NRL REPORT 3819

FR-3819

UNCLASSIFIED

# INTERMITTENT FAULTS IN 120/208-VOLT A-C AND 120-VOLT D-C AIRCRAFT ELECTRICAL SYSTEMS

P. E. Toomire and M. Trbovich

May 9, 1951

**Distribution Unlimited**

Approved for
Public Release

Approved by:

L. R. Larson, Head, Airborne Systems Branch
W. C. Hall, Superintendent, Electricity Division

DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH

NAVAL RESEARCH LABORATORY
CAPTAIN F. R. FURTH, USN, DIRECTOR
WASHINGTON, D.C.

## DISTRIBUTION

| | |
|---|---|
| OpNav | |
| Attn: Code Op-42 | 2 |
| BuAer | |
| Attn: Code EL-61 | 10 |
| CO & Dir., USNEL | 2 |
| CDR, USNOTS | |
| Attn: Reports Unit | 2 |
| CDR, NADC | 1 |
| CDR, NATC | |
| Attn: Electronics Test | 1 |
| OCSigO | |
| Attn: Ch. Eng. & Tech. Div., SIGTM-S | 1 |
| CG, SCEL | |
| Attn: SCEL Liaison Office | 3 |
| Chief of Staff, USAF | 1 |
| Wright-Patterson AFB | |
| Attn: BAU-CADO | 1 |
| Attn: CADO-E1 | 2 |
| Dir., NACA | 1 |
| Office of Tech. Services, Dept. of Commerce | 2 |
| Div. of Public Documents, GPO | |
| Attn: Library | 1 |
| RDB | |
| Attn: Information Requirements Branch | 2 |
| Attn: Navy Secretary | 1 |
| Naval Res. Sec., Science Div., Library of Congress | |
| Attn: Mr. J. H. Heald | 2 |

## CONTENTS

## ABSTRACT

The results of the investigation of faults on a simulated 120/208-volt, 400-cycle aircraft electrical system show that, of the 225 faults established, approximately five percent developed into welded faults, while the remaining 95 percent were of the intermittent type. The fault-current magnitude is primarily determined by the contact resistance and the arc resistance in the external circuit, and the subtransient reactance of the generator. It is believed that the intermittent fault usually begins by fault-current flow in excess of the capacity of the contact strands. This results in melting these strands, causing separation of the faulted conductor and the grounded plate. The duration of the first fault pulse for 98 percent of the intermittent faults was less than 0.01 second. No correlation was observed between structure vibration and the first fault-pulse duration, but faults established on a vibrating platform usually last longer and result in more welds than faults established on a stationary platform. Damage to the grounded structure from intermittent faults is less in the 120/208-volt, 400-cycle system than in either the 30-volt or 120-volt d-c systems used in this investigation. Although the current is greater in the a-c faults, the arc duration is much shorter than the duration of intermittent faults on a 30-volt d-c system. Small values of effective current are obtained when considering duration over several fault pulses.

The results of the investigation of faults on a simulated 120-volt d-c aircraft electrical system show that, of the 180 faults established, approximately 91 percent resulted in intermittent-type faults. It has not been possible to correlate the fault-current magnitude with structure vibration. It is concluded that the resistance of the contact and the arc resistance will primarily determine the fault-current magnitude for a particular system with a given fault-circuit cable resistance. First fault-pulse durations are longer without batteries connected to the system than with batteries connected. The structure-vibration frequency and displacement have little effect on the pulse durations. However, the direction of structure vibration has an effect on the duration. Horizontal vibration perpendicular to the cable run caused first fault pulses of longer durations than horizontal vibration parallel to the cable run or vertical vibration. The average currents obtained when considering the duration over several successive pulses of the fault are small, because of the relatively long time between pulses. The simulated 120-volt d-c system does not give considerably higher minimum fault currents than the simulated 30-volt d-c system. However, as a whole, the magnitude and duration of the faults on a 120-volt system are much greater than on a 30-volt system.

## PROBLEM STATUS

This report concluded the work on this problem and, unless otherwise notified, the Laboratory will consider the problem closed one month from the mailing date of this report.

## AUTHORIZATION

NRL Problem E03-24R
NR 423-240
March 20, 1951

# INTERMITTENT FAULTS IN 120/208-VOLT A-C AND 120-VOLT D-C AIRCRAFT ELECTRICAL SYSTEMS

## INTRODUCTION

Both d-c and 400-cycle a-c electrical systems of higher voltage than the present 30-volt d-c systems are being developed to keep pace with the rapid increase in electrical-power requirements in military aircraft. It has been demonstrated in 30-volt d-c aircraft electrical systems that electrical faults may be considered as being either of two types depending upon the nature of the contact at the point of the fault.

The first type of fault is characterized by continuous metal-to-metal contact between the electrical conductor and the plane structure. This type of fault usually results in damage to the electrical system and has received attention to the extent that circuits have been devised which are capable of minimizing damage from these faults in a limited section of the electrical system.

A second type of fault in an aircraft electrical system is characterized by the separation of a faulted conductor and the aircraft structure after contact has been made. Due to the intermittent nature of this type of fault, large areas of the plane structure may be melted or vaporized by the arc while the faulted cable a short distance from the arc is not excessively hot.[1,2,3]

The purpose of this investigation was to obtain data as to the types of faults and the approximate values of fault-current magnitude and duration in a simulated 120-volt d-c system and a 120/208-volt, 400-cycle a-c system. It was further desired to determine the contribution of certain environmental conditions found in aircraft to these faults. The cable used in this investigation conforms to the requirements of specifications AN-J-C-48a and AN-W-14a.

## PART I
## ELECTRICAL FAULTS IN A 120/208-VOLT, 400-CYCLE SYSTEM

### TEST CIRCUIT AND PROCEDURE

The circuit used in this investigation (Figure 1) utilized a Westinghouse Type A-1 40Kva aircraft generator driven by a 50-horsepower motor as the electrical power source. The

---

[1] Cunningham, J. C., and Davidson, W. M., "A-C and D-C Short-Circuit Tests on Aircraft Cable," AIEE Trans. 63:961-968, December 1944

[2] Trbovich, M., and Toomire, P. E., "Investigation of Intermittent Faults in 30-Volt D-C Aircraft Electrical Systems," NRL Report 3643, April 3, 1950

[3] Alm, E., "Physical Properties of Arcs in Circuit Breakers," Acta Polytechnica 47, 1949

grounded structure was an aluminum alloy plate, 0.091 inch thick, mounted on a vibrating platform (Figure 2). The parameters considered when faults were established on this structure are listed below:

Structure Vibration

Frequencies (cps) - 0; 30; 50
Total Displacement (in.) - 0.0125; 0.05
Direction - Horizontal and perpendicular to cable run;
Horizontal and parallel to cable run; Vertical

Faulted Cable

Size (No.) - 8; 12; 16
Length (ft) - 10

Load Prior to Fault

Type - No load; Balanced; Unbalanced
Power Factor - 1.00; 0.75 (lag)

Only single-phase faults were established, however, since faults of this kind seem most likely to occur in aircraft. In particular, only light-contact, line-to-ground faults were considered since these faults may result in relatively small fault currents but erratic system operation and extensive structure damage. The faulted cable was mounted so that the distance between the point where the cable was clamped to a bracket on the vibration platform and the point of the fault was from 8 to 12 inches.

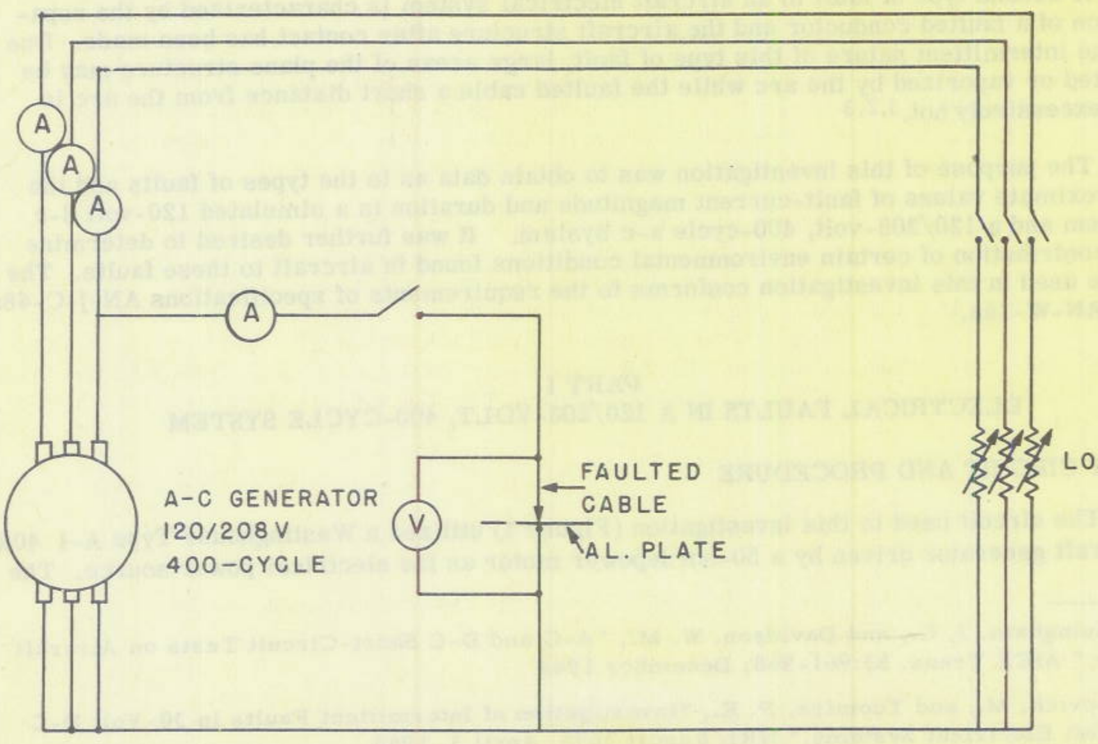

Figure 1 - Schematic diagram of circuit used in the study of faults in a 120/208-volt, 400-cycle aircraft electrical system

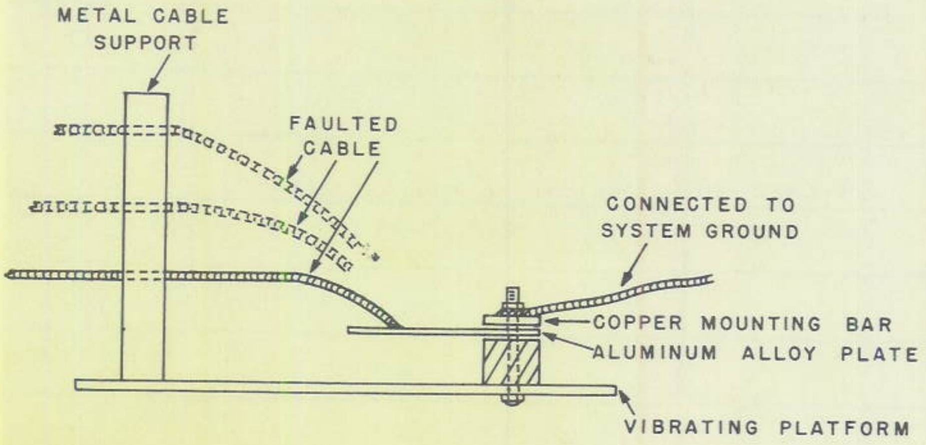

Figure 2 - Mounting arrangement for light-contact, line-to-ground faults

The cable sizes selected for this study were No. 8, No. 12, and No. 16. These sizes are considered representative of cables used in an aircraft installation. The footage of each size wire and the longest and shortest length of each size wire in a proposed 120/208-volt, 400-cycle, two-generator aircraft electrical system are shown in Table 1.

TABLE 1

Wire Sizes for a Proposed 120/208-Volt, 400-Cycle Two-Generator Aircraft Electrical System

| Cable Size (No.) | Cable Footage (Ft.) | Longest Length (Ft.) | Shortest Length (In.) |
|---|---|---|---|
| A-C power-distribution-system wiring | | | |
| 0 | 123 | 10 | 20 |
| 4 | 9 | 3 | 20 |
| 8 | 2343 | 58 | 50 |
| 12 | 2493 | 69 | 50 |
| 16 | 7 | 3 | 5 |
| 20 | 503 | 92 | 20 |
| A-C generator-control wiring | | | |
| 16 | 523 | 63 | 15 |
| 18 | 278 | 63 | 20 |
| 20 | 1073 | 63 | 4 |
| A-C power-instrument wiring | | | |
| 16 | 218 | 63 | 20 |
| 20 | 1200 | 63 | 4 |

With the cables used in this study, the calculated values of the fault circuit wire resistance at an ambient temperature of 20°C are 0.0104 ohm for faulted cable size No. 8, 0.0220 ohm for faulted cable size No. 12, and 0.0510 ohm for faulted cable size No. 16. The faulted cable was connected to the main alternator lead approximately 0.001 ohm from the a-c generator terminal.

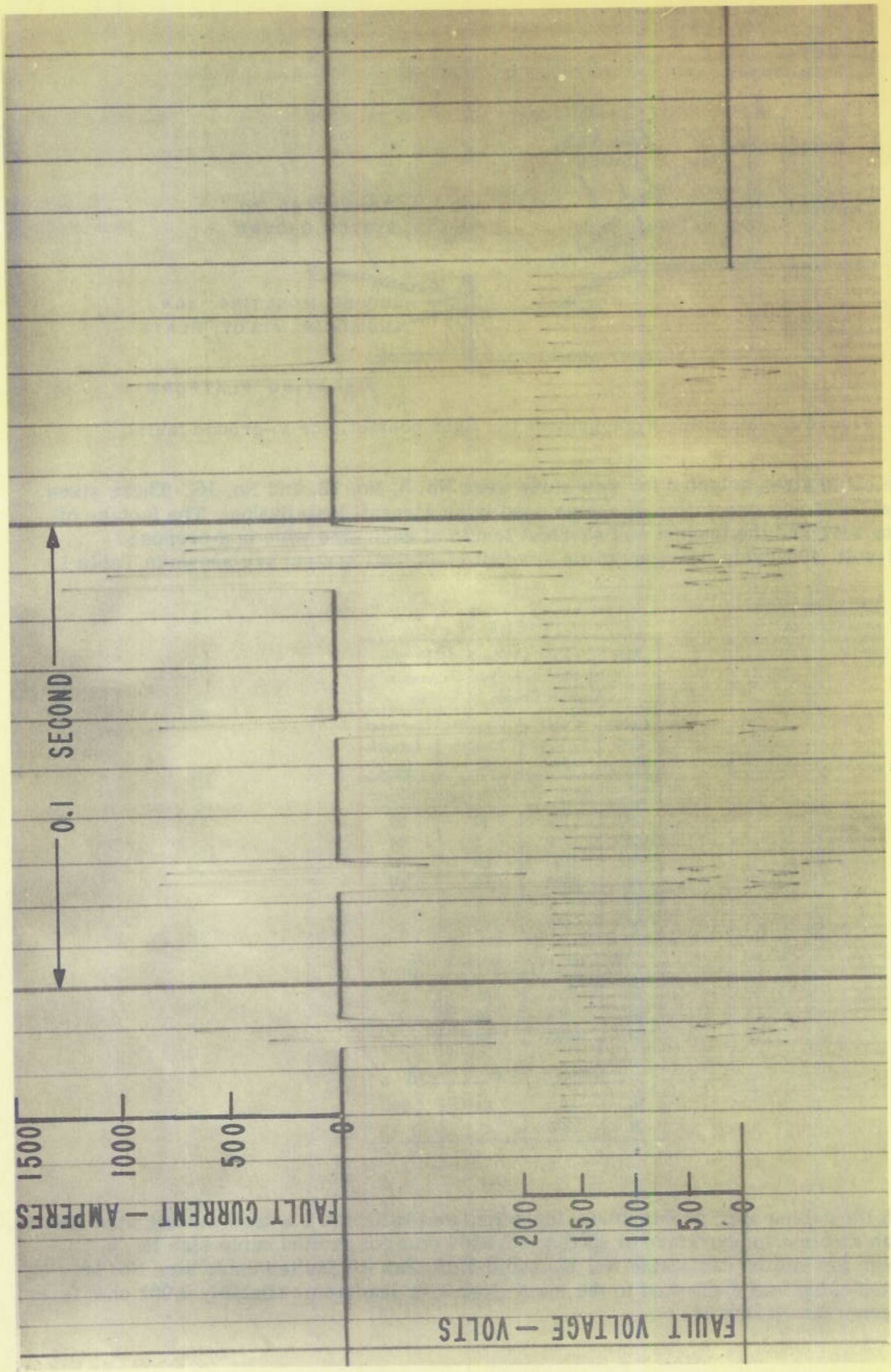

Figure 3 - Typical oscillogram showing fault current and voltage obtained on a simulated 120/208-volt, 400-cycle aircraft electrical system. Fault established on cable size No. 12. Load prior to fault balanced and at 0.75 lagging power factor. Structure vibration vertical, frequency 30 cps; displacement 0.05 inch.

There were established 225 faults by arbitrarily dropping conductors onto the aluminum alloy plate connected to the generator neutral. A clean (unburned) plate was used for each fault established. The current and voltage of all faults were recorded with a Consolidated Engineering Corporation oscillograph. A typical oscillogram is shown in Figure 3.

## DESCRIPTION OF FAULTS

Of the 225 faults established, approximately 4.5 percent developed into welded faults; however, no welds resulted from faults established on a nonvibrating platform.

Only the first fault-pulse data is reported, but the average magnitude of the succeeding fault pulses is approximately the same as the magnitude of the first. The time between the first and second fault pulses is shown in Figure 4.

The 400-cycle peaks of the first pulse were numbered consecutively without regard to polarity. Current peaks, plotted against half-cycle numbers (Figures 5 through 9), are considered to be accurate to ± 2 percent. It was found that the rms value of the current for single-phase faults on the particular generator used is 10 to 15 percent less than the rms value of a sine wave of the same amplitude.

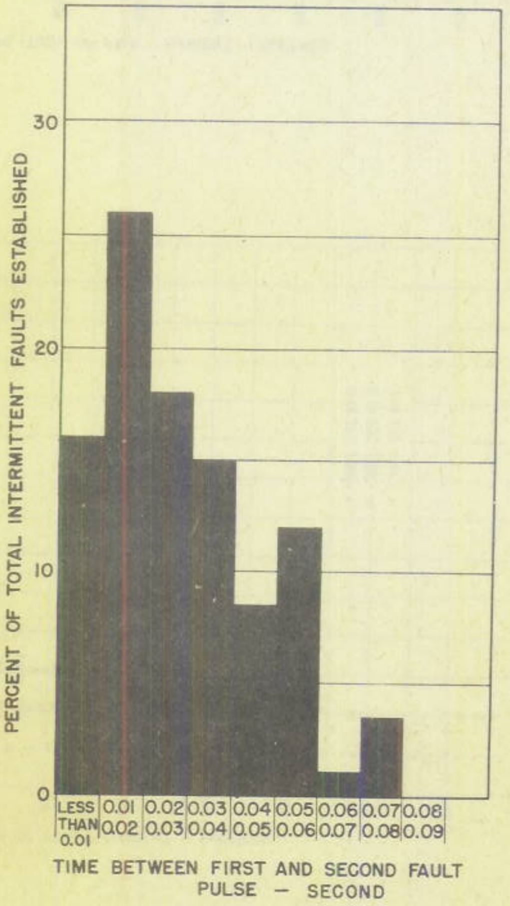

Figure 4 - Time between the first and second fault pulse of faults struck on a simulated 120/208-volt, 400-cycle aircraft electrical system

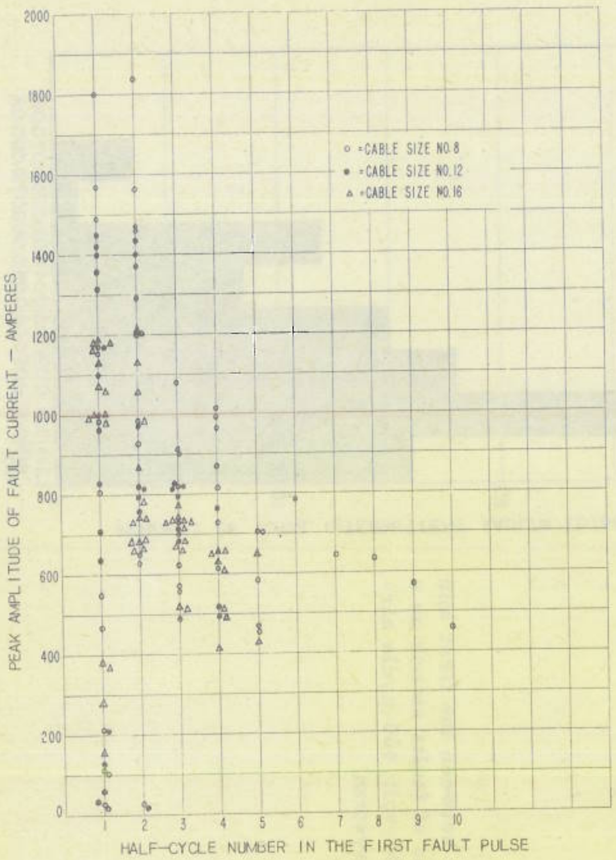

Figure 5 - Peak fault current versus the half-cycle number in the first fault pulse for various cable sizes. Structure-vibration frequency 50 cps, displacement 0.05 inch.

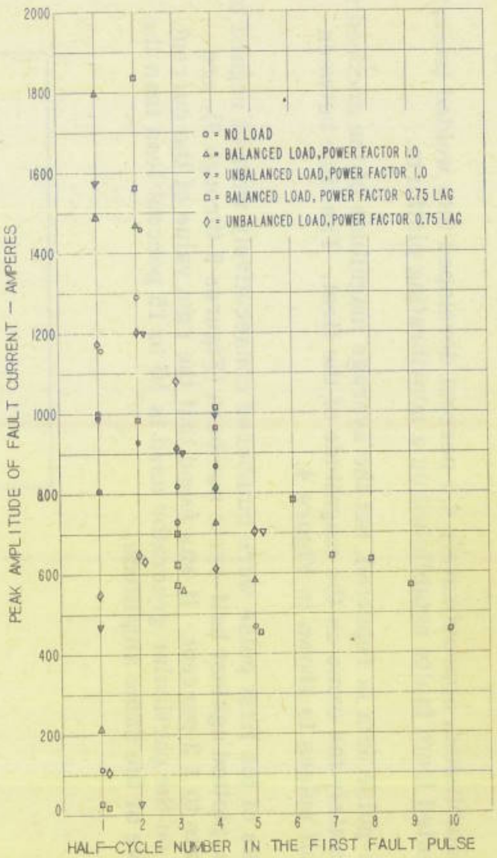

Figure 6 - Peak fault current versus the half-cycle number in the first fault pulse for various loads. Faults struck on cable size No. 8. Structure-vibration frequency 50 cps, displacement 0.05 inch.

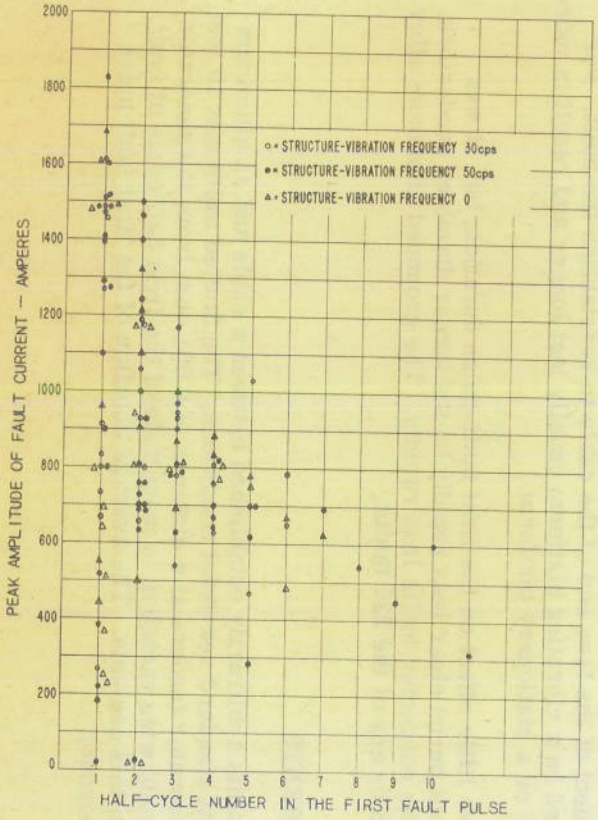

Figure 7 - Peak fault current versus the half-cycle number in the first fault pulse for various structure-vibration frequencies. Faults struck on cable size No. 8. Structure-vibration displacement 0.0125 inch.

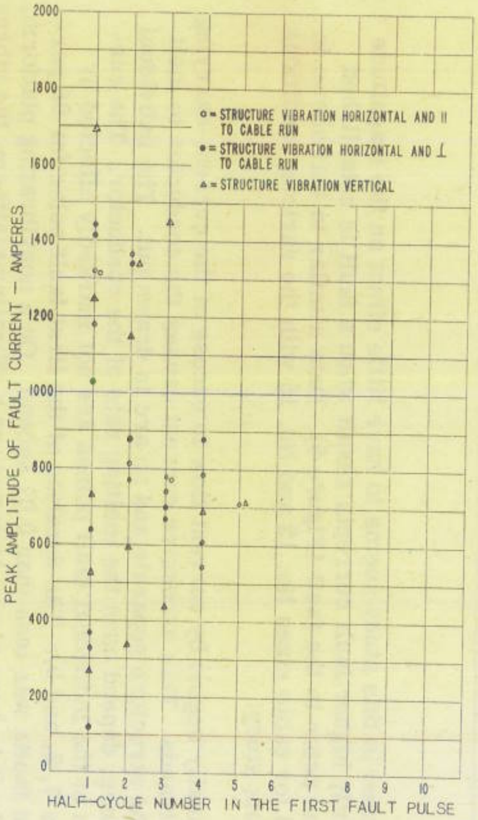

Figure 8 - Peak fault current versus the half-cycle number for various directions of structure vibration. Faults established on cable size No. 12. Structure-vibration frequency 30 cps displacement 0.05 inch.

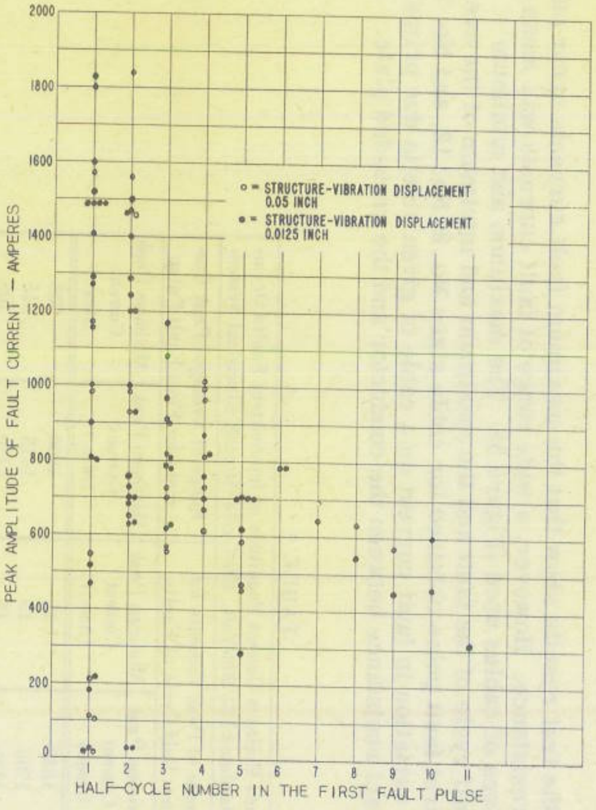

Figure 9 - Peak fault current versus the half-cycle number in the first fault pulse for various structure-vibration displacements. Faults established on cable size No. 8. Structure vibration frequency 50 cps.

As would be expected, the test results show that the maximum fault currents occur on the cable with the smaller resistance. However, a wide range of fault currents was measured on each of the three sizes of cables used (Figure 5). The maximum and minimum peak current for the first half cycle of the fault and the maximum and minimum of the averaged peak currents of the first fault pulse obtained for cable sizes No. 8, No. 12, and No. 16 are shown in Table 2. The variation in fault current on a cable of given size is due primarily to the variation in contact resistance between the conductor and the grounded plate.

TABLE 2

Maximum and Minimum Current Magnitude of Intermittent Faults Occurring in a Simulated 120/208-Volt, 400-Cycle Aircraft Electrical System

| Cable Size (No.) | Range of Peak Currents for First Half Cycle of Faults | | Range of Averaged Peak Currents for First Fault Pulse | |
|---|---|---|---|---|
| | Maximum Peak Current (Amp.) | Minimum Peak Current (Amp.) | Maximum Peak Current (Amp.) | Minimum Peak Current (Amp.) |
| 8 | 1840 | 15 | 1800 | 235 |
| 12 | 1700 | 15 | 1415 | 315 |
| 16 | 1320 | 15 | 1130 | 105 |

While the type of load used in this study seems to have little effect on the magnitude of the first fault pulse, slightly higher fault currents result when a fault is established on a generator supplying load prior to the fault (Figure 6). Data similar to that shown in Figure 6 were also obtained for cable sizes No. 12 and No. 16 with the various conditions of vibration considered in this study.

An intermittent fault usually begins by current flow in excess of the current-carrying capacity of the contacting-strands. This excessive current causes the conductor to melt. The faulted conductor and the structure separate and an arc is drawn out. The individual fault-current pulses, therefore, depend upon the melting rate of the conductor. The current magnitude and duration of the individual fault pulses are not markedly affected by structure vibration (Figures 7, 8, and 9). The duration of the first fault pulse for 98 percent of the total intermittent faults was less than 0.01 second. On a nonvibrating platform, there is a tendency for the fault to burn clear; however, on a vibrating platform, the vibration causes sufficient movement of the free end of the cable to reestablish the fault. For this reason, faults established on a vibrating platform usually last longer and result in more welds than faults established on a stationary platform.

Cable sizes seem to have little effect on the first fault-pulse duration; but, it was found that an intermittent fault burns clear less rapidly on the larger diameter conductors. This is due to the fact that the conductor melts less rapidly. The grounded aluminum alloy structure was not penetrated by any of the 225 faults.

## ANALYSIS OF FAULT CURRENTS

Data were taken from faults arbitrarily established between a cable and an aluminum alloy plate 0.091 inch thick at standard sea-level conditions. The faulted cable was 10 feet long and connected to the generator feeders at a distance of 0.001 ohm from the generator terminal. Due to the extremely wide variation in magnitude of the first half cycle of fault current, it was omitted from this analysis. The average duration of the first fault pulse was 2-1/2 cycles (0.00625 second).

For single-phase faults on the particular generator used, the rms value of fault current is 10 to 15 percent less than the rms value of a sine wave of the same amplitude. The value of 10 percent was used in this analysis. It was further found that the average magnitude of current pulses following the first is the same as for the first pulse. It is seen from Figure 4 that the time between the first and second pulse of 100 percent of the faults is 0.08 second or less, and the time between the first and second pulse of 75 percent of the faults is 0.04 second or less.

With the above interpretation, the rms current for each fault-current pulse of all (100 percent) of the faults struck on size No. 8 cable is 150 amperes or greater. The minimum effective fault current, considered over the duration of several pulses, is calculated to be 10 amperes rms. The rms current for each fault-current pulse of 75 percent of the faults struck on size No. 8 cable is 505 amperes or greater. The minimum effective fault current considered over the duration of several pulses for 75 percent of the faults established is 70 amperes rms. Similar data were obtained for cable sizes No. 12 and No. 16, and the results are shown in Table 3.

TABLE 3

Minimum Currents of 100 Percent and 75 Percent of the Intermittent Faults (Based on Fault-Pulse Duration of 0.00625 Second) Occurring on a Simulated 120/208-Volt, 400-Cycle Aircraft Electrical System

| Cable Size (No.) | Faults Established for Each Cable Size (%) | Effective (RMS) Current Due to Several Fault Pulses (Amp.) | Effective (RMS) Current of First Fault Pulse (Amp.) |
|---|---|---|---|
| 8 | 100 | 10 | 150 |
| 8 | 75 | 70 | 505 |
| 12 | 100 | 15 | 200 |
| 12 | 75 | 60 | 460 |
| 16 | 100 | 5 | 70 |
| 16 | 75 | 55 | 390 |

## PART II
## ELECTRICAL FAULTS IN A 120-VOLT D-C SYSTEM

### TEST CIRCUIT AND PROCEDURE

The circuit used in this investigation (Figure 10) consisted of a General Electric 120-volt, 20-kw aircraft generator, type 2CM65C (regulated by a Westinghouse AVR22A regulator) in parallel with four 24-volt, 34-ampere-hour (AN 3150) aircraft batteries connected in series. The generator was driven at 5500 rpm by a 50-hp motor. The grounded structure was an aluminum alloy plate, 0.091 inch thick, mounted on a vibrating platform (Figure 2). A total of 180 faults were established by arbitrarily dropping conductors onto the aluminum plate. In this d-c system, as in the a-c system, light-contact faults were considered to be of particular interest because of the small fault current but erratic system operation and extensive structure damage. A clean (unburned) plate was used for each fault established, and a Consolidated Engineering Corporation oscillograph was used to record the current and voltage of each fault. A typical oscillogram is shown in Figure 11. The first current pulse of each fault was evaluated for study, since for minimum damage it would be desirable to detect the first pulse. This study was conducted at standard sea-level conditions.

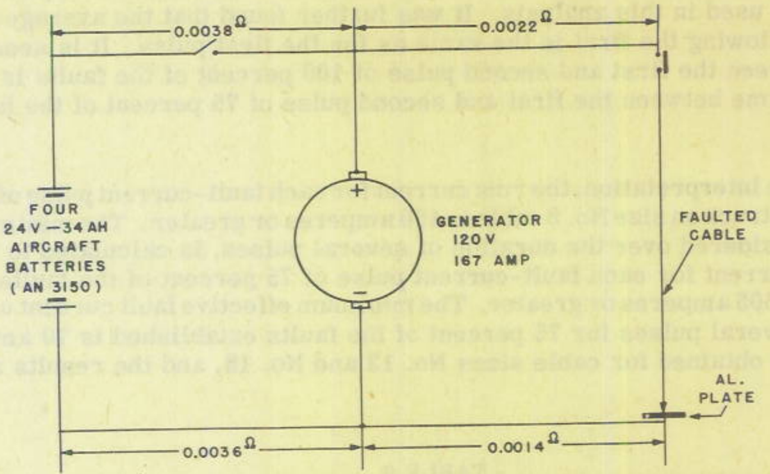

Figure 10 - Resistances of the main circuit used in the study of electrical faults in a 120-volt d-c system

Fault data were collected considering all meaningful combinations of the parameters listed below:

Batteries

Connected; Disconnected

Structure Vibration

Frequencies (cps) - 0; 30; 50
Total Displacement (in.) - 0.0125; 0.05
Direction - Horizontal and perpendicular to cable run;
Horizontal and parallel to cable run; Vertical

Faulted Cable

Size (No.) - 2; 8; 16
Length (ft) - 10

Load Prior to Fault

No load; 100 amperes

The effect of load on the system prior to the fault and of batteries connected to the system is seen from the transient and steady-state characteristics (Figure 12) of the system used in this study. Curves A, B, C, and D in this figure represent the transient characteristics of the system ($\Delta E$ vs. $\Delta I$). The increase of transient current with a steady-state load on the system prior to transient loading is due to the steady-state load causing the regulator to insert less resistance in the shunt-field circuit prior to transient loading. The figure also shows that, for the same fault resistance, the transient currents with batteries connected to the system will be greater than when the batteries are disconnected, due to the system maintaining higher voltage under load.

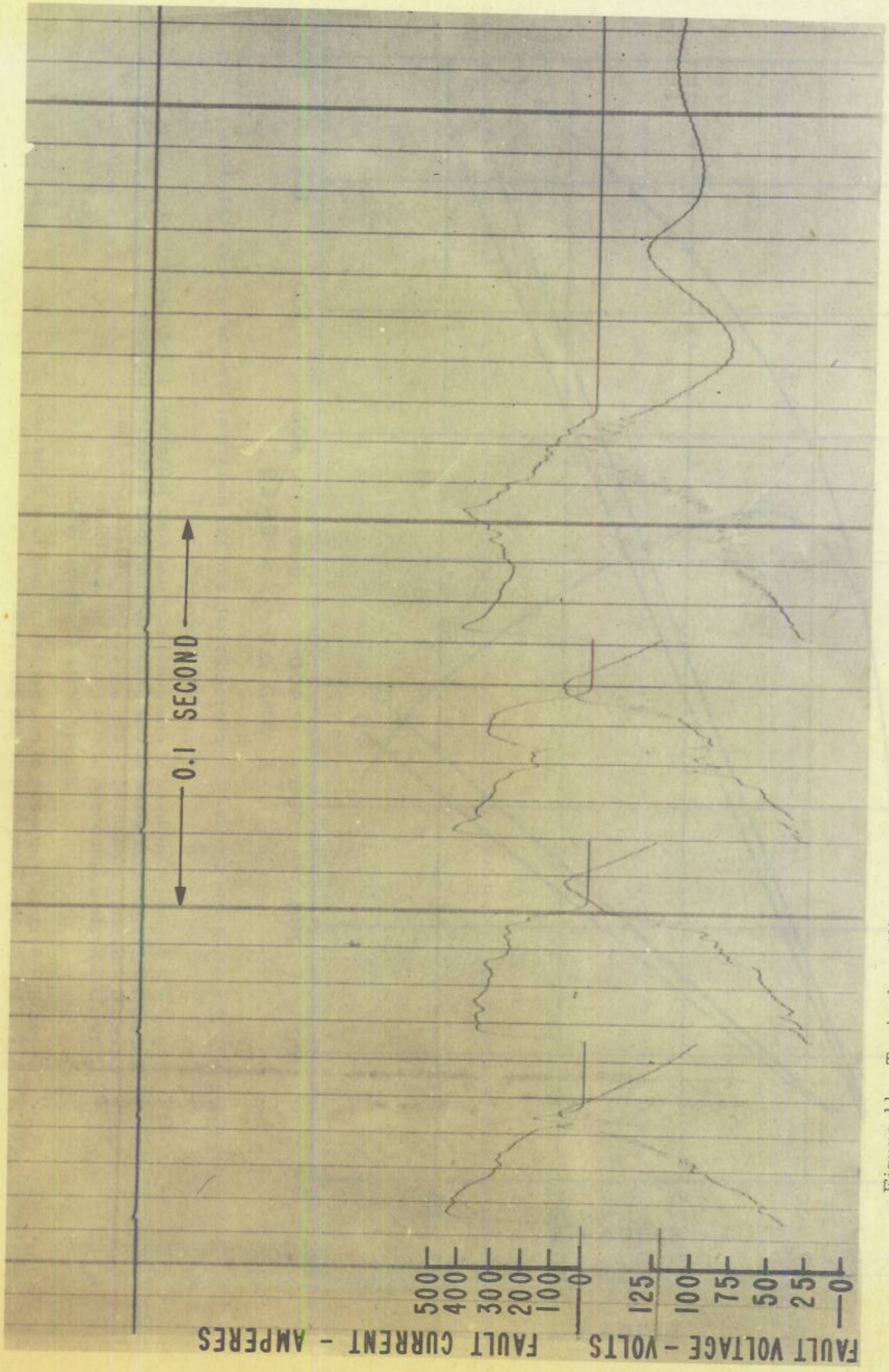

Figure 11 - Typical oscillogram showing fault current and voltage obtained on a simulated 120-volt d-c aircraft electrical system. Fault established on cable size No. 16, 100-ampere load prior to fault. Batteries disconnected from system. Structure vibration horizontal and parallel to cable run, frequency 30 cps, displacement 0.0125 inch.

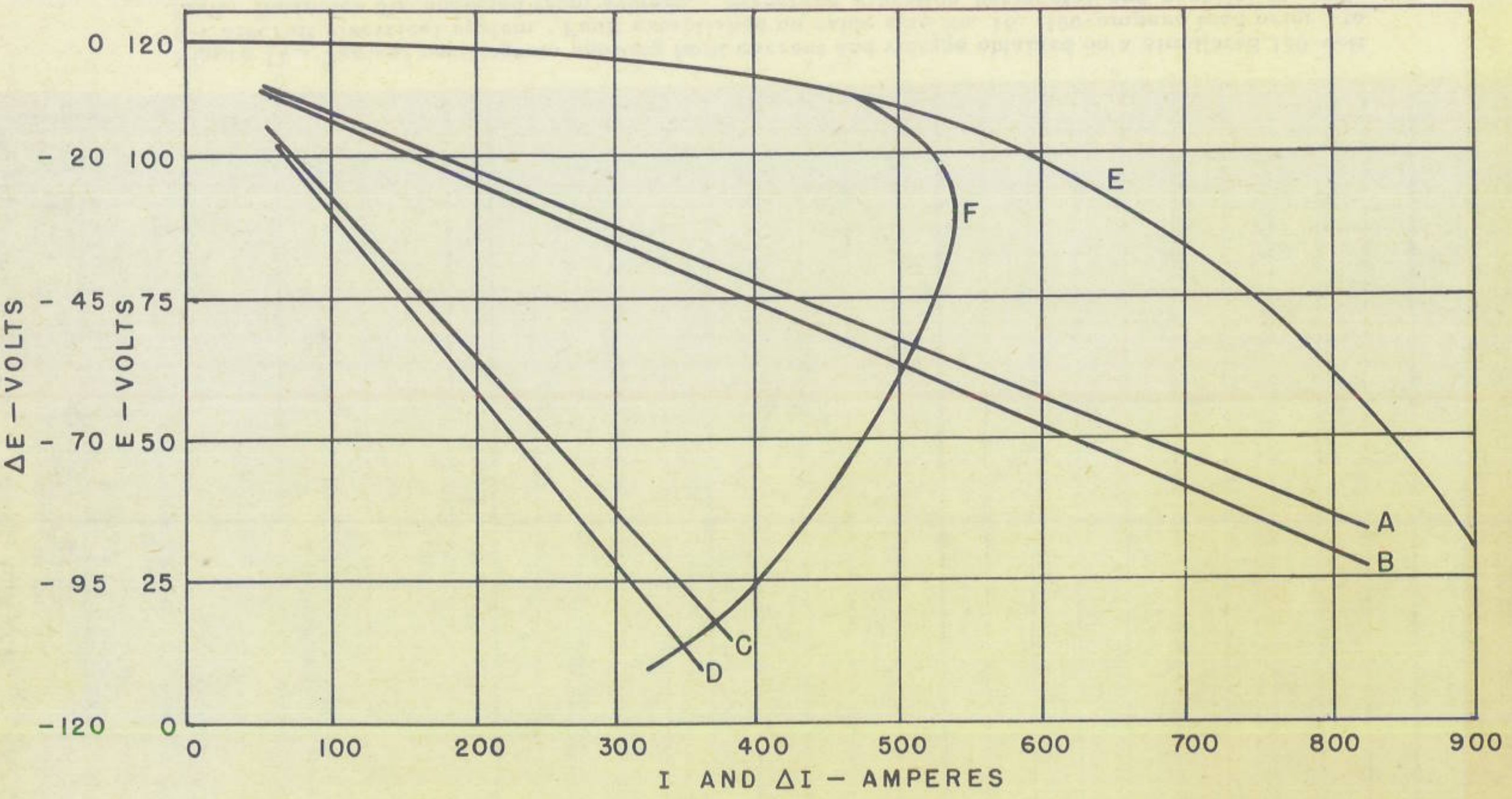

Figure 12 - Transient and steady-state characteristics of the electrical system used in this study.

Transient Characteristics

Curve A - System composed of one generator and four batteries, 100-ampere load
Curve B - System composed of one generator and four batteries, no load
Curve C - System composed of one generator, 100-ampere load
Curve D - System composed of one generator, no load

Steady-State Characteristics

Curve E - System composed of one generator and four batteries
Curve F - System composed of one generator

A Hartman Electrical Manufacturing Company reverse-current relay, type Q-1, was utilized in the fault circuit to interrupt the current. During the present investigation, the operating coil of the relay was energized by a separate 120-volt d-c source.

## DESCRIPTION OF FAULTS

### Proportion of Intermittent Faults and Welds

Of the 180 faults established, nine percent resulted in welded faults and the remaining 91 percent were of the intermittent type. Table 4 gives the number of intermittent faults and welds for each cable size and for batteries disconnected and connected to the system. There are more welds with batteries off than with batteries on the system. With batteries on, the system maintains higher voltage under load, which in most cases causes fault current in excess of the current-carrying capacity of the conductor strands in contact with the grounded aluminum alloy plate. This condition melts the conductor strands, initiating an arcing or intermittent type of fault.

TABLE 4

Number of Intermittent Faults and Welds Which Resulted from Establishing 180 Faults on a 120-Volt D-C System

| | No. of Intermittent Faults | No. of Welds | Total No. of Faults |
|---|---|---|---|
| Batteries Connected | 86 | 4 | 90 |
| Batteries Disconnected | 77 | 13 | 90 |
| Total | 163 | 17 | 180 |
| Cable, Size No. 16 | 60 | 0 | 60 |
| Cable, Size No. 8 | 52 | 8 | 60 |
| Cable, Size No. 2 | 51 | 9 | 60 |
| Total | 163 | 17 | 180 |

No welds occurred with size No. 16 cables. During the faults, the short-time current-carrying capacity of these cables was exceeded so that the conductor strands melted, always resulting in arcing faults being established. In many cases with size No. 16 cables, rapid melting and vaporization took place, burning the strands back into the insulation without setting fire to the insulation. This condition therefore prevented metal-to-metal contact between the conductor strands and the aluminum alloy plate, and the fault was self-clearing. No marked difference is noted in the proportion of arcs to total faults between size No. 8 and size No. 2 cables. Fewer welds occurred on a horizontally vibrating platform than on a vertically vibrating platform.

### Intermittent-Fault-Current Magnitude

The fault-current magnitude of the first pulse of intermittent faults were plotted within ranges of 100 amperes (Figures 13 through 18). The magnitude used in this study was the average current of the first pulse for the duration of the first pulse. These measured average currents are considered accurate to ± 2 percent. Henceforth, in this report, fault current means average current of the first fault pulse. The fault current magnitudes are plotted in percent of total faults established for each condition. For example, in Figure 13 the sum of all percentages of faults on size No. 16 cables equals 100 percent, the sum of all percentages of faults on size No. 8 cables equals 100 percent, and the sum of all percentages of faults on size No. 2 cables equals 100 percent.

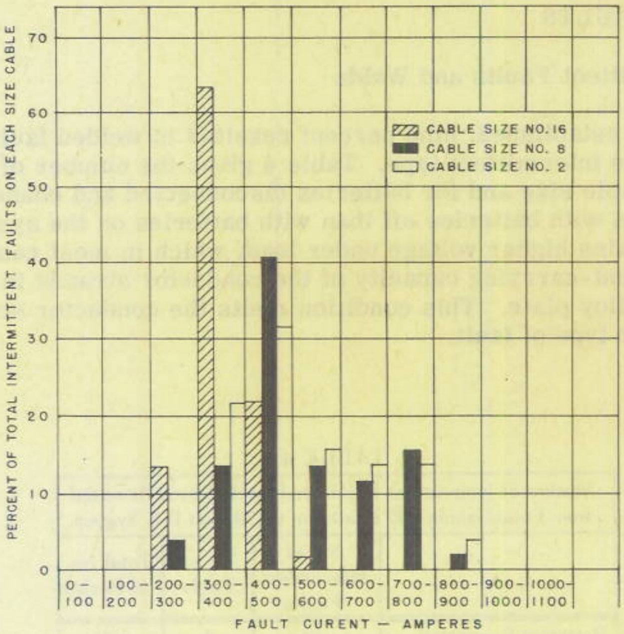

Figure 13 - Current magnitude of the first fault pulse of 163 faults established between cables 10 feet long and an aluminum alloy plate 0.091 inch thick

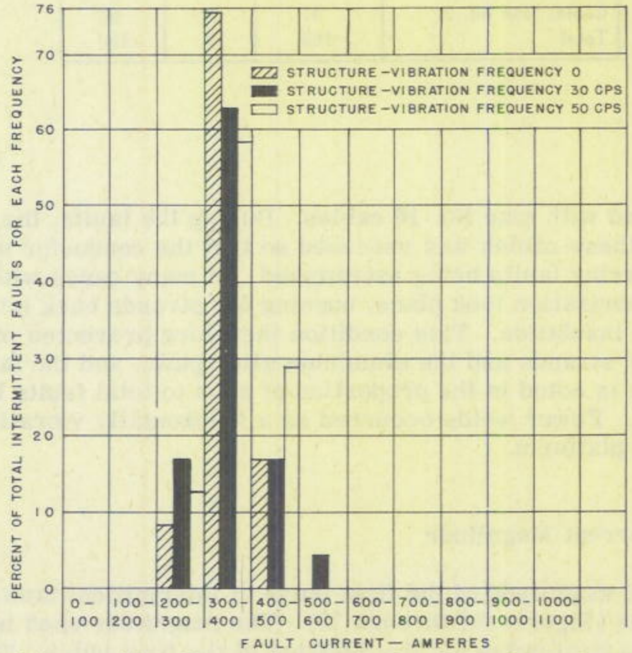

Figure 14 - Current magnitude of the first fault pulse of 60 faults established between cable size No. 16 and an aluminum alloy plate 0.091 inch thick

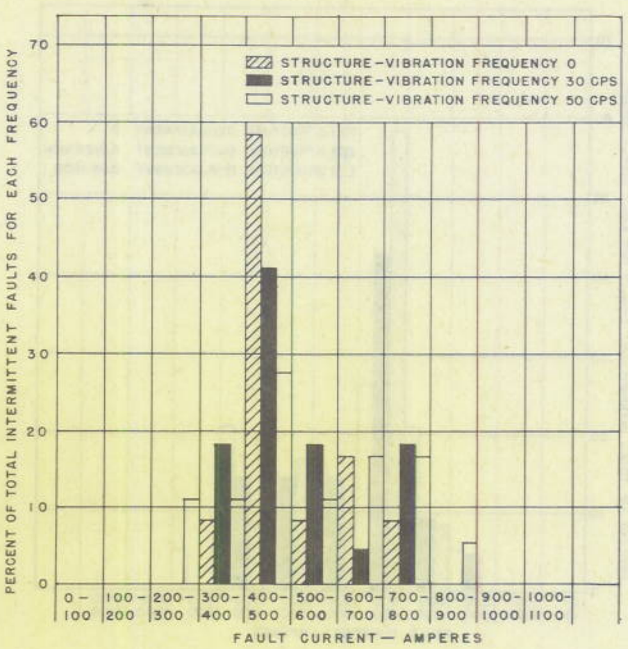

Figure 15 - Current magnitude of the first fault pulse of 52 faults established between cable size No. 8 and an aluminum alloy plate 0.091 inch thick

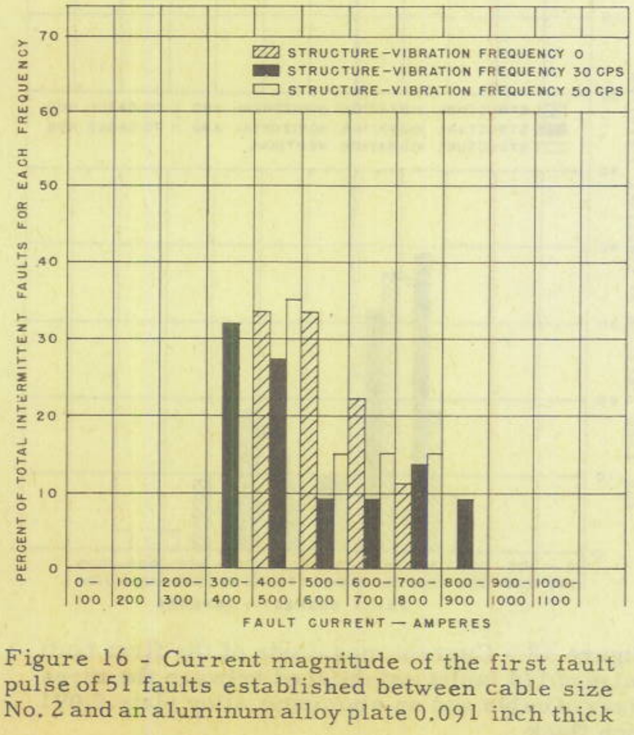

Figure 16 - Current magnitude of the first fault pulse of 51 faults established between cable size No. 2 and an aluminum alloy plate 0.091 inch thick

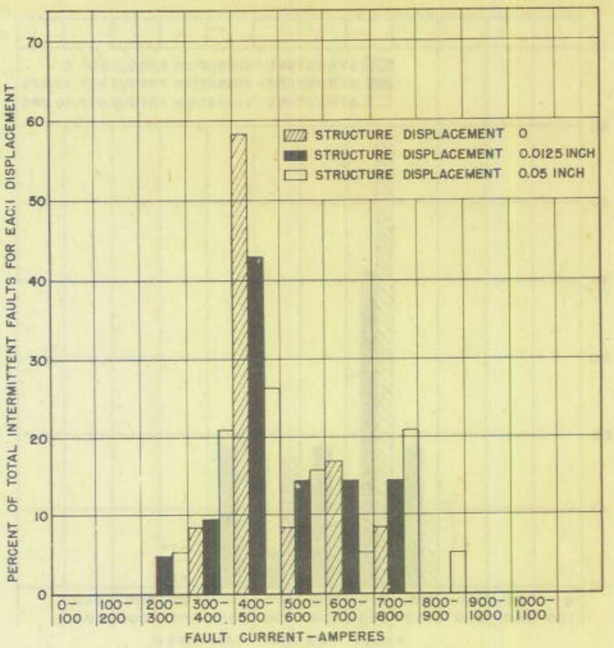

Figure 17 - Current magnitude of the first fault pulse of 52 faults established between cable size No. 8 and an aluminum alloy plate 0.091 inch thick

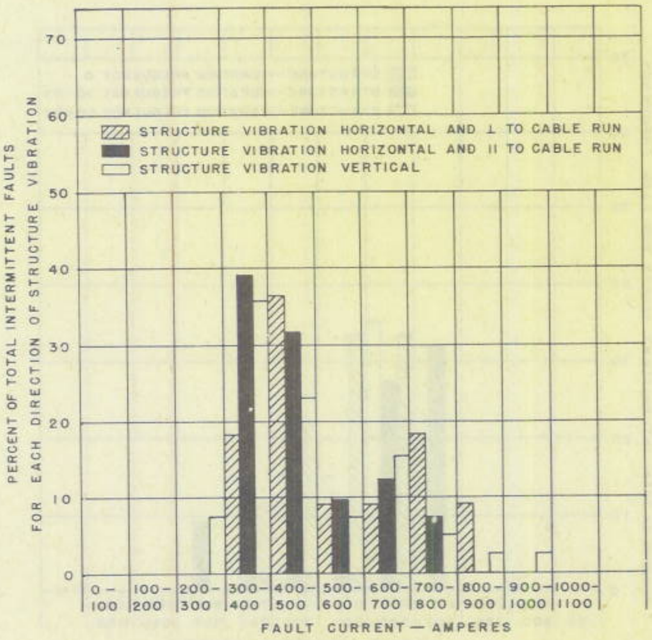

Figure 18 - Current magnitude of the first fault pulse of 124 faults established between the three sizes of cable and an aluminum alloy plate 0.091 inch thick

As expected, the larger current magnitudes occurred on the cables of smaller resistance, but there was considerable variation in magnitude for each cable size (Figure 13). For example, fault current on size No. 16 cables ranged from approximately 210 amperes to over 500 amperes; fault current on size No. 8 cables ranged from approximately 275 amperes to over 800 amperes; and fault current on size No. 2 cables ranged from approximately 315 amperes to over 800 amperes. The effect of structure-vibration frequency on fault-current magnitude for each of the three cable sizes is a slight increase of higher current faults as the frequency is increased from zero to 30 cps and 50 cps (Figures 14, 15, 16). Data from 52 intermittent faults established on cable size No. 8 show that structure-vibration displacement has a small effect on fault current (Figure 17). There is a tendency towards a greater number of higher current faults as the displacement is increased from zero to 0.0125 inch and 0.05 inch. The direction of structure vibration has no marked effect on the fault-current magnitude (Figure 18).

From the data presented in Figures 14 through 18, it has not been possible to correlate the fault-current magnitude with structure-vibration frequency, displacement, or direction. It is concluded that the resistance of the contact and the arc resistance will primarily determine the fault-current magnitude for a particular system with a given fault-circuit cable resistance.

Of the 180 faults established, 41 of these faults caused complete penetration of the aluminum alloy plate within 1 second. Only 1 penetration occurred when using size No. 16 cable for the faulted conductor, while there were 19 penetrations when using size No. 8, and 21 penetrations when using size No. 2 as the faulted cable. The arc energy produces the melting and vaporization necessary to penetrate the plates in the above cases.

### Intermittent-Fault-Current Duration

To further define the intermittent faults established on a simulated aircraft electrical system, it is necessary to know the duration of the first fault pulse. In this study the fault duration is defined as the time between the start of the first pulse of current and the return of this current to zero. Duration data (Figures 19 through 22) were taken from the oscillographic records, and the pulse duration is considered to be accurate to ± 0.002 second. These data were plotted only for the faults obtained when the batteries were connected to the system. The durations of the first fault pulses obtained with batteries disconnected from the system were much longer than with batteries connected, approximately 40 percent of the former being over 0.1 second. Since the fault current is less with the batteries off the system, a longer time is required to melt the conductor strands back away from the grounded plate far enough to increase the arc length to its breaking point, accounting for the longer duration of the first pulse when the batteries are off the system.

Cable size has no pronounced effect on first fault-pulse duration (Figure 19), although there is a slight increase in duration as the cross-sectional area of the conductor is increased. This is due to the necessity of melting a greater volume of conductor strands before the breaking point of the arc is reached. Data from 85 faults, established on the three sizes of cable used in this investigation with batteries connected to the system, show the structure-vibration frequency to have very little effect on the duration of the first pulse of the fault current (Figure 20). For 85 faults established on the three sizes of cable used in this investigation with batteries connected to the system, structure-vibration displacement has relatively little effect on the duration of the first pulse of the fault current (Figure 21).

The direction of structure vibration has an effect on the duration of the first fault pulse (Figure 22). Horizontal vibration perpendicular to cable run is seen to give first fault pulses of longer duration than horizontal vibration parallel to cable run and vertical vibration. This variation in duration with respect to direction of vibration is probably a function of the vertical component of the force with which the cable and aluminum alloy plate come together under vibrating conditions. The greater this force the more rapidly will the cable bounce away from the plate and stretch the arc to its breaking point.

From the data presented in Figures 19 through 22, it has not been possible to correlate the first fault-pulse duration with structure-vibration frequency or displacement. The direction of structure vibration, however, appears to affect the duration, with the longer duration occurring with horizontal vibration perpendicular to the cable run.

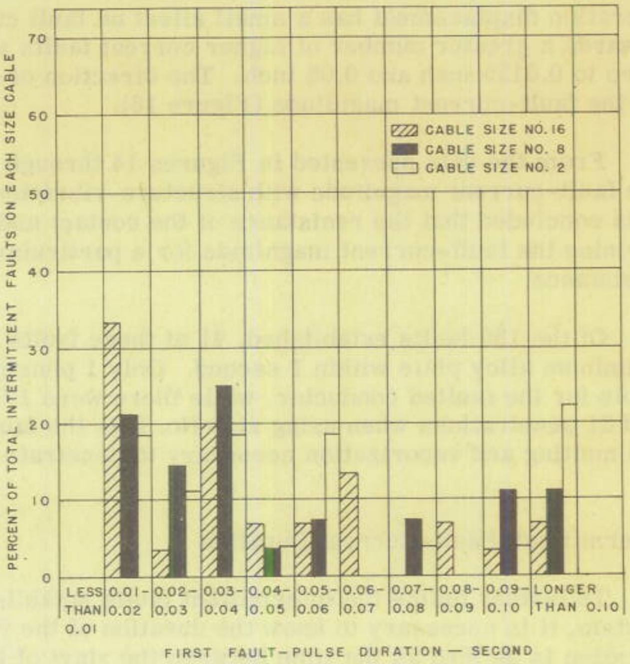

Figure 19 - Duration of the first fault pulse of 85 faults established between cables 10 feet long and an aluminum alloy plate 0.091 inch thick with batteries on the system

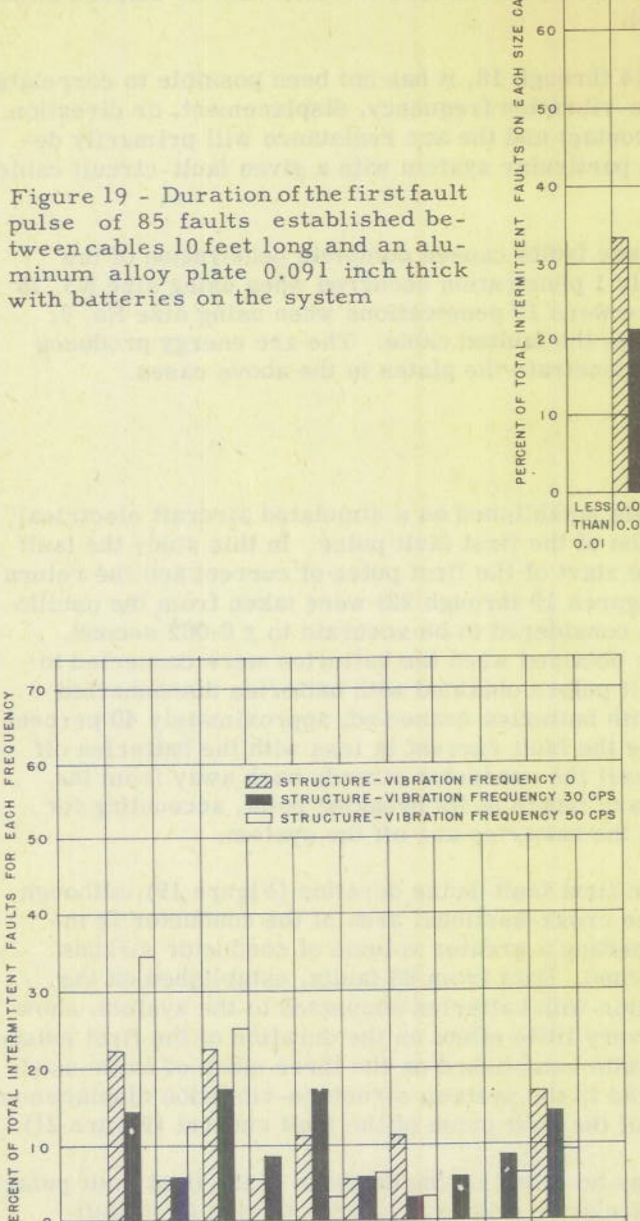

Figure 20 - Duration of the first fault pulse of 85 faults established between the three sizes of cable and an aluminum alloy plate 0.091 inch thick with batteries on the system

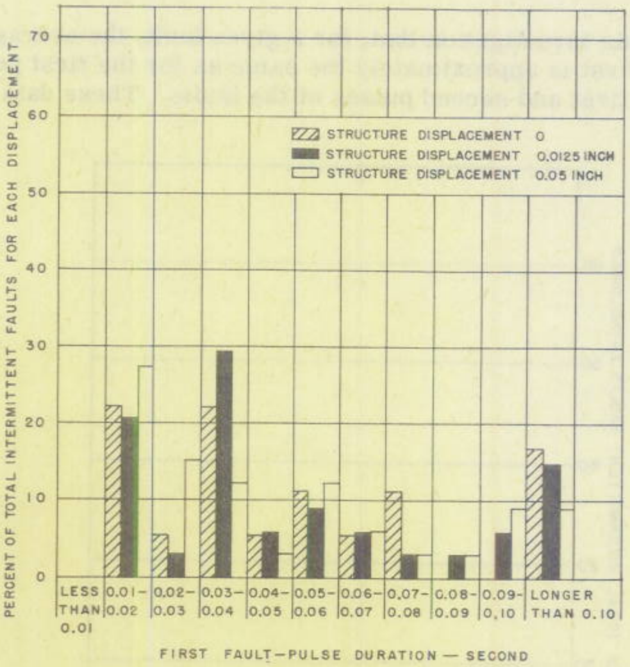

Figure 21 - Duration of the first fault pulse of 85 faults established between the three sizes of cable and an aluminum alloy plate 0.091 inch thick with batteries on the system

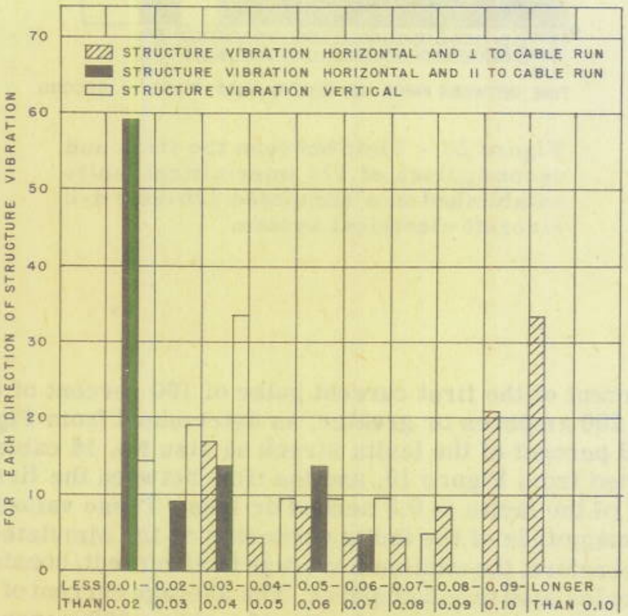

Figure 22 - Duration of the first fault pulse of 67 faults established between the three sizes of cable and an aluminum alloy plate 0.091 inch thick with batteries on the system

## ANALYSIS OF FAULT CURRENTS

It was found in this investigation that, for a given fault, the average magnitude of current pulses following the first is approximately the same as for the first pulse. Figure 23 shows the time between the first and second pulses of the faults. These data permit the following analysis to be made.

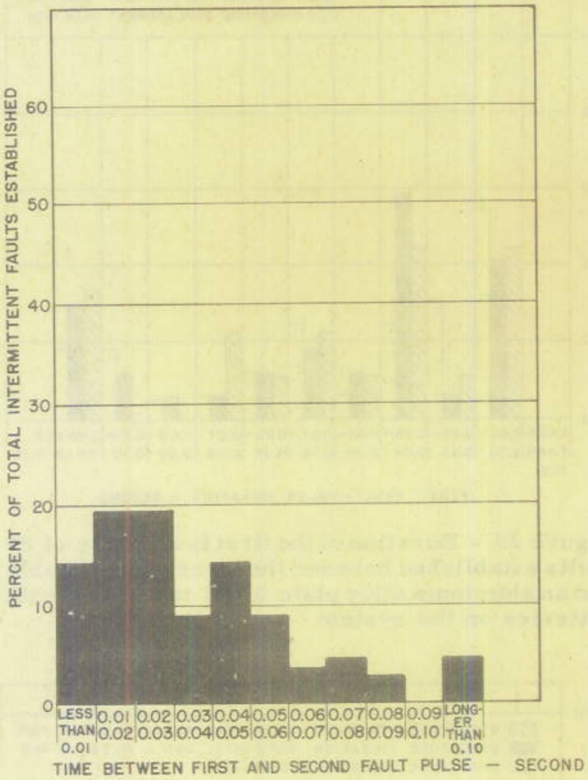

Figure 23 - Time between the first and second pulses of 113 intermittent faults established on a simulated 120-volt d-c aircraft electrical system

The average current of the first current pulse of 100 percent of the faults struck on size No. 16 cable is 200 amperes or greater, as determined from Figure 13. The first pulse duration of 100 percent of the faults struck on size No. 16 cable is 0.01 second or greater, as determined from Figure 19, and the time between the first and second fault pulse of 100 percent of the faults is 0.3 second or less. These values for No. 16 cable give the minimum magnitude of the faults occurring on the simulated 120-volt d-c system used in this study. Therefore, the minimum average fault current, considered over the duration of several pulses, is calculated to be 5 amperes. The average current of the first fault-current pulse of 75 percent of the faults struck on size No. 16 cable is 300 amperes or greater and the first pulse duration of 75 percent of the faults struck on size No. 16 cable is 0.01 second or greater. The time between the first and second fault pulse of 75 percent of the faults is 0.05 second or less. From the above values, considered over the duration of several pulses, the minimum average fault current is calculated to be 50 amperes. Similar data were obtained for cable sizes No. 8 and No. 2, and the results are shown in Table 5.

TABLE 5

Minimum Currents of 100 Percent and 75 Percent of the Intermittent Faults Occurring on a Simulated 120-Volt D-C Aircraft Electrical System

| Cable Size (No.) | Faults Established for Each Cable Size (%) | Average Current Due to Several Fault Pulses (Amp.) | First Fault Pulse | |
|---|---|---|---|---|
| | | | Average Current (Amp.) | Duration (Sec.) |
| 16 | 100 | 5 | 200 | 0.01 |
| 16 | 75 | 50 | 300 | 0.01 |
| 8 | 100 | 5 | 200 | 0.01 |
| 8 | 75 | 115 | 400 | 0.02 |
| 2 | 100 | 10 | 300 | 0.01 |
| 2 | 75 | 115 | 400 | 0.02 |

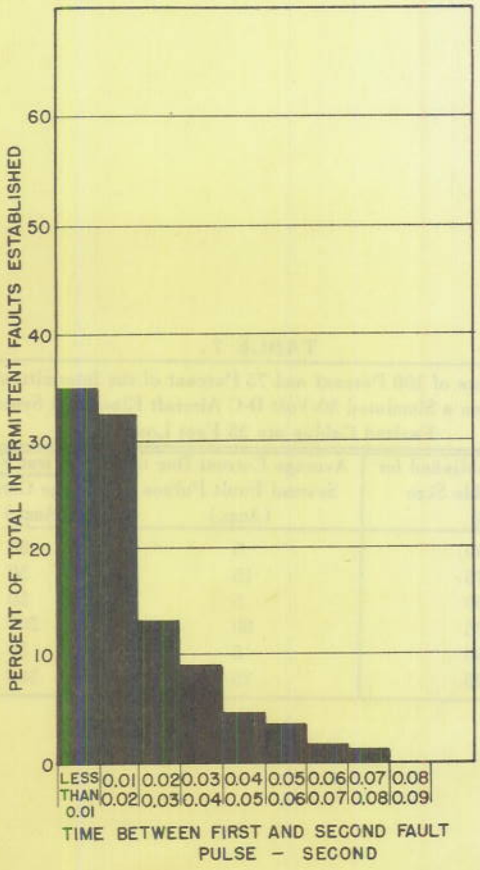

Figure 24 - Time between the first and second pulses of 300 intermittent faults established on a simulated 30-volt d-c aircraft electrical system

An analysis of fault currents was also carried out with data previously obtained on a simulated 30-volt d-c aircraft electrical system.[4] Figure 24 gives the time between the first and second fault pulse on the 30-volt system. The results of this analysis are as shown in Tables 6 and 7 for cable lengths of 5 feet and 25 feet, respectively. Comparison of the values in Tables 5, 6, and 7 shows that the 120-volt system does not give appreciably higher minimum fault currents than the 30-volt system.

TABLE 6

Minimum Currents of 100 Percent and 75 Percent of the Intermittent Faults Occurring on a Simulated 30-Volt D-C Aircraft Electrical System. Faulted Cables are 5 Feet Long

| Cable Size (No.) | Faults Established for Each Cable Size (%) | Average Current Due to Several Fault Pulses (Amp.) | First Fault Pulse | |
|---|---|---|---|---|
| | | | Average Current (Amp.) | Duration (Sec.) |
| 16 | 100 | 5 | 50 | 0.005 |
| 16 | 75 | 25 | 100 | 0.01 |
| 8 | 100 | 5 | 50 | 0.005 |
| 8 | 75 | 75 | 300 | 0.01 |
| 2 | 100 | 5 | 50 | 0.005 |
| 2 | 75 | 100 | 400 | 0.01 |

TABLE 7

Minimum Currents of 100 Percent and 75 Percent of the Intermittent Faults Occurring on a Simulated 30-Volt D-C Aircraft Electrical System. Faulted Cables are 25 Feet Long

| Cable Size (No.) | Faults Established for Each Cable Size (%) | Average Current Due to Several Fault Pulses (Amp.) | First Fault Pulse | |
|---|---|---|---|---|
| | | | Average Current (Amp.) | Duration (Sec.) |
| 16 | 100 | 5 | 50 | 0.005 |
| 16 | 75 | 15 | 50 | 0.01 |
| 8 | 100 | 5 | 50 | 0.005 |
| 8 | 75 | 80 | 200 | 0.02 |
| 2 | 100 | 5 | 50 | 0.005 |
| 2 | 75 | 75 | 300 | 0.01 |

---

[4] Trbovich, M., and Toomire, P. E., loc. cit.

## PART III
## CONCLUSIONS AND SUMMARY

### CONCLUSIONS

### 120/208-Volt, 400-Cycle System

a. Of the 225 faults established in a laboratory installation of a 120/208-volt, 400-cycle aircraft electrical system, approximately 4.5 percent developed into welded faults. No welded faults resulted from establishing faults on a nonvibrating platform.

b. Although the maximum peak currents decrease as the faulted conductor cross section is decreased, the fault current is primarily determined by the contact resistance and the arc resistance, in the external circuit, and the subtransient reactance of the generator.[5,6,7,8,9]

c. As in the nominal 30-volt d-c system, it was found that the vibrating platform contributes little to the fault current magnitude. It is believed that the intermittent fault begins by fault-current flow in excess of the capacity of the contact strands, which causes the separation of the faulted conductor and the grounded plate.[10]

d. Slightly larger fault currents result when a fault is established on a generator supplying load prior to the fault.

e. The first fault-pulse duration of 98 percent of the intermittent faults was less than 0.01 second. No correlation was observed between structure-vibration frequency, displacement and direction, and the first fault-pulse duration. However, faults established on a vibrating platform usually last longer and result in more welds than faults established on a stationary platform.

f. For the systems used in this investigation, the damage to the grounded structure from intermittent faults is less in the 120/208-volt, 400-cycle a-c system than in the 30-volt d-c system. Although the current is greater in a-c faults, the arc duration is much shorter than the duration of intermittent faults in a 30-volt d-c system.

g. Small values of effective current are obtained when considering duration over several fault pulses. It would appear that a protection system should include a fault-sensing device designed to operate within the duration of the first fault pulse because of the higher currents available. The fault-clearing device should be committed to clear a fault within 4 cycles of fault current (0.01 second), since the first fault-pulse duration of 98 percent of the total intermittent faults was less than 0.01 second. During this time, however, the fault current is primarily determined by the subtransient reactance of the generator on which the fault occurs.

---

[5] Electrical Transmission and Distribution Reference Book - Westinghouse Electric and Manufacturing Co., Chap. 7, 1943

[6] Doherty, R. E., and Nickle, C. A., "Synchronous Machine IV," AIEE Trans. 47: No. 2, 457-487, April 1928

[7] Park, R. H., and Robertson, B. L., ''The Reactance of Synchronous Machines," AIEE Trans. 47: No. 2, 515-535, April 1928

[8] Smith, G. S., "Transients in A-C Motors and Generators," AIEE Trans. 65: 61-69, February 1946

[9] "Test Code for Synchronous Machines," AIEE Standards, No. 503, June 1945

[10] Trbovich, M., and Toomire, P. E., loc. cit.

120-Volt, D-C System

a. Different loads on the system prior to the fault can cause various values of fault current for the same value of fault resistance. Also, higher values of fault current will occur, for a given value of fault resistance, when batteries are connected to the system, due to the system maintaining higher voltage under load.

b. Of the 180 faults established for the study, 91 percent resulted in intermittent-type faults.

c. It has not been possible to correlate the fault-current magnitude with structure-vibration frequency, displacement, or direction. It is concluded that the resistance of the contact, as determined by the area of contact, and the arc resistance, will primarily determine the fault-current magnitude for a particular system with a given fault-circuit lead resistance.

d. In most cases, intermittent faults start by fault-current flow in excess of the current-carrying capacity of the contact strands. The conductor strands melt, causing a separation which in turn causes an arc to be drawn out.

e. In this study, 41 (23 percent) of the 180 faults established caused complete penetration of the grounded aluminum alloy plate (0.091 inch thick) simulating the aircraft structure within approximately one second.

f. First fault-pulse durations are longer without batteries connected to the system than with batteries connected. The structure-vibration frequency and displacement have little effect on the pulse durations. However, the direction of structure vibration has an effect on the duration, with horizontal vibration perpendicular to the cable run causing fault pulses of longer duration than horizontal vibration parallel to the cable run or vertical vibration.

g. The simulated 120-volt d-c aircraft electrical system does not give appreciably higher minimum fault currents than the simulated 30-volt d-c aircraft electrical system. However, as a whole, the magnitude and duration of the faults on a 120-volt system are much greater than on a 30-volt system.

h. On the basis of the values obtained in the analysis of fault currents, it would appear that any protective system should include a sensing device designed to operate within the duration of the first fault pulse because of the higher currents available. The average currents obtained when considering the duration over several successive pulses of the fault are small, due to the relatively long time between pulses, and would be difficult to detect.

i. For the electrical systems used in this study, the damage to the grounded aluminum alloy plate from intermittent faults was much greater from faults in the 120-volt d-c system than from faults in either the 120/208-volt a-c or the 30-volt d-c systems.

## SUMMARY OF PROBLEM

The electrical faults occurring in a simulated aircraft electrical system can be considered as being either of two types depending upon the nature of the contact at the point of the fault. The first type of fault is characterized by continuous metal-to-metal contact between the electrical wire conductor and the plane structure. This type of fault usually results in damage to the electrical system and has received attention to the extent that circuits can be devised which are capable of minimizing damage in a limited section of the electrical system. The maximum permissible fault-current values of this type fault can readily be determined from the smoking time versus current characteristics of the cable sizes used in aircraft or from the current verus time characteristic of the equipment being protected. Complete system protection using present techniques is considered impractical, however, due to the space and weight requirement for the large number of components necessary.

The second type of fault occurring in aircraft electrical systems is characterized by the separation of a faulted lead and the aircraft structure after contact has been made. Due to the intermittent nature of the second type of fault, the average fault current may be small although large areas of the plane structure may be melted or vaporized by the arc while the cable a short distance from the arc is not excessively hot.

In order to determine the characteristics of these intermittent-type faults, simulated 30-volt d-c, 120-volt d-c, and 120/208-volt 400-cycle a-c systems were assembled in the laboratory. These systems consisted of a power source, control circuits, and various loads. Many light-contact, line-to-ground faults were established in these three systems and the resulting fault current, voltage and duration were recorded and evaluated.

In most instances when energized conductors were arbitrarily dropped onto an aluminum alloy plate connected to the system ground, the resulting faults were of the intermittent type. This condition applied while varying the parameters associated with the conductors, vibration, grounded structure, system load and system voltage. Further, the minimum fault currents encountered were not changed when the system voltage was increased but depended upon the resistance of contact, as determined by the area of the contact, and the arc resistance. It was further found that the fault-current magnitude and duration of the first fault pulse was not markedly affected by vibration frequency, displacement and direction although fault duration increased when the faults were established on a vibrating platform.

Damage to the grounded aluminum alloy structure was much greater from the faults established in the 120-volt d-c system. Further, damage to the aluminum alloy structure was greater for intermittent faults occurring in the 30-volt d-c system than for intermittent faults occurring in the 120/208-volt, 400-cycle system. Although in this latter instance the arc was more severe in the a-c system, the arc duration was very short.

A fault-clearing device designed to clear all of the intermittent-type faults, and based upon the average fault current over several fault pulses, should clear a fault current of approximately 10 amperes. With present techniques of fault protection however, this seems impractical. A fault-sensing device designed to clear a fault based upon the magnitude and duration of a single fault pulse appears to be more practical. A relay method of fault detecting and clearing, however, necessarily confines fault protection to a limited region of the aircraft. This is true because of the space and weight requirements for the numerous items required to protect each lead. In addition, it may be desirable in an emergency to permit faults on electrical leads to vital equipment to exist until the emergency has passed or the vital equipment has failed.

If complete protection from ground faults is required, it is necessary to insure the electrical isolation of the wire conductors from the plane structure. One suggested method is to anodize the aluminum plane structure. This study has shown, however, that anodizing the surface affords adequate protection only so long as it remains unscratched. This surface insulation is relatively easily damaged and consequently is of little value as protection against electrical faults.

Another means of preventing the occurrence of some electrical faults consists of the installation of an ungrounded system monitored by a ground detector. That is, this method, from a protection standpoint, would have merit if the possibility of simultaneous faults to ground on donductors of different polarity is disregarded and, if the electrical faults in aircraft are line-to-ground and not line-to-line.

Another means of gaining limited protection from faults is to provide cables able to withstand the conditions leading to a sustained intermittent fault. First, this requires a cable insulation which is fire resistant when heat is applied from the conductor side of the insulation. Second, a cable insulation is needed which is secured to the conductor in such a manner so as to expose a minimum of bare wire when the cable is parted. Third, an abrasion-resistant cable insulation is required.

It is recognized that isolating electrical faults can be accomplished in limited portions of the aircraft electrical system. Further, with the present relaying techniques and aircraft-equipment requirements, a protection system should be committed to clear on the first fault pulse of an intermittent fault in order to minimize structural damage. For the large majority of wire footage, however, fault-preventative measures seem to be the most practicable means to minimize fault damage in aircraft electrical systems.

* * *

NAVY-DPPO PRNC. WASH., D.C.