PPS5000 Thruster Emulator Architecture Development & Hardware Design

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PPS5000 Thruster Emulator Architecture Development & Hardware Design

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MASTER’S THESIS FOR DEGREE IN M.SC. SPACE ENGINEERING

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Abstract

This Master’s Thesis handles prestudy work and early hardware manufacture that resulted in architectural definitions and prototype hardware of electronic ground support equipment. This equipment is destined to emulate the electric power consumption of the PPS5000 Hall Effect Thruster (HET), for use in satellite end-to-end tests of the all-electric Geostationary Satellite Electra, developed at OHB Sweden AB. The Thruster Emulator (TEM) was defined through a resulting compilation of intricate interdependent components that interface the satellite power system and the thruster, which yielded an architecture development to support some basic predefined emulator requirements. This architecture was then analyzed to form a base-line conceptual function of the emulator system, which incorporates the entire HET functionality.

Six primary HET impedances were defined, of which the three most complex impedances were investigated fully. For the primary thruster discharge, research is shown of the complexity of implementing advanced electronic load hardware directly to the satellite’s 5kW power system with respect to the transient primary plasma discharge during thruster start up, and with limitations on the electronic load reducing emulator-thruster similarities. Additionally, a fully functional plasma ignition emulator prototype circuit board was built to be used in the final hardware of the TEM to emulate the external HET cathode start-up functionality. Finally, a feasibility study for designing a possible solution for the large PPS5000 electromagnet impedance was performed, resulting in the manufacture of two prototype inductors with unsatisfying performance results according to the design requirements.
Preface

On the 16th of February 2018 I was accepted as a Master Thesis student at OHB Sweden after applying for the position through their web page and began my six month internship on the 14th March 2018 after relocating to Stockholm. After the internship completion I was offered a project employment to continue the development of the Hall Effect Thruster Emulator which opened the doors for a future career in the Swedish space industry. I am grateful for the internship I did at OHB Sweden as I have met very professional and kind people at the company as well as being exposed to a professional and enjoyable work environment.

I would like to give a special thanks to the following people at OHB Sweden

- Enrique Lamoureux, for providing professional electrical engineering support and guidance, and supervising my work both during and after my internship.
- Nils Pokrupa, for welcoming me on my first day at the company and integrating me into the company through a pleasant introduction, as well as being continuously interested and helpful in my thesis project throughout my internship.
- Vincent Garcia, for explaining complex and in-depth electric propulsion background and functionality, as well as providing thesis project support.
- Ulrika Asp, for answering my miscellaneous questions and requests that occur when one is a newcomer to a company.

The educational lessons I received during my Electrical Engineering gap year of 2015, in addition to my Space Engineering studies, were a major factor in my advances in this thesis project as I utilized every academic experience I had to fulfill the difficult level of Electrical Engineering required to produce the results. However, education does not prepare you fully for the inevitable challenges that engineering implies, and for every mistake I made during my thesis, I have learned something new and something fascinating.
Acronyms

CC  Constant Current
CLK  Clock
CRP  Cathode Reference Potential
CV  Constant Voltage
DC  Direct Current
EM  Electromagnetic
EP  Electric Propulsion
ESA  European Space Agency
ESR  Equivalent Series Resistance
GEO  Geo-Stationary Orbit
HET  Hall Effect Thruster
IC  Integrated Circuit
LSB  Least Significant Bit
LTU  Lule\textae\ tekniska universitet Lule\textae\ University of Technology
MOSFET  Metal Oxide Semiconductor Field-Effect Transistor
MSB  Most Significant Bit
NPN  Negative-Positive-Negative, regarding transistor doping
PCB  Printed Circuit Board
PPT  Pulsed Plasma Thruster
PPU  Power Processing Unit
PPS  Propulseur Plasma Stationnaire
RC  Resistor/Capacitor Pair
RMS  Root Mean Square
SR  Set Reset
SSC  Swedish Space Corporation
TASB  Thales Alenia Space Belgium
TEM  Thruster Emulator
TT  XFC Thermal Throttle
XFC  Xenon Flow Control
List of Figures

2.1 Types of EP and their characteristics compared to traditional propulsion methods. [1] . . 4
2.2 Principle of the Hall Effect. The Hall-voltage is indicated as $V_H$, courtesy of HyperPhysics.org. [8] .......................................................... 4
2.3 Principle of Anode-Cathode discharge by means of trapped electrons in a magnetic field. 5
2.4 Photograph of PPS5000 Hall Effect Thruster, thrust vector is pointing up from the reader's perspective. .................................................. 6
2.5 Xenon Flow Control unit, providing Xenon gas to the thruster anode. ...................... 6
3.1 Thruster Electrical Topology. .................................................. 9
3.2 Concept schematic presenting PPU, emulator loads, emulator controller and user interface through a computer. The listed electronic load is explained in detail in section 3.2. 9
3.3 Diagram of Operation for Emulator. ...................................................................... 11
3.4 Voltage-Current elbow curve relationship. ........................................................... 12
3.5 Reproduced image of SPT-140D Coupling Test Discharge Current and Voltage during HET start-up. .................................................. 13
3.6 Impedance Model of Ignitor and Keeper. The supply on the impedance is shared, but are named differently in the model due to simulation reasons. ...................... 14
3.7 Ignitor and Keeper impedances with PPU internal supplies. Diodes block any cross-supply currents from impeding their functionality towards the Ignitor and Keeper loads. .... 15
3.8 High level block diagram realizing the requirements set for the Ignitor and Keeper functionality. The arrows show the flow of information. ...................................................... 16
3.9 Thruster magnet impedance. The inductance value is the collective series inductance. 16
3.10 Heater impedance and expected current from the PPU. ........................................ 17
3.11 XFC Xenon flow-chart, containing the dual-valve assembly, thermothrottle, and distribution to the Anode (92%) and Cathode (8%). [17] ........................................... 17
3.12 Impedance schematic of series-connected valves, connected in parallel electrically. 18
3.13 Schematic of Thermo thrott le impedance. ....................................................... 19
4.1 Expanded Ignitor and Keeper logics block diagram.............................................. 22
4.2 Non-inverting hysteresis loop with a positive bias value $V_R$. ............................... 24
4.3 Voltage measuring circuitry. ................................................................................. 24
4.4 JK Flipflop truth table. Only a rising edge is used to trigger here. ......................... 25
4.5 Counter internal JK Flipflop layout. Image from datasheet of counter used in final product. .................................................. 25
4.6 Counter and comparator functional connection. .................................................... 26
4.7 SR latch circuit containing two NAND logic blocks. ............................................. 27
4.8 Methods for which electrical energy is coupled, courtesy of Wikipedia. ............... 28
4.9 Inductive isolator for coupling the user input and output signals not referenced to the CRP. .................................................. 28
4.10 Ignitor pulse input with buffering and filtering through a Low-Pass filter and a Schmitt Trigger. ............................................................................. 29
4.11 Ignitor and Keeper Counter, Comparator, and Latch. ......................................... 29
4.12 Ignitor and Keeper gate driver and low-side MOSFET. ....................................... 29
4.13 Ignitor and Keeper Input and Output isolation. ................................................... 30
4.14 Ignitor and Keeper input power and power regulation. ........................................ 30
4.15 Ignitor and Keeper Latch and Counter reset circuits, which allow reset on circuit power cycling. .................................................. 30
4.16 The B-H curve, from TDK N27 Ferrite Core Datasheet, May 2017. ..................... 33
Chapter 1

Introduction

This Master’s Thesis report contains the architectural development and hardware design of equipment intended as prototype material for a Hall Effect Thruster Emulator and is based on a wide range of undisclosed internal documents, of which only a few have been referenced in this report. The project was facilitated at the prime-contract space engineering company OHB Sweden AB, for which the final product is being manufactured.

1.1 OHB Sweden AB

OHB Sweden AB is currently Sweden’s only spacecraft prime contractor and has a long successful history as Sweden’s center for satellite development. In 2011 the Swedish Space Corporation (SSC) sold its satellite division to the German space company OHB, which created the Swedish company OHB Sweden AB, and has since then greatly expanded its capacity, employment, and project count.

This Master’s Thesis project, named initially Hall Effect Thruster Emulator, was facilitated during a six month internship at OHB Sweden AB starting on the 14th of March and ending on the 14th of September, 2018. All development was done at OHB Sweden’s premises in Kista, Stockholm. The responsible supervisor for the project at OHB Sweden was Dr. Enrique Lamoureux of the Spacecraft Department. The head of the Spacecraft Department was Nils Pokrupa, who was responsible for the internship and therein signing the confidentiality agreement and handling all administrative tasks regarding the Master’s Thesis student’s integration in the company. The responsible supervisor, i.e. examiner, at Luleå University of Technology (LTU) was Dr. Soheil Sadeghi of the Department of Computer Science, Electrical and Space Engineering.

1.2 Thesis Scope

The Thesis’ tasks are divided among the below listed categories gathered from the original thesis description. While these tasks are not necessarily traceable or verifiable, they give a general idea of the thesis content since the student took part in all of these tasks.

- Verify the topology of the thruster emulator able to cope with the requirement specifications and trade-offs.
- System Design based on existing/off-the-shelf hardware and custom/specific hardware.
- Electric architecture design and board design for custom hardware.
- Procurement of hardware, such as industrial loads, electronics, acquisition boards, etc..
- Thruster performance modeling.
- Documentation, such as design report, interface control description, test reports.

Specifically, the thesis covered the development of the following areas of work.

- Thruster Emulator general architecture development.
- Thruster Anode-Cathode discharge electronic load feasibility study.
- Thruster Ignitor-Keeper phenomena modeling, circuit design, implementation, and prototype testing.
- Thruster Magnets research, design, construction, and prototype testing.
Limitations

The student was limited to internal undisclosed design documents, user manuals, technical notes, and information which was only accessible to the student during work hours at OHB Sweden. Additionally, the student was limited to a plethora of design critical To Be Decided (TBD) requirements, interfaces, and functions. However, this also gave the student tremendous architectural freedom to develop the project accordingly.

1.3 Outline of Report

This thesis report embeds the traditional method and result structure within two chapters that cover the Emulator Architecture, named Architecture, and the Manufactured Hardware, named Hardware. Sectioning has been made within these two chapters to incorporate the thruster’s components, named units, in such a fashion that they are all to be handled as separate minor reports based on the theory in the background that simultaneously includes the design method, as well as the designed results. Additionally, there are test reports presented in the appendix that can aid the reader in understanding the hardware manufacturing, testing, and prototyping details.
Chapter 2

Background

This chapter summarizes background information relating to the various parts of the master’s thesis project. The chapter contains explanations on how the emulator project arose, thruster theory, as well as product bench marking.

2.1 Electra Satellite

The telecommunications satellite Electra, planned to launch 2022 is designed and integrated by OHB-Systems, including OHB Sweden, and run by the satellite operator company SES SA. The project started in 2012 to become an all-electric Geostationary Earth Orbit (GEO) satellite, based on the SmallGEO platform. [7] It uses the Hall Effect Thruster PPS\textsuperscript{5} 5000 developed by Safran SA with an Electric Propulsion (EP) thrust of up to 300mN [4] The EP thrusters are mounted on two boom-arms oriented in the North and South direction, which allow the satellite to configure its thrust angle depending on operation, which includes primarily the four to five month Orbit Raising (OR) position, and the Station Keeping (SK) position used during the remainder of the mission. [7]

During Satellite Flat-Sat\textsuperscript{2} and satellite end-to-end testing, the thrusters pose the issue of requiring a vacuum chamber for firing. And during later integration with the satellite, no vacuum chamber exists to fit the whole spacecraft to run the thrusters. Because of this a thruster emulator was proposed that can interface with the satellite and impose, on an electrical level, the same configurations that a normal thruster would, without using the expensive thruster or constraining the test by having to be in a vacuum chamber. [23] This electrical emulator has been in slow development at the OHB Sweden for several years, and this Master’s Thesis helped jump-start the project into full development.

2.2 Electric Propulsion

In the beginning of the 1900s Konstantin Tsiolkovsky and Robert Goddard independently proposed the idea of alternative propulsion systems for spacecraft, specifically the use of electric power to propel charged particles at high velocity as a means of spacecraft propulsion. [1] Because conventional propulsion methods rely on its inherent chemical energy to expel mass through combustion inside pressure chambers of varied sizes and shapes, the available thrust energy is constrained and stored within its own depletable propellant mass. EP on the other hand separate the propulsion energy from the propulsion mass, generally by using solar energy or in some cases nuclear energy. [5] There are several methods of EP, but the common denominator of all EP thrusters is that they all propel small masses at incredibly high velocities. EP thrusters have the highest specific impulse of all thrusters currently available. However, this comes with drawbacks; the most notable being the EP’s lack of thrust. [2] [3] The PPS5000 thrust, considered a medium to high-power EP thruster, is equivalent to the force exerted on ones hand by approximately four standard A4 papers. [1] These thrusters, however, are able to reduce launch costs significantly by lowering the propellant mass of the spacecraft. [6] Figure 2.1 presents some comparisons between thruster types.

\textsuperscript{1} Propulseur Plasma Stationnaire, French for Stationary Plasma Thruster.

\textsuperscript{2} Assembly of satellite in a 2D configuration, such as on a table, for testing communications, electrical systems, etc, before full satellite integration.
Hall Effect Thrusters

The Hall Effect, discovered by and named after Edwin Hall in 1879, is an electromagnetic interaction utilized in many electronic applications and is fundamental for propulsion in Hall Effect Thrusters (HET) by which it is named. The Hall Effect is an occurrence of intrinsic voltage across a ferro-magnetic load powered by a current source when being subject to an external magnetic field. This Hall voltage is perpendicular to both the current and the magnetic field lines. It is easily recalled by most physics students as stemming from the so-called "right-hand rule" in electromagnetism for positive charge carriers, namely the Lorentz Force. As seen in figure 2.2, the magnetic field pushes the charge carriers flowing through the conductor to the edges, leaving opposite charge at the opposite edge such that an electrical potential is produced.

A Hall Effect Thruster utilizes this effect to collect electrons into a dense, trapped plasma to ionize heavy, non-reacting noble gases and at the same time create an electric field. For this electric field to hold, an anode must exist down-range from the electron cloud, and it is from this anode that the propellant is released, i.e. the noble gas.

Generally speaking, all Hall Effect Thrusters have an annular chamber, open at one end, surrounded by magnet...
coils, with one pole in the center of the chamber, producing a strong magnetic field pointing towards this central chamber coil. An external cathode produces electrons that drift towards an anode positioned at the bottom, i.e. closed end, of the annular chamber. [6] Under non-magnetic circumstances the electron-producing cathode would feed a high electron current to the anode. [17] However, this strong magnetic field surrounding the chamber stops the electrons from reaching the anode, and because of the aforementioned Hall Effect, the electrons begin to spin within the chamber in the $E \times B$ direction. [1] [17] This hot and dense electron movement then has the capability of ionizing a noble gas, fed into the bottom of the chamber, by removing one or two electrons from the atom which then flow to the anode. Due to the specific design characteristics of the chamber, the ionized particles are heavy enough not to produce an opposing Hall Effect current at the top of the chamber. [17] Instead the ions are accelerated by the large electric potential out of the chamber and are then neutralized by the same external cathode that feeds the Hall Effected electrons from the start. This net flow of mass out of the chamber produces a thrust, albeit in the order of hundreds of mN. [4] Figure 2.3 shows a cross-section of a Hall Effect thruster. The annular chamber is, therefore, represented as two U-shaped areas. The magnetic coils are represented with permanent magnets. The thrust vector is parallel to the center line pointing to the right and Xenon atoms are used as a noble gas. [1]

![Figure 2.3: Principle of Anode-Cathode discharge by means of trapped electrons in a magnetic field.](image)

The cathode has two vital purposes, both involving creation of electrons, which tends to be done by ionization of the same propellant used as thrust. During start-up, the cathode creates a plasma by heating an emissive material to the point at which electrons are created through thermionic emission. [17] At the same time, a portion of the propellant gas is fed into the cathode while an ignition spark is pulsed within the cathode until a self-sustained ionization is catalyzed, fed by a so-called Keeper current supply. [17] From this point, the cathode acts like a thruster all in itself and, depending on the mode of start-up, the cathode will feed the annular chamber with electrons to form the hall-current electron cloud at the chamber exit. [5] Once the anode
has reached its desired voltage, the power supply will shut off the internal cathode Keeper supply, and the thruster enters a self-sustaining thrust, depending on the flow of Xenon gas. [6] The ignition supply, keeper current supply, and heater supply are all positioned within the cathode. [17]

Propulseur Plasma Stationnaire 5000

The Propulseur Plasma Stationnaire 5000 (PPS5000), is a French developed HET from Safran SA, previously known as Snecma³, before being purchased by Safran in 2016. [4] This 5 kW thruster has been chosen for Electra’s orbit raising and station keeping electric thruster and can be seen in figure 2.4 and its Xenon Flow Controller (XFC) in figure 2.5. [7] The XFC manages the Xenon flow to the thruster by a capillary membrane tubing that contracts and dilates depending on the supplied current. [4] [17] This is called a Thermo throttle, and is the primary throttle of the thruster. Additionally, the XFC also contains two solenoid valves in hot redundancy that must be opened for thruster operation. [20] The external component in figure 2.4 is the thruster cathode angled towards the exhaust plume to fulfill its task of supplying electrons into the annular discharge chamber and to neutralize said thruster plume. [17] The coils in each thruster corner are the thruster magnets. Table 2.1 summarizes the general performance of the PPS5000. [22]

Figure 2.4: Photograph of PPS5000 Hall Effect Thruster, thrust vector is pointing up from the readers perspective.

Figure 2.5: Xenon Flow Control unit, providing Xenon gas to the thruster anode.
Table 2.1: PPS5000 Characteristics. [17]

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Thrust</td>
<td>$\leq 316mN$</td>
<td></td>
</tr>
<tr>
<td>Nominal Power</td>
<td>2kW to 5kW</td>
<td></td>
</tr>
<tr>
<td>Specific Impulse</td>
<td>$\lesssim 2000s$</td>
<td></td>
</tr>
<tr>
<td>Primary Discharge</td>
<td>300V to 400V</td>
<td>Anode to Cathode</td>
</tr>
<tr>
<td>Primary Current</td>
<td>6.25A to 16.67A</td>
<td>Anode to Cathode</td>
</tr>
<tr>
<td>Dimensions</td>
<td>200x200x150mm</td>
<td></td>
</tr>
</tbody>
</table>

The PPS5000 basically follows a linear start-up and steady state functional procedure which relies on different parts of the thruster starting, running, and stopping in different orders. While the actual procedure of the thruster is undisclosed, table 2.2 summarizes the basic operation.

Table 2.2: PPS5000 Operating Sequence, see flow chart in figure 3.3. [17]

<table>
<thead>
<tr>
<th>Action</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnets ON</td>
<td>Creates the magnetic field over the annular chamber</td>
</tr>
<tr>
<td>Cathode Heater ON</td>
<td>Heating up the thermoemissive material</td>
</tr>
<tr>
<td>XFC Thermo throttles ON</td>
<td>2.5A preheating of capillary tube</td>
</tr>
<tr>
<td>XFC Valves Open</td>
<td>Allowing Xenon flow to the closed Thermo throttle</td>
</tr>
<tr>
<td>Cathode Ignition</td>
<td>Pulse-train is sent creating sparks within the cathode</td>
</tr>
<tr>
<td>Cathode Keeper on ignition</td>
<td>Cathode Xenon ionization creates high electron density</td>
</tr>
<tr>
<td>Anode Voltage Ramp</td>
<td>Ramping causes less violent discharge transient</td>
</tr>
<tr>
<td>Anode Current Discharge</td>
<td>Occurs at critical anode voltage, around 70V</td>
</tr>
<tr>
<td>Cathode Keeper OFF</td>
<td>Since the primary discharge is self sustaining</td>
</tr>
<tr>
<td>Cathode Heater OFF</td>
<td>Similarly, ionization will sustain from primary discharge</td>
</tr>
<tr>
<td>Thruster Control Loop</td>
<td>$Thrust = f(I_{thermothrottle})$ [22]</td>
</tr>
<tr>
<td>Shutdown</td>
<td>All supplies are turned off</td>
</tr>
</tbody>
</table>

2.3 Thruster Emulator

The thruster emulator concept implies filling a standardized 19-inch electronics rack with appropriate off-the-shelf electric impedances, analog and digital monitors and converters, and control systems for it to act as a passive load that can be escorted into clean-room and test environments for use during different levels of satellite testing. [23] [24] The complete thruster emulator is meant to have a plethora of internal current, voltage, and temperature measuring devices compiled through data acquisition boards and monitored through LabView that interfaces with a user through an associated laptop. [23] From the knowledge given to the thesis student at the time, there was one thruster emulator commercially available, developed by a company called DACTEM, which OHB Sweden was in contact with. Some of the design has been inspired by the DACTEM thruster emulator.

Goal & Purpose

The ultimate purpose of the Hall Effect Thruster Emulator is to interface with the flight hardware in such a way that the satellite Power Processing Unit (PPU) can run real flight programs through the emulator, but without an actual thruster being used. All power produced by the satellite to feed the thruster is meant to be dissipated through the emulator impedances, without degrading the quality of the satellite tests. This also allows for an additional end-to-end test for the Electra satellite during late 2020, despite the thrusters already being integrated to the satellite and there is no vacuum chamber available that would fit the satellite. The idea is to use the emulator at this stage to perform final verification of the complete hardware.
Chapter 3

Architecture

This chapter presents the architecture design portion of the Master’s Thesis where the student analyzed and help create the thruster emulator requirements. These requirements were written in conjunction with the thesis which created a baseline for the hardware developed in a later chapter and served to define the function of the emulator.

3.1 Introduction

The purpose of the emulator is to act as a realistic electrical load to the satellite’s power unit and, therefore, it is essential that all components connected electrically to the power unit be included in the emulator content list.

The following definition is made to clarify and differentiate the various significant parts of the complete Hall Effect Thruster. Any device which interfaces to the PPU electrically and imposes an impedance which is vital for thruster operation, is denoted as a unit henceforth. Any previous definition of the term unit from applicable documents will not be used. Therefore, the following list depicts the relevant units for the emulator.

- Primary Anode-Cathode Discharge
- Cathode Ignitor & Keeper
- Thruster Magnets
- Cathode Heater
- Xenon Flow Control’s Thermo throttle
- Xenon Flow Control’s Dual Valves

Each section in this chapter is dedicated to addressing the architecture of each unit separately. Therefore, at the start of each section a list of addressed requirements specific to that unit are taken from the Thruster Emulator Requirements Specification, which was developed in conjunction with the thesis. [23] The bold text at the beginning of each stated requirement indicates the category of said requirement.

In addition to the listed requirements for each unit, the following general requirements have been addressed throughout the project, with requirement 1 acting as the fundamental requirement for the thesis.

1. **Functional** The TEM shall represent the operation and behavior of one actual PPS5000 HET, as seen from the PPU, at an electrical point of view.

2. **Electrical** The TEM ground scheme shall be identical to PPS5000 scheme, see figure 3.1b, which implies:
   - Anode discharge load, cathode heater load and ignitor keeper load are all referenced to the Cathode Reference Potential, which is connected to the chassis through the $V_{CRP}$ voltage source.
   - Magnet, TT and valve are left isolated from other loads.

3. **Software** The TEM internal software shall be based on National Instrument LabView.
Thruster Electrical Layout

The following figure 3.1 schematizes the thruster units and emulator design concept with its electric interfaces to the PPU, with physical representation of its components and with voltage reference clarification which presents the same topology but with focus on the electrical interconnections and references. The CRP, a separate and isolated reference within the cathode, can be seen acting as a reference potential for three of the six unit functions. Heritage from the SMART-1 mission operated by the European Space Agency (ESA) and manufactured by SSC in 2003, that used a PPS1350 thruster, has shown that this potential converges to $-20V$ compared to the satellite ground. The Magnet and Valve’s supplies are isolated from the rest as well, but not through the CRP. Please see chapter 2: Background for more information about the thrusters function. It is useful to note here that the Ignitor and Keeper supply is labeled at the same point. This is due to an internal supply switch occurring within the PPU on the same interfacing pin to the thruster. More information about the Ignitor and Keeper can be read in section 3.3: Cathode Ignitor and Keeper.

(a) With representative physical components. (b) Expanded impedances and reference points.

Figure 3.1: Thruster Electrical Topology.

The complete setup of the emulator requires acquisition boards measuring each emulator load’s respective currents, voltages and temperatures and a computer using the program LabView to completely emulate both the loads and the functionality over time of the HET. The following figure 3.2 shows the conceptualized layout of the emulator, used as input for the Master’s Thesis.

Figure 3.2: Concept schematic presenting PPU, emulator loads, emulator controller and user interface through a computer. The listed electronic load is explained in detail in section 3.2.
Power Processing Unit

Electra’s power supply for the EP is the Power Processing Unit Mark 3, referred to as PPU Mk3, and is developed by Thales Alenia Space Belgium, also referred to as TASB. The PPU’s role of supplying the electric propulsion is an active one, especially with regards to start-up. It supplies the thruster with the corresponding voltage or current, depending on the unit, and can produce up to 10kW of power in total with regards to all units. [18] There are a total of three PPU’s on-board the Electra satellite, one for each pair of thrusters on each arm, and one in cold redundancy. Different units are supplied at different times in a sequence that is important to follow for the functionality of the thruster.

Emulator Step-by-Step Function

Figure 3.3 depicts the resulting functional diagram for the emulation of the HET start-up1, steady-state, and shut down, produced in conjunction with the undisclosed TASB and Safran documents on the PPU and PPS5000, respectively. Since the PPU supplies the passive loads according to its internal scheme, the emulator is able to allow or block certain steps based on the theory of HET function, as seen in table 2.2, since it stops the closing of circuits within the emulator, which results in power not being drawn from the PPU. For this reason, control loops have been added to guarantee that the right order of function occurs. This gives the emulator the ability, to a certain degree, to emulate failure cases when breaking the expected procedure of the PPU’s sequence.

The requirements for each unit is more thoroughly explained in their individual architecture sections below. What can be explained in general is that for each loop expecting a YES or NO, the emulator monitoring system, i.e. LabView connected to an acquisition board, checks the voltage, current, and temperature levels of that impedance to confirm it is within the correct range corresponding to that specific unit. As an example, the Thermothrottle (TT) is considered OK in the first diamond intersection when it draws the correct pre-heating current of 2-2.5A. Later on however, during the closed loop operation, the TT will experience a varied current depending on the PPU input since it follows a thermothrottle current to thrust scheme. [22] The top left box in the functional diagram shows the abbreviated units’ inputs in terms of voltage, current, or both.

---

1The precise start-up method is according to the PPS5000 soft-start ability, implying that the cathode discharges before the anode voltage is raised, to allow for a smoother current transient.
The following critical values are to be settable by the user of the emulator through LabView, listed together with nominal values presented from the requirements of each unit, explained in this section.

Table 3.1: Table of critical values for emulator operation

<table>
<thead>
<tr>
<th>Variable</th>
<th>Nominal Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{crp}$</td>
<td>-20V</td>
<td></td>
</tr>
<tr>
<td>$V_{crit}$</td>
<td>70V</td>
<td></td>
</tr>
<tr>
<td>$I_{crit}$</td>
<td>2A</td>
<td></td>
</tr>
</tbody>
</table>

### 3.2 Anode-Cathode Discharge

The requirements for an Anode-Cathode Discharge load element are the most complex of all emulated loads of the Hall Effect thruster. Therefore, a programmable electronic load is required to emulate the proper behavior of the thruster. Since the primary discharge draws the greatest power and has the largest dynamic range of all units, this programmable load is required to allow high voltage and current transients in both steady-state and during start-up and shut down of the thruster emulator.

The following requirements, specific to the Anode-Cathode discharge, are concluded from this section and addressed in the Hardware chapter.

1. **Functional** The anode main discharge equivalent load shall be represented by an active load in the TEM.
2. **Functional** The TEM shall be able to produce a noise towards the PPU similar to the oscillation current created by the thruster.

3. **Functional** The TEM anode to cathode equivalent load shall be able to produce large current peaks (the PPU being the voltage source) similar to the ones produced by a thruster during ignition and single event phenomena (corresponding to plasma pollution).

4. **Performance** The anode to cathode discharge equivalent load of the TEM shall have an IV curve, as presented in figure 3.4b with settable critical values.

5. **Performance** The TEM shall be able to generate an oscillation current $5k\text{Hz}$ to $40k\text{Hz}$ up to $8A_{rms}$.

6. **Performance** The TEM shall be able to drain current peaks of $150A$ with a rise time of $20\mu s$ as part of the anode cathode discharge load.

7. **Performance** The rising time of the main anode current from 0 to ignition current set point shall be lower than 0.5ms.

8. **Physical** The TEM shall be 19inch cabinet, 20U max., 800mm deep max.

Since there is no way of replicating the Hall Effect Thruster transient, noise, and behavior in perfect detail, analysis of the thruster voltage and current during operation is vital for taking justifiable simplifications.

**Steady State Discharge Voltage & Current**

For the steady-state behavior of the discharge voltage, $V_d$ and discharge current, $I_d$, the PPS5000 operates according to the following elbow curve relationship:

For an electronic load to emulate figure 3.4b, the device needs to enter a constant voltage (CV) mode once reaching a critical voltage, until it reaches the steady state discharge current, in which the emulator electronic load enters a constant current (CC) mode, allowing the voltage to vary accordingly. The modes CV and CC are typically used for electronic loads to express the users impedance requirements on a power supply. This characterization is not a problem for most electronic load devices, and it was the natural course of action to take for replicating this type of variable impedance behavior.

**Discharge oscillation current**

As per requirement 5, the oscillation current is distinguished from the DC discharge current. This is according to a previous PPS5000 to PPU coupling test performed by Safran. [21] The noise is present as a root-mean-square (RMS) value of the current, which is necessary to emulate due to a fundamental behavior of the thruster. This
oscillation is caused by the so-called *Breathing Frequency*\(^2\) of the thruster, which is inherent to all Hall Effect Thrusters and can cause disruptions and ringing in the satellites PPU. \([17]\) Therefore, it is vital for the emulator to be equipped with a current injecting function to emulate this oscillation behavior, as per requirement 5. This too, however, is possible to superposition on a DC current through an electronic load that can be set with a user input frequency, giving more justification for the use in the TEM.

**Start-Up**

The previous section’s architecture is designed from the detailed coupling tests performed by *Safran* for the PPS5000 \([21]\). However, no detailed start-up current peaks and voltages are documented by *Safran* that OHB Sweden has access to and, therefore, the decision was made to base the Anode-Cathode’s start-up sequence requirements on available data from the Russian *Stationary Plasma Thruster* (SPT) developed by FAKEL OKB, with the reason that these thrusters’ designs are nearly identical, regarding power, discharge voltage and currents, and operational behavior. The following start-up sequence in figure 3.5 was recorded by FAKEL during a test of the SPT-140D.

![Figure 3.5: Reproduced image of SPT-140D Coupling Test Discharge Current and Voltage during HET start-up.](image-url)

The orange and blue curves are of interest, as they represent the discharge current and voltage respectively during a total time interval of 1 millisecond. The discharge voltage is initially at 150V, and after start-up, occurring at 400 microseconds from the start of the graph, and has a total drop of 50V. The discharge current has a starting value of 0A, and a final value of 10A, with a dramatic 50\(\mu\)s long 60A peak. There is a general uncertainty whether this peak comes from a collapsing plasma field within the thruster, or if it is a discharge of large output capacitors within the PPU itself. While there was no information available or resources to research this peak at the time, the choice of adding this peak to the final emulator architectural design was natural, since it was noticed during this particular coupling test. To solve the high current peak issue, a programmable electronic load, therefore, needs to have a sufficiently high slew-rate for the user of the emulator to be able to impede the PPU in this manner.

---

\(^2\)The breathing frequency of a thruster is usually between 10kHz to 30kHz and is due to the difference in ionization and acceleration time-scale, as these two phenomena do not directly synchronize.
3.3 Cathode Ignitor and Keeper

The dual-function Ignitor and Keeper impedances represent two distinct physical phenomena occurring in the cathode, both supplied by a single power supply within the PPU. From an electrical perspective, the impedance seen from the PPU power supply switches from one load to another after a certain trigger event. As stated in chapter 2 Background, a number of ignition pulses are supplied to the cathode ignitor after cathode heat-up, which then causes Xenon ionization and therein a plasma flow from the Keeper to the cathode; the Keeper impedance represents the plasma flow which occurs after a successful ignition. The following requirements are addressed in this section, as well as in chapter 4 Hardware.

1. **Performance** The Ignitor load shall switch to keeper mode in more than 100 µs and less than 1 ms.

2. **Electrical** All loads connected to the PPU shall be galvanically isolated from the TEM internal electronics and power / communication signals.

3. **Electrical** For the components used in the various loads of the TEM (except the anode to cathode active load), components shall have a 100% margin towards the highest current and voltage that can be delivered by the associated PPU supply.

The current limited high-voltage pulse train of the PPU is only able to supply current for the high impedance Ignitor sequence. As soon as current flows through the low resistance loop from keeper activation, the pulse supply voltage will drop due to current limitation, and a parallel 5 A DC supply feeds the cathode keeper current, i.e. the Keeper impedance. The following impedance models in figure 3.6 represent the two phenomena. The voltage pulse-fed Ignitor impedance represents the cathode ignition. Upon successful ignition, the 5 A DC Keeper supply feeds the keeper impedance. The supply values can be seen in table 3.2.

![Impedance Model of Ignitor and Keeper](image)

(a) Ignitor Impedance. (b) Keeper impedance.

Figure 3.6: Impedance Model of Ignitor and Keeper. The supply on the impedance is shared, but are named differently in the model due to simulation reasons.

<table>
<thead>
<tr>
<th>#</th>
<th>Impedance</th>
<th>Voltage</th>
<th>Current</th>
<th>Waveform</th>
<th>Impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>Ignitor</td>
<td>350 V</td>
<td>115 mA max</td>
<td>Pulse&lt;sup&gt;3&lt;/sup&gt;</td>
<td>100 kΩ &amp; 10 nF</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>Keeper</td>
<td>25 V</td>
<td>5 A</td>
<td>DC</td>
<td>5 Ω</td>
</tr>
</tbody>
</table>

Table 3.2: The characteristics of the Ignitor and Keeper impedances with associated supplies.

To emulate the switching from high voltage pulses to high current DC, an amount of electronic logic is required for activating the DC discharge. This logic measures the voltage along the supply line against a user input value, then an electric switch sinks the keeper impedance, in turn activating the keeper discharge. All power supply switching is done internally on the PPU side passively, with no requirements on supply switching on the emulator side. Therefore, the supply switching is controlled by the sinking of current through the keeper resistance, which is ultimately done by the active logics. Figure 3.7 depicts the internal PPU supplies connected to the two impedances representing the Ignitor and Keeper. The logics is represented by an arbitrary N-Channel MOSFET with its *gate* connected to a power supply. A representative series resistance of 3 kΩ limits the current out of the pulse-train supply.

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<sup>3</sup>10 Hz square wave pulse with 4% Duty cycle.
Figure 3.7: Ignitor and Keeper impedances with PPU internal supplies. Diodes block any cross-supply currents from impeding their functionality towards the Ignitor and Keeper loads.

The electrical reference for both phenomena is the CRP. These aforementioned supplies are the PPU interfaces to this emulator. As the function of the Ignitor is present during thruster start-up, independent of mode, its duration as an impedance is significantly smaller in comparison to the Keeper’s on-time. While the Ignitor impedance on-time is in the order of milliseconds, the Keeper impedance is seen by the PPU up until the Anode-Cathode discharge has occurred, which can be up to several minutes later [7]. While a successful ignition has previously always occurred on the first Ignitor pulse, as seen during the SMART-1 mission, the PPU is still instructed to supply the pulse-train until an internal time-out has been reached. For this reason, it is vital that a selectable pulse triggering event exists in the emulator such that the user of the emulator can set the number of pulses the Keeper shall engaged. From the previously stated behavior, in addition to requirements 1 to 3 set for the Ignitor and Keeper emulator and general emulator requirements 1 to 3, the conceptualized Ignitor and Keeper shall...

- ...measure the voltage on the shared Ignitor and Keeper supply
- ...count the Ignitor pulse train pulses
- ...compare the amount of Ignitor pulses to a value that the user sets (above 10 pulses)
- ...sink current through the Keeper resistance when compare value has been reach
- ...reset both counter value and latch upon user command in such a way that the Keeper logic can be disabled or restarted

The following figure 3.8 is a block diagram realizing the higher level schematic of the Ignitor and Keeper emulator circuit according to the above mentioned requirements.
3.4 Magnets

The following section handles the electromagnet’s architecture and impedance. These powerful magnets are responsible for trapping the free electrons from the plasma to produce the HET thrust by transferring the ion-acceleration into a reactive force on the body of the thruster. The following requirement is specific for the inductance that models the magnets.

1. **Performance** Inductor saturation current shall have a 100% margin towards the highest current that can be delivered by the associated PPU supply.

The Hall Effect thruster cannot be credited to its name without keeping the azimuthal flow of electrons in place. This is done by using the five large magnetic coils biased with a steady state current positioned in such way that there is a strong magnetic field across the opening of the thrusters annular chamber. For the emulator, these five solenoid coils together make up a large series inductor, and equivalent series resistance (ESR), between the Magnet supply and Magnet return.

The following figure 3.9 shows the simplified schematic of the emulator equivalent series load.

![Figure 3.9: Thruster magnet impedance. The inductance value is the collective series inductance.](image)

The ESR is temperature dependent, ranging between $1.35\Omega$ at room temperature, up to $4.3\Omega$ during hottest case scenario of firing, which quadruples the dissipated power in the emulator to just above $200W$. The magnet supply in the PPU is a current source, implying it will raise the required voltage across the magnets to conform to the corresponding current. [19] It is, therefore, important that the emulator takes into account the worst case scenario, i.e. highest power and largest resistance, and with a series current sense resistor, the current can be used to monitor the impedance according to figure 3.3. While this emulator load is completely passive, no
off-the-shelf inductor existed on the market that could fulfill these above stated design parameters in conjunction with the previously listed requirement 1, as far as the student knew at the time of the internship. Therefore, the development of such an equivalent inductor required meticulous research and understanding of electromagnetic theory. The primary challenge of using a single equivalent coil is to match the marginless 7A current requirement without saturating, therein degrading the inductance of the core material.

3.5 Cathode Heater

The Cathode heater passively loads the PPU during the cathode heating phase of the thruster operation, which is required prior to cathode ignition and, therefore, only during start-up. The schematized impedance and expected current are presented in figure 3.10. Since the heater coil sits within the cathode, its electrical reference is to the CRP, just like the Anode voltage and ignitor and keeper supplies.

![Figure 3.10: Heater impedance and expected current from the PPU.](image)

As a heating element the coil’s nominal output heat is:

\[ W_{\text{dissipated}} = I_{\text{nominal}}^2 \cdot R_{\text{heater}} = 10A^2 \cdot 0.5\Omega = 50W. \] (3.1)

The heater supply in the PPU is a current source which regulates the current through the heater. [19] If the heater resistance increases, a higher voltage is required to pass the same amount of current through the heater. For a current source constantly providing 10A, the dissipated heat will increase. This scenario could risk the heater cascading into a destructive positive feedback-loop in which the heat eventually destroys the wire, causing an open circuit. Without the ability to pre-heat the cathode, no ignition can occur. The choice was made to choose the nominal hot case resistance of 500m\(\Omega\) to emulate the hottest case.

3.6 Xenon Flow Control Valves

A mechanical dual-valve assembly is positioned down-stream from the filter within the XFC, to figure 3.11. The purpose of these valves are to facilitate the separation of Xenon flow between the thruster and the propellant tank. They remain closed at all times except for during thruster firing according to the resulting sequence presented in figure 3.3.

![Figure 3.11: XFC Xenon flow-chart, containing the dual-valve assembly, thermosthrottle, and distribution to the Anode (92%) and Cathode (8%).](image)

As for the Valve’s representation, it is important to understand the setup and operation of the dual valve block electrically. In the mechanical setup of the XFC, two values are in series with the Thermosthrottle, of which both
require individual biasing to be opened. On an electrical level they are controlled separately and the following figure 3.12 shows the resulting electric impedance.

![Impedance schematic of series-connected valves, connected in parallel electrically.](image)

Figure 3.12: Impedance schematic of series-connected valves, connected in parallel electrically.

Since the valves are each solenoid-valves, they are controlled electrically using solenoid coil inductors to create a magnetic field that open or close either the primary valve, or a pilot valve, depending on the structure. Nonetheless, all solenoid valves convert electrical energy to magnetic energy, which then mechanically moves a piston to open or close the valve. This is the reason for there being two inductors in the emulator equivalent model. Additionally, a higher voltage is required to open the solenoid valve than to maintain its opened position. This procedure optimizes the opening response time of the valve, which is due to the static friction of the valve piston. The two valves are each electrically represented as,

\[
Z_1 = (200 + j\omega 0.500)\Omega \\
Z_2 = (200 + j\omega 0.500)\Omega.
\]

For which the equivalent impedance follows as

\[
Z_{eq} = Z_1/Z_2 = \frac{Z_1Z_2}{Z_1 + Z_2}
\]

However, since the values are identical for each valve, \(Z_{eq}\) becomes

\[
Z_{eq} = \frac{Z^2}{2Z} = \frac{Z}{2} = (\frac{200}{2} + j\omega \frac{0.500}{2})\Omega
\]

leading to

\[
\begin{align*}
R_{eq} & = 100\Omega \\
L_{eq} & = 250\,mH.
\end{align*}
\]

With these equivalent values, the maximum current through the XFC Valve emulator will be \(I_{opening} = \frac{27V}{100\Omega} = 270mA\) during valve opening at 27V, and approximately 100mA during its maintain voltage of 10V. Ultimately, this impedance is purely passive, with no additional requirements, and only needs its voltage to be measured for the TEM.

### 3.7 Xenon Flow Control Thermothrottle

The Thermothrottle is covered in this section, and it can be seen as the component downstream from the valves in figure 3.11. The TT is, apart from thruster biasing, the true “gas pedal” of the thruster. It’s capillary tube allows for Xenon to flow through when it is not contracted by a current flow through it, and it, therefore, has an inverse relationship to the massflow. The following requirement adheres to the TT.

1. **Performance** The anode discharge current shall be a function of the Thermothrottle current provided by the PPU to the TEM Thermothrottle load.
Fortunately for the design of this impedance, nearly no factors exist for which its power changes. Therefore, the TT has a constant impedance model according to the following figure. Since the current through the thermothrottle is of importance for the thrust, it only requires a current sensing series resistor for architectural design completeness. The impedance is seen in figure 3.13.

![Figure 3.13: Schematic of Thermothrottle impedance.](image)

To fulfill the requirement, the measure current needs to be used in a look-up table to adhere to Safran’s mathematical models for converting TT current to HET thrust. [22]
Chapter 4

Hardware

This chapter presents the hardware design portion of the Master’s Thesis where the student conducted high and low power electronic load laboratory tests, prototype Printed Circuit Board (PCB) development, as well as pre-study work and manufacturing of different inductors.

4.1 Anode-Cathode Electronic Load

The following section presents a technical summary of the actions taken by the student to test a representative electronic load for use in emulating the Anode to Cathode discharge voltage and current. For additional detailed information of the procedure, please see Appendix A: Test report - Electronic Load.

*Electro-Automatik* Recoverable Electronic Loads

To fulfill the complex voltage and current behavior of the HET Anode-Cathode discharge at the high power intended, a programmable electronic load was chosen as a solution for impeding the PPU, before the thesis project began. This served as a starting point for the master’s thesis. The suggested programmable load was the *EA-ELR-9000* series, with two examples from this series presented in table 4.1. The primary reason for choosing this specific series was that it impeded the power supply by re-supplying the power-grid with energy, rather than running the load energy through, e.g. resistors that would heat up. [16] Because of this recovery function the load saves up to 80% of its energy since it does not dissipate as much heat as a standard 5kW load would otherwise do, therein requiring less cooling for the final product.

Table 4.1: Technical summary of the two programmable loads [16]. The first load was the preliminary choice for the final product and the second load was used for concept testing.

<table>
<thead>
<tr>
<th>Name</th>
<th>Voltage</th>
<th>Current</th>
<th>Power</th>
<th>Interface</th>
<th>Unit Size</th>
<th>Input Supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>EA-ELR 9500-30 HP</td>
<td>≤500V</td>
<td>≤30A</td>
<td>5kW</td>
<td>LabView &amp; Front Panel</td>
<td>3U - 19”</td>
<td>3-Phase 16A</td>
</tr>
<tr>
<td>EA-ELR 9080-170 HP</td>
<td>≤80V</td>
<td>≤170A</td>
<td>5kW</td>
<td>LabView &amp; Front Panel</td>
<td>3U - 19”</td>
<td>3-Phase 16A</td>
</tr>
</tbody>
</table>

Minimal Time-step issue

The first load was intended to drive the primary Anode-Cathode discharge according to the simplified elbow curve presented in chapter 3: Architecture. With regards to the Anode-Cathode requirement 6, i.e. ability to step from one current to another within time-frame required, it was noted that the minimum time-step of the load was 5ms. This minimum time-step did not comply with the requirement and, therefore, the load would be unable to properly emulate the large initial start-up current peak that can be seen in figure 3.5, which a piece-wise linear curve would require at least 30µs per point. OHB Sweden organized a loan of the second electronic load, namely the low voltage version in the table above, so that the student could get familiarized with handling the device, as well as verify the previous conclusion. This test was conducted during the last week of April and the results agreed with the reviewed conclusion that the load series was unsuitable for the intended

1Standardize unit of height for assembly racks. [24]
use. For more information regarding the test and conclusions, see Appendix A: Test report - Electronic Load. Further analysis showed that electronic loads from the same company, Elektro Automatik, without the recovery function, was able run at a much higher time-stepping frequency, allowing for the large current spike, as well as emulating the previously mentioned Breathing Frequency. In other words, by review of the datasheet, the non-recoverable load, namely EA-EL 9750-120 B\textsuperscript{2}, was able to step current draw from 10\% to 90\% in \( \leq 18\mu s \). [16] An electronic load from this series was never lent to OHB Sweden and, therefore, this was never confirmed through testing.

**LabView Compatibility issue**

Simultaneously, it was noted that interfacing with the electronic load using National Instruments, NI, LabView, was problematic. The bundle of drivers required to fully connect the LabView and load were poorly documented and seemed outdated, with missing files making the program unable to run after installation. There was also no clear way of properly synchronizing the electronic load for use in additional LabView instruments which would be developed for monitoring the system. Because of the lack of software support for the project, integration miss-match, and with *ad hoc* solutions being the only way to progress to run an electronic load with possible non-deterministic behavior, the idea of having a complete electronic load for use as primary discharge emulator was abandoned. An in-house designed current sink was chosen as a new architectural solution at the end of the thesis project and is not presented in this thesis report.

\footnotesize{\textsuperscript{2}Electronic Load for up to 750V, 120A, and maximum 7.2kW.}
4.2 Ignitor & Keeper Circuit

The following section contains the design development of the Cathode Ignitor and Keeper circuitry from electric schematic to a routed PCB and verification. For additional detailed information of the procedure, please see Appendix B: Test report - Ignitor and Keeper.

While procuring the two Ignitor and Keeper impedances only required input on their characteristics and expected values, the logic driving this active setup required a deeper level of electrical engineering. The choice was made to produce a PCB housing all required logic to fulfill the necessary tasks to impede the PPU correctly for thruster Ignitor and Keeper emulation. The block diagram in the previous Architecture chapter is expanded block by block to bring the logic to a lower level, eventually reaching an electric schematic, with final component choices present at the end. An expanded block diagram is presented in figure 4.1 and represents a more detailed layout of the circuit schematic to be developed to fulfill the Ignitor and Keeper logic's circuit. The diagram arrows show the direction of information. Each block in the diagram is addressed in the following paragraphs.

Figure 4.1: Expanded Ignitor and Keeper logics block diagram.

Voltage Divider

During the PPU’s Ignitor mode supply, a pulse train is impeded by the Ignitor load only, since the Keeper impedance has no closed circuit loop to the CRP. However, since the node is supplied with a high voltage, most integrated circuits will take damage when presented with such a high electric potential. A voltage divider is a fundamental dual-resistor layout which splits the voltage magnitude according to the following correlation

$$V_{\text{out}} = V_{\text{in}} \times \frac{R_{\text{shunt}}}{R_{\text{shunt}} + R_{\text{series}}},$$  \hspace{1cm} (4.1)

where $V_{\text{out}}$ is the desired output voltage from the divider, $V_{\text{in}}$ is the nominal supply voltage pulse, i.e. 350V, $R_{\text{shunt}}$ lies in parallel with the output voltage, and $R_{\text{series}}$ between the input and output. [14] The following list summarizes the characteristics of the voltage divider when resistors from the E-series\(^3\) are chosen to match the voltage input and output relationship of $\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{5}{350} = \frac{1}{70}$.

Table 4.2: Resulting Voltage Divider Values.

<table>
<thead>
<tr>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{\text{in}}$</td>
<td>350V  \quad Input voltage pulses</td>
</tr>
<tr>
<td>$V_{\text{out}}$</td>
<td>5V \quad Typical IC voltage level</td>
</tr>
<tr>
<td>$R_{\text{series}}$</td>
<td>68kΩ</td>
</tr>
<tr>
<td>$R_{\text{shunt}}$</td>
<td>1kΩ</td>
</tr>
<tr>
<td>$I_{\text{in}}$</td>
<td>5mA \quad Through series resistor</td>
</tr>
</tbody>
</table>

\(^3\)System of preferred values for electronic components. The E-Series is an approximately logarithmic division of values between 1 to 10. The number after the E determines the amount of times the value span is divided logarithmically, e.g. the E6 series span is divided 6 times, yielding 1.0, 1.5, 2.2, 3.3, 4.7, 6.8.

22
**Low Pass Filter**

Designing any electronics virtually risks neglecting the reality of electric noise that is present in any real world system. A switching high voltage Ignitor supply risks introducing a high level of noise coming from the supply’s switching. The length of wiring from supply to load, and noise producing by the load itself rippling back through the wires and into the voltage divider can also increase noise. Indeed, the divider input does not discriminate between voltages and any noise present on the supply line will be reduced in amplitude. However, implementing a low-pass filter after the divider will smooth out any undesired voltage behavior on that node. Implementing a shunt capacitor on the desired 5V voltage divider output node, creates a Resistor/Capacitor (RC) low-pass filter together with the 68kΩ resistor. An RC filter causes a first order bend to the step response transfer function such that the time-constant \(^4\) is

\[
\tau = R_{eq} * C_{shunt}[s],
\]

where \(R_{eq}\) is the equivalent parallel resistance of the voltage divider and \(C_{shunt}\) is the capacitor to be sized. Following the E-series of preferred numbers was more comfortable prior to any simulations. The equivalent resistance \(R_{eq}\) is

\[
R_{eq} = \frac{R_{shunt} * R_{series}}{R_{shunt} + R_{series}} \approx 985.5\Omega.
\]

Using the result from equation 4.3, together with a preferred number capacitance of 1\(\mu\)F in equation 4.2

\[
\tau = 985.5\Omega * 1\mu F \approx 1ms,
\]

meaning after 1ms the 63% of the voltage has been reached. This first-order voltage behavior fits well with the input, as it reaches its final value of 5V by 4ms with just a 2% error, while simplifying design choices. \[14\]

**Buffer & Schmitt Trigger**

The next two blocks were solved using an operational amplifier in two different types of configurations. Indeed, the operational amplifier has many applications, but for this circuit no amplification is needed. To avoid compromising the voltage after the divide circuit, the output voltage has to be buffered by a unity gain operational amplifier. The high impedance input of the buffer will draw a minuscule current from the shunt resistor and the voltage at the output of the divider will not be modified. Therefore, a load can be placed after the buffer, drawing current from its low output impedance.

Fundamentally a comparator function, the Schmitt Trigger’s distinct function is its ability to vary the trigger value depending on the previous output state, i.e. *hysteresis*. The practical implication of a Schmitt Trigger is that it defines the input trigger level differently depending on the output state in such a way that there is no need for a harsh definition when the value is exactly at the trigger value.

For the Ignitor and Keeper logics, a Schmitt Trigger is used as a tool, in conjunction with the input low-pass filter, to smooth out any noise and let register only Ignitor pulses of the correct voltage amplitude and temporal length for the counter circuit coming thereafter. For describing a Schmitt Trigger function best, figure 4.2 presents the output voltage as a function of the input voltage in a non-inverting configuration. The output is presented as two states, \(V_H\) and \(V_L\), and two thresholds on the abscissa, \(V_{TL}\) and \(V_{TH}\), centered around a value \(V_R\). Starting with an output state of \(V_L\), the input is required to be at \(V_{TH}\) before the output changes state (seen by following the blue line), but once in the \(V_H\) state, the input must fall past \(V_{TL}\) before the output flips back to its original \(V_L\) state (seen by following the red line). This is the fundamental idea of hysteresis, which a Schmitt Trigger accomplishes. \[14\] The \(V_R\) threshold is a bias value used in this particular case since all input values are positive.

---

\(^4\)Time-constant is defined as the time it takes for a value to reach \(1 - \frac{1}{e} \approx 63\%\) of its final value for a low to high step response.
In figure 4.3 a schematic of the Ignitor and Keeper logics input blocks are presented, designed according to the previously mentioned specifications, requirements, and design explanations.

The choice of using a 1kΩ input resistor and 3kΩ feedback resistor to the positive lead of the Schmitt Trigger is a result of the iterative design through simulations in LTSpice. Since a time-constant of 1ms was chosen previously, a shark-fin shaped 5V wave inputs the Schmitt Trigger. Having the time-constant as a starting point, the center reference value, $V_R$, is set to 63% of 5V, i.e. 3.15V, is set on the Ref inverting input. Thereafter simulations were made to find an appropriate feedback resistance. Finally, a Zener diode, i.e. a diode with a very precise reverse breakdown voltage of 5.6V, is shunted to the buffer input as a clipper in case any higher voltages are presented to the Ignitor and Keeper supply. [14]

Digital Design

The following titles describe the logics portion of the Ignitor and Keeper circuit, which encompasses digital electronic design.

Counter

From the Schmitt Trigger onwards, the signal is seen as digital, and the first digital circuit to receive this signal is a 4-bit integrated counter circuit which receives the pulse values, known here as the clock (CLK) input and outputs four signals, each representing its own bit. Internally, a counter contains a series of state-changing circuits that requires either a rising or a falling edge to switch states. These toggle circuits are called Flip-Flops. [14] In particular for this setup, a series of developed flip flops called a JK flip flops are shown in figure 4.4.
(a) Logics diagram.

(b) Truth table. Only a rising edge is used to trigger here.

Figure 4.4: JK Flipflop truth table. Only a rising edge is used to trigger here.

If several of these latches are connected in series, such as in figure 4.5a, with the first one’s output connected to the second one’s input, etc, it is evident that twice as many input cycles are required per JK Flipflop to cycle its respective output from low to high. The following table 4.5b is produced, corresponding directly with the behavior of bit-wise counting of a clock pulse. [14] The series of Q-values represent the bits, with A being the least significant bit (LSB) and D the most significant bit (MSB).

(a) String of JK Flipflops in series.

(b) Table of pulse counter to 4-bit representative value.

Figure 4.5: Counter internal JK Flipflop layout. Image from datasheet of counter used in final product.

The counter chosen for this application is presented after the explanatory section in table 4.4, with device choice justification and trade-off considerations.
Comparator

The four output bits of the counter can be directly connected to a comparator circuit that contains a series of logical AND circuits which compare the individual bits to the desired value to be compared to in equally many bits. If there is a bit-wise match between the counter’s bits and the user’s bits to compare, the comparator changes output state. Depending on the comparator design, the output can behave differently. [14] For the intended design of the Ignitor and Keeper logics, the comparator output should...

- go to a logic high value when the counter bits match the user bits
- go to a logic low value during all other bit-wise combinations, independent on previous value.

The counter and comparator circuits connect in the following manner present in figure 4.6. Quasi-code has been written within the comparator block to further clarify its internal operation.

It is important to note the issue that would arise if one were to connect the comparator output directly to the current sinking Keeper MOSFET. While the comparator would indeed raise the voltage on the output pin, which might activate the MOSFET, this only occurs if, and only if, the conditions are fulfilled. For a pulse with the characteristics listed in chapter Architecture, table 3.2, the counter will cycle through all its bit values every 1.5 seconds, and only one combination of these bits allow for the output to go high. The solution is complementing the counter and comparator pair with a circuit that toggles the output value and does not return to its original state once the condition no longer holds.

The comparator chosen for this application is presented after the explanatory section in table 4.4, with device choice justification and trade-off considerations.

Latch

A simplified version of the JK Flipflop from the counter can be setup to toggle the comparator output, called an SR latch as seen in figure 4.7 with associated truth table in table 4.3. [14] The Q pin can be used as the
desired output of the latch, which is the input from the comparator. \(^5\)

![SR latch circuit containing two NAND logic blocks.](Image)

Figure 4.7: SR latch circuit containing two NAND logic blocks.

<table>
<thead>
<tr>
<th>(S)</th>
<th>(R)</th>
<th>(Q)</th>
<th>(\overline{Q})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>Last value</td>
<td>Last Value</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4.3: SR latch truth table. Having \(S\) and \(R\) both high at once gives a non-deterministic value.

The latch chosen for this application is presented after the explanatory section in table 4.4, with device choice justification and trade-off considerations.

**Gate Driver**

A latched signal fed directly into the gate of the N-Channel MOSFET will, according to the theoretical design, activate the transistor to sink the current through the Keeper impedance. However, a signal is generally considered steady voltage transferring information between high impedance components. The gate input capacitance of MOSFET needs to be charged for its activation, i.e. a gate current is required. [14] Therefore, it is good practice for an electrical engineer to add a low output impedance gate driver circuit to, in a sense, convert the digital signal to an analog switching voltage. [13] A gate driver is nothing more than a current source to deterministically drive the MOSFET into a conducting switch.

The driver used for this circuit incorporates two output NPN transistors in a high-side and low-side series configuration, able to swing its output voltage between the drivers positive and negative supply. In this way the high-side NPN can source current, and the low-side NPN sink current, depending on what is needed. For the final setup, no negative supply was used, the driver was connected from 12V to CRP. The driver chosen for this application is presented after the explanatory section in table 4.4, with device choice justification and trade-off considerations.

**Reference Potential & Isolator**

The reference potential for the Ignitor and Keeper impedances is the CRP and because of this, any measurement system and thereafter logic upstream from the signal, must also be referenced to this specific potential. However, a grounding problem arises when any external system measures, inputs, or outputs a voltage from this logic circuit that is not referenced at the same voltage. To avoid this problem, electrical isolators need to be implemented to handle these inputs and outputs.

The general types of electrical coupling between a source and a load, denoted victim, is presented in the following figure 4.8.

---

\(^5\)Most real logic circuits contain a large amount of periphery circuitry to avoid non-deterministic behavior, current protection, over-heating protection, etc.
Two common methods of isolating a signal are by inductive isolation through transformers or electromagnetic radiation through optical isolators. These methods are represented by the radiative and inductive paths in the figure above.

For the Ignitor and Keeper logics, the input and output signals were chosen to be isolated inductively because of heritage from previous projects. Therefore, a multichannel transformer-style isolator was implemented in the design, allowing all signals referenced to the CRP to become signals referenced to the common ground outside the circuit. The following figure, 4.9, presents the internal functionality of the isolator circuit taken from the datasheet of the final chosen component. This digital isolator receives signals referenced to one ground and encodes the signal internally to match the parameters required for sending the signal through the minuscule internal inductor. [15]
Ignitor Keeper Result

The resulting Ignitor and Keeper logics schematic, figures 4.10 through 4.15, was developed from the previous design explanation. The primary components, those explained in the previous section, are listed in table 4.4 with some design justifications.

Figure 4.10: Ignitor pulse input with buffering and filtering through a Low-Pass filter and a Schmitt Trigger.

Figure 4.11: Ignitor and Keeper Counter, Comparator, and Latch.

Figure 4.12: Ignitor and Keeper gate driver and low-side MOSFET.
Figure 4.13: Ignitor and Keeper Input and Output isolation.

Figure 4.14: Ignitor and Keeper input power and power regulation.

Figure 4.15: Ignitor and Keeper Latch and Counter reset circuits, which allow reset on circuit power cycling.
The following table contains the chosen primary components for the Ignitor and Keeper logics circuit. The datasheets can be found by clicking the hyper-link of each component on their names. The short justification column explains the primary reason for choosing that particular model. Digital I/O matching is included in this justification by noting that all components are Transistor-Transistor-Logic (TTL) compatible, meaning they all output a voltage range which is deterministic for the receiving component. [14]

Table 4.4: Primary components in the Ignitor and Keeper Circuit, the names contain hyperlinks to their datasheets.

<table>
<thead>
<tr>
<th>Device</th>
<th>Name</th>
<th>Attributes</th>
<th>Justifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Op-Amp</td>
<td>OPA171AID</td>
<td>12V Supply Range</td>
<td>Single channel SO-8 package</td>
</tr>
<tr>
<td>Counter</td>
<td>SN74LS93N</td>
<td>TTL 4-bit Counter</td>
<td>Rising Edge triggering JK flip flop design with simplistic reset</td>
</tr>
<tr>
<td>Comparator</td>
<td>SN74LS85N</td>
<td>TTL 4-bit Comparator</td>
<td>Versatile yet simple design, I/O implementation easy</td>
</tr>
<tr>
<td>Latch</td>
<td>SN74HC74D</td>
<td>TTL D-Flipflop Latch</td>
<td>Fewest channels available</td>
</tr>
<tr>
<td>Driver</td>
<td>LM5110-1M</td>
<td>TTL Dual Channel 3A Output</td>
<td>Non-inverting, dual channel can be connected in parallel</td>
</tr>
<tr>
<td>MOSFET</td>
<td>FCP22N60N</td>
<td>600V, 22A, 205W N-Channel</td>
<td>Matches Requirements, TO-220 Package</td>
</tr>
<tr>
<td>Isolator</td>
<td>ADuM260N0</td>
<td>6 Channel one way isolation</td>
<td>Used in opposite direction for remaining PCB outputs</td>
</tr>
</tbody>
</table>

Power Regulators

The following table lists the power regulators and some power-associated decouple capacitors to stabilize voltage levels.

Table 4.6: Power related components for the Ignitor and Keeper Circuit, the names contain hyper-links to their datasheets.

<table>
<thead>
<tr>
<th>Device</th>
<th>Name</th>
<th>Attributes</th>
<th>Justifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Regulator</td>
<td>LD1086DT50TR</td>
<td>5V Output</td>
<td>Low dropout, simple 3-lead setup</td>
</tr>
<tr>
<td>DC/DC Isolated</td>
<td>THM 6-1212</td>
<td>18V 6W</td>
<td>Regulator with heritage and brand offers wide range of well documented products.</td>
</tr>
<tr>
<td>Power Regulator</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supply Capacitors</td>
<td>Tantalum Type</td>
<td>10µF</td>
<td>Low ESR, recommended from datasheet</td>
</tr>
<tr>
<td>Decouple Capacitors</td>
<td>Ceramic Type</td>
<td>100nF</td>
<td>Heritage from previous student projects</td>
</tr>
</tbody>
</table>
4.3 Magnets Emulator Inductor

The following section covers a summary of the prestudy results of manufacturing an inductor for use as the final product electromagnet for the TEM. For additional detailed information of the procedure, and testing of the magnetic cores, please see Appendix C: Test report - Magnet Core.

For the previous two hardware components, consideration had to be made of the dynamic behavior including steady state oscillations, transient peaks, internal supply switching, and integrated electronic logic. For the case of the magnet inductors, an analysis based on fundamental electromagnetism was required, even though there is no dynamic range for the magnet during steady state use. [17] The equivalent inductance and ESR, presented in figure 3.9, requires a design involving a ferromagnetic core of which the wiring is wound around to take advantage of the materials high magnetic permeability, rather than using air as the magnetic core which is the case in low inductance inductors. [9] Balancing this design requirement with a high DC current, however, was a challenge. The following section contains theoretical calculations for inductors constructed around a ferromagnetic core which is designed to encapsulate the magnetic field lines in a closed-loop fashion.

Inductance of a Coil

A current through a conductor, such as a wire, will induce a magnetic field perpendicular to the current around the conductor concentrically, inversely proportional to the distance from the conductor. Winding the conducting wire in a solenoid loop will focus the magnetic field through the center of the solenoid loop, therein creating a solenoid inductor. [9] Henceforth, all calculations are based on a solenoid winding geometry.

The inductance of an inductor is the ratio of voltage across the inductor per rate of change of current through the inductor and is one of the primary properties used to define the inductors ability to store electric energy within its induced magnetic field. [14] While an inductor can be used for a smorgasbord of electrical and electronic applications, from transformers, to radio receivers, to filtering, etc, the inductor analyzed in the following section only encompasses DC voltages and currents. [14]

The inductance of a solenoid coil is

\[ L = \mu \frac{N^2 A l}{l} = N^2 A_l \]  

(4.5)

where \( \mu \) is the permeability of the material, \( N \) is the total number of windings of the coil, \( A \) is the cross-section area, and \( l \) is the length of the coil over which it is wound. This is generally lumped into a single inductance constant called \( A_l \). [11]

For the TDK N27 Ferrite Core, the primary core chosen for the test, the following values are given:

Table 4.8: Characteristics of the TDK N27 Ferrite Core, from the TDK Datasheet. The relative permeability is listed here as \( \mu_r \), is multiplied by \( \mu_0 = 4\pi \times 10^{-7} \frac{H}{m} \).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_c )</td>
<td>1720mm²</td>
</tr>
<tr>
<td>( l_c )</td>
<td>200mm</td>
</tr>
<tr>
<td>( \mu_r )</td>
<td>1480</td>
</tr>
<tr>
<td>nominal ( A_l )</td>
<td>16000nH/N²</td>
</tr>
</tbody>
</table>

Therefore, the copper wire turns required for this core is,

\[ A_l = \frac{L}{N^2} * 10^{-9} \Rightarrow N = \sqrt{\frac{20 \times 10^{-3}}{16000 \times 10^{-9}}} \approx 35 \text{ turns}. \]  

(4.6)

Core Saturation

Saturation is an effect that occurs in ferromagnetic materials, such as the core used within a solenoid coil. In a demagnetized ferromagnetic core, the random distribution of small permanent magnetized regions, called domains, cancel each others fields out when summed across the whole core. Upon external magnetization, the regions will align with the external field lines, causing the core to be magnetized accordingly. However, this

\[^{6}\text{Permeability is the ratio between the } \vec{B} \text{ and } \vec{H} \text{ fields at the origin. This is also called the BH-Curve.} [11][9] \]"
effect is limited since each magnetic dipole within a domain rotates in accordance with the magnetic field lines, therefore altering the shape of the domain structure until the much larger crystalline structure wall restricts further deformation. [10] When this occurs, the material acts as paramagnetic, where large external magnetic fields are required for further internal magnetization. The effect of this is loss of inductance with increased magnetization. [10]

The following BH-curve realizes the relationship between the \( H \) and \( B \) fields.

![Figure 4.16: The B-H curve, from TDK N27 Ferrite Core Datasheet, May 2017.](image)

The saturation can be seen here as the right-hand tending bend in the curve as \( H \) increases. The non-linearity begins at around \( \sim 350mT \), and this is denoted as the saturation \( B \)-field since it marks the end of the linear behavior of the core. Exceeding this limit would, therefore, be considered driving the core into saturation. [9]

The ratio between the two fields is called the permeability,

\[
\mu = \frac{B}{H},
\]  

(4.7)
The B-Field within a solenoid inductor can be concluded from Ampère’s Law under certain conditions\(^7\) to

\[ B = \mu \frac{IN}{l}, \]  

(4.8)

where \( I \) is the current passing through the solenoid wire and the remaining parameters are the same as the previous equation 4.5.

Defining, as before, a maximum B-Field at the upper boundary of the linear region of the BH-curve, for which the same permeability holds, and assuming a constant number of windings and path length, a maximum current \( I_{\text{max}} \) can be defined. Applying some formula tricks by combining equation 4.5 with 4.8 yields:

\[ B_{\text{sat}} = \frac{I_{\text{max}} N}{\mu N^2 A} = \frac{I_{\text{max}} L}{\mu N^2 A} = \frac{I_{\text{max}} L}{N A}. \]  

(4.9)

In this way, one can simplify the design of inductor by simply using this one equation [12], which is

\[ B_{\text{sat}} NA > I_{\text{max}} L. \]  

(4.10)

This leads to the following maximum current for the TDK EPCOS Ferrite core

\[ I_{\text{max}} = \frac{B_{\text{sat}} NA}{L} = \frac{0.350 \times 10^{-3} \times 35 \times 1720 \times 10^{-6}}{20 \times 10^{-3}} \approx 1.1 A. \]  

(4.11)

From the saturation test, in Appendix C: Test report - Magnet Core, the resulting saturation current was 0.68A. Whichever the case, both theoretical and practical, these currents are nearly twenty-fold times less than what is required.

\(^7\)The length of the coil is much greater than the radius of the winding and thickness of the wire.
Chapter 5

Conclusions

The project focused on solving four major emulator challenges which were deemed particularly difficult. This included the general on-paper development summarizing and simplifying all impedances within the TEM, as well as a broad functionality basis explaining how the TEM works in accordance with the PPU. Additional studies and manufacturing were made on, 1) the primary thruster Anode to Cathode discharge electronic load feasibility study, 2) the prototyping of the Cathode Ignitor and Keeper Emulator, and 3) finally performing a feasibility study for the large power inductors used to emulate the thruster magnets.

5.1 Emulator Architecture

The primary focus of this development was towards the general conceptualized architecture of the TEM, which culminated in the compilation of the HET information into its electrically interfacing units within the Cathode, Anode block, and the XFC. These impedances underwent simplifications in the form of Thévenin and Norton equivalent circuits for which electrical design began through defining power ranges for each unit within the conceptual TEM. Once defined, these units could be directly correlated to the PPU’s and PPS5000’s operational schematics, thus producing a first draft to the operational diagram of the TEM. The developed functional diagram of the emulator is only preliminary, and does not take into account the periphery inputs and outputs such as the LabView functions and the additional sensors, nor does it take into account the measurement system which limits the function of the emulator to a set amount of upper and lower voltage, current, and temperature limits. However, the diagram can be, and was in parallel to the thesis, a base-line for the requirement specification’s development used to further define the TEM’s abilities, therein reducing the amount of TBD’s in the project. Additionally, it also defines the emulator’s role and responsibilities as passive electrical ground support equipment. The remaining units’ load values all have low power ranges, and simplified dynamic ranges with typical off-the-shelf values. Any previous or updated procurement can, therefore, be made without much additional trouble, or even iteration.

Anode Discharge Electronic Load

Any complex electronic load required a plethora of software drivers, pre-designed LabView configurations and possible superfluous functions, which would drive the user to require support from the developer or provider of the electronic load. In addition to the tested load being unable to fulfill the requirements set forth, synchronization was not possible between the load and the rest of the TEM, therefore increasing emulator uncertainties. With a primary goal of the emulator to be an off-the-shelf alternative for the thruster, and with inter-company communication possibly leading to complications, it was concluded that an in-house current sink be developed at OHB Sweden in its stead. In this way, the design can be custom made for the exact application, removing any additional complexity. While this does imply work-hours spent on electrical design and prototyping, it was decided to be the better choice.

Cathode Ignitor and Keeper Emulator

A functional PCB was proven to fulfill nearly all requirements of translating a physical behavior into an electrical circuit to perform as a Cathode Ignitor and Keeper emulator, with the exception of a full end-to-end test due to the lack of high voltage equipment available in the lab during the test phase. However, the prototype requires improvement with not only design errors, but also in properly tailoring to the interface of the future emulator by
improving usability towards the housing of this load, further testing, and final implementation. Apart from that, the design development was a success, allowing the user to further modify the emulator behavior by changing trigger count functionality and potentially also increasing or decreasing the delay between ignition and keeping, therein tuning the load for the correct behavior. While the final TEM will not contain the prototype model, it lays the foundation for the next version to become final hardware.

Electromagnet Inductor Emulator

The thesis work performed on the magnet load is seen as a prestudy resulting in proof that a magnet load cannot be designed directly without hefty EM considerations. With a lack of proper off-the-shelf components at the time, too many variables were introduced without the expertise needed to implement them properly to construct an inductor. Had the magnetic inductor test occurred earlier in the internship, a resulting magnet load could have been spawned through iterative design and testing, however the thesis came to an end before this stage. Fortunately for the project however, an off-the-shelf component was found and procured by the supervisor from a lesser known supplier a few days before the internship ended which solved the issue all together.

5.2 Future work

The following two areas have been chosen to be discussed in terms of suggested future work for the project at the time of the internship termination, since they are seen as the project’s bottleneck.

Anode-Cathode Discharge Current-Sink

Replacing the electronic load for an in-house developed current sink array requires more time for prototyping and design tweaking, including a Failure Mode and Effects Analysis. The design work alone could take an employees full effort to finish disregarding the parallel advances within the project. Since Anode-Cathode Discharge also is the primary power dissipater, the project is more or less pointless without a solved discharge current sink design. However, the freedom of designing the current sink in-house is that the system can be adapted to the exact requirements of the TEM, therein, designing well defined current transient peaks, oscillations, and systems that adhere to all thruster modes of operation. Therefore, this should be of top priority.

LabView Integration

The next architectural challenge for the project would be to focus on the LabView integration plan, with goals to have finalized emulator functions as soon as possible for higher level testing on the more complex components, since any issue arising from here could cause issues with the complex hardware developed. This can occur before the final procurement of the impedances, since tests can be made with power supplies in the lab or with simplified impedances. This development includes the inter-load relationship of the other components of the emulator, to fully adhere to the functional block diagram.
References


[20] Safran SA, *PPS 5000 Thruster Unit - XFC & Thruster Design & Technical Description*, June 2017. UNDISCLOSED.


Appendix A: Test report - Electronic Load
Test Report

EA-ELR-9080 Electronic Load

Master’s Thesis Project - Hall Effect Thruster Emulator

OHB Sweden AB

Author: Robert PERSSON
Supervisor: Enrique LAMOUREUX

May 3, 2018
## Contents

1 Introduction ................................. 1  
  1.1 Equipment Scope .......................... 1  
  1.2 Goals .................................... 1  

2 Method ...................................... 2  
  2.1 Setup of Load ............................. 2  
  2.2 Manufacture of Test Equipment ....... 3  
  2.3 Transient Behavior ....................... 4  

3 Results .................................... 5  

4 Conclusion ................................... 6  
  4.1 Graph Analysis ............................ 6
1 Introduction

The following test report summarizes the activities during week 17 of 2018 of the Elektro Automatik Electric Load ELR-9080 on loan from Divisoft Power Technologies to OHB Sweden. The initial intention of the loan was to try out an identical but scaled down version of a high power electric load for OHB Sweden to be used for the Hall Effect Thruster Emulator Master’s Thesis project 2018.

It came to show through prior research that this specific series of electric loads from Elektro Automatik, ending with \(-R\), was unable to perform quick enough for the intended purpose of acting as the Anode-Cathode emulator regarding current transients. The minimum time step for the \(ELR9000\) series is 5ms. A required time step is close to 30\(\mu\)s.

Even though it was concluded early on that this series was not to be used, the test was still carried out with the goal of introducing and understanding electric load behaviors, as well as also initiating setup for future tests with more suitable devices.

1.1 Equipment Scope

Apart from a power supply, it was concluded that certain manufactured test equipment should be used, both for simulating certain behavior and for measuring current. Therefore, a filter unit matching that which can be found in the Power Processing Unit (PPU) of the Electra satellite was to be manufactured.

The block diagram in figure 1 shows the setup. Component level information can be found in figure 3.

![Block Diagram of device setup.](image)

In addition to this setup, an oscilloscope with differential probes was required for measuring these transients.

1.2 Goals

Even though no final design could be conducted based on the borrowed load, due to the minimal time step being two orders of magnitude larger than required, the test still had clear and useful goals that were met during the test week.

The test goals were to:

- Get familiarized with electric loads and high power setups.
- Begin manufacturing test circuit, wires, equipment and setups.
- Perform and measure current and voltage step responses.
- Confirm inadequate temporal behavior of load.

2 Method

The testing of the electric load was divided into two parts. The first part, consisted of learning to use the machine, exploring the various menus and options, correlating the behavior and functions with the datasheet, and in general, getting comfortable with the electronic load. The power supply used for this test was the TDK-Lambda Gen 125-80, found in-house at OHB Sweden. This part also consisted of planning and preparing setups, manufacturing wires, measurement circuits and setting up the oscilloscopes needed.

The second part of the testing done during the week-long loan of the electric load was measuring and analyzing the transient behavior of the load when stepping the current. It was concluded that stepping the voltage was not feasible, as this required communication with a laptop towards the power supply through LabView.

2.1 Setup of Load

A 19 inch wheeled rack was used for housing the ELR-9080 electric load and TDK-Lambda power supply for convenience, and each were powered by their own three-phase grid supply in the OHB Sweden electronics lab. To connect the two devices, two AWG 10 wires were connected between each positive and negative lead respectively, with no connection to ground on the negative end.

All initial behavioral tests were performed with this setup, with an oscilloscope measuring the load voltage in unison with the displayed values from both supply and load. Figure 2 displays the setup, with all additional setup equipment.

Figure 2: Rear setup of load (top) and power supply (bottom) in rack, with connected cables, filter unit (bottom) and current sensor (top).
2.2 Manufacture of Test Equipment

The test equipment used for this setup was a filter unit designed to match that which can be found in the Power Processing Unit designed for Electra. This consisted of an inductor with a small parallel resistor for dissipating energy during switching as well as a shunt capacitor. As for the current sensor, a small and accurate high power resistor was used for measuring the voltage drop across the resistor with a differential probe.

A technical circuit diagram can be found in figure 3 with component values and measured voltages. Component product information can be found in table 1.

![Figure 3: Circuit Diagram of setup, with component values.](image)

In figure 3 the filter unit is represented by the inductor-resistor-capacitor trio, and the series resistance by the load is the current sensor. $V_{FU}$ is the filter unit voltage and $V_i$ is the current sensor voltage. The resulting circuit board can be seen in figure 4.

![Figure 4: Filter unit circuit board. Input on left lead, output on right lead and negative on the bottom lead.](image)

As for the current sensor, the resistor used was attached to an overzealous, yet in-house available heat sink and can be seen in figure 5.
Figure 5: The current sensor resistor and measured resistance schematic. The differential probes and chosen 90 mΩ resistance can be seen.

Table 1: Component list containing value and specific component information.

<table>
<thead>
<tr>
<th>Component</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter Inductor</td>
<td>100 µH</td>
</tr>
<tr>
<td>Filter Resistor</td>
<td>4.7 Ω ± 5%</td>
</tr>
<tr>
<td>Filter Capacitor</td>
<td>20 µF</td>
</tr>
<tr>
<td>Current Sensor Resistor</td>
<td>90 mΩ ± 1%</td>
</tr>
</tbody>
</table>

2.3 Transient Behavior

The power supply was arbitrarily chosen to 30V, and the current limit was set to 80A so to not interfere with the tests. The power limit on the load was set to 1500 W and the voltage set to constant voltage mode at 30V.

The current stepping was done by setting the new current value through the digital touch-screen interface on the load front panel. The current was stepped up from 2A to 12A, and then later stepped down from 12A to 2A. The filter unit was not used in the first pair of tests and load voltage was measured instead of $V_{FU}$, then the filter was connected in the second pair of tests for comparison. This produced eight transient curves.
3 Results

The four test results that follow in figures 6 and 7 all contain voltage and current information from stepping the load current setting between 2A and 12A, either up or down, and with or without a filter unit. When the filter unit is absent the voltage is measured across the load instead.

![Figure 6: Current stepping without filter unit. The voltage measured here is across the load terminals.](image)

![Figure 7: Current stepping with filter unit. The voltage measured here is $V_{FU}$.](image)

It should be noted that an additional, approximately 20mΩ resistance, has been added to the current sensor resistor to account for resistance in the oscilloscope probe wires. This was an ad hoc solution when creating the curves as to match the displayed current with the true values.
4 Conclusion

While the lending of the electronic load from Divisoft can be seen only as a partial success, since more testing could have been done had it not been for issues with LabView, the primary goal of concluding the load’s slow behavior was fulfilled, therefore concluding that this load series will NOT be used in the prototype or final product.

However, as it was the first time the student had handled this type of electronic equipment, the week was fruitful in an educational sense. A prototype of the filter unit was manufactured and tested, and is, therefore, available for future tests, as goes for wiring and setups.

4.1 Graph Analysis

It can be seen in figures 6 and 7 that the current’s rise and fall times are close to 5ms, does is not suffice for the requirements for use of Anode-Cathode load, which required closer to 30µs rise and fall time. It is still quicker than what was possible through .csv or LabView connection, according to the load’s datasheet; the device will not be controlled from the front panel in the final product whichever the case.

What can also be noted is the small stepping in voltage as a result of current stepping. This is more evident in the case of figure 6 where no filter was used. This could be a result of possible non-linearities in power supply or load, or even continuous current saturation in the filter unit’s inductor. Whichever the case, the ~500mV difference is within acceptable ranges.
Appendix B: Test report - Ignitor and Keeper
Assembly & Test Report

Ignitor-Keeper Printed Circuit Board

Master’s Thesis Project - Hall Effect Thruster Emulator

OHB Sweden AB

Author: Robert PERSSON
Supervisor: Enrique LAMOUREUX

August 22, 2018
## Contents

1 Introduction .................................................. 1
   1.1 Circuit Functionality ..................................... 1
   1.2 Goals ..................................................... 2
   1.3 Report Outline ............................................ 2

2 Part 1: Assembly ............................................. 3
   2.1 Method ..................................................... 3
   2.2 Results ..................................................... 3
   2.3 Errors ..................................................... 4
       2.3.1 Back Ordered Voltage Regulators ...................... 4
       2.3.2 24V input range reduced .............................. 5
   2.4 Conclusions ............................................... 5

3 Part 2: Low Power Test ..................................... 6
   3.1 Method ..................................................... 6
       3.1.1 D-Sub .................................................. 6
       3.1.2 Power Supply .......................................... 6
       3.1.3 Breadboard Set-up .................................... 8
       3.1.4 Ignitor Keeper Pulse Generator ...................... 8
   3.2 Results ..................................................... 9
       3.2.1 Conclusion ............................................. 9
1 Introduction

The following test report summarizes the assembly and testing of the Printed Circuit Board (PCB) aimed to emulate a Hall Effect Thruster Cathode Ignitor & Keeper start up functionality and relation. The assembly and testing was facilitated during week 31, and later week 33, of 2018 at OHB Sweden’s premises.

1.1 Circuit Functionality

The circuit’s purpose is to emulate two separate, yet dependant, functions of the PPS5000 cathode Ignitor and Keeper, as a prototype. It has been designed and intended for proof of concept and is to be connected to a similar setup to Electra’s\(^1\) Power Processing Unit (PPU); the interface of the circuit is realized in table 1 below.

<table>
<thead>
<tr>
<th>Name</th>
<th>Voltage</th>
<th>Color</th>
<th>PPU</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circuit Power</td>
<td>9 to 18V</td>
<td>Red</td>
<td>No</td>
<td>Circuit Power Supply</td>
</tr>
<tr>
<td>Digital Ground</td>
<td>GND</td>
<td>Black</td>
<td>No</td>
<td>Isolated Ground</td>
</tr>
<tr>
<td>Cathode Reference Potential (CRP)</td>
<td>~-20V</td>
<td>Black</td>
<td>Yes</td>
<td>Not simulated during test</td>
</tr>
<tr>
<td>Ignitor/Keeper</td>
<td>350V pulses / 40Vdc</td>
<td>White</td>
<td>Yes</td>
<td>Simulated as two supplies</td>
</tr>
<tr>
<td>Keeper-</td>
<td>15Vdc</td>
<td>Pink</td>
<td>No</td>
<td>Output lead of Keeper resistance</td>
</tr>
<tr>
<td>Circuit Power 2</td>
<td>5V</td>
<td>Yellow</td>
<td>No</td>
<td>Ad Hoc solution, see section 2.3.1</td>
</tr>
</tbody>
</table>

The circuit design and realization was facilitated during the last half of July 2018 in KiCad and manufactured at Eurocircuits.com. The PCB is a two layer circuit with components only on one side - denoted Top-Side; the side with no comments is denoted Bottom-Side. The circuit schematic and PCB design in KiCad can be seen in figures 1 and 2, respectively.

\(^{1}\)Electra is a telecommunications satellite that is being developed at OHB SE and is scheduled to be launched in 2021.
1.2 Goals

The goals and purpose of the circuit assembly and test activities were to:

- Verify proof-of-concept for circuit logics functionality for counting and comparing pulse values with integrated circuits
- Verify isolated ground-plane set-up for splitting CRP and GND
- Verify circuit can emulate equivalent Ignitor and Keeper impedance switching

1.3 Report Outline

This report is divided up into three sections which follow in a chronological order from receiving the components and circuit board from manufacturers, to running the full circuit test. Each section comprises of its own Method, Results, Errors, and Conclusion sub section.

- Part 1: Assembly Section 
  
  *Includes details of PCB assembly*

- Part 2: Low Power Test Section
  
  *Test of functionality, without high voltage input pulses*
2 Part 1: Assembly

The following section summarizes the assembly of the Ignitor and Keeper emulator printed circuit board at OHB Sweden’s premise.

2.1 Method

All electronic components for the PCB were hand-soldered using 60/40 Sn-Pb solder. The circuit board pads were pre-tinned and the remaining surface layered in solder mask during PCB manufacturing from Eurocircuits.com. Figures 3 and 4 show the circuit prior to assembly.

![Figure 3: Circuit board top-side before assembly.](image1)

![Figure 4: Circuit board bottom-side before assembly.](image2)

2.2 Results

The resulting circuit post-assembly can be seen in figures 5 and 6. Please note the two yellow wires in figure 5 as a solution for the two missing D-PAK voltage regulators. For more information on the solution and error, please see section 2.3.
2.3 Errors

An error in the assembly is defined here as an unintentional anomaly which strays from the intended design of the circuit detected after PCB manufacture.

Therefore, two (2) errors are present after the assembly of the circuit board. In addition to this, minor visual design errors are also present, such as indicative input silkscreen text being covered when input and output wires are connected to the circuit drill holes, therein making input and output identification difficult.

2.3.1 Back Ordered Voltage Regulators

The supplier, Elfa Distrelec, ran out of stock on the D-PAK linear 5V regulator LD1086DT50TR. Because the footprint of this specific D-PAK was unique, the choice was made to not purchase a similar component in the identical package since the pin-out of other commercially available D-PAK regulators were not identical. Instead, the issue was solved by wiring the two 5V pads to the floating M3 drill hole near each respective pad. This can be seen as the two yellow wires soldered and connected to the screws.
2.3.2 24V input range reduced

The second mistake realized during assembly can be traced to failure in updating the design from procurement. The original Traco DC/DC power supply to be used for the circuit was rated for a 24V input and 12V output. However, after trade-offs were made, a supply with lower wattage was chosen to be more suitable for the circuit. This also affected the input range of the converter, which was reduced to 9-18V input, rather than the originally designed 24V. While this mistake has no real practical implications, other than supplying the circuit with a lower voltage, the mistake can be seen on the silkscreen on the power input drill hole in figure 3 where 24V is still present.

CAUTION: Applying 24V to the circuit risks damaging the DC/DC converter and is absolutely not recommended!

2.4 Conclusions

Assembly and soldering went with ease. Only one quick-fix was required to re-solder the output of the counter least-significant-bit on the isolator that had not fused properly with its pad. This however had no impact on the functionality of the circuit during later testing, see section 3.

Fixes required for future models are:

- Replace D-PAK voltage regulator with an available one with a commercially common pin configuration.
- Change Silkscreen 24V input text to read "18V Max", and possibly adding a shunt zener diode at around that voltage.
- Move silkscreen text of interface drill holes to the side of the hole-pads for easy identification after connecting the screws.

Suggested additions to the circuit:

- Add an LED to indicate if circuit is powered.
- Add an array of LED to indicate what comparator bit value is currently set.
- Add an LED to indicate if latch is triggered.
3 Part 2: Low Power Test

The following section summarizes the low-power test of the Ignitor-Keeper emulator PCB at OHB Sweden’s premises. The signal to the circuit bypassed the 68k\(\Omega\) input resistance from the voltage divider. Two different grounds were used during the test, one for the CRP representative side, and one for the digital side. The breadboard connections were referenced to the digital logics ground. No high voltage pulse was used in this test. No representative CRP potential was set. The two grounds were left to float in comparison to each other.

3.1 Method

The following equipment was used to realize a low-power logics test:

- Non-Solder Breadboard with banana connectors.
- Standard hand-held multimeter.
- Oscilloscope.
- 5V to digital ground Power Supply. \textit{Ad hoc 5V power solution}
- 15V to digital ground Power Supply. \textit{Nominal circuit supply}
- 5V to CRP-ground Power Supply. \textit{Ad hoc 5V power solution}
- 5V square wave pulse to CRP-ground function generator. \textit{Ignitor and Keeper Pulses}
- 20V to CRP-ground Power Supply. \textit{Ignitor and Keeper Steady State Sustain}
- Several red LEDs and 270\(\Omega\) current limiting series resistors.
- Several periphery cables for all various connections.

3.1.1 D-Sub

The 15 pin two row D-Sub was assembled using crimped AWG26 cables. All except the last 5 pins, 11-15, were connected with wires to interface with the breadboard. The final 5 cables were not connected, since they were grounded on the PCB.

The following table 2 denotes the D-Sub connector and its isolated logics values which connect the breadboard and the PCB.

Table 2: D-Sub Pin-out as seen from the PCB. Logics High = 5V, Logics Low = Digital GND.

<table>
<thead>
<tr>
<th>Pin #</th>
<th>I/O</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I</td>
<td>Compare Bit 3</td>
</tr>
<tr>
<td>2</td>
<td>I</td>
<td>Compare Bit 2</td>
</tr>
<tr>
<td>3</td>
<td>I</td>
<td>Compare Bit 1</td>
</tr>
<tr>
<td>4</td>
<td>I</td>
<td>Compare Bit 0</td>
</tr>
<tr>
<td>5</td>
<td>O</td>
<td>Counter Bit 0</td>
</tr>
<tr>
<td>6</td>
<td>O</td>
<td>Counter Bit 1</td>
</tr>
<tr>
<td>7</td>
<td>O</td>
<td>Counter Bit 2</td>
</tr>
<tr>
<td>8</td>
<td>O</td>
<td>Counter Bit 3</td>
</tr>
<tr>
<td>9</td>
<td>I</td>
<td>Latch Clear</td>
</tr>
<tr>
<td>10</td>
<td>I</td>
<td>Counter Reset</td>
</tr>
<tr>
<td>11 to 15</td>
<td>NC</td>
<td>GND on PCB</td>
</tr>
</tbody>
</table>

3.1.2 Power Supply

The following schematic, figure 7, shows the setup of the power supplies to the circuit board and periphery systems:
Figure 7: Test setup with associated power supplies and split ground. Dashed line indicates PCB isolation. *Ad hoc* supplies imply solutions for missing voltage regulators. Please see figure 8 for details on the breadboard block of this figure.

On the side of the PCB referenced to the digital GND, two power supplies were used. The 5V supplies are ad hoc solutions for the missing regulators, while the 15V supplies is the designed proper power supply for the circuit. The reason for it being connected in addition to the 5V ad hoc solution is that it supplies two components on the CRP referenced side of the PCB with 12V through the DC/DC converter, namely the Ignitor and Keeper voltage divided signal input buffer and the Keeper MOSFET gate driver. The breadboard is supplied with 5V referenced to digital ground.
3.1.3 Breadboard Set-up

An LED for each compare and counter bit was set-up on the bread board from the D-Sub. For the compare values, jumper wires were used to set to high (5V rail) or low (digital GND rail). Similarly the Latch Reset and Counter Clear were settable.

Please see the schematic of the test setup in figure 8 as well as figure 9 for further visualization.

Figure 8: Breadboard schematic of test setup. The long-dashed line represents what is present on the bread-board. High & Low connections indicate using jumper wires to tie the inputs to set values.

3.1.4 Ignitor Keeper Pulse Generator

Since no high voltage Ignitor and Keeper pulse was used during this test, the large 68kΩ voltage divider resistor was bypassed with a crocodile cable and the Ignitor and Keeper input pad was instead connected to a function generator with the characteristics and resulting waveform listed in table 3. This served as a simulated pulse, since the voltage divider would, under normal circumstances, split the 350V input pulse to a 5V pulse at this point. However, this solution also bypassed the input RC filter and, therefore, this function was untested.
Table 3: Function generator settings and the resulting waveform used to create pulses. Each pulse was activated by a trigger button on the generator.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Peak-to-Peak</td>
<td>5V to CRP</td>
</tr>
<tr>
<td>Voltage Offset</td>
<td>2.5V to CRP</td>
</tr>
<tr>
<td>Duty Cycle</td>
<td>20%</td>
</tr>
<tr>
<td>Frequency</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Cycles</td>
<td>1</td>
</tr>
<tr>
<td>Resulting On-Period</td>
<td>20ms</td>
</tr>
<tr>
<td>Resulting On-Voltage</td>
<td>5V</td>
</tr>
</tbody>
</table>

Additionally, the potentiometer on the PCB was set to the desired design value of 3.15V for use in comparison in the circuits Schmitt Trigger. This however did not serve its intended purpose as it is designed to work in conjunction with the input RC filter.

3.2 Results

The following section summarizes the results of the low-power testing of the Ignitor and Keeper PCB. Figure 9 shows the test bench.

Figure 9: The test setup at OHB Sweden’s electronics lab. The large case-mount resistor is the Keeper resistance.

3.2.1 Conclusion

Apart from not providing the circuit with the designed 350V input, the test was a complete success with respect to the stated goals.

The test concluded that the circuit was able to...

- ...detect, count and display current counter value on the LEDs when pulsed by the function generator.
- ...compare counted values with counted binary value set on breadboard and display such value through the LEDs, from 1 up to 15 pulses.
- ...activate the N-channel MOSFET, and remain latched, upon matching the correct counted value with the compare value, from 1 to 15 pulses.
• ...automatically reset both the counter and the latch upon power cycling.
• ...reset counter and latch according to design when their respective pins pulled high for both cases.
• ...remain latched independent of any user input or changes, with the exception of removing power or using the reset pin.
• ...function correctly with split ground planes and signals generated from separate grounds. The measured CRP to GND voltage was approximately 10V.
• ...permit at least 3A current without heating up more than 60°C.
Appendix C: Test report - Magnet Core
Contents

1 Introduction .................................................. 1
    1.1 Background ............................................. 1
    1.2 Goals .................................................. 1

2 Inductor Tests ....................................... 2
    2.1 Test Setup .............................................. 2
    2.2 N27 EPCOS Core ........................................ 3
    2.3 Custom Made Iron Core .................................. 5

3 Conclusions ............................................. 6
    3.1 Test Analysis ........................................... 6
    3.2 Use in Emulator ......................................... 6
1 Introduction

The following test report summarizes the method and results of testing two different types of magnetic core inductors to use in the Hall Effect Thruster PPS5000 Emulator Magnet Impedance for the Electra mission. The Emulator's purpose is to electrically impede the thruster’s power supply in such a way that qualification testing can be made on the Power Processing Unit during stages which otherwise cannot be tested.

1.1 Background

The PPS5000 Hall Effect Thruster uses 5 interacting coils to create a strong magnetic field across the opening of the annular ceramic anode chamber. The field strength is great enough to trap electrons in the field, but not affect any $Xe^+$ ions, which is used for propellant in the thruster. This is due to the larger Debye-length of the ions than the electrons. The trapped electrons rotate around the chamber opening in the $\vec{E} \times \vec{B}$ direction due to the Hall Effect, which acts as the driving force ionizing the xenon gas. Ionization further feeds any electrons lost from recombination with the chamber walls, causing erosion, or flowing into the anode. The trapped electrons in the magnetic field create a potential which accelerates the ions.

Magnet Impedance

The equivalent thruster magnet impedance, as seen from the thrusters power supply, is presented in figure 1, as well as the operational DC current expected through the impedance.

![Figure 1: Equivalent Impedance model for Magnets.](image)

1.2 Goals

The following goals are set to be fulfilled by this test report:

- Drive the core(s) into saturation.
- Find the maximum allowed current through the coil.
2 Inductor Tests

The following section summarizes the test setup and test results of measuring the saturation current through the planned inductors. Unfortunately, the second inductor, i.e. the custom designed iron core inductor, was never finished due to having an exceptionally low resulting value. More information regarding this can be found in section 2.3: Custom Made Iron Core.

2.1 Test Setup

The following diagram shows the test setup for measuring the saturation current of an inductor. The diode is in parallel to the inductor to close the circuit during the off period of the NMOS for which a large voltage will appear across the inductor. The fly back resistor is used to increase the energy dissipation. The resistor, in series with the inductor, is used to measure the current using a differential oscilloscope probe.

Listed below are the periphery components used to realize the test circuit.

- **Flyback Diode** 400V, 10A
- **NMOS** 600V, 22A
- **10V pulse Supply** 0-10V Single Pulse Trigger, variable width
- **10VDC Supply** 10V, 3A power cube

The large resistance is due to there being a lack of high power resistors in supply.
To find the saturation current in the core of the inductor, denoted $L$ in figure 2, the current through it is ramped at a constant rate to eventually drive the core into saturation. Since

$$V = L \frac{di}{dt} \Rightarrow \frac{di}{dt} = \frac{V}{L},$$

(1)

a drop in the core inductance will increase the rate of change of current when a DC voltage is applied, which is a direct indicator of core saturation. The current will eventually be halted by the series measurement resistor at $I = \frac{10V}{4 \Omega} = 2.5A$, which is larger than the theoretical saturation current of the core.

### 2.2 N27 EPCOS Core

**Design**

The N27 Ferrite transformer by TDK EPCOS is a two-part steel core, depicted in figure 3.

![Figure 3: The TDK EPCOS Ferrite Transformer Cores.](image)

The core was wound 35 times with an enameled $\odot 2\text{mm}$ copper wire yielding 21mH inductance.

**Test Results**

The following two oscilloscope curves were generated from the pulse test according to the characteristics stated previously in this document. The bottom green curve represents the differential probes voltage across the series resistor, and the top curve shows the NMOS $V_{GS}$. 
The differential voltage probe across the 4.7Ω series resistor has a 1:50 ratio. The 50mV per division on the scope yielded 2.5V across the resistor. Using Ohm’s law, and this gain factor, resulted in an effective 0.53A per division.
2.3 Custom Made Iron Core

The following section summarizes the design and results of a Custom Iron Core constructed out of residual metals from a workshop. Unfortunately, it was concluded that several hundreds of copper wire windings were required to reach the desired inductance and the lack of time resulted in testing being canceled.

Design

The following image, figure 5 shows two parallel \( \Phi \)50mm solid iron tubes closed in a loop shape by two 30x50mm iron bars, locked in place by two threaded rods with nuts on each end. The contact surfaces were milled to remove the primer paint and to create an even surface to avoid magnetic hot-points.

Figure 5: Custom Made Iron Core with exemplary winding of a \( \Phi \)2mm enameled copper wire.

In table 1 below, the intended design values are listed, used to calculate the inductance and maximum current. The B-Field strength, however, was not certain due to the varying documentation available on iron cores, and specifically there being no documentation available for the one in which this core was constructed.

Table 1: Iron Core Intended Design Characteristics.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_{\text{cross-section}} )</td>
<td>1500( \text{mm}^2 )</td>
<td>Smallest Cross-section Area (Bars)</td>
</tr>
<tr>
<td>( l_{\text{ampere}} )</td>
<td>100( \text{mm} )</td>
<td>Winding Path-length</td>
</tr>
<tr>
<td>( B_{\text{max}} )</td>
<td>*</td>
<td>Generally 2-4 times that of Ferrite.</td>
</tr>
</tbody>
</table>

Test Results

When the core was wound 30 times it gave a value of approximately 45\( \mu \text{H} \), independent on the iron core structure, i.e. the disassembled and assembled inductance showed no change. When pressing the windings together tightly, the inductance reading from the RLC-device read 80\( \mu \text{H} \), proving that tightly wound wiring gave a far better result. Nonetheless, the resulting \( A_p \) value was so low that the value was 250 times less than the desired 20\( \text{mH} \). A thinner copper wire was procured, but no more tests were made on the custom iron core.

\( ^2 \)Norrköpings Svets & Reparation AB
3 Conclusions

The following conclusions only encompass the N27 Ferrite core, since the custom iron core was deemed unsuitable for saturation tests as the student was unable to wind enough turns to yield the sought after 20mH. This section summarizes both test conclusions, as well as conclusions for use in the Hall Effect Thruster Emulator project.

3.1 Test Analysis

From the test results, the following zoomed in figure presents the different phases of the current through the inductor.

Figure 6: Resulting pulse behavior of the inductor.

The first part, between 0s to approximately 1.7ms, shows the linear increase of current according to the definition of inductance as previously stated. At the first crossing point, marked with a red circle, is an approximate point where the linearity and saturation meet. After this the inductance has decreased, a tell-tale sign of core magnetic saturation. The second crossing occurs right before the plateau, at 25ms. This point marks where the 4.7Ω series resistor limits the current. The following table summarizes the theoretical and practical values from the N27 Ferrite core test.

<table>
<thead>
<tr>
<th></th>
<th>Theoretical</th>
<th>Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation Current</td>
<td>1.1A</td>
<td>0.68A</td>
</tr>
<tr>
<td>Plateau Current</td>
<td>2.1A</td>
<td>2.1A</td>
</tr>
</tbody>
</table>

3.2 Use in Emulator

Clearly, the N27 Ferrite core is not suited for the Hall Effect Thruster Emulator, as the saturation current is too low by a factor of at least ten. Unfortunately, this core was the only off-the-shelf core found by the student, who opted to design an iron core from scratch using spare workshop bits. Despite the construction effort, it was concluded that this custom core had a very low effective *A_l* value which would require several hundreds of turns to yield the desired inductance, which was deemed impractical.