ELECTRIAL POWER TECHNOLOGY FOR THE MORE ELECTRIC AIRCRAFT

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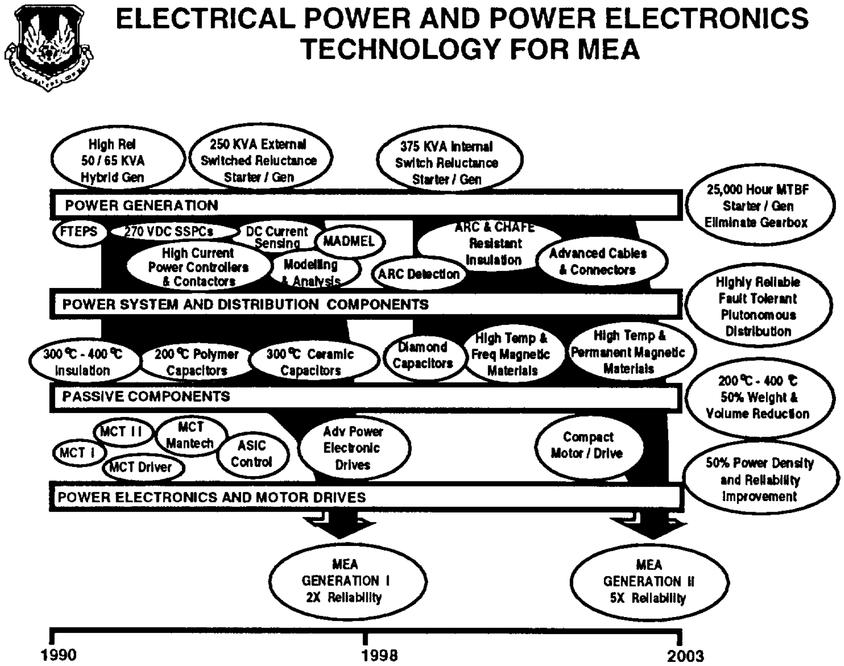
ABSTRACT

The Air Force's More Electric Aircraft (MEA) initiative embraces the concept of utilizing electrical power for driving aircraft subsystems currently powered by hydraulic, pneumatic or mechanical means including utility and flight control actuation, environmental control system, lubrication and fuel pumps, and numerous other utility functions. An important part of this initiative is the development and demonstration of electrical power and power electronic components and systems to enhance reliability, fault-tolerance, power density and performance. This paper describes some of the key electrical power and power electronic technologies being pursued by the Air Force to make the concept of a MEA a reality. The paper describes the results or progress to date of Air Force funded MEA programs such as the Power Management and Distribution for the More Electric Aircraft program, Integral Starter Generator program, and MOS Controlled Thyristor program. Also a brief discussion of future related programs will be included. The integration of advanced MEA technologies will dramatically increase aircraft reliability and reduce susceptibility to battle damage. The needs for aircraft maintenance and support will be reduced along with ground support equipment and maintenance personnel.

INTRODUCTION

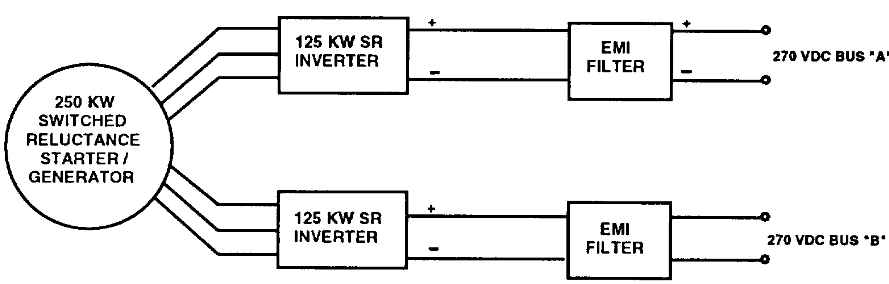
Military aircraft have numerous subsystems powered by one or more sources of secondary power: hydraulic, pneumatic, electrical and mechanical. Secondary power is typically extracted from the main engines mechanically by a driven shaft and pneumatically by bleeding the compressor. Mechanical power is distributed to a gearbox to drive lubrication pumps, fuel pumps, hydraulic pumps and electrical generators. Pneumatic power typically drives air turbine motors for engine start systems and environmental control systems. Electrical power and hydraulic power are distributed throughout the aircraft for driving subsystems such as flight control actuators, landing gear brakes, utility actuators, avionics, and weapon systems. Recent and projected advancements in aircraft electrical power system and component technologies have resulted in renewed interest in the More Electric Aircraft (MEA). The MEA emphasizes the utilization of electrical power as opposed to hydraulic, pneumatic, and mechanical power for optimizing aircraft performance and life cycle cost. For example, hydraulically driven actuators would be replaced by electric motor driven actuators, gearbox driven fuel and lubrication pumps would be replaced by electric motor driven pumps, and a pneumatically driven compressor for environmental control would be replaced by an electric motor driven compressor. Studies on two different military fighter aircraft have shown that the MEA concept provides significant reliability, maintainability and supportability payoff. The decision to convert to electrically driven subsystems depends on the overall cost and performance benefits. Each subsystem of a selected aircraft would be studied to determine the benefit. Therefore, a MEA could be as simple as adding an additional electric motor driven pump to a full implementation where all subsystems are electrically driven (which is commonly called the All Electric Aircraft). Our studies have shown the answer lies between these two extremes for the near-term and closer to the All Electric Aircraft concept for the far term. This presents several key challenges for electrical power technology development based on two observations. First, the MEA equates to increased use of electric motors for servo and variable speed applications. Thus reliable, high power density motors and motor drives with power ratings ranging from a few horsepower to hundreds of horsepower will be required. Second, the magnitude, reliability, and fault tolerance of electrical power to be generated and distributed in the MEA must be significantly greater than present state-of-the-art technology can provide.

It is the purpose of this paper to review and update the Air Force's on-going and planned programs to develop the electrical power technologies for the near and far term MEA. The roadmap shown in Figure 1 illustrates the timing, relationship and goals established for these programs. There are four major technical thrusts in the roadmap: (1) power generation, (2) power systems and distribution components, (3) passive components, and (4) power electronics/motor drives. Each of the thrusts and selected programs will be briefly discussed from a technical and programmatic viewpoint. All thrusts support the Air Force's 1998 near term MEA and the 2003 far term MEA goals.



JW/FIGURE 1

FIGURE 1



JW/FIGURE 2

FIGURE 2

TABLE 1

250 KW SWITCHED RELUCTANCE STARTER/GENERATOR SYSTEM DESIGN GOALS

OUTPUT VOLTAGE	270 VDC
OUTPUT POWER CONTINOUS	250 KW
OUTPUT POWER 5 SECONDS	330 KW
POWER QUALITY	MIL/STD 704E
SYSTEM WEIGHT	250 POUNDS
SYSTEM EFFICIENCY	85%

POWER GENERATION

The Air Force has placed high emphasis on and devoted significant resources to the development of electrical power generation equipment for the near and far-term MEA. The Air Force has two programs (The High Reliability Generator program and the Switched Reluctance Starter/Generator program) that are on-going and support the near-term MEA and a planned program to support the far-term MEA. All of these programs support the increased magnitude, type, quality and reliability of power required for an MEA. The High Reliability Generator program has evolved from a conventional 400 Hz Variable Speed Constant Frequency (VSCF) system to a dual output (270 VDC and 400 Hz) system capable of supporting very near-term MEA concepts. The Switched Reluctance Starter/Generator program developed the preliminary design for a 375 KW, 270 VDC switched reluctance starter/generator in which the electrical machine is integrated internally with an advanced gas turbine engine. In addition, an externally mounted 250 KW, 270 VDC switched reluctance starter/generator will be built and tested to demonstrate the critical technologies. The switched reluctance starter/generator system offers a robust, high temperature, fault tolerant solution for the environmental demands of the turbine engine and the performance demands for the MEA.

The feasibility of the 250 KW switched reluctance starter/generator is based upon recent advancements in power electronic component technologies, high temperature wire insulation, and high temperature, high strength magnetic materials. Figure 2 illustrates the 250 KW system to be developed. The power electronic inverter is essential to the system since it provides the means to excite and process power to and from the switched reluctance starter/generator. The Electro-Magnetic Interference (EMI) filter will reduce unwanted frequency components for compliance with MIL-STD-704E and MIL-STD-461. The design goals of the 250 KW starter/generator system are defined in Table 1. Presently, the program is in the fabrication phase. Demonstration of the system will follow with testing of the system scheduled for completion in the fall of 1993. The planned follow-on demonstration/test program will build upon the preliminary design of the internally integrated 375 KW switched reluctance machine. This program will be a critical step in eliminating the engine gearbox and aircraft mounted accessory drive. The integration of the switched reluctance machine into the gas turbine engine is enabled by high strength, high temperature permendur cobalt-iron magnetic materials and reliable high temperature wire insulation. The time frame for starting the integrated starter/generator program has not been determined at this time.

POWER SYSTEMS AND DISTRIBUTION COMPONENTS

The MEA will need a highly reliable, fault tolerant, autonomously controlled electrical power system to deliver high quality power from the sources to the load. There are several challenges in designing an electrical power system for a MEA. First, the MEA concept adds a substantial amount of high power dynamic motor loads to the power system which could impact power quality. Second, most of these loads will have a low input impedance "capacitive" EMI filter which could present an in-rush current problem during power system initialization. Third, most of these loads have a constant power characteristic which could impact power quality and system stability. Fourth, MEA loads such as flight control actuators are capable of providing regenerative energy back to the power distribution system. Fifth, a significant amount of these loads are flight critical and loss of power to these loads could result in the loss of the aircraft. Thus, the performance and integrity of the power distribution system becomes a critical network which links sources to loads. The Air Force funded several 400 Hz distribution component programs which were brought together in the Fault Tolerant Electrical Power System (FTEPS) demonstrator in the late 1980's. FTEPS was designed for a two engine fighter with conventional type loads, including a flight critical fly-by-wire flight control system. FTEPS demonstrated the automation and protection needed for this type aircraft and is a starting point for MEA electrical power distribution. Presently, the Air Force has two programs for developing power systems and distribution components for the MEA. They are the Power Management and Distribution for More Electric Aircraft (MADMEL) program and the Remote Terminal utilizing 270 VDC Solid State Power Controller program. Future programs are focused toward the

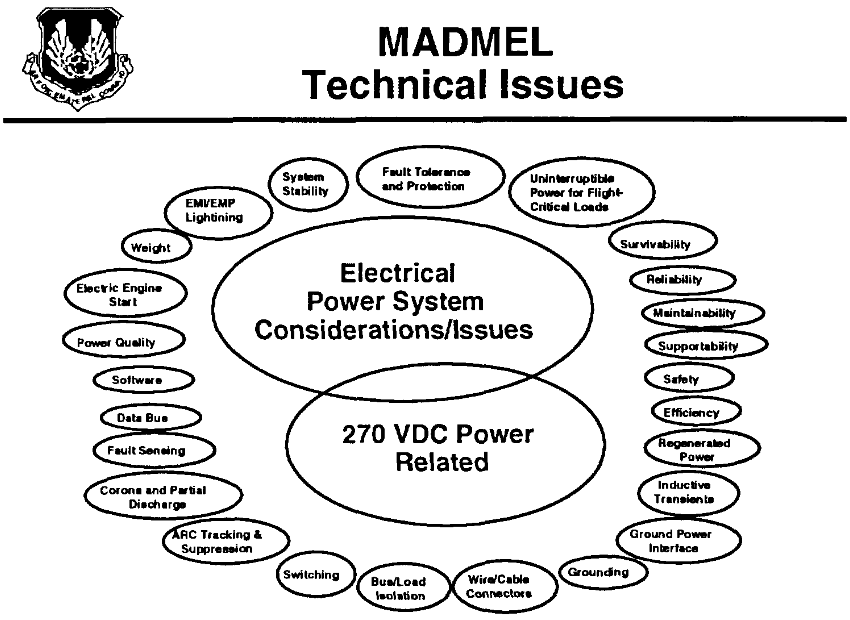


FIGURE 3

development of advanced distribution components. This includes the following: (a) Development of high current (>50 ampere) intelligent power controllers and contactors that provide control, protection, and status feedback. (b) Development of smart, overcurrent, differential current, and ground fault protection systems, (c) Development of arc detection circuits to trigger protection devices in the event of an arc. (d) Development of highly reliable and rugged connectors and interconnect components.

The Air Force awarded a contract to Northrop Corporation in the fall of 1991 to develop a power system design for a more electric F/A-18 and to demonstrate in the laboratory an advanced power generation and distribution system derived from a more electric F/A-18 design. The contract will bring together several state-of-the-art and emerging technologies to demonstrate in the laboratory a highly reliable, fault tolerant power system. The program is divided into five phases which include: (a) Phase 1 - Load requirements and load profile study (b) Phase 2 - Preliminary design of the power system and demonstrator (c) Phase 3 - Detail design of the power system and demonstrator (d) Phase 4 - Fabrication of the laboratory demonstrator (e) Phase 5 - Test and evaluation of the demonstrator. In Phase 1, Northrop determined the type of loads to be included in the more electric F/A-18 aircraft and which loads were flight critical, mission critical, and non-flight critical. However the Air Force required a minimum number of more electric loads which included electrical flight control and utility actuators, and an electrical motor driven compressor for the environmental control system and main engine electrical start systems. All other potential more electric loads were studied for their cost and performance benefit and would be included based on favorable results. Each load was characterized by its function power demand, voltage, frequency, power factor, maximum interruption time, and transient and steady-state electrical behavior. The load information produced in Phase 1 would be essential in designing the power system in the latter phases. Both a near term (CY 1998) F/A-18 MEA and a far term (CY 2003) F/A-18 MEA were studied. The load profile for the near-term F/A-18 MEA requires a generation capacity of 165 KW for continuous operation and 217 KW for a five second peak operation. The 165 KW total load can be divided into 125 KW of motor loads and 40 KW of avionic and electronic loads. Thirty-eight (38) KW of the 165 KW are flight critical in which 33 KW is interruptable (>50ms) and 5 KW is uninterruptable (<50ms). The large amount of flight critical loads clearly illustrates the need for a power system capable of delivering highly reliable, fault tolerant, uninterruptable electrical power. Also, the power system will supply a high percentage of motor loads (>75%) with the majority of the remaining loads being power supplies for radar and other avionic systems. The motor loads and radar load tend to be transient by nature and some motor loads may provide regenerative energy back to the power system. This presents a unique challenge for meeting power quality specifications (per MIL-STD-704E) and electro-magnetic interference specifications (per MIL-STD-461). Stability of this power system will be an issue since the majority of these loads (motor drives/motor and power supplies) have a constant power characteristic and low input impedance, plus the transient and regenerative nature of some of the loads. The majority of the more electric loads and avionic loads will require 270 VDC power. The generation and distribution of 270 VDC power has its own set of technical issues that must be addressed under this program. This includes corona and partial discharge, arc tracking and suppression, switching, current sensing, grounding, safety and other concerns. Figure 3 identifies many of the technical concerns and issues the MADMEL program will address. It is expected that many of the technical concerns and issues will be resolved under this program and the remainder will be better understood. Presently the MADMEL program is in the detail design phase and the program is scheduled to be completed in 1996.

The Air Force awarded a contract to the Leach Corporation in the fall of 1991 to develop an intelligent remote terminal for housing and controlling a large number of SSPCs and to develop high current 270 VDC, SSPC's for remote applications. The remote terminal will be a generic design to house and control a variety of SSPCs (400 Hz, 270 VDC, 28 VDC) with current ratings up to 15 Amperes. The program will also develop a 50 A, 270 VDC SSPC and a 130 A, 270 VDC SSPC using the MCT as the switching element. An auxiliary commutation circuit will be used to aid the MCT in turning off fault currents. Leach has demonstrated a breadboard SSPC turning of fault currents as high as 1300 Amperes. The forward drop of the device is expected to be between 1.1-1.4 colts under full load conditions. The program is expected to be completed in the fall of 1994.

PASSIVE COMPONENTS

The passive components thrust for the MEA includes the development of insulation, dielectric and magnetic materials and components such as capacitors and inductors. Passive components will play a major role in providing the reliability improvements and volumetric and weight reductions necessary to make the MEA a preferred option. The roadmap of Figure 1 identifies several programs to enhance the reliability of passive components and to minimize weight and volume. Reliability improvements can be achieved by significantly increasing the margin between the design temperature and operating temperature of the component. Only those materials that show promise for weight and volume reduction and provide superior electrical, mechanical and thermal properties will be pursued. Additionally, insulation materials to be developed for aircraft wiring will have to be resistant to arc tracking and chaffing.

The Air Force recently completed a program with TRW, Inc. to identify and evaluate advanced polymer insulation materials which offer improved electrical and thermal properties over Kapton. This program was originally intended for space applications but also has shown benefit for aircraft wiring. Materials were screened and evaluated for high temperature (up to 300°C) and low temperature (down to -269°C) capability, electrical properties and resistance to environmental concerns such as humidity, ultraviolet radiation, basic solution and solvents. Three materials, Eymyd, L-30N, and Upilex S, demonstrated superior performance and can be considered as candidate replacements for Kapton. Ceramic coated Upilex S insulated wires were developed which demonstrated improved arc tracking resistance. The Air Force continues to work on the development of new materials which offer improvements over known materials. Continuation of research and development in wire insulation is essential for ensuring the reliability of the distribution system to support the MEA.

State-of-the-art aircraft capacitors are considered to be the weakest link in power electronic systems. They are also considered to be large, heavy and lossy. This is a real concern for the MEA since 100s to 1000s of capacitors will be required for filtering and energy storage. The Air Force is pursuing several organic and inorganic capacitor technologies under contract that promise improvements in reliability, size, weight, and electrical and thermal performance.

Foster-Miller Corporation was awarded a Small Business Innovative Research (SBIR) contract to examine the application of PBZT polymer film for capacitors. This film demonstrated dielectric strengths as high as 100,000 Volts/Mil and low dissipation factor at high temperatures (up to 300°C). A follow-on SBIR contract to Foster-Miller Corporation will further develop the PBZT film to make highly reliable, high energy density capacitors with operating temperatures to 300°C. Westinghouse Science and Technology Center was under contract to develop and demonstrate high temperature (>200°C) AC and DC filter capacitors using a FPE polymer film from 3M Corporation. The capacitors were tested with a Variable Speed Constant Frequency (VSCF) generator system and demonstrated over 2000 hours of trouble free operation at 225°C. Olean Advanced Products, Division of AVX Corporation is under contract to develop multilayer ceramic capacitors with increased operating temperature (up to 300°C) and reduced dissipation factor over a wide frequency and temperature range. Ceramic capacitors offer tremendous volumetric density compared to other capacitor technologies. This technology is being used in the High Reliability Generator program and the Switched Reluctance Starter/Generator program. The Air Force is conducting an in-house research program to investigate the possibility of using diamond-like carbon and diamond films as dielectric materials for capacitors. Diamond has the highest thermal conductivity of any material known and a very high dielectric strength, electrical resistivity and operating temperature capability. The Air Force has recently awarded several contracts to investigate other promising dielectric materials and construction techniques for capacitors. This includes silicon carbide, barium titanate, and multi-layer diamond capacitors.

POWER ELECTRONICS AND MOTOR DRIVES

Power electronics and motor drives are essential elements of the MEA. Advancements in power semiconductor devices, capacitors, and integrated circuits for control has enabled high density, reliable power electronic and motor drive systems for the MEA. Power electronic systems include power conversion and conditioning for generators, battery chargers, DC to AC inverters, and DC to DC converters. These type of power electronic systems would be considered an integral part of the electrical power system. On the other hand, motor drive systems are an integral part of the utilization equipment and provide the interface between the electrical power system and the motor. A significant increase in the number of motor drives will be necessary for a MEA. Motor drives will control motors for (a) flight control and utility actuation, (b) compressors for cooling aircraft subsystems, (c) pumping fuel, and (d) for many other applications. To date, the Air Force has focused it's resources in this thrust area on the development of the MOS Controlled Thyristor (MCT) switching device and the MCT driver. Future work will center on Application Specific Integrated Circuit (ASIC) technology for motor drive controls and the development of advanced drives for induction, permanent magnet, and switched reluctance motors. The technology developed under these programs would be brought together with advanced motor technology to build a high performance motor and motor drive for a specific MEA application.

In September 1986, the Air Force awarded a contract to the General Electric Corporate Research and Development Center to develop a high power MCT device. At that time, General Electric had only demonstrated a small MCT device capable of a few Amperes and a 200 Volts. It was the objective of this contract to build upon this low power MCT device technology to develop and demonstrate a high power device (with several orders of magnitude increase in power handling capability) that would be applicable to aircraft power conditioning. Our goal was to develop a 150 Ampere 900 Volt device capable of high speed operation (200 nanosecond turn-on and 1 microsecond turn-off capability), low forward voltage drop (1 Volt) and high temperature capability (>200°C junction temperature). Later in the contract, an integrated circuit driver chip was developed that would provide an interface between logic control signals and the gate of the MCT. This program was successful in meeting the objectives and goals of the program and several hundred first generation MCT devices and driver circuits were produced. The MCT demonstrated significant performance improvements as well as size and weight reductions when compared to bipolar junction transistor technology available at that time. A second contract was awarded to General Electric which enhanced the technology developed under the first contract. The goal of this contract was to make the MCT an acceptable and preferred device for military weapon systems such as the MEA. This contract is focusing on advanced hermetic packaging, radiation hardening, and symmetrical voltage blocking for AC applications. Also improvements to the MCT are being investigated which offer improvements in peak current turn-off capability and current density.

CONCLUSION

This paper briefly addresses Air Force programs to develop electrical power and power electronic component and system technologies that are essential to the MEA initiative. The MEA initiative will emphasize the utilization of electrical power in place of hydraulic, pneumatic and mechanical power to optimize the performance and life cycle cost of the aircraft. The MEA will require a highly reliable, fault tolerant, autonomously controlled electrical power system to deliver high quality power to the aircraft's loads. Also, reliable high power density motors and motor drives ranging from a few horsepower to hundreds of horsepower will be required. Recent and projected advancements in electrical power technologies will enable systems capable of meeting these requirements.