LP,135)
      WRITE(LP,140)
      WRITE(LP,150)
      WRITE(LP,160)
      WRITE(LP,170)
      VAM=CMPLX(0.,0.)
      VA=CMPLX(0.,0.)
      VB=CMPLX(-.5,-.866)
      VC=CMPLX(-.5,.866)
```

```
**     WE WILL NOW COMPUTE "ZRN" VOLTAGES                                  0880
       VZ=(1./SQRT(3.))*(VA+VB+VC)
       VP=(1./SQRT(3.))*(VA+A*VB+AA*VC)
       VN=(1./SQRT(3.))*(VA+AA*VB+A*VC)
**     WE WILL NOW COMPUTE ZPN MOTOR CURRENTS.                             0900
**     THE VALUE OF SLIP IS NOW ADJUSTED TO COMPENSATE FOR THE SLOWDOWN
         CAUSED BY THE SHUNT FAULT.
       DO 799 I=1,NS
       S(I)=S(I)+.1
799    CONTINUE
       DO 800 K=1,NVAC
       DO 800 J=1,NCHP
       DO 800 I=1,NS
       R1=.229*(.75/CHP(J))
       X1=.135*(.75/CHP(J))
       X2=X1
       R2=.156*((.75/CHP(J))/S(I))
       XM=1.72*(.75/CHP(J))
       RZ=.247*(.75/CHP(J))
       XZ=.137*(.75/CHP(J))
       R=750./VAC(K)
       ZL=CMPLX(R,0.)
       Z1=CMPLX(R1,X1)
       R2P=R2
       Z2P=CMPLX(R2P,X2)
       R2N=.156*((.75/CHP(J))/(2-S(I)))
       Z2N=CMPLX(R2N,X2)
       ZZ=CMPLX(RZ,XZ)
       ZM=CMPLX(0.,XM)
**     BEGIN REDUCTION OF MOTOR EQUIVALENT CIRCUIT.
       Z2PP=ZM*Z2P/(ZM+Z2P)
       Z2NP=ZM*Z2N/(ZM+Z2N)
       ZP=Z1+Z2PP
       ZN=Z1+Z2NP
       CIZ=VZ/ZZ
       CIP=VP/ZP
       CIN=VN/ZN
       VCM=(1./SQRT(3.))*(VZ+A*VP+AA*VN)
       VBM=(1./SQRT(3.))*(VZ+AA*VP+A*VN)
**     WE WILL NOW COMPUTE ABC MOTOR CURRENTS.                             1115
       CIAM=(1./SQRT(3.))*(CIZ+CIP+CIN)
       CIBM=(1./SQRT(3.))*(CIZ+AA*CIP+A*CIN)
       CICM=(1./SQRT(3.))*(CIZ+A*CIP+AA*CIN)
**     WE WILL NOW COMPUTE CURRENTS (ABC) IN RESISTIVE LOAD.               1135
       CIAL=VA/ZL
       CIBL=VB/ZL
       CICL=VC/ZL
**     AND FINALLY WE WILL COMPUTE SYSTEM CURRENTS.                        1155
       CIA=0.
       CIB=CIBM+CIBL
       CIC=CICM+CICL
***    THIS COMPLETES COMPUTATION OF VOLTAGES AND CURRENTS FOR THE
         SSHUNT FAULT CONDITION. WE WILL NOW PRINT CURRENTS AND VOLTAGES
         OF INTEREST.
       WRITE(LP,405) S(I)
       WRITE(LP,410) CHP(J)
       WRITE(LP,420) VAC(K)
       WRITE(LP,430)CIA,CIAM,CIAL,VAM
       WRITE(LP,440)CIB,CIBM,CIBL,VBM
       WRITE(LP,450)CIC,CICM,CICL,VCM
```

```
**    WE WILL NOW CLOSE THE DO LOOP.
800   CONTINUE
      END
```

APPENDIX B

FORTRAN LISTING - "SOTPMS"

MAIN

```
C****   THIS PROGRAM IS WRITTEN IN FORTRAN AND SIMULATES PERFORMANCE
C        CHARACTERISTICS OF THE ORBITER AC POWER SYSTEM DURING TWO PHASE
C        STARTING OF INDUCTION MOTORS.
C***    THE ORBITER AC SYSTEM IS SIMULATED AND INCLUDES MOTOR AND NON-
C        MOTOR TYPE LOADS. THE NON MOTOR LOADS ARE BALANCED, UNITY POWER
C        FACTOR LOADS. THE MOTOR LOADS ARE REPRESENTED BY A COMPOSITE
C        EQUIVALENT CIRCUIT. THE EQUIVALENT CIRCUIT PARAMETERS ARE
C        CALCULATED BY THE COMPUTER BASED ON TOTAL CONNECTED HORSEPOWER.
C***    THE ANALYTICAL METHOD USED IS COMMONLY REFERRED TO AS THE "METHOD
C        OF SYMMETRICAL COMPONENTS." BRIEFLY THIS METHOD TRANSFORMS THE
C        PHASE QUANTITIES FROM THE "ABC" REFERENCE FRAME INTO A "ZPN"
C        REFERENCE FRAME (ZERO, POSITIVE, AND NEGATIVE SEQUENCE).
C        CALCULATIONS ARE MADE WHILE IN THE "ZPN" REFERENCE FRAME AND
C        THEN TRANSFORMED BACK INTO THE "ABC" REF. FRAME.
C****   DEFINITIONS*****************************************************
C        R1,R2,X1,X2,XM - COMPOSITE EQUIVALENT CIRCUIT PARAMETERS OF THE
C         MOTORS OPERATING PRIOR TO STARTING THE TEST MOTOR IN PU PER PH.
C        ZZ=RZ+JXZ - COMPOSITE ZERO SEQUENCE IMPEDANCE IN PU PER PHASE.
C        R1T,R2T,X1T,X2T,XMT,ZZT,RZT,XZT - TEST MOTOR PARAMETERS.
C        BASE VOLT-AMPERES=750-VA (SINGLE PHASE INVERTER RATING)
C        BASE CURRENT=6.25 AMPS; BASE IMPEDANCE=19.2 OHMS
C        CHP - SUM TOTAL OF ALL MOTORS OPERATING PRIOR TO STARTING THE
C         TEST MOTOR. THIS IS A REQUIRED INPUT AND AND IS EXPRESSED IN HP
C        HPT - HORSEPOWER OF TEST MOTOR.
C        VAC - SUM TOTAL OF ALL NON-MOTOR LOADS CONNECTED TO THE BUS
C         (EXPRESSED IN VOLT-AMPERES PER PHASE). VAC IS ALSO AN INPUT.
C        S - SLIP OF OPERATING MOTORS.
C        ST - SLIP OF TEST MOTOR. THIS IS A REQUIRED INPUT.
C        A - COMPLEX OPERATOR = COS(120)+JSIN(120)
C        AA - COMPLEX OPERATOR = COS(240)+JSIN(240)
C        Z1 - COMPLEX IMPEDANCE OF MOTOR STATOR WINDING = R1+JX1 (SAME
C         FOR POSITIVE AND NEGATIVE SEQUENCE)
C        Z2P - POSITIVE SEQUENCE IMPEDANCE OF ROTOR WHICH IS A FUNCTION
C         OF SLIP.
C        Z2N - NEGATIVE SEQUENCE IMPEDANCE OF ROTOR WHICH IS A FUNCTION
C         OF SLIP.
C        ZP=RP+JXP; ZN=RN+JXN - POSITIVE AND NEGATIVE SEQUENCE IMPEDANCES
C         OF MOTOR. BOTH ARE FUNCTIONS OF SLIP.
C        ZZ=RZ+JXZ - ZERO SEQUENCE IMPEDANCE OF MOTOR.
C**     NOTE: THE SUBSCRIPT "T" IS ADDED TO THE ABOVE IMPEDANCE NOTAITONS
C        TO INDICATE TEST MOTOR PARAMETERS.
C        ZL=R+J0 - IMPEDANCE OF NON-MOTOR LOADS.
C        CIPL,CINL,CIZL - POSITIVE, NEGATIVE, AND ZERO SEQUENCE CURRENTS
C         IN NON-MOTOR LOAD.
C        CIPM,CINM,CIZM - PNZ CURRENTS IN MOTOR.
C        CIP,CIN,CIZ - PNZ CURRENTS FROM SOURCE.
C        ZPS,ZNS,ZZS - TOTAL SYSTEM IMPEDANCES IN PNZ REF. FRAME.
C        EAP - PHASE A POSITIVE SEQUENCE VOLTAGE.
C        VP,VN,VZ - PNZ FAULT VOLTAGE ACROSS SERIES FAULT.
C        EAAP,EBBP,ECCP - ABC VOLTAGES ACROSS SERIES FAULT.
C**     NOTE: THE ADDITION OF THE SUBSCRIPT "E" INDICATES THAT THE
C         PARAMETER REPRESENTS THE EQUIVALENT VALUE FOR ALL MOTORS
C         INCLUDING THE TEST MOTOR.
C***    OPERATION:
```

ORIGINAL PAGE IS
OF POOR QUALITY

```
C        IN RUNNING THE PROGRAM, VALUES FOR VAC,CHP,HPT,ST MUST BE INPUT
C         AS DATA. SEE FOLLOWING FORMAT STATEMENTS. ALSO THE TOTAL NUMBER
C         OF TEST POINTS FOR EACH PARAMETER MUST BE INPUTTED.
C**     DEFINITIONS CONT:
C        CIA,CIB,CIC - ABC CURRENTS FROM SOURCE.
C        CIAM,CIBM,CICM - ABC CURRENTS INTO OPERATING MOTORS.
C        CIAL,CIBL,CICL - ABC CURRENTS INTO NON-MOTOR LOADS.
C        VA,VB,VC - ABC APPLIED VOLTAGES (PHASE TO NEUTRAL).
C        VAM,VBM,VCM - ABC PHASE VOLTAGES ACROSS MOTOR AND LOAD TERMINALS
C        NST - COUNTER OF NUMBER OF SLIP POINTS (REQUIRED INPUT)
C        NCHP - COUNTER OF NUMBER OF HORSEPOWER VALVES (REQUIRED INPUT)
C        NVAC - COUNTER OF NUMBER OF LOAD VALUES (REQUIRED INPUT)
C***********************************************************************
        INTEGER LP,TTI,CDR,TTO
        COMPLEX A,AA,ZP,ZL,ZZ,ZN,ZM,CIPL,CINL,CIZL,CIPM,CINM,CIZM,CIP,
      + CIN,CIZ,EAP,VP,VN,VZ,EAAP,EBBP,ECCP,CIA,CIB,CIC,CIAM,CIBM,CICM,
      + CIAL,CIBL,CICL,VA,VB,VC,VAM,VBM,VCM,Z2PP,Z2NP,Z1,Z2P,Z2N,ZPS,ZNS,
      + ZZS,ZA,ZB,ZC
        COMPLEX Z1T,Z2PT,Z2NT,ZZT,ZMT,Z2PPT,Z2NPT,ZPT,ZNT,ZPE,ZNE,ZZE,
      + CIZME,CIPME,CINME,CIAME,CIBME,CICME,CIZMT,CIPMT,CINMT,CIAMT,
      + CIBMT,CICMT
        DIMENSION CHP(10),VAC(10),ST(10)
        LP=6
        CDR=5
C**     READ INPUT DATA
        READ(CDR,10)NST,NCHP,NVAC
        READ(CDR,20)(ST(I),I=1,NST)
        READ(CDR,20)(CHP(I),I=1,NCHP)
        READ(CDR,30)(VAC(I),I=1,NVAC)
 10     FORMAT(3I5)
 20     FORMAT(10F5.2)
 30     FORMAT(10F7.2)
 32     FORMAT(F5.2)
        READ(CDR,32)HPT
 40     FORMAT(1H1,5X,'TWO PHASE STARTING OF ORBITER INDUCTION MOTORS'/)
        WRITE(LP,40)
 50     FORMAT(1H0,5X,'SLIP PTS.=',I2,5X,'CHP PTS.=',I2,5X,'VAC PTS.=',
      + I2)
        WRITE(LP,50)NST,NCHP,NVAC
 52     FORMAT(1H0,5X,'HP OF TEST MOTOR=',F5.2)
        WRITE(LP,52)HPT
 70     FORMAT(1H0,5X,'VALUES OF SLIP (ST) ARE:'/)
        WRITE(LP,70)
 80     FORMAT(1H ,5X,10F6.2)
        WRITE(LP,80)(ST(I),I=1,NST)
 90     FORMAT(1H0,5X,'VALUES OF CONNECTED HORSEPOWER ARE:'/)
        WRITE(LP,90)
        WRITE(LP,80)(CHP(I),I=1,NCHP)
 110    FORMAT(1H0,5X,'VALUES OF CONNECTED LOAD ARE:'/)
        WRITE(LP,110)
 82     FORMAT(1H ,5X,10F8.2)
        WRITE(LP,82)(VAC(I),I=1,NVAC)
C***    BEGIN CALCULATIONS
 130    FORMAT(1H0,5X,'PARAMETERS OF INTEREST ARE AS FOLLOWS:'/)
```

```
              WRITE(LP,130)
        140   FORMAT(1H0,10X,'COMPLEX',7X,'COMPLEX',7X,'COMPLEX',7X,'COMPLEX',
             +7X,'COMPLEX')
        150   FORMAT(1H ,10X,'SYSTEM',9X,'MOTOR',6X,'TEST MOTOR',6X,'MOTOR HTR
             +M.',4X,'LOAD')
        160   FORMAT(1H ,10X,'CURRENTS',6X,'CURRENTS',6X,'CURRENTS',6X,'VOLTAGE
             +',7X,'CURRENTS')
        170   FORMAT(1H ,12X,'(PU)',10X,'(PU)',10X,'(PU)',10X,'(PU)',10X,'(PU)
             +')
              WRITE(LP,140)
              WRITE(LP,150)
              WRITE(LP,160)
              WRITE(LP,170)
              S=.06
              PI=3.14159
              A=CMPLX(COS(2.*PI/3.),SIN(2.*PI/3.))
              AA=CMPLX(COS(4.*PI/3.),SIN(4.*PI/3.))
              VA=CMPLX(1.,0.)
              VB=CMPLX(-.5,-.866)
              VC=CMPLX(-.5,.866)
              EAP=VA
              DO 500 K=1,NVAC
              DO 500 J=1,NCHP
              DO 500 I=1,NST
              R1T=.097*(.75/HPT)
              X1T=.256*(.75/HPT)
              X2T=X1T
              R2T=.174*(.75/HPT)
              XMT=2.605*(.75/HPT)
              RZT=.165*(.75/HPT)
              XZT=.168*(.75/HPT)
              Z1T=CMPLX(R1T,X1T)
              R2PT=R2T/ST(I)
              Z2PT=CMPLX(R2PT,X2T)
              R2NT=.174*((.75/HPT)/(2-ST(I)))
              Z2NT=CMPLX(R2NT,X2T)
              ZZT=CMPLX(RZT,XZT)
              ZMT=CMPLX(0.,XMT)
        C*    BEGIN REDUCTION OF TEST MOTOR EQ. CKT.
              Z2PPT=ZMT*Z2PT/(ZMT+Z2PT)
              Z2NPT=ZMT*Z2NT/(ZMT+Z2NT)
              ZPT=Z1T+Z2PPT
              ZNT=Z1T+Z2NPT
              R1=.097*(.75/CHP(J))
              X1=.256*(.75/CHP(J))
              X2=X1
              R2=.174*(.75/CHP(J))
              XM=2.605*(.75/CHP(J))
              RZ=.165*(.75/CHP(J))
              XZ=.168*(.75/CHP(J))
              Z1=CMPLX(R1,X1)
              R2P=R2/S
              Z2P=CMPLX(R2P,X2)
              R2N=.174*((.75/CHP(J))/(2-S))
```

```
                  Z2N=CMPLX(R2N,X2)
                  ZZ=CMPLX(RZ,XZ)
                  ZM=CMPLX(0.,XM)
                  R=750./VAC(K)
                  ZL=CMPLX(R,0.)
            C*    BEGIN REDUCTION OF COMPOSITE MOTOR EQ. CKT.
                  Z2PP=ZM*Z2P/(ZM+Z2P)
                  Z2NP=ZM*Z2N/(ZM+Z2N)
                  ZP=Z1+Z2PP
                  ZN=Z1+Z2NP
            C*    BEGIN COMPUTATION OF THE PARALLEL COMBINATION OF TEST MOTOR AND
            C      OTHER MOTORS.THE SUBSCRIPT "E" WILL BE USED TO INDICATE EQ. IMP.
                  ZPE=ZPT*ZP/(ZPT+ZP)
                  ZNE=ZNT*ZN/(ZNT+ZN)
                  ZZE=ZZT*ZZ/(ZZT+ZZ)
            C*    BEGIN COMPUTATION OF THE COMBINED SYSTEM IMPEDANCE.
                  ZPS=ZL*ZPE/(ZL+ZPE)
                  ZNS=ZL*ZNE/(ZL+ZNE)
                  ZZS=ZL*ZZE/(ZL+ZZE)
            C**   BEGIN COMPUTATION OF POSITIVE, NEGATIVE, AND ZERO SEQUENCE
            C      CURRENTS (CIP, CIN, CIZ) FOR THE INTERCONNECTED SYSTEM.
                  CIP=(EAP*(ZNS+ZZS)/((ZPS*ZNS)+(ZPS*ZZS)+(ZNS*ZZS)))
                  CIN=-(EAP*ZZS)/((ZPS*ZNS)+(ZPS*ZZS)+(ZNS*ZZS))
                  CIZ=-(EAP*ZNS)/((ZPS*ZNS)+(ZPS*ZZS)+(ZNS*ZZS))
            C*    BEGIN COMPUTATION OF FAULT VOLTAGES IN THE ZPN REF. FRAME.
                  VP=EAP-(CIP*ZPS)
                  VN=-(CIN*ZNS)
                  VZ=-(CIZ*ZZS)
            C*    BEGIN COMPUTATION OF THE VOLTAGE DROP ACROSS THE FAULT IN THE
            C      ABC REF. FRAME USING THE TRANSFORMATION.
                  EAAP=VP+VZ+VN
                  EBBP=VZ+AA*VP+A*VN
                  ECCP=VZ+A*VP+AA*VN
            C*    BEGIN COMPUTATION OF SYSTEM CURRENTS IN THE ABC REF. FRAME.
                  CIA=CIZ+CIP+CIN
                  CIB=CIZ+AA*CIP+A*CIN
                  CIC=CIZ+A*CIP+AA*CIN
            C*    BEGIN COMPUTATION OF TOTAL MOTOR CURRENTS IN THE ZPN REF. FRAME.
                  CIZME=CIZ*ZL/(ZZE+ZL)
                  CIPME=CIP*ZL/(ZPE+ZL)
                  CINME=CIN*ZL/(ZNE+ZL)
            C*    COMPUTE TOTAL MOTOR CURRENT IN THE ABC REF. FRAME.
                  CIAME=CIZME+CIPME+CINME
                  CIBME=CIZME+AA*CIPME+A*CINME
                  CICME=CIZME+A*CIPME+AA*CINME
            C*    COMPUTE CURRENT TO RESISTIVE LOAD (ABC).
                  CIAL=CIA-CIAME
                  CIBL=CIB-CIBME
                  CICL=CIC-CICME
            C*    COMPUTE PHASE VOLTAGE ON MOTOR AND LOAD TERMINALS.
                  VAM=VA-EAAP
                  VBM=VB-EBBP
                  VCM=VC-ECCP
            C*    COMPUTE STARTING CURRENT OF TEST MOTOR.
```

```
                  CIZMT=CIZME*ZZ/(ZZ+ZZT)
                  CIPMT=CIPME*ZP/(ZP+ZPT)
                  CINMT=CINME*ZN/(ZN+ZNT)
                  CIAMT=CIZMT+CIPMT+CINMT
                  CIBMT=CIZMT+AA*CIPMT+A*CINMT
                  CICMT=CIZMT+A*CIPMT+AA*CINMT
            C*    COMPUTE OPERATING MOTOR CURRENT.
                  CIAM=CIAMF-CIAMT
                  CIBM=CIBMF-CIBMT
                  CICM=CICMF-CICMT
            C***  THIS COMPLETES COMPUTATION OF VOLTAGES AND CURRENTS. PARAMETERS
            C      OF INTEREST WILL NOW BE PRINTED.
             410  FORMAT(1H ,1X,'CHP=',F4.2)
             404  FORMAT(1H ,1X,'ST=',F4.2)
                  WRITE(LP,404)ST(I)
                  WRITE(LP,410)CHP(J)
             420  FORMAT(1H ,1X,'VAC=',F6.2)
                  WRITE(LP,420)VAC(K)
             430  FORMAT(1H ,2X,'PH A',2X,2F6.3,2X,2F6.3,2X,2F6.3,3X,2F6.3,3X,
                 +2F6.3)
                  WRITE(LP,430)CIA,CIAM,CIAMT,VAM,CIAL
             440  FORMAT(1H ,2X,'PH B',2X,2F6.3,2X,2F6.3,2X,2F6.3,3X,2F6.3,3X
                 +2F6.3)
                  WRITE(LP,440)CIB,CIBM,CIBMT,VBM,CIBL
             450  FORMAT(1H ,2X,'PH C',2X,2F6.3,2X,2F6.3,2X,2F6.3,3X,2F6.3,3X
                 +2F6.3)
                  WRITE(LP,450)CIC,CICM,CICMT,VCM,CICL
            C*    CLOSE DO LOOP
             500  CONTINUE
                 END
```