A STUDY OF VOLTAGE FLICKER CAUSED BY ELECTRIC ARC FURNACES

by 6408

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INTRODUCTION

In the past twenty years, the capacity of electric arc furnaces has increased from 20 MVA to 80 MVA and even 100 MVA furnaces are under consideration.[1,2] The advantages of the arc furnaces are not entirely cost; the high heat concentration combined with quick regulation, metallurgical flexibility, contamination free melting and refining, inherent nature which can remove sulfur and phosphorus (eliminating the expense of buying premium grade of scrap) as well as easy starting and shut down, makes the electric arc furnace one of the most effective production tools in the steel industry.

As a power company looks at the electric arc furnace, the arc furnace represents a large increment of load, good revenue, high load factor (above 60%)[3] and concentrated service area. However, with accompanying flicker voltage, such a load may affect other electricity users which is of paramount concern to an electric utility company. In lighting, flicker is annoying; in television, objectionable from the critical user's viewpoint, and in certain technical or utilization processes it may even disrupt production.

The agony for the utility is that there is no criterion of how much arc furnace capacity a utility company should supply. Usually, the higher the short circuit capacity, the larger the furnace that may be served.[4]

CAUSE OF FLICKER

A. Arc Furnace Principle

The general construction features of an arc furnace as manufactured in this country vary, of course, with size and with the different manufacturers. The shell of a typical furnace consists of a steel plate construction with a refractory lining and is usually circular in cross-section. The hearth is a

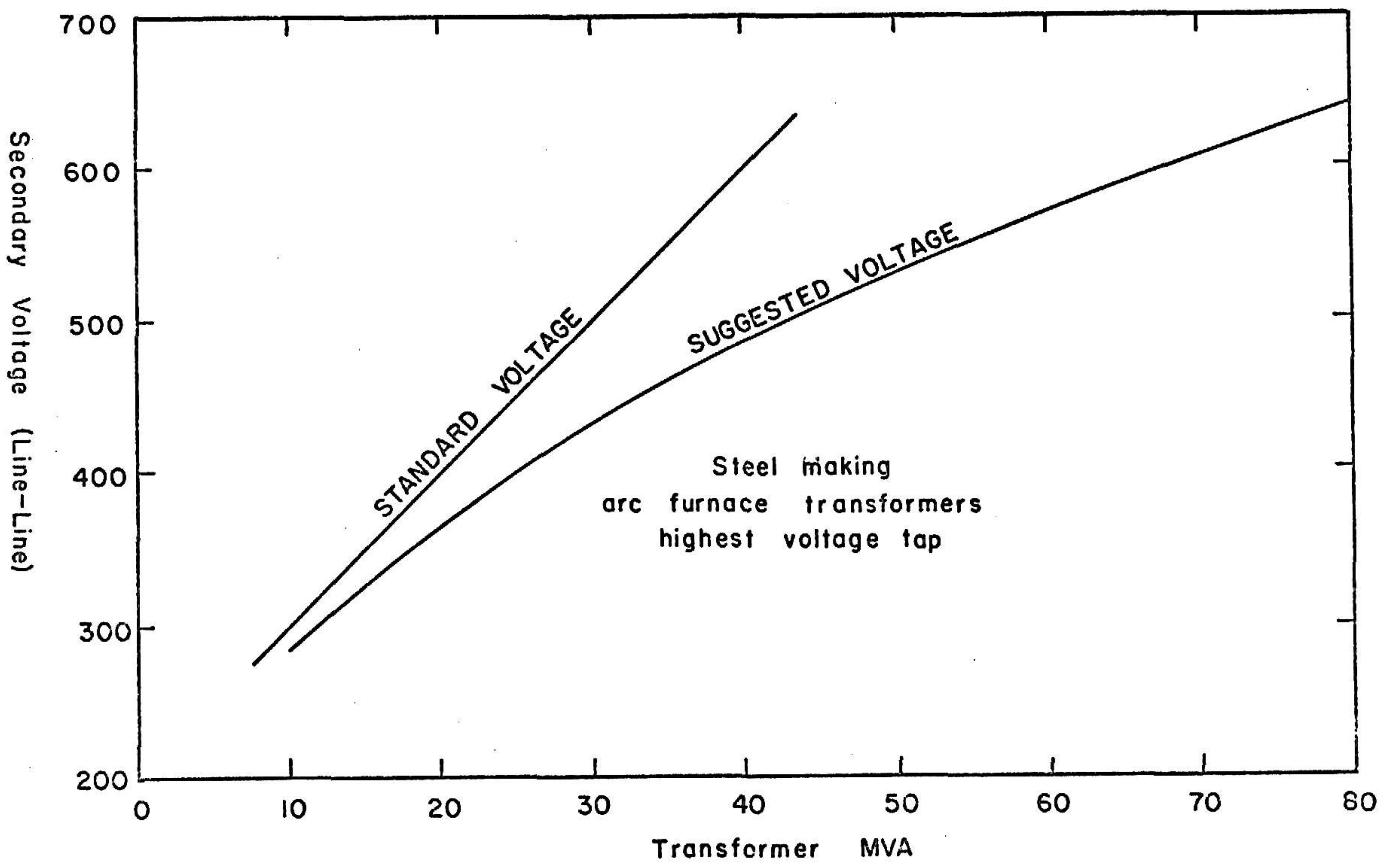


FIG. 1 ARC FURNACE TRANSFORMERS HIGHEST VOLTAGE TAP
IEEE-NEMA STANDARD AND INDUSTRY SUGGESTED

shallow bowl formed in the refractory lining of the bottom. The lining may be of acid or basic refractories. Suitable doors for charging the metal to be melted and a pouring spout for discharging the finished metal are provided. The roof is a removable member, made as a separate part of convenience in refilling and also in some cases to provide for overhead mechanical charging. In the roof are three equidistant opennings through which the vertical carbon or graphite electrodes can travel. The electrodes are manipulated by winches operated by motors with reversing control.

The methods of stating the size of a three-phase arc furnace is to rate the furnace in terms of the holding capacity in tons of molten metal or by the capacity of furnace transformer in MVA.

The method of operating an arc furnace so far as the charging of cold scrap is concerned, varies with the kind and degree of subdivision of the scrap. For instance, the weight of cold scrap in the form of roll turnings that can be charged in a furnace initially will rarely be enough to form the weight of molten metal desired, so that additional quantities can be added as the metal in the furnace becomes molten. This practice affects adversely both the energy consumption of KWH per ton and consumption of electrodes.

The open circuit voltage of three-phase arc furnaces varies with the capacity of the furnaces (Fig. 1).[5]

For arc furnace applications, transformers of special design are required. The secondary coil construction involves large heavy coils, requiring special bracing of the winding to meet the mechanical strength required with large variations of secondary current. Because of the magnitude of current required, multiple secondary coil terminals are brought out through the transformer tank cover.

Since a certain degree of flexibility of secondary voltage is desirable the general method of changing secondary voltage delivered to the furnace is by use of suitable tap in the primary winding.

B. Types of Flicker

Essentially, the furnace operation may be considered as a random occurrence of phase to phase short circuits, with the load swings causing corresponding voltage fluctuations. Three types of load swings may be generated by large arc furnaces, causing corresponding voltage swings.[6,7]

1. Cyclic

Single phase swings occur at a rate of 2-8 per second, and at a magnitude of roughly 40-50% of furnace rating, with the power factor of the swings at about 60%, well below normal furnace power factor. This flicker results from arc excursions in the molten metal and is most severe just after a charge of scrap.

2. Very Frequent

Single phase swings at a rate of no more than once per second, and at a magnitude of about 60-80% furnace rating. Power factor is about 60%. This flicker occurs in the initial melt-down period and just after a charge of scrap.

3. Gradual

Three phase power swings, lasting several seconds and having a magnitude equal to (or greater than) the furnace rating. Power factor may be as low as 50%. The character of such swings will depend on the sensitivity of the current control devices on a particular furnace.

C. Limitation of Flicker

After the study of the mechanism of the load swings in electric arc furnaces, the question arises as to what happens to the performance of such sensitive devices as light bulbs when their operating voltage is fluctuating.

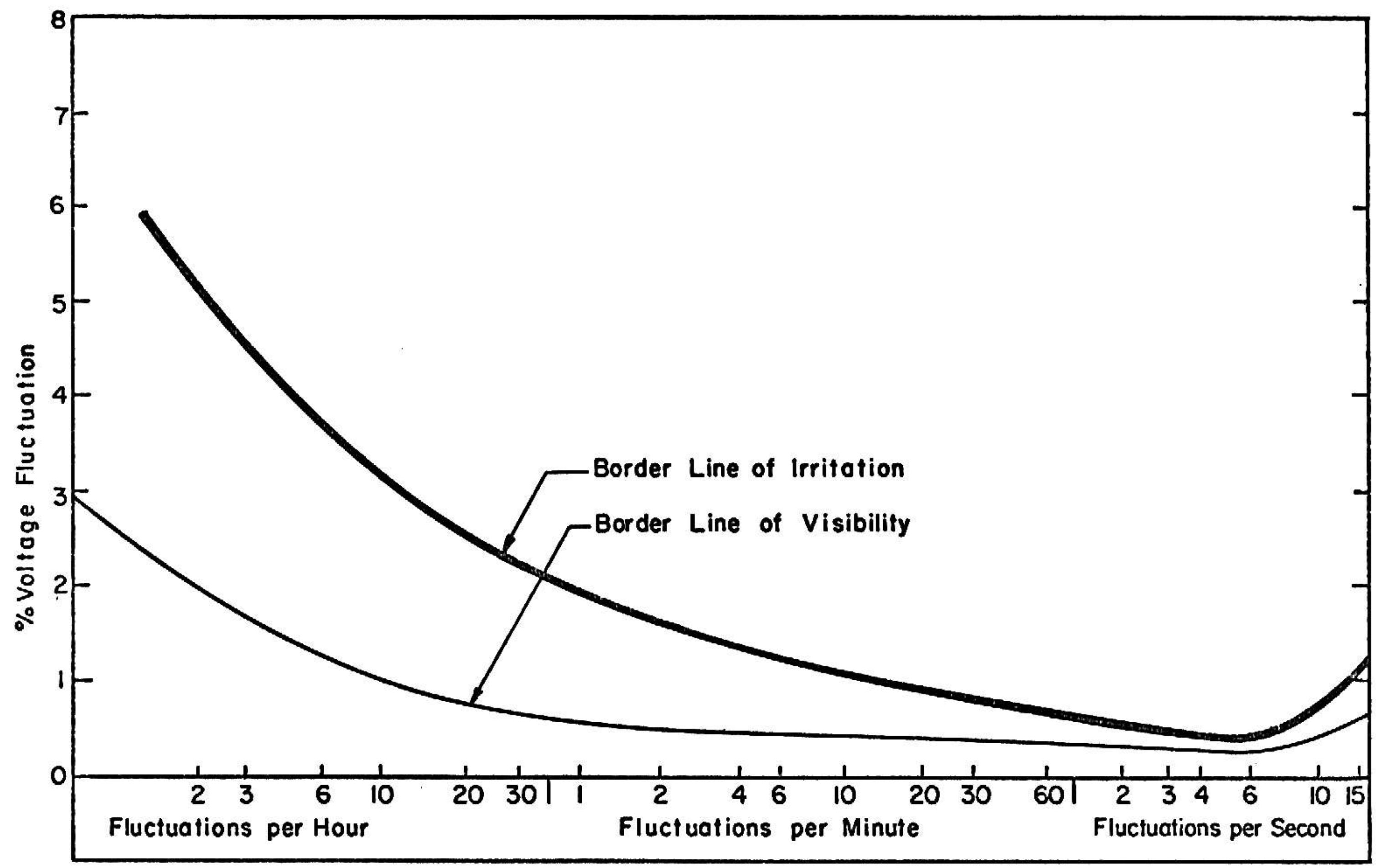


FIG. 2 RELATIONS OF VOLTAGE FLUCTUATIONS TO FREQUENCY OF THEIR OCCURRENCE (INCANDESCENT LAMPS)

The emission of visible light from the filament of a light bulb is a function of the power which in turn depends on the operating voltage. A drop of the line voltage from 100 to 99 per cent results in a decrease of approximately 3.4 per cent of the visible light emission after the filament has adjusted itself to the lower power level.[8]

It is obvious that the thermal inertia given by the diameter of the filament determines the speed of reaction. Small bulbs of the 15 or 25 watt type react much faster than 75 or 100 watt bulbs with their heavier filament. As for fluorescent light bulbs, the light output follows line voltage variation almost instantaneously.[8]

The problem of lighting flicker, however, cannot be entirely attributed to the light bulb. The human element enters the picture in a variety of factors including perceptibility, speed of reaction, irritation, etc. Contrary to physical conditions, these factors vary over a wide range and cannot be easily pinned down in figures and formulae. They require a statistical approach. Customer reaction to the flicker may vary, not only among utilities, but in different types of service territory served by one company. Customers have had differing experiences with electric service. Supposedly, the rural areas are more tolerant, but again, effects on television reception in fringe areas may counteract this tendency.

Based on the above facts, many flicker curves have been proposed to show permissible voltage fluctuation as a function of occurrence frequency.[6,9,10] The most widely adopted curve is shown on Fig. 2.

CALCULATION OF VOLTAGE FLICKER

A. Symmetrical Component Analysis of Electric Arc Furnace.[11,13]

An equivalent circuit for a three phase arc furnace could be present

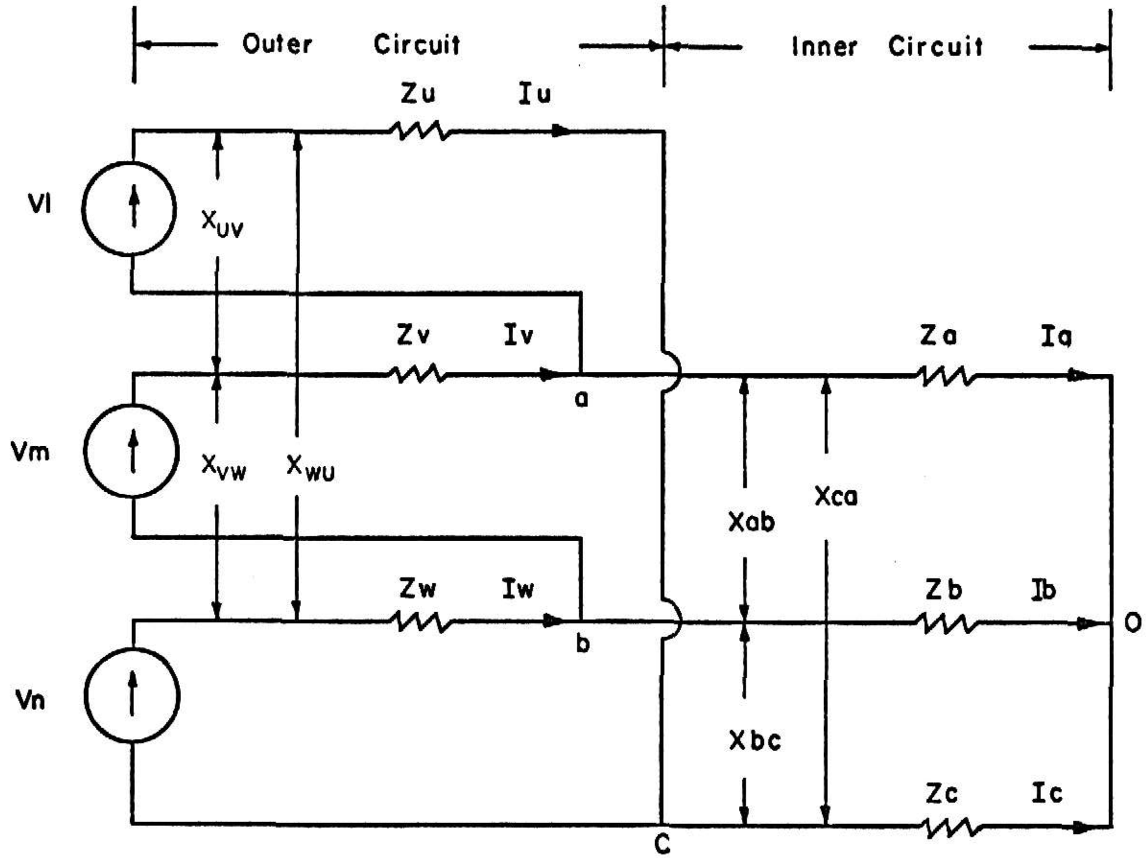


FIG. 3 SIMPLIFIED CIRCUIT FOR UNBALANCED ELECTRIC ARC FURNACE

as Fig. 3. The X_{uv}, X_{ab}, etc., denotes the mutual reactance between the u and v phases, the a and b phases, etc.

Taking the circuit constants, voltages and currents as shown in Fig. 3, the following five equations may be set up from Kirchhoff's laws:

$$I_a + I_b + I_c = 0 \tag{1}$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} Z_a & X_{ab} & X_{ca} \\ X_{ab} & Z_b & X_{bc} \\ X_{ca} & X_{bc} & Z_c \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} -1 & 1 & 0 \\ 0 & -1 & 1 \\ 1 & 0 & -1 \end{bmatrix} \begin{bmatrix} I_u \\ I_v \\ I_w \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} V_u \\ V_v \\ V_w \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} + \begin{bmatrix} Z_u & X_{uv} & X_{wu} \\ X_{uv} & Z_v & X_{vw} \\ X_{wu} & X_{vw} & Z_w \end{bmatrix} \begin{bmatrix} I_u \\ I_v \\ I_w \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} V_l \\ V_m \\ V_n \end{bmatrix} = \begin{bmatrix} V_u \\ V_v \\ V_w \end{bmatrix} - \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{5}$$

Solving these equations simultaneously for V_l, V_m, and V_n, one obtains

$$\begin{bmatrix} V_l \\ V_m \\ V_n \end{bmatrix} = \begin{bmatrix} -Z_a + X_{ca} - (Z_u - X_{uv})/3, & -X_{ab} + X_{bc} - (X_{uv} - X_{wu})/3, & -X_{ca} + Z_c + (Z_u - X_{wu})/3 \\ Z_a - X_{ab} - (X_{uv} - Z_v)/3, & X_{ab} - Z_b - (Z_v - X_{vw})/3, & X_{ca} + X_{bc} + (X_{uv} - X_{vw})/3 \\ X_{ab} - X_{ca} - (X_{wu} - X_{vu})/3, & Z_b - X_{bc} - (X_{vw} - Z_w)/3, & X_{bc} - Z_c + (X_{wu} - Z_w)/3 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} Z_u & X_{uv} & X_{wu} \\ X_{uv} & Z_v & X_{vw} \\ X_{wu} & X_{vw} & Z_w \end{bmatrix} \begin{bmatrix} I_{u0} \\ I_{u0} \\ I_{u0} \end{bmatrix} \tag{6}$$

Where $I_{u0} = (I_u + I_v + I_w)/3$.

With $a = e^{j2\pi/3}$, substituting

$$\begin{bmatrix} V_l \\ V_m \\ V_n \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_{10} \\ V_{11} \\ V_{12} \end{bmatrix}$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix}$$

into (6) and simplifying yields

$$\begin{bmatrix} V_{10} \\ V_{11} \\ V_{12} \end{bmatrix} = \begin{bmatrix} 0 & (a-1)(Z_{u2}-aX_{uv2})/3, & (a^2-1)(Z_{u1}-a^2-a^2X_{uv1})/3 \\ (a-1)(Z_{a1}-a^2X_{ab1}), & (a-1)\{Z_{a0}-X_{ab0}+(Z_{u0}-X_{uv0})/3\}, & (a^2-1)\{-aZ_{a2}-2a^2X_{ab2}+(Z_{u2}+2aX_{uv2})/3\} \\ (a^2-1)(Z_{a2}-aX_{ab2}), & (a-1)\{-a^2Z_{a1}-2aX_{ab1}+(Z_{u1}+2a^2X_{uv1})/3\}, & (a^2-1)\{Z_{a0}-X_{ab0}+(Z_{u0}-X_{uv0})/3\} \end{bmatrix} \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} + \begin{bmatrix} Z_u & X_{uv} & X_{wu} \\ X_{uv} & Z_v & X_{vw} \\ X_{wu} & X_{vw} & Z_w \end{bmatrix} \begin{bmatrix} I_{u0} \\ I_{u0} \\ I_{u0} \end{bmatrix} \quad (7)$$

Where

$$\begin{bmatrix} Z_{u0} \\ Z_{u1} \\ Z_{u2} \end{bmatrix} = 1/3 \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} Z_u \\ Z_v \\ Z_w \end{bmatrix},$$

$$\begin{bmatrix} Z_{a0} \\ Z_{a1} \\ Z_{a2} \end{bmatrix} = 1/3 \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} Z_a \\ Z_b \\ Z_c \end{bmatrix},$$

$$\begin{bmatrix} X_{uv0} \\ X_{uv1} \\ X_{uv2} \end{bmatrix} = 1/3 \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} X_{uv} \\ X_{vw} \\ X_{wu} \end{bmatrix},$$

$$\begin{bmatrix} X_{ab0} \\ X_{ab1} \\ X_{ab2} \end{bmatrix} = 1/3 \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} X_{ab} \\ X_{bc} \\ X_{ca} \end{bmatrix}.$$

Moreover, since $I_{a0} = (I_a + I_b + I_c)/3 = 0$, Eq. (7) becomes

$$\begin{bmatrix} V_{10} \\ V_{11} \\ V_{12} \end{bmatrix} = \begin{bmatrix} Z_{u0} + 2X_{uv0}, & (a-1)(Z_{u2}-aX_{uv2})/3, & (a^2-1)\ (Z_{u1}-a^2X_{uv1})/3 \\ Z_{u1} - a^2X_{uv1}, & (a-1)\{Z_{a0}-X_{ab0}+(Z_{u0}-X_{uv0})/3\}, & (a^2-1)\{-aZ_{a2}-2a^2X_{ab2}+(Z_{u2}+2aX_{uv2})/3\} \\ Z_{u2} - aX_{uv2}, & (a-1)\{-a^2Z_{a1}-2aX_{ab1}+(Z_{u1}+2a^2X_{uv1})/3\}, & (a^2-1)\{Z_{a0}-X_{ab0}+(Z_{u0}-X_{uv0})/3\} \end{bmatrix} \begin{bmatrix} I_{u0} \\ I_{a1} \\ I_{a2} \end{bmatrix} \quad (8)$$

To avoid needless complexity Eq. (8) may be abbreviated as

$$\begin{bmatrix} V_{10} \\ V_{11} \\ V_{12} \end{bmatrix} = \begin{bmatrix} A_0 & B_0 & C_0 \\ A_1 & B_1 & C_1 \\ A_2 & B_2 & C_2 \end{bmatrix} \begin{bmatrix} I_{u0} \\ I_{a1} \\ I_{a2} \end{bmatrix}$$

In a three phase balanced system, where zero sequence, negative sequence currents and mutual impedance elements do not exist, as shown in Fig. 4A,[12] the balanced electric arc furnace can be represented by simple diagram as Fig. 4B.

B. Computer Program for Flicker Calculation

For the study of the flicker problem, Mr. Bob Oltroggie of the

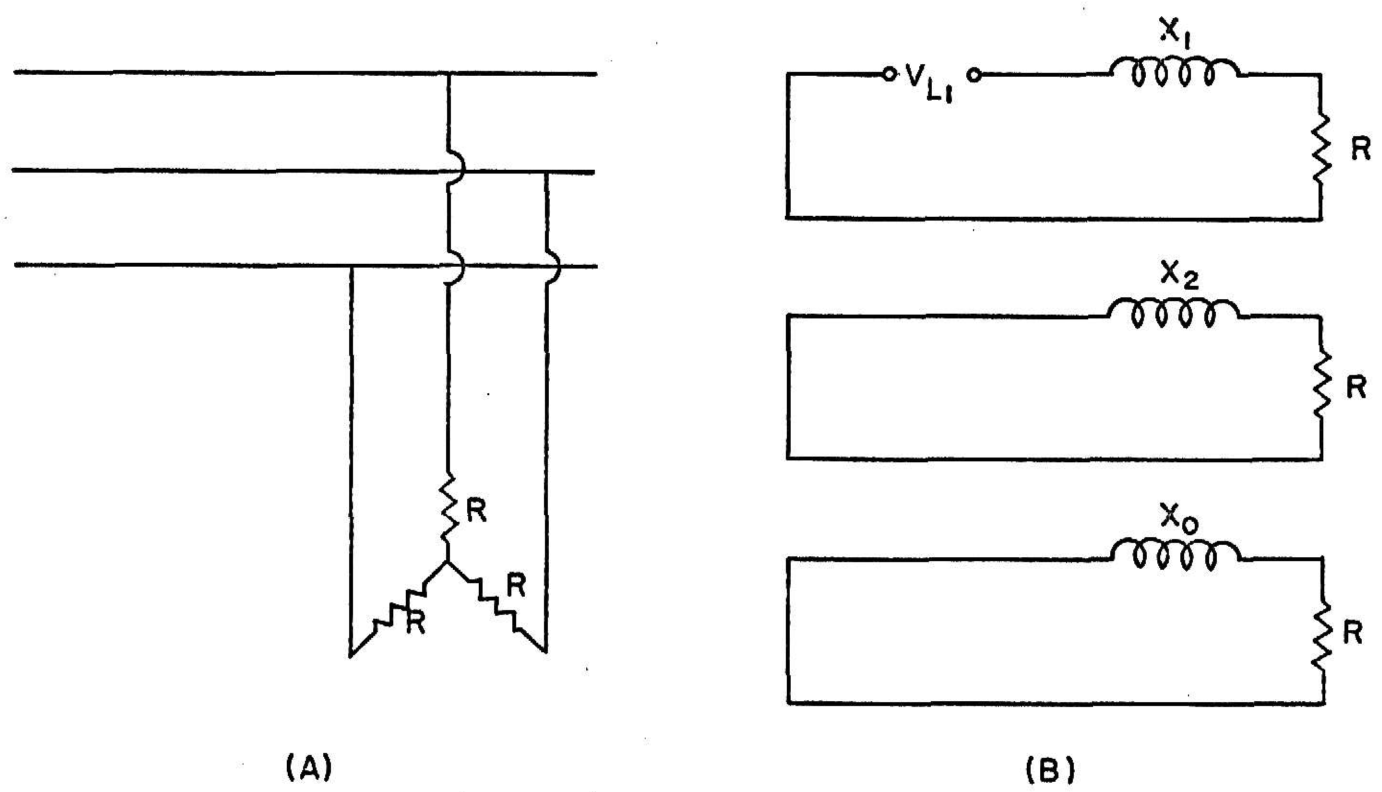


FIG. 4 POSITIVE, NEGATIVE AND ZERO SEQUENCE DIAGRAMS OF BALANCED THREE PHASE SHORT CIRCUIT

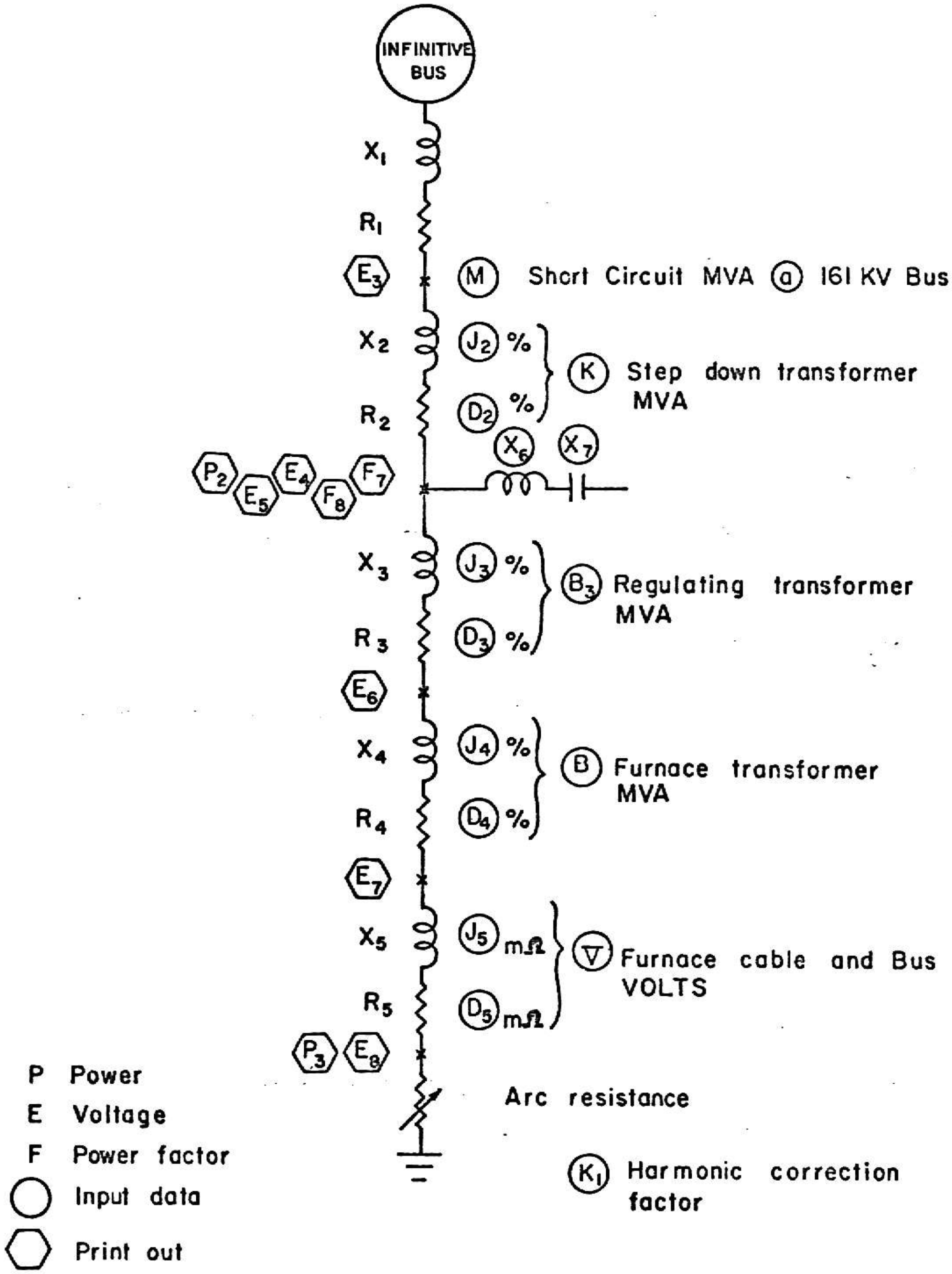


FIG. 5 EQUIVALENT CIRCUIT OF ARC FURNACE
FOR FLICKER PROGRAM

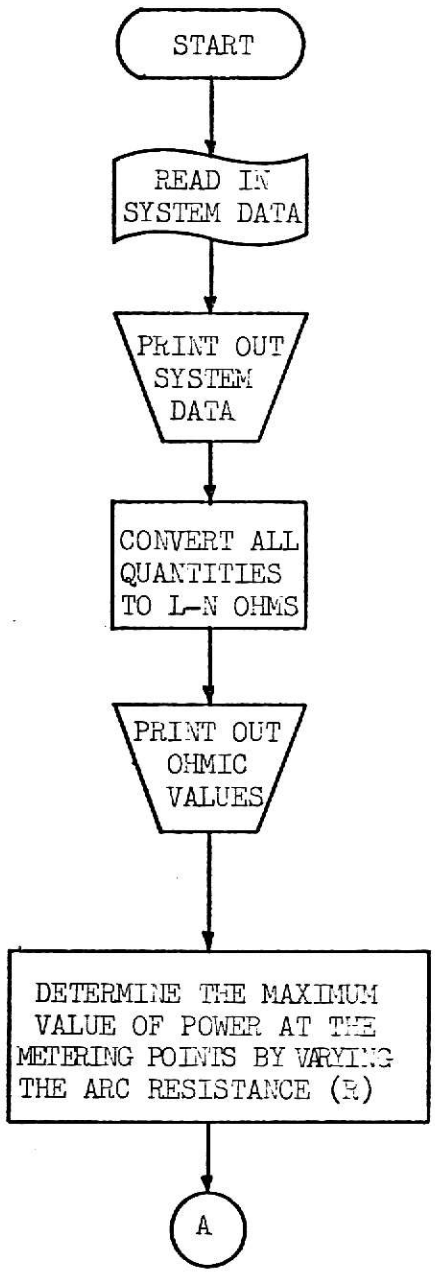


FIG. 6 FLOW DIAGRAM OF "FLICKR" PROGRAM

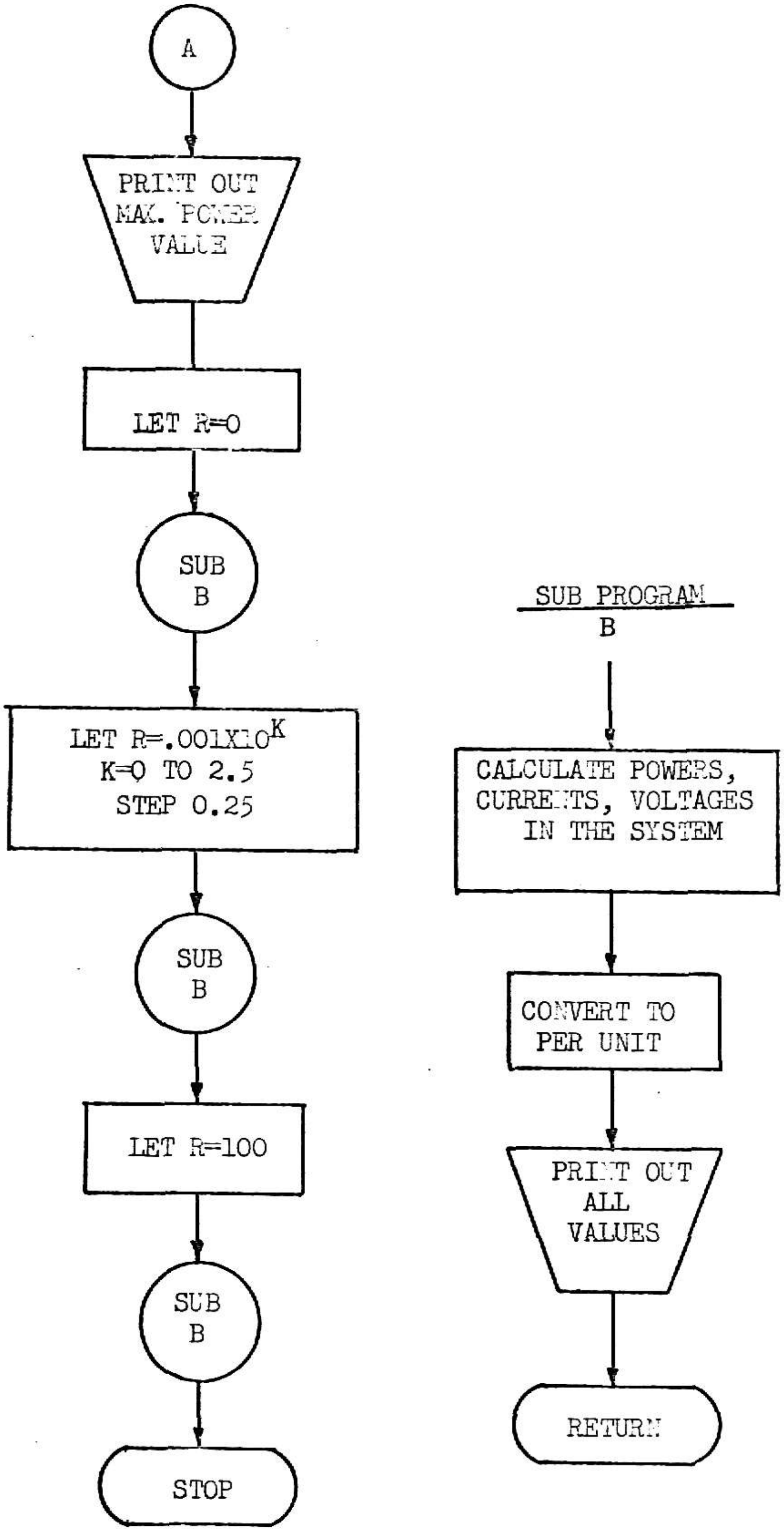


FIG. 7 FLOW DIAGRAM OF "FLICKR" PROGRAM

General Electric Company has written a program (appendix A) in BASIC using a G. E. 265 time sharing digital computer to calculate voltages and power factors at different metering positions of a furnace.

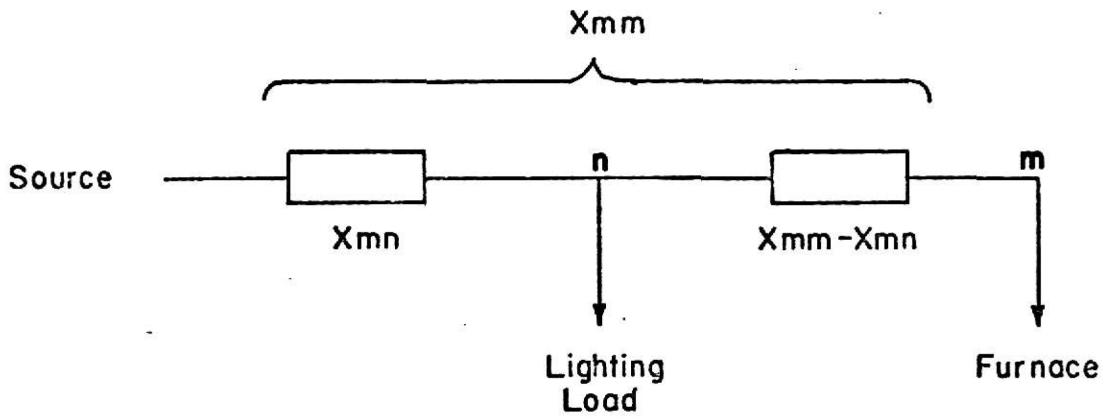
Fig. 5, 6, 7 present the equivalent circuit for the program and a brief explanation of the program which simulates the different operating conditions of an arc furnace by varying the arc resistance R.

VOLTAGE FLICKER OF MULTIPLE FURNACES

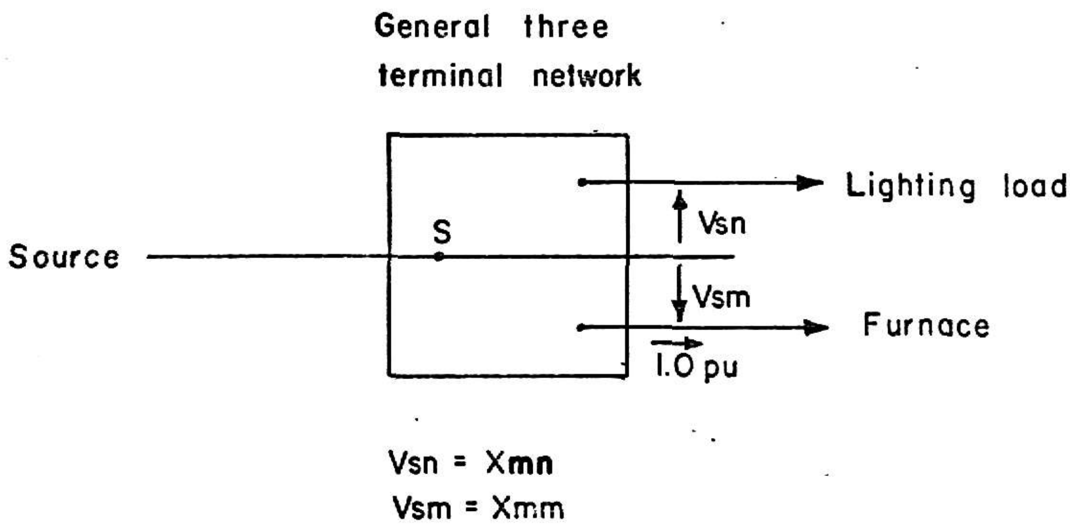
With two or more furnaces operating in parallel, the magnitude of the voltage fluctuations obviously is greater than with one furnace. It is also reasonable to assume that few fluctuations occur at the same instant in all furnaces (although that may happen on occasion). Generally, adding a second furnace which is substantially smaller than the first furnace will not appreciably increase the flicker.[15] The voltage swings are too irregular and difficult for the analyst to determine how much worse one condition is than another. Also, operating procedures of various plants vary.

Investigation has shown that the resultant rms voltage fluctuation is the square root of the sum of the squares of the individual rms voltages.[15,16] Moreover, when N furnaces of equal size are operated in parallel, the magnitude of the voltage fluctuation is the fluctuation produced by one furnace multiplied by a factor K_f, which is equal to $\sqrt{N}$. It is also found that the flicker level is reduced if one or more furnaces are in the refining cycle and that the fluctuation of a refining furnace can be considered about half that of a furnace in the melt-down cycle. Assuming, therefore, a mill with several equal sized furnaces, some of which are on the refining cycle, the multiplier becomes:

$$K_f = \sqrt{N + (0.25)N_r},$$



(A) Simple Radial Circuit



(B) General three terminal network.

FIG. 8 DEFINITION OF X_{mm} (SELF DROP CONSTANT)
AND X (MUTUAL DROP CONSTANT)

Where N is the number of furnaces on melt-down and N_r is the number of furnaces on the refining cycle.

The problem of flicker level of two or more furnaces of different sizes operating in parallel can be estimated with a similar routine:

$$K_f = \sqrt{N + F_1^2 + F_2^2 ----- F_n^2}$$

Where N is the number of largest furnaces of the same size and F is the per-unit MVA of smaller furnace sizes. For any furnace on the refining cycle, one-half the per-unit size should be used in this equation.

The AIEE Committee on System Engineering and Working Group on Arc Furnaces has recommended and approved the mutual drop constant (X_{mn}) as an index of the ability of a power system to supply arc furnaces without objectionable flicker by correlating many operating furnaces.[14]

Referring to the Fig. 8A, the furnace transformer bus is designed as m and the location of the closest lighting load as n. With 1.0 per-unit reactive current (based on the furnace transformer name-plate kva) drawn from the system at point m, X_{mn} is defined as the voltage drop from the generator equivalent internal voltage to the point n. The quantity X_{mm} is defined as the voltage to the point m, and this quantity is designated as the "self-drop constant." The quantity X_{mn} is the reciprocal of the short-circuit capacity at the furnace transformer bus. For the simple radial circuit in Fig. 8A, X_{mn} is the reciprocal of the short-circuit capacity at the lighting tap, but in more general networks, this is not the case. The determination of X_{mn} and X_{mm} for the general 3-terminal net work is shown in Fig. 8B.

The assumptions used by the working group for setting up the 3-terminal network for the various furnaces covered by the survey are as follows:

1. Voltage of generators and synchronous condensers are equal and in phase.

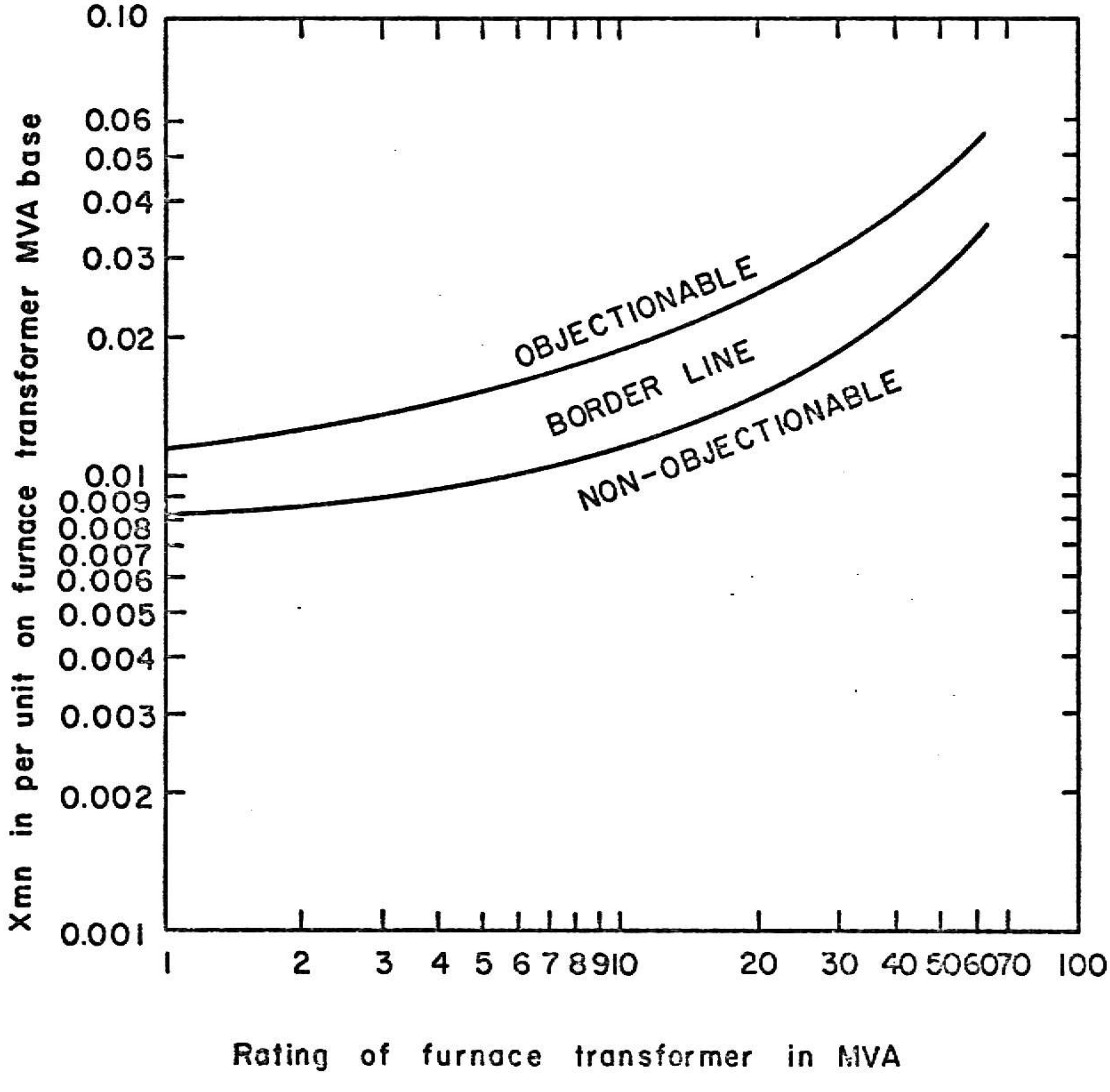


FIG. 9 ARC FURNACE FLICKER APPLICATION LIMITS
(SINGLE FURNACES INSTALLATION)

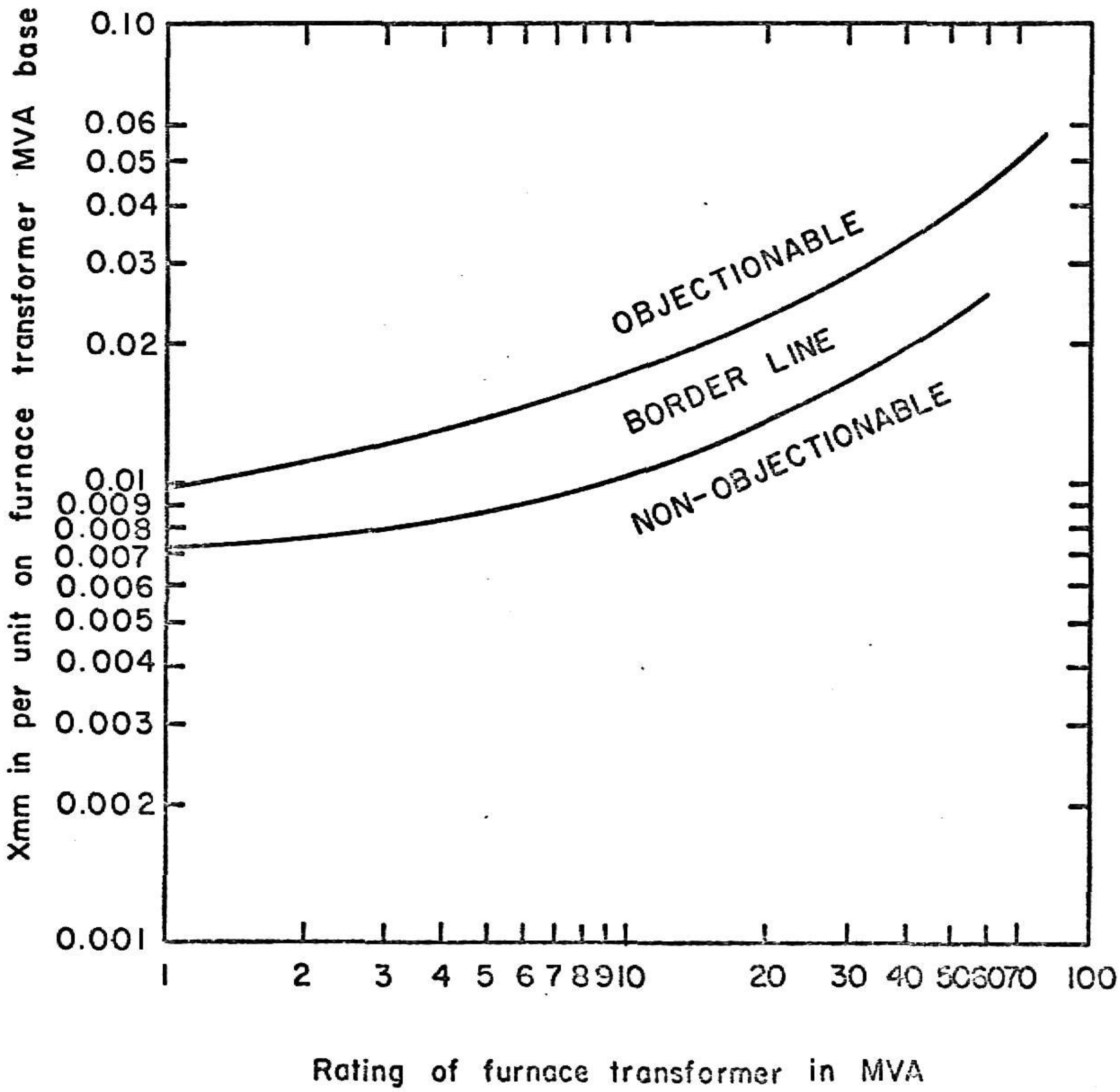


FIG. 10 ARC FURNACE FLICKER APPLICATION LIMITS
(TWO-FURNACE INSTALLATION)

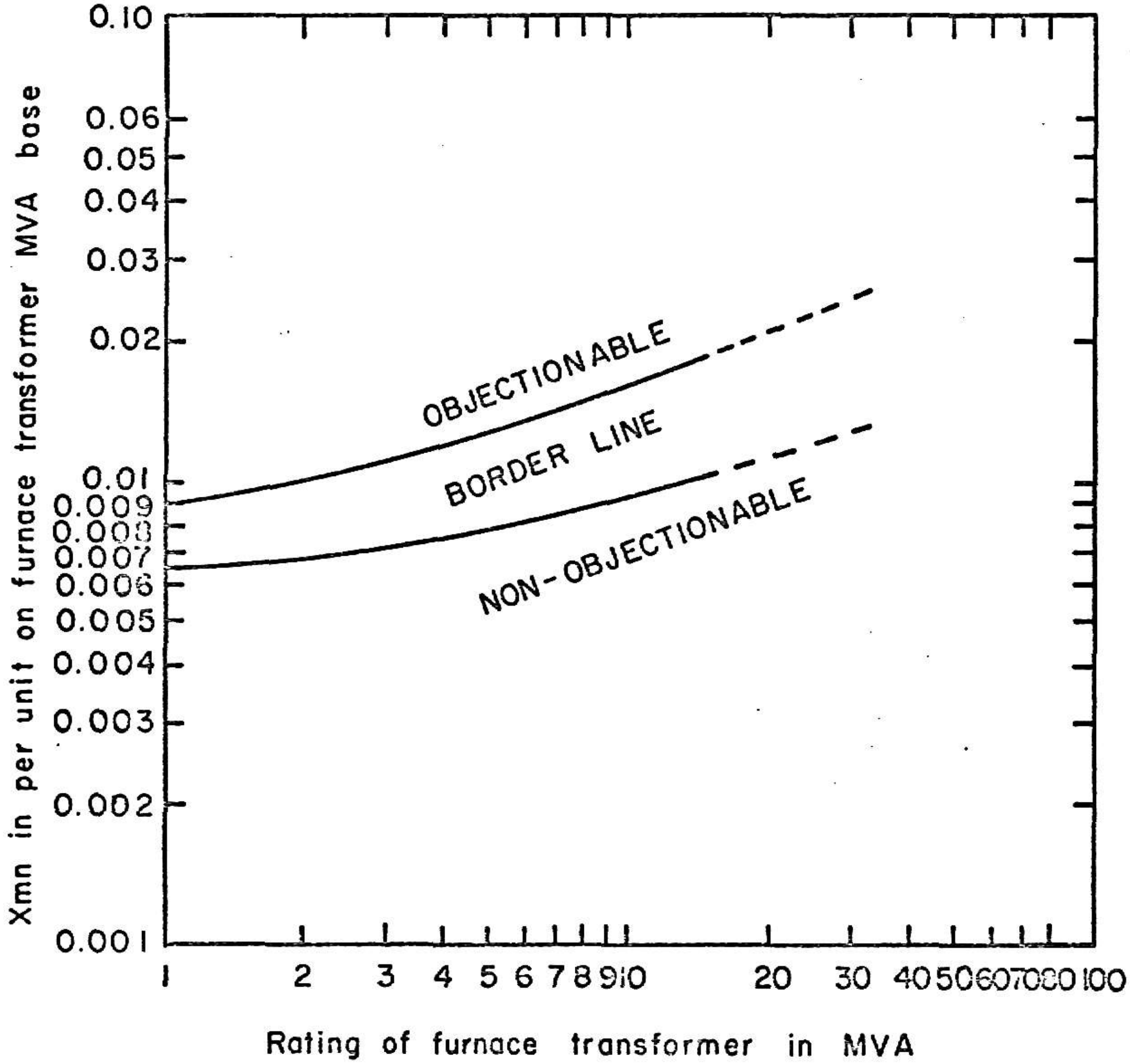


FIG. 11 ARC FURNACE FLICKER APPLICATION LIMITS
(THREE OR MORE IDENTICAL FURNACE
AT SAME LOCATION)

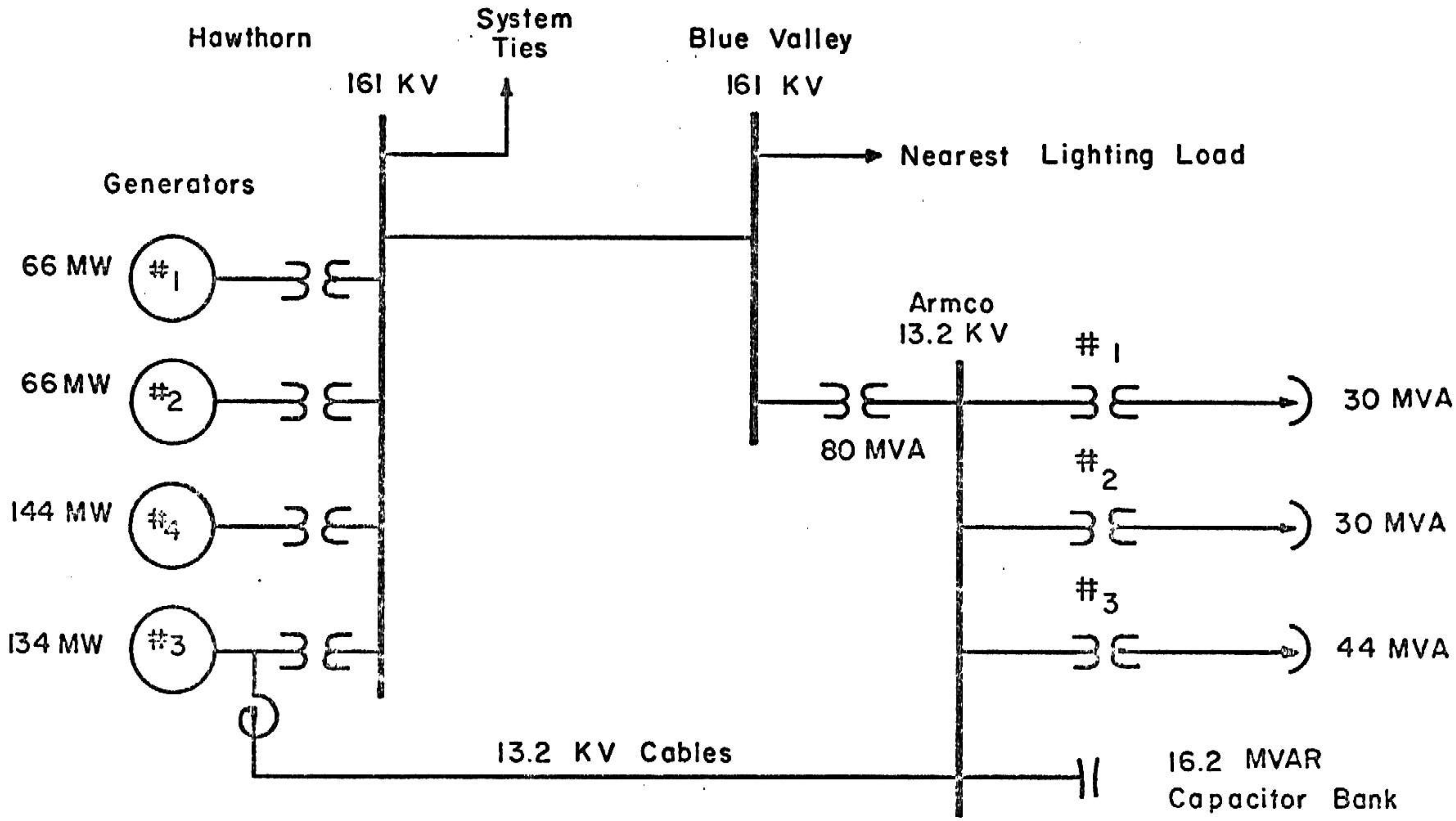


FIG. 12 POWER SUPPLY TO ARMCO SHEFFIELD PLANT
(1968)

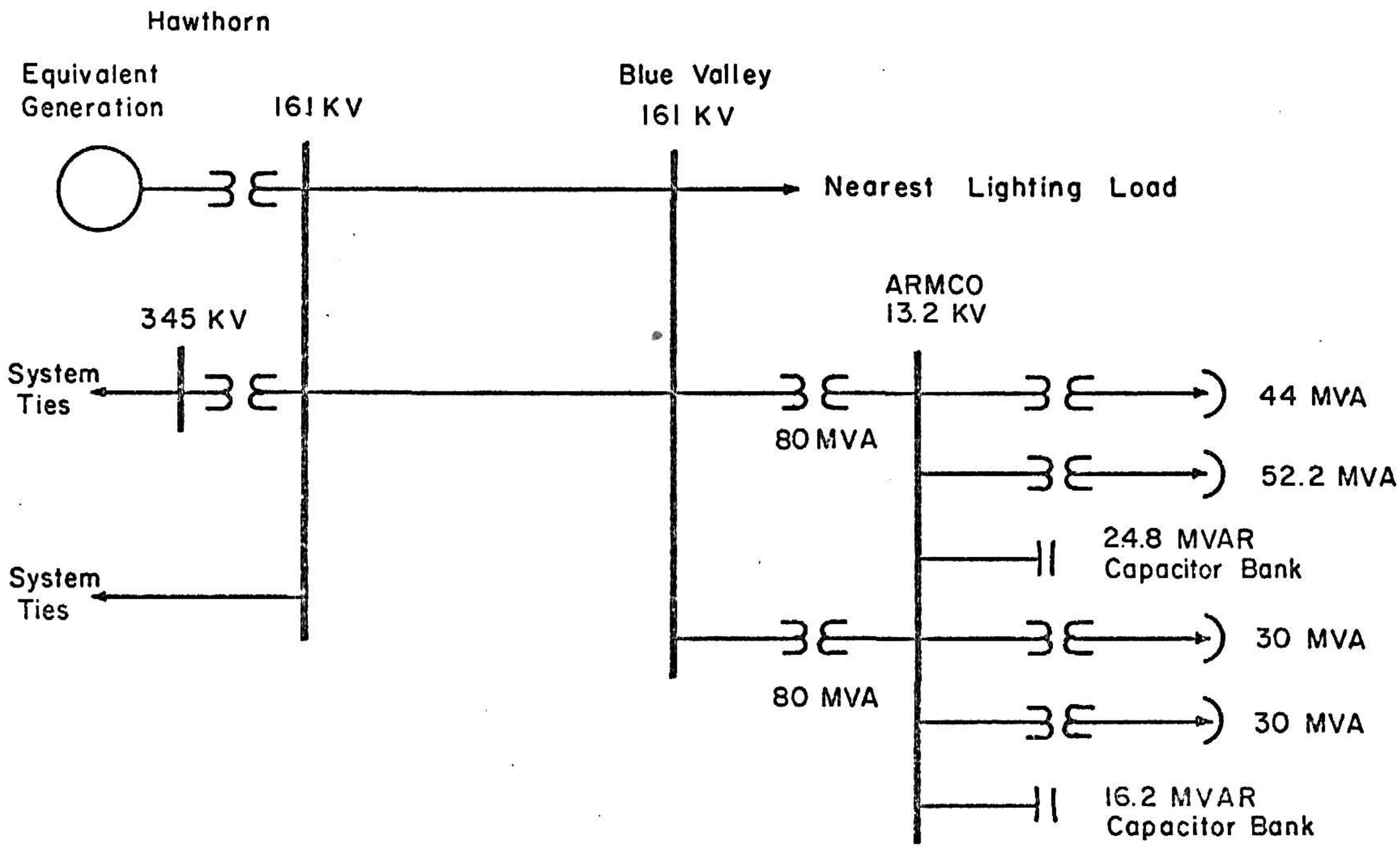


FIG. 13 POWER SUPPLY TO ARMCO SHEFFIELD PLANT
(1969)

2. Shunt impedance branches are neglected.

3. Subtransient reactance is used for all synchronous machines.

4. The resistance in lines, transformers, and generators are neglected.

The self- and mutual-drop constants can be determined by network deduction by use of calculating board or digital computer.

Fig. 9, 10, 11 present the results of the study, plots of X_{mn} against furnace size for installations with one, two and three or more larger furnaces with some smaller furnaces ignored.

The AIEE working group's survey mainly dealt with electrode voltages of 350 volts or below. However, it is understood [14] that the larger furnace operates with higher electrode voltages and consequently, the gap between electrodes and melt is larger. The influence of wave ripple decreases with increased gap or arc voltage. Therefore, the problem of lighting flicker in relative terms is less critical with large furnaces.

FLICKER STUDY OF SHEFFIELD PLANT OF ARMCO STEEL CORPORATION

Since 1950's, Kansas City Power and Light Company has been serving the Sheffield Plant of Armco Steel Corporation at Kansas City, Missouri.

In 1968, the capacity of Sheffield Plant consisted of three furnaces of 30, 30, 44 MVA, supplied by an 80 MVA transformer which steps down from the 161 KV bus at Blue Valley substation to 13.2 KV bus at the Sheffield plant. Also, there were six overhead 13.2 KV, 500 MCM cables connected directly from Hawthorn station generator Unit No. 3 to the Sheffield bus.[17] (Fig. 13) These cables were removed after the new 80 MVA transformer was installed.

Armco Steel has planned to add a new furnace of 52.2 MVA which probably will be uprated to 58 MVA in the future. To meet the increased load, the Kansas City Power and Light Company has installed another 80 MVA transformer at Blue Valley substation in 1969. (Fig. 14)

To investigate to what extent the furnace operation at Sheffield Plant may cause voltage fluctuations at the Blue Valley 161 KV bus where the nearest lighting loads are connected, the following studies were conducted.

A. Field Tests

1. A visicoder (Honeywell Model 1612) record of voltages at different furnace operating conditions were made. The operating conditions and results were analyzed below:

Operating Condition No. 1

Scrap was just contacted by electrode.
#1 furnace working in high tap but flat bath.
#2 furnace refining (low tap)

Voltage Fluctuation	Average Flicker Per Second A-Phase	B-Phase	C-Phase
0-2.2%	4.1	0.9	1.8
2.2-5%	4.1	4.5	4.1
5-8%	0.9	2.3	2.7
8-10%	0.5	0.5	0.9
10-15%	0	1.4	1.4
15% Up	0	0.5	0.5

Operating Condition No. 2

3 minutes after breaker was closed.
#1, #2 furnace conditions same as condition No. 1.

Voltage Fluctuation	Average Flicker Per Second A-Phase	B-Phase	C-Phase
0-2.2%	1.5	0.7	0.4
2.2-5%	5.5	4.6	4.4
5-8%	3.0	2.6	3.3
8-10%	0.4	0.4	1.7
10-15%	0	0	1.7
15% Up	0	0	0.7

Operating Condition No. 3

7 minutes after breaker was closed.
#1 furnace on low tap.
#2 furnace off.

Voltage Fluctuation	Average Flicker Per Second A-Phase	B-Phase	C-Phase
0-2.2%	0.4	2.7	0
2.2-5%	4.2	5.4	5.8
5-9%	4.2	1.9	4.2
8-10%	0	0	0.8
10-15%	0	0	0
15% Up	0	0	0

Operating Condition No. 4

$13\frac{1}{2}$ minutes after breaker was closed, cave-in on #3 furnace.
#1 furnace off.
#2 furnace off.

Voltage Fluctuation	Average Flicker Per Second A-Phase	B-Phase	C-Phase
0-2.2%	1.6	2.8	3.6
2.2-5%	6.8	5.6	6
5-8%	2.8	3.2	1.2
8-10%	0	0	0
10-15%	0	0	0
15% Up	0	0	0

Operating Condition No. 5

18 minutes after the breaker was closed.
#1 furnace off.
#2 furnace off.

Voltage Fluctuation	Average Flicker Per Second A-Phase	B-Phase	C-Phase
0-2.2%	4.4	0.4	2.5
2.2-5%	4	2.4	3.1
5-8%	0.4	0	0.8
8-10%	0	0	0
10-15%	0	0	0
15% Up	0	0	0

Operating Condition No. 6

22 minutes after breaker was closed.
#1 furnace off.
#2 furnace off.

Voltage Fluctuation	Average Flicker Per Second A-Phase	B-Phase	C-Phase
0-2.2%	3.7	2.5	3.7
2.2-5%	6.6	6.1	4.2
5-8%	0.8	1.2	0.8
8-10%	0	0	0
10-15%	0	0	0
15% Up	0	0	0

Operating Condition No. 7

#3 furnace cave in.
#1 furnace off.
#2 furnace off.

Voltage Fluctuation	Average Flicker Per Second A-Phase	B-Phase	C-Phase
0-2.2%	2.3	3.5	1.9
2.2-5%	5.8	4.1	6.2
5-8%	4.1	1.9	3.1
8-10%	0	0.4	0.4
10-15%	0	0	0
15% Up	0	0	0

Operating Condition No. 8

#3 furnace tried to catch a cave-in but the electrodes pulled out.
#1, #2 furnaces off.

Voltage Fluctuation	Average Flicker Per Second A-Phase	B-Phase	C-Phase
0-2.2%	2.7	2.7	1.9
2.2-5%	4.1	3.9	6.5
5-8%	0.4	0	1.1
8-10%	0	0	0.4
10-15%	0	0	0
15% Up	0	0	0

Operating Condition No. 9

3rd charge for #3 furnace.
2nd charge for #2 furnace.
1st charge for #1 furnace.

Voltage Fluctuation	Average Flicker Per Second A-Phase	B-Phase	C-Phase
0-2.2%	5.3	2.9	4.1
2.2-5%	5.3	1.0	7.6
5-8%	0.6	2.3	2.3
8-10%	0	0.6	1.2
10-15%	0	0	0
15% Up	0	0	0

Operating Condition No. 10

3rd charge for #3 furnace.
2nd charge for #2 furnace.
1st charge for #1 furnace.

Voltage Fluctuation	Average Flicker Per Second A-Phase	B-Phase	C-Phase
0-2.2%	3.9	3.9	2.6
2.2-5%	6.5	7.0	6.1
5-8%	1.3	1.7	1.7
8-10%	0	0	0
10-15%	0	0	0
15% Up	0	0	0

2. The voltage was recorded at the Blue Valley 161 KV bus by a Brush recorder. The magnitude of the very frequent flicker was about 0.071%.

3. A visual test was performed with a light bulb. No flicker was observed during the test.

B. Computer Calculation

Table 1 shows the system and input data for the cases of:

1. The year 1968, normal system condition with no. 3 furnace (44 MVA) in operation.

2. The year 1969, with normal system condition with no. 4 furnace (52.2 MVA) in operation.

3. The year 1969, furnace no. 4 (52.2 MVA) operated at all system ties connected, with Hawthorn Unit no. 3 the only generating unit in the metropolitan Kansas City area.

DATA / CASE	M	K	B3	B	J2	D2	J3	D3	J4
1968	5492.1,	100,	100,	44,	10.4,	0.153,	0,	0,	5.6,
1969N	7153.0,	200,	100,	52.2,	10.4,	0.153,	0,	0,	4.32,
1969H3	4683.9,	200,	100,	52.2,	10.4,	0.153,	0,	0,	4.32,
1969H5	5566.6,	200,	100,	52.2,	10.4,	0.153,	0,	0,	4.32,
1969UR	7153.0,	200,	100,	58.0,	10.4,	0.153,	0,	0,	4.8,

D4	J5	D5	J6	C	V	K1
0.56,	3.1166,	0.34033,	0,	16.1,	540,	0.05
0.432,	2.8,	0.3,	0,	41,	540,	0.05
0.432,	2.8,	0.3,	0,	41,	540,	0.05
0.432,	2.8,	0.3,	0,	41,	540,	0.05
0.48,	2.8,	0.3,	0,	41,	540,	0.05

TABLE 1. INPUT DATA FOR ARMCO FLICKER STUDY

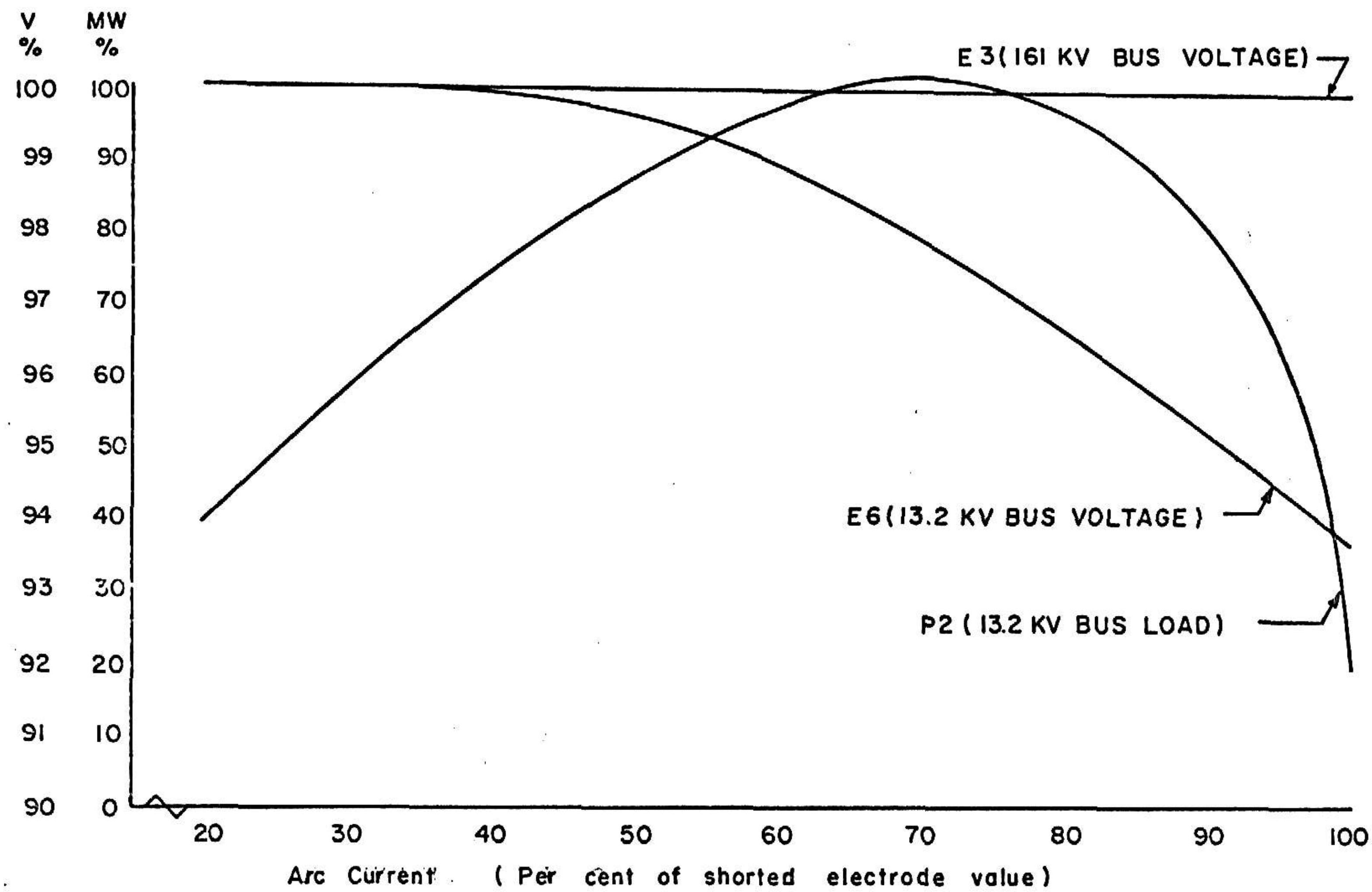


FIG. 14 1968, NO. 3 FURNACE (44 MVA) WITH NORMAL SYSTEM

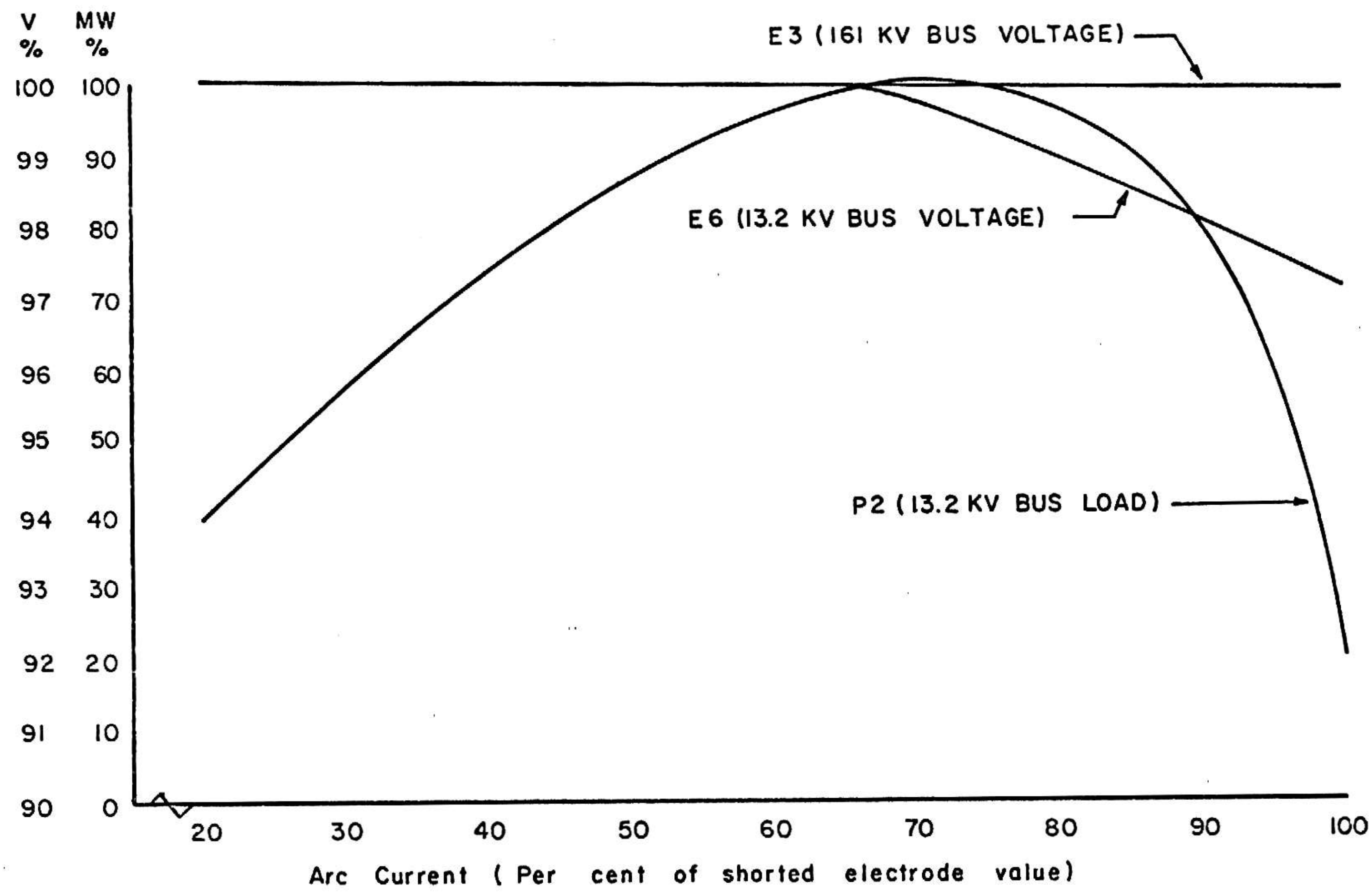


FIG. 15 1969, NO. 4 FURNACE (52.2 MVA) WITH NORMAL SYSTEM

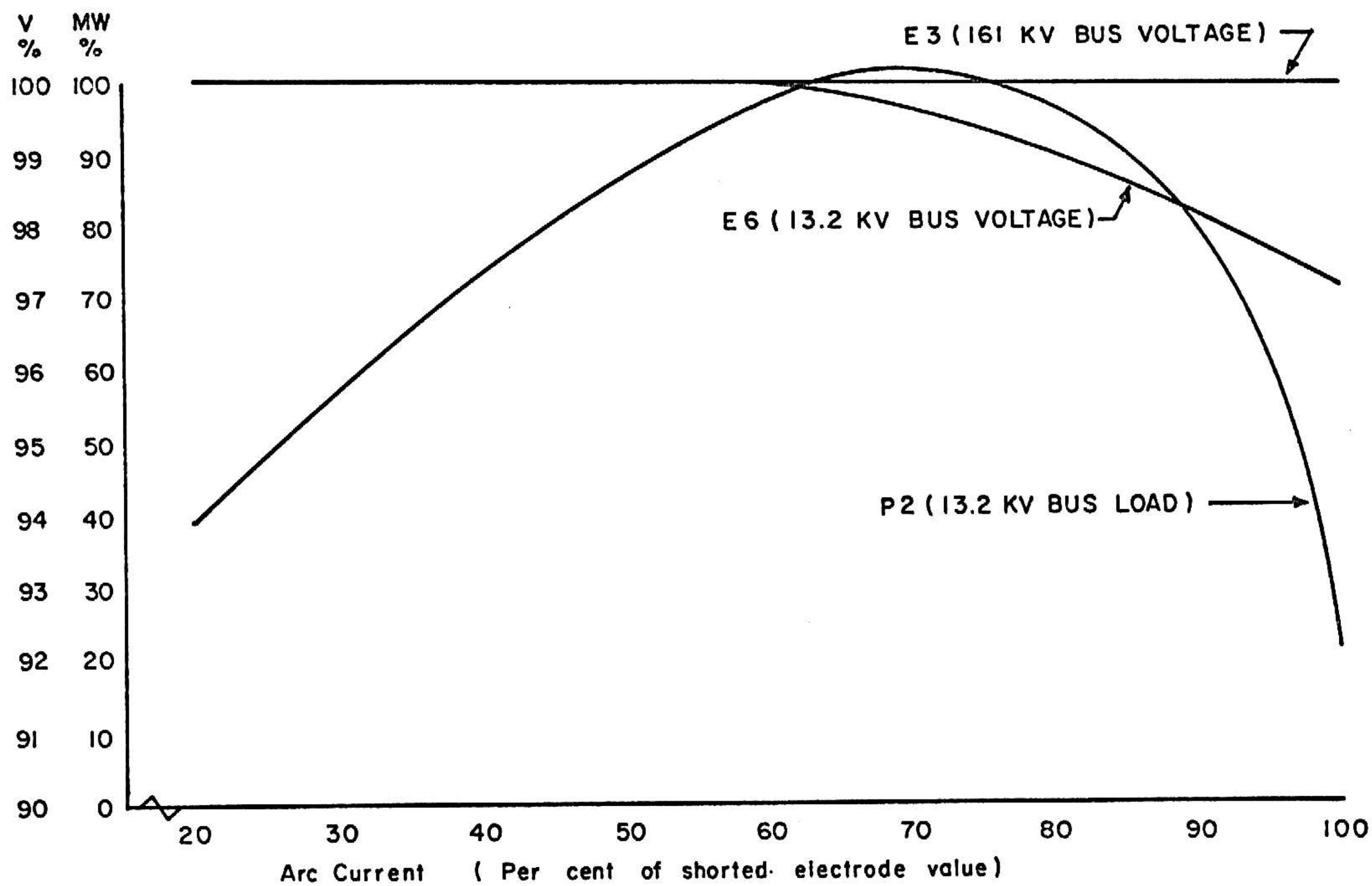


FIG. 16 1969, NO. 4 FURNACE WITH HAWTHORN UNIT 3 AND NORMAL SYSTEM

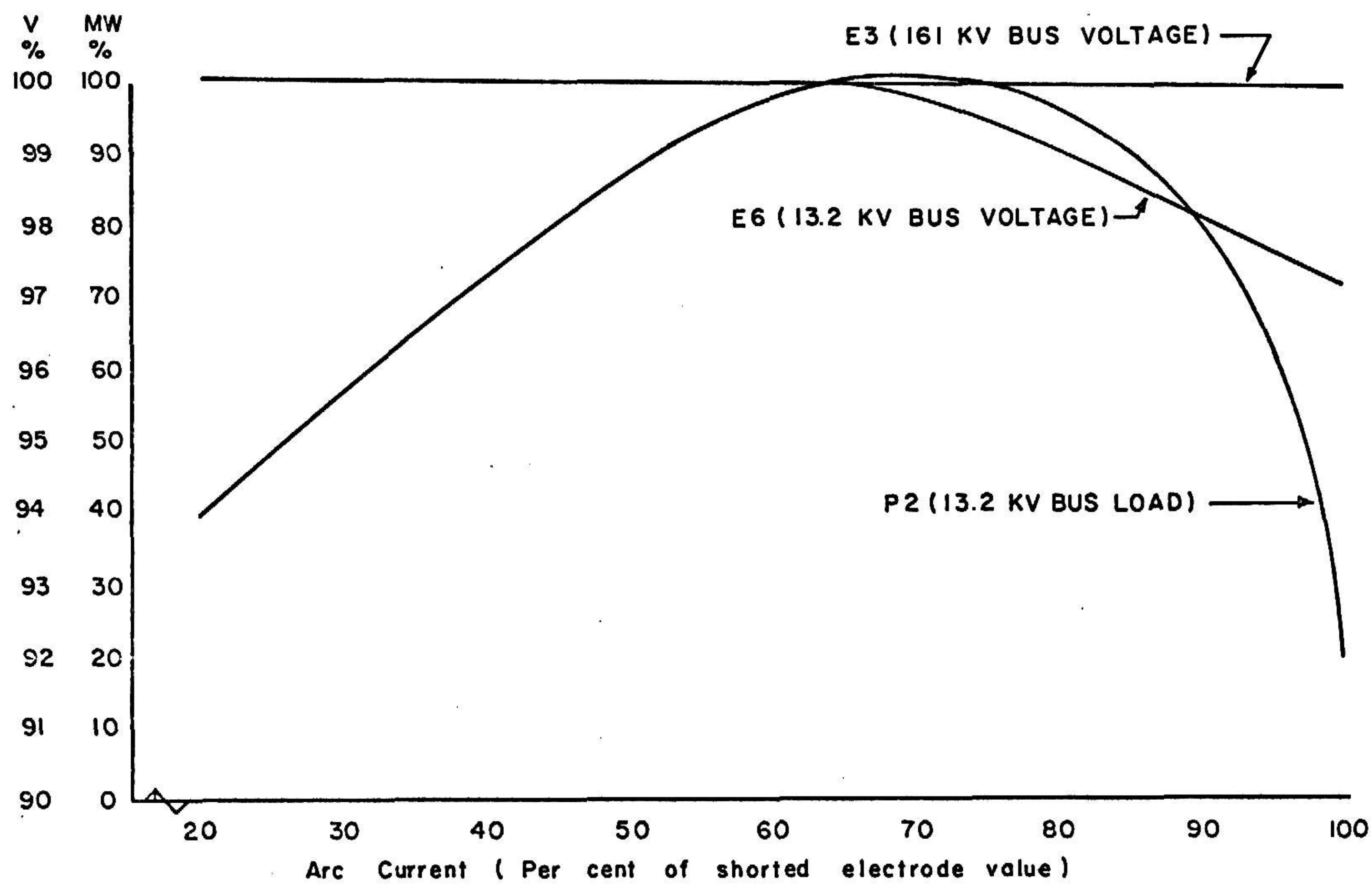


FIG. 17 1969, NO. 4 FURNACE WITH HAWTHORN UNIT 5 AND NORMAL SYSTEM

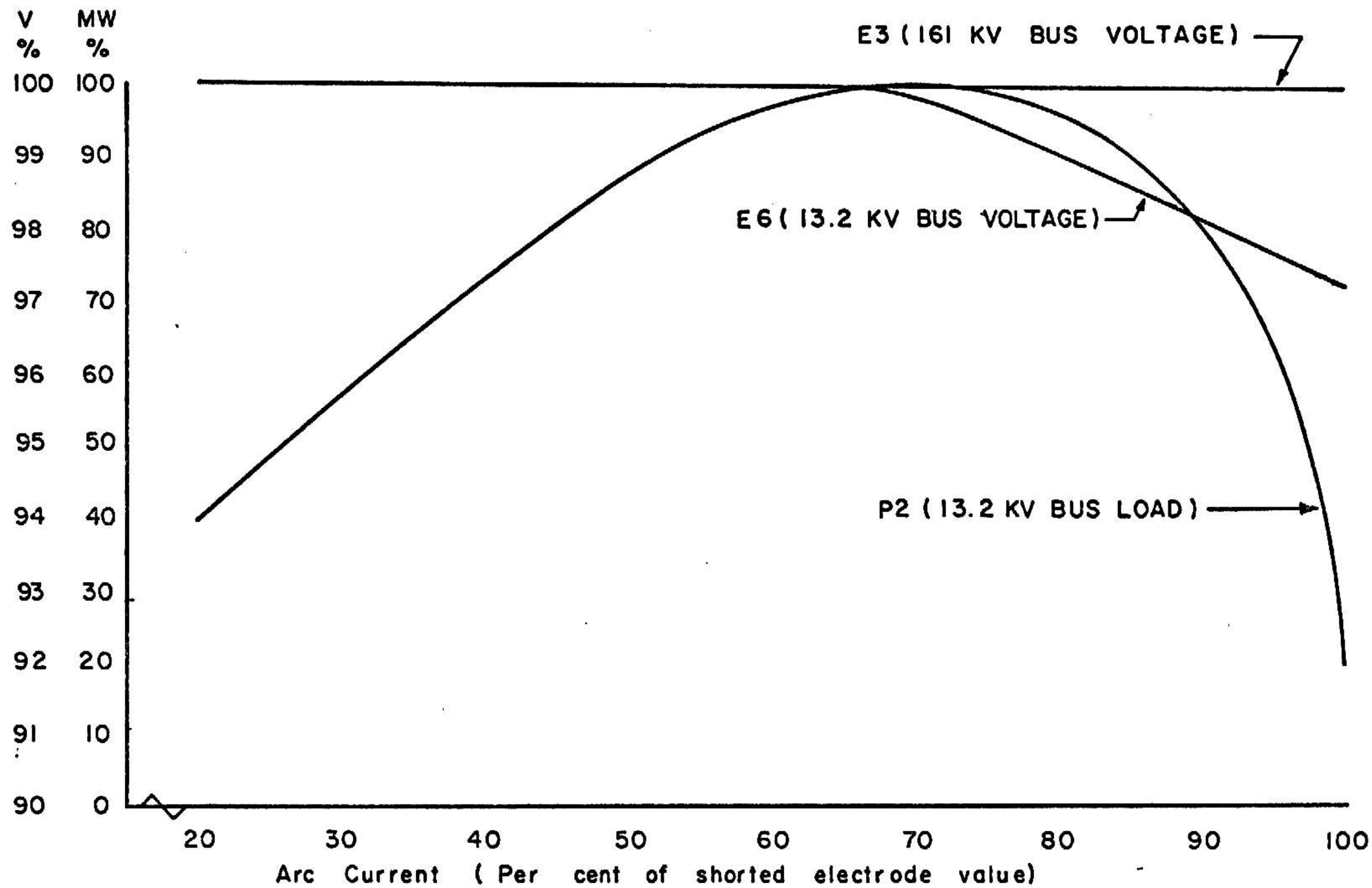


FIG. 18 1969, NO. 4 FURNACE UPRATED TO 58 MVA, SYSTEM NORMAL

4. The year 1969, furnace no. 4 (52.2 MVA) operated at all system ties connected, with Hawthorn unit no. 5 the only generation unit in the metropolitan Kansas City area.
5. The year 1969, normal system connection and furnace no. 4 uprated to 58 MVA.

The result of the computer calculations (see Appendix 2) for the voltages at Sheffield plant 13.2 KV (E6) and at Blue Valley 161 KV bus (E3) were plotted with respect to the per cent value of dead shorted electrode current. (Fig. 14 to Fig. 18)

C. Comparison of Computer Results and Field Tests

A comparison of the computer calculations and recorded voltages at both the Armco 13.2 KV bus and the Blue Valley 161 KV bus shows that they are very closely correlated. Condition 4 through condition 8 in the field tests are referred to case no. 1 of computer calculation. The record at the Armco 13.2 KV bus shows cyclic flicker of 5-8%, while the computer results show 6.3% (see Fig. 14 and Appendix 2). At Blue Valley 161 KV bus, the Brush recorder recorded approximately 0.071% voltage fluctuations, while the calculation shows less than 0.12%.

The computer results for all cases of voltage fluctuations at the Blue Valley 161 KV bus (E6) show no one case has a fluctuation that exceeds 0.15%. According to the flicker curve (Fig. 2), this amount of fluctuation is below the border line of visibility at any occurrence frequency.

D. Multifurnace Operation at Sheffield Plant

By applying the factor K_f to the computer results for the case of year 1969,

$$K_f = \sqrt{1 + (\frac{44}{58})^2 + (\frac{30}{58})^2 + (\frac{30}{58})^2} = 1.42$$

the maximum fluctuation is only 0.21% at worst (assumed furnaces on melt-down), which is still under the border line of visibility for any occurrence frequency on flicker curve.

CONCLUSION

As it has been proved in the case of the Sheffield Plant, the results of computer calculations agree very well with the field tests. Once the maximum voltage fluctuation is determined, this approach to the flicker problem provides a nearly exact answer to the question of how much furnace capacity could be supplied at a particular bus where the short circuit capacity is known, thereby eliminating the guessing art in determining the power supply to the arc furnaces.

ACKNOWLEDGMENT

The author wishes to express his sincere gratitude to his major professor, Prof. Leo A. Wirtz, for encouraging and directing the study and for guidance in writing this report.

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APPENDIX A

FLICKR

```
50 PRINT"STUDY 1968"
55 PRINT
90 READ M,K,B3,B,J2,D2,J3,D3,J4,D4,J5,D5,J6,C,V,K1
95 PRINT M;K;B3;B;J2;D2;J3;D3;J4;D4;J5;D5;J6;C;V;K1
100 LET F=B/(1.73205*(V/1000))
105 LET X1=(V/1000) 2/M
106 LET X2=J2*(V/1000) 2/(K*100)
107 LET X3=J3*(V/1000) 2/(B3*100)
108 LET X4=J4*(V/1000) 2/(B*100)
109 LET X5=J5/1000
110 LET X6=J6*(V/1000) 2/(C*100)
111 LET X7=(V/1000) 2/C
115 LET R1=X1/10
116 LET R2=D2*(V/1000) 2/(K*100)
117 LET R3=D3*(V/1000) 2/(B3*100)
118 LET R4=D4*(V/1000) 2/(B*100)
119 LET R5=D5/1000
125 LET X0=X3+X4+X5
126 LET R0=R3+R4+R5
128 LET E=V*(1-K1)/1.73205
130 PRINT "X1="X1;"X2="X2;"X3="X3;"X4="X4;"X5="X5;"X6="X6;"X7="X7
132 PRINT "R1="R1;"R2="R2;"R3="R3;"R4="R4;"R5="R5;"F="F;"E="E
134 LET Q1=1
135 LET R=0
136 GOSUB 980
137 LET Q1=0
140 LET X=.0037
150 LET Y=.0001
160 LET N7=0
170 LET N1=1
180 LET N2=0
190 LET N3=1
200 LET N4=0
210 GOSUB 720
220 LET N4=1
230 LET S2=S1
240 LET S3=S1
250 LET A1=X
260 IF N2 1 THEN 290
270 LET N2=0
280 LET S3=S1
290 IF N3=3 THEN 690
300 IF N3=2 THEN 350
310 LET X=X+Y
320 LET N3=2
330 GOSUB 720
340 GOTO 260
350 IF S1-S3 0 THEN 410
```

FLICKR CONTINUED

```
360 LET Y=-Y
370 LET X=X+2*Y
380 LET N3=3
390 GOSUB 720
400 GOTO 260
410 LET S3=S1
420 LET N3=1
430 IF S3-S2 0 THEN 570
440 IF N1 1 THEN 650
450 LET X=A1
460 LET N4=2
470 GOSUB 720
480 IF N7 0 THEN 1340
490 LET N7=1
500 LET X=R
510 LET Y=.1*Y
520 GOTO 170
570 LET S2=S3
580 LET N2=1
590 LET N1=0
600 LET B1=X
610 LET X=2*X-A1
620 LET A1=B1
630 GOSUB 720
640 GOTO 260
650 LET N1=1
660 LET X=A1
670 LET S3=S2
680 GOTO 290
690 IF S1-S3 0 THEN 410
700 LET X=X-Y
710 GOTO 420
720 IF N4=0 THEN 770
730 IF N6 100 THEN 780
740 LET N4=2
750 LET N6=0
760 GOTO 450
770 LET N6=0
780 LET N6=N6+1
790 LET R=X
800 GO TO 980
810 LET Q1=2
820 LET R=0
830 GOSUB 980
840 FOR K=0 TO 2.5 STEP .25
850 LET R=.0001*10 K
860 GOSUB 980
870 NEXT K
880 LET R=100
890 GOSUB 980
900 GO TO 2000
```

FLICKR CONTINUED

```
980 LET C8=ATN(XO/(RO+R))
990 LET F8=COS(C8)
1000 LET G1=(RO+R) 2+(XO-X7+X6) 2
1010 LET G2=(X6-X7) 2*(RO+R)
1020 LET G3=(RO+R) 2+XO*(XO-X7+X6)
1030 LET G4=R1+R2+G2/G1
1040 LET G5=X1+X2+(X6-X7)*G3/G1
1050 LET Z=SQR(G4 2+G5 2)
1060 LET C1=ATN(G5/G4)
1070 LET F1=COS(C1)
1080 LET I1=E/(Z*10 3)
1090 LET G6=I1*COS(C1)
1100 LET G9=I1*SIN(C1)
1110 LET T2=E-G6*(R1+R2)*1000-G9*(X1+X2)*1000
1120 LET T1=G6*(X1+X2)*1000-G9*(R1+R2)*1000
1130 LET E5=SQR(T2 2+T1 2)
1140 LET C5=ATN(T1/T2)
1150 LET I5=E5/((X7-X6)*1000)
1160 LET G8=I5*SIN(C5)
1170 LET G7=I5*COS(C5)
1180 LET S4=G6-G8
1190 LET S5=G9+G7
1200 LET C4=ATN(S5/S4)
1210 LET F4=COS(C4)
1220 LET I4=SQR(S4 2+S5 2)
1230 LET F7=COS(C1-C5)
1250 LET A8=I4*R*1000
1260 LET I6=I4 2
1270 LET P3=3*I6*R
1280 LET P2=3*I6*(RO+R)
1285 LET V2=3*I6*XO
1290 IF Q1=2 THEN 1404
1300 LET S1=P3
1310 IF Q1=0 THEN 1330
1320 LET Q7=I4?
1330 RETURN
1340 LET P7=P2
1350 PRINT "P7="P7
1360 PRINT
1370 GOTO 810
1404 LET H6=I4*COS(C4)
1407 LET H9=I4*SIN(C4)
1410 LET V2=3*I6*XO
1413 LET V3=V2/P7
1416 LET I9=I4/Q7
1419 LET P9=P3/P7
1422 LET P8=P2/P7
1425 LET A9=A8/E
1428 LET W3=E-G6*R1*10 3-G9*X1*10 3
1431 LET Y3=G6*X1*10 3-G9*R1*10 3
1434 LET E3=SQR(W3 2+Y3 2)
```

FLICKR CONTINUED

```
1437 LET W4=E-G6*(R1+R2)*10 3-G9*(X1+X2)*10 3
1440 LET Y4=G6*(X1+X2)*10 3-G9*(R1+R2)*10 3
1443 LET E4=SQR(W4 2+Y4 2)
1446 LET W6=W4-H6*R3*1000-H9*X3*1000
1449 LET Y6=Y4+H6*X3*1000-H9*R3*1000
1452 LET E6=SQR(W6 2+Y6 2)
1455 LET W7=W4-H6*(R3+R4)*1000-H9*(X3+X4)*1000
1458 LET Y7=Y4+H6*(X3+X4)*1000-H9*(R3+R4)*1000
1461 LET E7=SQR(W7 2+Y7 2)
1464 LET W8=W4-H6*R0*1000-H9*X0*1000
1467 LET Y8=Y4+H6*X0*1000-H9*R0*1000
1470 LET E8=SQR(W8 2+Y8 2)
1474 PRINT "P3="P3;"P2="P2;"V2="V2;"R="R;"A8="A8
1476 PRINT "I4="I4;"F7="F7;"F8="F8;"P.U. V2="V3
1478 PRINT "P.U. I="I9;"P.U. P3="P9;"P.U. P2="P8;"P.U. A8="A9
1480 PRINT "P.U. E3="E3/E;"P.U. E4="E4/E;"P.U. E5="E5/E
1490 PRINT "P.U. E6="E6/E;"P.U. E7="E7/E;"P.U. E8="E8/E
1500 PRINT
1510 RETURN
1900  DATA54921,100,100,33,10.4,.153,0,0,5.6,.56,3.1166,.34033,
1901 DATA 0,16.2,540,.05,
2000 END
```

APPENDIX B

ARMCO 9:12 CH-E WE 07/10/8

STUDY 1968

5492.1 100 100 33 10.4 .153 0 0 5.6
.56 3.1166 .34033 0 16.2 540 .05
X1= 5.30944 E-6 X2= 3.03264 E-4 X3= 0 X4= 4.94836 E-4 X5= 3.11
X6= 0 X7= .018
R1= 5.30944 E-7 R2= 4.46148 E-6 R3= 0 R4= 4.94836 E-5 R5= 3.40
F= 35.2825 E= 296.181
P7= 34.4817

P3= 0 P2= 6.82293 V2= 63.2111 R= 0 A8= 0
I4= 76.3829 F7= .134202 F8= .107315 P.U. V2= 1.83318
P.U. I= 1 P.U. P3= 0 P.U. P2= .197871 P.U. A8= 0
P.U. E3= .9989 P.U. E4= .936773 P.U. E5= .936773
P.U. E6= .936773 P.U. E7= .808527 P.U. E8= 7.70268 E-9

P3= 1.74035 P2= 8.52449 V2= 62.8518 R= .001 A8= 7.61655
I4= 76.1655 F7= .168034 F8= .134398 P.U. V2= 1.82276
P.U. I= .997153 P.U. P3= 5.04718 E-2 P.U. P2= .247218 P.U. A8= 2.5715
P.U. E3= .998904 P.U. E4= .937215 P.U. E5= .937215
P.U. E6= .937215 P.U. E7= .80942 P.U. E8= 2.57159 E-2

P3= 3.07849 P2= 9.8268 V2= 62.5198 R= 1.77828 E-4 A8= 13.5085
I4= 75.9641 F7= .194094 F8= .155273 P.U. V2= 1.81313
P.U. I= .994517 P.U. P3= 8.92789 E-2 P.U. P2= .284986 P.U. A8= 4.56092
P.U. E3= .998909 P.U. E4= .937629 P.U. E5= .937629
P.U. E6= .937629 P.U. E7= .810314 P.U. E8= 4.56091 E-2

P3= 5.41329 P2= 12.0862 V2= 61.8217 R= 3.16228 E-4 A8= 23.8875
I4= 75.5388 F7= .239739 F8= .191869 P.U. V2= 1.79288
P.U. I= .988949 P.U. P3= .15699 P.U. P2= .350512 P.U. A8= 8.06516 E-2
P.U. E3= .99892 P.U. E4= .938508 P.U. E5= .938508
P.U. E6= .938508 P.U. E7= .812313 P.U. E8= 8.06516 E-2

P3= 9.38419 P2= 15.8893 V2= 60.2666 R= 5.62341 E-4 A8= 41.9409
I4= 74.5827 F7= .31823 F8= .254938 P.U. V2= 1.74779
P.U. I= .976431 P.U. P3= .27215 P.U. P2= .460803 P.U. A8= .141606
P.U. E3= .998946 P.U. E4= .940489 P.U. E5= .940489
P.U. E6= .940489 P.U. E7= .81706 P.U. E8= .141606

P3= 15.6978 P2= 21.817 V2= 56.6915 R= .001 A8= 72.3367
I4= 72.3367 F7= .447224 F8= .359159 P.U. V2= 1.6441
P.U. I= .947027 P.U. P3= .455249 P.U. P2= .632712 P.U. A8= .244231
P.U. E3= .999013 P.U. E4= .945086 P.U. E5= .945086
P.U. E6= .945086 P.U. E7= .828578 P.U. E8= .244231

```
P3= 24.0643 P2= 29.3394 V2= 48.8712 R= 1.77828 E-3   A8= 119.433
I4= 67.1623 F7= .636712 F8= .514711 P.U. V2= 1.41731
P.U. I= .879285 P.U. P3= .697885 P.U. P2= .850867 P.U. A8= .403245
P.U. E3= .999169 P.U. E4= .955176 P.U. E5= .955176
P.U. E6= .955176 P.U. E7= .854553 P.U. E8= .403245

P3= 30.699  P2= 34.4832 V2= 35.0593 R= 3.16228 E-3   A8= 179.888
I4= 56.8854 F7= .85166  F8= .701225 P.U. V2= 1.01675
P.U. I= .744741 P.U. P3= .890297 P.U. P2= 1.00004 P.U. A8= .607357
P.U. E3= .999461 P.U. E4= .972906 P.U. E5= .972906
P.U. E6= .972906 P.U. E7= .900477 P.U. E8= .607357

P3= 29.6725 P2= 31.7294 V2= 19.0561 R= 5.62341 E-3   A8= 235.839
I4= 41.9388 F7= .989507 F8= .857273 P.U. V2= .552644
P.U. I= .549061 P.U. P3= .860529 P.U. P2= .92018  P.U. A8= .796269
P.U. E3= .999818 P.U. E4= .993226 P.U. E5= .993226
P.U. E6= .993226 P.U. E7= .952818 P.U. E8= .796269

P3= 22.0655 P2= 22.9256 V2= 7.9688  R= .01     A8= 271.204
I4= 27.1204 F7= .957996 F8= .944565 P.U. V2= .231102
P.U. I= .355058 P.U. P3= .639917 P.U. P2= .664862 P.U. A8= .91567
P.U. E3= 1.00008 P.U. E4= 1.0072  P.U. E5= 1.0072
P.U. E6= 1.0072  P.U. E7= .988905 P.U. E8= .91567

P3= 14.0081 P2= 14.3152 V2= 2.84485 R= 1.77828 E-2   A8= 288.157
I4= 16.2042 F7= .761664 F8= .98082  P.U. V2= .082503
P.U. I= .212145 P.U. P3= .406247 P.U. P2= .415152 P.U. A8= .972908
P.U. E3= 1.00021 P.U. E4= 1.01368 P.U. E5= 1.01368
P.U. E6= 1.01368 P.U. E7= 1.00608 P.U. E8= .972908

P3= 8.27929 P2= 8.38135 V2= .945526 R= 3.16228 E-2   A8= 295.417
I4= 9.34192 F7= .509624 F8= .993697 P.U. V2= 2.74211 E-2
P.U. I= .122304 P.U. P3= .240107 P.U. P2= .243067 P.U. A8= .997422
P.U. E3= 1.00026 P.U. E4= 1.01612 P.U. E5= 1.01612
P.U. E6= 1.01612 P.U. E7= 1.01294 P.U. E8= .997422

P3= 2.72511 E-3   P2= 2.72512 E-3   V2= 9.84156 E-8   R= 100  A8= 301.3
I4= 3.01392 E-3   F7= 1.80027 E-4   F8= 1.        P.U. V2= 2.85414 E-9
P.U. I= 3.94580 E-5   P.U. P3= 7.90305 E-5   P.U. P2= 7.90308 E-5
P.U. A8= 1.01759
P.U. E3= 1.0003  P.U. E4= 1.01744 P.U. E5= 1.01744
P.U. E6= 1.01744 P.U. E7= 1.01744 P.U. E8= 1.01744




RAN     11.50 SEC.
READY.
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ARMCO 9:26 CH-E WE 07/10/8

STUDY 1969 NORMAL

7153.0 200 100 52.2 10.4 .153 0 0 4.32
.432 2.8 .3 0 41 540 .05
X1= 4.07661 E-6 X2= 1.51632 E-4 X3= 0 X4= 2.41324 E-4 X5= .0028
X6= 0 X7= 7.11220 E-3
R1= 4.07661 E-7 R2= 2.23074 E-6 R3= 0 R4= 2.41324 E-5 R5= .0003
F= 55.8106 E= 296.181
P7= 42.7155

P3= 0 P2= 8.61465 V2= 80.831 R= 0 A8= 0
I4= 94.1233 F7= .184566 F8= .105976 P.U. V2= 1.89231
P.U. I= 1 P.U. P3= 0 P.U. P2= .201675 P.U. A8= 0
P.U. E3= .999255 P.U. E4= .971975 P.U. E5= .971975
P.U. E6= .971975 P.U. E7= .894904 P.U. E8= 6.74693 E-9

P3= 2.63854 P2= 11.1909 V2= 80.2466 R= .0001 A8= 9.37824
I4= 93.7824 F7= .240009 F8= .13812 P.U. V2= 1.87863
P.U. I= .996378 P.U. P3= 6.17701 E-2 P.U. P2= .261987 P.U. A8= 3.1663
P.U. E3= .99926 P.U. E4= .972321 P.U. E5= .972321
P.U. E6= .972321 P.U. E7= .89559 P.U. E8= 3.16639 E-2

P3= 4.65966 P2= 13.153 V2= 79.6923 R= 1.77828 E-4 A8= 16.6194
I4= 93.458 F7= .282365 F8= .162844 P.U. V2= 1.86565
P.U. I= .992932 P.U. P3= .109086 P.U. P2= .30792 P.U. A8= 5.61125 E-2
P.U. E3= .999266 P.U. E4= .972653 P.U. E5= .972653
P.U. E6= .972653 P.U. E7= .896295 P.U. E8= 5.61125 E-2

P3= 8.16265 P2= 16.5293 V2= 78.5044 R= 3.16228 E-4 A8= 29.3329
I4= 92.7588 F7= .355591 F8= .206036 P.U. V2= 1.83784
P.U. I= .985503 P.U. P3= .191093 P.U. P2= .386963 P.U. A8= 9.90371 E-2
P.U. E3= .99928 P.U. E4= .973375 P.U. E5= .973375
P.U. E6= .973375 P.U. E7= .897898 P.U. E8= 9.90372 E-2

P3= 14.0194 P2= 22.1001 V2= 75.8212 R= 5.62341 E-4 A8= 51.2629
I4= 91.1598 F7= .477697 F8= .279831 P.U. V2= 1.77503
P.U. I= .968515 P.U. P3= .328203 P.U. P2= .517378 P.U. A8= .17308
P.U. E3= .999316 P.U. E4= .975025 P.U. E5= .975025
P.U. E6= .975025 P.U. E7= .901741 P.U. E8= .17308

P3= 22.916 P2= 30.3438 V2= 69.6949 R= .001 A8= 87.3994
I4= 87.3994 F7= .663215 F8= .399187 P.U. V2= 1.63161
P.U. I= .928564 P.U. P3= .536479 P.U. P2= .710369 P.U. A8= .295088
P.U. E3= .999403 P.U. E4= .978829 P.U. E5= .978829
P.U. E6= .978829 P.U. E7= .910957 P.U. E8= .295088

P3= 33.3337 P2= 39.4095 V2= 57.0093 R= 1.77828 E-3 A8= 140.566
I4= 79.0462 F7= .882698 F8= .568639 P.U. V2= 1.33463
P.U. I= .839816 P.U. P3= .780364 P.U. P2= .922604 P.U. A8= .474596
P.U. E3= .999595 P.U. E4= .986745 P.U. E5= .986745
P.U. E6= .986745 P.U. E7= .93063 P.U. E8= .474596

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P3= 38.8037 P2= 42.7811 V2= 37.3195 R= 3.16228 E-3   A8= 202.244
I4= 63.9552 F7= .999959 F8= .75357  P.U. V2= .873676
P.U. I= .679484 P.U. P3= .908422 P.U. P2= 1.00154 P.U. A8= .68284
P.U. E3= .999911 P.U. E4= .999019 P.U. E5= .999019
P.U. E6= .999019 P.U. E7= .961505 P.U. E8= .68284

P3= 33.8865 P2= 35.8398 V2= 18.3269 R= 5.62341 E-3   A8= 252.03
I4= 44.8181 F7= .878596 F8= .890346 P.U. V2= .429046
P.U. I= .476163 P.U. P3= .793308 P.U. P2= .839034 P.U. A8= .850934
P.U. E3= 1.00023 P.U. E4= 1.01082 P.U. E5= 1.01082
P.U. E6= 1.01082 P.U. E7= .991426 P.U. E8= .850934

P3= 23.5338 P2= 24.2966 V2= 7.1574 R= .01      A8= 280.082
I4= 28.0082 F7= .61475  F8= .959244 P.U. V2= .16756
P.U. I= .29757  P.U. P3= .550944 P.U. P2= .568801 P.U. A8= .945646
P.U. E3= 1.00043 P.U. E4= 1.01778 P.U. E5= 1.01778
P.U. E6= 1.01778 P.U. E7= 1.00936 P.U. E8= .945646

P3= 14.4639 P2= 14.7275 V2= 2.4737  R= 1.77828 E-2   A8= 292.807
I4= 16.4657 F7= .377929 F8= .986186 P.U. V2= .057911
P.U. I= .174938 P.U. P3= .338609 P.U. P2= .344781 P.U. A8= .988609
P.U. E3= 1.00052 P.U. E4= 1.02073 P.U. E5= 1.02073
P.U. E6= 1.02073 P.U. E7= 1.01727 P.U. E8= .988608

P3= 8.43711 P2= 8.52359 V2= .81144  R= 3.16228 E-2   A8= 298.22
I4= 9.43053 F7= .219846 F8= .995499 P.U. V2= 1.89964 E-2
P.U. I= .100193 P.U. P3= .197519 P.U. P2= .199543 P.U. A8= 1.00688
P.U. E3= 1.00056 P.U. E4= 1.0218  P.U. E5= 1.0218
P.U. E6= 1.0218  P.U. E7= 1.02034 P.U. E8= 1.00688

P3= 2.75292 E-3   P2= 2.75293 E-3   V2= 8.37252 E-8   R= 100  A8= 302.9
I4= 3.02926 E-3   F7= 7.11475 E-5   F8= 1.       P.U. V2= 1.96007 E-9
P.U. I= 3.21839 E-5   P.U. P3= 6.44478 E-5   P.U. P2= 6.44480 E-5
P.U. A8= 1.02277
P.U. E3= 1.00059 P.U. E4= 1.02238 P.U. E5= 1.02238
P.U. E6= 1.02238 P.U. E7= 1.02238 P.U. E8= 1.02238




RAN     12.00 SEC
READY.
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ARMCO 9:39 CH-E WE 07/10/8

STUDY 1969 HAW NO.3 ONLY

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 4683.9   200   100   52.2    10.4    .153    0    0    4.32
 .432    2.8    .3     0     41    540   .05
X1= 6.22558 E-6   X2= 1.51632 E-4   X3= 0   X4= 2.41324 E-4   X5= .0028
X6= 0   X7= 7.11220 E-3
R1= 6.22558 E-7   R2= 2.23074 E-6   R3= 0   R4= 2.41324 E-5   R5= .0003
F= 55.8106 E= 296.181
P7= 42.712

P3= 0    P2= 8.60789 V2= 80.7675 R= 0    A8= 0
I4= 94.0863 F7= .184566 F8= .105976 P.U. V2= 1.89098
P.U. I= 1    P.U. P3= 0    P.U. P2= .201533 P.U. A8= 0
P.U. E3= .998863 P.U. E4= .971594 P.U. E5= .971594
P.U. E6= .971594 P.U. E7= .894553 P.U. E8= 7.11221 E-9

P3= 2.63648 P2= 11.1822 V2= 80.184 R= .0001   A8= 9.37458
I4= 93.7458 F7= .240009 F8= .13812 P.U. V2= 1.87732
P.U. I= .996381 P.U. P3= .061727 P.U. P2= .261804 P.U. A8= 3.16516 E-2
P.U. E3= .998871 P.U. E4= .971942 P.U. E5= .971942
P.U. E6= .971942 P.U. E7= .895241 P.U. E8= 3.16516 E-2

P3= 4.65605 P2= 13.1428 V2= 79.6307 R= 1.77828 E-4   A8= 16.613
I4= 93.4218 F7= .282365 F8= .162844 P.U. V2= 1.86437
P.U. I= .992938 P.U. P3= .10901  P.U. P2= .307707 P.U. A8= 5.60908 E-2
P.U. E3= .99888  P.U. E4= .972277 P.U. E5= .972277
P.U. E6= .972277 P.U. E7= .895948 P.U. E8= 5.60908 E-2

P3= 8.15646 P2= 16.5168 V2= 78.4449 R= 3.16228 E-4   A8= 29.3218
I4= 92.7236 F7= .355591 F8= .206036 P.U. V2= 1.8366
P.U. I= .985516 P.U. P3= .190964 P.U. P2= .386702 P.U. A8= 9.89996 E-2
P.U. E3= .998902 P.U. E4= .973006 P.U. E5= .973006
P.U. E6= .973006 P.U. E7= .897558 P.U. E8= 9.89996 E-2

P3= 14.0092 P2= 22.0841 V2= 75.7665 R= 5.62341 E-4   A8= 51.2444
I4= 91.1269 F7= .477697 F8= .279831 P.U. V2= 1.77389
P.U. I= .968546 P.U. P3= .327993 P.U. P2= .517048 P.U. A8= .173017
P.U. E3= .998955 P.U. E4= .974673 P.U. E5= .974673
P.U. E6= .974673 P.U. E7= .901416 P.U. E8= .173017

P3= 22.9016 P2= 30.3247 V2= 69.651  R= .001    A8= 87.3719
I4= 87.3719 F7= .663215 F8= .399187 P.U. V2= 1.63071
P.U. I= .928636 P.U. P3= .536186 P.U. P2= .709981 P.U. A8= .294995
P.U. E3= .999088 P.U. E4= .978521 P.U. E5= .978521
P.U. E6= .978521 P.U. E7= .910671 P.U. E8= .294995

P3= 33.3194 P2= 39.3927 V2= 56.985  R= 1.77828 E-3   A8= 140.536
I4= 79.0293 F7= .882698 F8= .568639 P.U. V2= 1.33417
P.U. I= .839966 P.U. P3= .78096 P.U. P2= .922286 P.U. A8= .474495
P.U. E3= .999382 P.U. E4= .986534 P.U. E5= .986534
P.U. E6= .986534 P.U. E7= .930432 P.U. E8= 474495
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P3= 38.8001 P2= 42.7771 V2= 37.316  R= 3.16228 E-3   A8= 202.235
I4= 63.9522 F7= .999959 F8= .75357  P.U. V2= .873666
P.U. I=.679719  P.U. P3= .908412 P.U. P2= 1.00152 P.U. A8= .682808
P.U. E3= .999864 P.U. E4= .998972 P.U. E5= .998972
P.U. E6= .998972 P.U. E7= .96146 P.U.  E8= .682808

P3= 33.8948 P2= 35.8485 V2= 18.3314 P= 5.62341 E-3   A8= 252.061
I4= 44.8235 F7= .878596 F8= .890346 P.U. V2= .429187
P.U. I= .476409 P.U. P3= .793567 P.U. P2= .839308 P.U. A8= .851038
P.U. E3= 1.00035 P.U. E4= 1.01095 P.U. E5= 1.01095
P.U. E6= 1.01095 P.U. E7= .991547 P.U. E8= .851038

P3= 23.5445 P2= 24.3077 V2= 7.16066 R= .01      A8= 280.146
I4= 28.0146 F7= .61475  F8= .959244 P.U. V2= .16765
P.U. I= .297754 P.U. P3= .55124  P.U. P2= .569107 P.U. A8= .945862
P.U. E3= 1.00066 P.U. E4= 1.01801 P.U. E5= 1.01801
P.U. E6= 1.01801 P.U. E7= 1.00959 P.U. E8= .945861

P3= 14.4718 P2= 14.7356 V2= 2.47506 R= 1.77828 E-2   A8= 292.888
I4= 16.4703 F7= .377929 F8= .986186 P.U. V2= 5.79477 E-2
P.U. I= .175055 P.U. P3= .338824 P.U. P2= .344999 P.U. A8= .988881
P.U. E3= 1.0008  P.U. E4= 1.02101 P.U. E5= 1.02101
P.U. E6= 1.02101 P.U. E7= 1.01755 P.U. E8= .988881

P3= 8.44208 P2= 8.52862 V2= .811918 R= 3.16228 E-2   A8= 298.308
I4= 9.43331 F7= .219846 F8= .995499 P.U. V2= 1.90091 E-2
P.U. I= .100262 P.U. P3= .197651 P.U. P2= .199677 P.U. A8= 1.00718
P.U. E3= 1.00085 P.U. E4= 1.0221  P.U. E5= 1.0221
P.U. E6= 1.0221  P.U. E7= 1.02064 P.U. E8= 1.00718

P3= 2.75463 E-3   P2= 2.75464 E-3   V2= 8.37773 E-8   R= 100  A8= 303.02
I4= 3.03020 E-3   F7= 7.11475 E-5   F8= 1.       P.U. V2= 1.96145 E-9
P.U. I= 3.22066 E-5   P.U. P3= 6.44932 E-5   P.U. P2= 6.44934 E-5
P.U. A8= 1.02309
P.U. E3= 1.0009  P.U. E4= 1.0227  P.U. E5= 1.0227
P.U. E6= 1.0227  P.U. E7= 1.0227  P.U. E8= 1.0227




PAN     12.33 SEC.
READY.
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ARMCO 9:59 CH-E WE 07/10/8

STUDY 1969 HAW NO.5 ONLY

5566.6 200 100 52.2 10.4 .153 0 0 4.32
.432 2.8 .3 0 41 540 .05
X1= 5.23839 E-6 X2= 1.51632 E-4 X3= 0 X4= 2.41324 E-4 X5= .0028
X6= 0 X7= 7.11220 E-3
R1= 5.23839 E-7 R2= 2.23074 E-6 R3= 0 R4= 2.41324 E-5 R5= .0003
F= 55.8106 E= 296.181
P7= 42.7136

P3= 0 P2= 8.61099 V2= 80.7967 R= 0 A8= 0
I4= 94.1033 F7= .184566 F8= .105976 P.U. V2= 1.89159
P.U. I= 1 P.U. P3= 0 P.U. P2= .201598 P.U. A8= 0
P.U. E3= .999043 P.U. E4= .971769 P.U. E5= .971769
P.U. E6= .971769 P.U. E7= .894714 P.U. E8= 6.98943 E-9

P3= 2.63743 P2= 11.1862 V2= 80.2128 R= .0001 A8= 9.37626
I4= 93.7626 F7= .240009 F8= .13812 P.U. V2= 1.87792
P.U. I= .99638 P.U. P3= 6.17468 E-2 P.U. P2= .261888 P.U. A8= 3.16572
P.U. E3= .99905 P.U. E4= .972116 P.U. E5= .972116
P.U. E6= .972116 P.U. E7= .895401 P.U. E8= 3.16572 E-2

P3= 4.65771 P2= 13.1475 V2= 79.659 R= 1.77828 E-4 A8= 16.616
I4= 93.4384 F7= .282365 F8= .162844 P.U. V2= 1.86496
P.U. I= .992935 P.U. P3= .109045 P.U. P2= .307805 P.U. A8= 5.61007 E-2
P.U. E3= .999057 P.U. E4= .97245 P.U. E5= .97245
P.U. E6= .97245 P.U. E7= .896108 P.U. E8= 5.61008 E-2

P3= 8.1593 P2= 16.5226 V2= 78.4722 R= 3.16228 E-4 A8= 29.3269
I4= 92.7398 F7= .355591 F8= .206036 P.U. V2= 1.83717
P.U. I= .98551 P.U. P3= .191024 P.U. P2= .386822 P.U. A8= 9.90168 E-2
P.U. E3= .999076 P.U. E4= .973175 P.U. E5= .973175
P.U. E6= .973175 P.U. E7= .897714 P.U. E8= 9.90169 E-2

P3= 14.0139 P2= 22.0915 V2= 75.7916 R= 5.62341 E-4 A8= 51.2529
I4= 91.142 F7= .477697 F8= .279831 P.U. V2= 1.77441
P.U. I= .968532 P.U. P3= .328089 P.U. P2= .517199 P.U. A8= .173046
P.U. E3= .999121 P.U. E4= .974835 P.U. E5= .974835
P.U. E6= .974835 P.U. E7= .901565 P.U. E8= .173046

P3= 22.9082 P2= 30.3335 V2= 69.6712 R= .001 A8= 87.3845
I4= 87.3845 F7= .663215 F8= .399187 P.U. V2= 1.63112
P.U. I= .928603 P.U. P3= .53632 P.U. P2= .710159 P.U. A8= .295038
P.U. E3= .999232 P.U. E4= .978662 P.U. E5= .978662
P.U. E6= .978662 P.U. E7= .910802 P.U. E8= .295038

P3= 33.326 P2= 39.4004 V2= 56.9961 R= 1.77828 E-3 A8= 140.55
I4= 79.0371 F7= .882698 F8= .568639 P.U. V2= 1.33438
P.U. I= .839897 P.U. P3= .780219 P.U. P2= .922432 P.U. A8= .474541
P.U. E3= .99948 P.U. E4= .986631 P.U. E5= .986631
P.U. E6= .986631 P.U. E7= .930523 P.U. E8= .474541

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P3= 38.8017 P2= 42.7789 V2= 37.3176 R= 3.16228 E-3   A8= 202.239
I4= 63.9536 F7= .999959 F8= .75357  P.U. V2= .873671
P.U. I= .679611 P.U. P3= .908417 P.U. P2= 1.00153 P.U. A8= .682823
P.U. E3= .999886 P.U. E4= .998994 P.U. E5= .998994
P.U. E6= .998994 P.U. E7= .961481 P.U. E8= .682823

P3= 33.891  P2= 35.8445 V2= 18.3294 R= 5.62341 E-3   A8= 252.047
I4= 44.821  F7= .878596 F8= .890346 P.U. V2= .429122
P.U. I= .476296 P.U. P3= .793448 P.U. P2= .839182 P.U. A8= .85099
P.U. E3= 1.0003  P.U. E4= 1.01089 P.U. E5= 1.01089
P.U. E6= 1.01089 P.U. E7= .991492 P.U. E8= .85099

P3= 23.5396 P2= 24.3026 V2= 7.15916 R= .01      A8= 280.117
I4= 28.0117 F7= .61475  F8= .959244 P.U. V2= .167608
P.U. I= .29767  P.U. P3= .551104 P.U. P2= .568967 P.U. A8= .945763
P.U. E3= 1.00055 P.U. E4= 1.0179  P.U. E5= 1.0179
P.U. E6= 1.0179  P.U. E7= 1.00949 P.U. E8= .945763

P3= 14.4682 P2= 14.7319 V2= 2.47444 R= 1.77828 E-2   A8= 292.851
I4= 16.4682 F7= .377929 F8= .986186 P.U. V2= 5.79308 E-2
P.U. I= .175001 P.U. P3= .338725 P.U. P2= .344899 P.U. A8= .988756
P.U. E3= 1.00067 P.U. E4= 1.02088 P.U. E5= 1.02088
P.U. E6= 1.02088 P.U. E7= 1.01742 P.U. E8= .988756

P3= 8.4398  P2= 8.5263  V2= .811698 R= 3.16228 E-2   A8= 298.267
I4= 9.43203 F7= .219846 F8= .995499 P.U. V2= 1.90033 E-2
P.U. I= .100231 P.U. P3= .19759  P.U. P2= .199616 P.U. A8= 1.00704
P.U. E3= 1.00072 P.U. E4= 1.02197 P.U. E5= 1.02197
P.U. E6= 1.02197 P.U. E7= 1.0205  P.U. E8= 1.00704

P3= 2.75383 E-3   P2= 2.75384 E-3   V2= 8.37528 E-3   R= 100  A8= 302.9
I4= 3.02976 E-3   F7= 7.11475 E-5   F8= 1.        P.U. V2= 1.96080 E-9
P.U. I= 3.21961 E-5  P.U. P3= 6.44719  E-5   P.U. P2= 6.44721 E-5
P.U. A8= 1.02294
P.U. E3= 1.00075 P.U. E4= 1.02255 P.U. E5= 1.02255
P.U. E6= 1.02255 P.U. E7= 1.02255 P.U. E8= 1.02255




RAN     11.83 SEC.
READY.
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ARMCO 10:11 CH-E WE 07/10/8

STUDY 1969 NORMAL, UPRATED

7153.0 200 100 58 10.4 .153 0 0 4.8
.48 2.8 .3 0 41 540 .05
X1= 4.07661 E-6 X2= 1.51632 E-4 X3= 0 X4= 2.41324 E-4 X5= .0028
X6= 0 X7= 7.11220 E-3
R1= 4.07661 E-7 R2= 2.23074 E-6 R3= 0 R4= 2.41324 E-5 R5= .0003
F= 62.0117 E= 296.181
P7= 42.7155

P3= 0 P2= 8.61465 V2= 80.831 R= 0 A8= 0
I4= 94.1233 F7= .184566 F8= .105976 P.U. V2= 1.89231
P.U. I= 1 P.U. P3= 0 P.U. P2= .201675 P.U. A8= 0
P.U. E3= .999255 P.U. E4= .971975 P.U. E5= .971975
P.U. E6= .971975 P.U. E7= .894904 P.U. E8= 6.74693 E-9

P3= 2.63854 P2= 11.1909 V2= 80.2466 R= .0001 A8= 9.37824
I4= 93.7824 F7= .240009 F8= .13812 P.U. V2= 1.87863
P.U. I= .996378 P.U. P3= 6.17701 E-2 P.U. P2= .261987 P.U. A8= 3.1663
P.U. E3= .99926 P.U. E4= .972321 P.U. E5= .972321
P.U. E6= .972321 P.U. E7= .89559 P.U. E8= 3.16639 E-2

P3= 4.65966 P2= 13.153 V2= 79.6923 R= 1.77828 E-4 A8= 16.6194
I4= 93.458 F7= .282365 F8= .162844 P.U. V2= 1.86565
P.U. I= .992932 P.U. P3= .109086 P.U. P2= .30792 P.U. A8= 5.61125 E-2
P.U. E3= .999266 P.U. E4= .972653 P.U. E5= .972653
P.U. E6= .972653 P.U. E7= .896295 P.U. E8= 5.61125 E-2

P3= 8.16265 P2= 16.5293 V2= 78.5044 R= 3.16228 E-4 A8= 29.3329
I4= 92.7588 F7= .355591 F8= .206036 P.U. V2= 1.83784
P.U. I= .985503 P.U. P3= .191093 P.U. P2= .386963 P.U. A8= 9.90371 E-2
P.U. E3= .99928 P.U. E4= .973375 P.U. E5= .973375
P.U. E6= .973375 P.U. E7= .897898 P.U. E8= 9.90372 E-2

P3= 14.0194 P2= 22.1001 V2= 75.8212 R= 5.62341 E-4 A8= 51.2629
I4= 91.1598 F7= .477697 F8= .279831 P.U. V2= 1.77503
P.U. I= .968515 P.U. P3= .328203 P.U. P2= .517378 P.U. A8= .17308
P.U. E3= .999316 P.U. E4= .975025 P.U. E5= .975025
P.U. E6= .975025 P.U. E7= .901741 P.U. E8= .17308

P3= 22.916 P2= 30.3438 V2= 69.6949 R= .001 A8= 87.3994
I4= 87.3994 F7= .663215 F8= .399187 P.U. V2= 1.63161
P.U. I= .928564 P.U. P3= .536479 P.U. P2= .710369 P.U. A8= .295088
P.U. E3= .999403 P.U. E4= .978829 P.U. E5= .978829
P.U. E6= .978829 P.U. E7= .910957 P.U. E8= .295088

P3= 33.3337 P2= 39.4095 V2= 57.0093 R= 1.77828 E-3 A8= 140.566
I4= 79.0462 F7= .882698 F8= .568639 P.U. V2= 1.33463
P.U. I= .839816 P.U. P3= .780364 P.U. P2= .922604 P.U. A8= .474596
P.U. E3= .999595 P.U. E4= .986745 P.U. E5= .986745
P.U. E6= .986745 P.U. E7= .93063 P.U. E8= .474596

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P3= 38.8037 P2= 42.7811 V2= 37.3195 R= 3.16228 E-3   A8= 202.244
I4= 63.9552 F7= .999959 F8= .75357  P.U. V2= .873676
P.U. I= .679484 P.U. P3= .908422 P.U. P2= 1.00154 P.U. A8= .68284
P.U. E3= .999911 P.U. E4= .999019 P.U. E5= .999019
P.U. E6= .999019 P.U. E7= .961505 P.U. E8= .68284

P3= 33.8865 P2= 35.8398 V2= 18.3269 R= 5.62341 E-3   A8= 282.03
I4= 44.8181 F7= .878596 F8= .890346 P.U. V2= .429046
P.U. I= .476163 P.U. P3= .793308 P.U. P2= .839034 P.U. A8= .850934
P.U. E3= 1.00023 P.U. E4= 1.01082 P.U. E5= 1.01082
P.U. E6= 1.01082 P.U. E7= .991426 P.U. E= .850934

P3= 23.5338 P2= 24.2966 V2= 7.1574  R= .01      A8= 280.082
I4= 28.0082 F7= .61475  F8= .959244 P.U. V2= .16756
P U. I= .29757  P.U. P3= .550944 P.U. P2= .568801 P.U. A8= .945646
P.U. E3= 1.00043 P.U. E4= 1.01778 P.U. E5= 1.01778
P.U. E6= 1.01778 P.U. E7= 1.00936 P.U. E8= .945646

P3= 14.4639 P2= 14.7275 V2= 2.4737  R= 1.77828 E-2   A8= 292.807
I4= 16.4657 F7= .377929 F8= .986186 P.U. V2= .057911
P.U. I= .174938 P.U. P3= .338609 P.U. P2= .344781 P.U. A8= .988609
P.U. E3= 1.00052 P.U. E4= 1.02073 P.U. E5= 1.02073
P.U. E6= 1.02073 P.U. E7= 1.01727 P.U. E8= .988608

P3= 8.43711 P2= 8.52359 V2= .81144  R= 3.16228 E-2   A8= 298.22
I4= 9.43053 F7= .219846 F8= .995499 P.U. V2= 1.89964 E-2
P.U. I= .100193 P.U. P3= .197519 P.U. P2= .199543 P.U. A8= 1.00688
P.U. E3= 1.00056 P.U. E4= 1.0218  P.U. E5= 1.0218
P.U. E6= 1.0218  P.U. E7= 1.02034 P.U. E8= 1.00688

P3= 2.75292 E-3   P2= 2.75293 E-3   V2= 8.37252 E-8   R= 100  A8= 302.9
I4= 3.02926 E-3   F7= 7.11475 E-5   F8= 1.       P.U. V2= 1.96007 E-9
P.U. I= 3.21839 E-5   P.U. P3= 6.44478 E-5   P.U. P2= 6.44480 E-5
P.U. A8= 1.02277
P.U. E3= 1.00059 P.U. E4= 1.02238 P.U. E5= 1.02238
P.U. E6= 1.02238 P.U. E7= 1.02238 P.U. E8= 1.02238




RAN     11.00 SEC.
READY.


BYE

***OFF AT 10:20  ELAPSED TERMINAL TIME =    93 MIN.
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A STUDY OF VOLTAGE FLICKER CAUSED BY ELECTRIC ARC FURNACES

by

CHING-HUNG PENG

Taipei Institute of Technology

Taipei, 1957

AN ABSTRACT OF A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Electrical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1971

A STUDY OF VOLTAGE FLICKER CAUSED BY
ELECTRIC ARC FURNACES

Electric arc furnace principles and flicker problems were probed. Equivalent circuits for an unbalanced furnace are presented and the circuit theory is derived.

A computer program was used to determine the possibility of flicker of a furnace installation, and the results were compared with field tests. The study provides a new approach to help system planning on a power supply to new furnace installations without permitting flicker problems to the other electric users.