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ABSTRACT

The simulation of a power system such as the More Electric Aircraft is a complex problem. There are conflicting requirements of the simulation, for example in order to reduce simulation run-times, power ratings that need to be established over long periods of the flight can be calculated using a fairly coarse model, whereas power quality is established over relatively short periods with a detailed model. An important issue is to establish the requirements of the simulation work at an early stage. This paper describes the modelling and simulation strategy adopted for the UK TIMES project, which is looking into the optimisation of the More Electric Aircraft from a system level. Essentially four main requirements of the simulation work have been identified, resulting in four different types of simulation. Each of the simulations is described along with preliminary models and results.

INTRODUCTION

The UK Department of Trade and Industry (DTI) which is a government body, recently initiated the More Electric Aircraft Challenge as part of the Civil Aircraft Research And technology Demonstration (CARAD) programme. This resulted in a series of funded research projects, exploring various technologies, which were anticipated to contribute toward the More Electric Aircraft (MEA). Each of these projects looked at particular aspects of the aircraft sub-system. However the objective of the most recent of these projects, known as the Totally Integrated More Electric System (TIMES) [1], is to investigate the MEA at a system level for a single isle and also a wide-body aircraft.

The TIMES venture is a major collaborative project between various partners; TRW Aeronautical Systems, AIRBUS, Rolls Royce Plc, BAE SYSTEMS Avionics Ltd, FR-HiTEMP Ltd, Smiths Aerospace, FHL Division Claverham Ltd, QinetiQ, Birmingham University, Cranfield University and Moir Associates, and is sponsored by the DTI for a three-year period.

The TIMES project has looked at various power system architectures - fixed frequency AC, variable frequency AC, DC and hybrid AC/DC generation, both high and low voltage, from the point of view of the generation, distribution and electro-hydraulic and electro-mechanical actuator loads (EHA and EMA respectively). Each of the architectures was assessed using a scoring system based on criteria such as safety, weight, cost of ownership, maintenance and efficiency. The outcome of this work was that a 115V Variable Frequency (VF) three-phase architecture scored the most highly, followed by a 270V DC system, and it was decided that the 115V VF architecture would be evaluated further.

This initial work is being followed by a modelling and simulation phase that assesses the performance of the proposed system architectures through different stages of the flight profile. Finally a hardware system demonstrator consisting of the electrical power generation, distribution and loads is to be built in order to test a small-scale MEA power system and validate the simulation phase. Important system features that will be addressed are for example system ratings, the management of regenerative energy from the actuators, power quality, fault conditions, load interaction and system stability with constant power loads. This work will therefore result in a set of validated simulation tools, which can be used to assess various power system architectures and increase the understanding of MEA behaviour.

This paper describes the approach to modelling and simulation which is being adopted as part of the TIMES project, and the reasoning behind the chosen strategy. Also there is a discussion of the various simulation software packages that were evaluated for the project. Preliminary results from the modelling work in progress are presented using hypothetical architectures and loading scenarios.

TIMES SIMULATION STRATEGY

An MEA electrical system has numerous components such as generators, actuators, fuel pumps, fans and electronic equipment, many of them supplied by different manufacturers and each with their own characteristics. Approaches to the simulation of power equipment and systems have been discussed previously [2], and in particular the simulation of an MEA electric power distribution system is described in [3]. When confronted with the task of modelling such a complex system, it is often tempting to try to compile a system simulation from very detailed models of each of the individual components; this becomes more attractive with the availability of the manufacturers own detailed model files. It is also tempting to envisage the simulation being used to output system parameters for various phases of the flight, with very detailed disturbance signals being input to the model representing fairly long periods of the flight. The simulation would then be the ultimate tool for assessing any proposed power system architectures. However, many problems can arise from this approach to modelling:

- Simulation run times can be impractical.
- The amount of simulation data available to the user is overwhelming.
- The system model compiler usually has no idea what assumptions have been made in the manufacturer's models. What may be important from a power system simulation point of view may not be important for a component level model and vice-versa.
- Realistic load duty cycles for each phase of flight are often unavailable for such a detailed model. For example surface actuation profiles during a gusty take-off or landing. Some assumptions therefore have to be made about realistic duty cycles. This point itself raises an important question – what happens to an MEA under extreme actuator load conditions? Whereas the response of an existing hydraulic system may simply reduce, an MEA system could possibly trip for example on overload or undervoltage conditions. Should an MEA flight controller have the necessary functionality to prevent this situation occurring?

What is often overlooked at the start of the project is the question of what is the purpose of the modelling and simulation work; in particular what are the requirements of this task? Once these requirements have been identified, the likely conclusion is that more than one simulation will be required, with different levels of detail for each simulation.

The strategy adopted for the TIMES project has identified four major requirements of the simulation work:

1. Establish power flow within the system in order to calculate the rating of the generator and distribution system. In particular voltages and currents should be made available as separate variables so that voltage regulation and peak current demands can be assessed, this would then for example, allow the system availability due to fault tripping to be determined or the magnitude of actuator regenerated energy.
2. To evaluate a proposed power system architecture against the AIRBUS steady-state & quasi-steady-state power quality specification document. The effect of steady-state current harmonics generated by each load, along with individual bus and generator impedances can be used to calculate the distortion of the supply voltage; this can then be compared against the specification. Also the regulation of the supply with long duration transients can be verified. Power quality specifications tend to be conservative, the question arises as to whether the requirements are appropriate from an overall system point of view, and could they be relaxed?
3. System stability and interaction. The problems of controlled power loads are well documented; especially for DC distribution systems and methods of design have been proposed [4,5]. The negative incremental impedance characteristic of such equipment may cause instabilities within the overall power system. Simulation is needed to validate and investigate the results of stability analysis and modelling work [6-10].
4. To look at dynamic characteristics of the power system and the effect on power quality. For example, changes in generator frequency, load switching and fault conditions. This would also look at the consequences of the distorted supply voltage on the behaviour of individual equipment, in particular the effect on the current harmonics drawn from the supply will be fed back into requirement 2.

Attempting to achieve all of these requirements with a single simulation would be problematic because of the conflicting needs of each requirement. For example, the simulation would need to be run over several tens of minutes or hours of flight time to satisfy requirement 1, and a very detailed model would suffer from unacceptable execution times. However, a less detailed model would not have the accuracy required for requirements 2 and 3, to calculate the high order current harmonics present in electronic loads. Therefore the following four simulations were proposed for the TIMES project:

Requirement	Simulation	Flight simulation times	Model Detail
1	Power budget	Several minutes - hours	Low
2	Steady-state power quality	Minutes	Medium

3	Dynamic stability	Hundreds - thousands of fundamental supply cycles	Medium /High
4	Dynamic power quality	Tens-hundreds of fundamental supply cycles	High

Each of these simulations will be described in more detail, after a brief discussion of available simulation software packages.

SIMULATION SOFTWARE

Various factors will influence the choice of simulation software:

- Performance
- Cost
- Ease of use, e.g. schematic entry or netlist
- Portability to other software packages

The choice of simulation software for a project such as TIMES is made more difficult due to conflicting requirements of the individual project partners, such as:

- Preference for software already used within an organisation. There is a large commonality through the use of Matlab/Simulink
- Reputation within the industry
- Package support

There is an extensive range of alternative suppliers of simulation software available to the user [11]. Several packages were evaluated for the TIMES project, and while an exhaustive study was not carried out, the final choices were based on:

- Performance .
- Preferences by the industrial partners – which packages were already in use.
- Availability for evaluation – either existing ownership or availability of evaluation versions of the software.
- Cost – some partners were unable to meet the cost of certain packages.
- Interface – some packages had the facility to interface to other simulators, this was an attractive feature in terms of the partners' existing software.

To satisfy the tight harmonic limits such as AIRBUS ABD0100 which are being placed on aircraft equipment, it is likely that many more electric loads will have a 12-pulse uncontrolled rectifier input stage. However, it was found at an early stage of the software evaluation phase, that some packages had great difficulty in simulating such a circuit. The problem appeared to be due to a difficulty in determining the switching transitions of individual diodes within the converter, the simulator taking smaller and smaller time-steps until either the software was manually interrupted, or a fatal system error occurred. The rectifier topology was therefore used as a "benchmark" on which to judge the performance of individual software packages.

The following table gives a summary of the packages that were tested using the benchmark rectifier circuit and some of their key advantages and disadvantages; performance was judged on robustness, accuracy and speed of execution:

Package	Advantages	Disadvantages
Matlab/Simulink PSB[1]	Cost of PSB. Analysis of results[6].	Difficulty with benchmark
Matlab/Simulink PLECS[2]	No cost for PLECS at present. Performance. Analysis of results.	Netlist entry
Simplorer[3]	Co-simulation with Simulink[7]. Performance. Analysis of results.	Cost of such a package when combined with Matlab/Simulink
Saber[4]	Reputation. Performance. Analysis of results.	Cost
Micro-Cap Spice[5]	Cost. Performance	Analysis of results.

[1] Power System Blockset, The Mathworks, Inc.

[2] Piece-wise Linear Electric Circuit Simulation for Simulink, Swiss Federal Institute of Technology, Zurich.

[3] Simplorer, Ansoft Corporation.

[4] Saber, Synopsys Inc.

[5] Micro-Cap Spice, Spectrum Software.

[6] Availability of Matlab's extensive functions to analyse simulation results.

[7] Allows existing behavioural models of control systems to interface to a Simplorer electrical circuit simulation.

The PLECS and Micro-Cap Spice packages were chosen for further evaluation of the detailed power quality and stability simulations, primarily on the basis of cost and performance. Whereas, Matlab/Simulink was chosen for the power budget and steady-state power quality simulations due to its availability to other TIMES partners.

POWER BUDGET SIMULATION

The main requirements for this simulation are to identify all significant power sources and sinks, including major energy storage elements. The resolution of the simulation time-step is of the order of tens of milliseconds. This allows the model to simulate up to several hours of flight duration within a reasonable execution time. System components that have bandwidths in the region of a few kilohertz must be included. Higher frequency effects are decoupled from the distribution system by the inherent DC link filtering within the power equipment.

For example, an EMA would be modelled as follows:

ACTUATOR SPECIFICATION

Mechanical

- Surface driven through a gearbox by a DC brushless machine.

Electrical

- Machine fed by three-phase trapezoidal drive with control loops for motor current, speed and actuator position.
- Motor drive supplied from a 12 pulse three-phase rectifier with LC filter on the DC link.
- Dump resistor circuit used on the DC link for regenerated energy.
- External position demand signal.

The significant power terms for the actuator are identified as:

- Power required to hold the surface load.
- Power required to accelerate/decelerate the surface.
- Power losses in the load due to friction.
- Power losses in the gearbox.
- Copper losses in the motor.
- Power dissipated in the regenerative dump circuit.

The value of the motor drive bandwidth used in practice ensures that changes in these parameters will be over several milliseconds.

Other terms that may be included depending on the application are:

- Losses in the drive power bridge.
- Losses in the 12-pulse converter circuit.
- Energy storage in the DC link filter capacitor.
- Energy stored in the motor inductance.

With the total power drawn by the actuator defined, the current I_s drawn from the distribution bus can be calculated from the regulation characteristics of the supply. Since the actuator is rectifier fed, the overlap caused by supply inductance must be included in the regulation equations. The regulation equation will be of the form:

$$V_i = V_s - I_s Z \tag{1}$$

Where V_i is voltage input to the actuator, V_s is the supply voltage and Z is the total impedance of the supply including overlap effects. The actuator will appear as a controlled power load to the supply and will ideally have the relationship:

$$V_i = \frac{P_L}{I_s} \tag{2}$$

Where P_L is the power drawn by the actuator. Equation (1) and (2) are shown plotted in Figure 1.

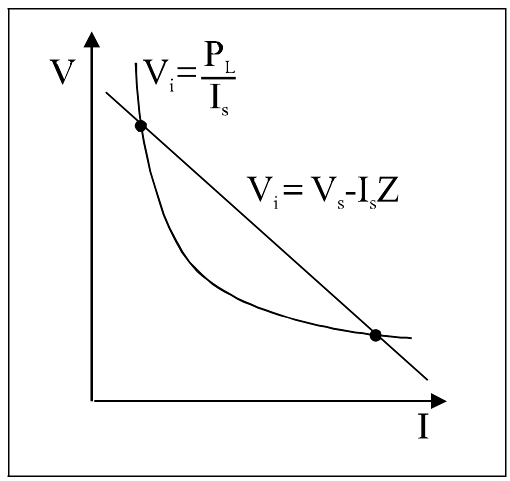

Figure 1. Constant power and impedance regulation voltage and current curves.

The intersections of the two plots give the solutions for the supply current I_s, these being the roots of a quadratic equation [6]. By calculating I_s, then for example, the model can be used to specify supply cable rating and impedance.

In general the DC link filter and rectifier of the actuator will isolate any high frequency energy terms from the distribution bus. Therefore PWM switching frequency harmonics generated by the motor drive controller can safely be ignored. However there will be current harmonics generated by the rectifier circuit that will appear on the bus, and depending on the application these may need to be included in the power budget model.

An example Matlab/Simulink model of a power budget simulation for an MEA wing actuation comprising seven actuators is shown in Figure 2. The “Rectifier/Regen. & Bus” block solves for the quadratic regulation relationship shown in Figure 1, and calculates regenerated energy, which for the rectifier converter is dumped into a resistor.

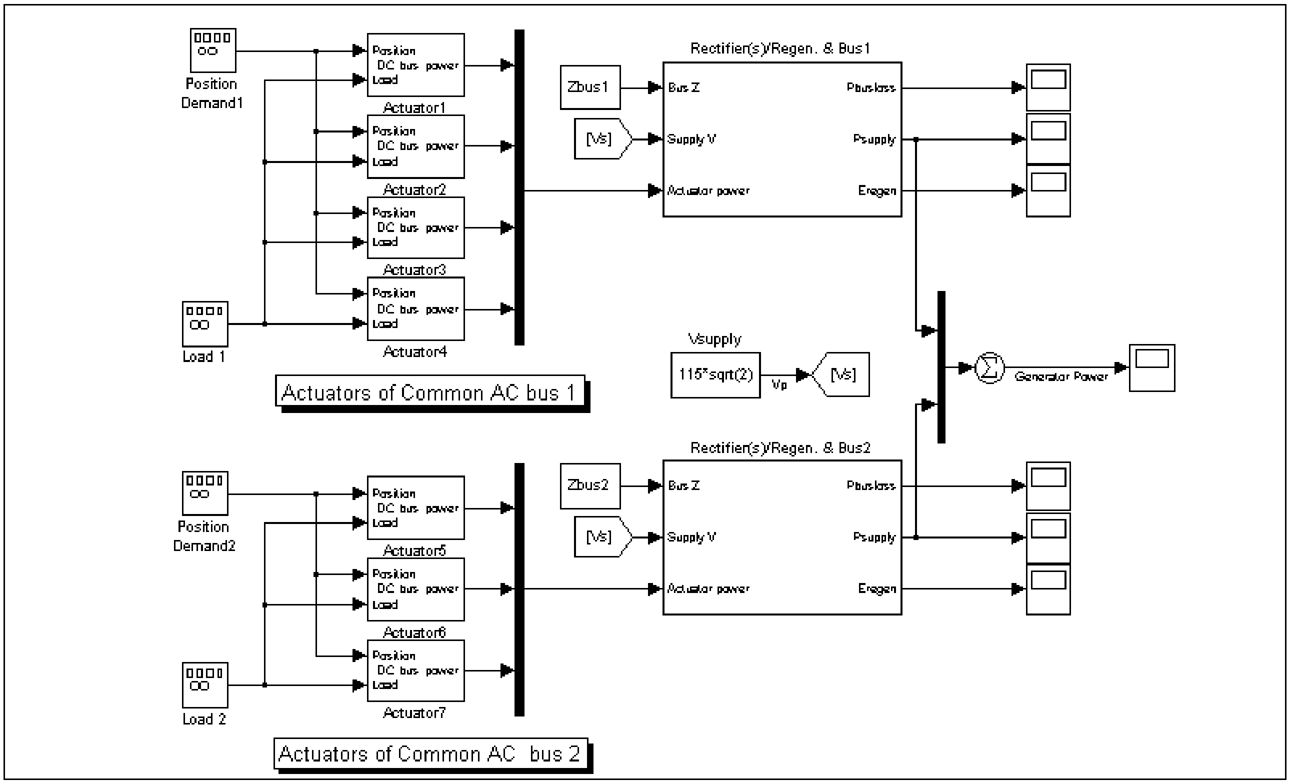

Figure 2. Example Simulink model of a power budget simulation for a hypothetical wing electrical system

The actuator block is shown in more detail in Figure 3, which includes all the significant power terms for the simulation. The dynamic model block approximates the torque, speed and position control loops of the actuator.

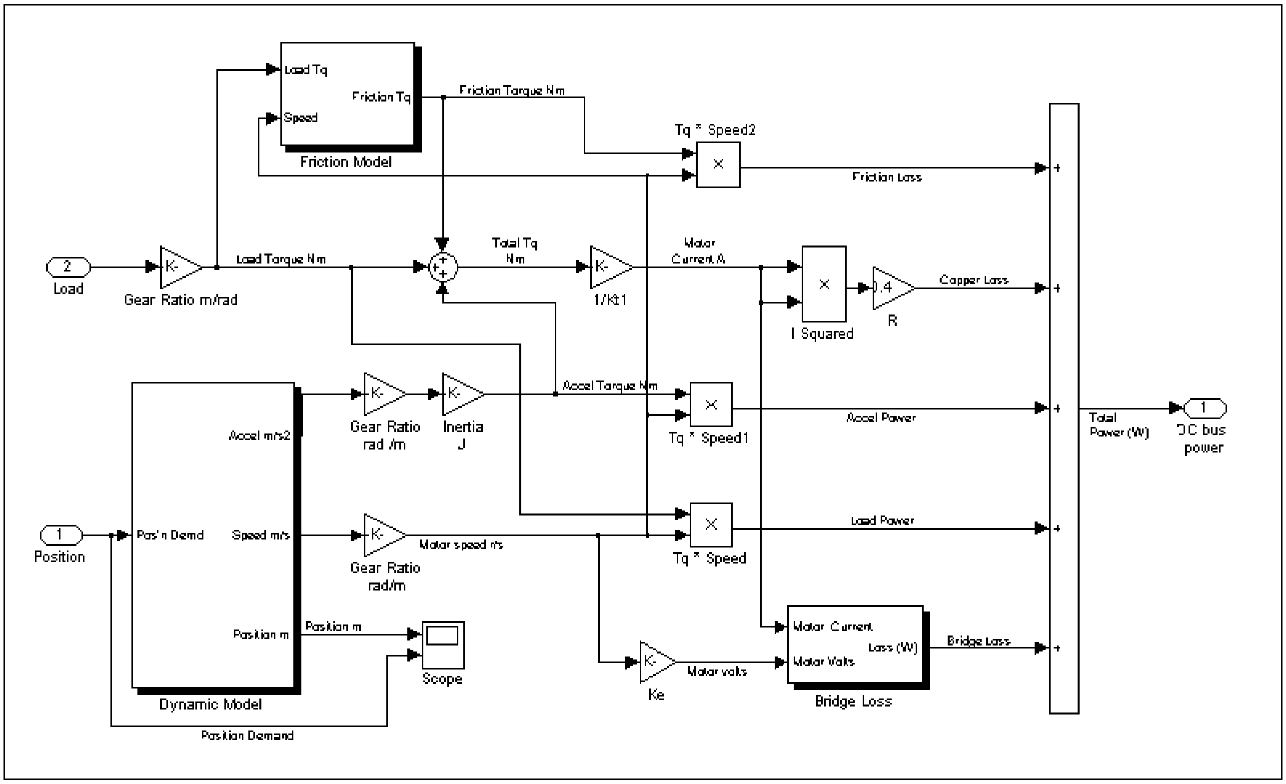

Figure 3. Actuator block model for the power budget simulation showing individual power terms

The power drawn from the generator for a purely hypothetical set of load and position input profiles, is shown in Figure 4. Large peak power demands arise from several actuators accelerating simultaneously against a load.

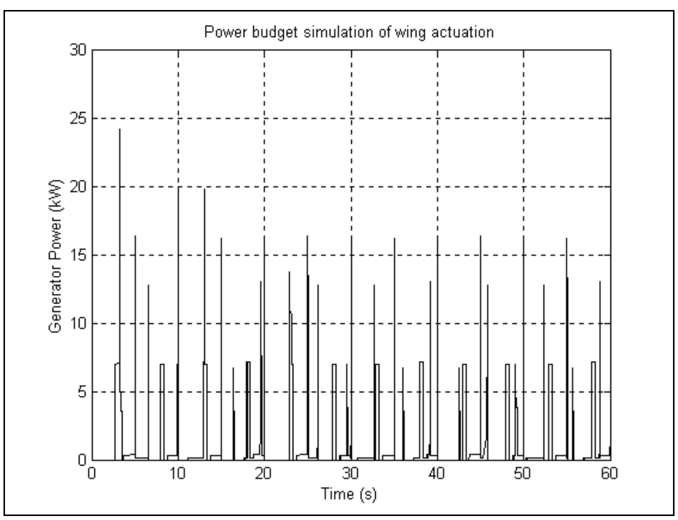

Figure 4. Power drawn from generator for a hypothetical set of load and position input profiles

The above simulation, which is equivalent to 1 minute of flight time, had an execution time of approximately 10s on a Pentium IV 1.3GHz PC computer. It is therefore feasible to extend the simulation further, to include all of the aircraft equipment running over several hours of flight.

STEADY-STATE POWER QUALITY SIMULATION

This simulation is similar to the power budget described above and is implemented in Matlab/Simulink. However the rectifier input stage of the load models are replaced by steady-state harmonic equivalent current sources, the magnitudes of which are assumed to be proportional to the load fundamental current, and a simplified generator and Generator Control Unit (GCU) are included. Therefore the current and voltage distortion at various nodes can be calculated and compared with the power quality specification. This simulation also includes the effects of filter components that are connected to the power distribution bus, for example to identify resonance modes within the system, and the effect of long duration transients on the regulation of the system.

DYNAMIC POWER QUALITY SIMULATION

This simulation requires more detailed models than the previous two simulations described above. A judgement on the level of detail required for each equipment model has to be made to satisfy the requirements of accuracy for power quality calculations and practical simulation run-times.

For example, the Micro-Cap 7 Spice schematic shown in Figure 5 represents the main electrical components of say a civil-aircraft wing system, or even the proposed TIMES hardware test-rig:

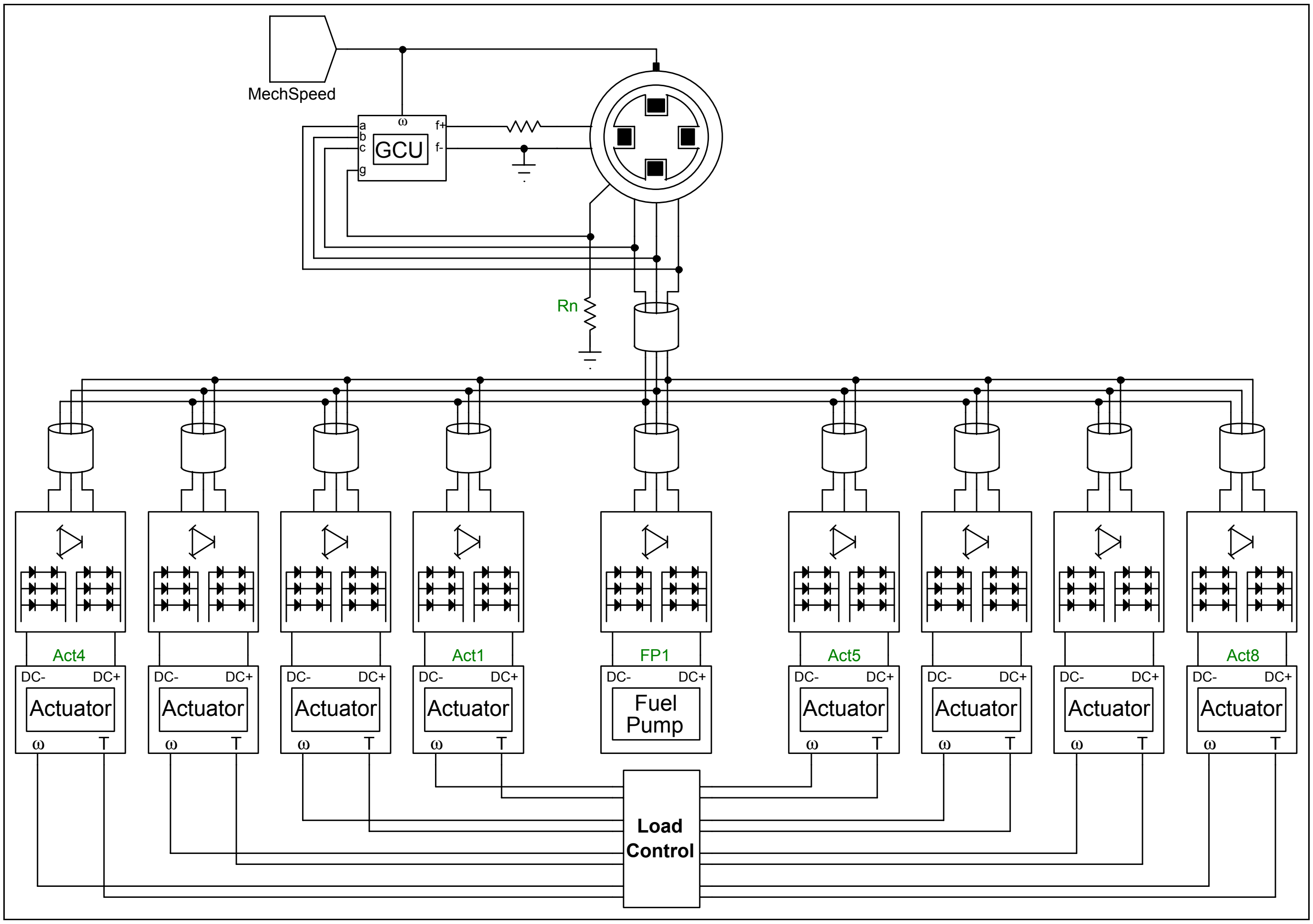

Figure 5. Example Micro-Cap 7 Spice model for a detailed simulation of a typical wing electrical system

The simulation includes

- Dedicated variable frequency generator
- Generator control unit (GCU)
- 8 wing-surface actuators
- Fuel pump
- Interconnecting cable impedances

The load control block provides actuator speed and torque signals. Figure 5 is a high-level schematic of the simulation, each component being modelled as a macro sub-circuit. The models of some of these components will now be discussed.

The generator is a four-pole salient pole machine with damper windings, and is modelled as its equivalent DQ0 circuit [12] as shown in Figure 6.

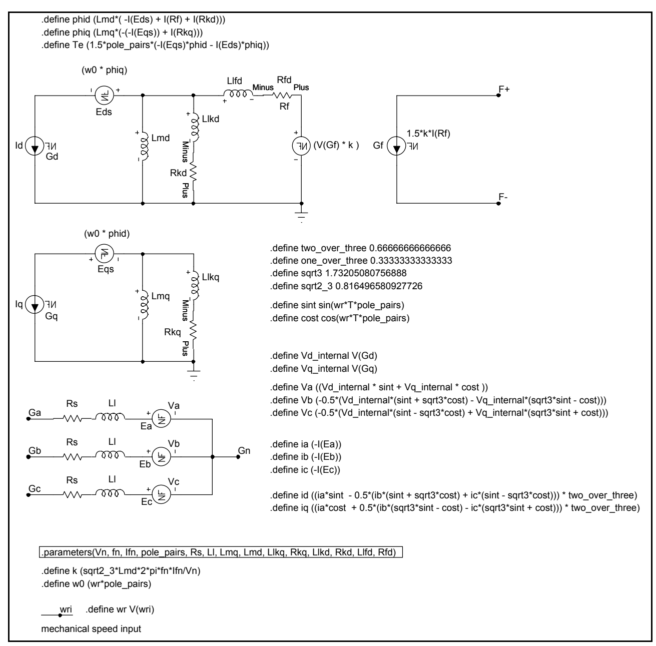

Figure 6. Spice DQ0 equivalent circuit of a salient pole machine.

The macro circuit includes the equations for the Park transformation and torque calculations. The referred inertia of the aircraft engine is sufficiently high that it appears as a speed input to the model. This model is sufficiently detailed to include the important effects of transient and sub-transient reactances and generator saliency on for example load current harmonics. The GCU is an optional component for dynamic power quality studies as the short-term transients associated with this type of simulation are affected more by the machine parameters rather than the GCU.

The electrical interface between the actuators or fuel-pump, and the power distribution system, is a 12-pulse uncontrolled rectifier converter with DC-link filter. These converter models are critical in determining the characteristics of the harmonics injected back into the supply, and therefore a fairly detailed component level model of the converter is required, which includes the magnetising and leakage inductances of the transformer and coupled inductors. Validation of the 12-pulse converter circuit was carried out by comparing the model results with those from measurements of actual hardware. For example, the important low-order supply current harmonics from the hardware measurements and model predictions are shown plotted in Figure 7, and show very good agreement.

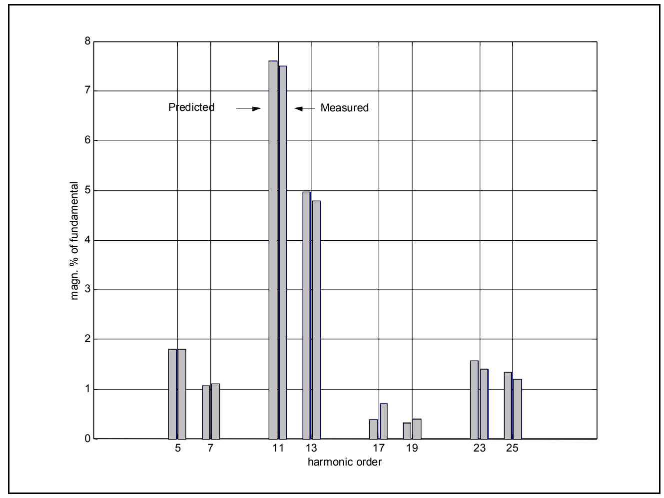

Figure 7. Measured and predicted input current harmonics for a 12-pulse rectifier converter

For the actuators and fuel-pump, a motor-controller load is connected across the DC link of the 12-pulse converters. The high-frequency effects of the controller bridge are decoupled from the input of the 12-pulse converter by the relatively large DC-link filter. However the negative input impedance characteristic presented by the controller to the converter and DC-link filter is very important in terms of stability of the system. This impedance characteristic is determined by the control loops within the motor, and therefore its model can be approximated by an equivalent control structure as shown in Figure 8, which is for an EMA actuator.

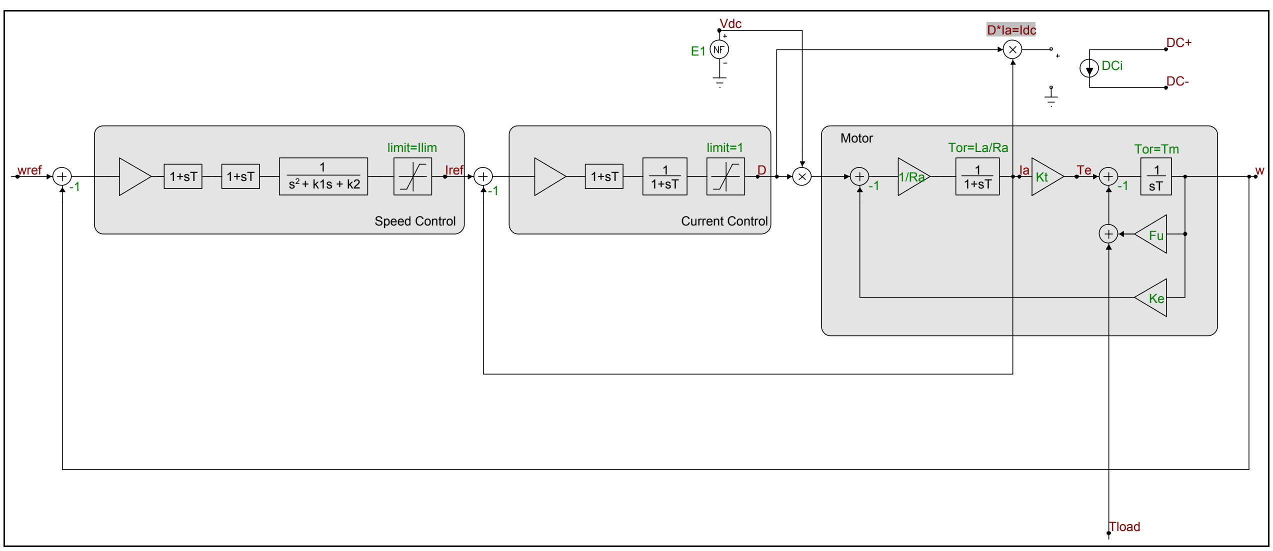

Figure 8. Spice control structure model of an EMA actuator

The control structure is limited to the speed and current loops as these determine the input impedance of the drive (see following section) .The control structure includes an electrical interface for the DC-link voltage and current variables. The motor controller bridge is assumed lossless therefore the DC link current I_{DC}, is calculated from:

$$I_{DC} = DI_A \tag{3}$$

Where D is the bridge duty ratio and I_A is the motor armature current.

Figure 9 shows the waveforms from a simulation of the model shown in Figure 5 for hypothetical values of load torque and speed. The GCU is enabled at t=0s, and the actuators are enabled at t=75ms.

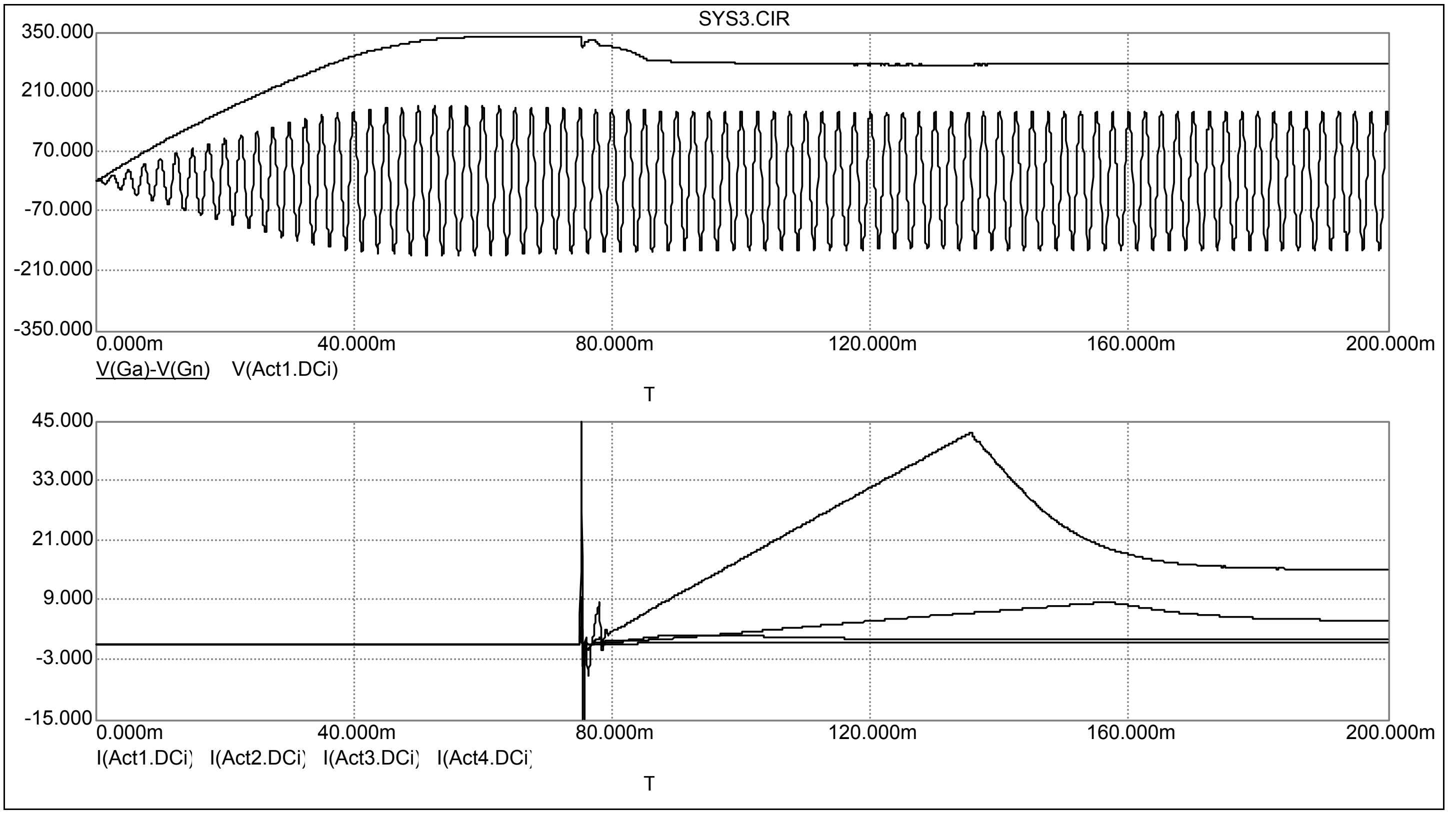

Figure 9 Top plot – generator line-line voltage and actuator 1 DC-link voltage (V), bottom plot - DC-link currents (A) of actuators 1 to 4. Time in (s).

The upper plot shows the generator line-line voltage, the DC-link voltage of actuator 1, and the lower plot shows DC–link currents of actuators 1 to 4. The above simulation had a run time of approximately 2 minutes on a Pentium IV 1.3GHz PC computer.

DYNAMIC STABILITY SIMULATION

This simulation is similar to the dynamic power quality simulation described above and shown schematically in Figure 5. However, the 12-pulse rectifier does not lend itself to stability analysis techniques because of the diode switching, nor the non-linear nature of the salient-pole machine, and more appropriate models will need to be developed [8-10].

The actuator and fuel pump models, which are already in a convenient control structure form, have non-linear input impedances. The EMA model is limited to the current and speed loops (Figure 8), which determine the actuator power. It can be shown that to a first approximation, besides the operating point parameters, the small-signal input admittance ΔY, of the motor drive controller depends on the characteristics of the current control loop only:

$$\Delta Y = \left[-Y + \frac{D^2}{V_{DC} H} \right] G_{ICL} \tag{4}$$

where,

Y :Operating point input admittance $\frac{I_{DC}}{V_{DC}}$.

V_{DC} :The operating point value of the DC link voltage.

H :Transfer function of the current controller.

G_{ICL} :Closed-loop transfer function of the current controller.

This relationship shows the importance of the current controller in the model of the drive system, the inclusion of the speed loop allows realistic values of the operating point to be modelled. Equation (4) also shows that for low to medium values of duty ratio D, the small-signal input impedance of the drive depends on the term -YG_{ICL}, which for frequencies below the bandwidth of the current controller is equal to the ideal negative input admittance value of –Y. However, as the frequency approaches the current-controller bandwidth, the magnitude of the small-signal input admittance reduces, as does the destabilising 180° phase characteristic.

CONCLUSION

A strategy for modelling and simulating the power system of a large civil aircraft has been described. Four simulation requirements have been identified, and a set of four simulations has been proposed to meet these requirements. For a power budget model, it is important to identify the low-frequency power terms, whereas for the detailed power quality simulation, the interface between for example actuator and fuel-pump loads needs to be sufficiently detailed to give accurate values of supply current harmonics. The actuator and fuel-pump motor controller are modelled as an equivalent control structure, as the effect of the controller bridge is decoupled from the supply by the DC-link filter.

The results presented in this paper are preliminary and work is now in progress to refine the models, gather data for further validation and undertake accurate studies, which will be reported in subsequent papers.

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