Technical Documentation
Future Aircraft Energy Management Systems

Version 0.1

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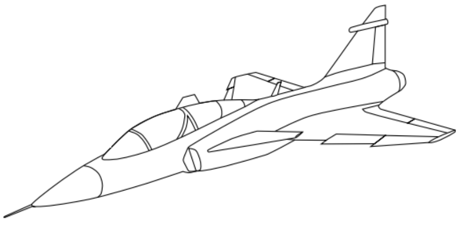

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Document History

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Contents

1 Introduction

This document is the technical documentation for the project *Future Aircraft Energy Management Systems* in the Automatic Control - Project Course (TSRT10) at Linköping University autumn term of 2021.

This is a new project at Linköping university, supported by Saab Aeronautics who is the customer. The project is a bilateral collaboration between the departments IEI (Department of Management and Engineering) and ISY (Department of Electrical Engineering).

1.1 Parties involved

The total project was divided into two collaborative projects, one from each department. These two projects worked together to deliver the final demonstration. The IEI-project focused on the development and implementation of the aircrafts electric consumers. These mainly consisted of the electro-machanical actuators (EMAs), the servo hydarulic actuators (SHAs), the hydarulic pumps and electric motors. This project (the ISY-project) has focused on the electric supply system and energy management.

From Saab, Alessandro Dell'Amico is the customer for both projects and supervisor for the IEI-project. Kristoffer Ekberg from Linköping University has been the supervisor for this project.

1.2 Background

The aircraft industry is trending towards electrification, also known as More Electric Aircraft, MEA. Electrification is expected to help the industry reach objectives such as reduced aircraft weight, increased efficiency, lower maintenance and higher safety. In practice this means the development and implementation of a more efficient electric power distribution, electrically driven components and intelligent control of available power. Energy management will be important when more high power electric consumers, such as actuation system and sensors, are integrated in the aircraft.

1.3 Goal

This project has been a newly started project where the scope has been to develop a Digital Twin of the power generation system in an aircraft, as well as an effective and safe energy management system. Furthermore, this will result in a platform where different parameters for an aircraft energy system can be changed and evaluated. Additionally, a flight mission and a failure mode have been developed to enable a simulation of an aircraft in a real scenario. The goals for this project can be summarized in the following bulleted list:

- Develop a Digital Twin of the power generation system.
- Develop an effective and safe energy management system.
- Develop a hardware in the loop (HIL) simulation environment where different control strategies can be evaluated.
- Develop interfaces for communication and data logging.

1.4 Definition of terms

- **AC** - Alternating current.
- **DC** - Direct current.
- **Digital Twin / D.T** - Virtual representation of a physical object or system.
- **EHA** - Electro Hydraulic Actuator
- **EMA** - Electro Mechanical Actuator
- **FAEM** - Future Aircraft Energy Management Systems.
- **Iron Bird** - The test rig used in the project.
- **ME** - Main Engine.
- **MEA** - More Electric Aircraft.
- **MGEN** - Main Generator.
- **SOC** - State of charge.
- **SHA** - Servo Hydraulic Actuator
- **SSPC** - Solid-State Power Controllers.
- **VDC** - Voltage of direct current.
- **PSU** - Power supply unit.
- **PCU** - Power consumption unit.
- **TCP** - Transmission Control Protocol
- **RPM** - Revolutions per minute

2 System Overview

The system overview contains an explanation of the complete system as well as the subsystems which form parts of the complete system.

2.1 Complete system

The goal was to develop a simulation platform for the next generations aircraft electric power system. The platform can be used to study and evaluate the power system as well as the energy management system. To be able to reach this goal, the complete system had to be divided into smaller parts. The systems different parts and their connections are illustrated in Figure 1 while Figure 2 illustrates the Digital Twin of the power generation system and how it is connected to actuators, pumps and motors.

2.2 Redundancy

The aircraft has two power supply systems, consisting of: rectifiers, converters, SSPCs and batteries. To ensure that it will still operate if one or multiple components of one supply system fails. Each consuming component in the aircraft is cross-linked to both supply systems. By doing this, if one supply system fails, the other system will ensure that the components still operate as requested. These cross-linked connections can be seen in Figure 6.

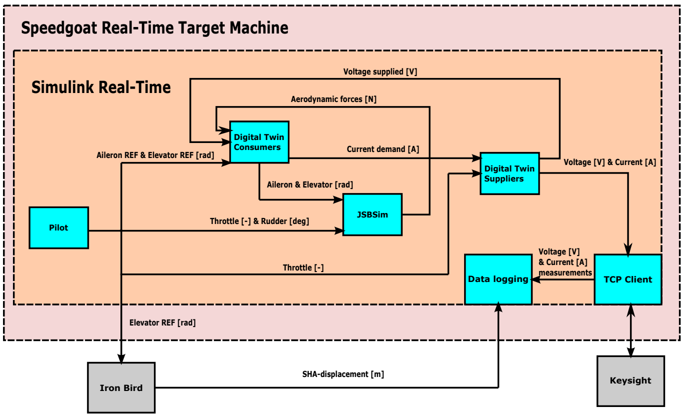

Figure 1: System overview

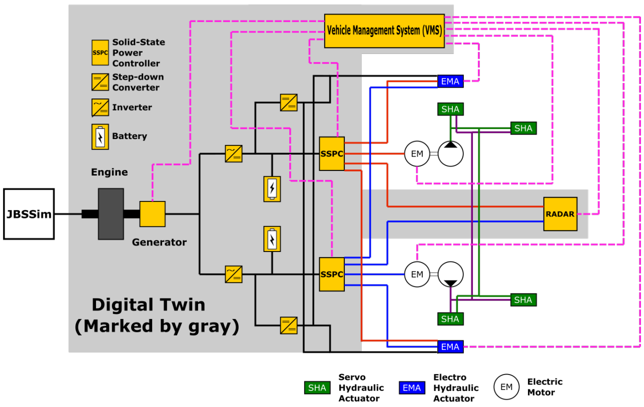

Figure 2: System overview

2.3 Subsystem Producers

This part of the system consists of the power producing components of an aircraft. This includes the following components and forms the Digital Twin of the producers.

- Main engine (ME)
- Constant speed drive (CSD)
- Generator (MGEN)
- Rectifier
- Converter
- Battery
- Solid state power controller 1 & 2 (SSPC)

The main engine is what drives the generator, which generates 270V AC power. In between the components is a constant speed drive, that tries to keep the RPM constant into the generator. After the generator, there are two versions of every producer component. The AC power is converted to DC in the Rectifier. A converter transforms the 270V to 28V, that is used to supply sensors and controllers on the EMAs. There is a battery for back up use if the generator malfunctions. The battery and the rectifier is connected to the SSPC, which secures and distributes power to the consumer components.

2.4 Subsystem VMS

The Vehicle management system (VMS) consists of control logic for the different components of the aircraft power system. It has been connected to the Digital Twin (DT) of the producing parts. The VMS monitors aircraft systems status and controls the current setting for the radar, and maximum allowed current for every consumer in SSPC1 and SSPC2, as well as controlling the battery engagement and handling different failure modes.

2.5 Subsystem Hardware

2.5.1 Hardware in-the-loop simulation

Hardware in-the-loop (HIL), is a simulation technique that is used in the development of complex real time systems. HIL simulation is a combination of software and hardware of a system. The purpose of combining both software and hardware is to get more realistic results than what is possible with only software simulations and maintaining the economic benefits with software testing.

In this project, the hardware consists of Keysight components and an Iron bird with installed actuation system. The long term goal is to connect all hardware together with software simulations to achieve a complete HIL system where different components can be added and removed to allow for flexible testing.

2.5.2 Speedgoat

Speedgoat is a real-time target machine which compiles the Simulink models into high performance C-code. The Speedgoat enables real-time simulation of the D.T with the Keysight hardware and the Iron Bird. The Speedgoat is seen in Figure 3.

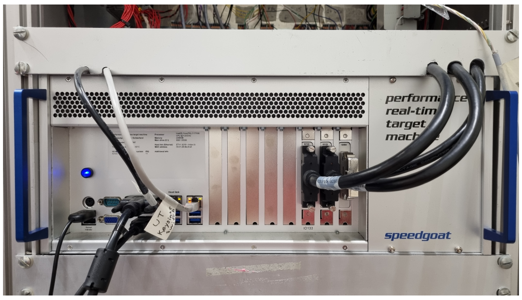

Figure 3: Speedgoat.

2.5.3 Keysight components

The purpose of the Keysight components is to simulate the energy producing and consuming parts of an aircraft system. This means that there are two different varieties of keysight, Power Supply Unit (PSU) and Power Consuming Unit (PCU). In total there are eight keysight components, two PCU's and six PSU's. These are divided equally on two sides, see Figure 4, this is done due to the redundancy of the system. The two PCU's and four of the PSU's are operating on 270 V and the final two PSU's are operating on 28 V. The four 270 V boxes are connected two and two through a "master and slave"-connection which enables a larger power to be delivered for the system.

Figure 4: Keysight components

2.5.4 Iron Bird

An Iron Bird is a test rig used to test and evaluate aircraft systems before real flight testing. Components are easily accessible to can be replaced and analyzed [1]. The hardware mounted in this Iron Bird consists primarily of actuators controlling the empennage of a SAAB 2000. The elevators are controlled by a SHA and an EMA on each surface. To simulate the aerodynamic loads there is a SHA mounted underneath each control surface. The rudder is not taken into consideration in this project and therefore the elevators power consumption is the main focus of this project but is mostly of the IEI-group's interest and will not be considered much in this documentation. In Figure 5, the Iron bird can be seen inside of the FLUMES laboratory.

Figure 5: Iron Bird.

The Keysight boxes communicate via Ethernet connection, using a TCP. Signals sent and received are encoded using ACSII.

2.6 Subsystem Consumers

This part of the system consists of the power consuming components of the aircraft. In this project, that includes the following components and forms the Digital twin of the consumers.

- Electromechanical actuator (EMA)
- Servo-hydraulic actuator (SHA)
- Electric motor to SHA (EM)
- Radar

2.7 JSBsim

JSBsim has been used to enable simulation of a complete system. JSBsim is an open-source Flight Dynamics Model software library that models the flight dynamics of an aircraft. This means that a flight mission can be constructed in JSBsim which can be simulated with the complete system. Inputs to JSBSim include actuator angles and throttle angle. Outputs are actuator forces, aircraft speed, altitude etc.

2.8 System Boundaries

The systems and components of interest for this project are mainly the components related to power generation and supply. Those components and systems are thoroughly presented in section 3. The power consumption system components are developed by the FLUMES group. Focus has been put on exploring the basic concepts of efficient energy management and developing a software environment where different components and control strategies can be tested.

2.9 System integration

Since this project has depended on two groups working with separate parts of the system, system integration has been an important part. Where the IEI group's project and this project integrate is in voltage supplied and current consumed. The IEI group calculates current demand for each actuator based on the voltage supplied, that this project has modeled.

3 Subsystem Producers

The digital twin of the producers subsystem consists of models for a main engine, constant speed drive and a generator. It has two replicas of rectifier, converter, battery and SSPC. There is also a VMS that communicates with some of the models. Figure 6 shows the complete system and how it is connected.

Figure 6: Complete system of the producer digital twin

3.1 Main engine

The main engine is the first model in the system and can be seen in Figure 7. The model has throttle setting as input and RPM as an output to the constant speed drive model.The throttle setting varies in the range [0, 1] and a lookup table is used to linearly convert throttle setting to RPM. The linear relationship generates 5000 RPM in idle mode (throttle setting equal to 0) and a maximum of 13 000 RPM in full thrust (throttle setting equal to 1). This relationship is presented below in Equation 1. The available power for powering the subsystems is considered unlimited with respect to the engine power. The throttle setting is also an input to JSBSim but has no influence on generated thrust.

$$\text{Engine speed [RPM]} = 5000 + 8000 * \text{Throttle setting}, \quad \text{Throttle setting} = [0, 1] \qquad (1)$$

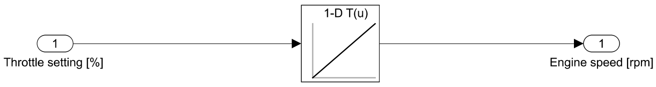

Figure 7: Main engine Simulink model

3.2 Constant speed drive

A constant speed drive (CSD) is a type of transmission that takes a varying rotating shaft as input, delivering the power to an output shaft that rotates at a constant speed. There are different kinds of CSDs, mechanical, electro-mechanical, hydraulic and pneumatic. The model created for this system simply models the general behavior of the CSD. [2]

In this model the CSD is placed between the main engine and the generator, providing the generator with a constant speed even though the shaft from the main engine varies.

The CSD model is a first order system, where the reference voltage is compared to the current voltage in the system and converts this value to an RPM through a lookup table. The reason a first order system is used is because the CSD is not infinitely fast in adjusting the rotational speed, therefore a first order system with a defined time constant is assumed. The first order system works such that the RPM is divided with a CSD time constant and sent into an integrator, which creates a gear ratio for the CSD, that gives a constant speed as the output to the generator. This loop can be seen in Figure 8.

$$csd_{RPM} = \left(\frac{U_{ref,csd} - U_{keysight}}{\tau_{csd}} \cdot \frac{K\ T_s}{z-1} \right) \cdot RPM_{csd,lookup} \tag{2}$$

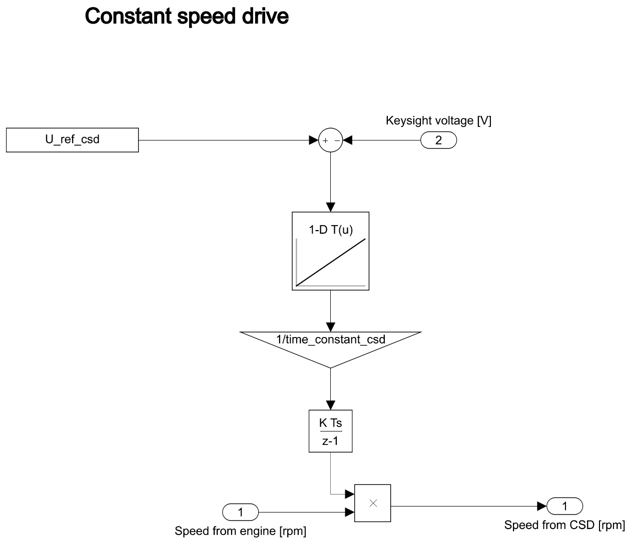

Figure 8: Constant speed drive Simulink model

3.3 Generator

The generator model has three inputs, CSD speed [RPM] and the demanded currents $I_{req,1}$ and $I_{req,2}$ from the power consuming components of the aircraft. These have been divided equally between the two power supply systems. When they are added together it gives the total current required I_{req}.

The speed (RPM) from the CSD is used together with a lookup table to get the voltage $U_{gen,lookup}$ that the generator is producing. The currents are summed and multiplied by an internal generator resistance R_{gen}, this voltage is then subtracted from the generator voltage and the output from the model. The following relationship is presented below in Equation 3 and the model can be seen in Figure 9.

The lookup table, described above, generates a linear relationship between RPM and voltage. The electric generators within the aviation industry operates at 400 Hz which corresponds to 24 000 RPM [3]. Therefore 24 000 RPM returns a voltage of 270 V while 0 RPM returns a voltage of 0 V.

$$U_{gen} = U_{gen,lookup} - I_{req}R_{gen} \tag{3}$$

The requested currents are the values that the IEI group calculates as the current consumed by the actuators, as well as the radar consumption. These currents are then divided between the two power supply systems. The generator produces the amount of power that is requested by the components, up to the specified max power generation of the generator. The max power, is managed in the VMS and not limited in the actual generator model.

If the variable status_generator is set to zero, the voltage output from the generator will be zero. This is used to test a generator failure.

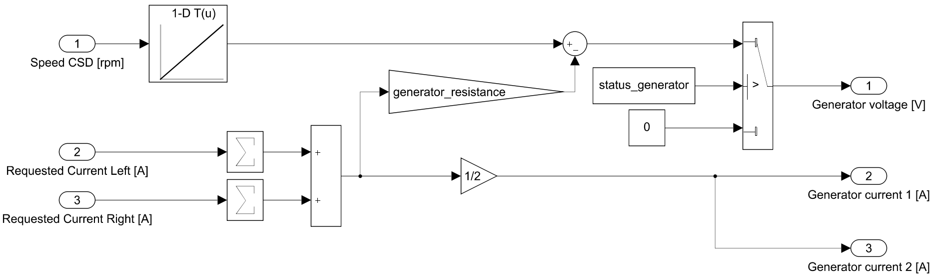

Figure 9: Generator Simulink model

3.4 Rectifier

The task of a rectifier is to convert the alternating current to direct current, which simply means that input to the rectifier is AC and output is DC. The simplest model of this is with an ideal single-phase full-wave rectifier.

The input to the rectifier is the generator AC voltage. The voltage is multiplied by the efficiency of the rectifier and then output as a DC voltage, see Eq 4. This model can be seen in Figure 10.

$$AC_{voltage} = \eta_{rect} \cdot DC_{voltage} \tag{4}$$

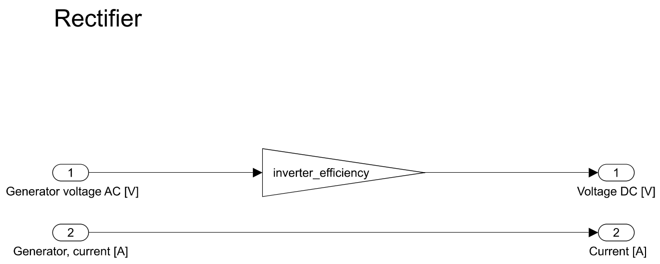

Figure 10: Rectifier Simulink model

3.5 Converter

The converter is used to convert the high-voltage of 270 V to a low voltage of 28 V which will be used to power the smaller components such as sensors and controllers.

The model has the voltage from the rectifier, the current demand from the components using 28 V and the actual Keysight voltage as input. Outputs from the model is the voltage level for the low voltage system and the power from the converter. The keysight voltage is used as feedback to control and keep the voltage level as close to 28 V as possible. This works in the very same way as the feedback loop that controls the gear ratio in the CSD. This loop can be seen in Figure 11 and its equation in Eq 5.

$$U_{conv} = \left(\frac{U_{ref} - U_{conv}}{\tau_{conv}} \cdot \frac{K\ T_s}{z-1} \right) \cdot U_{inv} \tag{5}$$

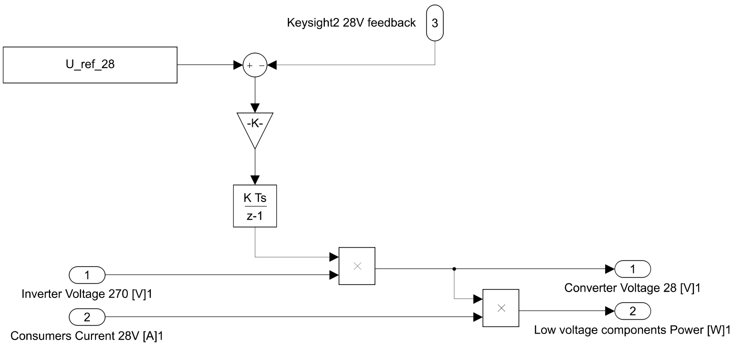

Figure 11: Converter Simulink model

3.6 Battery

The battery is related to the redundancy of the system. The function of the battery is to deliver power to the aircraft in the case that the main power supply shuts down and a forced landing is necessary.

The only input to the battery model is the current that the system requires to operate. This current is zero in case that the main power supply systems are functioning. The current is calculated in the VMS and sent to the battery model as a signal.

A Simscape model of a lithium ion battery is then given this current as a negative value and outputs the available voltage and current. The SOC can also be read from this block, which shows how much capacity is left in the battery. A switch-block in Simulink stops the simulation if the SOC ever reaches below 5%. This is due to the battery model showing unwanted behaviours when reaching a low SOC. The Simscape model of the battery can be seen in Figure 12

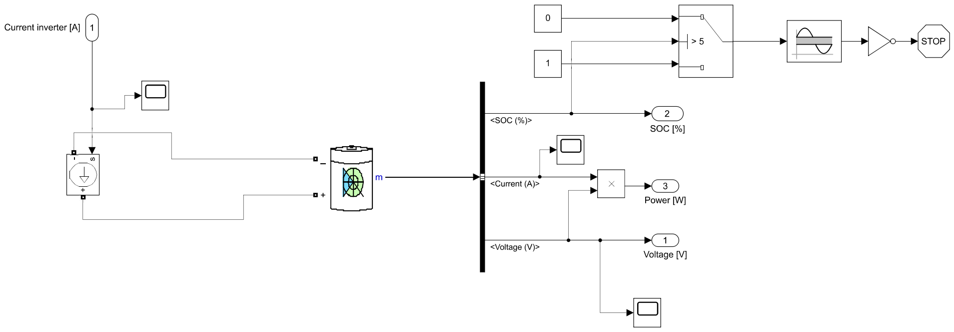

Figure 12: Battery Simulink model

The battery parameters were set for the battery model according to Table 1.

Table 1: Caption

Nominal voltage [V]	270
Rated capacity [Ah]	1
Inital state of charge [%]	100%
Cut off voltage [V]	202.5
Fully charged voltage [V]	314
Nominal discharge current [A]	30
Internal resistance	2.7

3.7 SSPC

Solid state power controller (SSPC) is a semiconductor device that distributes and secures the power supplied to a load. The SSPC monitors the electric system, protecting it from overloads and preventing short circuits.

The main purpose for the SSPC is to protect the power consuming components of the aircraft. If an actuator suddenly demands a higher power this will lead to a rapid increase in current. To protect the electronic circuit, the SSPC will limit the maximum flow of current by limiting the voltage.

As inputs, the SSPC has the rectifier voltage, current demand from the IEI group via the VMS, battery voltage and the signals of maximum voltage, dropout voltage, max current and a battery on/off signal. The outputs consist of the voltage to the Keysight PSU, [V], and voltage for each of the power consuming components, EMA right and left, SHA right and left, and the radar. The SSPC is only connected to the 270 V system and hence does not consider nor protect the 28 V system.

The voltage from the rectifier is compared to the maximum- and dropout-voltage and then sent to the Keysight, see Figure 13. If any of these voltage limits are violated, the voltage will be set to zero. If the battery is signaled to be on, the model will switch from the rectifier voltage to only use the battery voltage instead. This is a fail-safe in case the generator fails.

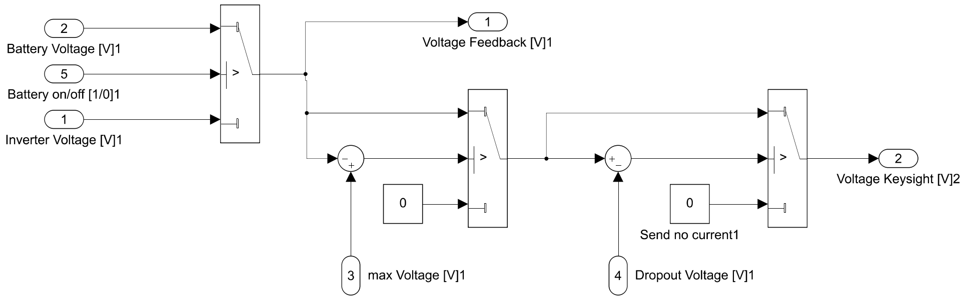

Figure 13: SSPC input variables, where rectifier voltage or battery voltage are checked against set limitations

The current demand from the IEI-group is compared to the maximum current allowed for each component. If the demand is not higher than the maximum, the voltage will go through the SPCC and be sent to the IEI-group. If any of the current demands is over the limit, SPCC will protect the system and the voltage for the specific component will become zero, see Figure 14.

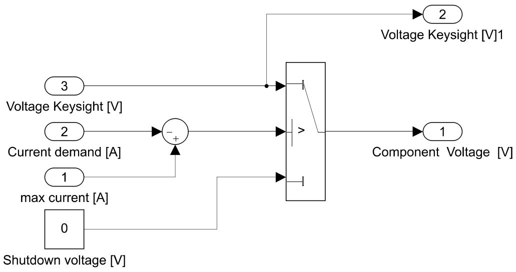

Figure 14: SSPC output variables, where current demand is compared with maximum current allowed

4 Subsystem Consumers

This part of the complete system has mostly been developed by the IEI-group. Therefore, the consuming components will only be briefly explained in this report.
The D.T. of the consumers components can be seen in Figure 15. Note that the Figure 15 only shows one of each components, the system has two of each component shown in Figure.

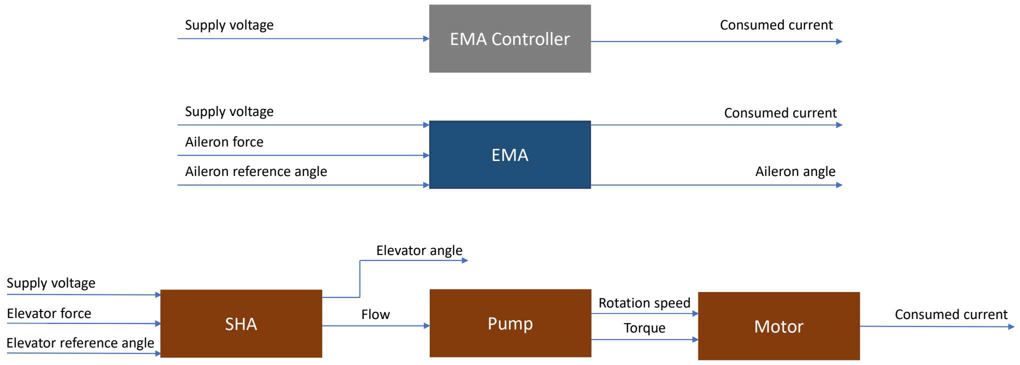

Figure 15: Schematic overview for the digital twin of the consumers

The consumers consist of two EMAs and two SHAs, one for each side of the aircraft.

4.1 EMA

The EMA's takes in Aileron ref angle from the pilot model and Aileron force from JSBSim. It also inputs the voltage from the D.T. producer system. The output of the models are, the actual Aileron angle which is an input in JSBSim, as well as current demand which is a input for the D.T. producer.

The EMA's also consists of controllers which is used to control the actuators. There are two controllers, one for each EMA. These controllers are supplied by the 28 V system and inputs the voltage of the 28 V system and outputs a demanded current. The controllers can be seen in the top of Figure 15.

4.2 SHA

The SHA's takes in Elevator ref angle from the pilot model and Elevator force from JSBSim. Similar to the EMA model it also inputs the voltage from the D.T. producer system. A SHA is a hydraulic cylinder which means it is controlled by a pump supplying the cylinder with hydraulic fluid. The pump in turn is controlled by an electric motor. This means that the output of the electric motor is the demanded current for the D.T. producer system.

4.3 Radar

The radar is the only consuming component which is modeled by the ISY group. The radar model is a simple model that consumes the available power in the system. Since the available power for the radar is determined in the VMS, the Radar is more detailed explained in the VMS chapter 5.

5 Subssytem VMS

The VMS monitors aircraft systems status and controls the setting for the radar, SSPC-1 and SSPC-2 as well as controlling the battery discharge.

5.1 Energy management

To control the distribution of electrical power in a safe manner, power to primary flight controls must be of highest priority. The power that the radar model should consume is calculated by comparing maximum available power and power consumption from the actuators. If the radar is functional and is demanded from the pilot, this value is compared to the maximum radar power, and the smallest value is sent as radar power consumption.

The VMS has servicability of the radar, generator, SSPC-1 and 2 as inputs to check whether these are functional and thereafter turns on/off the appropriate function in the aircraft.

When the generator is out of function, the battery will be switched on and be the supporting power supply. In the VMS, a signal ”Battery on/off” is set to one to indicate that the battery has been turned on when the generator status becomes zero.

The voltage level for the 270 V generation is fed back to the VMS and used together with the current demands from all components to calculate the available current for the radar. If the radar is active, this value is then sent as the current consumption of to the radar.

The current demands from the EMAs, motors and radar are inputs to the VMS. The VMS then divides the current between the two cross linked systems and checks that both SSPCs are functional. If one system is out of order, the other system will supply full power to all components. After the checks the currents are sent to respective SSPC, or in case the generator is broken, to the battery. If the generator is broken, the VMS will also switch the battery on.

The sensors for the EMAs are a part of the 28 V system. The current demand for these components are summed and sent to the converter.

5.2 Failure modes

Two failure modes is taken into consideration, one where the generator fails and another where one of the two cross-links fails.

- Generator failure.
- SSPC failure.

If the generator fails the battery will supply the aircraft with power. The battery should be able to supply the aircraft long enough so that the pilot can land the aircraft in a safe manner. If one of the two cross-links fails, the power shall be distributed so that the functional one will supply all of the consumers with all of the demanded power. These failure modes are managed by the status checks in the VMS, that makes sure the intended actions occurs upon failure.

6 Hardware and Software communication

The following section will explain how the hardware and relevant software have been set up to enable real-time simulation and testing of the energy management system.

6.1 TCP

The communication between the Simulink simulation and the Keysight hardware has been done with the help of a TCP server. The TCP server has been set up with help of TCP-blocks from a real-time library in Simulink. TCP is a standard for transmitting data over ethernet, in this project this is used to connect the Keysight and Speedgoat.

TCP in Simulink is set up using three blocks, TCP Client, TCP send and TCP receive, see Figure 16. In the TCP client block the IP address for the client (Speedgoat) and the server (Keysight) are set. Input is either a zero or a one to disable or activate the TCP client. The TCP send block takes in the signals that should be sent from the client to the server. The TCP receive block receives signals that are sent from the server to the client. Figure 16 shows the TCP connection set up for the six Keysight boxes that are communicating with the Speedgoat.

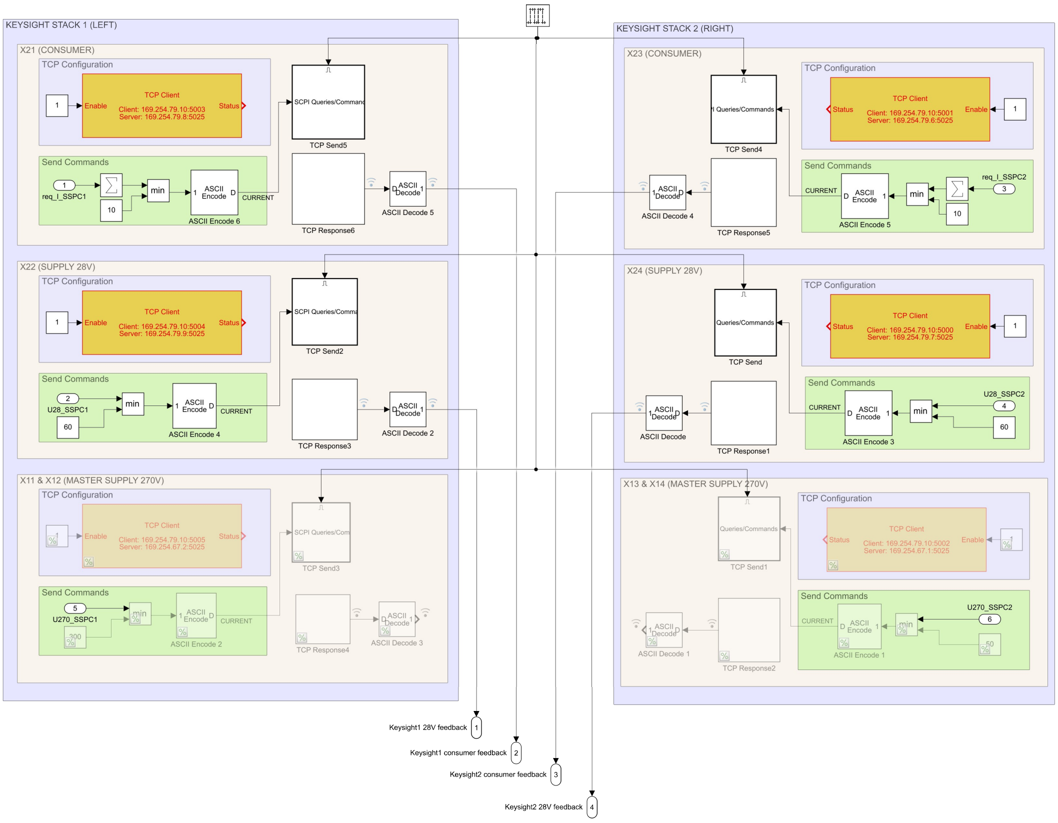

Figure 16: TCP connection using Simulink

6.2 Real-time target machine - Speedgoat

To enable a real-time simulation with external hardware, the simulation has been run on a real-time target machine. The real-time target machine used is of the brand Speedgoat. Speedgoat is specifically designed to perform well in Simulink real-time, and it makes sure that the simulation is run with concurrent execution. The Simulink file is compiled to C-code and sent to the Speedgoat through a ethernet connection, where it then can be executed. This connection is set up with help of real-time libraries in Simulink. [4]

In the real-time Simulink model the connection is established by setting the IP address for the Speedgoat and the two are connected.

6.3 Keysight

As previously described in 2.5.4 the purpose of the Keysight components is to act as the physical representation of the energy producing and consuming components of the aircraft system. To enable the Keysight boxes as a part of the HIL-simulation a connection between the Keysight and Speedgoat have been setup in Simulink using TCP.

A Keysight component can either be set in voltage priority or current priority mode. As the name suggests, the Keysight either aims to hold a constant voltage supplied or consume a constant current. Keysight X22 and X24 are set in voltage priority mode and have a reference of 28V, see Figure 17 of the physical setup of the Keysight boxes. Keysight X11/X12 and X13/X14 are voltage priority with reference 270V. Lastly Keysight X21 and X23 are set in current priority, and consume a current specified by the consumer models from the IEI group.

Figure 17: Keysight components used are the eight in black.
Left side from top to bottom: X21, X22, X11, X12.
Right side from top to bottom: X23, X24, X13, X14

The information that is sent to the Keysight is coded via the ASCII protocol. This is done using an ASCII coder block in Simulinkm, see Figure 18. ASCII code from the Keysight manual is used for setting voltage, current, limits etc. The information sent from Keysight is also coded in ASCII and has to be decoded in Simulink.

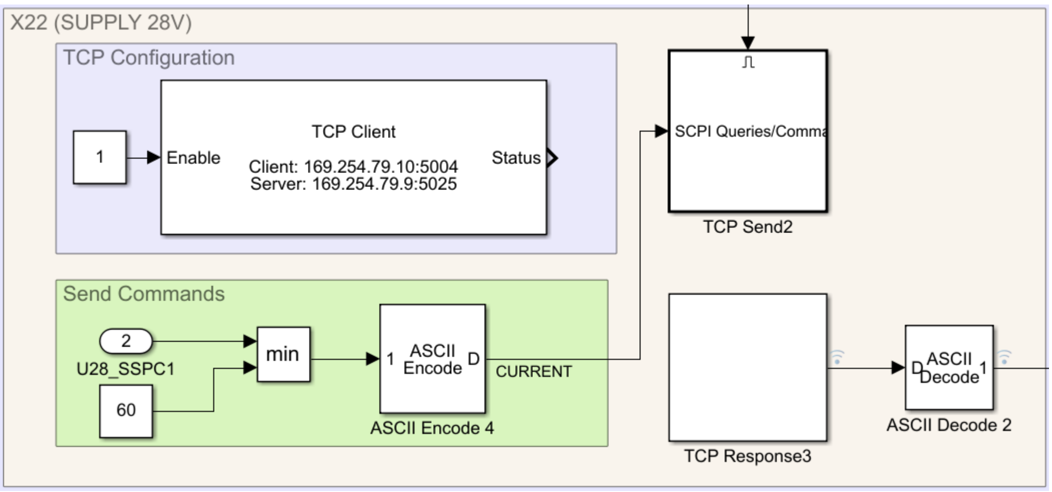

Figure 18: ASCII coder and decoder in Simulink

Every individual Keysight has standard settings that has been defined in the file ”TCP_configuration.slx” that shall be run before simulation. This file sets a starting voltage/current, limits and sampling time for measurements.

To set a voltage, for a voltage priority Keysight, or current, for a current priority, a command ”VOLT/CURR *number*” is sent coded in the ASCII protocol. The Keysight takes up to 0,6ms to reach the desired current or voltage. To measure either the voltage or the current, the command ”MEAS:VOLT/CURR” is sent. This command takes 3,3ms for the Keysight to process and send back to Simulink via the TCP connection. [5]

6.4 Iron Bird

The Iron Bird can be controlled via the Speedgoat using Simulink. The same flight mission actuator references used for simulating the power used by the actuators, can be sent as commands to the Iron Bird. These signals are sent as analog -10V to 10V signals. The angle of the actuators are measured and sent back to the Speedgoat and can be used by the IEI group to more accurately calculate the power used by the actuators. For this project the Iron Bird is only used to visualize the flight mission simulated in JSBSim.

7 Flight mission Simulation

7.1 Mission profile

The entire system is tested in real-time with a predefined flight mission. The flight is designed to simulate a mission where the aircraft manoeuvres for radar lock, establishes radar lock, maintains contact and then performs a defensive maneuver and returns to base (RTB). See Figure 19 for a simplified visualisation of the profile.

The method used was based on making light or hard adjustments on the reference angles for the elevators and ailerons and maintain these positions for various time duration to control the aircraft. Emphasis has not been put on making realistic manoeuvres since this would require a pilot and flight-control model to be developed, which is out of the scope for this project.

1. Level flight at cruising speed.
2. Maneuvering for radar lock and increases speed.
3. Finds radar lock and increases speed.
4. Defensive turning maneuver while maintaining radar lock.
5. Descends at full speed with radar OFF.
6. RTB at full throttle.

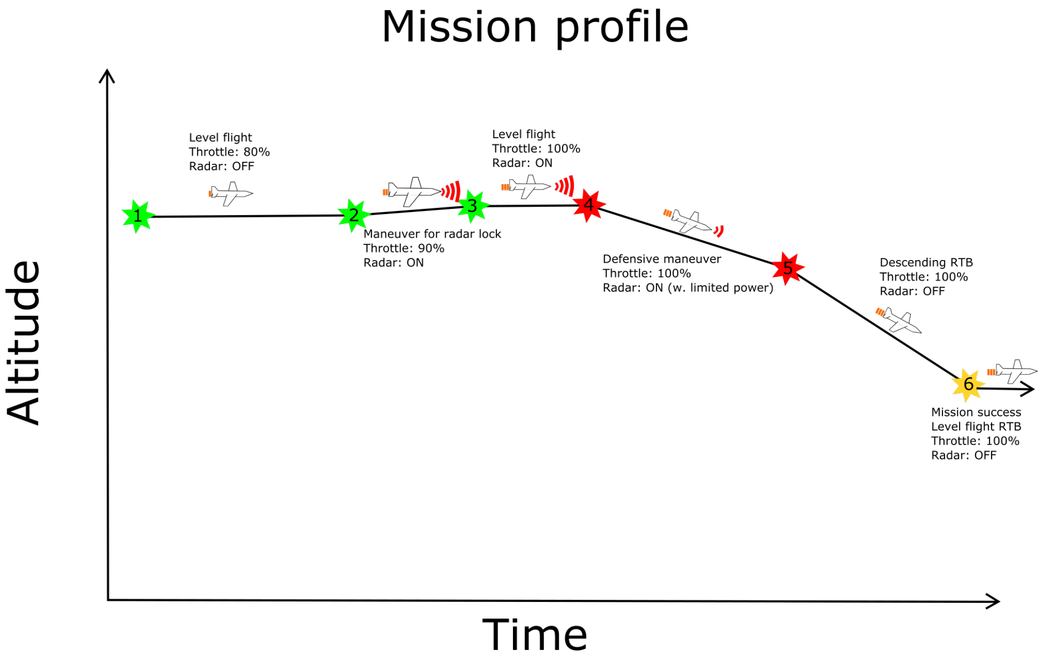

Figure 19: Mission profile.

8 Simulation Results

This section will cover the acquired results from various simulations of the system.

8.1 Offline simulation

This subsection will cover the acquired results from an offline simulation. An offline simulation means that the simulation has been executed in normal simulation mode in Simulink and no harwdare was connected. Each simulation has been run with the previously defined flight mission in section 7.

Figure 20 and 21 shows the output voltage from the SSPC and the converter. As can be seen in the figures, the voltage is controlled to keep it's constant reference voltage. The various spikes seen are due to changes in the aircraft's rudders from the flight mission and the resulting current demands, as well as changes in throttle angle from the pilot. All of these voltage levels are within the acceptable requirements set up in the requirement specification document.

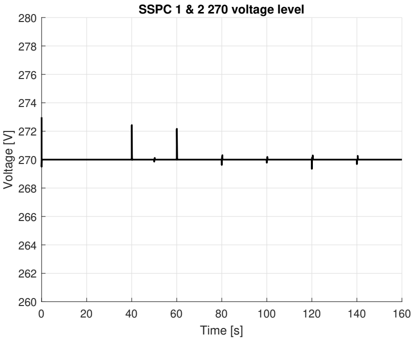

Figure 20: Voltage level in the 270 voltage system in offline simulation

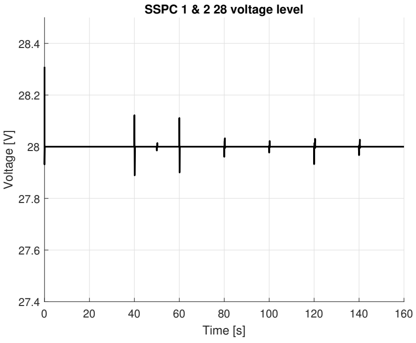

Figure 21: Voltage level in the 28 voltage system in offline simulation

Figure 22 and 23 shows the power consumption of the radar and the total current consumption of the system. As previously mentioned in section 7, the radar is switched on at time 40 seconds and switched off at time 120 seconds which can be seen in 22. At 80 seconds, there is a drop in the radar power, as can be seen in Figure 23, this drop coincides with the peak of the current consumption while the radar is active. The various spikes in the current consumption appear because of changes in the rudders and radar settings from the flight mission.

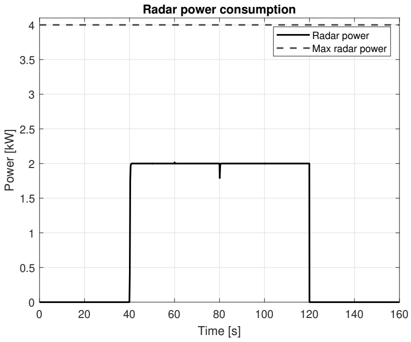

Figure 22: Radar power consumption for offline simulation

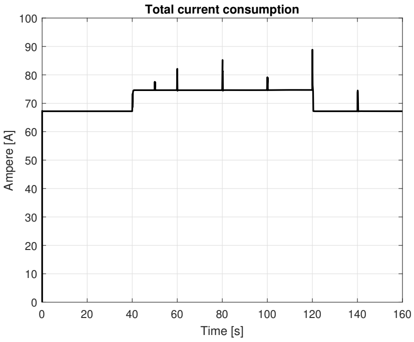

Figure 23: Total current consumption for the complete system in offline simulation

8.2 Real-time simulation

This subsection cover the acquired results from an real-time simulation. A real-time simulation means that the simulation has been executed in real-time simulation mode on the Speedgoat unit and signals were sent to and from Keysight. Each simulation has been run with the previously defined flight mission in section 7.

8.2.1 Discrete simulation with hardware

To simulate in real time in Simulink together with physical hardware, the best practice is to do it as a discrete simulation. For the best simulation result, the smallest time step possible was aimed for. The limiting factor for this system was the communcation with the Keysight components. As described in section 6.1, the communication with Keysight was done using a TCP protocol with ASCII encoded messages. With each message, a voltage or current setting was sent as well as a request for a measurement of said parameter.

The time step for the Simulink simulation was set to 1 ms with Fixed-step and a discrete solver. The communication with Keysight is managed using a pulse generator that activates and deactivates the TCP send block, see Figure 24. When the pulse is 1, the TCP send block is activated and sends a signal and when the pulse is 0, the block is deactivated. Every fourth millisecond an ASCII encoded message is sent to the Keysight component. The TCP send block is then active for one millisecond, and after that it is inactive for three milliseconds, see the plot to the right in Figure 24. During this time, the Keysight will measure its voltage or current and then send the measurement back via the TCP receive block to Simulink. The reason Keysight needs three milliseconds, is that it is the time it takes to do an average measurement [6]. These settings result in that the total step time for communication with Keysight varies between 5-6 milliseconds.

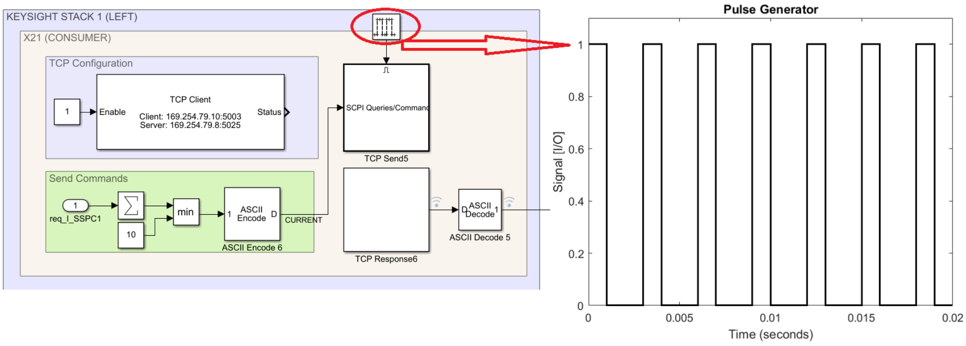

Figure 24: Pulse generator activating or deactivating the TCP send block

8.2.2 Normal operation

This section presents the results from a simulation with the defined flight mission in a fully functional operating mode.

Figure 25 and 26 shows the output voltage from the SSPC and the Keysight. At the time of writing this report, the Keysight PSU for 270 V is not configured for testing and therefore, Figure 25 was from the Simulink SSPC and not from an actual Keysight PSU. As can be seen in the figures, the voltage is controlled to keep it's constant reference voltage. The various spikes seen are due to changes in the aircraft's rudders from the flight mission and the resulting current demands. All of these voltage levels are within the acceptable requirements set up in the requirement specification document.

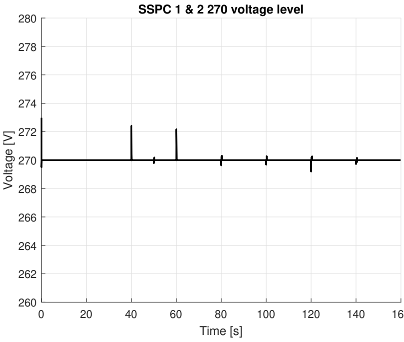

Figure 25: Voltage level in the 270 voltage system in real-time simulation

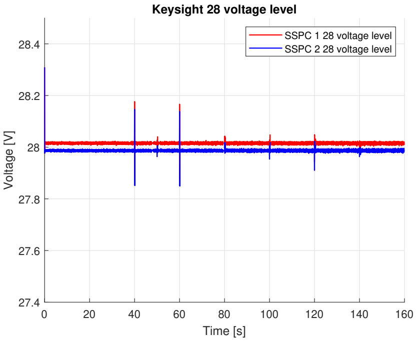

Figure 26: Voltage level in the 28 voltage system in real-time simulation

Figure 27 and 28 shows the power consumption of the radar and the total current consumption of the system. As previously mentioned in section 7, the radar is switched on at time 40 seconds and switched off at time 120 seconds which can be seen in 27. At 60, 80 and 100 seconds, there are drops in the radar power, as can be seen in Figure 28, these drops coincides with the peaks of the current consumption while the radar is active. The various spikes in the current consumption appear because of changes in the rudders and radar settings from the flight mission. Also to be noticed is that the radar does not reach max power (4kW). Since this is not available in the supply system at any point in time.

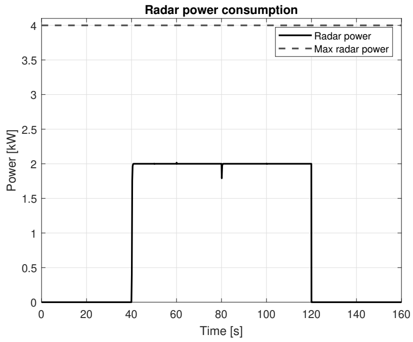

Figure 27: Radar power consumption for real-time simulation

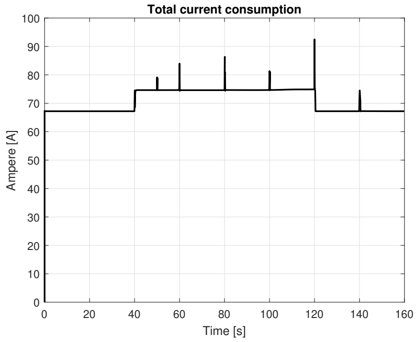

Figure 28: Total current consumption for the complete system in real-time simulation

8.2.3 Failure mode

This section presents the results from when running a real-time simulation for the defined flight mission in section 7, where it is defined that the generator breaks down after 80 seconds. When the generator breaks down, the battery becomes the power supplying component and as a safety feature, the radar is switched off too improve battery durability.

The transient in the 270 output voltage, Figure 29, is due to the exponential area defined in the battery model. The voltage can also be seen to drop after the initial increase, this is because of how the voltage varies with the SOC of the battery. The various spikes appear because of changes in the rudders and radar settings from the flight mission. In Figure 30, it can be seen that the converter is not as effective at keeping the voltage at a constant 28 V.

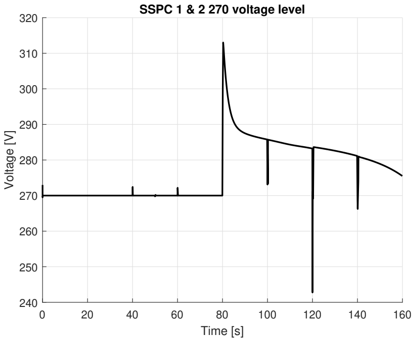

Figure 29: Voltage level in the 270 voltage system in real-time simulation for failure mode

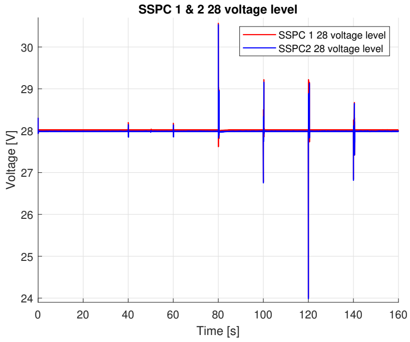

Figure 30: Voltage level in the 28 voltage system in real-time simulation for failure mode

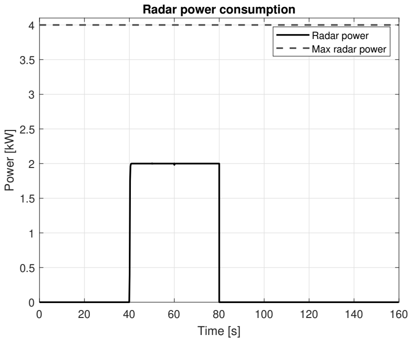

Figure 31:

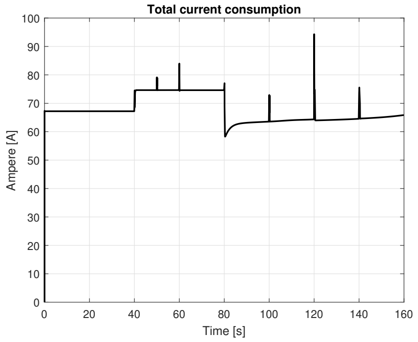

Figure 32:

As seen in Figure 33 the SOC for the battery drops linearly after 80 seconds.

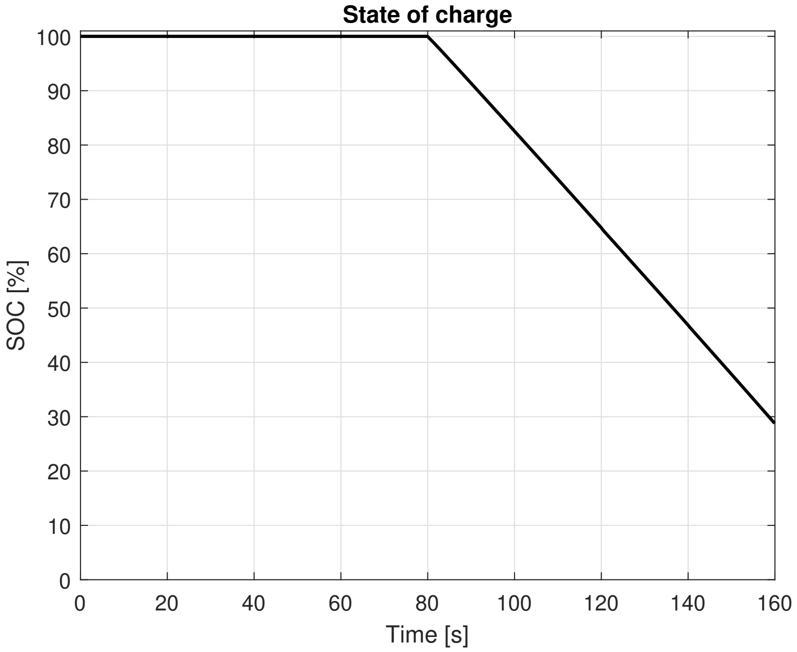

Figure 33: State of charge (SOC) for the battery

8.3 Requirement testing

This section covers the testing of the performance for the voltage regulation from the requirement specification. The tests for the 270 V system can be seen in Figure 34 and 35. The dotted line in the figures are the demand from the requirement specification. The red line shows the measured voltage from the Keysight, this line should reach the reference voltage faster than the dotted line for the test to be passed according to the requirement specification. As can be seen in the figures for the 270 V system the Keysight voltage does not reach its desired level within the time span for either of the tests.

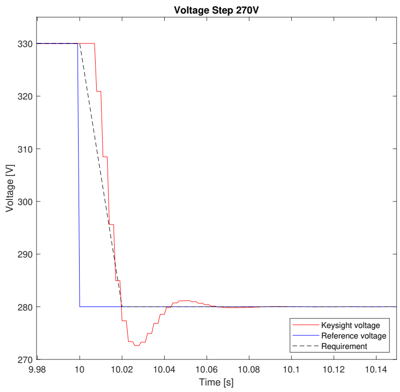

Figure 34: Step from 330 to 280 V in the 270 V system

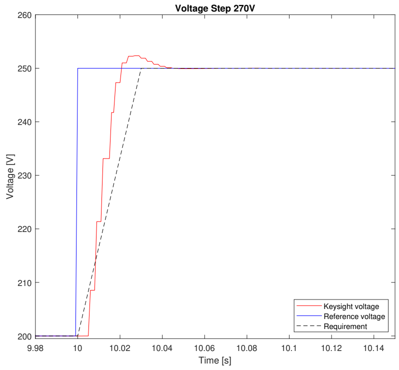

Figure 35: Step from 200 to 250 V in the 270 V system

The tests for the 28 V system can be seen in Figure 36 and 37. The dotted line in the figures are the demand, set in the requirement specification. The red line shows the measured voltage from the keysight, this line should reach the reference voltage faster than the dotted line for the test to passed according to the requirement specification. As can be seen in the figures for the 28 V system, the Keysight voltage manage to reach it's desired voltage level within the time span.

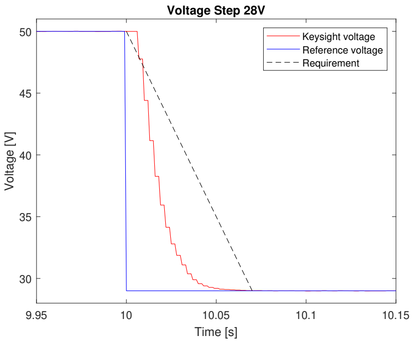

Figure 36: Step from 50 to 29 V in the 28 V system

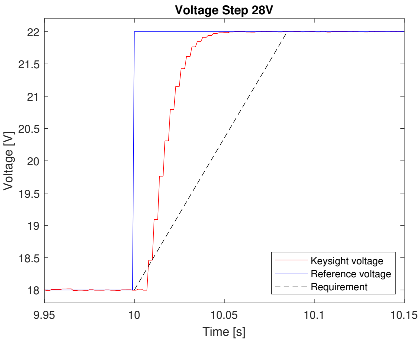

Figure 37: Step from 18 to 22 V in the 28 V system

8.4 Flight mission

This section shows the result from JSBSim when simulating with the flight mission in Figure 38. As can be seen in the figure, the circles on the path indicates that a new command has been sent to the aircraft.

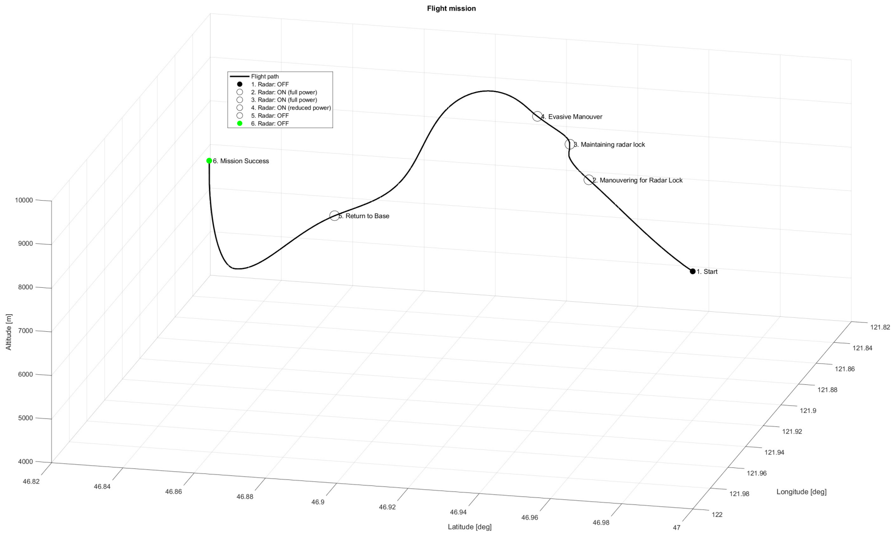

Figure 38: Flight mission

9 Discussion

As mentioned in sections 1.3, the goal of this project was to develop a platform where different parameters for an aircraft energy management system can be changed and evaluated. With the system that has been developed, voltage behavior and current consumption can be studied when changing the size of different components. For example the size of the generator, battery and actuators. The system is built modular, such that specific models can be improved and swapped out.

9.1 Simulation results

Section 8.3 shows the results from different voltage steps which has been performed in accordance with the requirement specification. The steps which were performed on the 270 V system did not manage to reach it's desired level within the time span. This is mainly due to a too big time constant in the CSD. As the system is built currently, a smaller time constant would lead to instability in the system. This instability occurs due to the fact that in the steps the Keysight voltage has been used as feedback in the CSD. However, in the end of the project, it was decided that this feedback could be replaced with an internal feedback within Simulink. This would open up the possibility to lower the time step in Simulink, which in turn results in that the CSD time constant could be lowered. With this solution, the 270 V system would very likely pass the test within the time span.

9.2 Further Development

9.2.1 Model sophistication

Currently, the models in the Digital Twin of the power generation system are relatively simple. This concerns all of the models presented in Section 3 but primarily the *Main engine* and the *Rectifier*. More sophisticated models could be created and used in the future to achieve a more accurate Digital Twin.

9.2.2 Simscape

At the moment, all of the models except for the battery are modeled in Simulink which uses a block diagram approach, the signal flow is unidirection. However Simscape uses a physical modeling approach and the signal flow is bi-direction between blocks. A higher implementation of Simscape could be beneficial in regards to the modeling of the physical systems since it probably would lead to more accurate results.

9.2.3 Current consumption with Keysight

During this project, the Keysight components have not been connected to each other or to any consumers on the Iron Bird. Therefore, no current has been consumed, and all current simulated has only been sent as information to Keysight. An important implementation for the future of the project is to connect the PSU Keysight components to the PCU and the Iron Bird, so that current is consumed.

At the moment, the "master and slave"-connection described in Section 2.5.3 is not implemented. This should be a future development since it is required to enable larger power transfers for the system.

9.2.4 Battery energy management

A powerful 270V battery offers multiple interesting energy management possibilities. The basic functionality necessary would be to control charge and discharge of the battery in different scenarios. When the state of charge (SOC) of the battery is less than desired and excess power is available from the generator, the battery could be charged. This would enable discharging the battery to support the generator during high power demand. A set value that the SOC is not allowed to go below can then be set. In case of catastrophic failure of the power supply system, the battery will support in an emergency mode where basic control is needed.

9.2.5 Degraded operating mode

When the supply system is not functioning to 100% and full specified power supply is not available. The consumers could be operated in degraded mode, where the VMS limits the control outputs to keep power consumption at a lower level while maintaining necessary margins.

9.2.6 Flight mission

A more sophisticated way of defining and executing the mission profile is needed. Since the control surfaces realistically are controlled continuously during the flight and not only when maneuvering. This would require a pilot and flight control model to be developed.

References

[1] Airbus. Taking flight with the Airbus "Iron Bird"; 2017. Last accessed 1 December 2021. Available from: `https://www.airbus.com/en/newsroom/news/2017-05-taking-flight-with-the-airbus-iron-bird`.

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[6] Keysight. Keysight Regenerative Power System RP7970 Series; 2020. Pages, 174. Available from: `https://www.keysight.com/se/en/assets/9018-04512/service-manuals/9018-04512.pdf`.