SIMEAD Main Scientific and technical results/foregrounds

1. Introduction

The aim of the SIMEAD project (Suite of integrated models for electrical aircraft drives) is to develop software tools to enable investigations to be undertaken into the behaviour and energy efficiency of alternative electric drive solutions and technologies, for use in future green regional aircraft, over a range of electrical system architectures and operating scenarios. This report identifies the main scientific results and foreground arising from each work package, highlighting specific results of interest. A complete index to the models and test examples is given in the Summary Report, deliverable D5.1. Models are implemented in SABER v2006.06-5.9, with MAST v2006.06-3.7 and Library v2006.06-3.7.

The machine models form Deliverable 1.2 of Work Package 1, “Motor models”, covering the synchronous permanent magnet (PM) machine, asynchronous or induction machine (IM), switched reluctance (SR) machine and variable reluctance (VR) machine. The SIMEAD models give enhanced functionality beyond the standard SABER library models, incorporating representative loss mechanisms and allowing adjustment of the equivalent circuit parameters. Underpinning analytical equations are documented in Deliverable D1.1.

Deliverable D2.1 of Work Package 2 comprises a set of averaged-value DC:AC, AC:DC and DC:DC converter models, verified against fully switched models under Task 2.1, together with appropriate open- and closed-loop controllers for the asynchronous machine (Task 2.2) and closed-loop controller for the synchronous machine (Task 2.3). The power converter models provide appropriate fidelity models for aircraft drive system control and energy management, whilst running fast enough to be useful in network studies. Machine, converter and controller models have been integrated in Task 2.4, to show test examples of full drive systems and a network study with multiple DC:DC converters.

Deliverable D3.1 of Work Package 3 is a supporting report, investigating the energy optimisation strategies for aircraft drive applications within the drive system and driven load. The outcomes of Work Package 4, “Parameter Identification and Model Validation” are documented in deliverable D4.1, which reports on methods of calculating or measuring parameter values for use with the motor models (Tasks 4.2 and 4.3) and validation of the models against experimental results (Tasks 4.4 to 4.6).

2. Machine models – Work Package 1

The SIMEAD models cover three main types of machine: PM synchronous; asynchronous or induction and switched reluctance. Variable reluctance machines can be modelled as a salient pole synchronous machine, by setting the magnet flux-linkage to zero. Machine models have been implemented in MAST, as full dynamic d-q models for the PM and IM machines and a dynamic circuit model for the SR machine. Five-phase versions of the PM synchronous and asynchronous machines are presented as examples of multiphase machines, with guidelines for how these may be extended to a higher number of phases. An unbalanced two-phase IM model is included in the SIMEAD modelling suite.

The standard SABER library includes induction and permanent magnet synchronous machines but neglects key loss mechanisms in these machines, with insufficient detail for evaluating power and energy use. The SIMEAD models are enhanced by the incorporation of iron loss, and include representation of thermal variations, saturation (including cross-saturation), high frequency loss and saliency, as appropriate. A general thermal model for electrical machines is also presented, which is applicable to all machine types. The wound-field synchronous machine in the standard SABER library includes iron loss and it is suitable for use with the SIMEAD machine models in energy management studies.

A single MAST model has been provided for the synchronous machine. Higher-order effects and losses can be enabled by setting non-zero parameters in the model. However, the induction machine model increases in order with the inclusion of core losses, so separate baseline and core-loss models of the machine have been implemented. Parameter changes due to saturation, thermal effects, frequency and space harmonics for the induction machine are modelled as hierarchical blocks that can be connected to either the baseline or core loss models. During development, a third version of the induction machine with saturation was used, but since this model differed from the baseline model only by additional model outputs, these outputs have been standardised for the baseline and core-loss models and the separate development version of the saturated machine model has been withdrawn.

Test examples are available for the induction machine models with a direct-on-line supply. The synchronous machine would normally be used with a controller, so test examples for the PM including appropriate control are given in Section 3 .

2.1 Significant electrical machine research contributions

The primary contribution of the SIMEAD PM machine models relative to standard SABER library blocks lies in their enhanced stator loss estimation and scaling with the electrical and thermal operating point of the machine. The standard SABER PMSM models account for only the dc copper loss and mechanical loss in the machine. In contrast, the SIMEAD model includes stator iron loss estimates and a detailed stator copper loss model. In both cases, rotor losses and higher harmonic losses are neglected. However, the inclusion of the dominant stator loss components more accurately accounts for the total loss and serves as a basis for informing the thermal modeling of the PM machine.

The total stator iron loss is approximated by two separate components due to the resultant stator flux and demagnetizing flux. This approach allows the variation in stator iron loss to be estimated under both maximum torque per amp (MTPA) and field weakened (FW) operation. In the constant torque region the core losses are associated with the main open-circuit magnetizing flux path which flows through the stator teeth and back iron. A polynomial function of the magnetizing voltage is used to approximate the open-circuit core losses based on open-circuit hysteresis, eddy current and excess loss coefficients. In the constant power region the core losses are associated with the short-circuit flux path across the face of the stator tooth tip. A polynomial function of the demagnetizing voltage is used to approximate the short-circuit core losses based on short-circuit hysteresis, eddy current and excess loss coefficients. Parameterisation of both the open and short-circuit iron loss models is straightforward requiring only two FEA calculations or two sets of experimental data which are then scaled for the operating point of the machine.

The stator copper loss estimation accounts for variation due to the fundamental excitation frequency and mean winding temperature, the latter being informed through the inclusion of a reduced order thermal network. The relationship between copper loss and frequency is primarily due to the proximity effect and skin effect affecting the value of the winding resistance. The relative significance of each effect depends on the operating frequency, temperature and physical properties of the winding. A simple empirical model of the winding resistance variation was implemented which accounts for both the frequency and temperature dependence of the stator copper loss.

Models accounting for the dynamic variation in the permanent magnet (PM) flux linkage and winding resistance with temperature are informed by the inclusion of a reduced order thermal network. The stator iron and copper loss estimates are used as inputs to the thermal network which in turn estimates the PM and mean winding temperature. The linear reversible change in PM flux linkage with temperature is approximated by a standard linear model. A model of the variation in winding resistance with temperature is included which also accounts for the fundamental frequency dependence of this parameter. Hence, the parameter and loss estimates are updated based on the operating point of the machine. This allows both the steady state and dynamic transient thermal behavior of the machine to be investigated.

The primary contribution of the SIMEAD induction machine models relative to standard SABER library blocks lies in the incorporation of iron loss, based on the eddy current and hysteresis loss coefficients, and the representation of slip-dependent rotor parameter variations. This work is supported by simple experimental tests to parameterize the models. The incorporation of realistic loss mechanisms allows energy optimisation strategies based on optimal flux control open and closed-loop applications to be evaluated. The SABER modelling of the unbalanced two-phase and the balanced 5-phase machines in based on standard theory, but offers new functionality, again including iron loss and saturation.

3. Drive and control models – Work Package 2

The power electronic models in Work Package 2 are essential for the effective use of the SIMEAD machine models, providing the interface between the electrical network and the machine, with full representation of converter losses in a computationally efficient form. A DC:AC inverter and DC:DC converter model have been provided, in accordance with the original proposal and an additional AC:DC converter with controller is included. Controller models for the power converters and main machine types are also provided.

Test examples have been used to check the integration of the machine, converter, controller and power network as appropriate. In each case, parameter values and example results are included in the associated report. For the converter models, tests against a fully-switched converter equivalent were used to verify the averaged value SIMEAD models.

3.1 Model integration

Model integration was a high priority throughout the SIMEAD project and so each report detailing a specific model also contained appropriate integration with other models developed; all contributing to Task 2.4 of Work Package 2. This section summarises the integration of the electric machine models, developed in Tasks 1.2 and 1.3 of Work Package (WP) 1 (the thermal models from Task 1.5 are also included), with the converters, developed as part of Task 2.1 in WP2 and machine controllers where appropriate, which were developed in Tasks 2.2 and 2.3 of WP2. A variety of load types have been used in the model integration, both electrical, including resistive and constant power loads, and the actuator case studies for the synchronous machine, and mechanical as appropriate.

The integration of the electrical machine, control and converter models is split between the following reports:

- Power Converter Modelling Report (DC/AC) - *Section 6*
  SIMEAD–278407–D2.1T2.1DCACv1.0
- Power Converter Modelling Report (DC/DC) - *Section 7*
  SIMEAD –278407 – D2.1T2.1DCDCv1.0
- Synchronous Machine Drive and Control Models Report - *Section 3*
  SIMEAD –278407 –D2.1T2.3v1.0
- Asynchronous Machine Control Models Report - *Sections 1 and 2*
  SIMEAD –278407 – D2.1T2.2v1.0

Additional tests were performed throughout the development of the models to ensure successful model integration but these have not been documented in published reports and have since been superseded by the model integration results contained in the published reports. A comprehensive schedule of model integration has been undertaken as a core aspect of the SIMEAD project to ensure integration of the models developed by both research partners (the University of Manchester and the University of Bristol). All model integration undertaken has been successful. With the exception of the average value inverter and permanent magnet synchronous machine integration, which required line inductance between the inverter and the machine, no additional parameters or parameter changes have been made to any model from that detailed in the relevant technical report.

Integration of the switched reluctance machine (Task 1.4 WP1) or the direct torque controller (Task 2.2 WP2) for asynchronous machines with other SIMEAD models has been limited as both models require a switched power electronic inverter for correct operation. The use of a switched converter causes a lengthy simulation time and so future use of these models in the SIMEAD project for power management is likely to be limited. No integration of the two-phase asynchronous machine has been undertaken, as this machine is normally only specified for direct connection to a single phase AC supply.

This report presents an overview to model integration undertaken throughout the SIMEAD project. The key machine, converter and control models have all been successfully integrated and have been demonstrated to successfully work.

3.2 Significant drives and control research contributions

A key contribution to the success of the SIMEAD models has been the implementation of average-value converter models, to combine appropriate fidelity with significantly shorter run times than fully-switched models. The average-value models of the power electronics represent the dynamic behaviour and losses of the power converter at an appropriate level for energy management studies, in a computationally efficient manner. Switching transients are excluded, so the models are not suitable for deriving peak transient (sub-millisecond) ratings, or evaluating harmonic content. Whilst the power electronic circuits are not novel, the implementation in the SABER environment represents a major achievement. The provision of self-tuning features enhances the usability of the models.

The primary contribution of the SIMEAD control models lies in their integration with the SIMEAD machine models and average value converter models. The estimated variation in machine and converter loss and efficiency under different operating regimes such as maximum torque per amp (MTPA), field weakening (FW) and sensorless control for the PM machine, and optimal flux or V/F control for the IM can be investigated using the SIMEAD models.

Stator current vector optimisation techniques, such as maximum torque per amp control, are used to maximise the output torque of the PM machine per unit stator current. The standard SABER machine models allow only the impact of the given optimisation on the dc component of the copper loss to be investigated. In this case estimation of efficiency is of limited value as the ac copper loss and stator iron loss are neglected. The SIMEAD machine models, however, include estimates of ac and dc stator copper and iron loss, and rotor copper loss for the IM, which are scaled for the electrical and thermal operating point of the machine. Hence, the SIMEAD models can be used as a starting point to investigate the global stator loss and efficiency variation under an optimised control regime. The loss and efficiency variation with temperature can also be investigated using the integrated thermal capability of the SIMEAD models. A significant benefit of the SIMEAD models is their inherent ability to estimate losses and efficiencies over a dynamic operational envelope of the machine.

The SIMEAD control components can be used in conjunction with the SIMEAD machine models to investigate the transient thermal behavior of the machine under steady state and dynamic operation. Potential issues with sensored and sensorless controller stability for the PM machine in the presence of temperature dependent parameter variation can be investigated. Sensorless rotor position and speed estimation schemes, for example, often assume fixed permanent magnet flux linkage and stator winding resistance parameters. The SIMEAD models may be used as a basis for investigating the dynamic stability and accuracy of such a control scheme over a dynamic operating temperature envelope of the machine.

4 Optimal Power Control – Work Package 3

Optimal power control strategies are reviewed in Work Package 3, based on the SIMEAD models from Deliverable 2.1. Deliverable 3.1 is presented as two reports for the synchronous PM and asynchronous IM machines respectively.

For the PM machine, the maximum torque per amp (MTPA) strategy is applied to two machines, which both have significant saliency. In the second machine, an efficiency gain of 1.2% is achieved at rated torque and speed, whereas for the first, there is almost no improvement, showing that the additional complexity of MTPA can only be justified for some designs. Frequency-related losses in the machine are studied in detail, with some significant research on high-frequency loss mechanisms. The report concludes that there is no significant benefit in adjusting the inverter switching frequency with machine operating point.

Optimum flux control is investigated for both open-loop voltage/frequency control and closed-loop control of the induction machine. Reducing the flux at light loads is recognized as giving energy savings, and is particularly applicable to pump and fan loads at low speeds. This report also concludes that the majority of potential energy savings are in the machine, and there is no significant benefit in adjusting the inverter with machine operating point.

Energy management for the load is considered for a compressor load case study. A reduction in compressor speed can be shown to give a significant reduction in the power required, which can be used to reduce peak loading on the network. However, the case study also compared the energy use for a compressor switching between two different speeds, with the energy use of a machine running continuously at the weighted average of the two speeds, to give the same average flow. The energy use was higher for the switched system, showing that the use of the load reduction in the compressor to reduce peak loading on the network comes at the cost of a higher average energy use, if average flow is to be maintained.

5 Parameter Identification and Model Validation – Work Package 4

Software models are only as good as their parameter values, and are only credible if they have been validated. This work package investigated parameter measurement methods and validated the models against experimental results included calorimetric loss measurements. The results show expected trends on most of the electrical tests, allowing good parameterisation of the legacy PM machine and IM machines. The off-the-shelf 400Hz machine proved more challenging as the low inductance made it harder to get good quality electrical measurements and the high machine speed meant that a gearbox had to be used, leading to vibration problems with torque measurements.

The thermal modeling and experimental validation of the University of Bristol’s PM machine show an impressive match between the lumped parameter model and measured results, and a fair match with the MotorCAD thermal model. However this requires a fully-instrumented machine, and detailed knowledge of design parameters. Calorimetric and electrical tests showed good agreement on trends and a fair agreement between modelled and measured losses, with the SIMEAD models under-predicting both losses and temperatures, in both the PM and IM cases. This is thought to be due to additional harmonic and stray losses, not included in the models. The results give credibility to the SIMEAD models, and are significantly more accurate than the standard SABER library models.

The parameter identification and model validation results are summarised in a single report.

6 System Study examples

Two case studies were identified by the Topic Manager as relevant to other projects within the GRA platform. The first demonstrates the position response and dynamic power requirements of a rudder-type position actuator, allowing more accurate representation of the losses and motor temperatures. The second represents a high-speed compressor drive for an environmental conditioning system (ECS) and allows investigation of power management by varying the speed of the load. This section also presents an integrated network, demonstrating control of multiple DC:DC power converters on a DC network, fed from a controlled AC:DC rectifier unit.

6.2 Electromechanical actuator study

The electro-mechanical actuator position control system has an outer position loop and nested speed loop, with an inner current control loop, implementing maximum torque per amp control with field weakening (MTPA-FW). Linear position actuation is achieved through a lead screw arrangement. Actuator losses are calculated for the required position profile, which is then used to estimate the impact of the losses on the temperature of the machine. The simulation demonstrates that the actuator can meet its specification and can be used to assess the impact of the time-varying load on the electrical network.

6.3 Compressor Drive

A high-speed compressor drive for an ECS is modelled, using the SIMEAD induction machine model with saturation and core loss, integrated with the ideal average-value inverter, and v/f controller, with SABER library blocks for the simplified compressor load. Machine and compressor ratings are based on published literature, with a machine rating of 50kW at 45780rpm, operating from a 270V DC link, with a maximum power frequency of 800Hz. The compressor has a nominal rating of 23.8kW at 36700rpm and a 200% overload and 10% accelerating torque capability. Machine parameter values have been estimated by scaling from a smaller 8kW, 400Hz test machine.

Load shedding can be used to reduce the peak power drawn from the network during periods of high load, ensuring that the generator is able to supply critical loads. For a compressor, time constants are relatively slow so the compressor speed can be reduced for short periods of time without affecting passenger comfort. The case study looks at the scope for load reduction by reducing the speed of the compressor for a short period of time. Once the network has recovered to a normal state, this is followed by a short period of increased compressor speed to maintain the ECS at its required set point.

The simulation demonstrated that a significant reduction in power could be achieved by a temporary reduction in speed, but that more power was needed over the whole cycle, than if the machine had run continuously at the average speed.

6.4 Integrated power network

An aircraft power network was simulated, demonstrating successful integration of the developed SABER models. A three-phase PWM average value rectifier model with losses is used to regulate the 270VDC voltage using a simple d-q controller with decoupling. Three phase-shift full bridge (PSFB) DC/DC converters are connected to the 270V bus; two of these are directly connected to loads of different types, while the third feeds a lower voltage 110V DC bus, supplying two further loads via dedicated DC/DC converters. Bus voltages have been set to arbitrary values for illustrative purposes.

The system study looks at network voltages for step changes in the rectifier reference voltage and step increases and decreases in resistive and constant current loads. All transients are controlled with acceptable overshoot and settling times. Auto-tuning of the converter controllers is found to regulate the voltage acceptably, although with a non-optimal response.

7 Conclusions

The SIMEAD project has delivered a valuable modeling tool to enable investigations to be undertaken into the behaviour and energy efficiency of alternative electric drive solutions and technologies, for use in future green regional aircraft. Two case studies have been set up, allowing investigation of energy use in the compressor and demonstrating the position response and dynamic power requirements of the rudder-type position actuator. An integrated network example demonstrates control of DC:DC power converters on a DC network. All project objectives have been met.

Key research contributions include:

- An empirical model and parameterisation technique accounting for stator copper loss variation due to the fundamental excitation frequency and mean winding temperature.
- Effective use of average-value converter models, to combine appropriate fidelity with significantly shorter run times than fully-switched models,
- Integration in the SABER modeling environment machine of power converter and controller models, to allow energy management studies of aircraft drives,
- Inclusion of thermal modeling and evaluation of the lumped-parameter model against a detailed 3D commercial thermal model and experimental results.