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SIMULATION AND ANALYSIS OF A SWITCHED RELUCTANCE GENERATOR/ MORE ELECTRIC AIRCRAFT POWER SYSTEM

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ABSTRACT

A detailed system model for a More Electric Aircraft power system equipped with a switched reluctance generator is described. Example computer studies for several types of generator loads, including passive, constant power, a brushless DC motor, and an electro-hydrostatic actuator, are presented with corroborating experimental test results.

INTRODUCTION

More Electric Aircraft (MEA) offer potential life-cycle cost savings for military and civilian aircraft. The military is considering DC systems as an option, and one possible demonstration system is the MADMEL (Power Management and Distribution System for More Electric Aircraft). The MADMEL will include generators, power conversion devices, and a variety of electric loads. A switched reluctance machine is being considered as an integral starter/generator (ISG). Its advantages have been described previously (Radun, 1994), as well as the design and performance of a candidate 250 KW machine which may be incorporated into the MADMEL (Richter, et al, 1994). In order to provide the government with an in-house analysis capability, computer models of the switched reluctance machine and its controls as well as associated load components have been developed. These models, which are described in this paper, have been programmed in modular form, using the Advanced Continuous Simulation Language (ACSL). By combining the various modules of ACSL code that represent the different components, a variety of systems and operating conditions can be rapidly simulated.

The loads for the MADMEL are intended to be representative of the various aircraft loads including avionics, radars, electro-hydrostatic actuators (EHA), and distribution components. Computer models have been developed for passive loads, brushless DC motors, and EHAs. Several load studies are described and, where possible, compared to actual test data.

One area that is of particular interest to the aircraft designer is that of power system stability. Loads that include DC-DC or DC-AC converters may have the constant power characteristics, which may appear as a negative impedance generator load. The interaction of a negative load impedance with the generator may cause unstable operation depending on circuit parameters. An example of unstable operation caused by load switching is shown.

SWITCHED RELUCTANCE GENERATOR

The construction features and theory of operation for the switched reluctance ISG have been described previously (Radun, 1994), therefore, only a brief review will be given here.

Operating Theory

The switched reluctance machine does not have rotor windings; instead, the number of salient poles on the rotor is different from that on the stator. The ISG for the MADMEL system has 12 stator poles and eight rotor poles as shown in Figure 1. The 12 stator poles constitute two three-phase groups, or channels, that can be operated in parallel or separately. Since the number of stator and rotor poles are different, the inductance of each phase is a function of the rotor position, and at any instant in time, the inductance can be different for the three phases. In Figure 1, the rotor is aligned with phase a of the stator. This aligned position is designated as zero degrees. If the slot between two rotor poles were aligned with the center line of the stator pole, the position would be designated as 45 electrical degrees. Thus there are 90 electrical degrees between the rotor poles or 720 electrical degrees per revolution. This is similar to a four-pole conventional machine. At the position shown in Figure 1, the rotor is at −30 degrees with respect to the phase b poles of the stator and at -30 degrees with respect to phase c.

The flux linkages of a stator winding are a function of winding current and rotor position. A set of calculated flux-linkages curves was obtained for the test machine, some of which are shown in Figure 2. In particular, curves are shown for nine degree intervals to 45 degrees. The large air gap at 45 degrees results in essentially a constant reluctance path whereupon the flux linkages - current curve becomes essentially linear. The data set for the machine consisted of curves at

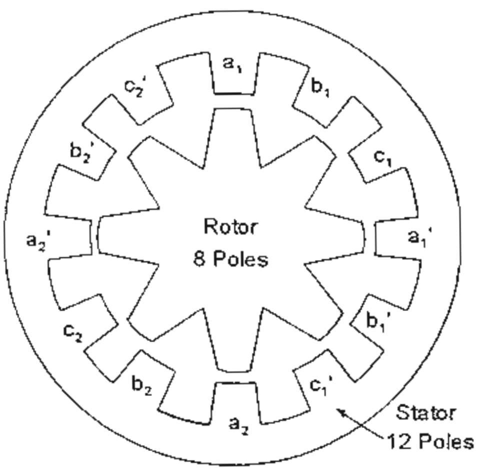

FIGURE 1: CROSS-SECTION OF SWITCHED RELUCTANCE MACHINE

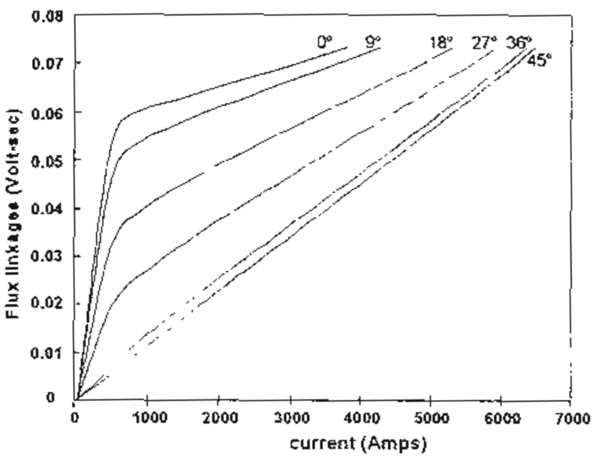

FIGURE 2: FLUX LINKAGE VS CURRENT CURVES

one degree intervals from zero to 45 degrees.

Since the switched reluctance machine does not have rotor windings, a source of excitation must be provided. The schematic for one set of three-phase stator windings is shown in Figure 3. The machine terminals are connected to a capacitor bank to provide a source of excitation. Switches provide a path to supply the winding current as the rotor pole nears alignment with the stator pole. Diodes provide a path for current to flow out of the machine as the rotor poles are driven past alignment. Since there is a reluctance torque attempting to keep the stator and rotor poles aligned, work must be done by the prime mover to force the poles apart, which appears as an electrical output from the generator.

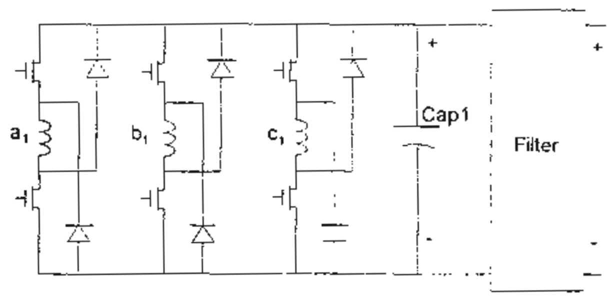

FIGURE 3: PHASE WINDING CONNECTIONS

Switched Reluctance Generator Model

The switched reluctance ISG computer model is a detailed model of all three phases including the variable inductance of the windings. The switches and diodes are modeled as ideal elements. Although experimental results indicate a small mutual coupling between the two groups three-phase groups, this mutual coupling is neglected.

A block diagram of the simulation is shown in Figure 4. The heart of the simulation is the routine that models the phases of the machine. The position of the rotor with respect to each phase must be calculated at each time step. At the appropriate time, the output voltage is applied to a phase winding. The angle at which the voltage is applied to the phase is an input to the simulation. The voltage is integrated to obtain the flux linkage in the phase, which is input to a table routine that performs a linear interpolation to determine the mmf for a given angle and flux linkage. The current is calculated from the mmf, based on whether the phase channels are operating separately or in parallel.

The control system for the machine has also been described previously (Radun and Xiang, 1995). It is a DSP system and uses the output voltage to establish a reference current level. The reference current determines the time of opening the phase switches to begin

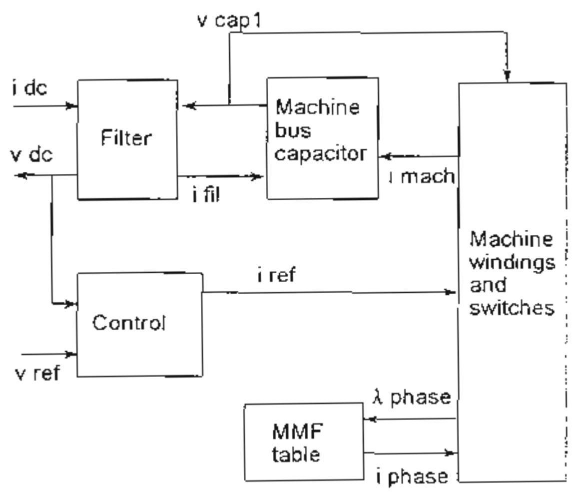

FIGURE 4: BLOCK DIAGRAM OF MACHINE SIMULATION

generation. The machine output capacitor and the EMI filter are modeled using the appropriate differential equations.

SYSTEM LOADS

There are a variety of loads in all-electric or more-electric aircraft. The MADMEL will provide actual or simulated devices for many of these loads. A schematic for the power system that has been modeled to date is shown in Figure 5. Ideal circuit breakers allow the simulation of the loads to be switched in or out at various times.

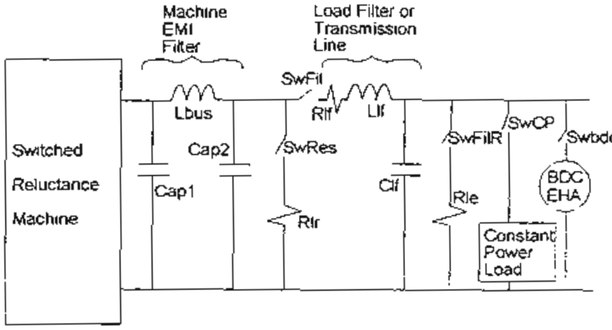

FIGURE 5: SCHEMATIC OF SYSTEM LOADS

Constant Power Load

The generator system provides 270 volts, and DC-AC and DC-DC converters are required to change the voltage level for individual loads. In some converters the output voltage is controlled to deliver constant power. This type of load appears as a negative impedance since in order to supply constant power, the current will increase when the source voltage decreases. In the case of the constant power load shown in Figure 5, the desired power is selected and the current is calculated by dividing the power by the actual voltage.

Electro-Hydrostatic Actuator

A type of electric load that is of interest to the aircraft system designer is the electro-hydrostatic actuator (EHA), which can be used to position the aircraft's flight control surfaces. A model of an EHA driven by a brushless DC motor was developed, based on the actuator requirements for the aileron on a military fighter. The simulation block diagram for the simulation is shown in Figure 6. Since a brushless DC motor is a controlled permanent magnet synchronous motor, the DC voltage from the generator must be inverted to provide AC to the motor. The inverter and motor are modeled in full detail, together with the specified mechanical system requirements.

SIMULATION RESULTS

Steady-state test results have been reported for the switched reluctance ISG with a resistive load (Radun and Xiang, 1995). Figure 7 shows the phase currents for one channel of the machine operating at ground idle speed (13,450 rpm) with an output of 252 volts and 102.5 KW ($R_{load} = 0.61955\ \Omega$). The phase currents resulting from a computer study for the same operating conditions are shown in Figure 8. The waveforms in Figures 7 and 8 are essentially the same except that the measured currents are slightly unbalanced. This is apparently due to slight differences in the actual windings, whereas the windings are assumed to be identical in the simulation.

A dynamic load change test was also done on the ISG operating at

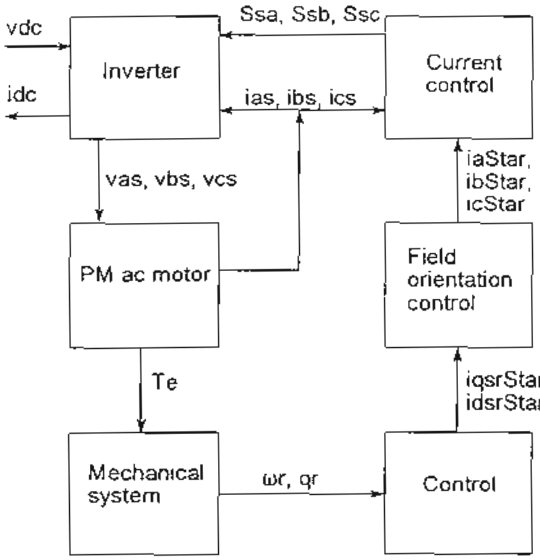

FIGURE 6: BLOCK DIAGRAM OF ELECTRO-HYDROSTATIC ACTUATOR SIMULATION

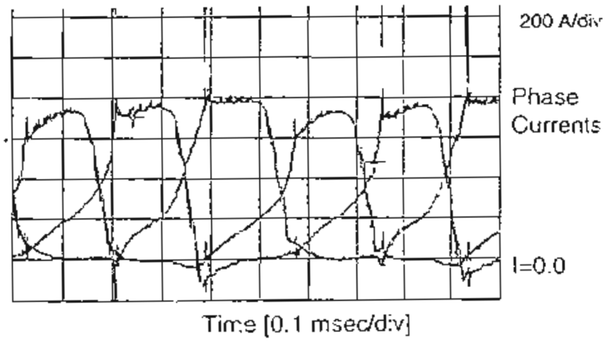

FIGURE 7: MEASURED GENERATOR PHASE CURRENTS

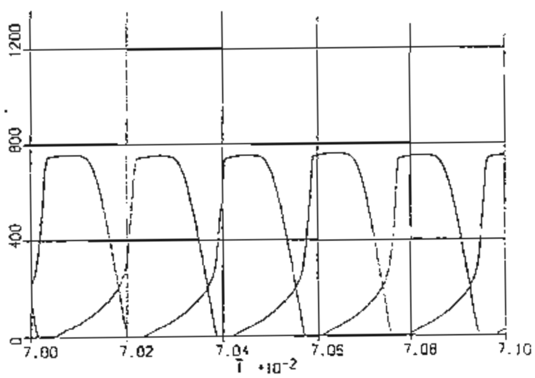

FIGURE 8. GENERATOR PHASE CURRENTS CALCULATED BY SIMULATION

ground idle speed. In this case the load was suddenly changed from 86 KW to 102.5 KW. The measured voltage transient (voltage at vcap2 in Figure 5) is shown in Figure 9. A drop of approximately 15 volts occurs with a recovery time of approximately 16 msec. The results of the computer study are shown in Figure 10. The computed response does not exhibit as much low frequency (about 400 Hz) ripple as the experimental waveform; however, a similar voltage drop and recovery time occurs.

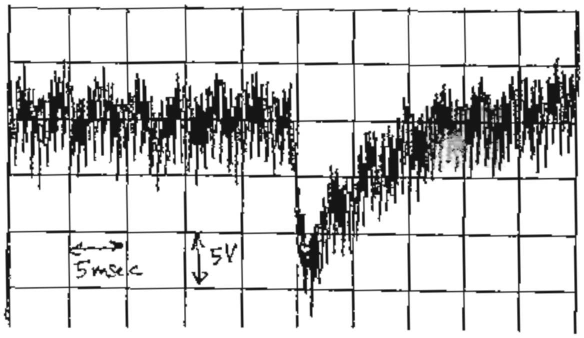

FIGURE 9: MEASURED BUS VOLTAGE DURING RESISTIVE LOAD INCREASE

ACSL is equipped with a variable time-step algorithm in which the user specifies minimum and maximum time steps. In Figure 10, a maximum time step of 0.5 μsec was used. It is interesting that with a longer time step of 5.0 μsec the waveform shown in Figure 11 was obtained. This waveform compares more favorably with the test results (Figure 9), specifically in regard to the 400 Hz ripple. Although the differences in 400 Hz ripple are of secondary importance, the computed results suggest the possibility that the sampling rate of the acquisition system used in the experimental tests was too low to capture the exact waveform. This is left to future investigation.

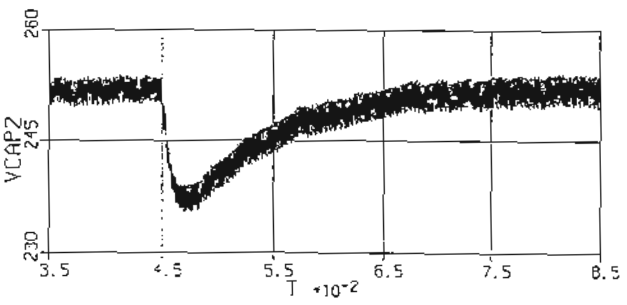

FIGURE 10: CALCULATED BUS VOLTAGE DURING RESISTIVE LOAD CHANGE

Constant power load switching

Testing has not been reported for the ISG with constant power loads; however, a computer study was conducted. The results of the study are shown in Figures 12 and 13. Therein, the voltage at the

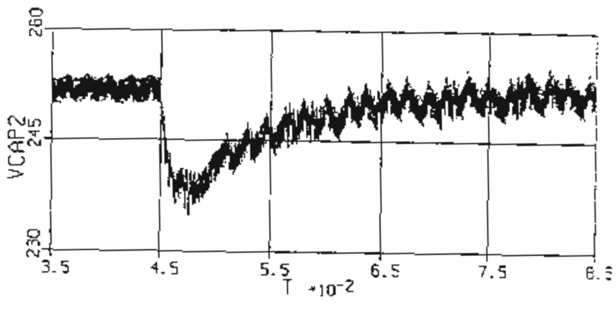

FIGURE 11: BUS VOLTAGE TRANSIENT CALCULATED WITH LARGER INTEGRATION TIME STEP

output of the generator EMI filter (Vcap2) and the voltage at the output of the constant power load filter (Vclf) are plotted. In both cases, the simulation was run at ground idle speed, with an output voltage of 270 volts and a resistive load of 86 KW at the output of the load filter (Figure 5). In the study, this load was switched to a 70 KW constant power load. The values for the load filter in Figure 12 were 10 μH for Llf and 624 μF for Clf. Since there was a reduction in load, the voltage increased and then returned to its controlled value. The

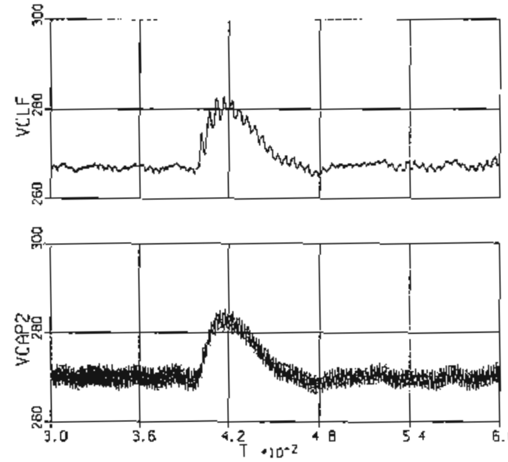

FIGURE 12: TRANSIENT VOLTAGES CALCULATED DURING CHANGE FROM RESISTIVE LOAD TO CONSTANT POWER LOAD

system remained stable.

In Figure 13 the same load switching occurred, but values of 90 μH and 670 μF were used for Llf and Clf, respectively. In this case, the system is stable with the 86 KW resistive load; however, when the load is switched to the 70 KW constant power load, the voltages oscillate with increasing amplitude until the system becomes unstable. It is interesting to note that if the load was switched back to its original configuration prior to 0.046 secs the system returned to stable operation.

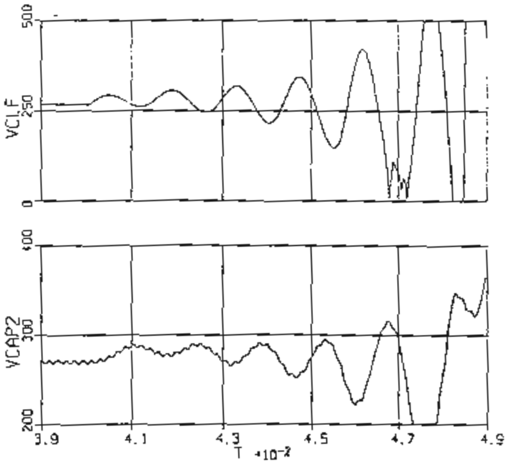

FIGURE 13: POSSIBLE UNSTABLE OPERATION PREDICTED BY COMPUTER SIMULATION

SUMMARY

A detailed computer model of a switched reluctance generator with various loads has been developed and a number of studies have been performed. Experimental verification has been obtained for steady-state operation and for switching of resistive loads. In addition, the computer simulation has been used to demonstrate potential system instability due to a constant power load.

ACKNOWLEDGMENTS

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