

SIMULATION OF A SWITCHED RELUCTANCE, MORE ELECTRIC AIRCRAFT POWER SYSTEM USING A GRAPHICAL USER INTERFACE

Timothy L. Skvarenina, Steven Pekarek, Oleg Wasynczuk, Paul C. Krause
 Purdue University
 West Lafayette, Indiana 47907
 Phone: (317) 494-7493 Fax: (317) 496-1354

Rene J. Thibodeaux, Joe Weimer
 Air Force Wright Laboratories/ POOC-1
 WPAFB, Ohio 45433
 Phone: (513) 255-6016 Fax: (513) 255-3211

ABSTRACT

A previous paper described a detailed system model of a More Electric Aircraft power system employing a switched reluctance generator (Skvarenina, et al, 1996a). That model was written in the Advanced Control System Language (ACSL®). The work has been extended to allow two separate phase groups in the switched reluctance machine with independent loads. In addition, the models have been converted to utilize the Graphics Modeller® front-end for the ACSL system, which offers flexibility in running different system configurations. The Graphics Modeller and the underlying models for the machine and loads are described, and examples of system studies are shown using various loads, including passive loads, constant power loads, a brushless DC motor, and an electro-hydrostatic actuator. Results from the simulations are presented together with corroborating experimental test results.

INTRODUCTION

More Electric Aircraft (MEA) offer potential life-cycle cost savings for the military and civilian sectors. The military is pursuing DC systems 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. Hardware testing is very expensive, so it is desirable to have simulations that accurately portray the system performance and help to determine what testing should be done. To provide the government with an in-house analysis capability, models of a switched reluctance generator, its control system, and associated load components have been developed.

These models were initially developed using ACSL, which allows the models to be used on a variety of computer platforms. By combining various modules of ACSL code that represent the components, different systems and operating conditions can be rapidly simulated. Unfortunately, to make changes in a system study programmed in ACSL, the analyst must thoroughly understand not only the system being studied, but also ACSL. To

alleviate this problem, the developers of ACSL have released a graphical front-end to the language, called Graphical Modeller. Graphics Modeller (GM) allows system models to be represented by block diagrams, which may be hierarchical in nature. That is blocks in the diagram may be composed of sub-blocks down to whatever level is desired. By wiring blocks together, new systems can be rapidly created without recoding the individual blocks. This allows an analyst who is less familiar with the actual programming of the simulations to utilize them to produce new system studies.

The loads for the MADMEL are intended to be representative of the various loads that would be found on an aircraft, including avionics, radars, electro-hydrostatic actuators (EHA), and distribution components. Models for resistive and other passive loads, brushless DC motors, DC-DC converters, vector-driven induction motors, and EHAs have been converted to the GM front-end. Figure 1 shows an example system containing some of these components.

In the system shown in figure 1, prime power is provided from

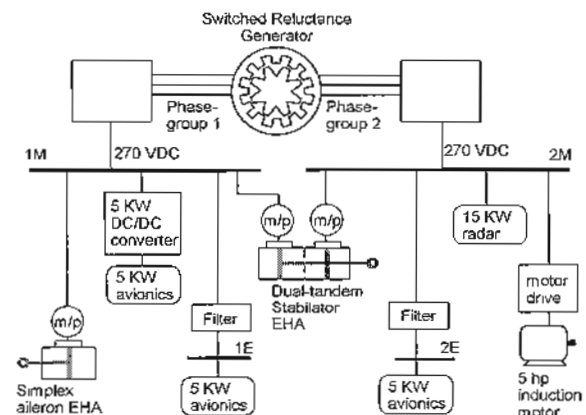


FIGURE 1: MODELED SYSTEM

a switched reluctance machine, which is designed to operate as an integral starter generator. For this study, it is considered to operate as a generator. The machine contains two three-phase groups that can be operated separately or in parallel. Each phase group feeds a motor bus and an electronic bus which contain the loads shown in the figure.

The models for these components and examples of studies using these components to form systems are described later.

GRAPHICS MODELLER

The GM front end to ACSL allows the simulationist to set up models in several different ways. The first method is to use predefined blocks that are available in the GM system. Blocks are provided for a wide range of functions and are grouped together in several racks. Figure 2 shows a screen capture from GM. In this figure the ten racks grouped at the top (parallel columns of five) come with the GM system. The racks can be opened to display a number of blocks containing functions such as integrators, transfer functions, logical (Boolean) operations, summers, multipliers, and trigonometric functions that can be dragged from the rack to the workspace where the simulation is being developed. Each block contains one or more inputs, output, and constants. The simulation is then "wired up," by connecting outputs of one block to inputs of others. Constants can be set to desired values, and the simulation can be run.

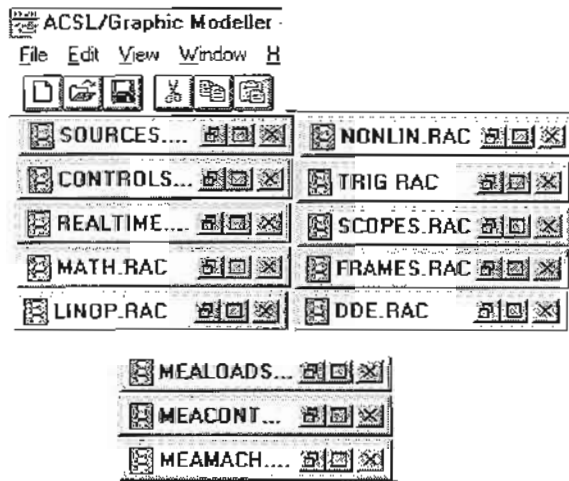


FIGURE 2: GRAPHICS MODELLER TOOL RACKS

Custom racks and blocks provide a second way to develop models. Not every conceivable function can be included in the racks provided with GM and it is desirable to be able to reuse models of components. Thus, the program allows the analyst to create additional blocks and racks; i.e., to customize the program. In figure 2, the three racks at the bottom were added and contain blocks unique to the MEA modeling effort. Figure 3 shows some of the blocks contained in the MEALOADS rack. The first thing that is noticeable is that images can be used to represent the blocks, making them more meaningful to the user. By representing blocks with circuit elements or pictures, the user can immediately identify what the block contains. The code associated with the custom

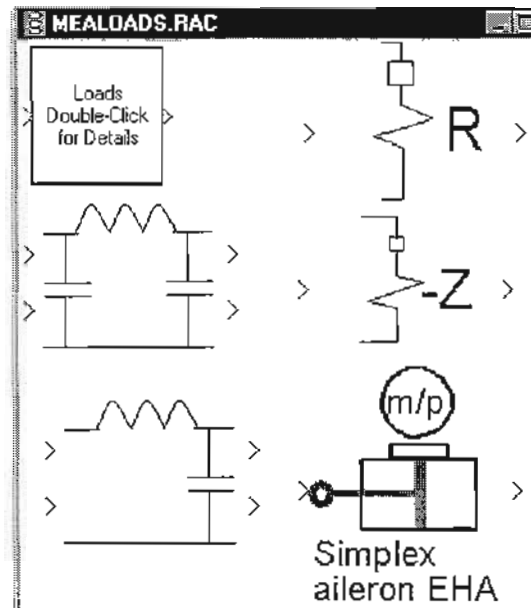


FIGURE 3: MEA CUSTOM LOAD RACK

blocks can be written separately in ACSL and then attached to the block or it can be written directly from the GM editor. Most of the blocks developed for the MEA modeling effort were developed first in ACSL and then imported into GM.

In many cases, it is desirable to have a hierarchical model; one in which a block is made up of a number of blocks. This is especially true when one wants to develop a set of component models that can be used to build new system models. Two of the blocks in figure 3, the simplex aileron EHA and the box marked loads, are complex blocks. Double clicking on one of these blocks reveals the next level of the model for that block. Figure 4 shows the details of the load block. This complex block consists of several loads with switches that allow the analyst to change the system configuration by turning loads on and off at various points in time. The block has one input, the system voltage, and one output, the total current to the loads in the block. The individual loads in this complex load are built up, in turn, from blocks in the MEA Loads

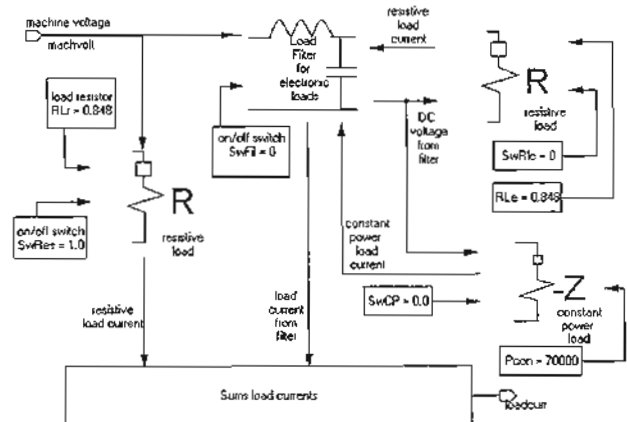


FIGURE 4: DETAILS OF A COMPLEX GM BLOCK

Rack, shown in figure 3. This load would be attached to an appropriate source and control system to define a system to be studied.

MEA COMPONENT MODELS

Switched Reluctance Generator Model

Figure 5 shows a schematic of one three-phase coil group of the switched reluctance generator built for the MADMEL. The coils, labeled a_1 , b_1 , and c_1 are physically inside the machine. The switches, diodes, and capacitors are contained in a switching and control module external to the machine. The machine actually contains two three-phase coil groups, which can be operated separately or in parallel. When the phase groups are operated in parallel, only one switching/control module is required, while two are required to operate the phase groups separately.

The operation of the machine has been previously described (Skvarenina, et al, 1996a and Radun, et al, 1995), but briefly, a winding is charged by turning on the switches and then discharged through the diodes by opening the switches. The variable reluctance geometry of the machine allows electromechanical conversion. The control system, not shown but part of the electronics package, determines at what position the switches should be closed and opened.

To accommodate the different modes of operation, four different models have been developed. The first two models contain only one phase group, which by setting a parameter can represent one phase group alone or two in parallel. The two models differ in the control

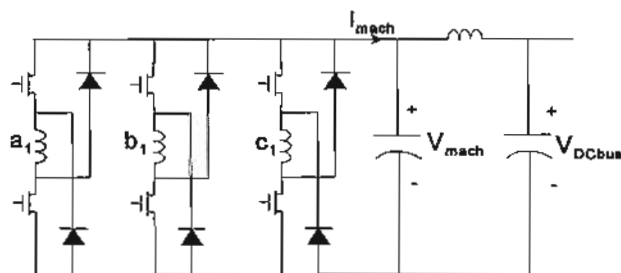


FIGURE 5: SWITCHED RELUCTANCE MACHINE PHASE GROUP AND POWER ELECTRONICS

scheme. One uses a constant, but user selectable, turn-on angle for the switches in the phase winding circuits. The second model uses the machine and DC bus voltages, as shown in figure 5, to calculate a variable turn-on angle. In both cases, the switches turn off when the current reaches a value calculated by the control system. The other two models contain two phase groups, which require separate controls and switching, can have separate loads.

Constant Power Loads

Two constant power loads have been simulated. The first is shown in the MEA Loads Rack of figure 3. It is a very simple negative-impedance load. The current is calculated by dividing the desired power by the bus voltage, with the proviso that the bus voltage must be greater than 150 volts. This load was included to allow quick stability studies.

The second constant power load is more realistic and consists of a resonant-link DC-DC converter that converts the nominal 270 VDC from the generator to a constant 28 VDC output. The schematic for this device is shown in figure 6. At the time, of the writing of this paper, the circuit was simulated in full detail to operate at full load, but the control system for other loadings had not yet been provided by the vendor. Fully detailed indicates that the state equations were derived for the circuit and programmed in ACSL and ACSL/GM. In addition to the fully detailed model, a reduced-order model will be provided in order to allow larger systems to be formulated without unduly long runtimes for the model. The reduced-order model, neglects the switching transients of the converter and uses average values of the state equations to represent the currents and voltage.

Electro-Hydrostatic Actuator

The electrohydrostatic actuator system was described previously (Skvarenina, et al, 1996a) and was originally programmed in ACSL. The model was converted to GM where it is programmed as a complex block containing six sub-blocks. The EHA is driven by a

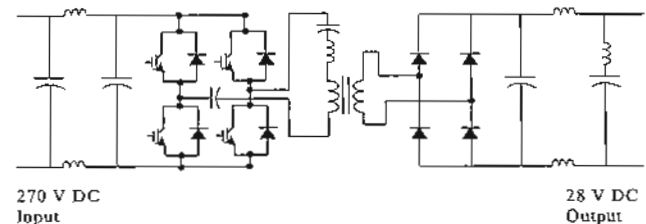


FIGURE 6: 5 KW DC-DC CONVERTER SCHEMATIC

vector-controlled brushless DC motor that is modeled in full detail together with the control system and mechanical system. The inputs to the EHA model are the bus voltage, the desired position, and the external force, which may be a function of position. The outputs of the model are the current, actual position, torque, and speed. Of these, however, only the current is required to be connected to the system model.

Induction Motor with Vector Drive

A general-purpose induction motor load was modeled using the well-known equations in the synchronous reference frame (Krause, et al, 1994). Since the motor is AC, an inverter and controller are required. A pulse width modulated inverter and a field-oriented (vector) controller were modeled for the MEA. Figure 7 shows a block diagram of a field-oriented controller (Wasynczuk, et al, 1997). Therein, i_{ϕ}^d is the commanded magnetization current, which is normally constant and i_{ϕ}^q is used to control the motor torque. The current command signals, i_{ϕ}^d , i_{ϕ}^q , and i_{ϕ}^s are provided to the inverter control system. The bold K represents the reference frame transformation from d-q axis quantities to phase quantities. The advantage of using vector control is the ability to rapidly and accurately control the motor's electromagnetic torque.

PREPARING A STUDY USING THE MODELS

The collection of models described above, plus some others provide a very flexible system for studying power systems in more

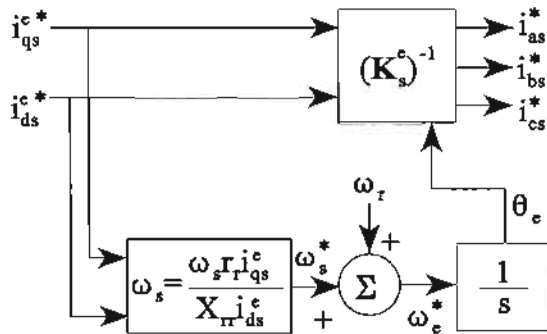


FIGURE 7: BLOCK DIAGRAM OF INDIRECT METHOD FIELD ORIENTED CONTROLLER

electric aircraft (and other types of vehicles). Within Graphics Modeller, it is relatively straightforward to create a new model work space and then drag and drop the desired components from the racks to the new work space. The inputs and outputs are then wired together, much like the complex block shown in figure 4.

Clearly, this requires that modules to be wired together must have compatible inputs and outputs. For example the switched reluctance generator module, provides a current output and requires a voltage input. Fortunately, the machine is connected to a pi type filter/excitation source that requires a current inputs and provides voltage outputs. The modules that have been developed to date are compatible but this could be a limitation for future models. However, a technique to avoid this problem has been developed in ACSL (Skvarenina, et al, 1996b) and will be incorporated into the GM model set for the final delivery.

Some expertise is required to complete the setup of the model once all the desired modules are wired together. The analog circuits, of course, are continuous and within the ACSL system are solved within so-called derivative blocks. A suitable integration algorithm, time-step limits, and data recording interval must be chosen to run a simulation. Other parts of the system, however, may not be continuous. For example, controllers implemented with DSP devices have a cycle time for executing instructions and must be simulated with a discrete block within ACSL. Graphic Modeller blocks may be assigned to discrete or derivative block using fill-in menus that can be selected with the mouse.

To simplify the task of setting up a simulation and to make the models more usable, documentation is included with each block and can be accessed from the same menu that is used to set up the block. This documentation includes the block inputs and outputs, the type of ACSL block (derivative or discrete) that is required, and the other components that must be used with the block.

SAMPLE RESULTS

Only limited experimental results were available at the time this paper was written. However, simulation results for the switched reluctance generator closely match the experimental results that are available. Some examples of other device simulations are also

included below.

Switched Reluctance Generator

To date, only resistive load switching has been studied experimentally with the switched reluctance generator. Figure 8 shows the generator transient response when the load was increased from 86 KW to 102.5 KW with the two phase-groups operating in parallel. Figure 9 shows simulated results for the same event. The simulation correctly predicts both the magnitude and the duration of the voltage transient caused by the load change.

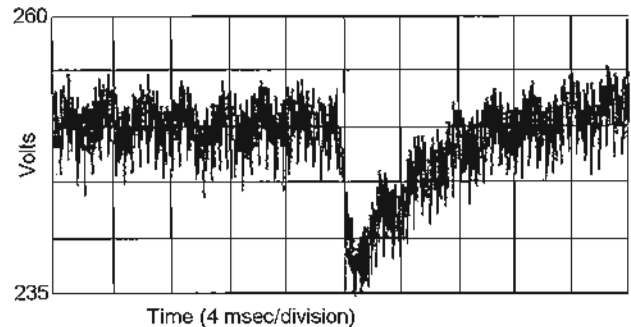


FIGURE 8: SWITCHED RELUCTANCE GENERATOR RESPONSE TO RESISTIVE LOAD CHANGE

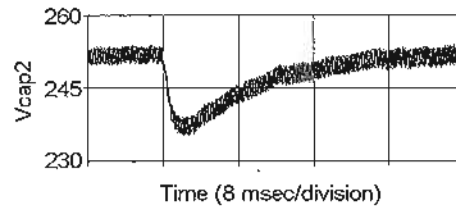


FIGURE 9: CALCULATED RESPONSE OF SWITCHED RELUCTANCE GENERATOR TO RESISTIVE LOAD CHANGE

Electro-Hydrostatic Actuator

Figure 10 shows simulated responses for a generic single motor aileron EHA. The response shown is for application and removal of a step change in the desired position (three inches) with no external force. The figure shows the actual position, the motor speed and the torque. Although no experimental results were available for the EHA, these results compare very closely to simulation results obtained from a reduced-order model of the EHA system by Northrop-Grumman.

SUMMARY

A family of models for components of MEA have been developed using the ACSL Graphics Modeller. These models offer flexibility in system configuration since they can be "wired together" using the graphical interface. Once a system has been configured, it becomes very easy to run a variety of simulation cases, including studies of stability, power quality, fault recovery, and protective device coordination.

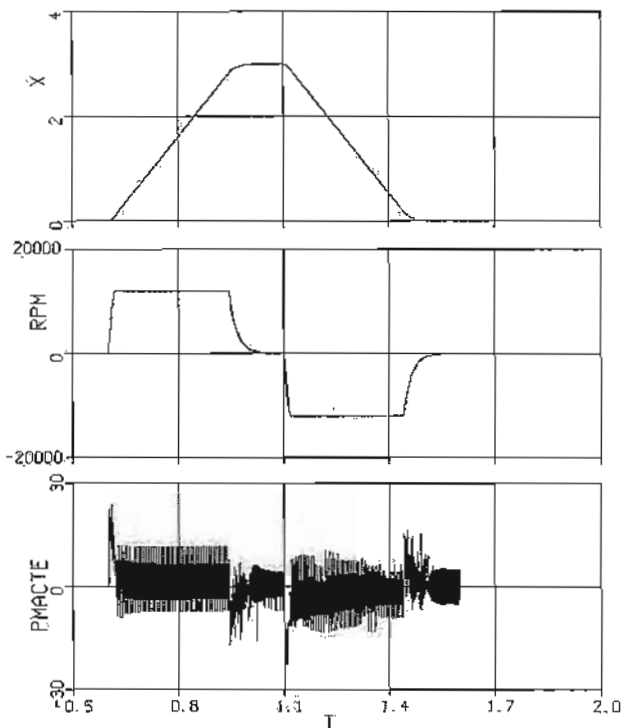


FIGURE 10: SIMULATION RESULTS FOR AILERON ELECTRO-HYDROSTATIC ACTUATOR

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REFERENCES

- Radun, A.V. and Xiang, Y.Q., "Switched Reluctance Starter/Generator System Modeling Results," Paper 951407, SAE Aerospace Atlantic Conference, Dayton, OH, May, 1995
- Krause, P.C., Wasynczuk, O., and Sudhoff, S.D., "Analysis of Electric Machinery," IEEE Press, 1994
- Skvarenina, T. L., Wasynczuk, O., Krause, P. C., Chen, W. Z., Thibodeaux, R. J., and Weimer, J., 1996a "Simulation and Analysis of a Switched Reluctance Generator/More Electric Aircraft Power System," Proceedings of the 31st Intersociety Energy Conversion Engineering Conference, Vol. 1, Washington D.C., August 1996
- Skvarenina, T. L., Pekarek, S., Wasynczuk, O., Krause, P. C., Thibodeaux, R. J., and Weimer, J., 1996b "Simulation of a More-electric Aircraft Power System Using an Automated State Model Approach," Proceedings of the 31st Intersociety Energy Conversion Engineering Conference, Vol. 1, Washington D.C., August 1996
- Wasynczuk, O., Krause, P.C., Sudhoff, S.D., Corzine, K.A., Tichenor, J.L., and Hansen, I.G., "A Maximum Torque Per Ampere Control Strategy for Induction Motor Drives," submitted to IEEE for publication in the Transactions on Power Apparatus and Systems, 1997.