Next generation design framework for the aircraft electric power system

Martin R. Kuhn Yang Ji
German Aerospace Center (DLR)
Institute of System Dynamics and Control
Münchener Str. 20, 82234 Weßling
martin.kuhn@dlr.de yang.ji@dlr.de

Abstract

Comprehensive understanding and analysis of the more electric aircraft network architecture (MEA) usually require a powerful simulation framework, which allows modelling, simulation and post-processing of aircraft electric power systems. Since the electric power network in the MEA typically covers several physical domains such as electrical systems, magnetic systems, mechanical systems and control, a modelling language to be selected for the design framework has to be capable of modelling multi-domain systems. In this regard, Modelica - an object oriented, equation based modelling language has been chosen as a candidate for modelling the extended electric network in JTI SGO project. By hand of some study cases at supplier level and airframer level, the capability of the Modelica technique based design framework was tested, demonstrated and improved. The selected applications are system specification, component design and virtual testing, which are associated to different phases of the design process for the aircraft electric power system. Essential components which were modelled are the generator, power converters and electromechanical actuators. Modelica and the simulation suite Dymola were demonstrated to fulfil all stated demands.

Keywords: V&V; electrical network; simulation; aircraft

1 Introduction

The design process of electric power systems for the future More Electric or All Electric aircraft (MEA) is becoming even more complex and challenging. Motivated by the need for fuel and cost saving, aircraft systems are developed for better efficiency through replacing the conventional pneumatic, mechanical and hydraulic power by an electrically powered system. One key enabler is the incorporating of an integrated high quality system modelling concept in the complete aircraft design process as it was developed in MOET project [2] and now in work package 2.1 of JTI Clean Sky SGO project [5].

The aircraft design process itself briefly can be divided into 4 major phases: concept phase, system specification phase, system development phase and system verification phase [6]. With each phase also the model types and level of detail change. For example a tool in the concept phase, applicable for optimal architecture design of the electrical energy system, in general does not demand more detailed electrical circuits than resistive elements. In contrast, the aircraft electrical network validation and verification process (V&V) strongly relies on detailed and numerical complex modelling and simulation and the associated analysis of network components and systems. The importance of this design phase rises as network margins are optimized to the tolerable minimum where new issues such as network stability, power quality and reliability can arise.

For the integrated model based design process, a tool chain has to be capable to concatenate not only different levels of abstraction. Also since the electric power network in the MEA typically covers several physical domains such as electrical systems, magnetic systems, mechanical systems and control systems, the design framework has to treat modelling in different and multi-domain systems. Substantial efforts were made to reach platform independence and link simulation tools each with special strengths and dedicated for specific domains. Especially the FMI standard [1] was a major step forward and was verified to improve an aircraft systems design process. Nevertheless, for the sake of performance and transparency, industrial processes often rely on a single common tool.

In this regard, Modelica - a non-proprietary, object-oriented, equation based language to conveniently model complex multi-physical systems was seen as a promising candidate for modelling of all systems in all design phases. Modelica was applied successfully for the earlier aircraft design phases [16]. Nevertheless, while Modelica has found attraction in the automotive sector, it is not the generally applied standard for detailed simulation in aeronautic industry yet. Therefore a study was performed in the context of the Clean Sky project to evaluate the potential and performance of Modelica and the commercial tool Dymola for complex modelling, simulation, analysis and post-processing of aircraft electric power systems.

In this paper we give an overview of the infrastructure which had to be developed and the results. Necessary tools are addressed.

The paper is structured as follows: In chapter 2 we give an short introduction to Modelica. Then the aim of the benchmark is presented. The following paragraph gives an insight to some models and the library structure developed. Some results and lessons learned from simulation are documented in the "simulation" chapter. It is concluded by an overview of the methods and tools developed for the study.

2 Modelica

Modelica [15] was primarily developed as a modelling language, also called hardware description language. It allows specification of mathematical models of complex physical systems without limitation to a certain domain. Models can be used for computer simulation to calculate the behaviour of dynamic systems as a function of time. As Modelica is an object-oriented language similar to Java or C++, it enables easy reuse of components and evolution of models by the the concept of inheritance of classes. Modelica is similar to other modelling languages for physical systems in that as no causality has to be defined by the equations. For example it does not matter whether a resistor is modelled by Ohm's law via $R = U/I$ or $U = R \cdot I$. In contrast to other numerical only implementations, all native Modelica based simulation suites on the market exploit the possibility to do symbolic manipulation of the equation system. By this the causality is detected, the equations reordered and the differential algebraic equation system (DAE) transformed into the explicit ordinary differential equation system (ODE) form where possible. For initialization additional equations may be defined, which are processed symbolically into the initial value equation system. Also guess values for the state variables may be set. The remaining initial conditions are set automatically by default values using zero for the states or state derivatives.

Among various simulation environments supporting Modelica language, Dymola [17] was selected as tool for the Modelica benchmark. It provided the necessary functionality for graphical construction of Modelica models, efficient simulation and some post-processing operations. Dymola has a built-in Modelica translator which can perform all necessary symbolic transformations for large systems for more than 100 000 equations as well as for the generation of real time code. A graphical editor for model editing and browsing, as well as a simulation environment are included. Convenient interfaces for data exchange and co-simulation with MATLAB and the popular block diagram simulator Simulink exist. For example, a Modelica model can be compiled into a Simulink input/output block based on a S-function C mex-file.

The JTI benchmark made use of the free standard conform libraries developed and maintained by the Modelica Association. This so called Modelica standard library provides generic model components and standard component interfaces for several physical domains. Furthermore some new libraries were developed in the project, see chapter 6. There also exist many free libraries provided by other users and commercial libraries.

3 Procedure of virtual testing

The Modelica benchmark was defined by the airframer involved in the project. Modelica had to be tested for typical model based work as it is performed in the validation and verification (V&V) phase for an extended electric network at supplier level. As electric network architecture an HVDC power distribution system (HVDC) was selected. Under several candidates, this is gaining more attention thanks to some benefits like mass/volume saving in the feeders, possible use of regeneration energy from electric actuators, etc. For instance, a possible DC power distribution network configuration architecture contains an 18-pulses auto-transformer rectifier unit (ATRU) which transfers 230V AC voltage to 540V DC voltage supplying DC loads such as electric environmental system (ECS), 230V/115V AC autotransformers (ATU) and electric actuators. Essential components which were modelled in the benchmark are the generator, power converters and electromechanical actuators.

In this chapter we want to review the general procedure of the V&V process. Details were published in [8].

Today, virtual testing of the integrated aircraft energy system is becoming an indispensable task in the system verification design phase. The virtual testing procedure enables integration of the system by software before the real physical integration on the test rigs and extends test coverage. The behaviour of the integrated system is estimated to be representative since component models are verified by in-house hardware tests at the suppliers. Each component is delivered as detailed (behavioural) and abstracted (functional) model.

The virtual testing process can be briefly divided into two steps. First, each subsystem or component model shall be tested for correct operation by so-called component standalone tests. A standalone test usually consists of a bunch of single tests such as power connection, power disconnection, power consumption at steady state, current harmonic analysis and so on, for one component. Standalone tests are required for both functional

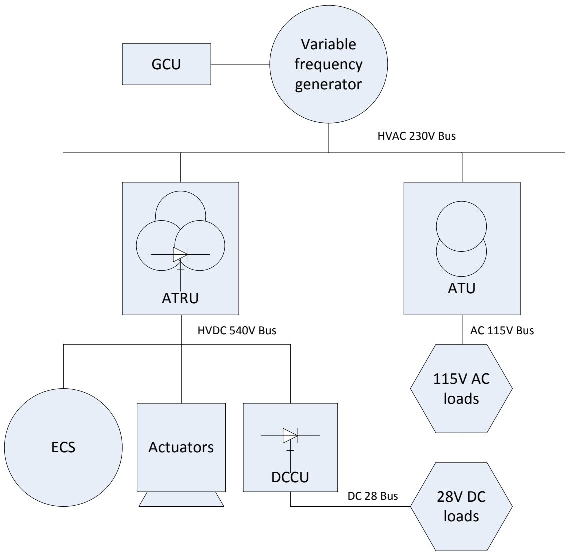

Figure 1: Electric network architectures for More Electric Aircraft

and behavioural models.

Once standalone tests for all components and subsystems are successful finished, in the next step simulations and tests of the total integrated system model are performed. Finally, specific analysis and post-treatment tasks can be performed based on the simulation results of the integrated models.

4 Modelling

To illustrate the type of system under investigation, a typical MEA energy system is depicted in figure 1. The system is powered by the variable frequency generator which controls the bus voltage by the generator control unit (GCU). The AC voltage is rectified by an auto transformer rectifier unit (ATRU) which feeds the environmental control system (ECS), DC loads and the direct current charging unit (DCCU) connecting low voltage DC loads. Low level AC voltage loads are supplied by an auto transformer unit (ATU).

4.1 Functional/behavioural model

As written before, different modelling levels apply for different test scenarios. Today, aircraft industry utilizes a three multi-level approach for the design of the aircraft system [11]. [1]

The models are split into three types:

- Architectural models consist of algebraic equations and are used for steady-state power consumption calculations.
- Functional models reflect the low frequency behaviour of the original system till around one third of the base grid frequency excluding switching ripples. Functional models are derived from behavioural models by state space time averaging of high frequency periodical switching waveforms. Typical applications are stability studies [13, 12] and control design. For the AC network in research often a dq equivalent network representation [10] is chosen. For an industrial project this might be further restricted to an equivalent one phase DC system. While this simplifies the system essentially by neglecting the AC phase information, no calculation of reactive power is possible .
- The behavioural models reflect both low and high frequency dynamics including switching effects. behavioural models are based on equations derived from the subsystem structure and electrical circuit. The behaviour at the terminals should be equivalent to the real hardware up to frequencies in the hundred kilohertzs. Applications include power quality simulation and analysis of transient effects [9, 18].

The table 1 presents an overview of model requirements in all aircraft design phases.

For the system verification phase, functional models are used for long term studies of the integrated system. behavioural models are mainly used for detailed investigation of transients as power on phases.

4.2 Electrical components

The library of components and systems developed for the project can be seen in figure 2. The structure follows the needs of the V&V procedure: All models are implemented as a “behavioural” and “functional” representation.

All models have to be verified by associated standalone tests. The Modelica language concept showed to be beneficial in organizing integrated libraries with both, models and scripts. For example, in figure 2 the test routines for the 230VAC/115VAC auto-transformer rectifier model are emphasized. Scripts can contain procedures for parameter setting, simulation commands and post processing and documentation features. The newly developed scripts are addressed in chapter 6.3.

In the project it was confirmed, Modelica language and the Modelica standard library are capable of modelling all subsystems sufficiently. While the Modelica electrical library is known to be of limited size compared to design environments specialized for electrics, it was found out most components can be modeled by generic objects (e.g. rectifier unit) or they are very specific and need to be written textually by equations anyway (e.g. the generator). The only type of model which was missing showed to be a detailed magnetic hysteresis model.

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[1] To improve the international common understanding of modelling levels and modelling needs, SAE Aerospace organisation will publish a document titled “AIRCRAFT ELECTRICAL POWER SYSTEMS. MODELLING AND SIMULATION. DEFINITIONS.” in the near future

Design phase	Typical task	Required model
Concept	Architecture optimization	Level 1
System specification	Stability studies	Level 2/3
System development	Control design	Level 2/3
System verification	Virtual testing	Level 2/3

Table 1: Model requirements in different aircraft design phase

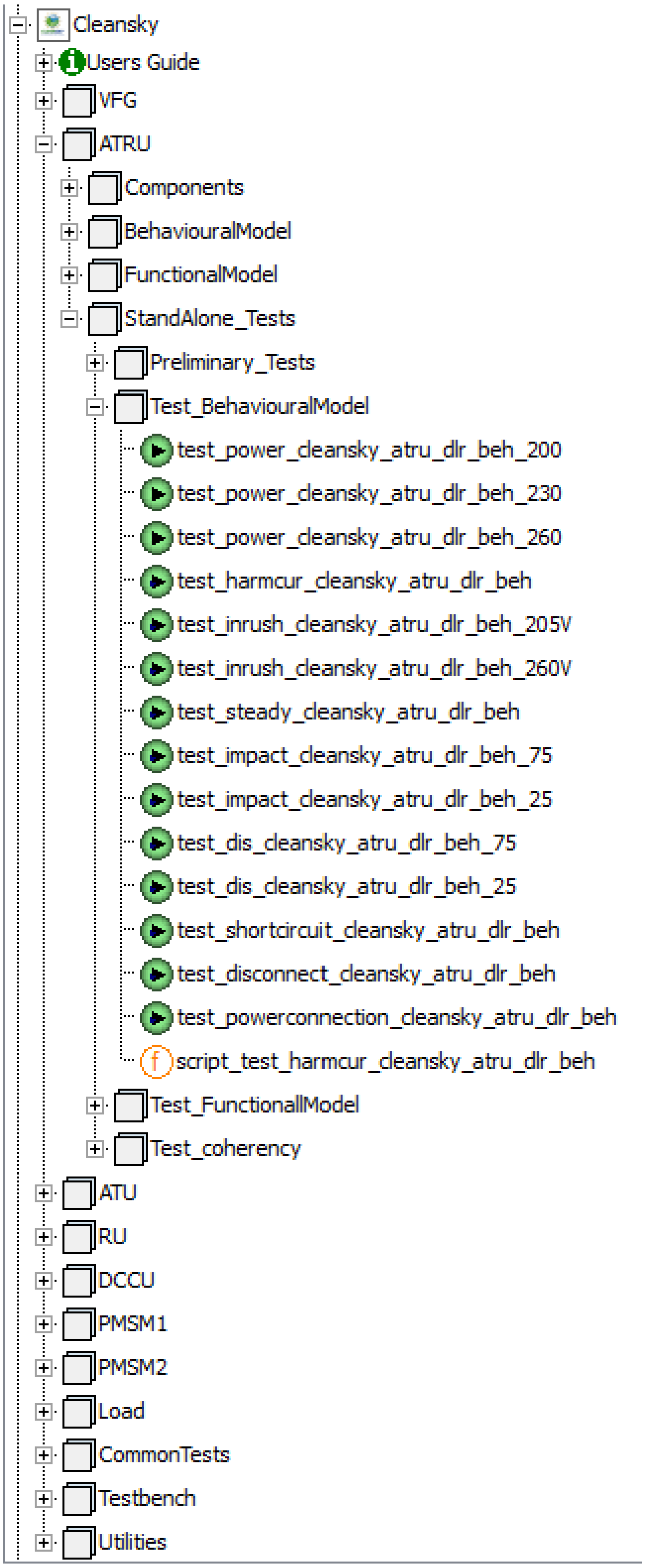

Figure 2: Library of the electrical system

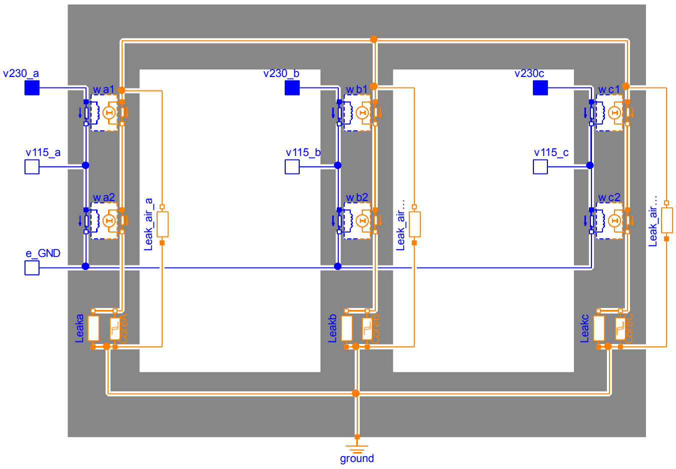

Figure 3: Modelica model of AC/AC auto-transformer

Magnetic hysteresis is of special importance for electrical power systems since the initial magnetizing effect of electrical transformers at power connection can lead to short-time excessive currents flowing into the transformer. This effect is called "inrush current" and investigated in [7]. The Modelica magnetic hysteresis model [19] was developed from JTI resources and will be part of the Modelica standard library in the future.

As an example for the library the ATU model is shown in figure 3 which is one of the critical magnetic elements. The component tests include harmonic current test, inrush current test, power connection and power disconnection test. The harmonic current analysis aims to determine disturbances due to the equipment on different frequency levels. Fast Fourier transformation (FFT) is performed after simulation of the ATU model reaches steady state condition (figure 4).

4.3 Integrated aircraft power system

The stand alone test are essential prerequisites to debug the single components for stable simulation before the integration. After successful stand-alone tests for all components, various scenarios for testing the complete electric power network can be performed. To demonstrate the capability of Modelica/Dymola to deal with large scale power systems, the proposed electric power network depicted in figure 5 has been simulated in Dymola at both behavioural and functional levels. The behavioural model is reduced by Dymola to a simulation model with 69 continuous time states. The linear system

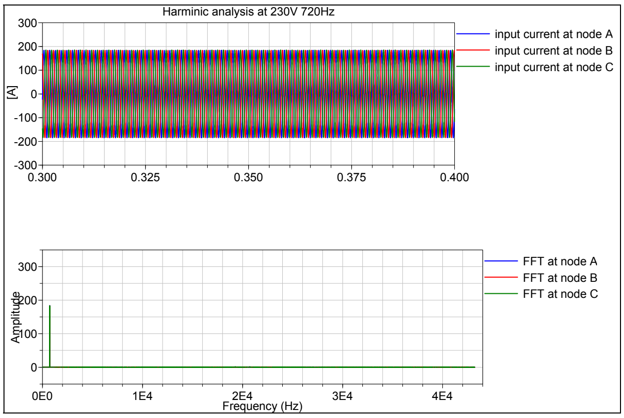

Figure 4: Current harmonic analysis of ATU at 230V and 720Hz input voltage

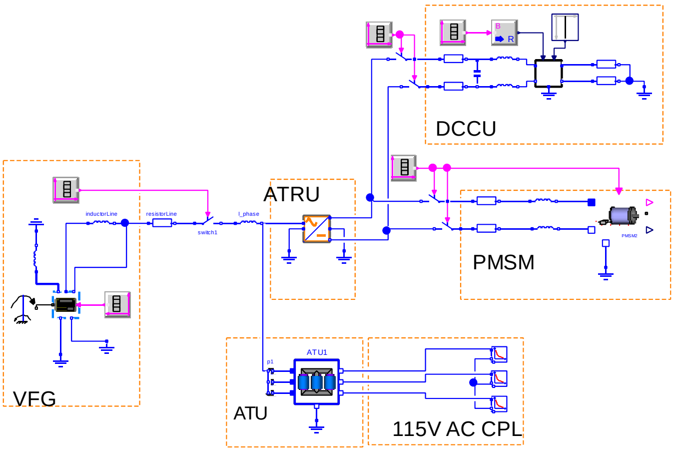

Figure 5: An integrated electric power network for MEA

to be solved reduces to one equation system of order 18. The initialization system was reduced to five independent non-linear equation systems where the largest was of order 33. While the numbers by itself seem not to be very impressing, complexity comes from the switching system.

In the demonstrated electric power network, the ATRU is connect to grid at 0.0025 second. After the pre-charging ATRU with 25e-3 second, the DC output of the ATRU is connected with the HVDC network. The PMSM which has a 20e-3 second pre-charging time is connected with the HVDC network at 0.055 second. After the power inverter in the PMSM is activated, a constant speed command is given for the PMSM under a constant load. AC currents and voltages of the VFG is recorded in the figure 6 for behavioural model and in figure 7 for the functional model. In the simulation results, it is clear to see the inrush currents at the moment of switching on ATRU and DC ripple at the ATRU output. These values are very important indicators for the stability study for the electric power network in MEA. [13]

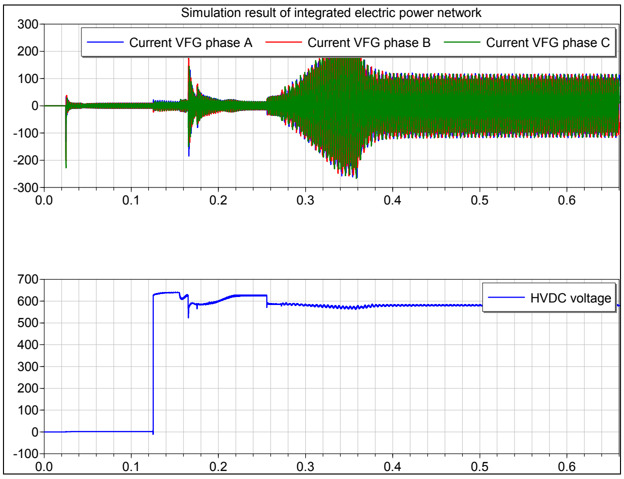

Figure 6: Simulation result of integrated electric power network: VFG current and HVDC voltage (behavioural level)

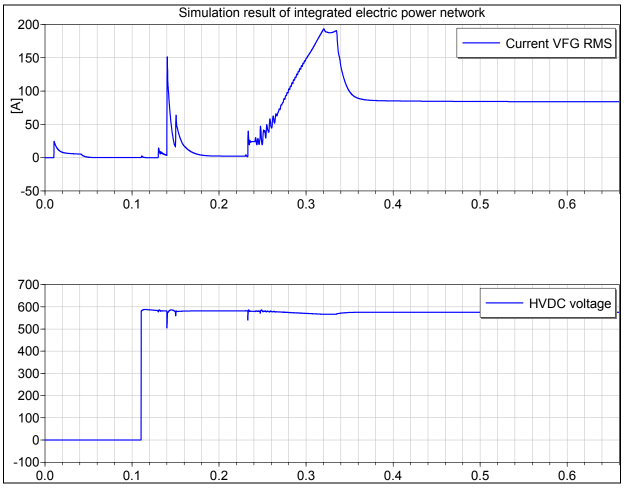

Figure 7: Simulation result of integrated electric power network: VFG current and HVDC voltage (functional level)

5 Simulation and lessons learned

5.1 General

As benchmark of the study, the components and especially the large aircraft power systems had to be simulated to demonstrate the performance and robustness of Dymola's numerical solver for such a usually very stiff power system and suffering from huge amount of event handling actions due to switching components.

In the study it could be demonstrated Modelica/Dymola is capable of simulating all component and integration tests. Compared to the traditional simulation platform for V&V tests, numerical speed showed to be excellent for the smaller component tests and competitive for the large integration test and might be further improved. Also it was detected, simulation speed is overwhelmingly dependent on the model quality and the experience of the designer. Stable and fast operation of the components with non-specialized integration algorithms as DASSL was almost mandatory for the successful large system integration.

From the example in the previous chapter it was seen, the complexity of the initialization in many cases prevents simulation already before start. As a workaround the designer may test initialization with the steady state option.

6 New developments

In the course of the project, some deficiencies were identified for the implementation of the models and the automation of the results within a single environment. The following tools and scripts were newly developed to overcome the obstacles:

6.1 Signal processing tool

In an industrial design process, a tool chain must fulfil higher demands on automation, ergonomics and single tools are preferred than in usual research projects. Especially, tools for signal post treatment are needed integrated in the design tool and must be script-able. In JTI, Dymola was selected as single simulation platform and there was co-funding in the project MODELSSA to extend it by the necessary features. Amongst other features, a library of signal analysis methods in time domain (e.g. min/max, period, duty cycle, root-mean-square) and frequency domain (like FFT, IFFT, total harmonic distortion) was developed. All features are accessible graphically from the user interface and scriptable. The features are documented in [4] and were presented on the Modelica conference vendor sessions.

6.2 Modelling of magnetic hysteresis

For efficient modelling of magnetic circuits, the free Modelica.Magnetics.FluxTubes library [3] was applied for this study. The library is well established and was proven by hardware design studies. Material properties can be taken into account by linear and non-linear permeability. As an important extension in the frame of the Cleansky project, DLR commissioned and supervised the development of magnetic hysteresis models for Modelica. As an outcome, a high fidelity model based on Preisach's equations was embedded (the original publication goes back to 1935, for implementation see [14] for example). For the study of inrush currents which was industrially motivated it was preferred to use another more efficient one. The so called "Tellinen hysteresis model" showed to model the flux density B versus magnetic field strength H relationship of a measured ferromagnetic material well via moderate complex equations and thus by efficient simulation speed. Details and comparisons about the first release of the magnetic hysteresis models for Modelica were published in [19].

6.3 Dedicated scripting for tests

Most simulation tools provide basic post processing functions but with a limited perimeter. Thus, specific analysis functions usually have to be developed for the simulation platform using a post treatment language. Also systematic design and test automation often demands user specific scripts. When performing simple/single simulations, it is sufficient to select menu commands or to type commands in the command input line of the command window. But wanting to perform more complex actions as part of an industrial process (e.g. automatically repeat more complicated parameter studies a number of times) it is much more convenient to use the scripting facility. The goal is often to fully automate the simulation. Just to name some features, the script facility makes it possible to load model libraries, set parameters, set start values, simulate and plot variables.

Dymola supports easy handling of scripting, both with functions and script files (.mos files). Whether a function or a Modelica script file (.mos) should be used is up to the user, essentially the same functionality can be obtained with both. When a function should be the final result, a function is created, and the functionality is then created as an algorithm in this function using the Modelica Text layer of the function as an editor. When a Modelica script file (.mos) should be created, the command input line can be used for input, creating a command log that can be saved as a script. Scripts can be nested; functions can be nested and a Modelica script file may run other Modelica script files.

The test scripts were customized by DLR from existing commands of Modelica language and Dymola functions. The built in functions and model management tools of Dymola were found to be sufficient for the study. Among others, the following scripts and tools were found to be necessary repeatedly for the V&V study:

- Transformation of input data: From input files data are edited into a Modelica compatible type. This function is of major relevance in an industrial process since input data might not be Modelica compatible and use of additional software is undesirable in standardized processes. By help of some Dymola buildt in functions conversions from text files, Microsoft Excel sheets and more was performed. Matlab's matrix data format .mat is supported immanent.

- Transformation of output data: Same as for the import, the output features are important. Typical outputs programmed in functions were time domain results (.mat result files), tables (Excel) and generic data (.txt). For generation of frequency domain data, it was necessary to have the Fast Fourier Transformation (FFT) function executable by script. Thanks to the co-funding by the JTI project this function is now provided in Dymola. Application of the FFT function include parameter studies with tabulated output of total harmonic distortion (THD) or harmonic content at specified harmonics.

- Coherency test models: Test of linear dependence of signals in time domain by convolution. Coherency is an important criterion in verification tests to analyze the validity of models and model abstraction levels. It is applied for verification of models versus hardware test data or between different models. The script calculates coherency by application of the coherency function to two simulation or measurement waveforms.
- AC modulation envelope: The AC envelope function is the smooth curve outlining the extreme positions of a distinctive alternating wave with a fixed frequency. The modulation envelope shows its amplitude variation in frequency domain. The AC amplitude is an important measure for the voltage quality which must be stabilized by the generator control. The developed function relies on peak finding and transformation of data to frequency domain by FFT.

As an example of an integrated test, the Dymola script for the worst case study of sympathetic effect is presented in Fig. 8. This script function firstly simulates the test bench till 5.791 second and records the simulation result in a “end.txt” file. This result will be always defined as initial condition for the following 20 time simulations with different connecting time for ATU2. A real variable Tatu2 is defined to vary the connecting time of ATU2 and has a time step $\varepsilon = 0.000125$ second for each simulation loop. Simulation setups such as used integrator, simulation time are also defined in the script function. Additional scripts have been made for post-processing. It is a big advantage for users, that a complex test like analysis of sympathetic effect can be easily formulated with Dymola scripting language in a very compact manner.

7 Test results

For demonstration of the post-processing features we present the inrush current test for the ATU. Simulations have been performed at a behavioural modelling level with the VFG model being set to 230Vac/400Hz. Once the first ATU reaches its steady-state (here 5.79S), the second ATU is connected at different times to cover one period. The automatic process with 20 simulations to capture maximum ATU2 inrush current has been implemented by Dymola script language as previously explained.

```
function Script_Case1_with_simulation_paper
  import Modelica.Utilities.Flies.*;

protected
  Real Tatu2 = 5.791;

algorithm

  //performe simulation till steady-state
  translateModel("Case1");
  simulateModel("Case1",
   stopTime=5.79,
   numberOfIntervals=0,
   method="Radau",
   resultFile="Case1");

  //backup dsfinal
   copy("dsfinal.txt","end.txt",true);

  //do parameter studies about
  //switch on time of ATU2 with
  //time step 0.000125s

for i in 1:1:20 loop

  Tatu2 :=5.791 + i*0.000125;
  importInitial();
  simulateExtendedModel("Case1",
    startTime=5.79,
    stopTime=5.8,
    numberOfIntervals=0,
    method="Radau",
    resultFile="dres_"+String(i),
    initialNames={"Tatu2"},
    initialValues={Tatu2},
    finalNames={"Tatu2"});

  //re-initialization
  Files.copy("end.txt","dsfinal.txt",true);

end for;
end Script_Case1_with_simulation_paper;
```

Figure 8: Scripting for the worst case study of sympathetic effect

Results to be recorded for the two test cases are inrush currents in the VFG, the ATU1 and the ATU2. As shown in Fig. 9, the maximum inrush currents of the VFG and the ATU2 reached 164.1A and 155.5A during the 8th simulation when the second ATU is connected at 5.7935S. The maximum reached current of the ATU1 at 5.793125S is 9.4A. For the test case 2, Fig. 10 shows, the maximum inrush currents of the VFG and the ATU2 are reached 276.9A and 266A during the 8th simulation when the second ATU is connected at 5.7935S. The maximum reached current of the ATU1 at 5.793125S is 13.4A. The magnetic flux through the leg a in the ATU2 core in the worst case is depicted in sub-Fig. 11a for test case 1 and sub-Fig. 11b for the second test case.

8 Conclusion

By the study, the applicability of Modelica and Dymola for large scale testing of aircraft electrical systems in V&V studies was demonstrated successfully. All demands on new functionality, additional models and specialized scripts could be met within the project. The developed library is an important base for propagation

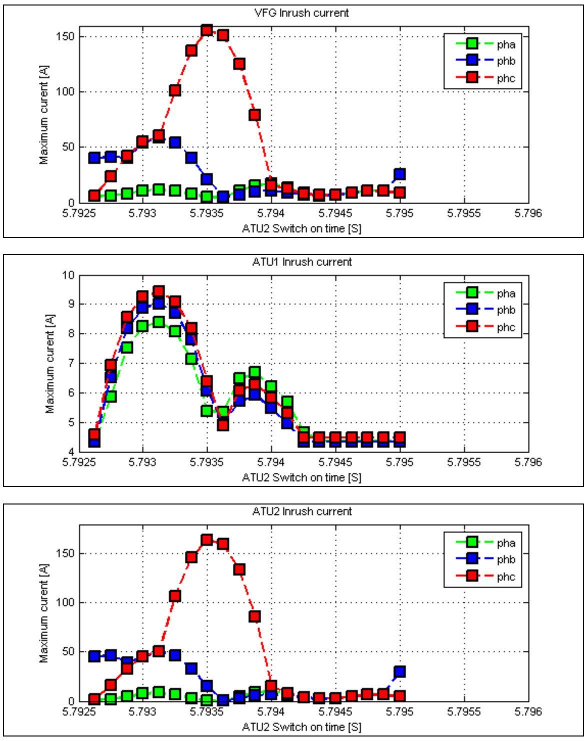

Figure 9: Test result of case 1

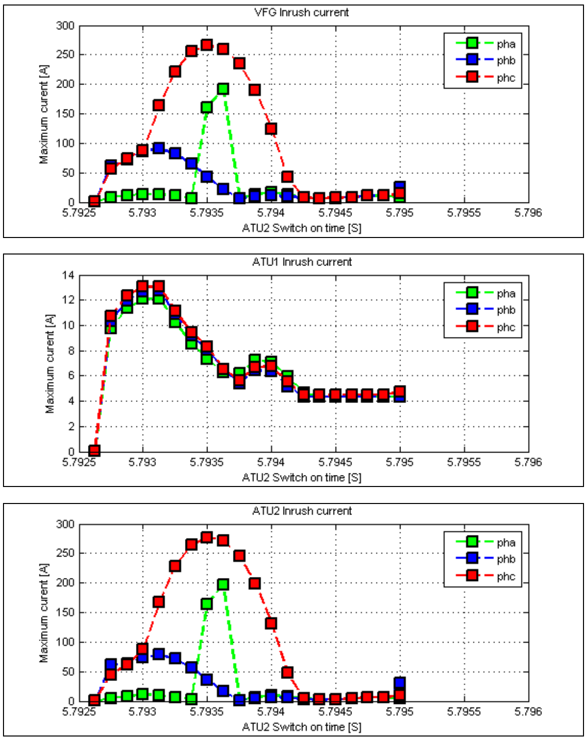

Figure 10: Test result of case 2

to a Modelica based V&V process in aircraft electrical systems simulation. Since Modelica has strong benefits as support by multiple simulation suite vendors, very strong activities in library development and capabilities for hardware in the loop simulation, it can be seen as strong competitor for the next generation design framework modelling language.

Acknowledgment

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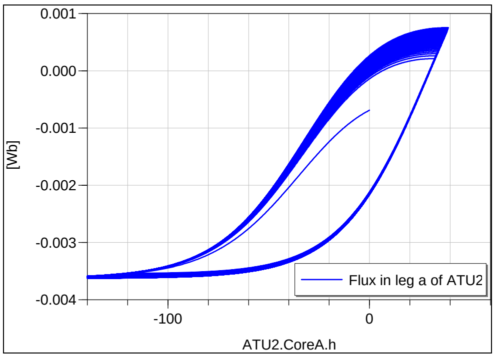
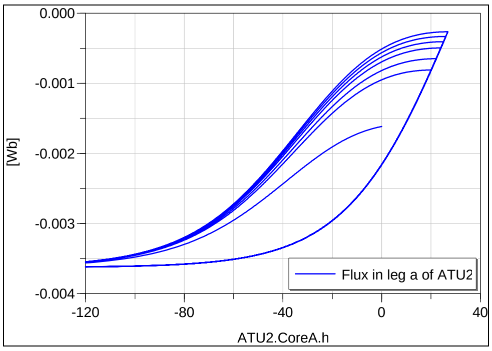


(a) Magnetic flux in ATU2 core for case 1



(b) Magnetic flux in ATU2 core for case 1

Figure 11: Magnetic flux in ATU2 core

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