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INTEGRATED ENGINE-GENERATOR FOR AIRCRAFT SECONDARY POWER

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Abstract

The integrated engine-generator (IEG) concept consists of an electric generator located inside a turbojet or turbofan engine and both concentric with and driven by one of the main engine shafts. The electric power-conversion equipment and generator controls are conveniently located in the aircraft. When properly rated, the generator serves as an engine starter as well as a source of electric power. The available generating capacity permits use of electrically driven engine accessories. This reduces or eliminates the need for an external gearbox on the engine, thereby simplifying the engine and nacelle assembly and increasing aircraft design flexibility. The nacelle diameter can then be decreased, resulting in less aerodynamic drag and reduced takeoff gross weight.

A large high-bypass-ratio commercial turbofan engine in the 180-kilonewton (40 000-lb) thrust class was selected as a base for preliminary concept feasibility evaluation. A generator with a rating of 200 kilovolt-amperes at engine idle speed will start this engine in the normally required 30 seconds. Preliminary designs for synchronous generators with this rating in both solid-rotor and wound-rotor rotating-rectifier types were prepared. The generators were designed to fit into the base engine without modification to the engine flow path. The weight of approximately 91 kilograms (200 lb) for the wound-rotor rotating-rectifier type led to its selection as the preferred type for an IEG although it is more complex than the 367-kilogram (810-lb) solid-rotor Lundell or the 211-kilogram (466-lb) solid-rotor homopolar generators of the same rating.

Introduction

Power for the operation of secondary power systems in present turbojet- or turbofan-powered aircraft is usually supplied by the aircraft propulsion engines. This includes bleed air for the pneumatic system and power taken off the engine shaft to drive hydraulic pumps, electric generators, and engine accessories such as fuel and lube pumps. These components are mounted on, and driven through, a gearbox located on the exterior of the engine. On some engines an air turbine for engine starting is also mounted on the gearbox.

The gearbox, along with the components mounted on it, may contribute to the frontal area of the engine and, thereby, to the aerodynamic drag of the nacelle in which the engine is located. This drag is a significant aircraft performance penalty at near-sonic speeds. The number of gearbox-mounted components and their associated connecting hardware along with the pneumatic piping result in a complex assembly of parts around the basic engine. This complicates maintenance and increases the possibility of accidental damage to the various components.

A possible alternative to the use of an externally mounted gearbox and its associated problems is an integrated engine-generator (IEG).[(1)(2)] In this concept, an electric generator is located within the propulsion engine concentric with, and driven by, one of the main engine shafts. In addition to supplying power for the operation of secondary-power-system components, the generator is also operated as a motor to start the engine. In a dual-rotor engine, the starting function requires the generator to be on the high-pressure (HP) shaft (also referred to as the N2 or high-speed shaft). Hydraulic functions in the aircraft can be accomplished with either electric or integrated electrohydraulic actuators. The degree to which electric power can be practically used remains to be determined, and is dependent on aircraft size and mission. The generator rating, however, must be greater than that presently used in aircraft. As a minimum, it must be sufficient to allow short-time duty as a motor for engine starting.

Electric power generated by the IEG will be of varying frequency because of the varying engine shaft speed. Several methods of dealing with this variable frequency are available.

Studies have been made of the use of the IEG concept in advanced transports.[(3)] This paper discusses the IEG concept and evaluates its technical feasibility by means of a generator design study. Different types of IEG generator were designed for an existing large turbofan engine. This approach allows a practical definition of problems and provides a base for evaluation. Results of a government-funded study to determine the economic payoff of the IEG are included.

Description of the IEG Concept

Generator Location

Figure 1 shows a cross-section of a recently introduced, large, commercial, turbofan engine with the two most likely IEG locations indicated. Although a generator driven by the low-pressure (LP) shaft can be made accessible from outside the engine, this discussion is limited to IEG's mounted on, and driven by, the high-pressure (HP) shaft. This location is used because of the engine starting capability of the HP shaft, and its narrower speed range is more advantageous in generator design. Turning the LP shaft is not a practical starting method. During normal operation, the maximum- to minimum-speed range of the HP shaft is in the order of 2 to 1, and as low as 1.5 to 1 in some engines. This allows a more optimum generator design than the 4 to 1 speed range typical of the LP shaft.

IEG Electrical System Descriptions

The generator in an IEG system is assumed to be of a synchronous ac type. The varying shaft speed, then, results in generated electric power of varying frequency. Several types of electric power systems can be used with such a source. These are; (1) wild frequency, (2) high voltage dc, and (3) variable speed, constant frequency (VSCF). Hybrid combinations might also be considered.

Wild frequency. - In the wild frequency system, the generator is designed to produce power at approximately conventional frequency (400 Hz) with the engine shaft rotating at normal cruise speed. Over the engine operating range, the frequency of the generated power is proportional to the engine shaft speed, and varies approximately 1.5 to 1 or 2 to 1. Some aircraft loads, such as lighting and heating are relatively insensitive to frequency. Others, such as motors, can be designed for satisfactory operation over the frequency range. It is not possible to parallel wild frequency systems at the ac bus.(4)

High voltage dc. - The generator in a high voltage dc system is designed to generate variable frequency power in a frequency range optimum for generator design and rectifier operation. The generated ac power is rectified by semiconductor rectifiers at a voltage level of approximately 200 to 300 volts dc. This type of power system can result in reduced distribution conductor weight, and systems can be paralleled at the dc bus.(5)(6)

Variable speed, constant frequency (VSCF). - The VSCF system uses a solid-state frequency converter to convert the generated variable frequency power to a standard constant frequency for the aircraft systems. The commonly used frequency standard is 400 Hz. The converter can be either a cycloconverter or a "dc link" type.

The cycloconverter has been developed considerably for aircraft applications. It uses controlled switching of thyristors to synthesize a constant frequency voltage from a varying frequency source. In order to operate satisfactorily, the source frequency should be at least three times the desired constant frequency. To generate the necessary 1200-hertz power at a typical idle speed of 5000 rpm, a generator needs 28 poles. Transmission of the high-frequency power presents added problems. The low effective power factor of a cycloconverter results in the requirement for a generator with a kilovolt-ampere rating approximately 1.3 to 1.5 times that desired for the system loads. The large number of poles and required rating penalizes the design of a generator for a cycloconverter system.(7)(8)(9)

The dc link type VSCF uses a rectifier section to convert the generated power to dc and then an inverter to convert this dc to constant frequency ac power. Since the generated power is first rectified, its frequency is not critical and may be selected for optimum generator design. Recent developments indicate dc link converters may become competitive in weight and efficiency with the cycloconverter.(9)(10)

With suitable controls, VSCF systems can be operated in parallel at the constant frequency bus.

Starting Mode

Serving as an engine starter, the IEG operates as a motor. It must accelerate the HP engine shaft from standstill to self-sustaining speed and then assist engine torque to accelerate the shaft to idle speed. Typically, the starter assists acceleration to approximately 75 percent of idle speed. Some types of synchronous generators have been operated as induction motors to start small gas-turbine power systems.(11) However, designing a large synchronous generator such as the IEG to operate as an induction motor compromises its performance as a generator. Additionally, excessive reactive power is required from the starting power source such as a ground power cart, an aircraft-mounted auxiliary power unit, or another IEG on the same aircraft. Therefore, operation of the generator as a controlled synchronous motor is preferred for the starting mode. Synchronous motor operation imposes little penalty on the generator design. Torque can be controlled for the desired starting characteristics.

For starting, the generator is supplied variable-frequency variable-voltage power at a programmed rate to ensure synchronism and high power factor. Initial torque at standstill can be obtained by either induction-motor operation to several hundred rpm, or sequenced application of dc voltage to various phases, as in a brushless dc motor. If a wound-rotor rotating-rectifier generator is used, the main field excitation at low speeds requires special consideration in the design of the exciter.

The variable-voltage variable-frequency power needed for engine starting is controlled by a converter. In the wild-frequency and high-voltage dc systems, a separate converter is needed. In the VSCF system, the frequency converter can be used. Variable-frequency variable-voltage power can be made to flow in the reverse direction through the cycloconverter by suitable programming of the conduction of the thyristors. With the dc link converter, the input and output connections can be interchanged to supply the required starting power.

Reliability Requirements

An electric generator located inside an aircraft engine is relatively inaccessible for maintenance or replacement. To be an acceptable source of power it must, therefore, possess a degree of reliability as high as the surrounding internal engine parts such as bearings and seals. The use of generators without high-maintenance items, such as brushes, is imperative. Past and present aircraft generators, although some are brushless, have not demonstrated the desired reliability. Their design reflects an optimization of weight, initial cost, and maintenance cost. Reliability data on these generators are very scattered with mean time between failure (MTBF) values up to approximately 47 000 hours as calculated from short-term maintenance records. MTBF values approaching 100 000 hours are desirable for the generator in an IEG system. Operation of the generator in the engine must not contribute to premature failure of engine parts such as bearings, seals, or oil system components. IEG-related engine failures might be caused by stray magnetic flux in bearings, overheated oil, or excessive dynamic loading of the engine structure.

Electrical control and conversion equipment associated with the IEG system will normally be located in accessible areas of the aircraft. The design of this equipment can reflect convenient maintenance procedures.

Benefits of the IEG Concept

Some significant benefits from the application of the IEG concept to aircraft secondary power systems can be predicted. The use of the IEG concept will provide the possibility of eliminating the engine accessory gearbox or, at least, reducing its size significantly. With a turbofan engine, the gearbox is normally located either on the circumference of the fan shroud or on the circumference of the core engine. Locating the gearbox on the fan shroud contributes directly to engine frontal area. With the gearbox on the core engine, frontal area is increased directly to accommodate accessory envelopes and indirectly to an extent determined by the engine size, bypass ratio, and flow type (mixing or nonmixing).

With wing- and pylon-mounted engines, the nacelle aerodynamic drag is directly effected by engine frontal area. For aircraft operating at speeds near Mach 1.0, this drag is significant.

Other benefits, although less tangible, will also result from the use of an IEG. Elimination of the gearbox, its associated components, and the pneumatic piping for the air turbine starter will greatly simplify the nacelle assembly. If the generator rating is selected to provide sufficient additional power for motor-driven compressors and air conditioning equipment, the quantity of bleed air required from the engine will be reduced or eliminated. The pneumatic piping on the engine will then be further reduced, or eliminated, with the result of further simplification of the nacelle assembly. The reduced engine and nacelle complexity will increase aircraft design flexibility and significantly simplify maintenance of the engine. The hydraulic constant speed drive conventionally used to drive the gearbox-mounted generator is eliminated, along with its problems. Also, separately located engine accessories are more readily maintained than those that are tightly packaged around the engine gearbox.

IEG Feasibility Evaluation

Base Engine Selection

The IEG concept is a significant departure from conventional practice for aircraft secondary power. As such, it would most probably be incorporated into the design of a new engine. However, to obtain a better definition of problems than would be possible with a conceptual engine, an existing operational turbofan engine which has internal space for a large generator was selected as a base for the IEG evaluation. This engine, shown in figure 1, is a recently introduced, large, high bypass ratio, commercial, turbofan engine. It is in the 180-kilonewton (40 000-lb) thrust class and is representative of the type and size applicable to advanced wide-body transport aircraft. Unlike most two-shaft turbofan engines, the selected engine can accommodate a large generator on the forward end of the HP shaft without extensive engine modification and without change to the engine flow path. This allowed the use of actual engine dimensions, dynamics, and operating characteristics. The generator would be installed between the forward HP and LP shaft bearings with the tower shaft and bevel gears (fig. 1) removed. The HP shaft extends well beyond the forward HP bearing thereby providing an available mounting and drive means for the generator rotor. The speed range of the HP shaft in this engine is from approximately 5000 rpm (idle) to about 7600 rpm (takeoff). An operational engine such as this could provide a means for economical experimental demonstration of the IEG concept.

Determination of Generator Rating

The generators normally used on the base engine are rated at 60 kilovolt-amperes. A generator with this rating is not adequate for starting the engine under all operating conditions in the generally allowed 30 seconds (standstill to idle). This start time requirement is typified by Specification MIL-E-5007C.

Figure 2 shows the speed-torque curves during start for the base engine. Torque supplied to the engine is positive; negative torque is that supplied by the engine. During a normal start, the starter drives the engine through the firing speed to self-sustaining speed (approximately 2000 rpm) and then assists the engine torque to accelerate the engine. Starter cutoff speed is approximately 3700 rpm. Engine torque after starter cutoff is dependent on the fuel control setting and was assumed to be constant to idle speed. The starter cutoff speed used was specified by the engine manufacturer and could possibly be a different value with an IEG system.

Several variations of engine starting using the generator can be considered for accomplishing the starting sequence described previously. Two of these, constant torque and variable torque, are shown in figure 2. To estimate the required generator rating, the constant torque method was assumed. Additional assumptions were:

(1) The generator operates as an 85 percent efficient motor.

(2) Power factor can be maintained near unity by means of control in the power converter.

(3) The generator can carry 1.65 times rated current for the 20 to 25 seconds required for starter operation.

(4) Constant torque results in approximately constant current in the generator.

As a result of the 30-second start requirement and the lower torque supplied by the engine, the 50° C condition is the worse of the two shown in figure 2. Using the following equation, a constant torque of 540 newton-meters (400 lb-ft) was found to be required from the generator to accomplish a 30-second start at this condition:

$$T_g = (I_e \alpha + T_e) \frac{n_i}{n_c}$$

where

T_g generator torque from 0 to n_c, N-m

I_e	engine shaft inertia, kg-m^2
α	average acceleration to idle, rad/sec^2
T_e	net average torque of engine from 0 to n_1, N-m
n_1	shaft speed at idle, rpm
n_c	shaft speed at starter cutoff, rpm

For the base engine I_e is 39.2 kilogram-meter squared and α for a 30-second start is 17.45 radians per second squared. With the aforementioned assumptions, this torque results in a generator rating of 200 kilovolt-amperes at engine idle speed (5000 rpm) as calculated from the following equation:

$$P_R = \frac{2\pi T_g n_1 \times 10^{-3}}{60\eta K}$$

where

P_R	generator rating at idle speed, kV-A
η	efficiency of generator as a motor
K	current overrating factor

With values substituted, this becomes

$$P_R = \frac{2\pi(540)(5000)\times 10^{-3}}{60(0.85)(1.65)} = 202 \text{ kV-A}$$

The 540 newton-meter torque allows an adequate margin above the peak engine requirement with -50° C air to assure satisfactory starts. The 200 kilovolt-ampere rating provides power in excess of that required for normal aircraft electrical loads which can be used to power engine accessories as described previously in this paper.

The other variation of engine starting torque characteristic shown in figure 2 has a greater torque margin above the peak engine requirements and the ramp decline of torque results in a more uniform engine acceleration. This characteristic may be preferable, but it requires a more sophisticated control. Because of the greater torque, the maximum generator current will be greater and the losses higher. To accommodate these penalties, the required generator rating might be greater. Current during the high torque operation can be approximately twice rated since its duration is short. For the purposes of this evaluation, however, it was assumed that either speed-torque characteristic can be delivered by the 200 kilovolt-ampere generator.

Generator Designs

Three types of brushless synchronous generators with a 200 kilovolt-ampere rating as derived in the preceding section were designed. These are the solid-rotor modified Lundell or Rice machine, the homopolar inductor machine, and the conventional wound-rotor, salient-pole, rotating-rectifier generator. The modified Lundell generator is shown in figure 3 mounted on the HP shaft of the base engine. Figures 4 and 5 show, respectively, similar drawings of the homopolar inductor and the rotating-rectifier generators. The rotating-rectifier generator is widely used in present day aircraft electrical systems. To eliminate the need for slip rings and brushes, it includes the rectifiers and a rotating exciter. The permanent magnet generator (PMG) is used for control power. Since static means of excitation and control power may be used with the homopolar and Lundell generators, a PMG is not included with these machines. All three generators fit in the base engine with the tower shaft and bevel gears removed and without enlargement of the bearing cavity or relocation of the bearings.

Electromagnetic design. - The generators were designed with the aid of digital computer programs. Existing programs were used for the Lundell and homopolar generators.(12)(13) A similar computer program based on reference 14 was developed for the wound-rotor, rotating-rectifier generator.

Table I summarizes some of the more important design data for the three generators. All were designed with a 20.8-centimeter- (8.2-in.-) diameter hole through the center of the rotor so they can be mounted around the engine shaft. Dimensions and weights given in table I are for the electromagnetic parts of the generators only. Additional weight will be needed for support and mounting structures and cooling hardware. For the rotating-rectifier machine, only the design data for the main generator are given. Sizes for the rotating exciter and PMG shown in figure 5 are estimated. The total weight of this machine including exciter and PMG is approximately 91 kilograms (200 lb), of which 45 kilograms (100 lb) is the rotor weight.

The electrical frequency of the generators at 5000 rpm was selected so that they can be used with a dc link frequency converter, be rectified to high voltage dc, or be considered for a wild frequency system. For the homopolar and rotating-rectifier generators, the number of poles (12) was selected to avoid the problems of high rotor leakage flux associated with a larger number of poles and the increased rotor diameter and weight resulting from a smaller number of poles. For the Lundell generator, the minmum number of poles possible to get a reasonable frequency was used (6 poles). More poles in the Lundell generator results in higher rotor leakage fluxes and, therefore, a larger rotor. Generally, the selected winding current densities are conservative in relation to those in presently used spray-oil-cooled aircraft generators. For the generator rotors, SAE 4340 steel was chosen because with the proper heat treatment it is possible to get both high strength and relatively good magnetic properties with this material.

Rotor mechanical stresses. - Rotational stresses were calculated to determine if rotor materials used in the electromagnetic designs are suitable. Maximum rotational speed is 7600 rpm with the base engine; however, other engines of similar size have maximum HP shaft speeds of up to 10 000 rpm. The 10 000 rpm speed was, therefore, used in the stress calculations so that the generators can be evaluated for use on other engines.

The calculated maximum stress for the Lundell generator is tangential and occurs at the inner diameter of the rotor. This stress is 26 400 newtons per centimeter squared (38 400 psi). In the homopolar and wound-rotor rotating-rectifier generators the maximum calculated stress occurs at the junctions of the salient poles and the rotor back iron. In the homopolar rotor this stress is 44 200 newtons per centimeter squared (64 200 psi). In the wound rotor it is 41 500 netwons per centimeter squared (60 200 psi). Stress concentrations at sharp corners could result in higher stress levels, but still within the range of the heat treated 4340 steel used in the generator designs.

Calculations for stress in the Lundell rotor assumed that the rotor acted as a simple unrestrained rotating cylinder. Those for the homopolar rotor considered it to be a rotating cylinder with the poles as attached centrifugal loads.

For the wound rotor it was assumed that the copper field coil is completely supported by the pole head and not restrained by bands or compression rings. The calculated rotor stress is, therefore, a "worst-case" stress since support rings or bands will probably be used in a final practical design.

A second area of concern was the stresses due to centrifugal force on the rotating rectifiers used with the wound-rotor design. Assuming that the rectifiers are mounted at a 14-centimeter (5.5-in.) radius near the inner diameter of the rotor (fig. 5) resulted in calculated forces of 15 650 g's at 10 000 rpm. Semiconductor rectifiers have been satisfactorily operated at levels as high as 20 000 g's. With adequate design considerations, no serious problems are expected with rectifiers used in this application.

Generator cooling. - The detail methods of cooling the generators were not selected, but engine oil was considered the cooling medium. It was estimated that the generator operating with a 200 kilovolt-ampere load will require from 0.02 to 0.04 meters cubed per minute (5 to 10 gal/min) of cooling oil flow. Inlet oil temperature was assumed to be approximately 100° to 120° C. The cooling oil would be supplied from the same source and pump which supplies engine oil

During the start mode, cooling oil may not be available depending on the detail design. In a worst-case analysis of the generators designed for this evaluation, it was found that conductor temperatures will not exceed reasonable limits during the start mode without cooling, even if all stator copper loss heat remains in the conductors during the start cycle. With the generator at 25° C at the beginning of a constant torque start cycle, the average conductor temperature at starter cutoff will be approximately 75° C. With a beginning temperature of 120° C (to represent a start cycle after normal operation) the final average conductor temperature will be approximately 188° C. Successive start attempts will, of course, result in higher temperatures but, with generator insulation such as a polyimide (ML), short-term temperature excursions to 250° C will not be detrimental. Also, some heat transfer, both active and passive, will occur during a start cycle.

Engine shaft dynamics. - Engine shaft dynamics are important to both the generator and the engine. Shaft deflection and rotational eccentricity ahead of the forward HP bearing in the base engine directly affect the generator airgap and must be accounted for in the generator design. The added weight of the generator rotor must not adversely affect the dynamic characteristics of the HP shaft. The manufacturer of the base engine has estimated the maximum radial displacements of the forward end of the HP shaft with the heaviest and lightest generator rotors installed as shown in figures 3 and 5. Both the present shaft design as well as one with a hub stiffness twice that of the present design were considered. These estimates are summarized in table II. The manufacturer further estimated that changes in overall shaft dynamics caused by the addition of the generator rotor will not cause serious engine problems if the stiffened shaft is used.

As table II shows, the maximum displacement with the stiffened shaft and the Lundell rotor is ±0.096 centimeter (0.038 in.). With the rotating rectifier rotor it is ±0.053 centimeter (0.021 in.). Both of these values are less than the design generator air gap of 0.178 centimeter (0.070 in.). Air gap variation should not be a problem with a stiffened shaft.

An alternative to the overhung mounting shown in figures 3 to 5 is the use of a separate shaft and bearings for the generator. The generator would straddle the engine shaft and be driven through a spline or other coupling. This approach will minimize the interactions between the engine shaft and the generator.

Reliability. - The solid-rotor generators use relatively simple rotors with no evident wearout mode. The rotating-rectifier generator has a complex rotor with rectifiers and windings. Armature and field windings in both the solid-rotor and rotating-rectifier generators have wearout and failure modes, associated with the insulation system. Both heat and mechanical stress can degrade or damage insulation and lead to failure. To achieve the required reliability an IEG-type generator must be designed to keep both thermal and mechanical stresses well below maximum material capabilities.

Preferred generator type. - From the observations stated in the preceding sections, the solid-rotor generators have the greater possibility of providing the high degree of reliability required of the generator in an IEG system. The wound rotor, rotating-rectifier type with a total weight of approximately 91 kilograms is significantly lighter than the 211-kilogram homopolar or the 367-kilogram Lundell type. In addition, the heavier solid-rotor types require more structure inside the engine for support. Reliability history of present aircraft generators is not directly applicable to the IEG. The present aircraft generators include bearings, seals, and drive splines which have failure modes. The IEG does not use these parts. Conservative design and advanced technology construction techniques, materials, and rectifiers should result in a rotating-rectifier type IEG with adequate reliability.

Therefore, because of its weight advantages, the wound rotor, rotating-rectifier type generator appears to be preferable over the solid-rotor types for an IEG system.

IEG Payoff

In a government-funded study under contract NAS1-10893, a major airframe manufacturer has evaluated the effects and payoff of the use of an IEG system in advanced transport aircraft.(15) The conceptual aircraft used for the evaluation had a payload capacity of 18 000 kilograms (40 000 lb), a TOGW in the 140 000 kilogram (300 000 lb) class, and a range of 5600 kilometers (3000 n-mi). Its design speed was a Mach number of 0.98, and it had one tail-, and two wing-mounted engines. The IEG approach to the secondary power system was compared with a conventional system (one using 747 or DC-10 technology) as well as with competing advanced approaches. One of the latter uses a gearbox-mounted generator-starter-drive (GSD). In that approach the generator is used as a motor to start the engine, but it drives through the hydraulic constant speed drive. The other competing approach uses advanced gearbox-driven components packaged and arranged to fit into a bifurcation in the engine fan duct.

IEG and comparison secondary power systems, complete with electric, hydraulic, and pneumatic subsystems were selected and subjected to preliminary optimization. All systems were equally responsive to aircraft operational requirements. Weight summaries were made, and using computer models, the systems were analyzed to determine variations in aircraft drag, fuel consumption, cruise thrust, and TOGW. The conventional system served as a baseline for the comparison. All three advanced systems were considered to have a potential reliability adequate for airline use.

The IEG system, with a wound rotor, rotating-rectifier generator, reduced TOGW 4200 kilograms (9300 lb) below the baseline. Approximately 35% of this reduction was in fuel load. The GSD system gave a reduction in TOGW of 3000 kilograms (6600 lb), and that with the bifurcation mount gave a 3100-kilogram (6800-lb) reduction below the baseline.

With the assumptions of a 300-airplane fleet, a 14 year airframe lifetime, and a 15 percent discount rate, the value of the technology for each of the advanced systems was determined. This value is the sum of the change in manufacturing cost and the present value of savings in direct operating cost over the airframe life. The system with the IEG has a value of technology of approximately $282 000 per airplane. The GSD system has a value of $193 000 per airplane. And the value of the bifurcation mount system was $236 000 per airplane.

The payoffs summarized above are applicable to a particular aircraft design. The relative benefits may well be different for other aircraft.

Concluding Remarks

The results of this investigation indicate that the integrated engine-generator concept is a technically feasible and economically attractive approach to secondary-power systems for future large aircraft. Generators of a size sufficient to allow starting of large turbofan engines in 30 seconds by motoring of the generator will have a rating of two to three times that of generators presently used in large commercial aircraft. The increase in available electric power can be used for electrically driven, remotely located engine accessories and other auxiliary equipment, thereby reducing or eliminating engine-shaft-driven accessories and bleed air requirements. This in turn results in reduced engine frontal area and reduced aircraft drag and takeoff gross weight.

The incorporation of a generator within the turbofan engine on the high-pressure shaft is not expected to adversely affect engine design or performance. This is evidenced by the fact that a generator of suitable size will fit in a recently developed large turbofan engine without change to the engine flow path and without major modification of the basic engine design.

The reliability of the generator inside the engine must be considerably better than the reliability of present aircraft generators. This increased reliability appears achievable through the use of a solid-rotor generator or a conservatively designed wound-rotor, rotating-rectifier type. Preliminary designs indicate that the wound-rotor, rotating-rectifier type is preferable because of its significantly lower weight.

Several electrical system approaches can be considered for use with an IEG. These approaches include: (1) use of the generated variable frequency ac power for the aircraft system and a programmed frequency changer for starting, (2) conversion of the generated power to high voltage dc for the aircraft systems and an inverter for starting, (3) conversion of the generated power to constant frequency ac with either a cycloconverter or dc link frequency converter and the use of the same converter for starting, and (4) hybrid combinations of these.

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TABLE I. - GENERATOR DESIGN DATA

	Modified Lundell	Wound-rotor, rotating-rectifier[a]	Homopolar
Rating			
Continuous, kVA	200	200	200
Overload-electromagnetic, kVA	400	400	400
Speed, rpm	5000	5000	5000
Frequency, Hz	250	500	500
Number of poles	6	12	12
Dimensions			
Rotor diameter, cm (in.)	37.8 (14.86)	31.4 (12.36)	40.3 (15.86)
Pole length, cm (in.)	12.3 (4.85)	13.2 (5.20)	10.2 (4.0)
Outside diameter, cm (in.)[b]	52.5 (20.7)	36.8 (14.50)	52.1 (20.5)
Main airgap, cm (in.)	0.178 (0.07)	0.178 (0.07)	0.178 (0.07)
Weights[b]			
Rotor, kg (lb)[c]	149.0 (329)	36.2 (80)	98.4 (217)
Total, kg (lb)	367.0 (810)	65.3 (144)	211.0 (466)
Current densities (at rated load)			
Armature winding, A/cm^2 ($A/in.^2$)	1250 (8060)	1220 (7880)	1220 (7880)
Field winding, A/cm^2 ($A/in.^2$)	624 (4020)	1660 (10 700)	616 (3970)
Materials			
Stator laminations	2V Permendur	2V Permendur	2V Permendur
Rotor (magnetic material)	SAE 4340	SAE 4340	SAE 4340

[a]Main generator only.
[b]Electromagnetic only.
[c]For wound-rotor generator, rotor weight includes field winding.

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TABLE II. - MAXIMUM RADIAL DISPLACEMENT OF BASE ENGINE HP SHAFT AT GENERATOR LOCATION

Generator type	Radial displacement, cm (in.)	
	Present HP shaft	Stiffened HP shaft[a]
Lundell	±0.127 (0.050)	±0.096 (0.038)
Rotating-rectifier	±0.069 (0.027)	0.053 (0.021)

[a]Stiffness is twice that of present shaft.

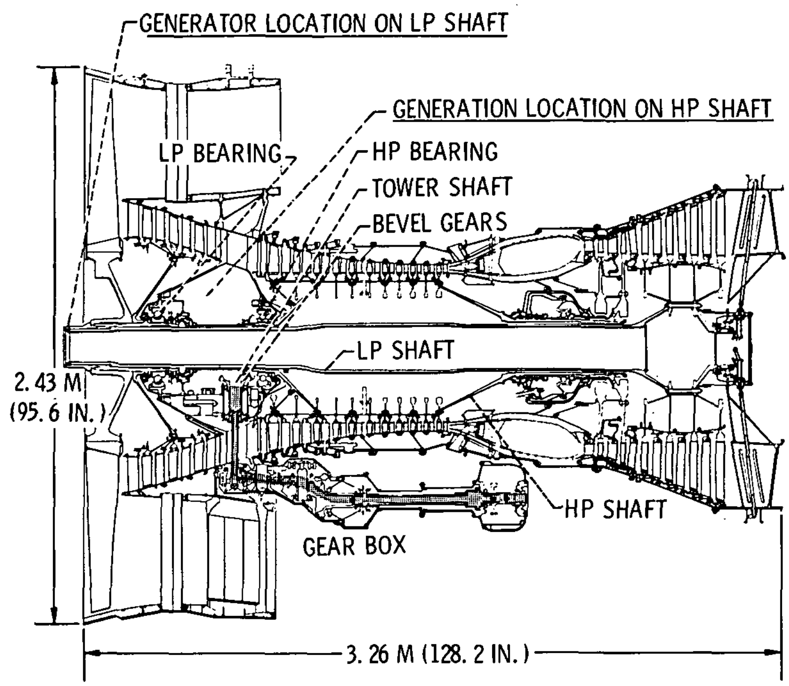

Figure 1. - High bypass ratio, commercial, turbofan engine.

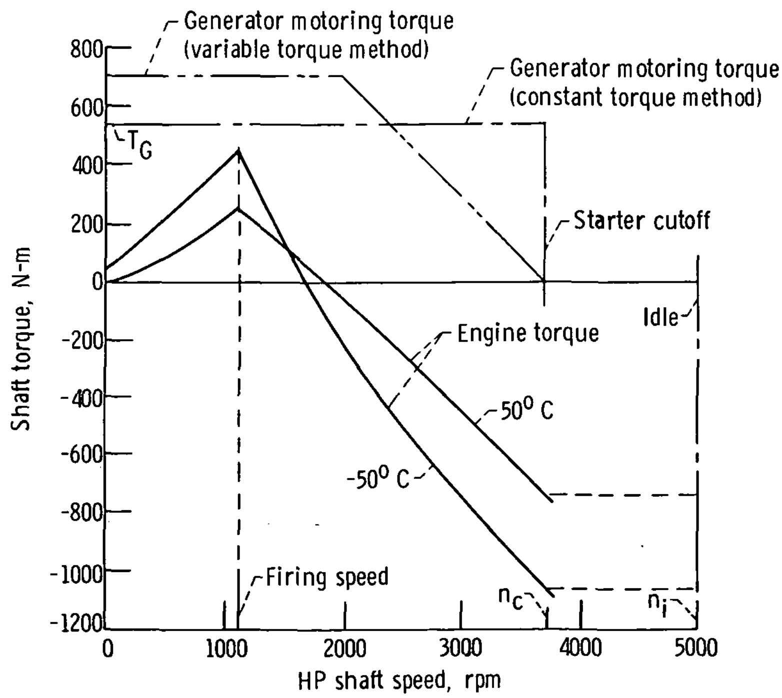

Figure 2. - Estimated starting characteristics for large turbofan engine.

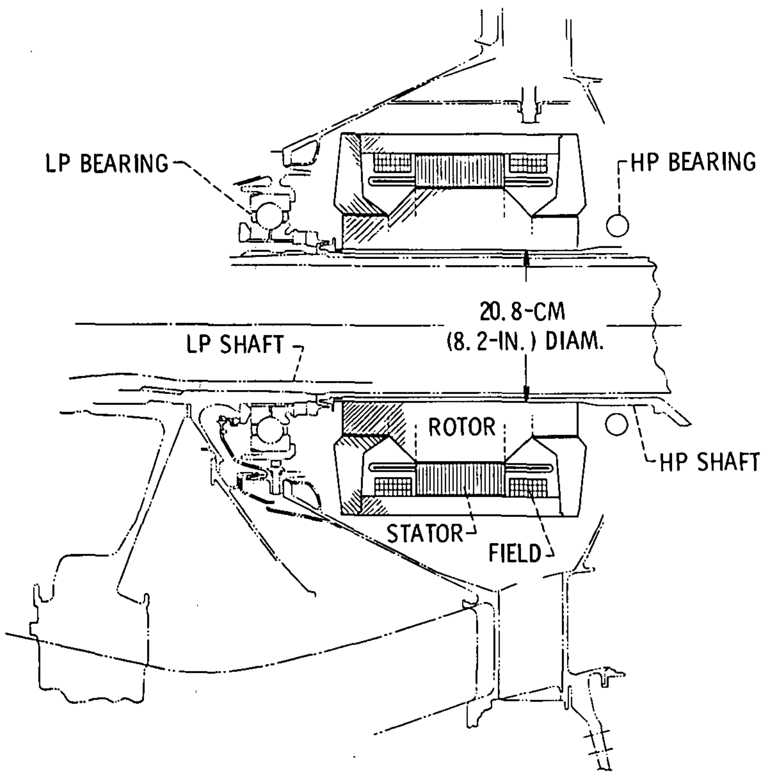

Figure 3. - Lundell generator in large turbofan engine.

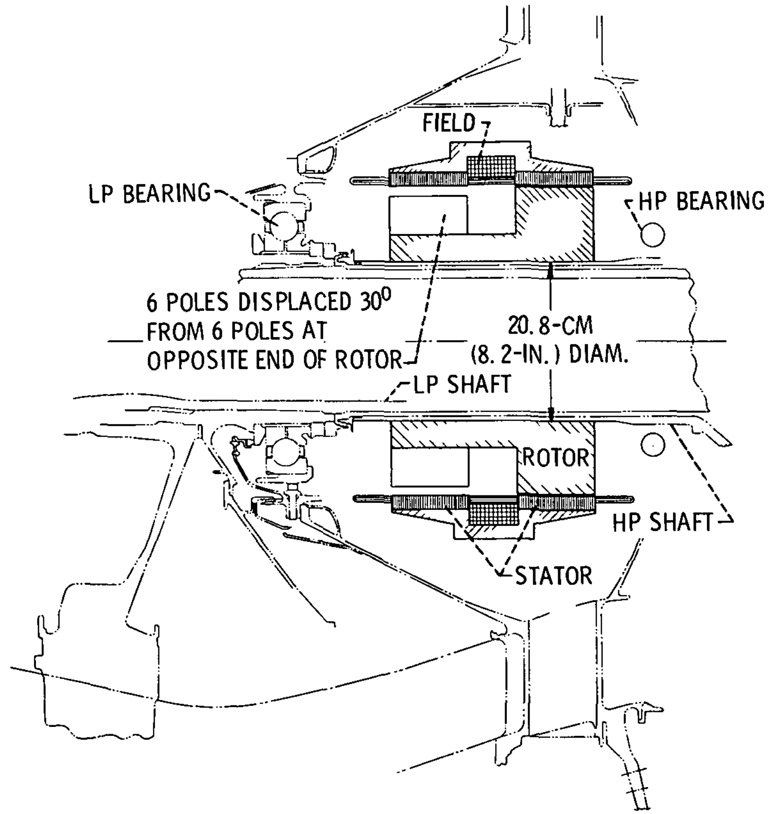

Figure 4. - Homopolar inductor generator in large turbofan engine.

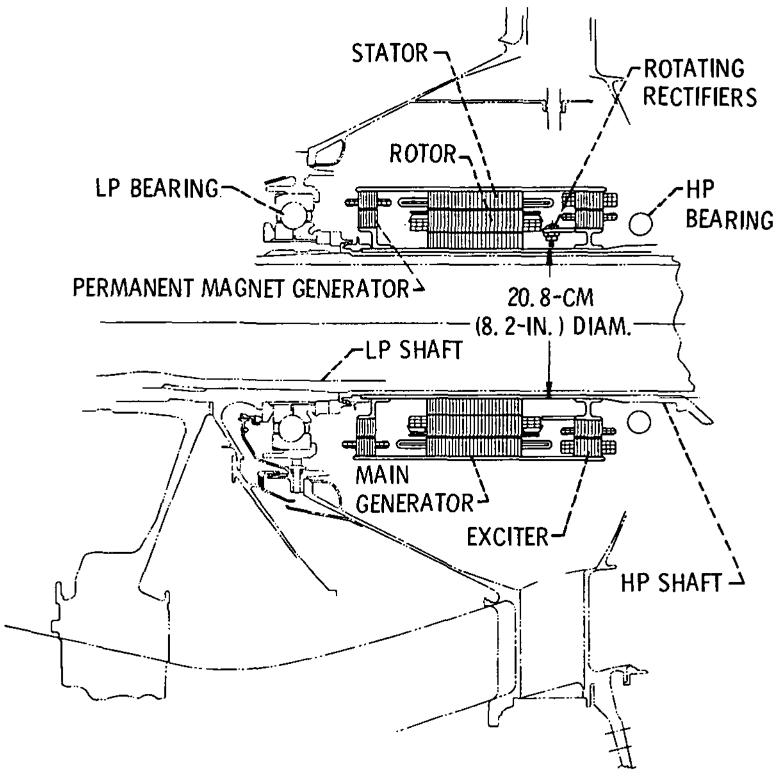

Figure 5. - Wound-rotor, rotating-rectifier generator in large turbofan engine.