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NRL Report 7126

An Assessment of High-Voltage DC Electrical Power in Aircraft Electrical Systems

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July 1, 1970

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ABSTRACT

If the presently installed three-phase ac transmission system on aircraft were replaced by a higher voltage dc (HVDC) transmission system using a ground return (the aircraft frame), a reduction in weight of wiring, number of wires, and total I^2R losses equal to one-third their present value could be achieved at a dc system voltage of 345 V. A plot of system wire weight vs values of dc system voltage shows an increase in wiring weight with decreasing values of dc system voltage. The weight reduction with increasing values of voltage is significant because the distribution wiring weight is about from one- to two-thirds of the total electrical system weight.

HVDC may have some disadvantages such as higher short-circuit currents, some increase in personnel hazard, and at present a limitation on the use of transistors. The compromise between the weight advantages to be gained at 345 V and the disadvantages that were anticipated at this value leads to the choice of a standard value of 230 V. At this voltage, a saving of approximately 50% in wire weight and 50% in I^2R losses results when compared to the ac systems on WF-2 and F4J aircraft.

A qualitative comparison is made between projected 230-V, dc generation equipment and the presently available constant-frequency three-phase ac equipment. While little if any weight savings or efficiency gains are anticipated in this area, the simplicity of the dc system would lessen present problems in paralleling and maintenance that are, after many years, perhaps the most objectionable feature of the ac system.

A comparison of utilization equipment for the proposed HVDC with that presently used on ac systems offers little in the way of saving weight. The biggest obstacles to ready acceptance of a higher dc voltage appear to be in this area. Light-weight power transforming equipment is today readily available for both ac and dc systems. However, from the viewpoint of saving weight and increasing efficiency, transforming equipment should be kept to a minimum. Some conversion equipment will be needed whether the primary system be ac or dc. Development work and problems exist in the areas of suitable utilization equipment to operate at the higher dc voltage. In addition, although considerable work has been done on solid state dc switches and circuit breakers, most of this has been at the 28-V level. Although considerable weight savings in transmission system wire can be demonstrated for the HVDC system, its adoption in preference to the present ac system will not be readily accepted, until proven generating and utilization equipment are available.

PROBLEM STATUS

This is an introductory report on general and comparative aspects of a new type of aircraft electrical system. Work on further phases continues.

AUTHORIZATION

NRL Problem E02-06
A34-536/652/70F32-431-402

Manuscript submitted May 22, 1970.

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AN ASSESSMENT OF HIGH-VOLTAGE DC ELECTRICAL POWER IN AIRCRAFT ELECTRICAL SYSTEMS

INTRODUCTION

From the complete system on down to the least component, required functional performance is indisputedly the paramount goal in aircraft development. Achieving this goal in today's technology seems to present relatively little challenge. What then, are the problems with electrical systems for aircraft? And how can they be alleviated?

Quite simply, there is need for more reliable, lighter, and more economical electrical systems because of bigger loads, higher speeds, and resulting higher temperatures (1). The high voltage dc (HVDC) systems appear to offer the best overall approach toward achieving these gains.

In any electrical distribution system, added economy in weight and efficiency can be obtained by an increase in system voltage (2). In aircraft electrical systems, the weight of wire in the distribution system is not only a consideration in initial cost and in the performance of the electrical system, but also in the performance of the aircraft itself. Hence, on aircraft, the distribution wiring weight is more important than on land-based installations.

Historically, system voltages on aircraft have increased with increased system loads. An increase in the present ac system voltage on aircraft would result in only modest savings in weight (3), but a change of the primary ac power system to a HVDC system would result in considerable savings in transmission wire weight. As the number and magnitude of loads on aircraft electrical systems increase, a higher dc voltage system will show increasing weight savings over the present three-phase system, even when compared with an equal increase in the ac system voltage.

Today it seems evident that developments in solid state technology and its application to brushless generators, to current limiting and switching, to static inverters and converters, and to brushless motors has removed the major disadvantages which characterized HVDC in the past. In any event, the time has come to examine and compare the advantages of a HVDC system with the present three-phase ac system.

THE HVDC SYSTEM COMPARED TO THE PRESENT AC SYSTEM

HVDC offers several attractive prospects for improving aircraft electrical systems. First and foremost is the resultant lightening of the distribution wiring which is a weight-contributing factor of first-order magnitude. Second is the opportunity to return, in high-power primary systems, to the simple and flexible paralleling techniques of dc sources. Third is the opportunity to utilize fast-acting semiconductor devices, not only to perform rectification processes, but also to provide circuit-interrupting or current-limiting functions which would offset or eliminate hazards often associated with high-voltage, high-power dc operation. All in all, it is felt that the technologies needed for realizing the potential gains of a HVDC system have matured sufficiently and that it is now time to test the hypothesis that HVDC power will indeed effect a lighter and better aircraft electrical system.

In pursuing a comparison of the HVDC system vis-a-vis the ac system, the treatment must in some areas remain qualitative, due primarily to the undeveloped status of HVDC system components. Stress will be placed on comparative weights and, to a lesser extent, on performance. The ac system will be considered as a reference in view of its advanced state of development.

The Distribution System

An aircraft electrical system may be conveniently thought of in terms of three major groupings: generation, distribution, and utilization. It may be shown that, with respect to weight at least, distribution wiring is most sensitive to voltage levels and that considerable weight savings over existing ac and low-voltage dc systems may be realized by operating the primary system at a higher dc voltage. This claim is based on calculations whereby the existing distribution wiring of operational aircraft is converted to that required of a HVDC system. For generation and utilization equipment, the net result of voltage level and type of system on weight indicates a second-order effect.

The mention of high-power, high-voltage direct current conjures visions of flashing commutators and arcing switches. Certainly the zero-current values, periodically recurring with alternating current, facilitate the interrupting capability of contact-type circuit breakers. However, it is altogether possible that, in dc systems, shutoff by means of solid state devices will be faster and will require or result in less dissipation than contactor breakers on alternating current. The question of sufficient capacity for semiconductor switches probably is of greater issue at present. Where current limiting rather than complete interruption is desired, the semiconductor device offers a control capability superior to that of the electromechanical device. Reliable methods have been developed for on-time modulation of a semiconductor switch which results in controlled average current levels. Although such switch modulation could also serve ac systems, it is cited as a newly available capability of considerable generality of purpose.

The critical function of signal sensing, in particular that of current sensing, has been conveniently and reliably provided on ac systems by magnetic-induction methods. Current sensing on dc systems would be awkward by comparison were it not for the development of Hall devices which await utilization on HVDC systems with, in addition, gains in weight savings over iron-core, ac, magnetic-induction methods.

The Generator

The conventional system has become characterized by its synchronous generator source, generally of the salient-pole configuration. This basic ac machine has proven highly adaptable to several methods of cooling and lubrication which have permitted operation at elevated ambient temperatures and at high rotational speeds. In its advanced versions for aircraft, the synchronous generator is brushless, possessing an integral rotating exciter. The dc output may be derived by straightforward rectification, which serves to show the relatively small weight penalty to be paid at the generation level for achieving direct current. If SCR's are used for rectification, current interruption by the same SCR's is also possible. Of course, filtering must be weighed into this comparison of primitive generators. Actually, in applying the equivalent ac section of the brushless machine for the HVDC system it is preferable to generate a three- to fourfold higher frequency than the conventional ac machine and to generate an output waveform more amenable to filtering.

The comparison of ac generation with dc generation extends to a consideration of the interaction between generators and loads. The frequency-dependent portions of the ac

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system, the motors, transformers, and certain electronic functions, ordinarily enjoy weight and performance advantages when operating at a single fixed frequency. Were they to function over a range of frequencies, their minimum weight would generally be fixed by the lowest frequency, and performance penalties would be paid at higher frequency operation because of higher impedances and higher losses. The nearly universal use of the constant-frequency ac generator in today's aircraft electrical systems bears out the consensus in favor of fixed-frequency operation, even at the expense of the constant-speed hydromechanical drive.

Now, a dc generator is also of the fixed-frequency category (that is, constant at zero frequency), achieving this status without the need for the constant-speed drive (CSD). The notion to be carried here is that the direct current will be derived by rectification of the output from a variable-speed generator. The minimum weight of the generator, as in the case of variable frequency, is set by the lowest speed. Generally, the generator weight per unit output, when comparison is made between the variable-speed ac and dc versions, would differ only to a second order if designed for the same minimum speed. Generalizing one step further, the overall weight difference between the CSD-driven, constant-frequency ac generator package and the variable-speed rectified generator may also prove to be of second-order significance. Over the years there have been improvements in CSD-drive, ac generator combinations. However, removal of the CSD would eliminate what is presently a maintenance program of considerable magnitude.

Power Processing

In ac systems, power is generally transformed to required ac voltage levels by an ordinary transformer and to required dc levels by a transformer–rectifier combination. The ease with which these transformations are achieved is considered to be one of the principal attributes of the ac system. To transform dc power from one voltage level to another or to alternating current is more difficult and calls for complex power processing methods. Solid state devices, however, have made possible dc-to-dc converters with specific weights comparable to those of transformers, and even less in step-down or low-voltage-ratio converters not requiring associated transformers. Generally, the dc-to-dc converter or dc-to-ac inverter is more complex and more expensive than the ordinary transformer, but greater simplicity, economy, and weight saving in the wiring and generating areas of the HVDC system will more than redress the imbalance. The prognosis for the reliability of solid state power processing devices is good, but hardly up to that for plain transformers.

In general, the solid state power converter adds a dimension of flexibility to the HVDC system in the same way as does the transformer for the ac system. Without recent developments in electronic converters, the feasibility indicated for applying HVDC to advanced aircraft might be considerably diminished. Without light-weight, efficient converters, some of the benefit of system weight saving through lighter distribution wiring would be lost.

Motor Loads

Few load categories give rise to as much controversy as do motors. The advent of brushless motors has only intensified the arguments. In the minds of many, the dc motor is irrevocably connected to the rotating commutator switch, and the notion of electronic switching seems somehow to extend only as far as dc-to-ac inverters driving rather conventional induction motors. In principle, it is possible to process power from any form to any other in order to tailor speed-vs-torque characteristics to those desired for brushless motor configurations. The "voltage drop" effect in such processing need be no more

severe than that with the commutator, particularly in the instance of HVDC, nor need the speed-vs-torque characteristics be any worse than the off-design operating points of the induction motor. From a realistic viewpoint, the slow progress in developing brushless dc motors indicates the considerable difficulty in achieving practicable circuits to process dc input power to these motors and the lack, until recently, of high-voltage transistor and gate turnoff SCR's.

EARLIER EXPERIENCE WITH HIGHER VOLTAGE DC SYSTEMS

In this country the metamorphosis of aircraft electrical systems tended to go directly from the 28-V dc system to the 400-Hz, three-phase, 115-V system. Experience here at approximately a 120-V dc level or higher is not well documented, particularly in the open literature. In Great Britain, however, careful studies were made and implemented both in mock-up test systems and in flight. Furthermore, this work is in the literature (4,5).

A 112-V dc system (5) was developed for post-WW II British bombers, with capacities up to 90-kW from four generators. Conventional dc generators were provided to operate over a 3.5:1 speed range. Systems employing rectified ac generators, paralleled at the dc level, were also successfully applied to several aircraft, with the obvious advantage of having alternating current directly available. Of course, these aircraft were not designed for the high performance expected from today's military or commercial vehicles.

A typical application of HVDC is illustrated by the case of the Princess Class flying boats (4). The system employed here was 120-V dc at a capacity of 160 kW from four generators, with 28-V dc for special purposes, such as instruments and electronic equipment not adapted to 120 V dc. This effort was characterized by an extensive system mockup test which is claimed to have been the underlying reason for what is reported to be an unqualified success of the system in its flight application.

The remaining HVDC types of applications were hybrid in nature with 200 V ac at levels from 7 to 35 kVA supplied in combination with 112 V dc at levels from 10 to 26 kW. These were employed on successful operational aircraft, namely, the *Britannia*, *Victor*, and *Herald*. They are touted to have had considerable success in their application and remain operational to the extent that these planes still are in service. No mention is made of difficulties such as arc damage and personnel danger, often cited in speculation as potential hazards.

NEW DEVELOPMENTS IN SUPPORT OF HVDC SYSTEMS

Today, considerably less engineering attention seems to be directed to the development of equipment for aircraft electrical systems than was expended 15 to 20 years ago. Fortunately, much progress has been made in the solid-state art which benefits aircraft hardware. Bearing and cooling technology, power handling capability of solid state devices, insulation and magnetics, analytic prowess especially through the computer, all have turned fresh ground for new methods in the development of aircraft electrical equipment.

Item by item, the system components discussed here relate to these developments.

Brushless Generators

Present thinking tends to envisage these machines as high speed, 10,000 to 20,000 rpm, with either conventional salient-pole or Lundell electromagnetic configuration. At these

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speeds, the inductor alternator, sometimes referred to as a homopolar generator (and in so doing creating an ambiguity with the Faraday disc type of machine), competes with the conventional synchronous machine in weight. Either oil or vapor cooling is feasible, along with hydrostatic bearings, or combined hydrodynamic/hydrostatic bearings. Multi-kilowatt machines have been built, and ratings as high as 1 MW have been designed. The synchronous impedance for the inductor type of machine is generally much greater than that for the conventional synchronous machine. Were the output of an inductor alternator to be rectified, one can readily see that sustained short-circuit currents would be strikingly reduced below levels expected from a conventional dc machine with an equivalent voltage and power output. In fact, in contrast to the worry about excessive short-circuit current ordinarily expected with HVDC, there is cause with this type of machine for concern of the ability to obtain sufficiently high short-circuit currents.

Switches

Current interrupting and limiting in aircraft electrical systems for both ac and dc circuits by purely static devices is within reach of existing solid state technology, although not entirely on an off-the-shelf basis. This ability is a rather recent achievement obtained by virtue of improved transistor voltage ratings (which now exceed anticipated HVDC levels) and by progress with gate turnoff SCR's. For example, the power transistor has broken the 1000-V barrier and is edging toward a 2000-V capability. Production transistors with 1400-V/5A rating are now available. Units with ratings of 800 to 1200 V at 3 A and 600 V at 10 A are also in production. The high power capabilities of thyristors are already well established, with over a dozen types available at peak inverse voltages in excess of 2000 V and with current ratings up to 650 A. At least one type of gate-controlled SCR is available with a rating of 600 V standoff, 50 A, and a gain of roughly 3.

Converters

The entire area of electronic power processing equipment has bloomed only in recent years, due to developments in solid state electronics and in magnetics. A dc-to-dc converter developed as an electrostatic ion-propulsion power supply for space use has resulted in the achievement of 90 to 95% efficiencies for units in the 1- to 3-kW power levels, at dc input voltages of 250 to 400 V. Specific weights of 5 to 10 lb per kW satisfy the weight requirements for aircraft use and place them in a weight class with transformers (5 lb per kW). Converters at the lower power levels typical of electronic power supplies are representative of the state of the art with efficiencies above 90% and very much competitive with the conventional transformer-rectifier power supply in all respects, including those of cost and weight. Hence the feasibility of dc-to-dc converters, as well as that of dc-to-ac inverters, has been demonstrated for application in a HVDC system.

Brushless Motors

Effort in this area has been confined to fractional horsepower size or to industrial equipment rather than aircraft application. It would appear that the basic engineering is available and need only be directed to aircraft requirements. Ratings to 10 hp are indicated for hardware development, as are performance profiles equivalent to those of the dc series motor and the ac induction motor. These applications may prove to impose the greatest demands on transistors and thyristors.

SELECTION OF A NEW DC VOLTAGE STANDARD

Two sets of data will be used to derive a method for determining the variation of distribution-wiring weight in aircraft as a function of voltage. These are (a) the maximum current ratings for wire sizes according to current military specifications and (b) the distribution of system loads among wire sizes for electrical systems already developed, i.e., for systems brought to operational status by the experienced efforts of the aircraft manufacturers and therefore representative of the state of the art in producing minimum weight configurations.

In general, the weight and the losses in a wire are determined by its dimensions, resistivity, and current. With a load at a given potential, the magnitude of the power transmitted by the wire is obviously proportional to its current. Hence, if the weight of a fixed length of wire, say 1000 ft, is divided by the maximum current rating specified for the wire, the minimum weight per 1000 ampere-feet is determined. Inversely, this minimum weight condition corresponds to the maximum ampere-feet per pounds, or "utilization." Judged from this notion, a conductor is well utilized if it carries a current near its upper specified limit. For current values less than this upper limit, the weight per 1000 ampere-feet increases inversely as the current decreases. Insulation adds to the wire weight and is relatively greater in the smaller sizes. However, the allowable current density increases as the wire size decreases. As a result, the weight per 1000 ampere-feet is the least for the four smallest wire sizes. Consequently, it is desirable that the maximum number of all aircraft loads be carried by these smallest wire sizes.

In Fig. 1, the weight per 1000 ampere-feet is plotted against current for copper wires from the smallest gage size (22) up to gage size 2. By examining Fig. 1 further, it is seen that the average utilization for all conductors is greatest for conductors in gage sizes 16 to 20. This fact leads to the conclusion that the system voltage should be at a level so that these conductors would be used almost exclusively. Actual data on present aircraft indicated that this has already been achieved in the present ac system. Tables 1 and 2 show predominant usage for sizes 16 through 22. The 22 size is so significantly represented because it is the smallest allowable size and carries all loads less than 5 A. Its utilization approaches zero as current approaches zero. This effect is significant in limiting an increase in system voltage above which actual conductor utilization falls off and incremental conductor weight savings also fall off.

Figure 2 depicts relative weight and utilization of the distribution wiring for actual aircraft electrical systems. The weight plotted (vs dc system voltage) is relative to the weight of the presently installed three-phase ac system. At 345 V dc, the weight of distribution wiring, total I^2R losses, and total number of conductors is only one-third of that for the ac system, as evidenced by comparing the dc weight curve to the 100% ac reference. Note that the utilization at 345 V dc is a maximum as it is also for the present ac system (100% reference) which reflects the excellent design or configuration for this system. Were the original design not optimum or nearly so, this shortcoming would be revealed by the appearance of maximum utilization at some voltage other than 345 V. This fact also relates to the previous comment that use of high-utilization conductor sizes, Nos. 16 through 20, results also in high system utilization.

Figure 2 also shows that by raising the voltage beyond 345 V, a fall-off occurs in utilization due to increased use of No. 22 wire. The fall-off of utilization is much less noticeable below 345 V. An observer may be willing to agree that utilization fall-off becomes appreciable below 200 V, and strengthen his opinion upon noting also the stiffer weight penalties below 200 V. An attempt to improve on this estimate may be made by noting that voltage points are designated at 195, 255, and 345 V corresponding to values at which loads would need larger or smaller wires, depending on whether the system voltage were being lowered or raised. The inclination is to consider lower values in

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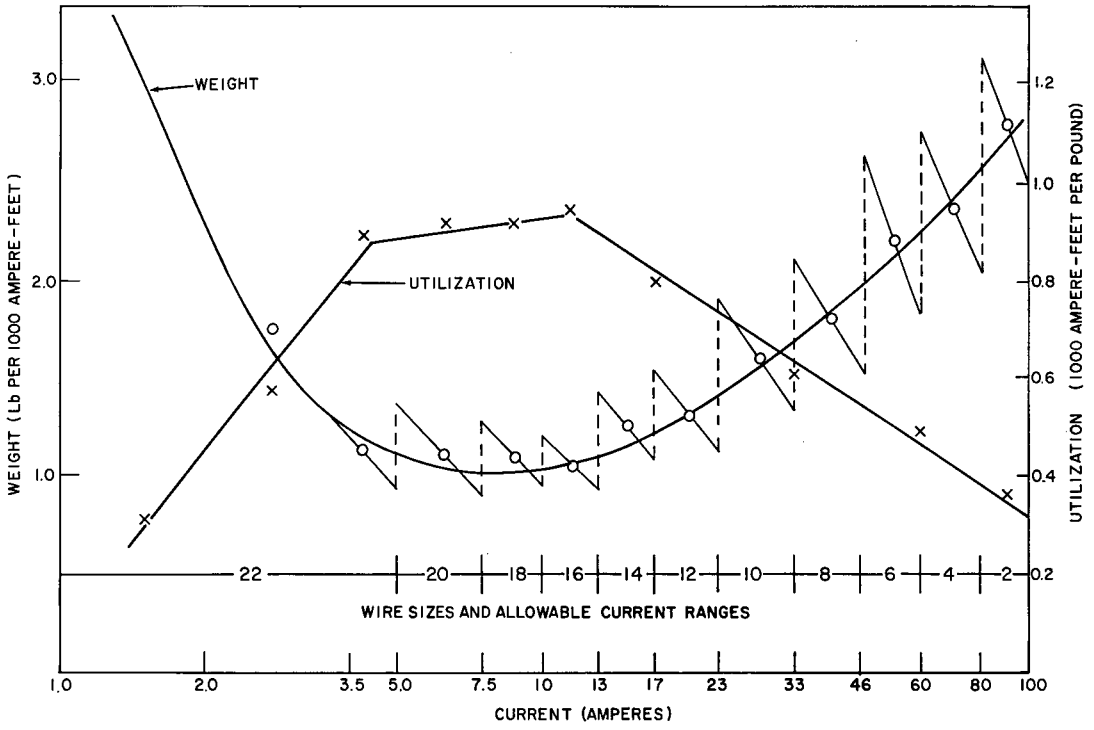

Fig. 1 - Weight and utilization of wire specified by MIL-W-5088B and MIL-W-5086A

Table 1
Systems Wire Weight on Aircraft WF-2

Wire Size	Wire Weight (lb)		
	Electronics	Direct Current	Alternating Current 3 Phase
2	-	20.50	-
4	-	1.75	-
6	-	-	-
8	0.09	0.53	4.48
10	-	0.78	1.43
12	0.12	8.00	11.30
14	0.02	5.26	5.70
16	2.54	20.20	34.00
18	3.17	20.60	10.80
20	8.07	50.00	76.80
22	68.50	40.00	23.40
Total	82.51	167.62	167.91

Table 2
Systems Wire Weight on Aircraft F4J

Wire Size	Wire Weight (lb)		
	Electronics	Direct Current	Alternating Current 3 Phase
8	-	15.40	12.90
10	-	-	28.10
12	-	-	4.35
14	-	1.51	2.46
16	2.35	11.60	46.30
18	5.67	9.70	38.70
20	7.90	32.50	129.00
22	50.16	18.90	79.00
Total	66.08	89.61	340.81

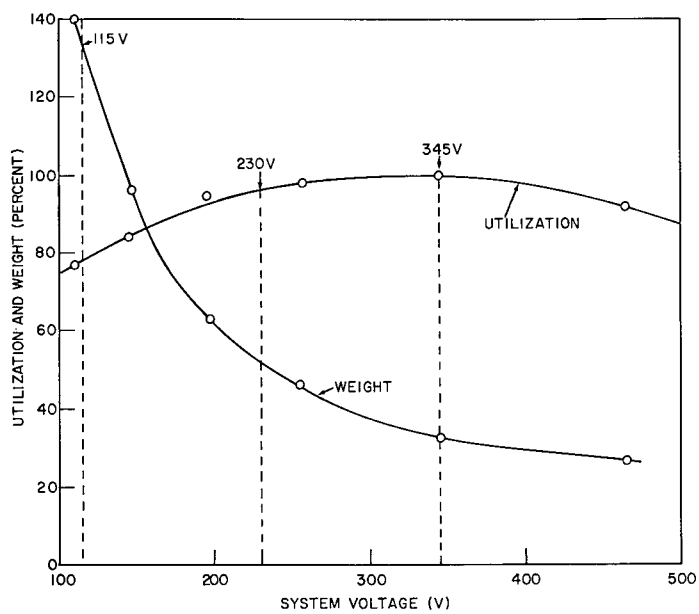

Fig. 2 - Relative weight and relative utilization of dc distribution wiring vs dc system voltage. Average of ac system wiring weight and utilization on WF-2 and F4J aircraft is taken as 100%.

deference to the anticipated widespread use of solid state devices. Figure 2 shows the price paid in pounds for this choice, a price that perhaps aerodynamic and propulsion people may not be willing to share. The mean of 195 and 255 is 225, which suggested the choice of 230 V as a standard. An alternate choice would be 250 V, which would also result in some further weight savings. Further case studies would indicate any need for changing from the first choice, although such a change is not anticipated.

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RECOMMENDED STUDY AND DEVELOPMENT AREAS

This topic is covered by title only, since the previous discussion has repeatedly mentioned specific areas in need of development effort. It is included nevertheless as a reminder and perhaps as an excuse for bringing up one more issue. If the environment for realization of developments mentioned above proves favorable, the evolution of a new generation of aircraft electrical systems is indicated. The goals for this system have already been defined: Lighter weight, more economy, and greater reliability.

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UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*

Naval Research Laboratory
Washington, D.C. 20390

2a. REPORT SECURITY CLASSIFICATION

Unclassified

2b. GROUP

3. REPORT TITLE

AN ASSESSMENT OF HIGH-VOLTAGE DC ELECTRICAL POWER IN AIRCRAFT ELECTRICAL SYSTEMS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

An interim report on a continuing problem.

5. AUTHOR(S) *(First name, middle initial, last name)*

B.J. Wilson and J.P. O'Connor

6. REPORT DATE

July 1, 1970

7a. TOTAL NO. OF PAGES

13

7b. NO. OF REFS

5

8a. CONTRACT OR GRANT NO.

NRL Problem E02-06

b. PROJECT NO.

A34-536/652/70F32-431-402

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)

NRL Report 7126

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT

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11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY

Department of the Navy (Naval Air Systems Command), Washington, D.C.

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HVDC may have some disadvantages such as higher short-circuit currents, some increase in personnel hazard, and at present a limitation on the use of transistors. The compromise between the weight advantages to be gained at 345 V and the disadvantages that were anticipated at this value leads to the choice of a standard value of 230 V. At this voltage, a saving of approximately 50% in wire weight and 50% in I^2R losses results when compared to the ac systems on WF-2 and F4J aircraft.

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DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

Security Classification

Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Aircraft HVDC systems Aircraft ac systems Feasibility of aircraft HVDC systems						

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