Modeling the electrical part of an aeronautical EMA using Simscape

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Abstract. The present paper contains an analysis of the operation of the electric motor of an aerospace electromechanical servomechanism present on a test bench. Particularly, the description focuses on the electromagnetic phenomena of the three-phase stator circuit and the switching of the stator phases as a function of the applied control logic and rotor position. The activity was made possible through the construction and validation of a 'digital twin' physical model in the Simscape environment, which faithfully reproduces the behaviour of a High-Fidelity numeric reference model, built in the Simulink environment, perfectly representative of the electromechanical servomechanism. The recourse to the construction of a 'digital twin' physical model was necessary as it allows the study of non-linear phenomena that are the main cause of failures of electromechanical servomechanisms. Therefore, the analysis conducted will allow prognostics algorithms to be developed in order to predict potential failure conditions and avoid potential hazardous situations in the operating environment.

1. Introduction

In recent years, in aeropace, a trend towards More Electric/All Electric designs has been observed [1]. In essence, the goal of More Electric (or even All Electric) design philosophies is to reduce or even eliminate the number of secondary power sources aboard an aircraft, to reduce complexity and streamline designs [2]. One of the key elements allowing adoption of these philosophies is the Electro-Mechanical Actuator (EMA), i.e. a simple mechanisms that allows conversion of electrical energy to mechanical force [3].

However, no mass adoption in safety-critical application has been observed for several reasons, chiefly the lack of reliable historical data on failure modes, e.g. in primary flight controls. One way to mitigate such problem in an efficient and cost-effective manner is to use numerical models capable to reproduce the behavior of the real system as accurately as possible. Synthetic datasets can then be used in complex prognostics [4][5] and diagnostics algorithms (possibly machine-learning based [6]) to increase the reliability of the system especially in safety-critical applications.

This paper focuses on the description, using a High-Fidelity numerical reference model defined and developed in the Matlab-Simulink environment, of the operation of a Permanent Magnet Synchronous Motor (PMSM) present on a physical test bench, and specifically on the adoption of Simscape for some of the subsystems used in the model. Simscape offers direct physical modeling over traditional Simulink abstracted modeling, where a mathematical model has to be derived and then implemented using elementar blocks. One of the advantages offered by Simscape is quicker modeling of different complexity or fidelity levels, since several mathematical models can be selected for many components, thus saving on time and the need of creating a new different model.

The original model was based on High-Fidelity model [7] of an EMA using a Brushless DC motor [8], then modified to model a PMSM analogous to the one found in the test bench [8][9][10], calibrated, and then tested against the Simulink-based High Fidelity model [7].

2. Simscape modelling

The use of Simscape was necessary to enable future applications to model various problems related to non-linearities and to perform multi-domain analyses, i.e., considering the interaction of different physical effects on the system. In fact, unlike the blocks of the "Power Systems" library in Simulink, through Simscape it is possible to create physical models that automatically implement precise linear and differential algebraic equations to solve the system and obtain the characteristic quantities useful for post-processing analysis. In this specific case, a 'digital twin' model was generated in Simscape which reproduced the same operation of the three-phase power transistor bridge and the electromagnetic phenomena characteristic of the stator windings.

3. Three-phase bridge and three-phase stator circuit Simscape physical models

Simscape model simulation runs in parallel with Simulink model simulation. It is possible to change the simulation parameters in Simscape through the "Solver configuration" block. In particular, the block allows you to set several parameters including the integration method for the simulation by choosing from the settings in "Use local solver" and the time integration step from the "Sample time" interface. In the present case, the same parameters of the Simscape model have been set, i.e., the fixed step Euler integration method (in Simulink ode1 (Euler)) and the time integration step equal to 10^{-6} s.

The three-phase bridge and three-phase stator circuit physical models produced through Simscape are shown in Figure 1.

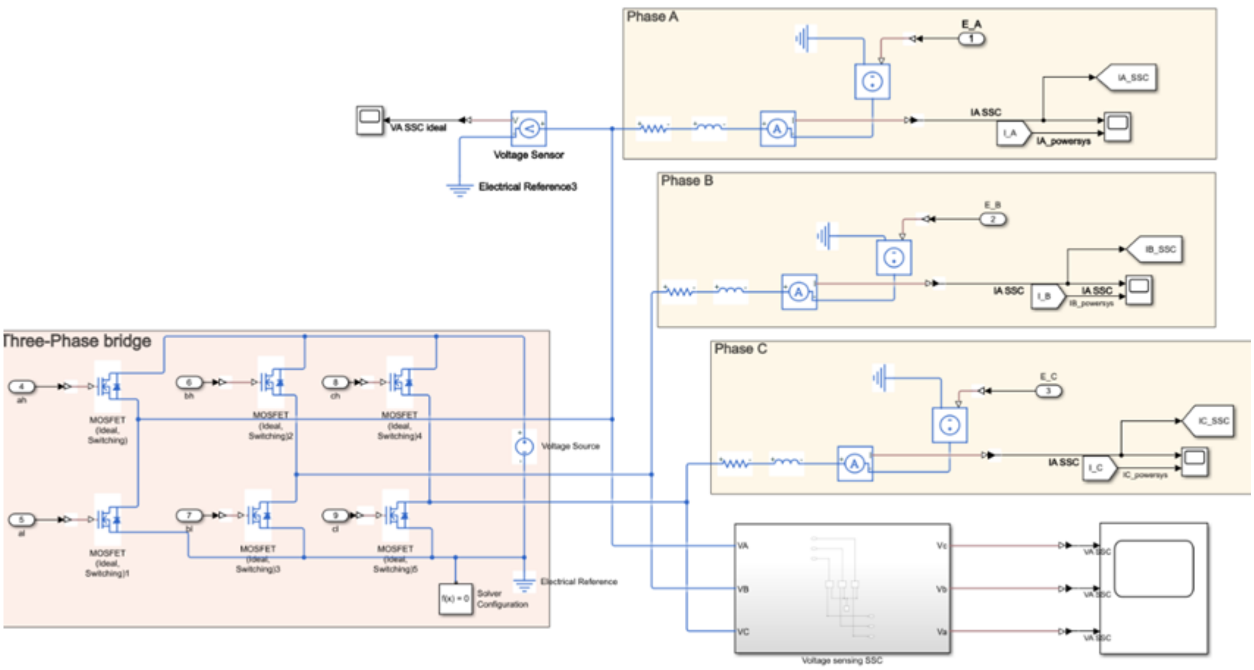

Figure 1. Three-phase bridge and three-phase stator circuit Simscape models.

3.1. Three-phase bridge

Figure 2 shows the construction of the model implementing the operation of a static three-phase bridge power transistor converter of the "Mosfet" type.

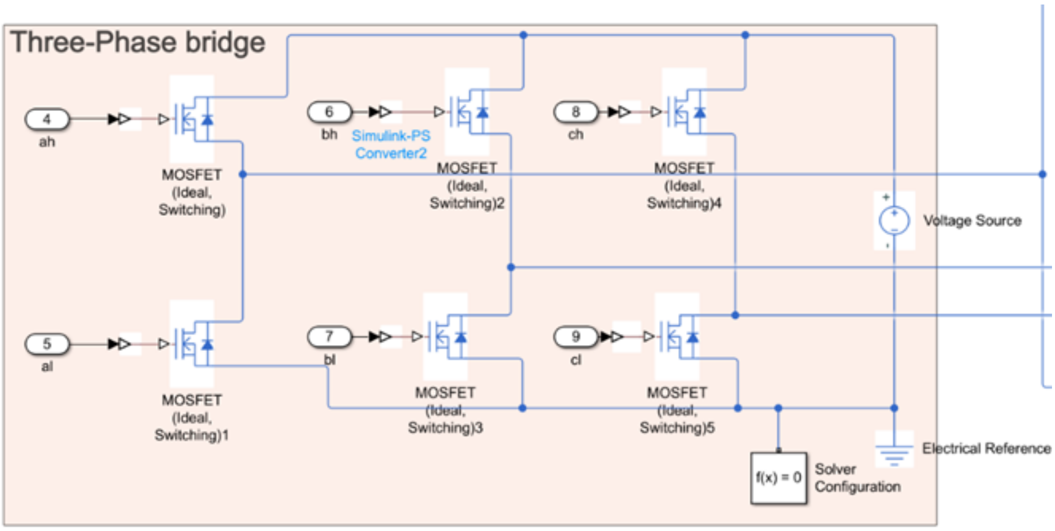

Figure 2. Three-phase bridge.

A preliminary analysis allowed us to select the "Mosfet (Ideal Switching)" blocks from the "Electrical" library in Simscape. These blocks represent a simplification of the actual devices since their characterisation required very precise technical data known only to the manufacturing companies. The "Mosfet (Ideal Switching)" blocks can be equipped with protection diodes which prevent dangerous over-voltages at the ends of the transistors during ON-OFF switching of the phases due to the inductive behaviour of the electric motor. The protection diodes must be able to switch from a non-current flowing condition to a conducting condition and vice versa. Therefore, they must have characteristic operating times in the order of nanoseconds. Moreover, the protection diodes must be able to dissipate high currents since in the ON-OFF transition all the current supplying the motor passes through the diode (in the order of amperes). The parameters set for the six "Mosfets (Ideal Switching)" and for the protection diodes are shown in table 1.

Table 1. Mosfet Ideal Switching data.

Physical quantity	
Drain-source on resistance, R_DS (on)	10^{-2} Ω
Off-state conductance	10^{-6} $Ω^{-1}$
Threshold voltage, Vth	0.5 V
Forward voltage	0.8 V
On resistance	10^{-3} Ω
Off conductance	10^{-5} $Ω^{-1}$

Being a three-phase stator circuit, it was necessary to construct three different branches with two power transistors each of which receives as input the Boolean signals for phase switching. These signals are "ah, al, bh, bl, ch, cl" which come from the "Three-phase bridge" subsystem implemented in "Power Systems" and correspond exactly to the signals for the switching implemented in the High-Fidelity reference model produced in Simulink. These signals are then transformed from Simulink signals to physical signals using a converter called the "Simulink-PS Converter". In this way and according to the data set for the "Mosfet (Ideal Switching)", it was possible to implement phase switching according to the angular position of the motor and the control logic applied. The three-phase bridge is supplied with a voltage of 380 V DC.

The Simscape electrical model requires the presence of two further blocks: the "Electrical Reference" block, which represents the "ground" reference required to solve the voltage and current equations, and the "Solver Configuration" block, which allows the model to be implemented by setting various parameters, such as the local time integration step or the degree of tolerance.

3.2. Three-phase stator circuit

The three stator phases have a star arrangement whose common point, called the star-centre, is referred to ground represented by the “Electrical Reference” block in Figure 3.

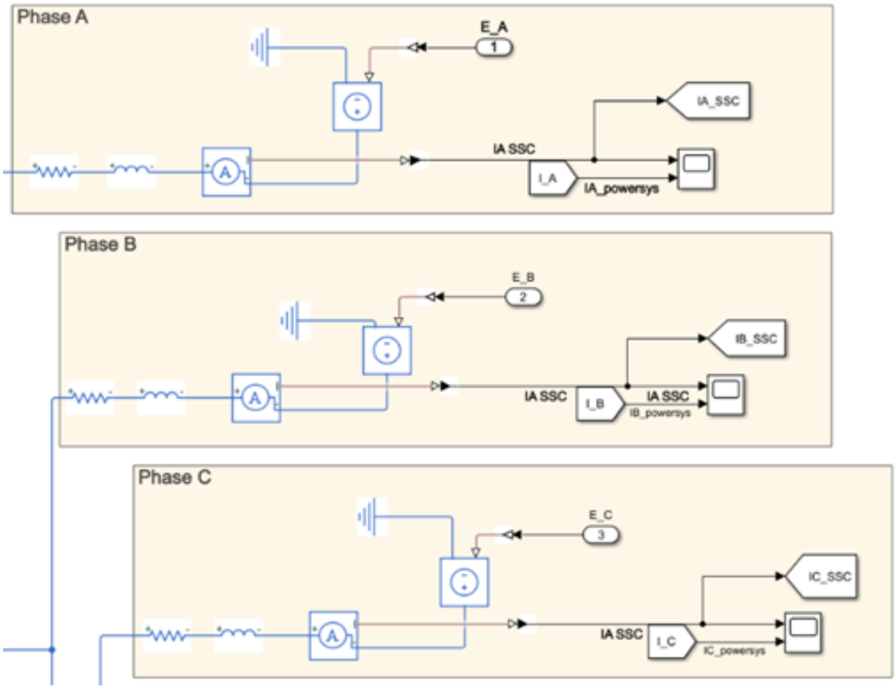

Figure 3. Electrical windings.

Initially, for the resolution of the model, it was not planned to connect the star-centre to a ground reference because the use of the electric motor in flight would not have allowed such a connection.

Therefore, the model to be modelled and analysed should have been a floating neutral. This problem was also addressed using Simscape’s "Foundation Library" but, while in "Power Systems" the floating-neutral model was solvable because Simulink works numerically on the final solution, Simscape differently implements automatically equations to find the solution, so eliminating the ground reference means depriving the system of an equation, making the system unsolvable. In fact, every physical model built through Simscape needs its own "reference" to implement the equations for resolution. Therefore, the initial intention to model a three-phase system with a floating neutral has been replaced by placing the neutral connected to the "ground" reference. In reality, this does not particularly affect the results since it is still necessary to implement a simulation as close to reality as possible even with the use of the electric motor connected to the ground.

Each phase of the system is characterised by a resistor and an inductance placed in series, making the ohmic-inductive circuit. In series with the ohmic-inductive circuit of each phase, a voltage source referring to the "ground" is placed which receives the signal of the counter-electromotive force so that the voltage generated is subtracted from the supply voltage acting on each phase driven by the three-phase bridge. In this way, the effect of the counter-electromotive force is taken into account to calculate the active currents acting on each phase of the stator.

As shown in Figure 3, an amp-meter called “Current sensor” is connected in series to the ohmic-inductive circuit to measure the active current on each phase while the voltages are calculated using the "voltage sensing SSC" subsystem shown in Figure 4.

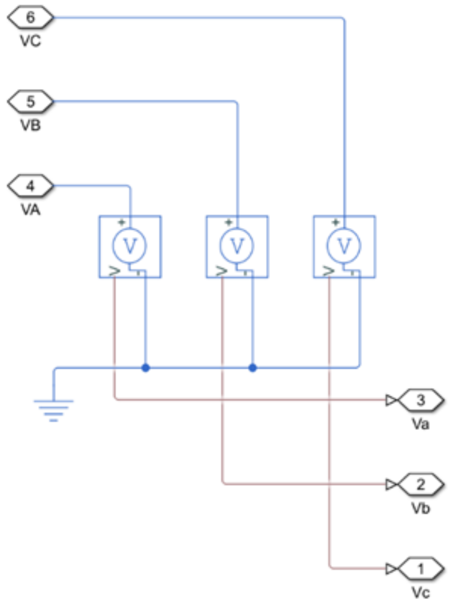

Figure 4. Voltage sensing SSC

The supply voltages on each phase are calculated respectively by means of a voltmeter called "Voltage sensor" connected in parallel to the ohmic-inductive circuit and with respect to the "ground".

The physical signals produced in Simscape are converted into Simulink signals by the "PS-Simulink Converter" blocks so that trends can be graphed and compared with those obtained in Simulink through the "Scope" blocks.

4. PMSM Simscape model validation

Several simulations have been conducted in parallel between the numerical High-Fidelity model produced in Simulink and the physical model produced in Simscape to validate the effectiveness of the latter in faithfully reproducing the same values and trends of the characteristic quantities of the system.

In particular, the interest falls only on the voltages and currents acting in the stator circuit since the Simscape model under examination has been produced to simulate the operation of the three-phase bridge and the electromagnetic effects on the windings.

In the following analyses, only for phase A (for synthesis reasons), the trends of the voltage and the current at steady state condition are shown in order to appreciate more clearly the overlapping of the two lines.

4.1. Three-phase stator circuit

The simulation parameters are reported in Table 2.

Table 2. Data step command.

Initial amplitude (rad)	Final amplitude (rad)	Instant of application (s)	External load (Nm)	Simulation time (s)
0	0.5	0.01	0	0.5

Figure 5 and Figure 6 show the trend of phase A current and voltage at steady state condition in order to highlight the overlapping of the two curves.

Differently from Brushless DC motor, the PMSM has a sinusoidal current pattern because of the control logic signal is characterised by three sine waves offset by 120 degrees, so that the induced magnetic field, the counter-electromotive force, and the currents on each phase will also have a sinusoidal pattern [8] [9].

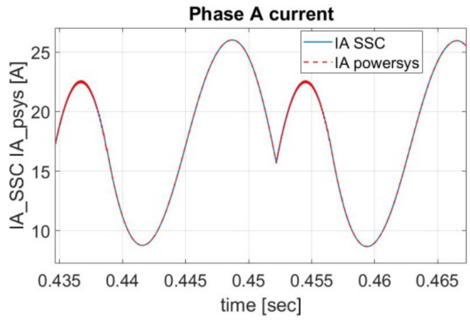

Figure 5. Phase A current steady state condition.

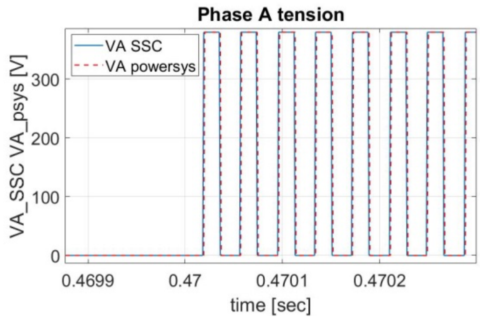

Figure 6. Phase A voltage steady state condition.

4.2. Ramp command

The simulation parameters are reported in Table 3.

Table 3. Data ramp command.

Initial output (rad)	Slope (rad/s)	Instant of application (s)	External load (Nm)	Simulation time (s)
0	0.3	0	0	0.5

Figure 7 and Figure 8 show respectively the trend of phase A current and voltage at steady state condition.

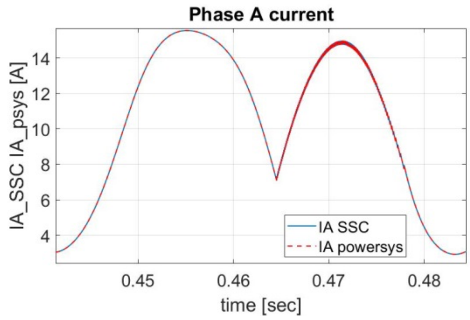

Figure 7. Phase A current steady state condition.

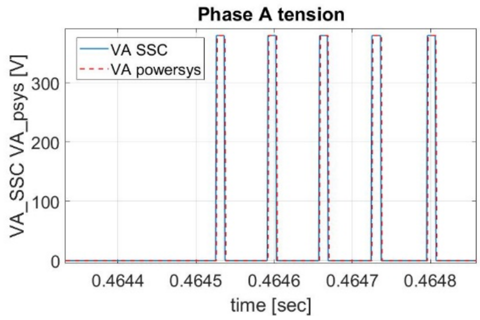

Figure 8. Phase A voltage steady state condition.

4.3. Sinusoidal command

The simulation parameters are reported in Table 4.

Table 4. Sinusoidal command.

Input semiamplitude (rad)	Bias input (rad)	Input frequency (Hz)	External load (Nm)	Simulation time (s)
0.005	0	15	0	0.5

Figure 9 and Figure 10 show respectively the trend of phase A current and voltage at steady state condition.

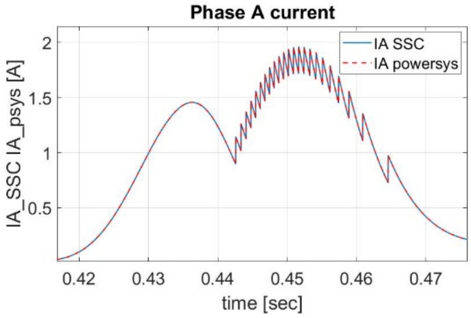

Figure 9. Phase A current steady state condition.

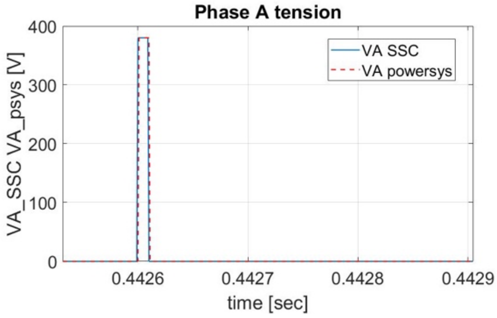

Figure 10. Phase A voltage steady state condition.

4.4. Step, ramp command and external load

The step and ramp commands parameters are reported respectively in Table 5 and in Table 6. External load parameters are reported in Table 7. All of these commands are provided as function of the time indicating the magnitude of the command at a specific time of application.

Table 5. Characteristics of step command.

t = 0 s	t = 0.05 s	t = 0.2 s
0 rad	0 rad – 0.1 rad	0.1 rad – 0 rad

Table 6. Characteristics of ramp command.

t = 0.2 s	t = 0.5 s
0 rad	0.1 rad

Table 7. Characteristics of external load.

t = 0 s	t = 0.35 s	t = 0.5 s
0 Nm	0 – 150 Nm	150 Nm

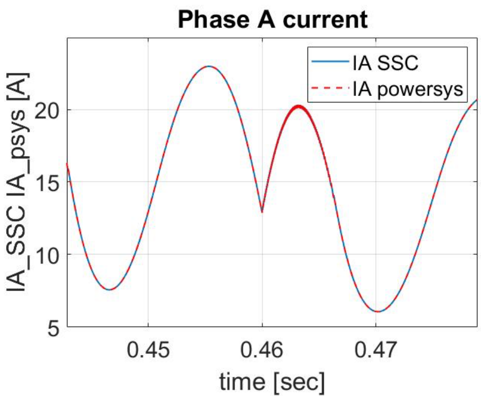

Figure 11. Phase A current steady state condition.

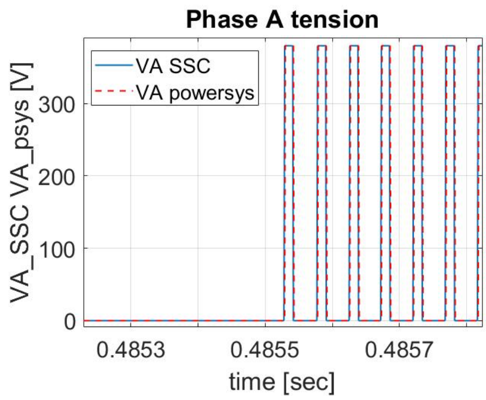

Figure 12. Phase A voltage steady state condition.

5. Results and conclusions

By an initial graphical analysis of the voltage and current trends of the two models, it can be stated that the curves produced by the Simscape model follow very well the trend of the curves provided by the High-Fidelity model produced in Simulink.

To quantify the difference between the values returned by the Simulink model and those returned by the Simscape model, the root mean square error of the voltages and currents was calculated through Matlab. For voltages, the order of magnitude of the root mean square error is around 10^{-5} V and for currents around 10^{-3} A. Therefore, it is possible to state that the two models return exactly the same values for voltages and currents with a tolerance of a few tens of microvolts and a few milliamperes respectively.

Confirmation of the validity of the model produced in Simscape allows future analysis of faults such as a partial short circuit or the percentage of rotor eccentricity to assess their overall effects on the whole system. Therefore, it will be possible to validate the Simscape model even in the presence of faults.

The model produced in Simscape allows the further modelling of the mechanical component of the servomechanism affected by transmission components and nonlinear phenomena such as backlash. In addition, it will be possible to perform multi-domain simulations in Simscape considering the interaction of different physical effects allowing, for example, a parallel thermal analysis of the stator windings to prevent potential overheating and demagnetisation of the components with consequent motor loss. These factors offer the possibility of developing highly accurate and effective prognostic algorithms for electromechanical servomechanism.

6. References

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