# Dynamic System Modeling and Stability Assessment of an Aircraft Distribution Power System using Modelica and FMI

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**In this work, the electrical distribution system of a Boeing 747 aircraft is implemented in Modelica. The electrical system is modeled in detail as far as generation and loads are concerned, aiming to capture any relevant dynamics and instabilities that can ensue during the aircraft's operation; while the power electronic interfaces of the loads are represented using averaged models. Small signal analysis is conducted at different operating points, aiming to capture relevant dynamics. Additionally, small signal analysis and time domain simulations are carried out to identify operational regions where low damping of unstable oscillations can occur, in order to characterize control loops interactions and system states. Finally, this paper proposes countermeasures for load startup and required controls that can alleviate any potential instabilities.**

## I. Introduction

Aircraft systems must adhere to the highest of design standards in order to ensure robustness and safety of reliable operation. In addition, due to the finite nature of the resources available and the need for autonomous operation, various considerations are required in order to achieve the required reliability of operation [1, 2]. This work's goal is to produce a high-level simulation prototype of the electrical system present on an aircraft, aimed to capture dynamics and oscillatory instabilities that can present in aircraft power system. The time scales considered in this work include the aircraft's steady state up to sub-transient at the millisecond scale. Due to the nature of the components involved, averaged converter models need to be used to ease the computational burden, as detailed switching models lead to a stiff system when combined with electro-mechanical dynamics. In addition, converter switching phenomena occupy much higher bandwidths than the ones examined in this work. The model is initially implemented using the Modelica language in the Dymola software, where time domain simulations are carried out to assess the performance of the system with respect to voltage support and small signal stability and disturbance rejection.

## II. Aircraft System Modeling

### A. System Overview

The modeled system is a conventional autonomous low voltage three phase power system [3, 4]. The electrical system consists of discrete parts, such as generation, distribution and loads as shown in Fig. 1. The system will operate at 200 Volts RMS, which will be regulated tightly to ensure smooth operation. The input of the system will be the aircraft's jet engine rotation speed, that will be used to drive the generator. In this study, it is assumed that the loading of the generator does not impact the rotational speed.

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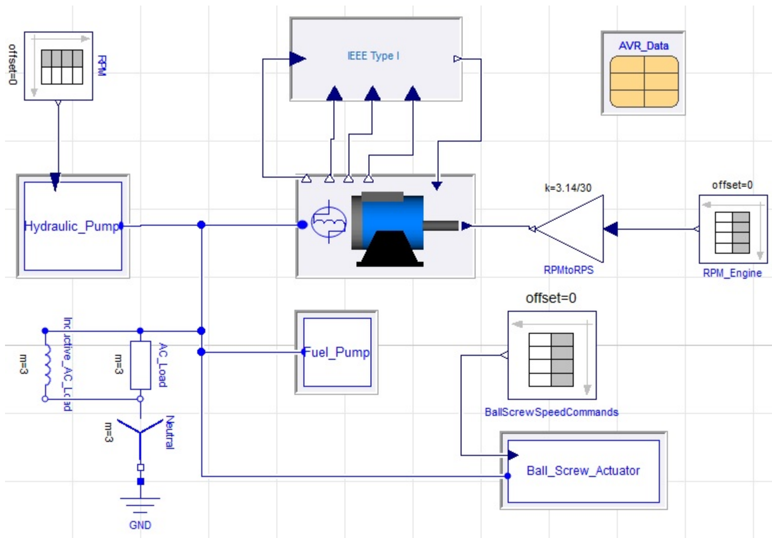


**Fig. 1 Aircraft Distribution System**

The system is modeled utilizing object-oriented modeling constructs available in the Modelica language [5, 6]. In Fig. 1, the system's template is shown. Notice that several components appear sunken (i.e. compare the RPM table at the top LHS with the Hydraulic Pump below it), this is an indication that the models are "`replaceable`". The concept of a replaceable model is one that can be changed or re-declared in the future. This is achieved by defining different types of models (known as variants) that inherit the same basic classes enabling to quickly change them to other model variants, without the need of having to reconnect components. This kind of models are declared with the "`replaceable`" keyword for class designation. In this model, specific classes for generation and voltage regulators are defined, for easy replace-ability of generating units (e.g. battery) and their respective controllers, as well as the AC and DC loads. Finally, `replaceable records`, allow seamless alteration of component parameters for easy parameter sweeping and scenario testing. The three inputs that can be observed are the Engine Speed, noted in Fig. 2, the ball-screw actuator commands, and the pump speed commands (which are a scaled version of the engine's rotation speed).The turbine speed profile that is assumed for this study, is emulating conditions such as take-off, cruising speed and landing, as depicted in Fig. 2.

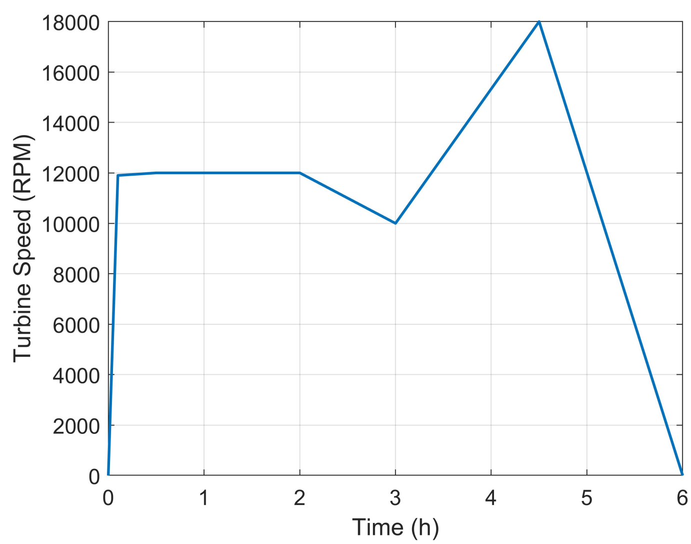


**Fig. 2 Used Turbine Speed Flight Profile**

### B. Structure of Generation Unit

The generation of electric power in the system is achieved through a 100 kVA synchronous generator, driven by the aircraft's turbine. The generator is modeled with a six-order sub transient model and the voltage is regulated by a Type-I IEEE Exciter as outlined in [7] and illustrated in Fig. 3. This excitation system model is comprised of three parts. In first part, the terminal voltage is compared against a reference and the error is fed to the voltage regulator, which is an amplifier modeled through first order system of equations. The output signal, VR, goes through the exciter model. The exciter model can incorporate a saturation function (SE in diagram) to account for magnetic core saturation and drop of exciter efficiency with loading. We will examine modeling of this Synchronous Generator and an Automatic Voltage Regulator (AVR) system together. The generator model and its interface with the excitation system model as implemented in Modelica is shown in Fig. 3.

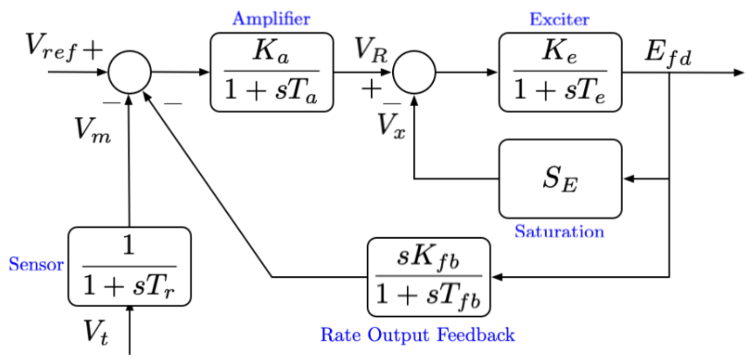


**Fig. 3 Type I IEEE Exciter with Saturation**

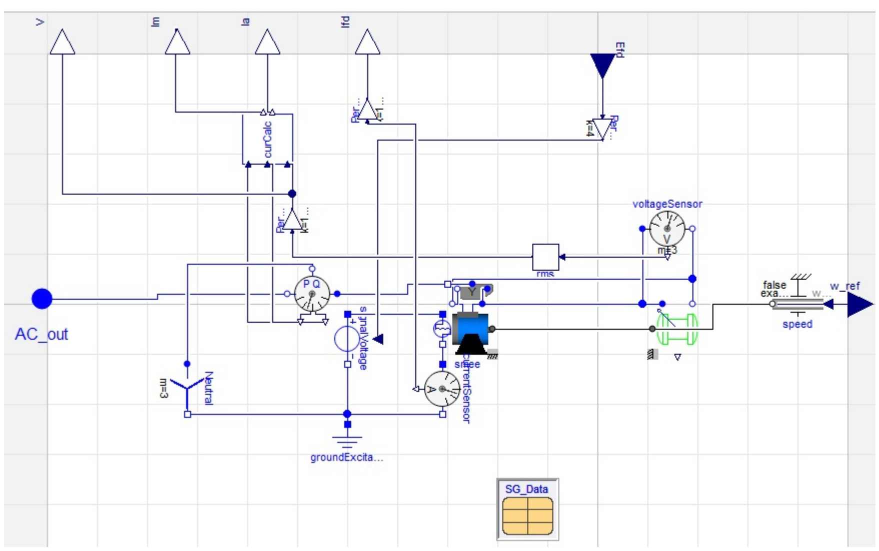


**Fig. 4 Synchronous Generator Block as Realized in Dymola**

### C. Type of Loads and Modeling

The loads of the studied system are categorized as AC and DC types, while the AC load consists of a hydraulic pump (distributing cooling fluid) modeled as an Induction Machine (IM) as discussed in [2]. In general, the pump's speed is roughly proportional to the speed of the engine. The pump is operated with a V/f drive, regulating its speed through a simple double PI controller. The double PI is utilized so that the reference must keep track of ramping speeds of the driving motor, without errors saturating the converters (overmodulation). Auxiliary AC loads are connected also, to emulate lighting and various other small power consumptions on the aircraft, e.g., heating loads. The loads consist of resistors, with average power consumption around 3 kW. The hydraulic pump is sized to have a rated power of 30 kVA.

The DC loads mainly consist of a fuel pump, that is modeled as a DC motor which is coupled with the network through an uncontrolled full bridge rectifier. The rectifier is implemented as an averaged model, to avoid any additional computation due to discontinuities power switches present during simulation. On the DC side, resistors are added, to emulate lighting and instrumentation loads.

The final load is the Motor Ball actuator, implemented as a Permanent Magnet Synchronous Motor (PMSM), that is decoupled from the generation unit, via an AC/DC/AC converter. Figure 5 shows the developed PMSM drive model with its controller. The Voltage Source Converters (VSCs) are implemented as an averaged model based on the approach discussed in [8]. The speed control of the PMSM is achieved through standard Proportional Integral (PI) d-q current control. The controller drives the modulation signals of the PWM, resulting in voltage commands along the d and q axis [9, 10]. The control system assumes measured angle and speed values are available by sensors, which are assumed ideal in this model.

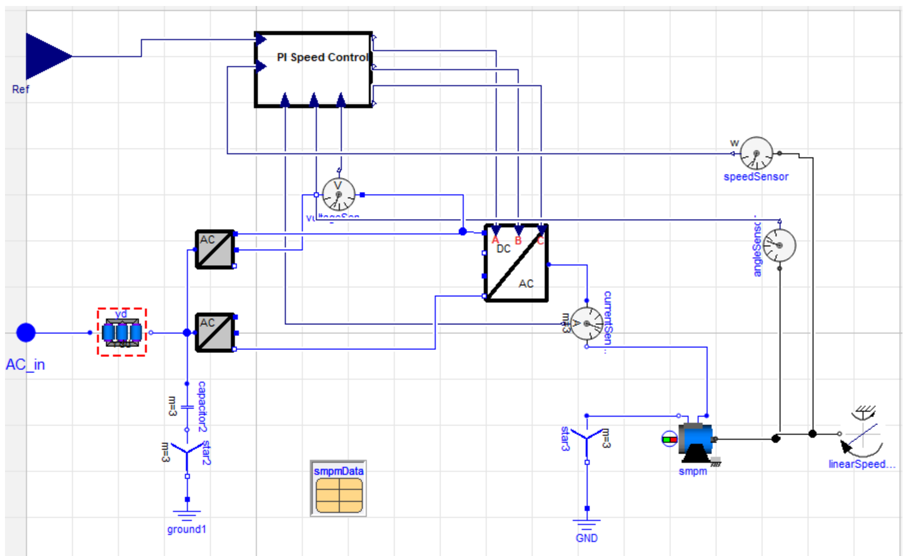


**Fig. 5 PMSM Load**

The ball screw commands are issued by a predefined profile. The commands are in terms of rotation speed and represent an aggregate profile from all the individual actuators present in the aircraft. A sample profile is presented in Fig. 6. It should be noticed that all the mechanical loads attached to the shafts of the motors, are have a linear torque to rotational speed relationship. Finally, all the components used, are part of the Modelica Standard Library.

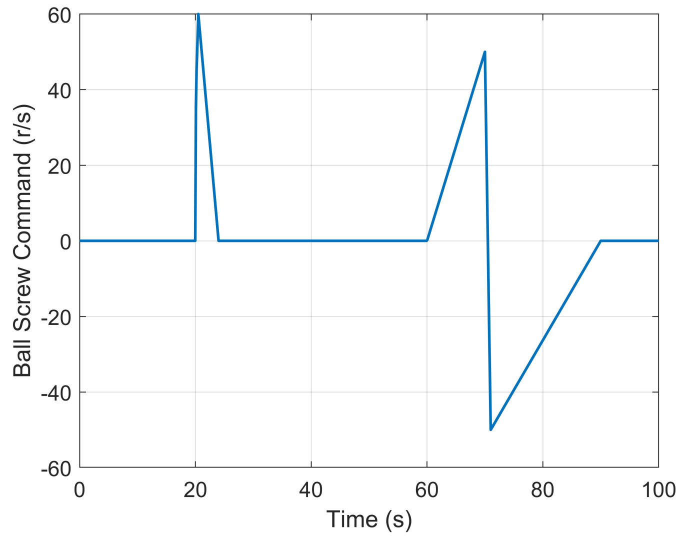


**Fig. 6 Sample Ball Screw Command Profile**

It should be noted, that all the mechanical loads attached to the shafts of the motors, are have a linear torque to rotational speed relationship. Finally, all the components used, are part of the Open Modelica electrical library, for easy reproducability and accessibility.

### D. Template Functionality Demonstration

The distribution system presented, has been modeled utilizing all of Modelica's template functionalities stemming from class inheritance. This allows fast replacement of compatible models in the system for design purposes. For demonstration purposes, three AVR models (DC1, AC1A and ST3 [7]) are compared in terms of voltage regulation during the jet engine and hydraulic pump startup . The responses can be noted in Fig. 7. In terms of the steady state response after startup, the DC1 and ST3 regulators outperform the AC1A. However, one can note that there exist nonlinearities in the response of both of those due to their power electronics's commutation behavior. The hydraulic pump initiates at the 40 sec. mark and as expected, the fast ST3 exciter achieved the fastest voltage recovery.

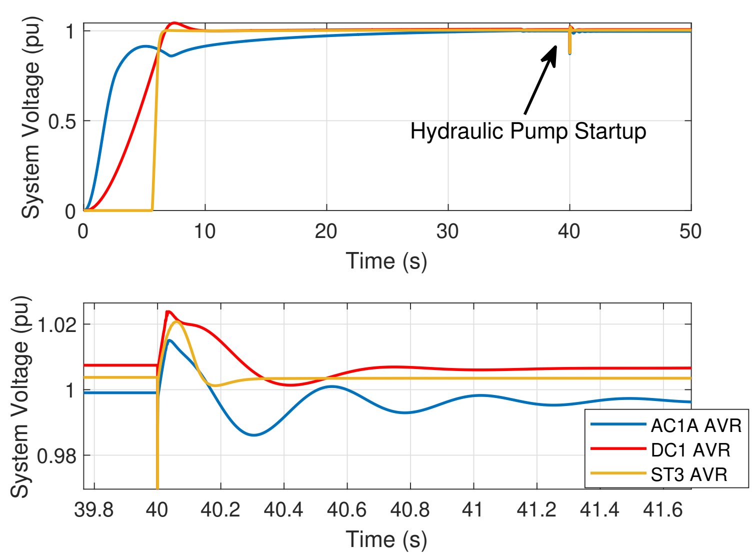


**Fig. 7 Different AVR Model Comparison for Jet Engine and Pump Startup.**

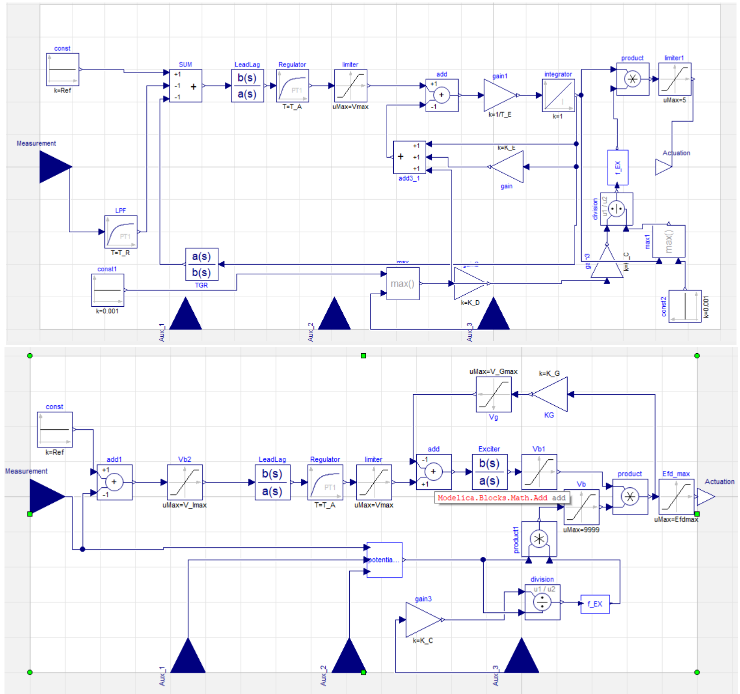


**Fig. 8 IEEE AC1A (Top) and IEEE ST3 (Bottom) Exciters Implementation in Dymola.**

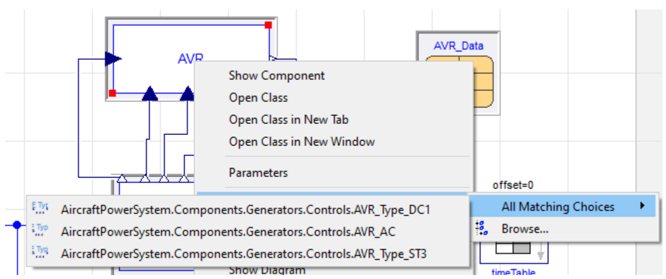


**Fig. 9 Replaceable AVR Block Option in Distribution System Template.**

## III. Evaluation of System Performance

In this section, the system performance will be assessed with respect to stability through small signal analysis and the use of the FMI will be presented for the purpose of compensator design.

### A. Small Signal Analysis

In various simulations, the operation range of interest is during the start-up period, where the turbine operates at sub-nominal rotations speeds. Since all the power electronics components in the system are modeled via average modeling techniques, any instability issues are expected to ensue, would be due to the PI regulators, driving the loads, or because of interactions between states [11]. An exemplary oscillatory instability can be noted in Fig. 10.

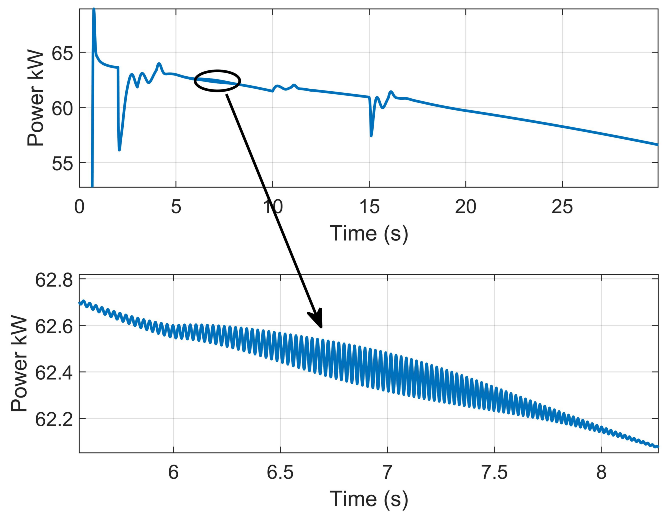


**Fig. 10 Oscillation on Synchronous Machine Active Power Output**

Around 7 seconds, an oscillation can be observed with peak to peak amplitude of a couple 100 watts. Upon first inspection, this might not seem like a significant oscillation, however further analysis reveals that this operating range made the system small signal unstable. Upon linearizing around that operating point we can see a pole on the right half plane, at 235 $r/s$ with damping ratio of around -5 %. The poles and zeros of the linearization can be noted in Fig. 11. The linearization reveals that the unstable mode, contributes to the the induction motor currents.

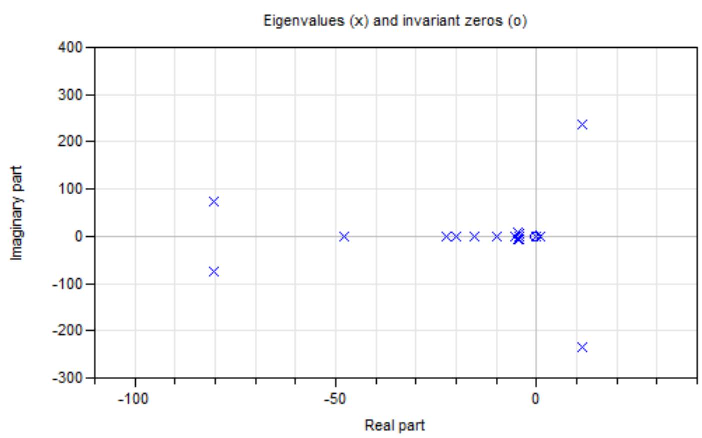


**Fig. 11 Linearization Around Unstable Operating Point**

Since this instability seems to occur right after the startup of the induction motor (around 2 sec.) we revisited the tuning of the PI controller for the motor drive based on the V/f control scheme. The initial proportional gain used was 1, that seemed to yield satisfactory behavior and reference tracking. However, tuning revealed that higher values introduce damping on the induction motor modes as the system moves to steady state. The obtained results are shown in Fig. 12. However, even though the mode is now stable during startup, a decrease in damping was observed again. Thus, this bandwidth should be approached carefully when designing controls for loads, as the pole appears to be heavily dependent on operating condition, as its trajectories indicate.

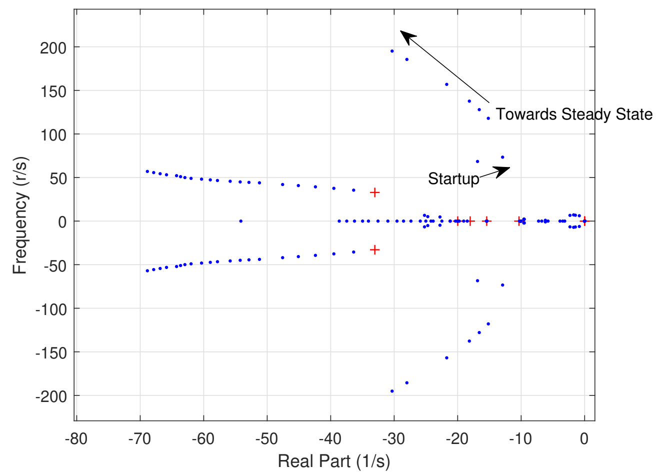


**Fig. 12 Pole Movement for 10 First Seconds of Startup**

Due to the decoupling of the motor's voltage dynamics from the generator through the converters, the hydraulic pump subsystem can be isolated for further small signal analysis. For that purpose, the Functional Mockup Interface (FMI) was utilized to export the subsystem as an FMU and perform compensator design in MATLAB, a tool preferred by the control community. The purpose was to asses pole movement and stability margins along the whole startup range. Upon evaluation, the most suitable and readily available signal that could be used for compensator design was the active power of the motor. Linearization along the startup sequence revealed again the poles of the system are on the right half plane during low rotational speeds. However, as it can be noted in Fig. 14, there exists a corresponding zero in the left half plane, thus, a low order feedback design can stabilize the system. The numbering indicated sequence of operating points with higher values corresponding to higher rotational speed.

In order to not affect the regulation range, a washout filter with time constant of 0.2 sec. is used to isolate the oscillations for our feedback design. The system required no further compensation except for a choice of gain due to the existence of the left half plane zeros. Due to the time varying nature of the pole locations, a feedback gain of 0.03 was chosen, as it achieves a gain margin of at least 181 dB and a phase margin of 44 degrees across all the examined operating ranges. A sample root locus plot can be noted in Fig. 13. The chosen gain offers 40% damping on the mode. With the chosen gain the damping never decreased below 20%.

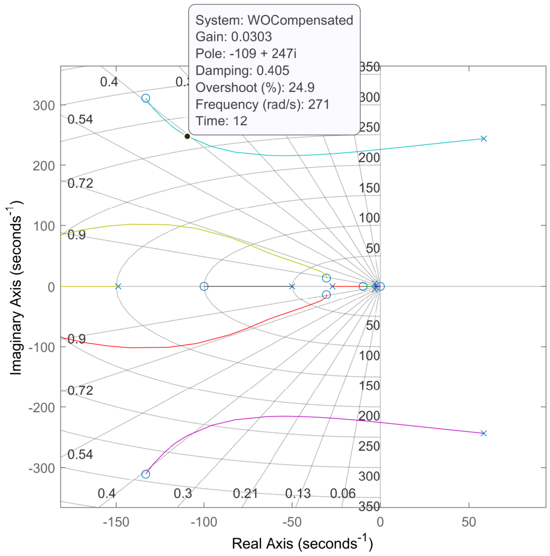


**Fig. 13 Root Locus Plot for Induction Motor Subsystem during Startup (12 sec. Mark) with Washout Filter Included**

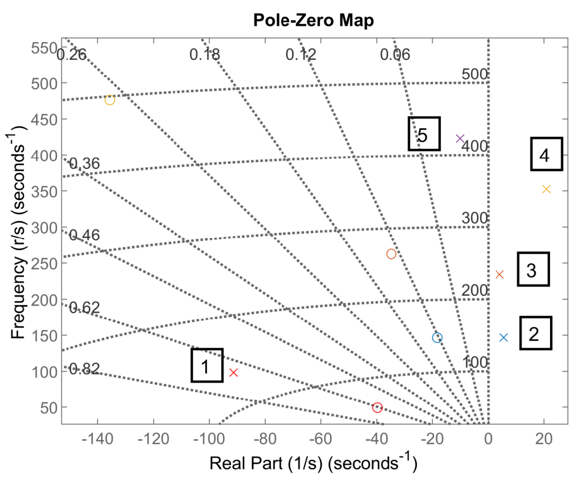


**Fig. 14 Pole-Zero Plot for Induction Motor Subsystem during Startup**

The compensated and uncompensated startup power can be observed in Fig 15. The startup oscillations were 10 kW peak to peak for the isolated subsystem and were unacceptable for the reliable operation of a pump. After the compensation, the mode appears to be well damped across the range of interest. However, as mentioned the IM poles need high gains to stabilize in the very low frequency range (IM can stall or oscillate with very low gain ). Thus, a gain scheduling approach is adopted, to achieve high startup torque and good steady state stability margins. The initial proportional gain is set to 5, persisting until the motor reaches at least 100 r/s and then is lowered to 1 to guarantee our design's stability margins in high frequencies. The compensator is deactivated as well after the 100 r/s speed mark, since its high pass nature might amplify disturbances as the system's frequency gets close to nominal.

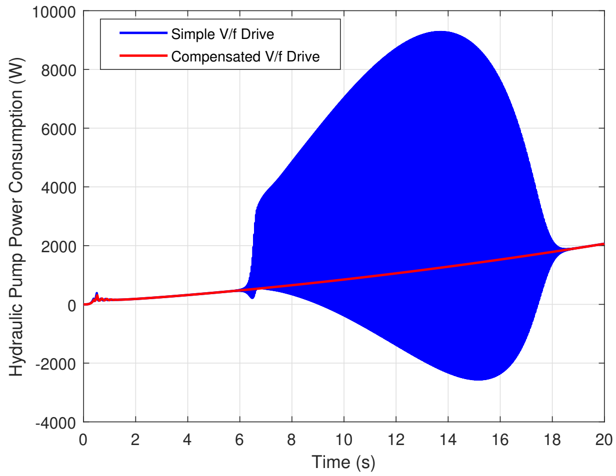


**Fig. 15 Compensated and Uncompensated Induction Motor Power Consumption during Startup**

Further investigations were carried out on the system to identify potential instabilities, after the compensated IM was implemented. In close to nominal operating frequencies, oscillations were observed between the generator and parasitic capacitances present in the network. Depending on the shunt capacitance, which is $1^{-6}$ F in the system, oscillations and interactions with the AVR can be observed at frequencies in the 20 – 80 Hz range. However, the IEEE AVR models incorporate already the Transient Gain Reduction compensator, that can be tuned to ad lead on that bandwidth. For the purposes of this work, the TGR lead compensator was tuned to have a zero time constant of 100 s. and a pole time constant of 500 s. The lead provided in that range improves damping significantly and stabilizes the voltage regulation loop.

# IV. System Performance

### A. System Performance Considerations and Modeling

The most significant loading in the power system comes from the hydraulic pump. However, due to its decoupling from the main AC network by the converter interface, startup currents and its impact on voltage regulation were minimal. On the other hand, the ball screw actuator is a much smaller load that requires rapid startups, and thus, high currents can be drawn during fast ramping periods. A sample flight profile is shown in Fig. 11. The peak engine speed was 18000 RPM. The base loads of the aircraft have an average consumption of 20 kW (including the fuel pump, parasitic loads and regular AC loads). The peak consumption of the pump reaches 20 kW, due to the fast converters and tuning of the V/f control, it only presents slight ripples in the main system's AC voltage. Regarding the PMSM ball screw actuator, the peak consumption reaches 2 kW during rapid movement periods. These large currents are the reason for the voltage spiking as it can be noted in Fig. 16. However, due to the small nature of the load, the voltage only presents at most a 1% variation. The presented system and components as modeled in Modelica, can be found in [12], along with instructions on how to run the presented example flight profile.

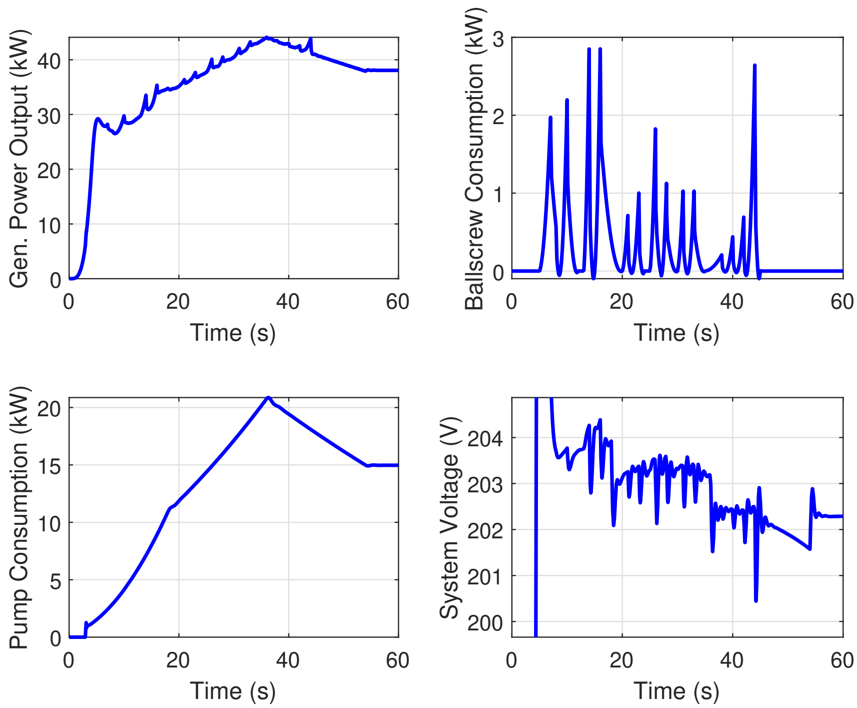


**Fig. 16 Loads and Generator Active Power, and System Voltage for Simulated Flight Profile**

In general, from the investigations and simulations of the implemented model, the following are important modeling considerations:

1) Due to the absence of significant dynamics and small power consumption, the fuel pump can be modeled as a resistor to avoid complexity.
2) As far as the synchronous generator is concerned, due to the simulation's burden, a simpler model can offer speed improvements. However, by neglecting the higher frequency components, interactions with the system that are present, like the ones discussed in Section III, will not be observable.
3) Modeling of small capacitors and inductors in the system is not necessary, as the system has very low reactive power loading. This is due to the averaged modeling of the converters, assuming very stiff voltage on the DC bus. However, smoothing capacitors or inductors can enhance numerical stability during switching events (relay opening/closing) as the averaged modeling of the converters can lead to integration difficulties.
4) Hydraulic pump startup is advisable to be connected once the voltage has reached close to its nominal value, as it can cause noticeable voltage dips.
5) Minor loads like the fuel pump and passive resistors or inductors did not pose any problem under any conditions, in terms of voltage regulation and can be connected to the generator almost immediately after startup.
6) The PMSM comprises a small percentage of the aircraft's load, thus not posing severe problem's during startup, however, due to the high initial currents it can draw during rapid startup, it is advisable to not be initiated in sub-nominal voltage levels.

# V. Conclusion

In this work, an aircraft power distribution network was modeled with reasonable amount of fidelity to allow for efficient simulation and testing of various operating scenarios. The main electric power generation unit was modeled as a synchronous generator with a Type-I excitation system, ensuring voltage control within tight bounds. Different load types were tested, included DC Motors, IMs and PMSM machines used for different purposes. Averaged converters were implemented to minimize the computational burden. For the PMSM machine, a simple PI controller (assuming availability of sensor measurements) was implemented, exhibiting very good reference tracking performance. The system operates well in reasonable simulation time steps and seems to perform properly in transient events. The outcome indicates oscillation problems observed during the startup period required a careful control tuning and adaptive gain scheduling to ensure stable system operation through the entire operation range of the system.


## Acknowledgments

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