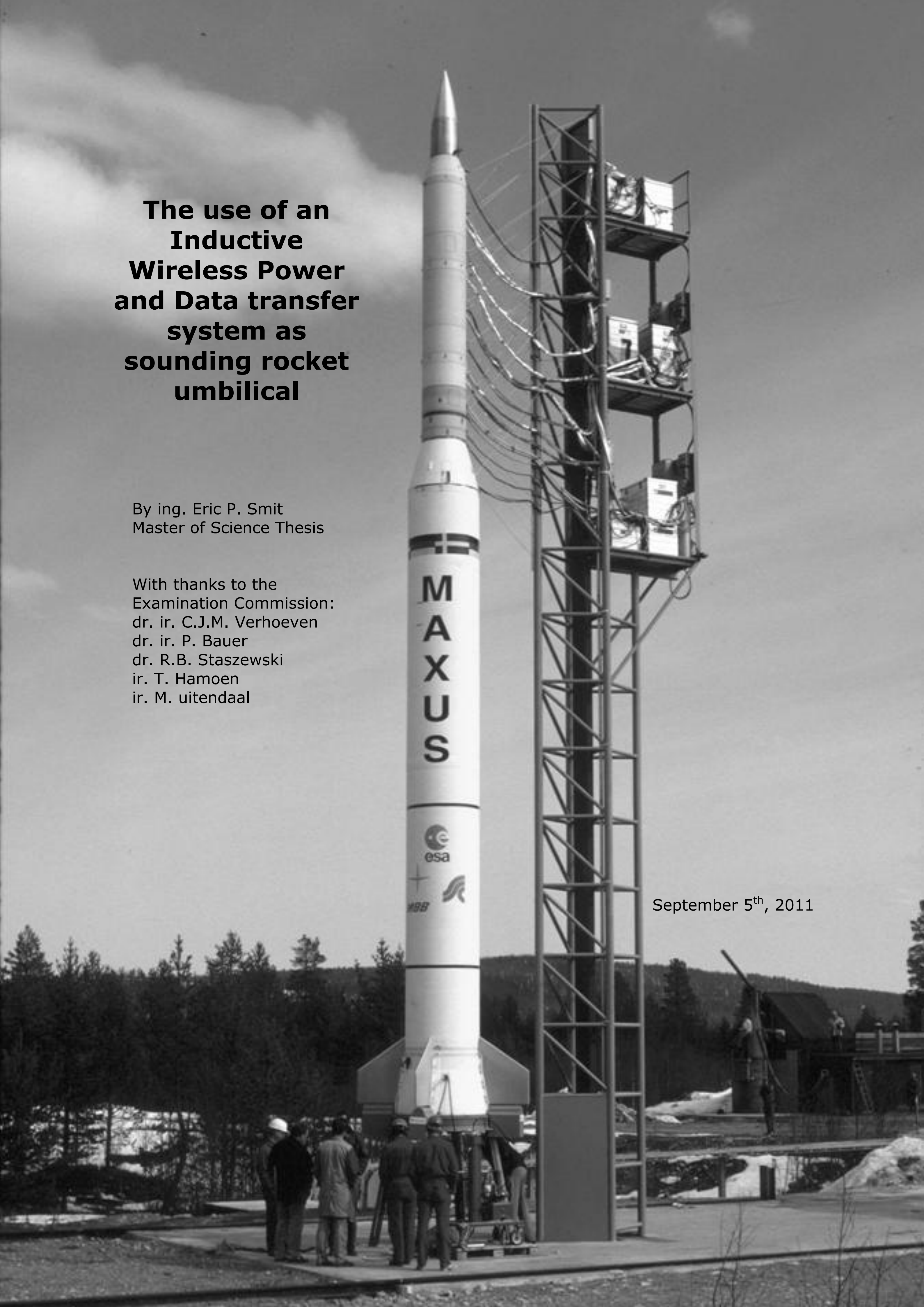
The use of an Inductive Wireless Power and Data transfer system as sounding rocket umbilical

Eric P. Smit
September 2011



The use of an Inductive Wireless Power and Data transfer system as sounding rocket umbilical

By ing. Eric P. Smit
Master of Science Thesis

With thanks to the
Examination Commission:
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September 5th, 2011

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Op 5 september 2011 heeft E.P.Smit voor een afstudeercommissie bestaande uit:

- ir.dr.C.J.M.Verhoeven (vz), (Electronics Lab, EWI and Space Systems Engineering Lab, AE)
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verantwoording afgelegd voor zijn afstudeerwerk. Naast zijn afstudeerverslag zijn ook zijn presentatie, zijn verdediging en zijn functioneren in de dagelijkse praktijk op het lab tijdens zijn afstudeerperiode beoordeeld. De commissie beschikte over voldoende informatie over het laatste door de aanwezigheid van de dagelijkse begeleiders in de commissie. De externe deskundige kent de kandidaat goed vanuit een samenwerkingsproject, de in Zweden gelanceerde Stratos raket, waar de kandidaat verantwoordelijkheid had voor de raketelektronica.

De commissie was van mening dat het verlag op zich geen recht doet aan de kwaliteit van de kandidaat. De kandidaat heeft een ernstige vorm van dyslexie en had daarom niet de mogelijkheid om een afstudeerverslag te produceren dat volledig recht deed aan zijn kwaliteit, zeker niet binnen een aanvaardbare periode. Omdat dit al bekend was bij de aanvang van het afstudeerwerk is er voor gezorgd dat een groter dan normaal aantal begeleiders zich gedurende de gehele afstudeerperiode goed op de hoogte heeft gehouden van het functioneren van de kandidaat. Het was duidelijk dat deze informatie van groot belang zou zijn voor de eindbeoordeling.

Deze informatie, samen met de kwaliteit van de presentatie en de verdediging heeft de commissie er toe doen besluiten dat de kwaliteit van het verslag niet tot een onevenredige verlaging van het cijfer zou mogen leiden.

Het eindcijfer is door de beperking van deze invloed uitgekomen op 7.

Deze bijlage bij het verslag dient ter verantwoording van deze beslissing omdat helaas het afstudeerverslag de enige niet vluchtige component is van het totaal aan informatie dat de commissie tot het bovengenoemde oordeel heeft gebracht.

Namens de afstudeercommissie

Ir.dr. C.J.M.Verhoeven

Preface

It was during the morning breakfast, and a very good one at that, that a discussion came up: The wires sticking out of the rocket to connect with a computer some distance away are they necessary? Why not use a wireless system to supply our rockets with power and data?

This breakfast might need some explaining (to some). It was March 2009 and we were at the restaurant of Esrange Space Center. During the launch campaign where we were going to launch Stratos we spend most of our time finishing our rocket. But during the breakfast the conversation turned to the future. And there at the breakfast table of Esrange my graduation assignment started to take shape.

This Thesis is the result of our thoughts exchanged at Esrang. I would like to thank Chris Verhoeven who was there at Esrange with us and allowed me to create my own graduation assignment. I appreciate the freedom to let me decide the direction to take.

I would like to thank Thijmen Hamoen who supported me by asking the good questions. And also for the experience of taking a broader look at the obtained results. Looking at the obtained transfer as a filter provided a larger understanding of the principles involved.

With the thesis spanning several fields of engineering I have not only worked on microelectronics. I would like to thank Pavol Bauer for his help on the subject of power electronics and Mark Uitendaal for the discussions on rocketry and rocket design.

During my time in Delft Aerospace Rocket Engineering (DARE) I learned a lot about designing electronics for rocket. The chance to use my graduation to go in to the theory of rocket related electronics has been very interesting. The two extremes of getting hands on experience and theoretical background on the same subject is very helpful.

I would also like to thank my parents who supported me during my study, supporting me in taking the right choices. Knowing that my study took very long I'm glad they supported me even when my study wasn't going very fast.

This thesis was done to obtain my Master Degree in Electrical Engineering at Delft University of Technology. The examination committee consists of C.J.M. Verhoeven, P. Bauer, R. B. Staszewski, T. Hamoen and M. Uitendaal.

Delft, August 29th, 2011
Ing. Eric P. Smit

Abstract

The objective of this thesis is defining the feasibility of using an Inductive Wireless Power and Data transfer system (IWPD) as sounding rocket umbilical. An Umbilical is used to supply power and communicate with the rocket in the last moments before launch. The power is used to keep the batteries fully charged and the communication is used for arming and disarming procedures.

An IWPD system uses magnetically coupled coils, or inductors, to transfer power and data. This principle is used in transformers where a magnetic core creates a high coupling. In the umbilical the coils cannot be placed around a core. This comes from the fact that one coil is outside the rocket and one coil is inside the rocket. Coupling of two coils separated by air is obtained by the magnetic field they produce. The coupling is defined as the magnetic field shared by the two coils in reference to the field that only passes one of the coils. To determine the coupling a simplified model was made which allowed the coupling to be plotted to the distance between the coils.

The power transfer between a pair of coupled coils is dependent on the coupling between the coils. The magnetic field will not dissipate energy unless it goes through conductive materials. This means that magnetic energy is stored in the field and can be reclaimed. Making the inductors resonate with the addition of capacitors keeps the energy in the circuit. This resonance makes the power transfer non linear to the coupling of the coils.

Circuit calculations are presented to determine the transfer of the IWPD in respect to frequency, supply and load conditions. The transfer is then used to determine the best setup to be used for an IWPD umbilical. The resonance of the system is used as frequency response of an oscillator. This oscillator is used to overcome the frequency shift of the system.

The proposed system is compared with a more conventional umbilical. This comparison is made in three fields. Performance, Interference and Safety. In Performance an IWPD is as suited for the task as conventional system. Both will be able of supplying sufficient power and date. In Interference the IWPD is much better. It separates the umbilical from the skin and structure of the rocket. For Safety the results are balanced. The conventional systems perform better on electromagnetic interference (EMI). While the IWPD performs better on Electrostatic discharge (ESD). The IWPD might perform less on EMI this however does not have to be a problem. Increasing the electromagnetic compatibility (EMC) of the electronics and the distance to dangerous materials in the rocket will create a safe working situation.

Table of contents

List of abbreviations

DARE	Delft Aerospace Rocket Engineering
EMC	Electromagnetic compatibility
EMF	Electromagnetic Field
EMI	Electromagnetic Interference
ESD	Electrostatic Discharge
FEM	Finite element method
IWPD	Inductive Wireless Power and Data
MCU	Master Control Unit
RF	Radio Frequency
RCS	Rocket Control System
TX	Transmitter or flight communications

1 Introduction

What does “The use of an Inductive Wireless Power and Date transfer system as Sounding Rocket Umbilical” actually means. This title describes two components, the “Inductive Wireless power and data transfer” and the “Sounding rocket”. In this chapter an introduction will be made as to what these components are and how they are intended to work together. First a description of a sounding rocket will be given to show what it is and how it is used. The second part will give an explanation of the principle of inductive wireless power and data transfer. Part three shows the idea of putting the two components together. Describing the basic idea and its advantages and disadvantages. Resulting in questions that need to be answered will be part four. The last part of this chapter is an overview of how the rest of the thesis report is build up.

1.1 The sounding rocket

A sounding rocket is a rocket used to carry scientific experiments during a sub-orbital flight. During this flight experiments can be done in fields like atmospheric research, astronomy, microgravity or testing components designed for spaceflight. Typical altitudes of sounding rockets are from 50 to 1000 km. These altitudes are mostly the ranges where there is no other option. Since balloons only reach approximately 40km and satellites only start around 550 km.

Figure 1-1 three sounding rockets, from left to right: a CanSat (by DARE), a Black Brand and a Maxus.

The rocket usually comprises of several modules. These modules can be one or several motor modules, a recovery module and a flight control and payload module. The precise build up of the rocket is of course dependent on the goal it is used for. The Payload stage is a part of the rocket that houses the devices that are doing the measurements. The size of the payload and altitude that needs to be obtained determines the size and number of motor modules required. A flight control module might be required in order to obtain a correct flight path or spin rate. For payloads that require micro gravity during flight the spin rate of the rocket needs to be almost zero during the part of the flight where measurements are taken. The recovery module is used to return the payloads safely to the ground. This module is critical in payloads that test new materials since it allows examining the materials after the rocket flight. A typical trajectory of a sounding rocket, shown in Figure 1-2, is comprised out of several flight stages.

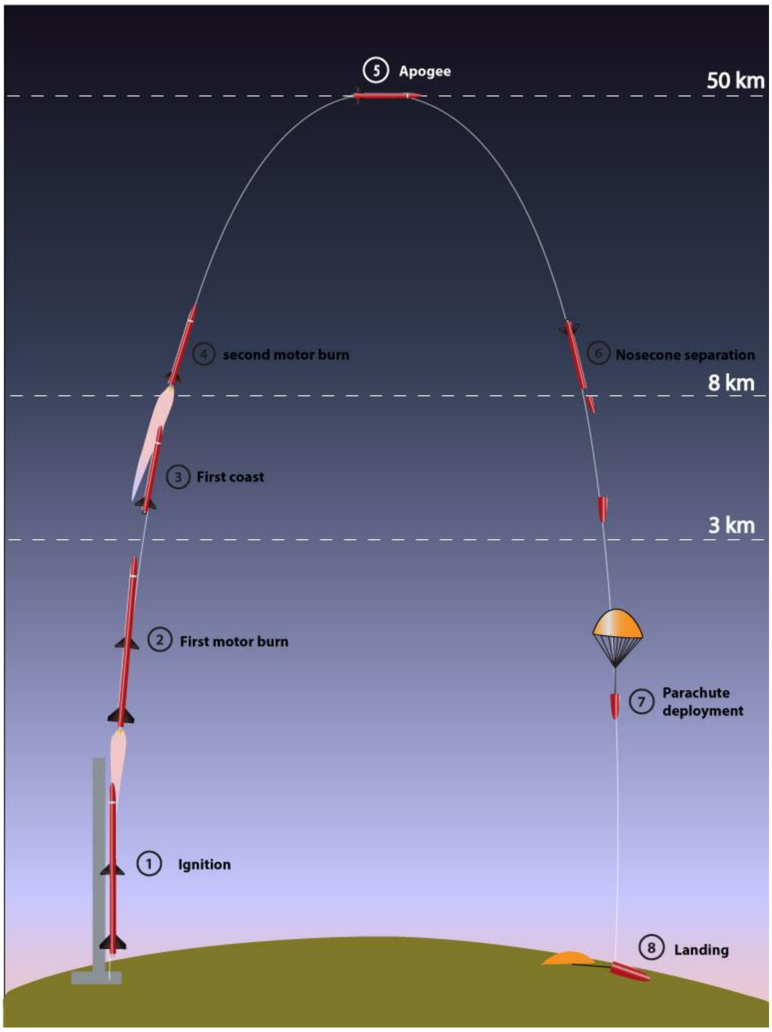


Figure 1-2 typical stages of a sounding rocket flight

The stages of the flight are:
- First motor burn stage
- First coasting stage
- Secondary motor burn stage
- Second coasting stage
- Descending stage
- Recovery stage

These stages can differ between flights depending on the specific needs of the payloads. The flight of the rocket starts with the launch which initiates the first flight stage and ends with the landing at the end of the recovery stage. The flight of the rocket is not the entire sounding rocket operation. While the real measurements take place during the few minutes of the flight there are many steps that need to be taking in to account before and after. An entire rocket launch campaign consists of many steps to ensure the proper and safe operation of the sounding rocket.

Typical steps of a launch campaign:
- Preparing the launch site
- Preparing of the rocket and payloads
- Testing of al systems (rocket, payload and launch site)
- Integrating payload and rocket
- Attaching rocket to launch tower
- Countdown and arming procedures
- Launch and flight
- Analyses of flight measurements

The steps undertaken during the launch campaign are to minimize the risk of failure of the sounding rocket. This also creates a safe operating condition of the rocket. Rocket motors use explosive chemicals to propel the rocket introducing high risk on personnel working in their proximity. Reducing the time of personnel near the rocket and decreasing the possibility of an accidental motor ignition is the best way of safe operation. A remote controlled arming device prohibiting the ignition of the rocket engine increases safety. Yet this requires a secure communication between the sounding rocket and the safe location from where the rocket launch is controlled.

To launch a sounding rocket many systems are required, from the internal systems of the rocket, to the launch site and its support equipment. The rocket used as reference throughout this thesis is the Stratos2 rocket which is currently being designed by Delft Aerospace Rocket Engineering (DARE).

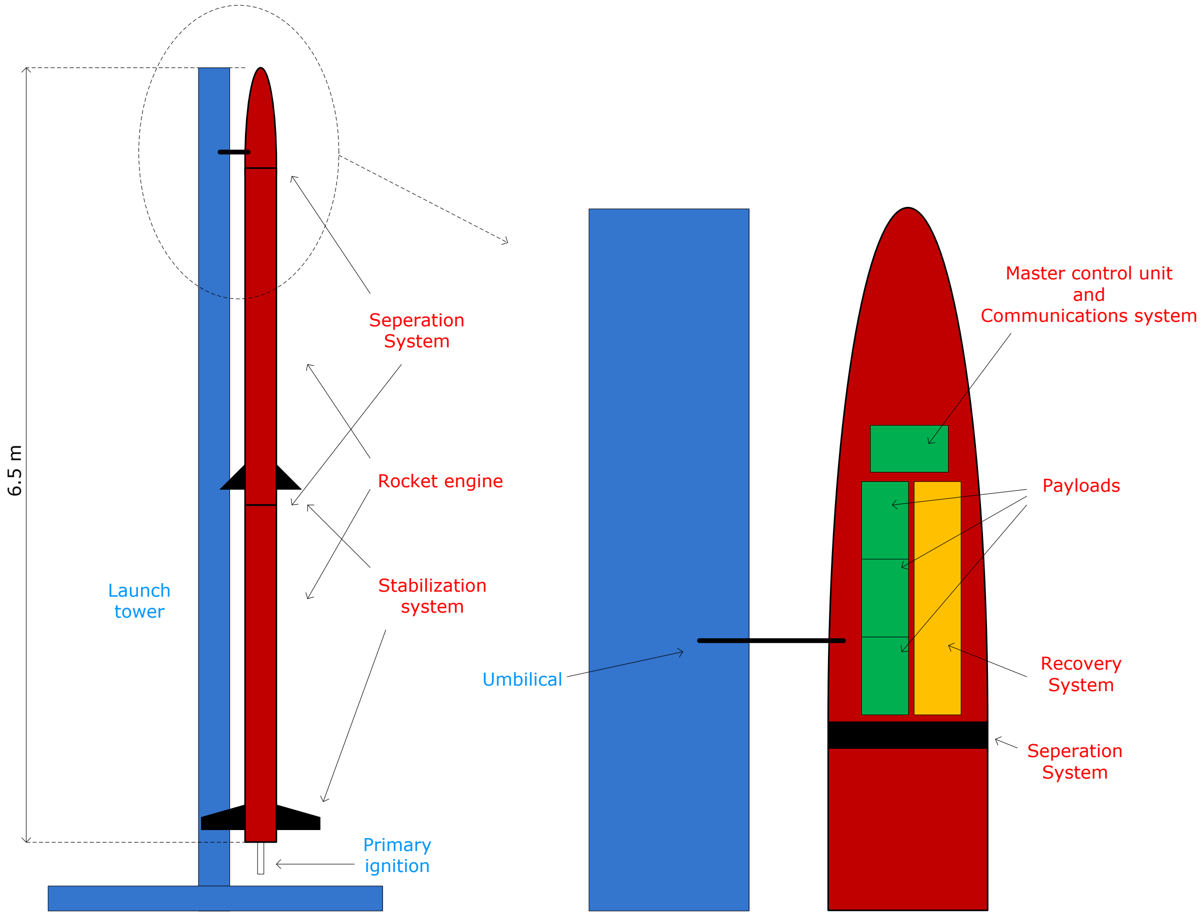


Figure 1-3 the systems of the Stratos 2 rocket as proposed by DARE

Rocket components: (written in red)
- Rocket engines
- Separation systems
- Stabilization systems
- Recovery system
- Payload and control system
  - Payloads
  - Master control unit
  - Communication system
  - Attitude determination system
  - Internal arming system

Support equipment: (written in bleu)
- Launch tower
- Primary stage ignition system

- Umbilical, pre launch communication system

Rocket preparation systems: (not displayed)

- Engine preparation and loading tools
- Payload assembly tools
- And several general support systems like communications and measurement tools

Figure 1-4 ASK t'Harde, launch site used by DARE in the Netherlands.

Site:
Launch area (Red)
Impact area (Orange)
Launch control (Bleu)
Assemble area (Yellow)
Launch towers (Black)
Safe areas, visitors (Green)

The Umbilical of the sounding rocket is a device that connects the rocket with the launch site before it is launched. It provides the operators the ability to communicate with the rockets systems. This communication is required to perform the arming and disarming procedures. Especially when disarming it is important that the rocket receives and acknowledges this command. Since a problem at this stage might result in a dangerous situation.

1.2 *An Inductive Wireless Power and Data transfer system*

An inductive wireless power and data transfer system (IWPD) uses an inductively coupled pair of coils to transfer electrical power and/or data signals from one system to the other.

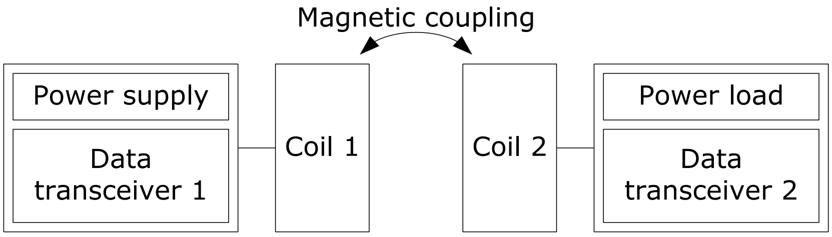


Figure 1-5 basic principal of an IWPD.

Magnetic coupling between the two coils provides the transfer of the power and data. Supplying an AC voltage on one of the coils will induce a voltage in the other and the other way around. The magnetic coupling is determined by the magnetic field lines running through the two coils. The fact that this coupling can be obtained without any galvanic connection negates the need of a connector with exposed contacts. This also allows the transfer to take place while several isolating materials are in between. As long as the materials between the coils are not conductive the inductive link can work.

Inductive Wireless (IW) systems are used in or proposed for several applications. One of the most seen applications is as charger of an electric toothbrush. This allows you to simply place the toothbrush on a charger without the possibility of short circuiting the supply with water. Other applications range from medical implants to chargers for electrical vehicles and chip to chip power delivery.

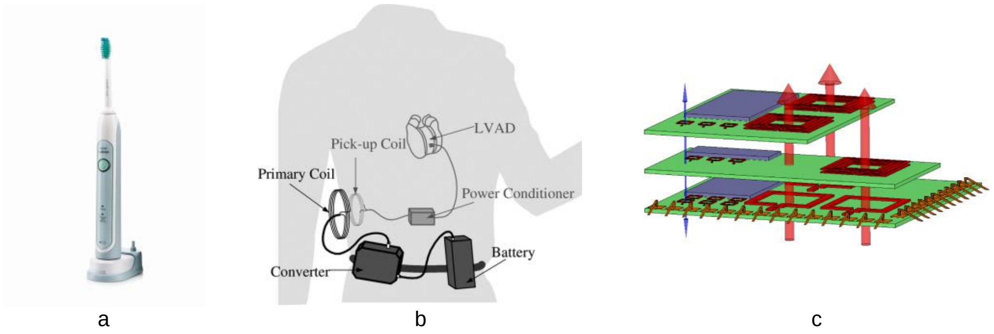


Figure 1-6 (a) a toothbrush on its charger. (b) A biomedical application for wireless power transfer, by Ping Si (1). (c) A chip to chip power and data transfer to limiting connections, by Yuxiang Yuan (5)

An IW system can implement power and/or data transmission. The implementation of both can be created using several setup possibilities, using one set of coils or multiple. The setup choice is dependent on the requirements of the system. Using separate coils increases system size while using a single set increases complexity. The schematic overview Figure 1-5 shows that an IWPD system can be separated in three different parts.

- Driving electronics
- Inductive Link
- Loading electronics

The form and position of the coils influences the magnetic coupling. In referencing to a transformer with a good magnetic coupling, an IWPD has a very low coupling [1-6, 15, 18] ranging from 0.01 to 0.5. Where the high coupling values are only obtainable when the coils are placed extremely close together. The coupling factor is also dependent on movement in the system. This dependency needs to be taken into a count by either having the electronics handle the change or by reducing the movement. To understand and operate an IWPD the influence of low and changing magnetic coupling needs to be researched, this will we a main part of this thesis. As pictured by the schematic overview Figure 1-5 the inductive link requires driving and loading electronics. Because the power delivered by the link needs to be DC and only AC can be delivered by inductive coupling a regulator is required. For the implementation of data transmission the driving and loading electronics also require a transmitter and a receiver.

1.3 Inductive Wireless Power and Data transfer system used as sounding rocket umbilical

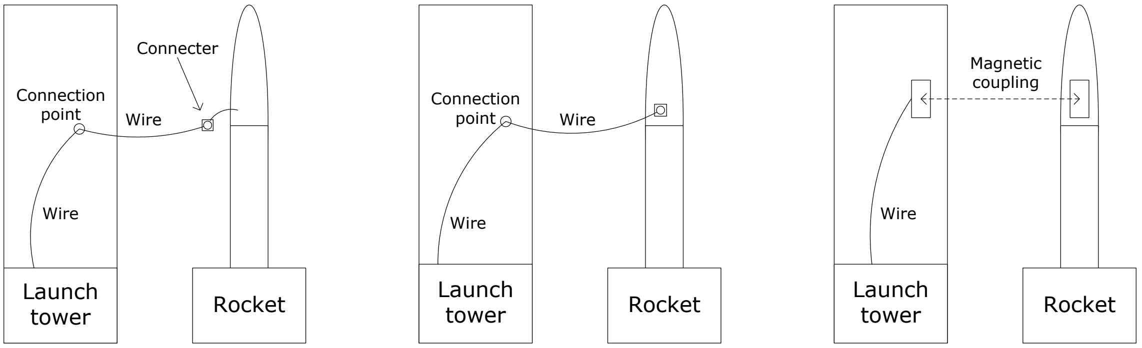
During the launch campaign of the STRATOS rocket the idea came to change the method of commanding the rocket. In the STRATOS rocket there were a few wires sticking outside the rocket and they were connected with connectors that separate during takeoff. This method worked yet has some drawbacks.

Some disadvantages are:

- Wires sticking out of the rocket create aerodynamic drag
- The wires might get stuck on something during launch
- Connection is easily broken

STRATOS had no battery charging system while awaiting the launch in the launch tower. This is a function of the umbilical that would be very interesting. It would allow the rocket to stay inside the launch tower and ready for launch during longer times. This can be a benefit since launching rockets is dependent on whether conditions.

Changing the Umbilical from several wires sticking out of the rocket to a connector in the rockets skin solves most of the original problems. This option requires very expensive connectors that allow easy disconnection during launch while keeping the impact on aerodynamics low. Using an Inductive wireless system solves the aerodynamic and connector problem while introducing a placement problem. Where is the IW inside the rocket and where to put the external components?



a, Stratos 1 b, Connecter c, Wireless

Figure 1-7 umbilical options. (a) The method used in stratos with a connector outside the rocket. (b) A version with the connector made into the skin of the rocket. (c) A wireless variant.

Using an IW system that supplies power and data is required to provide both the communication and charging capabilities. Having the power supplied externally is also beneficial for the battery load during test phases. During the procedures used to launch STRATOS it became apparent that the rocket was powered on for an extensive period of time before launch. During this time the batteries slowly deplete leaving only short battery time for the actual rocket launch and recovery. To overcome this problem extremely large batteries were implemented which is possible for systems that use relatively low power. Increasing power consumption requires even larger batteries making this a non viable option.

STRATOS was launched at Esrange space centre in Sweden. This vicinity is located 200 km above the polar circle where the cold dry air allows easy build-up of static electricity. The connectors on the outside of the rocket are very perceptible to resaving a static shock. Since an IWPD has no electric contacts on the outside it is automatically protected against an electro static discharge (ESD). Esrange also prohibits radio frequency (RF) transmissions to be made within the launch area except during the times that there are no personnel in the vicinity of the rocket. Is an inductive coupling an RF transmitter? Since it uses an Alternating Current it will transmit some electromagnetic waves.

Preliminary advantages and disadvantages of an IWPD transfer system.

Advantages:

- Optimizing rocket skin for aerodynamics and structure.
- ESD protected.
- No galvanic contact required with the rocket.

Disadvantages:

- Difficult to see if the connection is correct.
- Positioning the external components correctly in reference to the internal.
- Is an IWPD considered as an RF transmitter?
- The size and weight of the internal components.
- Influence of magnetic field with the rocket components unknown.

Using an IWPD has some advantages and disadvantages yet at the moment most of the implications are unknown. An alternating magnetic field can induce current in conductive components of the rocket. Is induced current a problem? And in which parts of the rocket. Where does the inductive link needs to be in the rocket to be of use? How much data and power is required to be transferred? These questions result in the research questions to determine the first steps for building an IWPD umbilical.

1.4 Research questions

The goal of this thesis is to determine the feasibility of using an inductive wireless power and data transfer system as sounding rocket umbilical. Two main aspects will be addressed. The first is safety the second is capabilities. The safety of the system determines if it is allowed to be used while capability determines if it is useful.

In sounding rocket systems safety has a high priority since explosive substances are used. The inductive link can have an influence on these substances. This is a direct safety issue and it is important to be understood. A secondary impact is the influence on the electronics that control the ignition. This can be solved by increasing the electromagnetic compatibility (EMC) of these electronics or decreasing the electromagnetic interference (EMI) generated by the inductive link. These safety problems can be summarised in understanding the magnetic field generated by an inductive link.

The capability of the link needs to be defined in power and data throughput and will result in a definition on required precision. The rocket needs power to operate while the data transfer allows the operators to communicate with the rocket. The last step in capabilities is determining the required precision of the system in terms positioning. Do the external components need precise placement or is it enough to have them placed in proximity.

The goal can be written as the following research questions. These questions need to be answered to determine if an IWPD is feasible as umbilical:

- "Does the magnetic field generated by an IWPD system create an unsafe situation for launching sounding rockets?"
- "Is it possible to create an IWPD system with a power through put required by a sounding rocket?"
- "Does communication through an IWPD system provide the reliability of communication required for arming and disarming procedures?"
- "How precise does the IWPD needs to be placed for it to operate correctly?"

1.5 Explaining the document

Chapter 2 describes the sounding rocket and gives an overview of how the umbilical is used. Chapter 3 gives the requirements to the umbilical and starts the comparison between an IWPD umbilical and a cable connected umbilical. Chapters 4 and 5 are designing an IWPD without applying it directly to the umbilical. Chapter 4 focuses on the link part while chapter 5 describes the electronics. Chapter 6 redirects the IWPD design to the application of an umbilical and finishes the comparison of chapter 3. Chapter 7 discusses the steps that have to be taken to go from the concept of chapter 6 to an operational IWPD umbilical. Chapter 8 and 9 then follow as a short conclusion and recommendations.

2 The Sounding Rocket

This chapter will provide some background information on sounding rockets. Describing the basic steps of a rocket flight and the operations required around the flight will be the first part of this chapter. These aspects will then be broadened to the components of the sounding rocket and the systems required for operating it. The last part will be a more detailed look on safety during rocket operations.

2.1 The rocket flight

The flight of a sounding rocket is its operational life and only lasts for several minutes. Even large sounding rockets like the Maxus travelling to 800 km altitude have a flight time of little over 15 minutes. The total life of the rocket is much longer when counting from the making of the components. Drawing a timeline for Stratos 2 as reference:

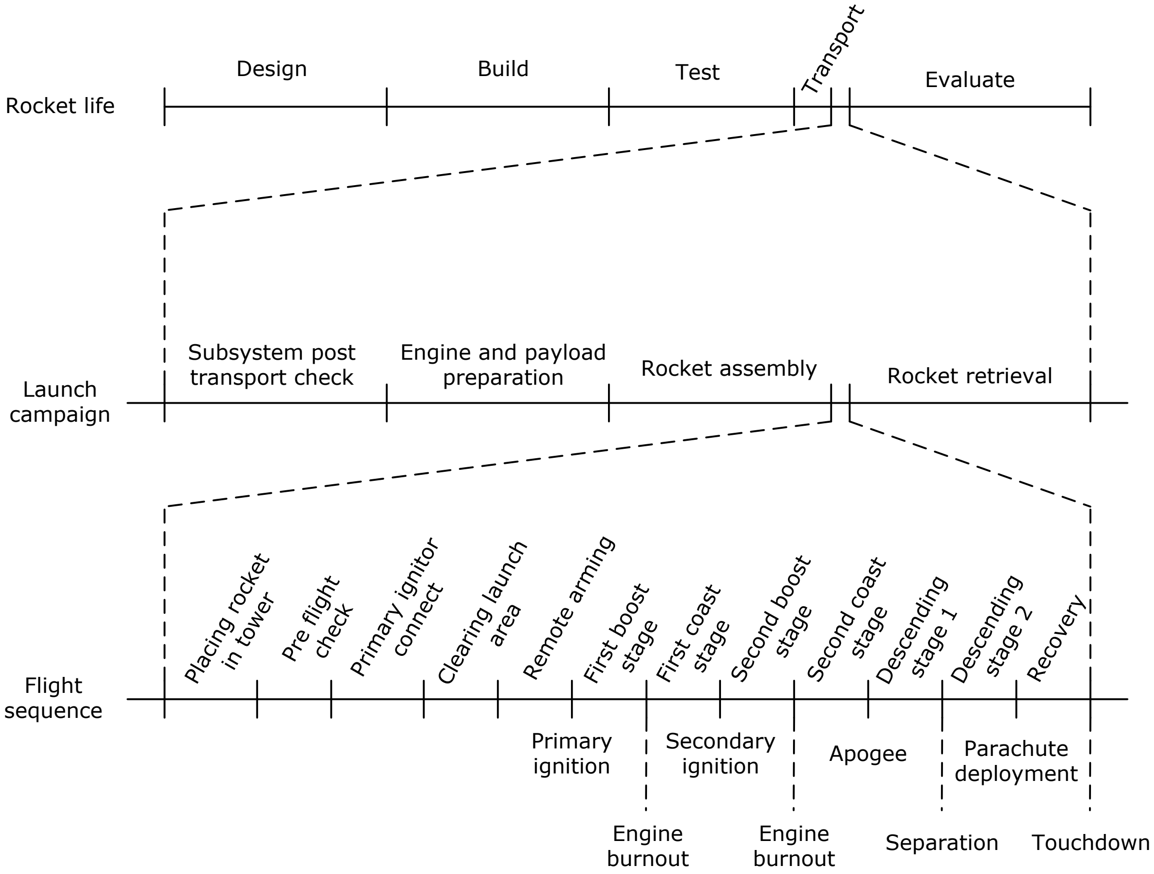


Figure 2-1 timeline for a sounding rocket. As an indication of the different stages and where they occur in the "life" of a sounding rocket.

This timeline is only an estimation to provide incite in to the relative times of the life of a sounding rocket. From the time line shows the short operational time as the rocket flight. All the steps before and after the flight are to ensure that the measurements made during the flight are correctly obtained, and more important that this is done safely. The first step in launching the rocket is a proper design of the payload and rocket. Mostly the rockets are chosen from the available sounding rockets which provide the flight needed by the payload.

During the Launch campaign the rocket and payloads are transported to the launch site where they will be assembled en tested. The campaign usually starts about a week before the actual launch and takes around two weeks. The moment of launch within this campaign is mostly dependent on the weather. The tests done during assembly are to ensure a successful flight. Considering the fact that a rocket launch is one shot system with no room for errors this is very important.

The last stage before the launch is the countdown. During the countdown the rocket with the payload inside will be placed in the launch tower and connected to the umbilical. The umbilical is then used to control the rocket in the moments before launch. Where the rocket will be put into flight mode and any separation or ignition system present will be armed. The procedures for arming the rocket need to be done from a safe distance. Mainly because of two reasons, one the arming is done as late as possible and two to keep a safe distance between the operators and an armed rocket.

Table 2-1 rocket stages and short description

	rocket stage	explanation
Rocket life	Design	Designing the rocket systems
	build	building the rocket systems
	test	testing the rocket systems
	transport	transporting the rocket and payloads to the launch site
	launch campaign	
	evaluation	evaluating measurement results
launch campaign	subsystem post transport check	testing the subsystems for damage obtained during transport
	engine and payload preparation	preparing the rocket systems like folding and placing of the parachute
	rocket assembly	building the subsystems together to for the sounding rocket
	Flight sequence	
	rocket retrieval	retrieving the rocket (can take several month)
flight sequence	placing rocket in tower	Putting the rocket into the launch tower
	pre flight check	making the last pre-flight checks of the rocket and support systems
	primary ignitor connect	connecting the primary ignition system after non essential personnel has left the launch area
	clearing launch area	clearing the launch area of all personnel to make it safe for launch
	remote arming	using the remote arming procedures to arm both rocket and launch systems
	primary ignition	
	first boost stage	
	engine burnout	
	first coast stage	waiting for the optimum altitude to ignite the second stage
	secondary ignition	
	second boost stage	
	engine burnout	
	second coast stage	
	apogee	Highest point of the flight
	descending stage 1	
	separation	separating the motor module which is not recovered
	descending stage 2	
	parachute deployment	
	recovery	last of the descending phases where the rocket descends slowly.
	touchdown	landing of the payload module. Activating a location beacon.

2.2 *The rocket systems*

A sounding rocket is comprised out of many systems. To launch a sounding rocket even more systems are needed at the launch site as support equipment.

Table 2-2 short list of rocket components with description

	component	explanation
Rocket	Rocket engine	solid propulsion rocket motor to propel the rocket.
	Stabilization system	Fins to control the rocket in its flight and keep the rocket on the correct track
	separation system	system used to drop the spent engine modules and allow the recovery system to be deployed
	Recovery system	usually a parachute. Used to slow the rocket in its descent preventing damage on landing.
	Master control unit	makes decisions on when to take actions like separation, ignition or deploying the recovery
	Payloads	measurement systems making the actual purpose of the rocket launch
	Transmitter	Used to send data back to the ground during flight
Launch tower	Tower	location of the launch rail. Keeps the rocket in the right direction at the beginning of the flight.
	Primary ignition system	system controlled by the launch officer. Used to launch the rocket.
	Umbilical	Communication system for rocket arming and testing. Used when the rocket is placed in the tower
general support	Launch control	system controlling the arming procedures
	receivers	for receiving the rocket data. Normally multiple receivers to increase the chance of getting the data
	Radar	used to track the progress of the rocket.
	Assemble area	A place to check the rocket systems and build it in to a single rocket.

The table above shows a list of the components required for a sounding rocket and its support equipment. Figure 2-2 presents how the components are located in respect to the rocket and is a redraw of figure 1-3. Figure 2-3 gives a schematic view of a launch site.

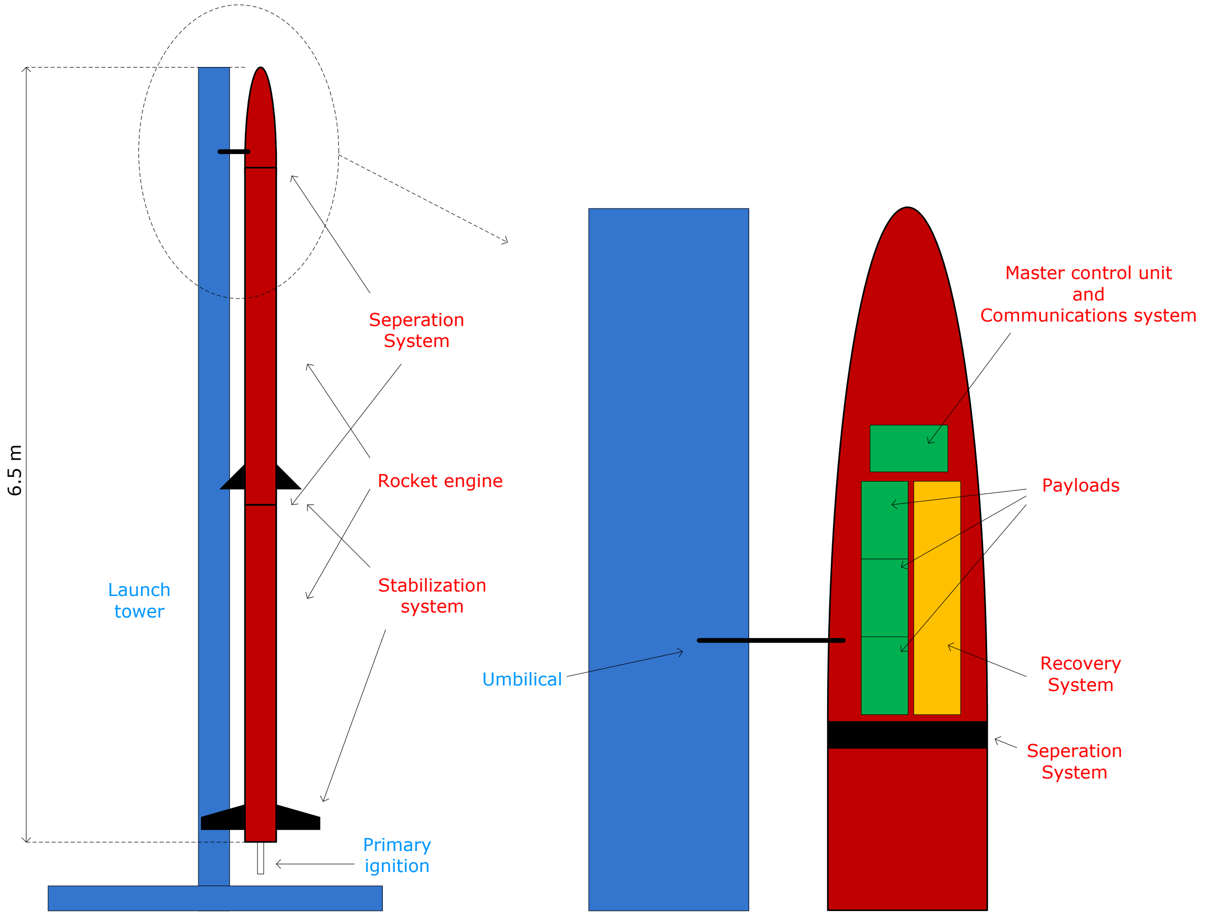


Figure 2-2 redraw of figure 1-3, location of rocket components

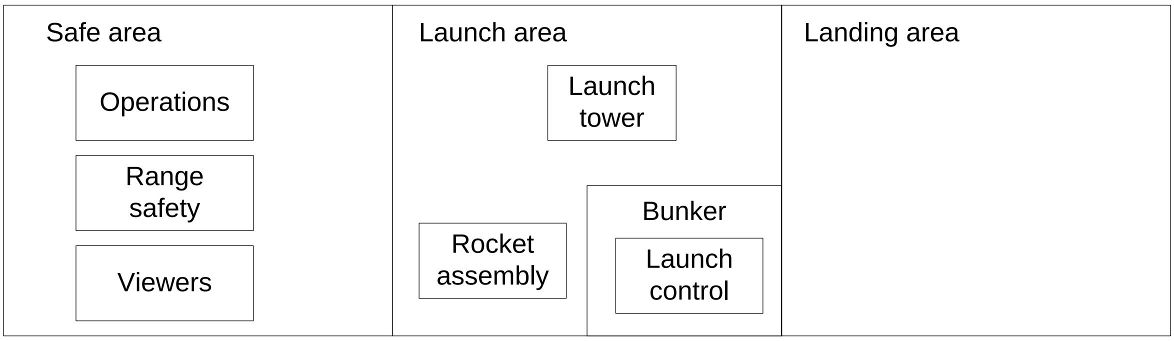
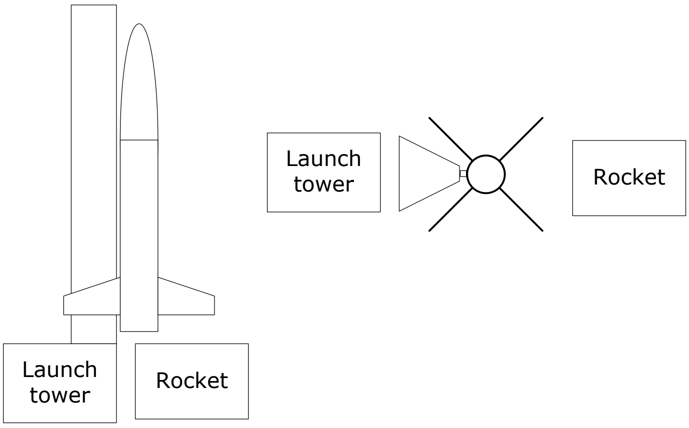


Figure 2-3 schematic view of a launch site

The umbilical is only used during the final steps before the launch as communication line between the operators and the rocket computer. It also provides power to the rockets internal electronics to ensure that the batteries remain fully charged until the moment of launch. The connection made by the umbilical should be very reliable just before launch yet should not interfere with the launch. This is made difficult by the fact that the electronics to which the umbilical connects are located in the top part of the rocket. In the Stratos 2 rocket this connection is 6 meters above ground. Care has to be taken when applying the umbilical because the fins of the rocket will pass the connection point during launch. This reduces the possible size of the umbilical system.



Side view

Top view

Figure 2-4 side and top view of a rocket in a launch tower

Figure 2-4 illustrates the difficulties of the umbilical connection. The rocket should not be interfered at both the launch rail and the rockets fins. This with the umbilical is placed 6 meters above ground. The side view shows there is only very little space between the tower and the rocket. The fins extend on either side of the tower where the top view shows only limited space between the fins and the tower.

2.3 Safety

Launching a rocket can be a difficult undertaking. While the energy density of the propellant can cause personal injuries, system failures can also cause high value experiments to go wrong. Defining these as personal safety and mission success for celerity. There are several systems that have difficulty with complying with both aspects. Working with propellant is dangerous jet necessary for rocketry. The ignition system should be designed such that the chance of personal injuries is minimized while providing a high chance of mission success. Making an igniter very safe is easy, just don't connect it. This will however not provide mission success.

Table 2-3 rocket components that can create dangerous situations

component	dangers	when
Engines	high energy density, direct ignition improbable, huge impact	dangerous until burned out
primary igniter	located in primary engine, huge impact	from placement to launch
Secondary igniter	located in secondary engine, huge impact	from assembly to launch
separation systems	If using igniter some danger is presented, low impact	from assembly to launch
recovery system	If using igniter some danger is presented, low impact	from assembly to launch

The table above shows the dangerous parts of launching rockets. One of the methods used to protect personnel working with the rocket is by using correct procedures. The time line of Figure 2-1 shows a basic step of these procedures. During these procedures steps are taken to arm the rocket. The arming process takes away layers of safety while at the same time increasing the distance of personnel with the rocket.

The Umbilical provides the necessary communication with the rocket to operate the internal arming mechanisms. The Umbilical itself should not add any dangers to the system. In case of an inductive link an electromagnetic field (EMF) is introduced. This field should not interfere with other systems of the rocket. Three of the rockets systems are of importance when adding the inductive link.

Table 2-4 three systems impacted by the IWPD

Rocket system	solutions
Rocket electronics	Electromagnetic compatibility
Igniters	Electromagnetic compatibility of igniter electronics
Propellant	Low magnetic field through the propellant

The law dictates the maximum level for EMF generated for home appliances. Standard values for electromagnetic compatibility (EMC) are created to protect appliances for the EMF surrounding them. The inductive link should minimize its electromagnetic interference (EMI) to the surrounding components. Creating the inductive link within the law for home appliances allows using the standard values for EMC at the rocket electronics. For the igniters the same holds as for the rocket electronics. This is because the electronics controlling the igniters should have sufficient EMC.

For the propellant a different aspect applies. The question here is: "Can an EMF ignite the propellant? And what field strength is needed for this ignition?" Direct Ignition of the propellant occurs when the temperature in the propellant reaches its ignition point. A magnetic field can generate heat inside conductive components. This generation comes from current being induced by the magnetic field. The bigger the surface exposed to the magnetic field the higher the current jet this also increases the radioactive surface cooling the component. The strength of the magnet decreases with respect to the distance to the inductive link.

Table 2-5 properties of rocket motors impacted by the inductive link

Element	Important property
Propellant	Conductivity, heat capacity, ignition temperature
Motor casing	Conductivity, heat capacity, heat distribution
Magnetic field strength	Strength relative to IWPD

The last of the safety issues with the wireless umbilical is its reliability. The umbilical is used to arm the rocket and is also used to disarm the rocket. The disarming procedures are initiated when something goes wrong. Failure in the umbilical can result in failure to disarm the rocket. Resulting in a dangerous situation where people are required to approach an arm rocket.

3 The Umbilical

This chapter provides the basic requirements of the sounding rocket umbilical. Both the electrical and non-electrical properties will be described. Stratos 2 will be used as reference for defining these properties. The last part of the chapter gives a comparison between and IWPD and a cable connected umbilical.

3.1 *Electrical properties*

The electric properties of an umbilical are defined by two aspects, being power transfer and data transmission. An estimate of the amounts of power and data required for Stratos 2 are made from the components of the rocket.

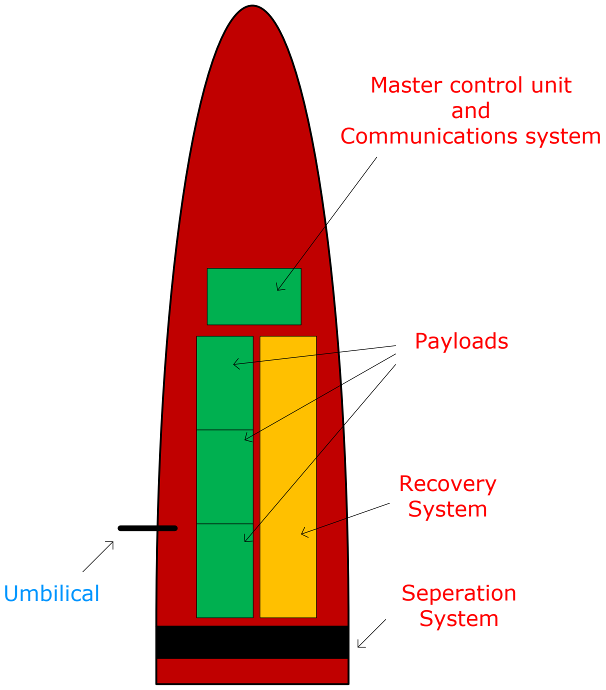


Figure 3-1 rocket payload module

3.1.1 Power requirement

The power used by the rocket when it is in flight is not important for the umbilical. During the flight most of the systems are on simultaneous. During the time the rocket is connected to the umbilical the systems are mostly operated separately.

The electronic components of the rocket are:
- Master control unit
- Rocket control system
- In flight communications
- Battery system
- Payloads

The master control unit (MCU) is determines the state of the rocket electronics. The rocket control system (RCS) is a collective noun for systems that control the rocket. Comprising of for example measurement systems, internal ignition systems, deployment systems and storage systems. The in flight communications (TX) system is a radio frequency transmitter, or multiple, that transmits payload and rocket housekeeping data to the ground station. The battery system is the internal power supply including the battery, battery charger and voltage regulators. The payloads are supplied by customers who buy space, power and data on a sounding rocket. The actions of the payloads are not predetermined.

For determining the power supply capabilities of the umbilical estimations should be made on each subsystem. The payloads are provided 1W of power per payload with an expected number of 12 payloads. This power is not always provided. During the launch sequence the rocket goes through several power modes:

- Power down mode
- Hold mode
- Testing mode
- Launch mode

The Umbilical should be able to provide the power for all of the modes. The umbilical has one more mode where the power transfer is turned off while the rocket is still on. This is used just before the launch where the power is switched to the internal batteries. The components use different amounts of power during different modes. Table 3-1 shows the power usage of the components during each mode.

Table 3-1 system components and there power usage

System	Power down	hold	Test	Launch
MCU	100mW	500mW	1W	1W
RCS	0mW	500mW	2W	2W
TX	0mW	0mW	10W	10W
Battery	0mW	200mW	200mW	100mW
Payload (each)	0mW	0mW	1W	1W
total	100mW	1100mW	25,2W	25,1W

The range of power required is very large form a small 100mW to operate only the MCU to more than 25W for operating the entire rocket. To allow the umbilical to charge the batteries the voltage must be within the range of the battery charger. This voltage is usually between 15 and 40 volts for a charger designed for a three cell lithium polymer battery.

The power delivered by the umbilical should be able to supply more than 25W at a voltage around 15V. To make the IWPD umbilical suitable for bigger rockets it will be designed for 50W of power transfer. This increase is not expected to produce bigger design issues while increasing its potential.

For the design of the umbilical an equivalent circuit should be made for the electronics of the rocket. This would allow calculations and simulations to determine the required effect of the umbilical.

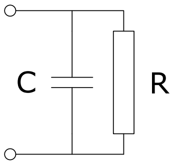


Figure 3-2 equivalent circuit of rocket electronics

The resistance in Figure 3-2 dissipates the power. The power dissipated should be around 50W for high power and about 200mW for the low power situation. At 15 volts this results in a resistor of 4 Ohm for high power and about 1 kOhm for low power. The exact numbers are not very important more important is the understanding of the relation. The capacitance of this circuit is an estimation of the capacitors in the circuit. These are used to uncouple power supply lines and to stabilise the power for the voltage regulators. This value is expected to be around 200 uF.

The efficiency of the umbilical is not very important. There is more than enough space outside the rocket to place batteries. And a generator or wall socket might be used to make a more long term solution. Still low efficiency means there is energy converted to heat. This heat should be controlled so that it won't ignite the rocket. Higher efficiency also means the IWPD is suitable for more applications.

3.1.2 Data requirement

The umbilical is only used for control communications. Test information to provide the status of the rocket and commands to control the state of the main control unit. Any tests that use high data rates should be made before the rocket is put in to the launch tower. The time it takes to get the information to and from the rocket is the important. A low data rate creates "long" times between giving a command and getting a reply. Especially for the arm and disarm commands this time should be low. From the launch experience of Stratos 1 it can be concluded that several kilo bits per second is sufficient for this. The higher the data rate the more options it would allow.

A nice to have would be to be able to look at images made by onboard cameras. This would allow images to be made from the state of the separation mechanisms while they are 6 meters above ground inside an enclosed rocket.

As with de power transfer efficiency is not very important. The data is not transmitted across large distances resulting in only low power required for the transmission. The data going from the launch tower to the rocket uses external power which is sufficiently available. And during the short time before launch the power transfer is turned off there is only little information being transmitted.

3.2 *Non-electrical properties*

The non electrical properties of the umbilical can be split is two situations. The situation when the umbilical is in use and when the rocket is in flight. During the last situation the umbilical should have as little impact as possible. The components inside the rocket should have little size and weight and also have little impact on aerodynamics. The components outside the rocket should have little interference with the takeoff of the rocket and be easily placed on the rocket.

Table 3-2 important aspects of rocket components

Rocket elements	support elements
Weight	Firm connection
Size	No obstruction for launch
Placement	Placement
Aerodynamics	Connection at 6 meter high
Structural	Low and high temperatures
Mechanical strength	
Low and high temperatures	

Connecting the umbilical when the rocket is places is the launch tower should be easy and take little time. While the connection should be sturdy enough to handle reasonable wind loads. A connection made with a cable can be sufficiently fastened at the rocket. An inductive link has no physical connection with the rocket and should be fastened to the launch tower in a method that keeps it on its place.

3.3 *Inductive or cable umbilical*

Making the choice between an inductive link or a cable connection as umbilical is a trade off. The trade off has three aspects:

- Performance
- Interference
- Safety

The table below provides the comparison, with the expected values for both umbilical types. At this stage much of the Inductive wireless umbilical is unknown. The next chapters will make a basic design for and IWPD to provide the information for the trade off.

Table 3-3 aspects of an IWPD or cable umbilical

	IWPD	Cable
Performance		
Reliability	TBD	High
Connectability	TBD	High
Efficiency	TBD	High
Usability	TBD	High
Reusability	TBD	Medium (exposed contacts corrode)
Interference		
At liftoff	TBD	Medium (cable is connected to housing)
Aerodynamics	No	High (connector in skin)
Structural	Low (only non conductive skin)	High (connector though skin)
Weight (impacts altitude)	Medium (mostly internal coil)	Medium (connector and increased structure)
Size (impacts size of payload)	Medium (mostly internal coil)	Low (connector is mostly in the skin)
Safety		
EMI (to electronics)	TBD	Very low
EMI (to motors)	TBD	Non
Electro static discharge (ESD)	low (no contacts on outside)	High (exposed contacts)

In the table only 5 of the aspects are filed in for the IWPD umbilical. These 5 are the reason we expect an umbilical to be practical. Only in size the cable has a slight advantage. This advantage is when only looking at the coil or connector. Going a little further, a connector needs to be attached to both skin and internal structure while a coil only connects to the internal structure. The extra connections will increase the size and placement of the connector. In chapter 6 the table will be completed to allow making a correct choice.

4 An inductive link

In order to design an IWPD understanding of the underlying principles is required. The basic of an IWPD is a transformer. This chapter will begin with the inductive link of a transformer and then extend the principles to an IWPD. The spread of the magnetic field will be described and as last part of the chapter the inductive link will be looked at from an electrical point of view.

4.1 Transformer

An IWPD is based on a transformer as both systems rely on magnetic coupling between two coils.

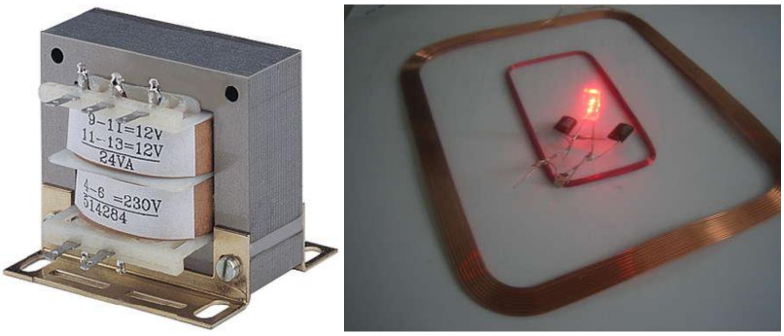


Figure 4-1 to transformers, left a 230 to 12 V transformer with metal core, right Inductive wireless power transformer

The main difference is that a transformer is mostly used to change (transform) voltage levels and an IWPD is used to transfer power and data over a short distance. A transformer works on two principles:

1. A current produces a magnetic field
2. A changing magnetic field creates a voltage.

In a transformer the primary coil produces the magnetic field and the secondary coil is used to create a voltage.

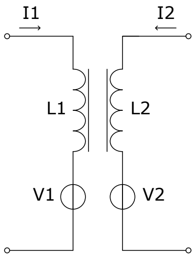


Figure 4-2 Schematic of transformer, showing the induced voltages

The strength of the Induced voltages is equal to the change of magnetic flux $\left(d\Phi/dt\right)$ and the number of windings of the receiving coil. This holds for both the transformer and the IWPD.

$$V = N\,\tfrac{d\Phi}{dt} \tag{4-1}$$

In an Ideal transformer the magnetic flux through both primary coils is equal. This results in a voltage transformation relative to the difference between the number of windings in the coils.

$$\frac{V_2}{V_1} = \frac{N_2 \frac{d\Phi}{dt}}{N_1 \frac{d\Phi}{dt}} = \frac{N_2}{N_1} \tag{4-2}$$

Where $\left(N_2/N_1\right)$is the turn ratio. The turn ratio defines the voltage difference between input and output voltages. This assumption only applies to the alternating component of the voltage. A non alternating voltage will not induce a secondary voltage.

4.1.1 Non ideal transformer

In the above equation for the ideal transformer (4-1) there is no mention of current while the main principle is that a current produces a magnetic field not a voltage. The voltage induced on the second coil is produced by a current going through the first coil.

$$V = M \, {}^{dI}\!/_{dt} \tag{4-3}$$

Here M is the mutual inductance or the inductance shared by the two coils. And the current$\left(I\right)$ is the current in the other coil then at with V is induced. The mutual inductance is determined by the coil inductances and the magnetic flux that are shared by the two coils. In a transformer most magnetic flux goes through both coils while air coupled coils only share less magnetic flux.

$$M = k\sqrt{L_1 L_2} \tag{4-4}$$

The difference in magnetic flux going through the coils is defined as the coupling factor$\left(k\right)$. This can be represented by drawing magnetic field lines. Where the closer the field lines the higher the magnetic flux. The total magnetic flux is dependent on the total current. While field lines only represent a relative difference of magnetic field.

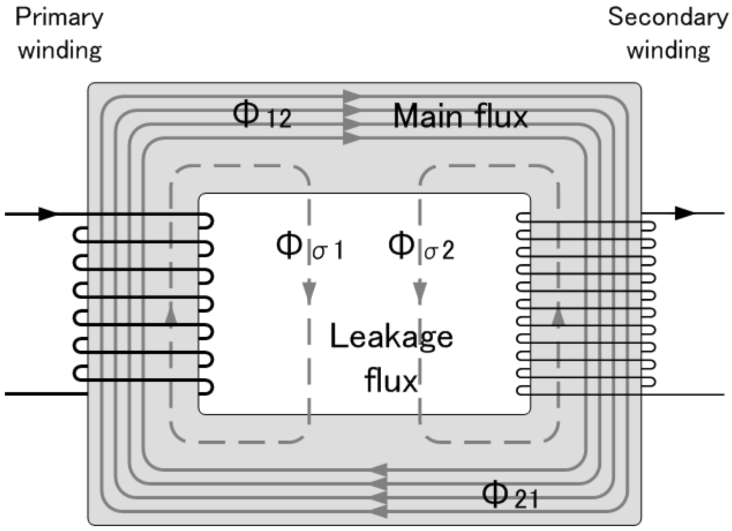


Figure 4-3 magnetic field lines through a metal cored transformer, where the leakage flux $\Phi_{\sigma 1}$ equals $\Phi_{\sigma 2}$

As shown in Figure 4-3most of the field lines go through both coils. The small leakage flux is represented by the dashed lines in the centre. In an air coupled transformer the field lines are not directed by a core material and therefore are only dependant on the distances and relative size of the coils.

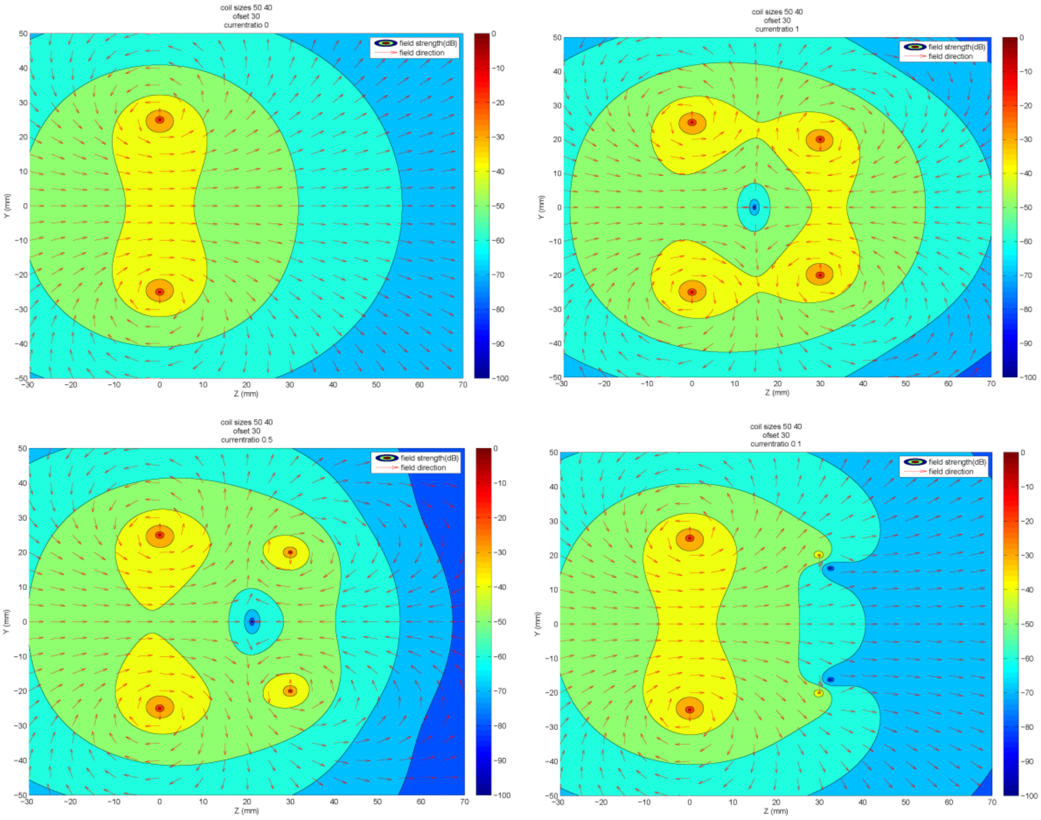


Figure 4-4 four magnetic fields. a (top left), only current through primary coil. b (top right), equal currents through both coil. c (bottom left), current second coil 0.5 times first. d (bottom right), current second coil 0.1 times first.

Figure 4-4 shows the magnetic field strength and direction where the total magnetic field is dependent on the current in both coils. The differences between the four are that the current in the secondary coil is altered. Figure 4-4 a has only current in the primary coil while b has equal currents in both coils. Figures c and d have a difference of 0.5 and 0.1 between primary and secondary coils respectively. The secondary currents are opposite to the primary. This is because the secondary coil only removes energy from the magnetic field. The situation in b is physically impossible without providing power to the secondary coil. If the secondary current is induced by the primary and the powers are equal then there cannot be a magnetic field. If there is a magnetic field left this could result in transfer to a third coil. The power delivered by this coil would exceed the power inserted in the primary coil. Giving a net result of getting more power from the system then is delivered to it. This is of course impossible. Figure 4-4 is made with Matlab and described in appendix-B

4.1.2 Magnetic coupling

The magnetic coupling or the magnetic flux going through both coils differs a lot between the setups in Figure 4-3 and Figure 4-4. While the definition of the coupling stays the same. As:

$$\Phi_1 = \Phi_{12} + \Phi_{\sigma 1} \qquad (4\text{-}5)$$

(4-5) uses Figure 4-3 as reference. $\Phi_{\sigma 1}$ is the leakage flux of the first coil and Φ_{12} is the mutual flux. Since there is only one magnetic field that is generated by both the coils the mutual flux$\left(\Phi_M\right)$ of both is the same. The coupling between the coils then becomes:

$$k = \frac{\Phi_{12}}{\Phi_1} = \frac{\Phi_{21}}{\Phi_2} = \frac{\Phi_m}{\Phi_1} \tag{4-6}$$

The coupling from coil 1 to coil 2 is equal to the coupling between coil 2 and coil 1. This is a consequence of electromagnetic field theory and will not be discussed in this thesis. A transformer has high coupling while an inductive link only has a low coupling. The difference between mutual and total flux of the coils still defines the coupling.

4.2 Coupling of two air coupled coils

The coupling factor between two coils can be calculated to a high precision using finite element methods (FEM) programming. While this results in high precision the drawback is that the FEM program requires large amount of data to determine the coupling of the coils. Using a simplified method many aspects of the magnetic field can be obtained while allowing flexibility to aid in the design.

4.2.1 Simplification method

There are two simplifications used. The coils that are used are square with only one winding and the conductors have an infinitely small area. This allows simple calculation of the magnetic field strength in a point in space. Dividing the coils in four separate line segments gives an influence per segment of:

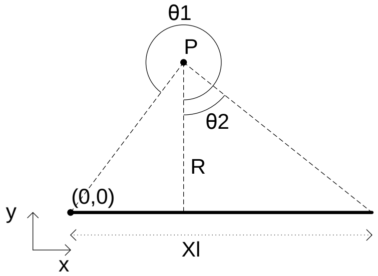


Figure 4-5 magnitude of magnetic field strength in a point (P) in space

$$\left|B_P\right| = \frac{\mu_0 I}{4\pi} \cdot \frac{\sin\theta_2 - \sin\theta_1}{R} \tag{4-7}$$

Where R is the distance between point P and the conductor, θ_1 and θ_2 are the angles to the beginning and end of the conductor and B_P is the magnetic field. $\left|B_P\right|$ is the magnetic field strength with the direction perpendicular to both R and I (the current through the conductor).

The main drawback of this method is that the magnetic field close to the wire will be infinite. This can be seen from (4-7) since R will be very small. This is not physically possible since the conductor has a size and the magnetic field in a conductor is zero. To allow the calculations R should always be larger than the half of the conductor radius.

4.2.2 Defining the coils

Creating a drawing of the magnetic field as generated by the two coils of an IWPD requires a definition of its size and layout. The simple square coil with one winding is used. The size and relative location of the coils is defined as:

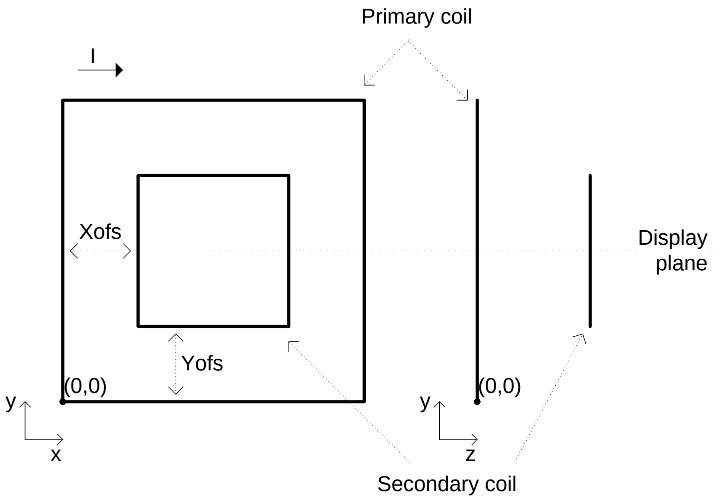


Figure 4-6 coil sizes used for the inductive link calculations

In Figure 4-4 the magnetic field is displayed according the display plane of Figure 4-6, where the X Z plane is used to show the magnetic field. This plane is chosen because all magnetic field vectors are in plane. All off plane components cancel out since the top half and bottom half are identical. To calculate the total magnetic field in a point of space the influence of every line segment is added together.

$$B_p = \sum_{i=1}^{n} B_i \tag{4-8}$$

Where B_i is the vector of the magnetic field as generated by line segment i and n is the number of line segments. In this basic setup $n = 8$ because both coils have 4 conductors.

4.2.3 Calculating the coupling

Modelling the couple factor of the IWPD by applying simplifications will allow an understanding of its properties. The couple factor(k) is relation between the magnetic flux going through the first and second coil as a result current going through the primary coil. The flux going through the first coil is the total flux(Φ_1) and the flux through the second coil is the mutual flux(Φ_M).

$$k = \frac{\Phi_M}{\Phi_1} \tag{4-9}$$

The magnetic flux going through the coils is the integral of the magnetic field (B) over the area inside the coil(S) and perpendicular to the area$(B_{\perp S})$.

$$\Phi = \iint_S B_{\perp S} dS \tag{4-10}$$

Calculating the magnetic field induced by the current(I) in the primary coil can be divided in calculating 4 fields induced by the 4 line segments of that coil. The field direction needs to be taken in to account when adding the field strength. The magnetic field created by one line segment is:

$$B_{sig} = \frac{\mu_0 I}{4\pi} \cdot \frac{\sin(\theta_2 - \theta_1)}{R} \tag{4-11}$$

For the first coil the line segments produce a field in the same direction. This makes it sufficient to add the magnetic field of the segments.

$$B_{tot1} = B_{sig1} + B_{sig2} + B_{sig3} + B_{sig4} \tag{4-12}$$

For the second coil a factor needs to be taken to correct for the non perpendicular field. The figure below gives a graphical view of the perpendicular and non perpendicular parts of the magnetic field.

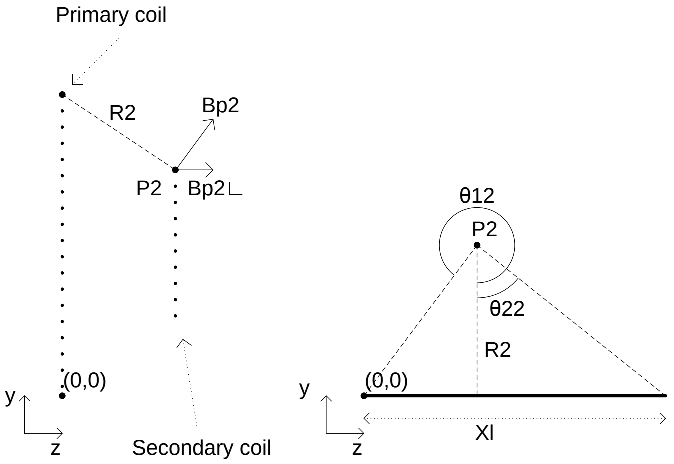


Figure 4-7 calculating magnetic flied of second coil

Form the figure a conclusion can be made that the calculations for the secondary coil are somewhat different from the primary. For the totals magnetic field this becomes.

$$B_{tot2} = B_{sig1\perp 2} + B_{sig2\perp 2} + B_{sig3\perp 2} + B_{sig4\perp 2} \tag{4-13}$$

With each line segment defined by:

$$B_{sig1} = \frac{\mu_0 I}{4\pi} \cdot \frac{\sin\theta_{22} - \sin\theta_{12}}{R} \cdot X_{\perp 2} \tag{4-14}$$

Where $X_{\perp 2}$ is a factor that corrects the vector to perpendicular to the area inside the second coil. Filling in (4-10) for both the first and second coils gives:

$$\Phi_1 = \iint_{S1} B_{tot1} dS1 \tag{4-15}$$

And:

$$\Phi_M = \iint_{S2} B_{tot2\perp 2} dS2 \tag{4-16}$$

In all the calculations μ_0 and I are the same the factor $\mu_0 I / 4\pi$ can be taken outside the magnetic field calculations with:

$$B = \frac{\mu_0 I}{4\pi} B^* \tag{4-17}$$

Rewriting equations (4-15) and (4-16) as equation (4-18) and (4-19) respectively:

$$\Phi_1 = 4\frac{\mu_0 I}{4\pi} \iint_{S1} B^*_{tot1} dS1 \tag{4-18}$$

$$\Phi_M = 4\frac{\mu_0 I}{4\pi} \iint_{S2} B^*_{tot2\perp 2} dS2 \tag{4-19}$$

Rewriting equation (4-9) with equations (4-18) and (4-19) then shows that the factor taken apart at equation (4-17) cancels in the calculation for the coupling factor, shown in equation (4-20). This was to be expected since the coupling is independent of current and magnetic permeability. For the magnetic permeability this only holds when there is no difference in permeability between the two coils.

$$k = \frac{\Phi_M}{\Phi_1} = \frac{4\frac{\mu_0 I}{4\pi} \iint_{S2} B^*_{tot2\perp 2} dS2}{4\frac{\mu_0 I}{4\pi} \iint_{S1} B^*_{tot1} dS1} = \frac{\iint_{S2} B^*_{tot2\perp 2} dS2}{\iint_{S1} B^*_{tot1} dS1} \tag{4-20}$$

Because of the simple forms the coils calculations can be rewritten to x, y and z. Using Figure 4-6 and Figure 4-7 as definitions for the coils. Starting with the first coil needs the rewrite of the angles and distance in equations (4-21) to (4-23). Using those relations in equation (4-24) to form the magnetic field strength.

$$\sin\theta_2 = \frac{X_L - x}{\sqrt{(X_L - x)^2 + y^2}} \tag{4-21}$$

$$-\sin\theta_1 = \sin(2\pi - \theta_1) = \frac{x}{\sqrt{x^2 + y^2}} \tag{4-22}$$

$$R = y \tag{4-23}$$

$$B^*_P = \frac{\sin\theta_2 - \sin\theta_1}{R} = \frac{\frac{X_L - x}{\sqrt{(X_L - x)^2 + y^2}} + \frac{x}{\sqrt{x^2 + y^2}}}{y} \tag{4-24}$$

These equations only apply when the angels θ_2 and $2\pi - \theta_1$ never exceed 90 degrees. For the first coil this is always the case. For the second coil the choice of size makes this apply. As long as the second coil is smaller and within the xy plane of the first coil. For the second coil a similar set of equations can be made.

$$\sin\theta_{22} = \frac{X_L - x}{\sqrt{(X_L - x)^2 + y^2 + z^2}} \tag{4-25}$$

$$-\sin\theta_{12} = \sin(2\pi - \theta_{12}) = \frac{x}{\sqrt{x^2 + y^2 + z^2}} \tag{4-26}$$

$$R_2 = \sqrt{y^2 + z^2} \tag{4-27}$$

$$B^*_{P2} = \frac{\sin\theta_{22} - \sin\theta_{12}}{R} = \frac{\dfrac{X_L - x}{\sqrt{(X_L - x)^2 + y^2 + z^2}} + \dfrac{x}{\sqrt{x^2 + y^2 + z^2}}}{\sqrt{y^2 + z^2}} \tag{4-28}$$

For the second coil the factor $X_{\perp 2}$ needs to be added to take only the perpendicular part. In terms of xyz this is:

$$X_{\perp 2} = \frac{y}{R_2} = \frac{y}{\sqrt{y^2 + z^2}} \tag{4-29}$$

Resulting in a magnetic field strength of:

$$B^*_{P2\perp 2} = \frac{\dfrac{X_L - x}{\sqrt{(X_L - x)^2 + y^2 + z^2}} + \dfrac{x}{\sqrt{x^2 + y^2 + z^2}}}{\sqrt{y^2 + z^2}} \cdot \frac{y}{\sqrt{y^2 + z^2}} \tag{4-30}$$

The square coils that have been chose allow for one more simplification. The effect of each line segment is the same. The field is only rotated around the z axis. This rotation makes the field strength at a particular point to differ while keeping the integral over the areas the same. Instead of calculating the field for each segment only one is calculated and then multiplied by 4. This holds for both the first and second coil as in equations (4-31) and (4-32) respectively.

$$\Phi_1 = \int_{\frac{r}{2}}^{X_L} \int_{0}^{X_L} \frac{\dfrac{X_L - x}{\sqrt{(X_L - x)^2 + y^2}} + \dfrac{x}{\sqrt{x^2 + y^2}}}{y} \, dy \cdot dx \tag{4-31}$$

$$\Phi_M = \int_{X_{ofs}}^{X_L - X_{ofs}} \int_{Y_{ofs}}^{X_L - Y_{ofs}} \frac{\dfrac{X_L - x}{\sqrt{(X_L - x)^2 + y^2}} + \dfrac{x}{\sqrt{x^2 + y^2}}}{\sqrt{y^2 + z^2}} \cdot \frac{y}{\sqrt{y^2 + z^2}} \, dy \cdot dx \tag{4-32}$$

Now we have a set of equations to calculate the coupling factor with only a small set of variables still to be chosen. The model can be used to determine the coupling factor in reference to several coil aspects. The main interest is distance since the affect of changing distance is expected to have a significant impact on the couple factor. Applied to an IWPD where the distance is expected to move under wind conditions. To calculate the model Maple is used as it can handle the analytical equations used.

4.2.4 Validation

The validation of the model is done in reference to the FastHenry program. The table below gives coil sizes displacement and the results of both FastHenry and the Maple model.

Tabel 4-1 Relation between Maple model and FastHenry

Primary size (mm)	Secondary size (mm)	Displacement (mm)	Wire size (mm)	Maple (k)	FastHenry (k)	Difference (Maple/FastHenry)
50	30	20	0.01	0.029	0.038	0.76
50	30	20	0.1	0.040	0.053	0.75

50	30	17	0.01	0.035	0.046	0.76
50	30	17	0.1	0.048	0.063	0.76

There is a difference between the proposed model and simulations made with FastHenry. The difference between the two simulations is a factor nearly independent of the simulated setup. During the calculations simplifications have been made. The wire area used is infinitely small a situations not physically possible. In a real wire the current is distributed over the entire aria of the wire creating a current density that is not infinite. This simplification is most accurate for systems where the area of the wires in the coil is small compared to the size of the coils.

This results in a change of the magnetic field close to the wire. The current distribution effect is shown in Figure 4-8 as the difference between an infinitely small wire and a real wire. The current at the side of the wire will have an influence that is cancelled by the current at the other side. Increasing the distance between the wire and a point in space this cancelling effect becomes smaller. This effect is part of the primary coil flux since it is integrated from the wires edge. The secondary coil is so far away that it does not have this effect resulting in a constant difference.

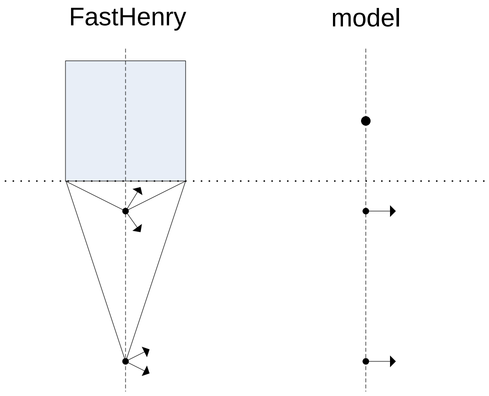


Figure 4-8 Current density error

The current distribution effect is expected to be the most important error made in the model. The reason for this is that the magnetic field strength is largest close to the primary conductor where the current distribution has most effect. Other effects with respect to wire and coil size will be the integration of area inside the wire, done for simplifying the calculations, and distance between the coils. The last is an effect that would decrease the distance between the coils by the wire thickness. These influences are shown in Figure 4-9.

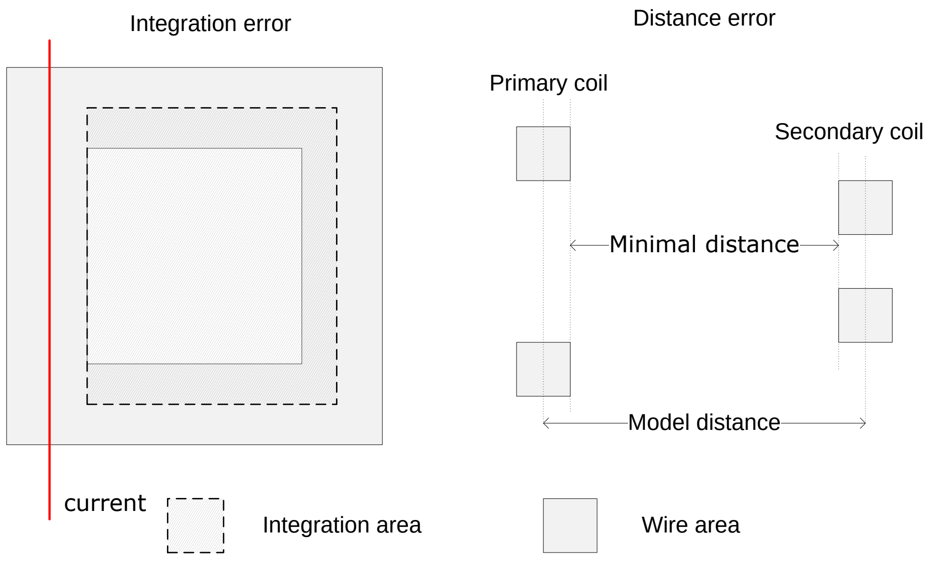


Figure 4-9 integration and distance errors

These differences have an influence on the values jet not on the difference between the values. In the results that are required from this model the true value is not of the most importance. The true value would be required once the basic design has been completed and more information on the coils can be obtained. Here the model is used to optimize the layout and understand the impact of variations in the eventual system.

4.3 Coupling results

Looking at the application in mind: the main interest in the coupling factor would be the distance between the coils. For two reasons, first the expected impact in this direction is largest, and second to allow movement of the rocket with respect to the launch tower.

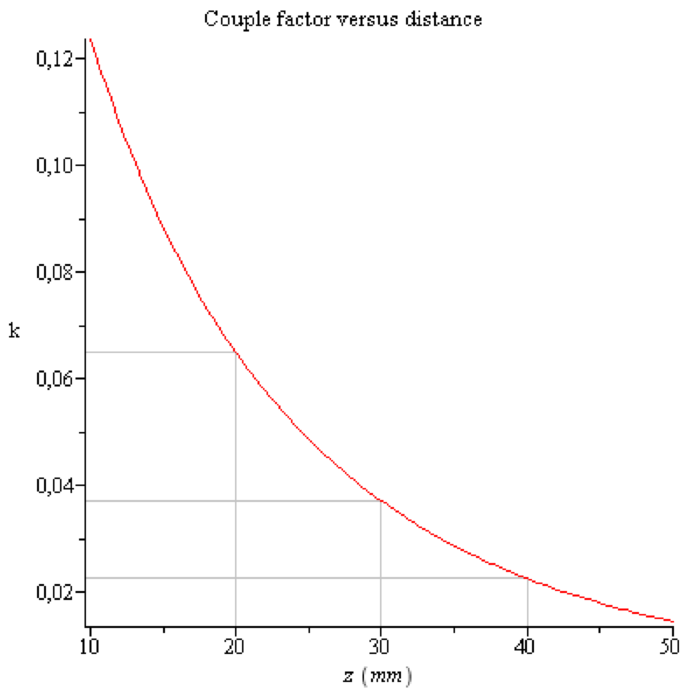


Figure 4-10 coupling factor versus distance

Figure 4-10 shows the change in coupling factor relative to distance between the coils. The coils used in this graph are square with 50 mm size for the primary and 40 mm size for the secondary coil. In both coils the number of windings is 1. This choice was made because of the size of the rocket. The distance that can be used is determined by the place of the coil inside the rocket and the curvature of that part. The other part is the package and size of the coil but this is expected to be less of influence on the distance. The expected distance would be around 20 to 30 mm depending mostly on the distance from the inner coil to the rocket surface. Since the coil needs some housing to hold it in place. Figure 4-10 shows that in this distance the coupling factor changes by a factor 2. The values might change once real inductors are used for simulation yet this effect cannot be completely removed resulting in an influence on other components. Figure 4-10 is created in Maple as described in Appendix-C

4.3.1 Influence of coupling factor variation

The coupling factor variation has influence on two aspects of the inductive link. The first is the transformer function and therefore has influence on the driving and loading electronics.

The second part is a change in magnetic field since less coupling means that the field will potentially couple in to other components. When the inductive link is placed with the rocket the magnetic field will potentially couple in aluminium and carbon components. These two aspects will be described shortly in section 4.4 and 4.5.

4.4 Transformer function

With the coupling of the coils determined it is possible to continue on with Figure 4-2. Redrawn here for clarity:

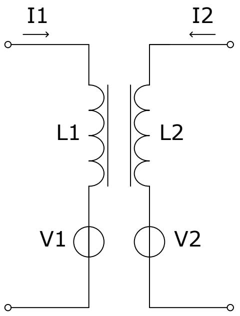


Figure 4-11 redraw of Figure 4-2.

This schematic is difficult to use when trying to determine the electrical properties of the system. This comes from the fact that each side has influence on the other. The normal of going around this would be to use an equivalent circuit, without the voltage sources.

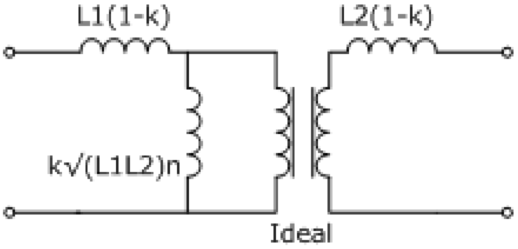


Figure 4-12 transformer equivalent circuit

Figure 4-12 gives a lossless version of the equivalent circuit. Where L_1 and L_2 are the inductances of the first and second coil, k is the coupling factor, n is the turn ratio and the ideal transformer to transform the signals according to the turn ratio.

The ideal transformer in this circuit still makes the calculations difficult. Yet because the transformer is ideal it can be moved out of the system, by making impedance transformations. Figure 4-13 shows the impedance transformation with a ideal transformer with a turn ratio of n and a resistance of R.

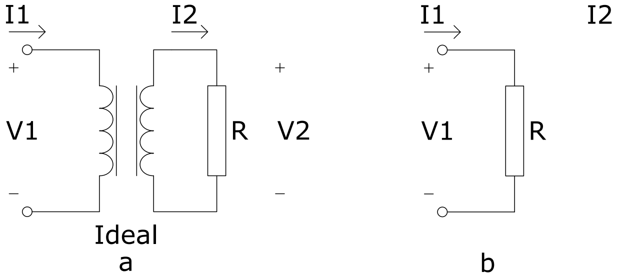


Figure 4-13 Impedance transformation of an ideal transformer

$$V_2 = R \cdot I_2 \tag{4-33}$$

$$V_2 = \frac{V_1}{n} \tag{4-34}$$

$$I_2 = n \cdot I_1 \tag{4-35}$$

$$\frac{V_1}{n} = R \cdot n \cdot I_1 \Rightarrow V_1 = n^2 R \cdot I_1 \tag{4-36}$$

$$R^* = n^2 R \tag{4-37}$$

The resistance R appears to have changes with a factor of n^2. With this information the equivalent circuit cal be changed it to Figure 4-14 will keeping in mind that the impedance of the load network needs to be transformed before using the equivalent circuit.

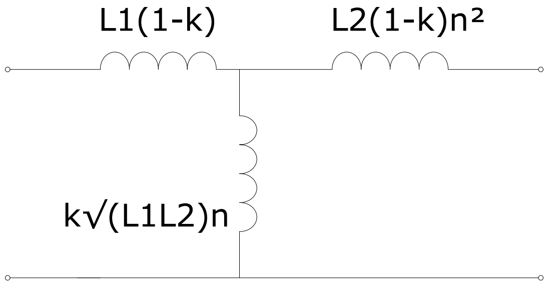


Figure 4-14 equivalent circuit without transformation of load impedance

4.5 Magnetic field

The magnetic field generated of the inductive link is generated by the first coil. In Figure 4-4 a difference in magnetic field is shown when the current through the second coil is changes. Figure 4-4 a shows the highest filed strength far from the first coil. This situation provides the highest chance of inducing energy into parts of the rocket.

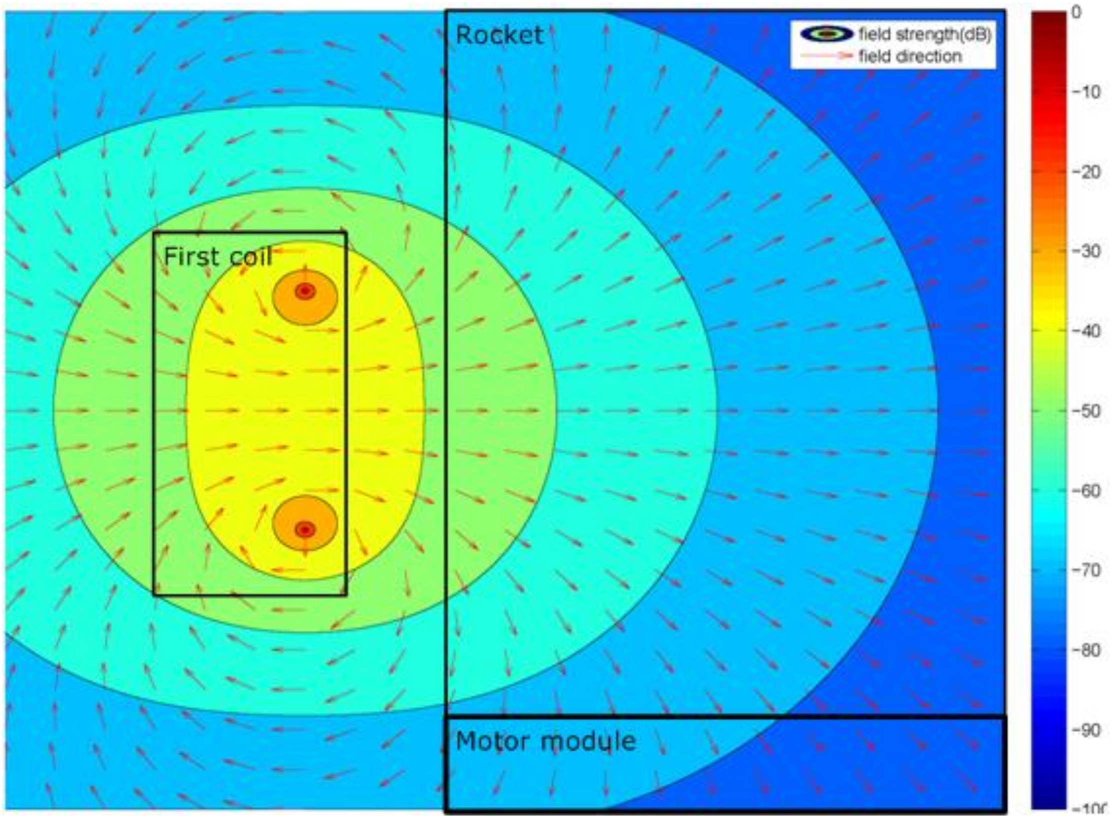


Figure 4-15 magnetic field with respect to the rocket

The field strength in Figure 4-15 drops very quickly. The field has already dropped about 70 dB at a distance similar to the size of the coils. When the inductive link is placed more than two times its size away from the rocket motors no problems are expected. The energy in the field will have been reduced to the point where it will not have much influence. Even if they are ideal conductors that do not lose the heat generated in them it is still very unlikely to form a hazard for the rocket motors.

For the electromagnetic interference only the components close to the link will be likely to be effected. This effect however is very small considering the low expected operation frequency. Designing the electronics in the vicinity of the link to be compatible with the EMI generated by the link removes the dangers of the inductive link.

5 Power and data transfer

In chapter 4, a description of the inductive link was given. In this chapter the circuitry that supplies and loads the link will be discussed. A description of different circuit possibilities and the implications they have on the power and data throughput of the system is provided. Starting with the equivalent circuit of chapter 4 and adding small parts at a time, until the circuit complies with the requirements of chapter 3.

5.1 Driving and loading circuit

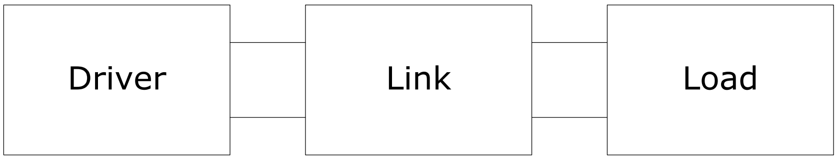


Figure 5-1 electrical top level design of an IWPD

The IWPD system can be divided in three parts as shown Figure 5-1. The link part was designed in chapter 4, and can be replaced with its equivalent circuit. Updating the system provides:

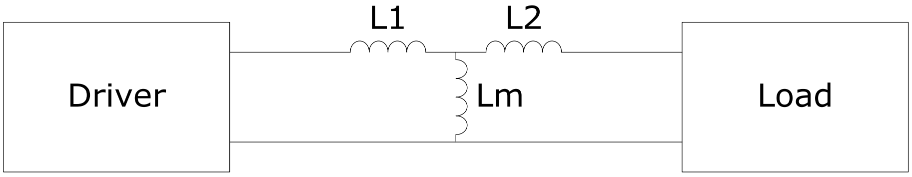


Figure 5-2 transformer equivalent circuit in the IWPD

The equivalent circuit is used since this will decrease calculation complexity. The load is the rockets electronics which is defined in chapter 3. This circuitry is also a simplified version of the electronics and is defined as the expected values. Providing:

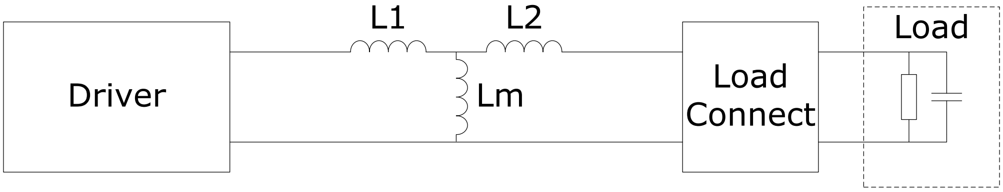


Figure 5-3 load connection in the IWPD

The output of the link and the load are not compatible. Since the load requires DC power and the link can only supply AC power. So a Load connection circuit is added in Figure 5-3. The requirements on the DC voltage are determined by the load circuit. The load circuit will have several voltage regulators which allow a relatively high range for the supplied DC voltage. Making the DC voltage for the load can be obtained by a diode bridge with a capacitor behind it. This is the simplest implementation and the preferred option if the results are suitable. The diode bridge is comprised out of 4 diodes. The capacitor is also required for the voltage regulator combining these two makes it a very small system. Other options will be investigated if and only if the diode bridge is unsuitable. Is a diode bridge the only part of the load connection or is there still other circuitry required.

In the situation of a transformer with high coupling between the coils the mains is connected directly to the primary coil and the diode bridge is connected to the secondary side. Creating the following circuit:

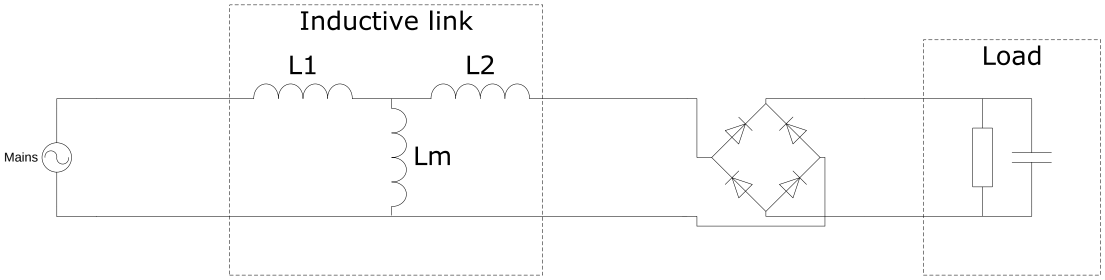


Figure 5-4 transformer connection used for high coupled transformers

While this situation works well with a high coupled transformer, it does not work for a loosely coupled transformer or IWPD. To increase the transfer efficiency a resonance circuit can be added, by adding a capacitor to both the inductors. This resonance allows the energy in the system to move between the inductor and the coil. This stores the energy and increases the potential efficiency. Using resonators will remove the effect of L1 and L2. The capacitors and leakage induction will cancel and result in having only Lm left in the system

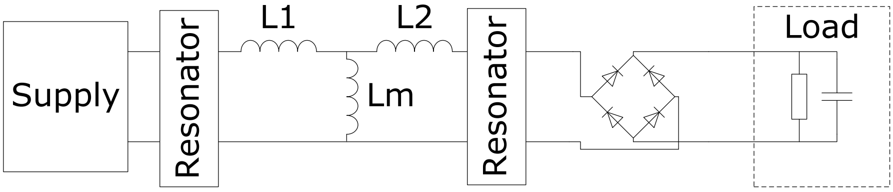


Figure 5-5 IWPD schematic with resonators

The transfer is still relatively low since the impedance of the primary coil at the low mains frequency is low. The current through Lm is loss in the system. An option would be to increase the operating frequency. This increase would yield better results for less power is lost in Lm while increasing the loss in the supply. Producing higher frequencies requires faster switching at the supply increasing switching losses. The impedance of Lm is linearly dependent on frequency:

$$Z_M = 2\pi \cdot f \cdot L_M \tag{5-1}$$

This is resulting loss of Lm is inversely proportional to frequency:

$$\frac{1}{f} \tag{5-2}$$

This chapter will continue on with designing the circuitry. The first step is to determine the basics of the resonance circuit. Then the control step will be implemented by creating the driving elements for the resonant transformer. The last step will be the simulations of a proposed design.

5.2 Resonant transformer

As defined above a pair of capacitors will be added to make the transformer in to a resonant transformer. The resonance and its effect on impedance will be described first. Second the implementation options will be described. After which the effect of the resonance and coupling will be related to the transfer of the inductive link.

5.2.1 Resonant circuit

Adding a capacitor makes an inductor resonate. The exact values are not very important at this stage since any combination of inductance and capacitance will result in a resonant circuit. Looking at only a single inductor there are two options for adding the capacitor with different results on the impedance of the circuit.

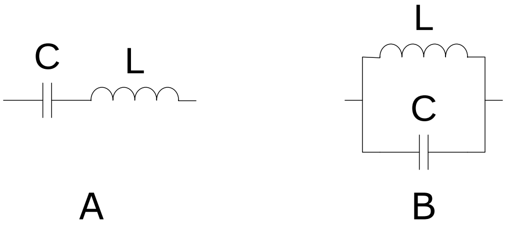


Figure 5-6 two resonant circuits. a, series connection. b, parallel connection

Both circuits A and B of the above figure have the same resonance frequency:

$$f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi\sqrt{L \cdot C}} \tag{5-3}$$

Circuit a is a series connected circuit while b is a parallel connected circuit. The difference between the circuits is the impedance they have. The impedance of circuit a at the resonance frequency is zero (with ideal components). The impedance of circuit a at the resonance frequency is infinite. Drawing the frequency response of both impedances gives:

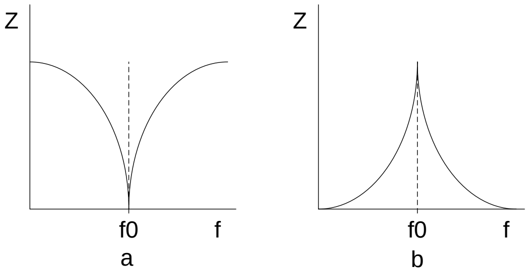


Figure 5-7 impedance versus frequency. a, series connection. b, parallel connection.

5.2.2 Resonance and a transformer

Applying capacitors to the transformer can be done in 4 ways. As in Figure 5-6 each of the two inductors of the transformer can be connected in series or in parallel. Resulting in de Following options:

- Series input, Series output (SS)
- Series input, Parallel output (SP)
- Parallel input, Series output (PS)
- Parallel input, Parallel output (PP)

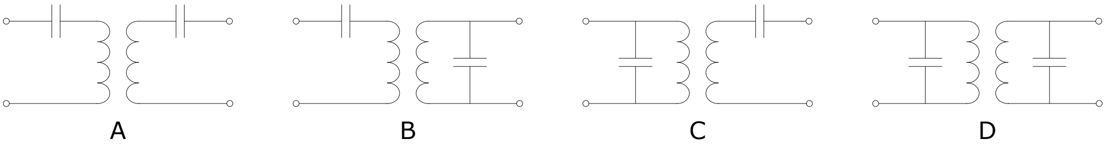


Figure 5-8 four connection options. a, series-series. b, series-parallel. c, parallel-series. d, parallel-parallel.

The capacitor values when the inductors are not coupled are dependent on the required frequency and the inductor value.

$$C = \frac{1}{\left(2\pi f_0\right)^2 L} \tag{5-4}$$

Determining the values for these capacitors when the inductors are coupled creates several dependencies. Chwei-Sen Wang (18) describes the different resonance setups and provides a calculation option under the different setups.

The secondary capacitor is calculated as (Chwei-Sen Wang, 18 equation 6):

$$\omega_0 = \frac{1}{\sqrt{C_s L_s}} \tag{5-5}$$

The primary capacitance is detriment by (Chwei-Sen Wang, 18 table 1):

$$SS \Rightarrow C_p = \frac{1}{\omega_0^2 L_p} \tag{5-6}$$

$$SP \Rightarrow C_p = \frac{1}{\omega_0^2 \left(L_p - \frac{M^2}{L_s}\right)} \tag{5-7}$$

$$PP \Rightarrow C_p = \frac{L_p - \frac{M^2}{L_s}}{\left(\frac{M^2 R}{L_s^2}\right)^2 + \omega_0^2 \left(L_p - \frac{M^2}{L_s}\right)^2} \tag{5-8}$$

$$PS \Rightarrow C_p = \frac{L_p}{\left(\frac{\omega_0^2 M^2}{R}\right)^2 + \omega_0^2 L_p{}^2} \tag{5-9}$$

This would indicate that only the Series-Series connection is not influenced at its frequency by the coupling between the two coils or the output inductance. The above equations do not show the frequency response of the circuits. It only calculates what the optimum capacitor value for a certain set of operation parameters. Since the set of parameters in our situation is not predefined a different method should be used to determine the influence of these parameters on the inductive link. Using the Equivalent circuit of chapter 4 to determine the relation between input and output under the different setups can provide the necessary insight to design the system.

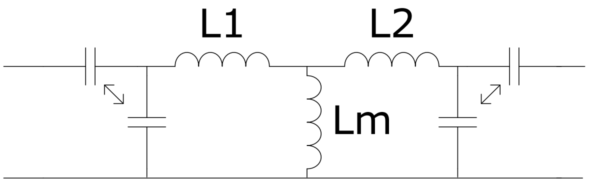


Figure 5-9 resonator connections showing the capacitors with the equivalent circuit

5.2.3 Load capacitor

In Figure 5-9 the layout of the secondary capacitance is shown. Taking only the secondary side of the link this circuit can be seen as a resonator with a resistor as damping element. The damping influence of the resistor is different in the series or parallel setup.

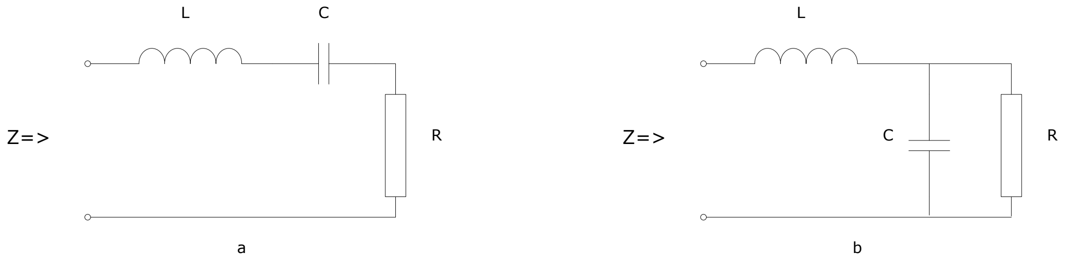


Figure 5-10 load side connection. a, series. b, parallel.

In the series output situation the damping is proportional to the resistance, or a high resistance produces a high damping. While in the parallel output situation the damping in inversely proportional to the resistance or a low resistance creates a high damping. Taking a good look at the circuits a and b gives an insight in their operation. Taking 0 Ohm for the resistor in circuit a gives an identical circuit to taking ∞ Ohm in circuit b. The circuits are not each other's inverse since taking ∞ Ohm in circuit a gives a different result as taking 0 Ohm in circuit b.

$$Z = j\omega L + \frac{1}{j\omega C} + R \tag{5-10}$$

$$Z = j\omega L + \frac{1}{j\omega C + \frac{1}{R}} \tag{5-11}$$

Chapter 3 shows that the load differs by a relative large amount. The load resistance can changes several orders of magnitude during operation. The output should have a relative constant voltage across the load. In the situation of circuit b (Figure 5-10) this means that the voltage over the capacitor needs to stay constant independent. In circuit a (Figure 5-10) neither a constant voltage across the capacitor or a constant current through the capacitor will imply a constant voltage on the load. This indicates that the parallel circuit in b (Figure 5-10) is more suited for voltage output. This is only a feeling at this point and will need to be validated later during the subchapter on transfer response versus coupling.

5.2.4 Supply capacitor

Taking only the supply side of Figure 5-9 creates a LC resonator where the load can be seen as series resistance to the inductor. This implies that high losses in the load create high losses in the inductor.

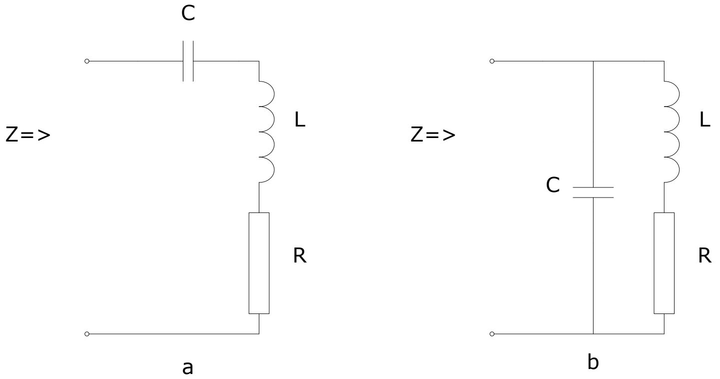


Figure 5-11 source side connection. a, series. b, parallel.

$$Z = \frac{1}{j\omega C} + j\omega L + R \tag{5-12}$$

$$Z = \frac{1}{j\omega C + \frac{1}{j\omega L + R}} \tag{5-13}$$

The driving part for the link can be implemented by a voltage or a current source. Both sources need to oscillate at the LC oscillation frequency. If the load side of the inductive link disappears the series system yields zero impedance at the LC oscillation frequency while the parallel circuit yields infinite impedance. The zero impedance of the series circuit would indicate that a current source would be the best option. Since a voltage source would yield an infinite current in this situation. At the same time a current source used with circuit B (Figure 5-11) would create an infinite voltage. Indicating that in a parallel circuit the voltage source is a better option. This is in the situation the load is not present. During the time the load is available a constant voltage across the load is desirable. At the resonance frequency the series circuit has a constant voltage across the load when driven with a voltage source. While the parallel circuit has a constant voltage across the load if a current source is applied. The circuit eventually used will be defined later in this chapter, after more information is available on the impact of the coupling.

5.2.5 Transfer versus coupling

The couple factor has impact on the transfer function of the inductive link. This aspect is most noted when comparing the unity and zero coupling factors.

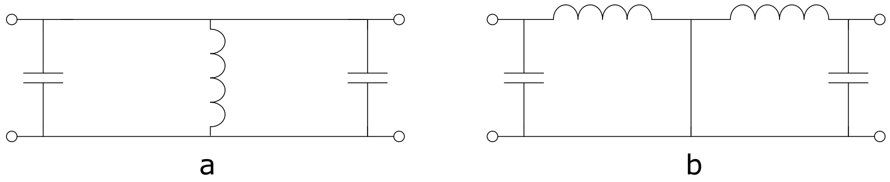


Figure 5-12 most extreme coupling factors. a, unity coupling. b, zero coupling

The situation in Figure 5-12a has no transfer between input and output. The reason this situation is drawn is to indicate the difference in resonance frequency between the two extreme situations. Determining the frequency response of input impedance in situation a only has two components.

$$Z_a = \frac{1}{j\omega C + \frac{1}{j\omega L}} \tag{5-14}$$

$$Z_b = \frac{1}{j\omega C + \frac{1}{j\omega L} + j\omega C} = \frac{1}{j\omega 2C + \frac{1}{j\omega L}} \tag{5-15}$$

The resonance frequency of the two circuits becomes.

$$\omega_{0a} = \frac{1}{\sqrt{LC}} \tag{5-16}$$

$$\omega_{0b} = \frac{1}{\sqrt{L2C}} = \frac{\sqrt{2}}{2}\frac{1}{\sqrt{LC}} = \frac{\sqrt{2}}{2}\omega_{0a} \tag{5-17}$$

The frequency difference between circuit a and b is $\sqrt{2}/2$. This difference indicates that the operation frequency should change if the coupling changes. Or that the system must prevent the coupling factor to change. The second situation is undesirable since this indicates that the circuit must build and used within very strict design parameters. Creating a supply circuit that can handle this difference will leave more design options in other components.

The influence on frequency response can be made visible by creating bode plots of several coupling factors. The bode plot can be created by calculating the poles and zero's of the circuit. Using the Slicap program to determine these poles and zeros for the bode plot. Slicap is an online program designed for symbolic linear circuit analysis. The input for Slicap is a text file with a nodal schematic of the circuit. Appendix-C describes the exact method used to input the circuit in Slicap. The basic principle used is looking at the voltage to voltage transfer of the circuits. For every setup there are two situations that are of interest. These are the high and low load or high and low output resistance. These results in 8 bode plots made out of a magnitude and a phase plot. Figures 5-13 to 5-16 show these plots.

The most important aspect to be noticed is that there is no circuit where the transfer is independent on the coupling factor or load impedance. The frequency at which the transfer is optimum changes with coupling and load. This means frequency control is required to keep the output within operating conditions.

Both Figure 5-13 and Figure 5-15 have only a single spike at the high resistance and double spikes at the low resistance. In Figure 5-14 and Figure 5-16 this effect is reversed. This effect results from the output where a parallel connection damps out one frequency at low resistance. The series connection damps a frequency at high resistance.

The other differences are much smaller. This comes mainly form the fact that Slicap cannot work with voltage source parallel to a capacitor. To overcome this problem the parallel inputs have been converted to current sources. Using this information it can be concluded that a voltage input with a series capacitor acts the same as a current source with a parallel capacitor.

Frequency control can be achieved at two places. Either change the frequency supplied by the driving element or change the resonance frequency to keep the transfer at an optimum. Changing the resonance frequency is possible by changing the capacitance values. The problem of this change is that it is difficult to do this precise enough and knowing when to change it. Changing the frequency of the power supply can be done actively. Resulting in the same difference as changing when changing the capacitance values. The frequency can also be changed passively by making a power oscillator. This oscillator can use the resonance of the inductive link to determine its oscillation frequency. The next subchapter will discuss the power oscillator. The last step after this is to combine the elements of the system together and simulate if the total system works in the same as expected.

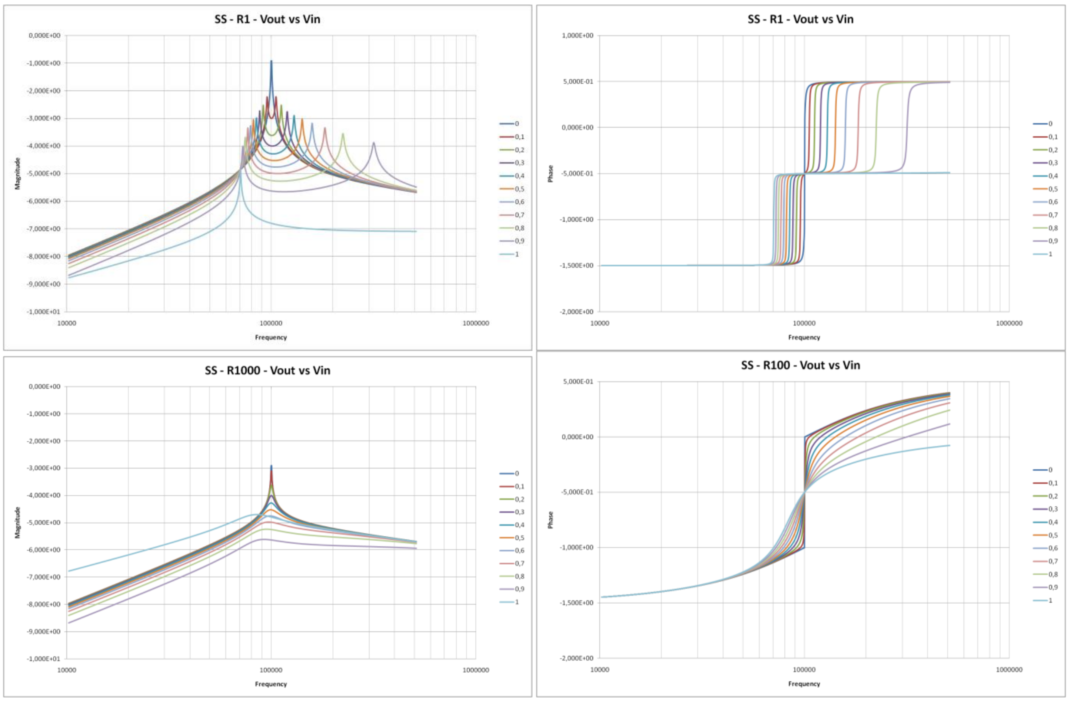


Figure 5-13 bode plots of the SS circuit. Top R is 1Ohm, bottom R is 1kOhm. Left is magnitude, right is phase. Large plots available in Appendix-F

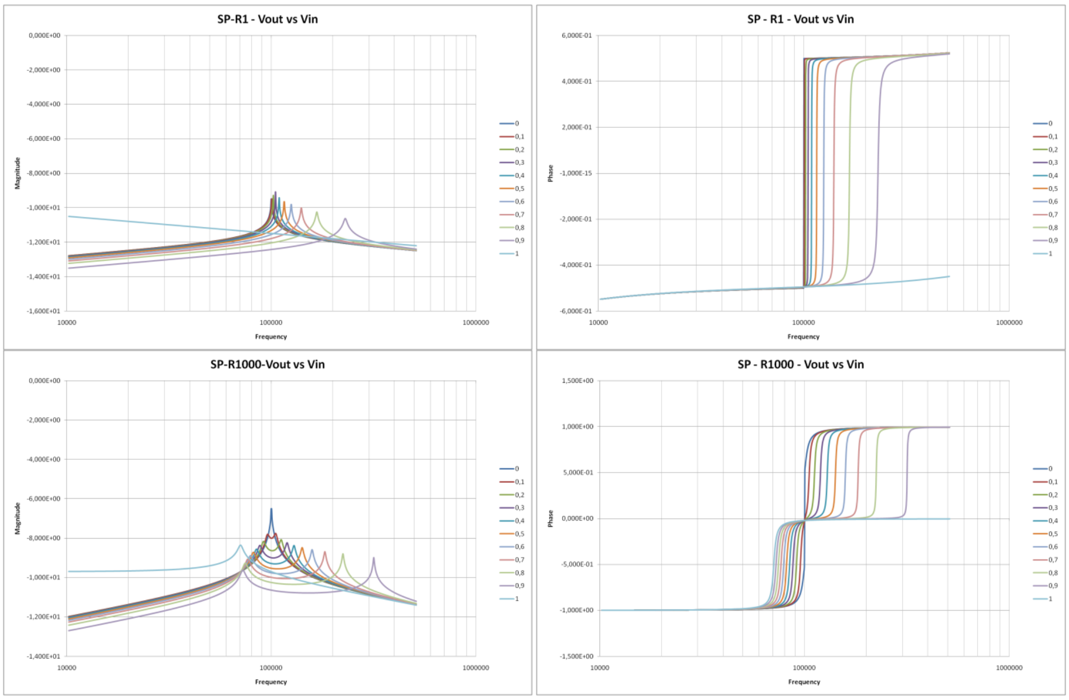
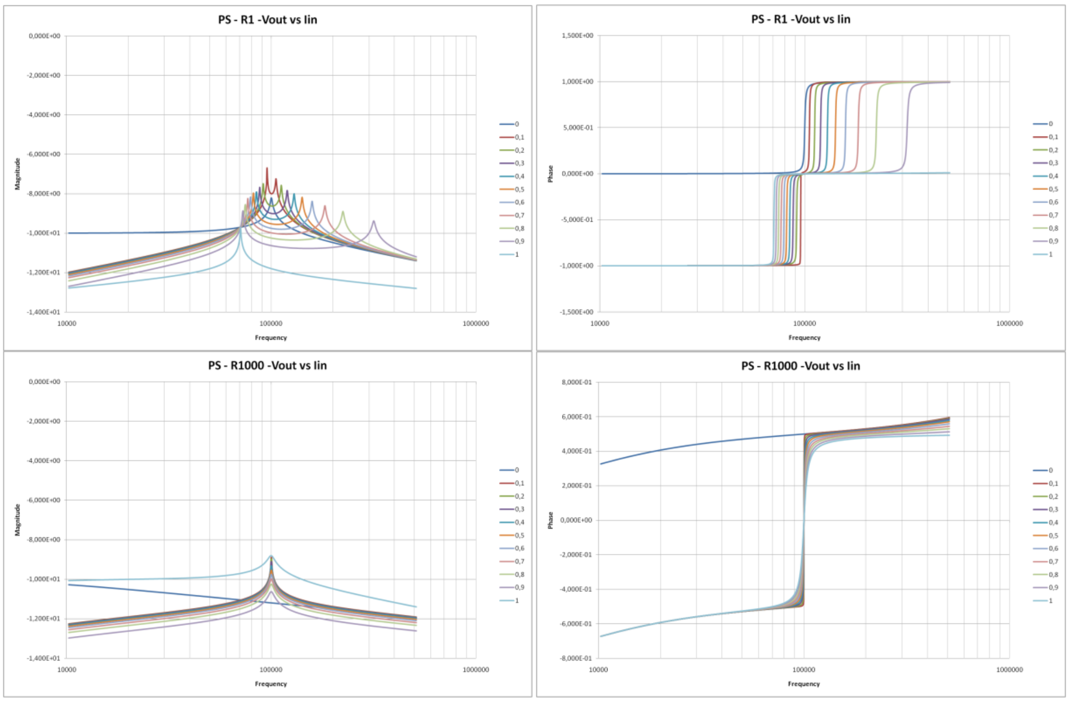


Figure 5-14 bode plots of the SP circuit. Top R is 1Ohm, bottom R is 1kOhm. Left is magnitude, right is phase. Large plots available in Appendix-F

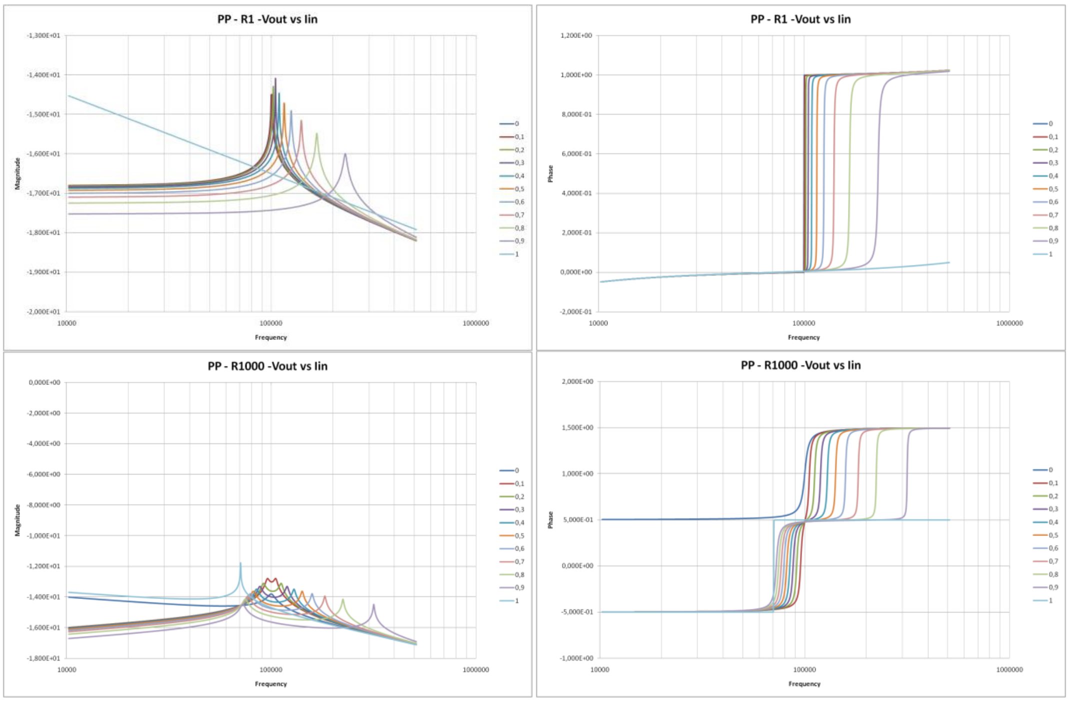

PS - R1 -Vout vs Iin

PS - R1 -Vout vs Iin

PS - R1000 -Vout vs Iin

PS - R1000 -Vout vs Iin

Figure 5-15 bode plots of the PS circuit. Top R is 1Ohm, bottom R is 1kOhm. Left is magnitude, right is phase. Large plots available in Appendix-F


PP - R1 -Vout vs Iin

PP - R1 -Vout vs Iin

PP - R1000 -Vout vs Iin

PP - R1000 -Vout vs Iin

Figure 5-16 bode plots of the PP circuit. Top R is 1Ohm, bottom R is 1kOhm. Left is magnitude, right is phase. Large plots available in Appendix-F

5.3 Power Oscillator

An oscillator requires two things, frequency determination and the supply of power. In the case of an ideal oscillator that has no losses power is only required to start the oscillation. In a real live oscillator there are always some losses that need to be cancelled to keep the oscillator oscillating. In the IWPD the power delivered to the load determines these losses. The efficiency of the inductive link is determined by the power going in to the link and the power delivered to the load. High efficiency requires the losses of the power oscillator to be equal to the power delivered to the load. Frequency determination is done by the components that will decide the frequency at which the oscillator will oscillate.

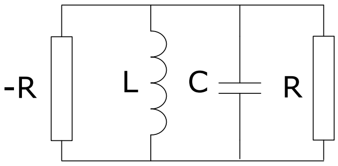


Figure 5-17 equivalent circuit of an oscillator circuit

Figure 5-17 shows a basic circuit for an oscillator. The inductor and capacitor are the frequency determining components. The resistor R represents the losses and resistor -R represents the supply. The supply of an oscillator is made by an amplifier used to amplify the voltage or current in the oscillator. There are two options for this a voltage controlled current source or a current controlled voltage source. Pictured in the figure below:

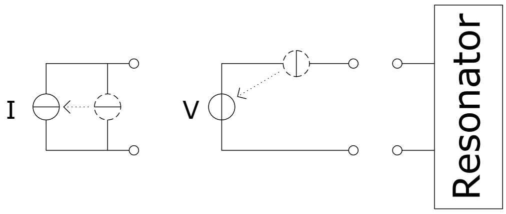


Figure 5-18 two source implementations of an oscillator. left current source, right voltage source.

The resonator will be determined by the inductive link where the losses will be defined as the power delivered to the rocket. The amplifier has two aspects the phase response and the amplification. The phase response determines the shape of the produced signal. With a very high phase response the voltage (or current) produced by the oscillator will be sinusoidal. Oscillators with a high phase response tend to be slower in their response to load changes while low phase response produces harmonic distortion. Figure 5-19 shows a high phase response in a and a low in b.

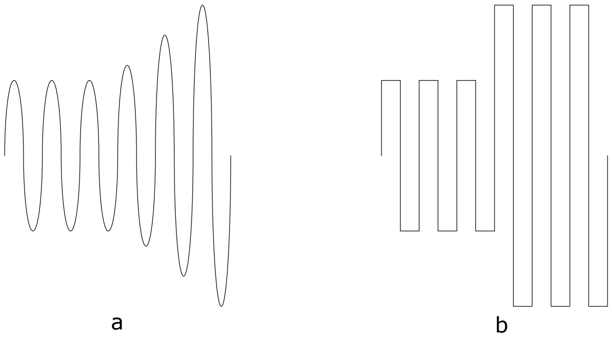


Figure 5-19 phase response of oscillators. a, high phase response. b, low phase response

For the inductive link the phase response is not of much interest in terms of power throughput. Since the power provided to the coil outside the rocket can have a power supply large enough to overcome these efficiency effects. The link will produce more EMI to other systems in the felinity. This interference comes from the harmonic content in the inductive link.

$$Square(x) = \sin x + \frac{\sin 3x}{3} + \frac{\sin 5x}{5} + \frac{\sin 7x}{7} + \ldots \tag{5-18}$$

The Fourier series of a square, given in equation (5-18), is given as reference for the amplitude of the harmonic signals. The harmonic signals of an ideal square would hold significant amounts of power. The resonator will lower harmonics of the square because it acts as a filter. The harmonics will not be completely damped out. The expected fundamental frequencies are around 100 kHz making the frequencies that have energy to produce interference relatively low. The sizes of the internal components of the rocket are very small compared to the size of the EM waves produced by the harmonics. This difference makes the interference very low and therefore phase response of the oscillator is not of importance.

The amplifier needs to provide the necessary power to keep the oscillator from damping out. This amplification can be done in two ways; the first is with an amplifier the second is by means of switching. With a switching amplifier the phase response is very poor, almost a square signal. The benefit of switching oscillators is that they use only few components.

5.3.1 Simulation of oscillating inductive link

Using Matlab Simulink to simulate the inductive link will provide a simple simulation with only little step. The complete setup is described in Appendix-E In this part only the principle and results are shown.

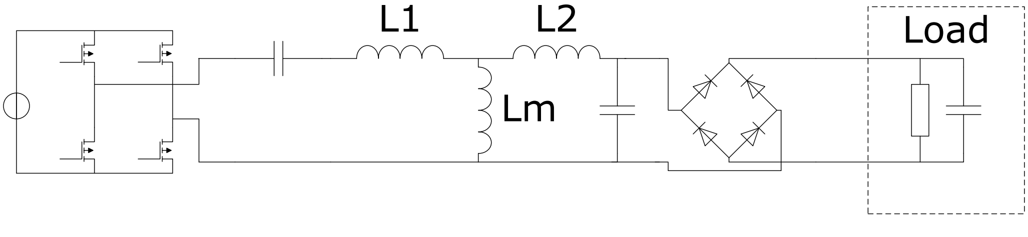


Figure 5-20 schematic used in matlab simulation, voltage source as input

In this simulation the input values are only determined to create the correct output values. When building the eventual system the values can be changed by using the turn ratio of the inductive link. For the output a there are two resistors in use. The first is a big resistor of $1k\Omega$ for the low power situation and the second is a large resistor of 4Ω for the high power situations. During operation the high power mode is only initiated after the system is connected. In the simulations the resistor is switched after 0.03 seconds, this is after the system reaches a steady state. The values for the inductors and coupling are determined as $L_1 = L_2 = 0.1mH$ and $k = 0.1$. These values are within the expected range for an inductive link and the principles stay the same when they change.

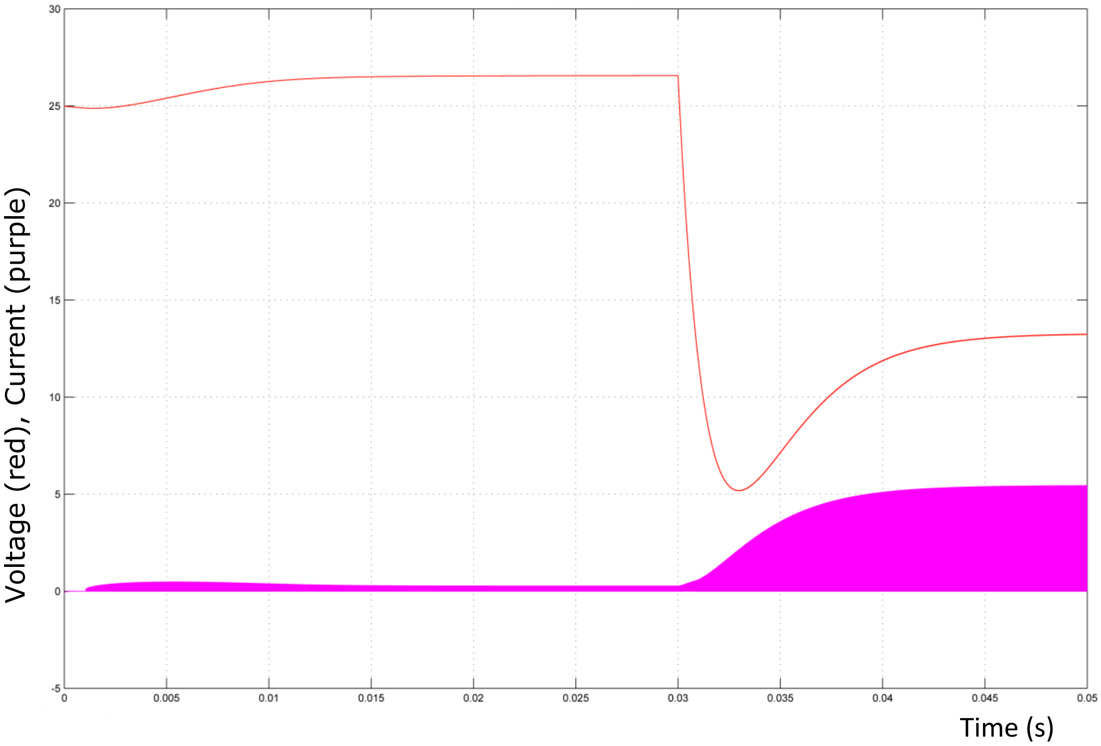


Figure 5-21 output voltages (red) and currents (purple) measured from diode bridge to load. Load resistance is switched at 0.03 seconds

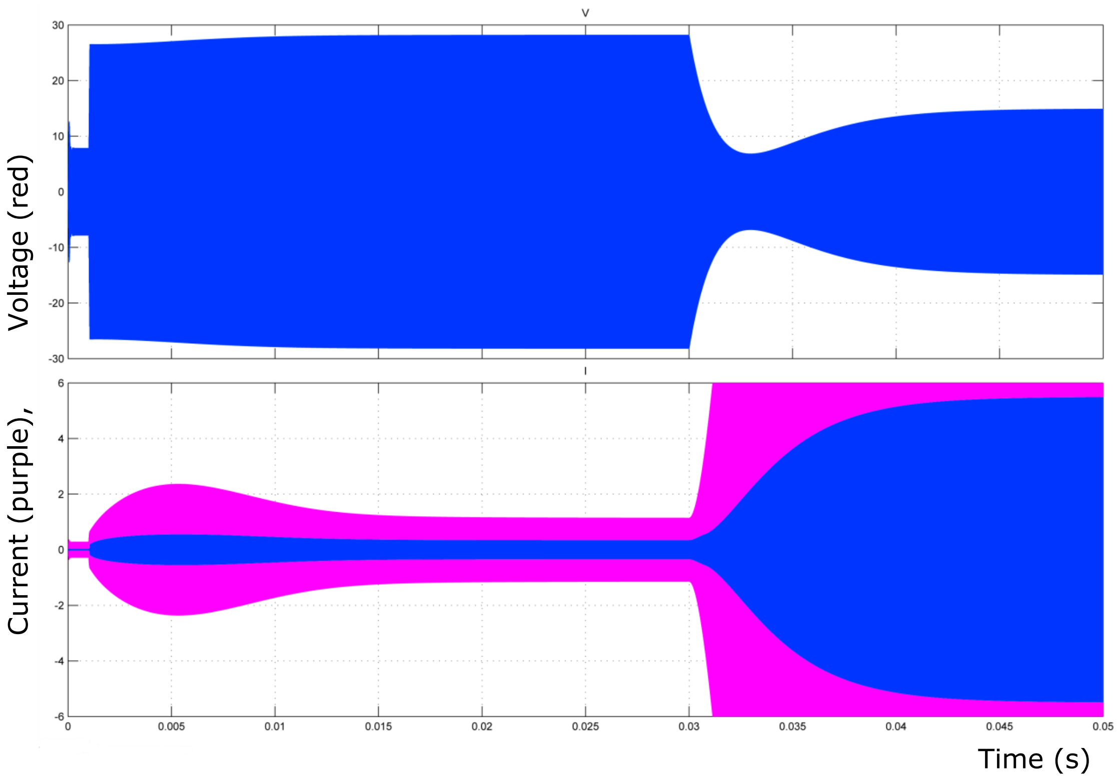


Figure 5-22 voltages (top) and currents (bottom) of the in (purple) and output (bleu) of the link. Load resistance is switched at 0.03 seconds

The system of Figure 5-20 is designed as an H-bridge, a control method used in many systems. The problem of an H-bridge is that it is difficult to use as part of a switching oscillator. Figure 5-21 and Figure 5-22 shows the Matlab results where a current controlled voltage source can be made with rather simple calculations. Figure 5-21 shows the voltage and current going in to the load. The current is rectified by the diode bridge resulting in the plane that is drawn. The important part of the plot is the voltage. The voltage is not constant as a result of the inductive link not behaving like an ideal voltage source. The difference between the two steady states is from approximately 27 Volt at 1000 Ohm resistance to approximately 14 Volt at 4 Ohm. From this difference the non ideal voltage source can be calculated.

$$V_s = V_L + V_{Rs} = V_L + R_s \frac{V_L}{R_L} \approx 27 + R_s \frac{27}{1000} \approx 14 + R_s \frac{14}{4} \tag{5-19}$$

$$27 + R_s \frac{27}{1000} = 14 + R_s \frac{14}{4} \Rightarrow R_s \approx 3.8\Omega \tag{5-20}$$

$$V_s \approx 14 + 3.8 \frac{14}{4} = 27.3 \tag{5-21}$$

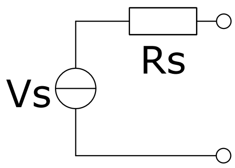


Figure 5-23 non ideal voltage source

The transition between the load setting and the start up behaviour can be explained using Figure 5-22 showing the voltages and currents on the in and output of the link. The start up behaviour is a result of the step function at the beginning of the simulation. The magnetic field in the coils needs to be charged at the beginning resulting in de overshoot of current of the input side. When the load is changed the magnetic field take time to adjust resulting in a slow change of the output voltage.

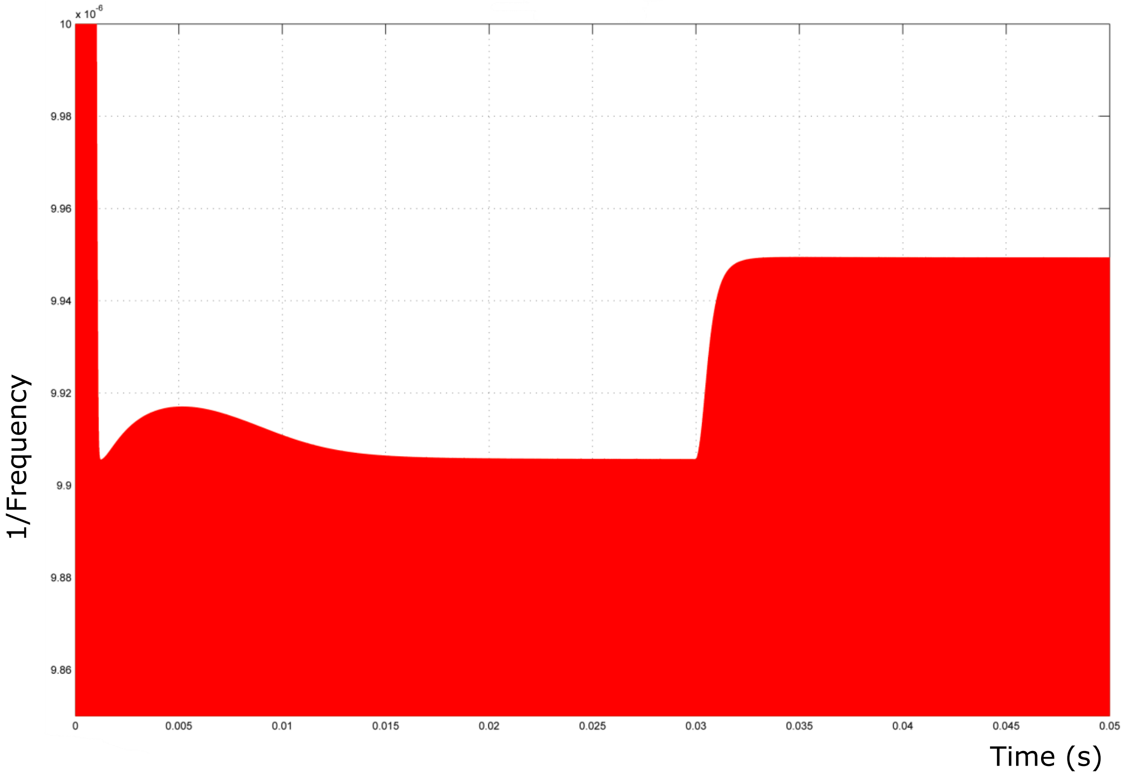


Figure 5-24 frequency response of the oscillator with voltage source, the frequency is the inverse of the figure. the top of the plain is the oscillation frequency, the plain is a result of the calculation method used in Matlab. Load resistance is switched at 0.03 seconds.

The frequency change of Figure 5-24 shows what was to be expected. When the load draws large currents the frequency is close to the oscillation frequency of the uncoupled coils, which would be the top of the plot. As in Figure 5-14 the relation of a SP configured transformer has only one oscillation frequency at high load and two at low load conditions. The highest oscillation frequency is used because this is more dominant during the start up. The start up is a preset frequency set to the natural oscillation frequency of the coils. In Figure 5-24 this frequency can be seen at the beginning of simulation during the first 0.001 seconds. The bump just after the start up is the result of building the magnetic field, during which the impedance of the link changes.

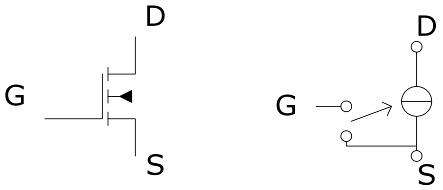


Figure 5-25 a mosfet. Most common used component for switching. Acts as voltage controlled current source

The component best suited (at the moment) for using in amplifiers is a mosfet. The mosfet acts like a voltage controlled current source, like in Figure 5-25. This is unfortunate since this would make it not very suited for the H-bridge implementation with a voltage as supply. Using a Current as supply allows the Mosfet can be used directly, using a cross coupling between two mosfets. The voltage in one branch drives the current through the other branch.

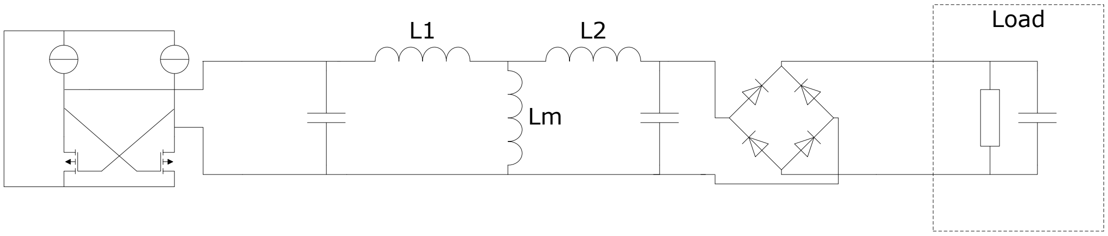


Figure 5-26 Current source version of power oscillator. Schematic as used in matlab.

With the current source setup a PP system is used. In a SP setup no oscillation would be occurring for the wanted frequency would yield no voltage and thus no signal to drive the mosfets. Using Current controlled circuit provides the following results.

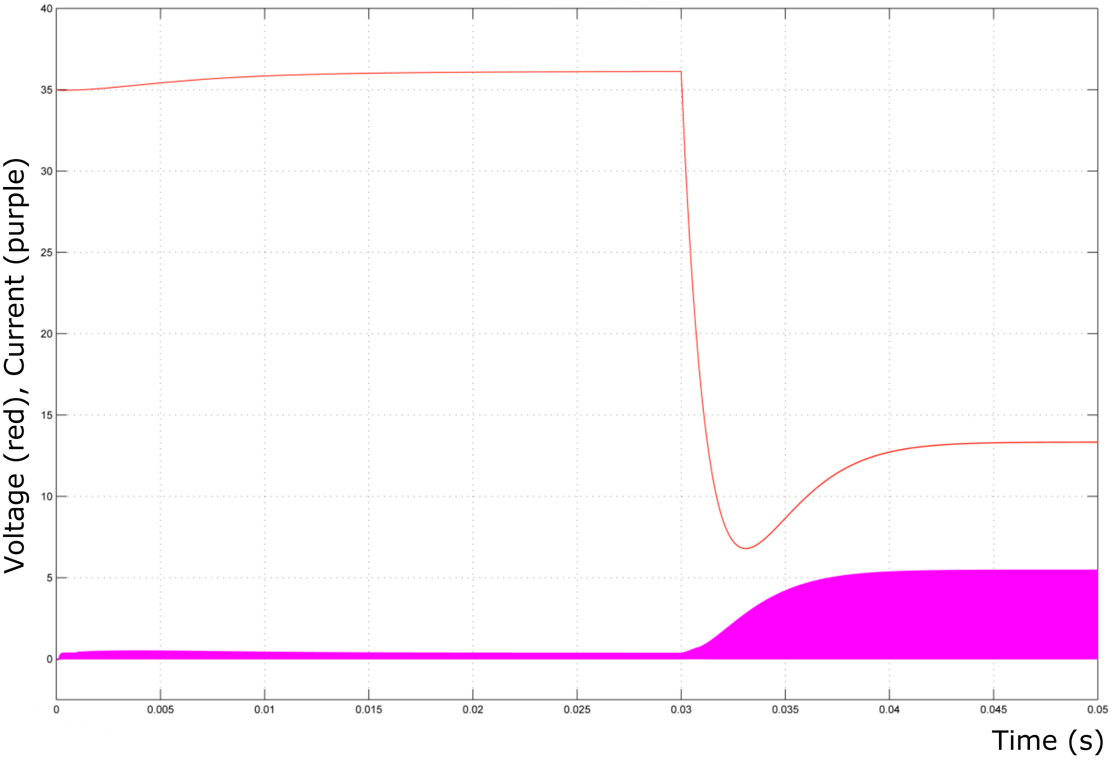


Figure 5-27 output signal behind the diode bridge in the current driven version. Output voltage (red) and current (purple)

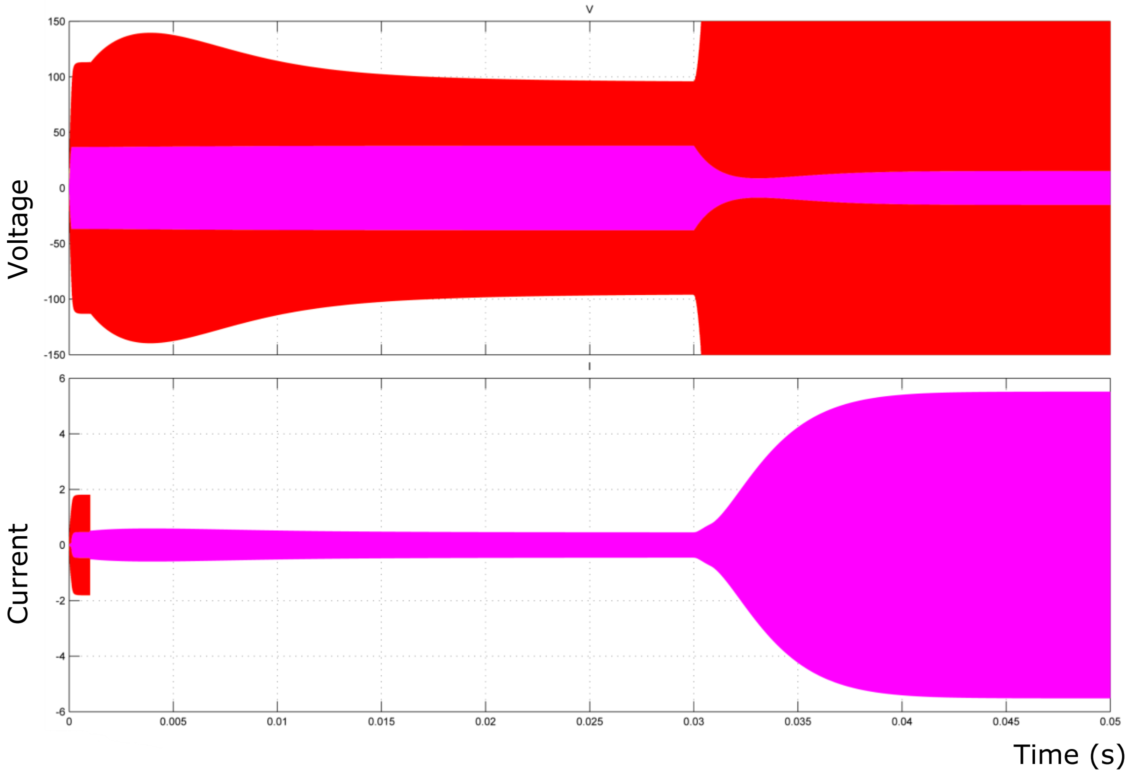


Figure 5-28 voltages (top) and currents (bottom) of the in (red) and outputs (purple) of the current driven link.

Figure 5-27 is almost the same as Figure 5-21. The difference between the two voltage levels has increased. The difference is not much of a problem since the values are still within the boundaries of most voltage regulators. The electronics of the rocket will always have a voltage regulator as first component.

Figure 5-28 shows the voltages and currents of the link where the output voltage is similar to the output voltage of Figure 5-22. The relation between these is similar to the voltages of the load. The output currents also show a high similarity. The difference is at input where in Figure 5-22 the voltage is constant in Figure 5-28 the current is constant. This is the difference of course between voltage and current drive.

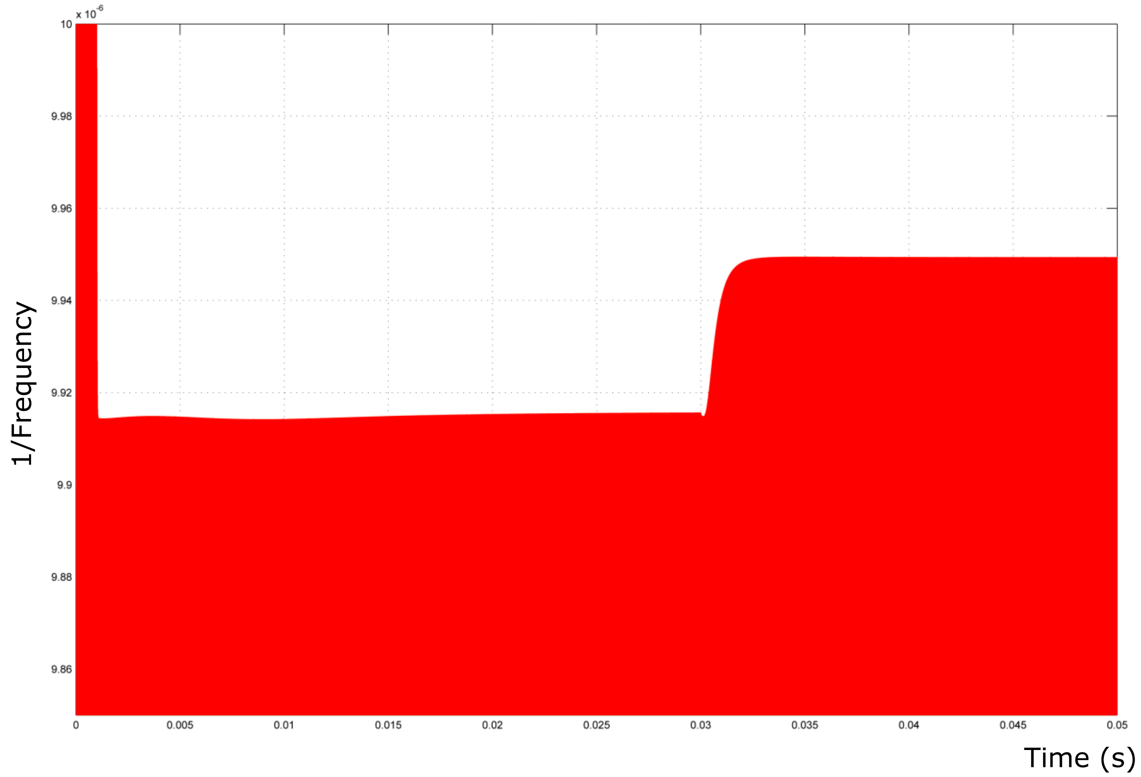


Figure 5-29 frequency response of current driven link. Like in Figure 5-24 the frequency is not shown directly jet an inversely proportional signal

The frequency of the current driven inductive link Figure 5-29 shows the same steady states as the voltage driven version of Figure 5-24. The difference is the start up behaviour, where the bump in the current driven version is much smaller. This difference is to be expected since the magnetic field of a coil is determined by the current through the coil. In a current driven system there is a current through the coil very quickly while in a voltage driven system the current is only a result of the voltage. At the moment a voltage is applied a current will need to build up.

5.3.2 Power oscillator results

The choice for one particular oscillator over another will be dependant of several aspects. While the components for the voltage controlled current coerces are more available this has slightly worse results. There is one other aspect to take into account. When the second coil is not there both oscillator types would need to be limited. The voltage source would need a maximum current and the current source would need a maximum voltage. This would result in an extra feedback, when calculating the maximum power the system should be able to deliver to the load the voltages and currents should be chosen in a method that would provide this maximum power.

5.4 Data transfer

With the power supply created the next step is to make the data transfer. While the intention was to include a complete design of the data transfer in the thesis this unfortunately turned out to be too much work. The required data rates for the sounding rocket are not very high, in the order of several kb/s. As shown in references 2, 3, 5, 7, 10 and 16 there are many ways of obtaining data transfer with an inductive link.

The methods can be divided in 3 categories:

- Separate coils for power and data
- Combined coils with separate driving and loading electronics
- Combined coils with combined driving and loading electronics

In the application of the sounding rocket a data transfer umbilical needs to comply with safety standards. The EMI should be low and the magnetic field should be kept local. For the rocket design the implementation should use as little room as possible. The methods have different impact on the rocket and safety.

Separate coils would increase the size of the system and has two magnetic fields. Because both fields can be designed separately the signals through them could be filtered to produce less interference. The field is spread around more so more systems will be inside the magnetic field. The systems affected receive less EMI yet more systems are in the magnetic field. The data transfer can be completely separate from the power providing large design flexibility.

Combining the coils while keeping the electronics separated needs extra components to separate the power and data. This situation provides a small system since components are a lot smaller than coils. The data signals for both the up and download could be modulated on different frequencies allowing simultaneous transmission. The separation allows the transfer of data while the power supply is turned off. This is a requirement of the sounding rocket because power supply should be cut off before data transmission is stopped.

Combining the coils and electronics might provide the smallest system yet the systems influences each other very highly. The upload data would be made by modulating the source and the download would be made by modulating the load. The load is already modulated by the power it requires. This would mean that the data would be difficult to derive from the changes in power.

From these options combining the coils while keeping the electronics separated seems to be the best option. Because of low interference between power and data, Small size and the option to turn power of while keeping data on.

6 The inductive wireless umbilical

In the past chapters the inductive wireless power and data transfer was handled with a small reference to an umbilical. This chapter will look into the wireless umbilical and compare it with the requirements made at chapter 3. Here table 3-3 will be completed with the information on inductive links provided in chapter 4 and 5.

6.1 System overview

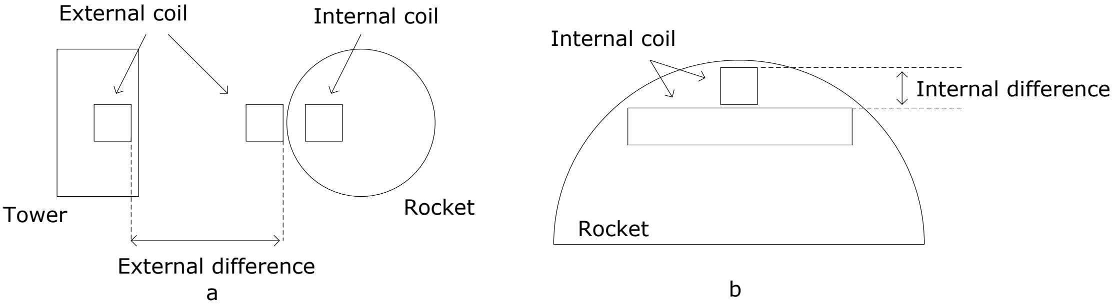


Figure 6-1 differences in coil size and distance. a, for the external coil. b, for the internal coil.

The figure above shows the part of the rocket and the launch tower where the umbilical is located. When defining the size of the umbilical system the main maximum is the size of the rocket. The internal coil distance increases with size. Having the internal coil as close to the rockets side as possible would require in a decrease in size. Estimating the size of the coil to be around 5 cm would result in a minimal distance to the external coil of about 3 cm. This would require a method of holding the outside coil against the skin of the rocket. The option of putting the outside coil to the launch tower would increase the external difference. The distance is estimated to be about 10cm with the coil in the launch tower. In this position the coupling from coil to launch tower is probably an issue, because the tower is conductive and very close.

Using a boom to place the coil close to the rocket would result in a better coupling and allows the system to be removed before the launch. The boom method would increase system variations which would not be a very big problem. One option to increase the allowed variation is choosing the coil sizes correctly.

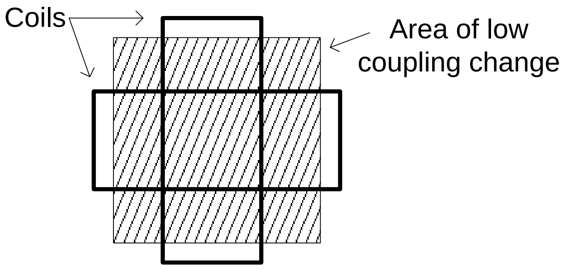


Figure 6-2 possible coil implementation to decrease required placement precision

Making both the internal and external coils rectangular and rotating them 90 degrees from each other. This would yield a low impact on coupling when the system is somewhat misplaced or moving.

The driving electronics can be placed on the launch tower and do not necessarily have to be close to the coil. The distance would however decrease the efficiency. When the coil is placed on a boom to place it the electronics could be placed near the mounting point. From there a cable would go to either a wall socket or a large battery.

The loading electronics should be placed on a convenient location. Wiring should be kept to a minimum mostly because of the weight it would take. The size of the rockets interior is not so big that losses would be a problem. Or the wire should be wound around the rocket several times which is unlikely.

6.2 System comparison

In chapter 3 table 3-3 was not completely filled. With the information of chapters 4 and 5 the table can be completed.

Table 6-1 completed version of "Table 3-3 aspects of an IWPD or cable umbilical"

	IWPD	Cable
Performance		
Reliability	High	High
Connectability	Medium	High
Efficiency	Medium	High
Usability	High	High
Reusability	High	Medium (exposed contacts corrode)
Interference		
At liftoff	Low (with a removable boom)	Medium (cable is connected to housing)
Aerodynamics	No	High (connector in skin)
Structural	Low (only non conductive skin)	High (connector though skin)
Weight (impacts altitude)	Medium (mostly internal coil)	Medium (connector and increased structure)
Size (impacts size of payload)	Medium (mostly internal coil)	Low (connector is mostly in the skin)
Safety		
EMI (to electronics)	Low (EMC of the electronics)	Very low
EMI (to motors)	Low (distance)	Non
Electro static discharge (ESD)	low (no contacts on outside)	High (exposed contacts)

From the table we can conclude that in terms of performance the IWPD and cable do not differ much. One bonus of the IWPD implemented with a movable boom would be that the connection could be re-established. The connector would need someone to reconnect it.

In terms of Interference the IWPD performs better than the cable. This was originally the reason for investigating the IWPD as it would minimize the aerodynamic and structural interference. For interfering with the liftoff the IWPD can outperform the cable this requires a mechanism for retracting the umbilical. One downside of the IWPD is that it takes more space inside the rocket. The IWPD components are all inside while the cable has its connector mostly on the outside. For the weight the components themselves do not differ much while taking the extra structural impact of the cable in to account it would slightly benefit the IWPD.

For the safety the only real problem of an IWPD would be the EMI which is much larger than in comparison of the cable. This comes mostly from the fact that the cable has no EMI (with a correct cable). The safety impact on the rocket motors is neglectable since the heat generation would not be sufficient to cause any dangers. The EMI towards the electronics would not be much problem either. The EMC of the electronics should be sufficient to prevent any problems.

One aspect of safety where the IWPD would be a better choice is static electricity. The IWPD has no electric contacts on the outside of the rocket making the need of ESD protection unnecessary. Where the connections made by the cable should be protected to a high level. In places like Kiruna the electro static build up can be very high. This is a result of the low humidity of the air.

There is one last comparison to be made, Comparing costs. The cost of a cable connected umbilical is defined by the connector. Connectors are expensive components especially when they have the special requirements for an umbilical. To make a connector suitable for an umbilical it should be connected very firmly while still allowing it to disconnect at launch. The connector should also be accompanied by a mounting that fastens it to the rocket and minimizing the aerodynamic drag. This makes a cable a rather expensive choice.

The prise of a IWPD umbilical has three parts. First are the coils which are not very expensive even when using copper wire. The second part is the mounting for both inside and outside the rocket. The inner mount is very simple a plastic (or nonconductive) material which fastens the coil to the rocket interior. The outer mount is more difficult requiring a movable boom to move the coil into an out of position. This movement can be realized with a servo motor and the boom should be sturdy to survive high wind conditions. The outer mount will most likely be the most expensive part of the IWPD.

The last part of the IWPD cost is the electronics. The electronics are not very difficult, no high frequencies (100 kHz is almost DC), no extreme powers (50 W is a decent lamp) and the components don't need to be of a very high precision (the oscillation frequency may change a little). This will make the components themselves not very expensive and the cost of the IWPD is expected to be low.

To conclude the IWPD can become a good replacement for cable connected umbilicals. Before this is done there are many steps to be taken which will be discussed in the next chapter.

7 From concept to operation

With the result of chapter 6 an IWPD would be a good choice for a sounding rocket umbilical. The design is at this stage not ready to be built. This chapter will give a short description of the steps needed to be able of building an inductive wireless umbilical. Choosing a setup is rather complicated since most choices have influence on other aspects of the design.

7.1 Design steps

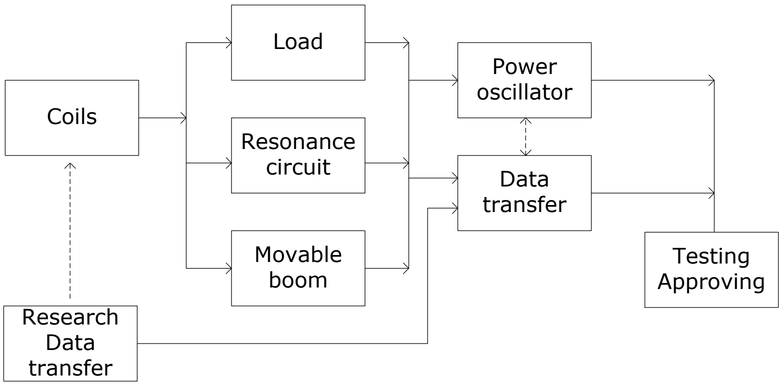


Figure 7-1 steps to be taken for an IWPD umbilical

The figure above shows the steps that need to be taken in making the design of a working IWPD umbilical. For the data transfer research has to be done before the actual designing process can start. Figure 7-1 also shows the sequence for making an IWPD umbilical. Several steps can be undertaken parallel to each other. The power oscillator and data transfer might have a dependency on each other, this need to be defined by researching the data transfer.

7.1.1 Researching data transfer

Having a system that allows high data rates is of course nice. It is not required for the main purpose of the umbilical yet would yield more suitable applications. The use of a single set of coils is preferred because this would limit the coil size inside the rocket. The single coil set also makes the placement more easily.

7.1.2 The coils

Defining the coils is the first real design step. Using the proposed rectangular coils will probably give the best results. Exact coil sizes are depending on space available. The inner coil will need to be designed to try and keep the distance to the outside small while keeping the coil size large. Having a rectangle where one side is more than two times the other will increase the losses more than it will decrease placement precision. Making the coils long will decrease the effective field going through the coils. Because some field lines will cancel the effect of other field lines. See Figure 7-2 on the next page.

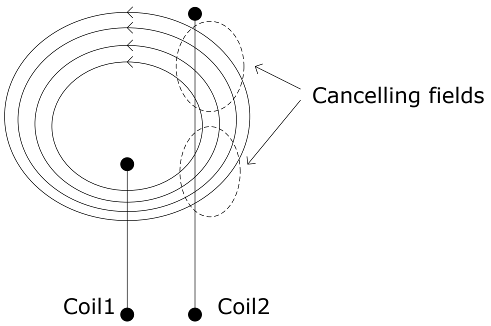


Figure 7-2 cancelling magnetic field lines in a long coil

7.1.3 The load

The only part of the load that needs to be designed for the umbilical is the diode bridge. The other parts of the load are the internal rocket electronics.

7.1.4 Resonance capacitors

The capacitors needed to make the coils resonate are very simple and not much design has to be made. The values need to be chosen when the coils are made while the placement is dependent on the power oscillator choice.

7.1.5 Movable boom

When the coils are defined the boom can be designed. For this design information on the launch tower and rocket are required. The mounting of the boom should also house the electronics controlling the boom and driving the exterior coil.

7.1.6 Power oscillator

Completing the design for the power oscillator will need the values for the coils, load and resonance circuit. This is not however the first step. The first step in completing the design starting with the definition of amount of power that needs to be transferred. Making the current supply with a maximum voltage suited to deliver the required power. The next step is to find components capable of handling the voltages and currents of the system. With these in place the power oscillator would be buildable.

7.1.7 Data transfer

When the research on this field is completed the design steps for this will be clear.

7.1.8 Testing and approving

The last steps in the design process are the testing and approving of the system. The reason that they are mentioned together is that the approval needs to be given by the launch site of the rocket. Before they allow the use of an IW umbilical they will require several tests. These tests are not known at this time. The tests should at least cover the basic performance. Using table 6-1 form chapter 6 a short list can be made to decide what test should be done.

7.2 Stratos 2 with an IWPD umbilical

Whether Stratos 2 will have an inductive wireless umbilical or not is mostly dependant on if it is possible to have a launch site allow the use. If the choice of Stratos 2 does fall on an IWPD umbilical than either have a second umbilical or make sure the system is tested beyond it limits. The most important is personal safety so testing the IWPD on hazardous systems of the rocket is important.

8 Conclusions

The goal of this thesis was to determine the feasibility of using an inductive wireless power and data transfer system as sounding rocket umbilical. Determining the results takes us back to the research questions from chapter 1.

8.1 Research questions

- "Does the magnetic field generated by an IWPD system create an unsafe situation for launching sounding rockets?"

The magnetic field generated by the IWPD diminishes rapidly with distance to the IWPD. This results in a local impact where only systems and materials close to the umbilical are affected. For direct impact on safety the motor modules of the rocket important. The magnetic field going through the motor module can create induced currents. The effect of these currents is dependent on the conductivity of both the propellant and motor casing. Safety is only impacted when the heat generated by the currents has a chance of igniting the propellant. The motor modules are cooled by the air around them and distribute the heat through them. To ignite the propellant a large amount of energy is required on a single spot. This concentrated heating is very unlikely with an IWPD. Tests should be performed to conclude this. The best test would be to make a magnetic field strong enough to ignite the propellant. From this test the magnetic field strength could be calculated where the system is still safe.

The magnetic field can also create an indirect hazard interfering with the electronics controlling the ignition systems. The interference effect known as EMI sets compatibility requirements to the electronics (EMC). The EMC of the electronics should be sufficient for the IWPD. The low frequency of the IWPD makes the interference not very high and thus the safety is not impacted.

- "Is it possible to create an IWPD system with a power throughput required by a sounding rocket?"

The power provided to the rocket by its umbilical can be divided in three parts: supplying the main controller, keeping the batteries fully charged and allowing subsystems to be tested. This results in a wide power range with a maximum of an estimated 50 W. The supplied voltage should be sufficient to charge the batteries.

An IWPD can supply this power. Choosing the correct setup will even allow the system to react on changes without having to keep the power constant. With a Power oscillator as driving element the system can follow the optimum transfer frequency under a wide variety of operations. Having the power oscillator built as voltage controlled current source with MOSFETs as active components only requires a few components. Fewer components mean fewer things that can break and lower costs.

- "Does communication through an IWPD system provide the reliability of communication required for arming and disarming procedures?"

Though data transfer was not completely researched in this thesis some information is available. During the literature study several options were found to create data transfer using an inductive link. The most promising option is using the same coils as the power transfer while having separate systems controlling it. The option of modulating the source and load has only few extra components. Yet because of the wide operating range this makes transferring data more difficult. And during operations the data transfer should be available even without transferring power.

- "How precise does the IWPD need to be placed for it to operate correctly?"

Precision of the components do not need to be very high because of the power oscillator is automatically tuned to the optimum transfer. For the placement this option decreases the requirements while using correct coils shape will also provide room for misalignment. Using a boom to place the coils closely together is possible when the placement is not required to be high. The boom minimizes the effect of the big metal construction of the tower from interfering with the IWPD. It also provides the method of moving the components out of the way before the launch.

8.2 General conclusion

The IWPD umbilical is considered a suitable option for replacing a cable connected umbilical. The IWPD provides several improvements. The greatest of these would be that the design of the umbilical and the design of the structure and skin of the rocket can be separated. This separation allows a more optimum design of both the systems.

With the prospect of removing the connector from the skin of the rocket the wireless umbilical will make an umbilical suitable for more rockets. The external components can be reused for more rockets and adding a coil to a rocket is only a small impact. When a cable is used the connector impacts the structural strength of the skin. The skin around the connector should be made stronger to prevent failure. Putting connectors in very small rocket can be difficult while the coil just shrinks in size.

Adding a cabled umbilical to a rocket has a greater impact on design than adding an IWPD umbilical.

9 Recommendations

During the completion of this thesis several improvements on modes and simulations were noted. There were also several design steps that could be of use to the making of an IWPD umbilical.

9.1 Model

Having made a model for calculating the magnetic coupling between two coils there are several simplifications made. Some of these simplifications could have been made different providing a more general model. The model used only allows square coils where the coil centres are aligned. Implementing rectangular coils and arbitrary placement would provide a useful design tool.

The biggest error made by the model is based on the fact that the current runs through a single point. Turning this in to an area would make the error smaller. The added bonus to this is that it gives an extra design option. The shape of the windings can then be taken into account during the design. This provides information to choose if the windings should be alongside or above each other.

The model can be used as tool to understand effects of coil sizes to coupling. It would be interesting to use an analytical model during the design. In contrast to a FEM program an analytic model would yield much quicker results. Using an analytic model to make a program capable of calculating couple factors between coils would require les information to start the design than a FEM program.

9.2 Simulations

Making time simulations is very slow. To understand how systems operate it is very important to do these simulations. Without the time simulation the effect of coupling on oscillation frequencies would not have been noted. The problem is that most programs for calculating time based signals can only calculate short times. Both ADS and PSpice did not allow simple calculations. They both needed extensive information on components before making successful simulations.

Choosing the simulation program based on the complexity of simulation required at the time it is used. While complex programs allow precise answers understanding the principles is much more important. Knowing what type of program yield the best result for the information that is looked for is important. This information should be made more available at the TUDelft.

9.3 Designing an IWPD umbilical

To build an umbilical on the principle of an IWPD it is necessary to have a space within an experimental rocket. The Stratos 2 rocket being designed by DARE is a viable option. Together with the builders of the rocket a location should be found to place the coils and required electronics. With the space available a set of coils should be designed to start the designing and building of an IWPD based umbilical.

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Appendix-A: Literature study

What are the possibilities and difficulties according to others looking at inductive wireless power and/or data transfer?

To find articles on inductive wireless systems the following texts were used as search task:

- Wireless power transfer
- Inductive links
- Wireless power and data
- Inductive power transfer
- Inductive data transfer

This resulted in a large amount of articles that mostly had nothing to do with the wanted topic. After filtering out some (hopefully) useful articles the reading could start.

In the articles wireless inductive links are proposed and/or used in two main system types. These types are the charging of electric vehicles and powering and/or communicating with biomedical implants. In recent articles a third group of systems is proposed for the use of inductive links. This is the powering or communication in system in a package ICs. Here the use inductive links removes the difficult and expensive internal connections.

The inductive link comprises out of two parts which will be looked at separately. Starting with the power transfer over an inductive link and ending with data communication over the link.

Inductive power transfer systems can be separated in three main groups when looking at the power output. The first group is high power where the power levels are over a kilo watt. In one article (9) a power delivery of up to 200 kW is proposed. In high power systems efficiency is very important because of heating problems. Even with a 99% efficiency a 200 kW system still has more los than an average electric heater. The use of a core material can be applied but only if the used frequency is low otherwise the material hysteresis would generate losses. Most systems use a coreless approach where the coils are operated in high frequency resonance to give them a good mutual coupling. These resonance frequencies are created with the help of parallel or series capacitors. This also allows for coils of different sizes making them less dependent to location changes.

The second group is low power where power levels up to 100 mW are used. This is used mainly in biomedical applications and small IC systems. In biomedical implants one of the coils is inside the body and one is outside. Here it is very important to make the inductive link unperceptive of movement sins the two coils will move because of body movement. The link must be as constant as possible since any exes energy transfer will be turned in to heat inside the body which is unacceptable. This is achieved by making the internal coil very small in reference to the external coil. This is also a good thing sins implanting a big coil is not wanted. This change will decrease the efficiency which is not a very big problem since this can be cancelled by providing more power to the external coil. In small IC systems the use of inductive links is to decrease the number of internal connections. This drastically decreases cost sins making physical connections is one of the most expensive parts in IC fabrication. The coils need to be very small since IC's are very small. There is no deference in coil size which provides a good mutual coupling.

The last group is those in between there are only a view articles about this group and they don't have a particular application in mind while designing there system. There are a view advantages to be named here. For instance a system in harsh environment will develop problems with galvanic connections because of corrosion or thermal cycling. Or systems with need to be electrically isolated can use an inductive link to provide power and data communications. Also an inductive link is very vibration resistant.

The operation frequency for the inductive link is dependent on the materials and size of the link or the materials the link should penetrate. When a core is used inside the link the frequency should be low since the magnetic hysteresis of the material will create losses at higher frequencies. In most biomedical applications it is required to penetrate the human tissue. This tissue is can be affected by the magnetic link at some frequencies. According to article (2) the allowed frequencies in biomedical implants are 1 to 100 MHz. The size of the coils and the frequency determine the coupling of the link and thus the efficiency. In large systems the frequency can be lower than in small systems.

In all articles a class E power amplifier is used to drive the primary coil. This is done because it has a high efficiency. The linearity of this amplifier is not very important because of the filtering properties of the resonant coil and capacitor of the primary side.

The implementation of data communications in the inductive link has several options. Using separate inductive links for the uplink, downlink and power requires three links. This uses more space jet the links themselves are easier to make. Combining them in one link makes the link more difficult jet only requires one set of coils. Most of the high power systems use separate links to protect the low power data electronics. In biomedical systems a combination is used because it is unwanted to implant multiple coils. While combing the channels in one link it is possible to have two different ways of making the downlink (from secondary to primary side). These are active or passive with both having advantages and disadvantages. For an active downlink it is required to have a system that generates a magnetic field which is measured by the primary side. The advantage is that the power generating components are not changed and therefore the link efficiency is not altered. Disadvantage is that this requires power usage at the secondary side. In a passive system the impedance of the secondary system is altered which can be measured by the primary side since the driving current will change. The advantage is that this requires only limited components and no extra power. Disadvantage is that the power link efficiency will change. The amount of data is not really a problem since most articles agree that an inductive link can achieve over 1 Mb/s communication speed.

Conclusions

There are many possibilities when making an inductive link for both power and communications. Choosing a class E power amplifier is a logical step since it is proposed by all articles. Since the requirements for the final system are not finished it is difficult to define the best options. The coil sizes need to be defined both by implementation constrains (size of available space in the rocket) and frequency constrains (permeability of rocket skin material). The biggest problem is the possible proximity of igniters. Since under no circumstance will it be allowable to have the igniters ignite because of the inductive link. There are no articles found discussing the possible EMC problems to electronics in the vicinity of the inductive link.

Appendix-B: Drawing the magnetic field

The Magnetic field is drawn using Matlab. The field is drawn in two ways first the strength shown as colours. Second is the direction shown as arrows.

The Matlab function file Plot_coils.m make two vector fields, for each coil one field. Then adding them together gives a total vector field. This is than split between strength and direction. Before making an automated PDF file.

The vector fields are made by the Vector_array_def_take3.m. Which calculates the field at 1000 by 1000 points. The first coil is at z is 0 and the second defined by the given offset. The calculations are a repeating numeric version of the model defined in the thesis.

Plot_coils.m

```
function [  ] = plot_coils( coil1size, coil2size, ofset, currentratio)
%PLOT_COILS Summary of this function goes here

[up1,vp1] = vector_array_def_take3(0,coil1size);
[up2,vp2] = vector_array_def_take3(ofset,coil2size);

[hp1,gp1] = cart2pol(up1,vp1);
normvalue = max(max(gp1));
gpn1 = gp1/normvalue;
[upn1,vpn1] = pol2cart(hp1,gpn1);

[hp2,gp2] = cart2pol(-up2,-vp2);
gpn2 = (gp2/normvalue)*currentratio;
[upn2,vpn2] = pol2cart(hp2,gpn2);

upnt = upn1+upn2;
vpnt = vpn1+vpn2;

[hpnt,gpnt] = cart2pol(upnt,vpnt);
[upt,vpt] = pol2cart(hpnt,1);
gpndt = mag2db(gpnt);

% [up1,vp1] = pol2cart(hp1,1);
% [up2,vp2] = pol2cart(hp2,1);
% gpnd1 = mag2db(gpn1);
% gpnd2 = mag2db(gpn2);

z = -30:5:70;
y = 50:-5:-50;
zp = -30:0.1:70;
yp = 50:-0.1:-50;
ut = upt(1:(length(upt)-1)/20:length(upt),1:(length(upt)-
1)/20:length(upt));
vt = vpt(1:(length(vpt)-1)/20:length(vpt),1:(length(vpt)-
1)/20:length(vpt));
% u1 = up1(1:(length(up1)-1)/20:length(up1));
% v1 = vp1(1:(length(vp1)-1)/20:length(vp1));
% u2 = up2(1:(length(up2)-1)/20:length(up2));
% v2 = vp2(1:(length(vp2)-1)/20:length(vp2));

f = figure();
hold on;
```

```
[c,h] = contourf(zp,yp,gpndt);
set(h,'LevelListMode','manual');
set(h,'LevelList',-100:10:0);
title({['coil sizes ', num2str(coil1size),' ', num2str(coil2size)];[ 'ofset
', num2str(ofset)];[ 'currentratio ', num2str(currentratio)]});
axis([-30 70 -50 50]);
xlabel('Z (mm)');
ylabel('Y (mm)');
caxis([-100 0]);
colorbar;
quiver(z,y,ut,vt,0.5,'r');
legend('field strength(dB)', 'field direction');
hold off;

filename = ['coil sizes ', num2str(coil1size),' ', num2str(coil2size), '
ofset ', num2str(ofset), ' currentratio ', num2str(currentratio),'.pdf'];
set(gcf, 'PaperType', 'A4');
orient landscape;
print(f, '-dpdf', filename);

end
```

Vector_array_def_take3.m

```
function [ u,v,g ] = vector_array_def_take3( ofset, coilsize)
%VECTOR_ARRAY_DEF will make 2 arrays defining the vectors for a quiver
%plot.
% plot axis z goes from -3 to 7
% plot axis y goes from -5 to 5

%if nargin < 2
%     ofset = 0;
%     coilsize = 50;
%     feeldsize = 100;
%end

zmin = -30;
zmax = 70;
zstep = 0.1;
zpoints = (zmax - zmin)/zstep + 1;
ymin = -50;
ymax = 50;
ystep = 0.1;
ypoints = (ymax - ymin)/ystep + 1;
[zp,yp] = meshgrid(zmin:zstep:zmax,ymax:-ystep:ymin);
%zp = -30:0.1:70;
%yp = 50:-0.1:-50;
xp = zeros(ypoints,zpoints);
%u = zeros(ypoints, zpoints);
%v = zeros(ypoints, zpoints);
%g = zeros(ypoints, zpoints);
m0 = zeros(ypoints, zpoints);
m1 = m0 + 1;

% coilsize defines the points where the current goes.
% coil is square senterd around y=z=0
% there are 4 parst of the coils
```

```
% define the 4 corners in (z,y,x) vector
c1 = [ofset;  coilsize/2;  coilsize/2];
c2 = [ofset;  coilsize/2; -coilsize/2];
c3 = [ofset; -coilsize/2; -coilsize/2];
c4 = [ofset; -coilsize/2;  coilsize/2];

% segment 1 goes from corner 1 to corner 2
% segment 2 goes from corner 2 to corner 3
% segment 3 goes from corner 3 to corner 4
% segment 4 goes from corner 4 to corner 1
% current goes from 1 to 2 to 3 to 4 (clokwize)

seg1z = (c1(1)+c2(1))/2;
seg1y = (c1(2)+c2(2))/2;
seg1x = 0;

A1cz = zp - seg1z;
A1cy = yp - seg1y;
A1cx = xp - seg1x;

[A1pt, A1pr, A1pz] = cart2pol(A1cz,A1cy,A1cx);
% probleem punt verwerking
A1pr((((ymax - seg1y)/ystep) + 1), (((seg1z - zmin)/zstep) + 1)) = 0.1;
B1pt = A1pt-(pi/2);
B1pr = (m1./A1pr).*(sin(cart2pol(A1pr,A1pz+(c2(3))))-
sin(cart2pol(A1pr,A1pz+(c1(3)))));
[B1cz,B1cy,B1cx] = pol2cart(B1pt,B1pr,m0);


seg3z = (c3(1)+c4(1))/2;
seg3y = (c3(2)+c4(2))/2;
seg3x = 0;

A3cz = zp - seg3z;
A3cy = yp - seg3y;
A3cx = xp - seg3x;

[A3pt, A3pr, A3pz] = cart2pol(A3cz,A3cy,A3cx);
% probleem punt verwerking
A3pr((((ymax - seg3y)/ystep) + 1), (((seg3z - zmin)/zstep) + 1)) = 0.1;
B3pt = A3pt-(pi/2);
B3pr = (m1./A3pr).*(sin(cart2pol(A3pr,A3pz+(c4(3))))-
sin(cart2pol(A3pr,A3pz+(c3(3)))));
[B3cz,B3cy,B3cx] = pol2cart(B3pt,B3pr,m0);


seg2z = (c2(1)+c3(1))/2;
seg2y = 0;
seg2x = (c2(3)+c3(3))/2;

A2cz = zp - seg2z;
A2cy = yp - seg2y;
A2cx = xp - seg2x;

[A2pt, A2pr, A2pz] = cart2pol(A2cz,A2cx,A2cy);
% probleem punt verwerking
% A2pr((((ymax - seg2y)/ystep) + 1), (((seg2z - zmin)/zstep) + 1)) = 0.1;
B2pt = A2pt-(pi/2);
```

```
B2pr = (m1./A2pr).*(-
sin(cart2pol(A2pr,A2pz+(c3(2))))+sin(cart2pol(A2pr,A2pz+(c2(2)))));
[B2cz,B2cx,B2cy] = pol2cart(B2pt,B2pr,m0);


seg4z = (c4(1)+c1(1))/2;
seg4y = 0;
seg4x = (c4(3)+c1(3))/2;

A4cz = zp - seg4z;
A4cy = yp - seg4y;
A4cx = xp - seg4x;

[A4pt, A4pr, A4pz] = cart2pol(A4cz,A4cx,A4cy);
% probleem punt verwerking
% A2pr((((ymax - seg2y)/ystep) + 1), (((seg2z - zmin)/zstep) + 1)) = 0.1;
B4pt = A4pt-(pi/2);
B4pr = (m1./A4pr).*(-
sin(cart2pol(A4pr,A4pz+(c1(2))))+sin(cart2pol(A4pr,A4pz+(c4(2)))));
[B4cz,B4cx,B4cy] = pol2cart(B4pt,B4pr,m0);

Btcz = B1cz +B2cz + B3cz + B4cz;
Btcy = B1cy +B2cy + B3cy + B4cy;
Btcx = B1cx +B2cx + B3cx + B4cx;
max(max(Btcx));


u = Btcz;
v = Btcy;
g = sqrt((abs(Btcz)^2)+(abs(Btcy)^2));



end
```

Appendix-C: Programs for calculation of the couple factor

The coupling factor is calculated by two programs, Maple and FastHenry. Maple is used for the model defined in the thesis and FastHenry is used as reference.

Here the files for both programs are given.

Maple

\>

\> $cmax := 50 :$

\> $r := 0.1 :$

\>

\> $xof := 5 :$

\> $yof := 5 :$

\>

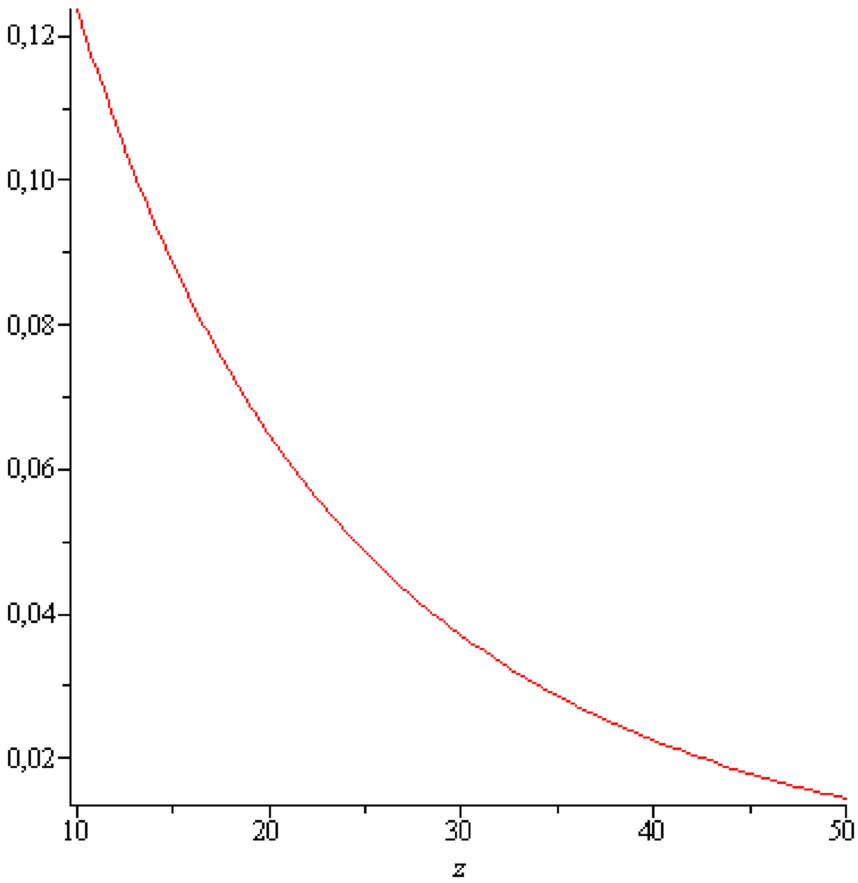
\> $$Bpr := 4\int_{\frac{r}{2}}^{cmax}\int_{0}^{cmax}\frac{\left(\frac{(cmax-y)}{\sqrt{(cmax-y)^2+x^2}}+\frac{y}{\sqrt{y^2+x^2}}\right)}{x}\,\mathrm{d}y\,\mathrm{d}x :$$

\> $$Bsec := 4\int_{xof}^{cmax-xof}\int_{yof}^{cmax-yof}\left(\frac{x}{(x^2+z^2)}\left(\frac{(cmax-y)}{\sqrt{(cmax-y)^2+x^2+z^2}}+\frac{y}{\sqrt{y^2+x^2+z^2}}\right)\right)\mathrm{d}y\,\mathrm{d}x :$$

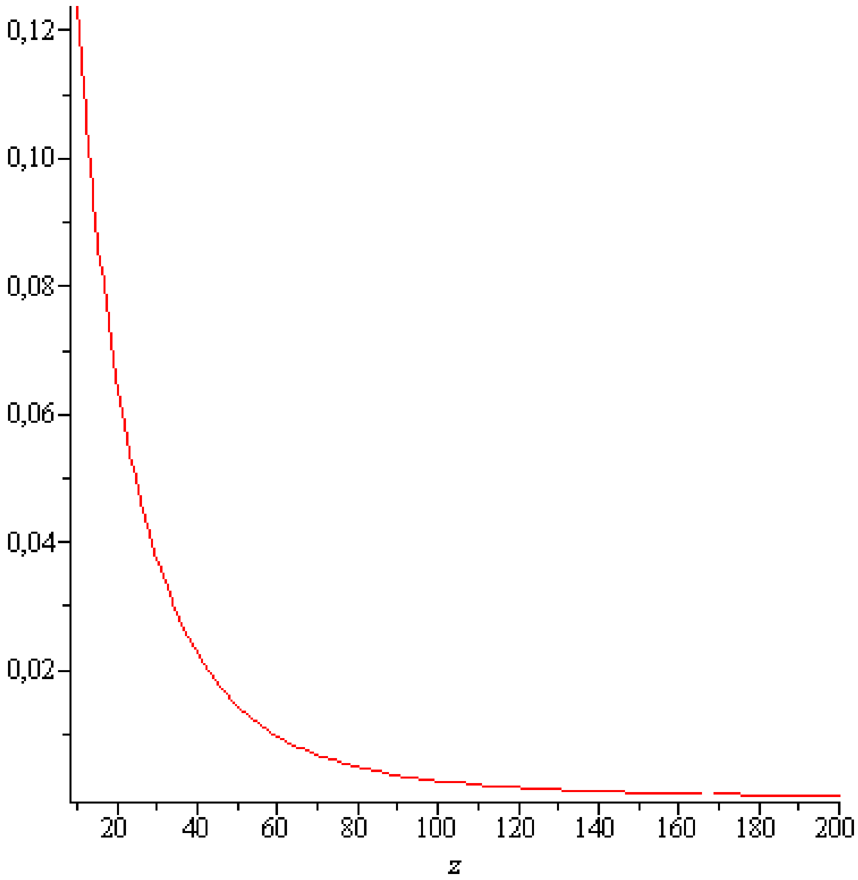
\> $k := \frac{Bsec}{Bpr} :$

\> $evalf(k) :$

\> $plot(k, z = 10..50)$



```
> plot(k, z = 10..200)
```



FastHenry

For FastHenry input (.INP) files had to be generated. The input files defines the coils as line segments with elements like starting point, ending point, thickness, conductivity, etc. The .INP files were made with Matlab to allow playing with the numbers. Making the Matlab program is some work yet after using it several times it turned out to be time well spent. Using the .INP files in FatsHenry than provides the self inductances of the coils and the mutual inductance.

The Matlab program:

```
function [ fname ] = Spoel_def( Z, W1, W2, L1, L2, X, Y, Nz1, Nxy1, Nz2,
Nxy2, rX, rY, rZ, Wd1, Wz1, Wxy1, Wd2, Wz2, Wxy2)
% SPOEL_DEF makes a text file for FastHenry

% Defenitions of input variables

% Coil 1 defenitions
% arguments (W1,L1,Nz1,Nxy1,Wd1,Wz1,Wxy1)
% W1 is the coil width (X derection)form the innerside of the inner most
winding on idher side
% L1 is the coil lenth (Y derection)see W1 for explenation
% Nz1 is number of windings next to each other
% Nxy1 is number of windings over each other
% Ww1 is the width of a winding
% Wd1 is winding diameter. (presumed square)
% Wx1 is distance between windings in x direction
% Wy1 is distance between windings in y direction

% Coil 2 defenitions
% Arguments (W2,L2,Nz2,Nxy2,Wd2,Wz2,Wxy2)
% explenation see coil1

% ofset defenitions
% Arguments (Z,X,Y,rZ,rX,rY)
% coils are in XY plane Z is distance between coils
% rZ, rX and rY are angels writen in deg



% controling input variables
% always required are the
% Z
% W1
% W2
% when the def stops here then L1 and L2 are defined by W1 and W2
if nargin <= 3
    L1 = W1;
    L2 = W2;
end
% then the X and Y ofset are defined (only 1 required if ofset is wanted)
if nargin <= 5
    X = 0;
end
if nargin <= 6
    Y = 0;
end
% the the number of windings in z and xy direction first for coil 1 or both
```

```
% the for coil 2
if nargin <= 7
    Nz1 = 5;
    Nxy1 = 3;
end
if nargin <= 9
    Nz2 = Nz1;
    Nxy2 = Nxy1;
end
% rotation of second coil for x y and z direction
if nargin <= 11
    rX = 0;
end
if nargin <= 12
    rY = 0;
end
if nargin <= 13
    rZ = 0;
end
% wire diameter and distance of windings
if nargin <= 14
    Wd1 = 0.1;
end
if nargin <= 15
    Wz1 = 2*Wd1;
end
if nargin <= 16
    Wxy1 = Wz1;
end
if nargin <= 17
    Wd2 = Wd1;
end
if nargin <= 18
    Wz2 = 2*Wd2;
end
if nargin <= 19
    Wxy2 = Wz2;
end


%----------------------------------------------------------------
% starting file creation

% defining file name starts with coilset
fname = 'coilset';
% write all inputed variables if they are given
fname = [fname '_' num2str(Z) '_' num2str(W1) '_' num2str(W2)];
if nargin > 3
    fname = [fname '_' num2str(L1) '_' num2str(L2)];
end
if nargin > 5
    fname = [fname '_' num2str(X)];
end
if nargin > 6
    fname = [fname '_' num2str(Y)];
end
if nargin > 7
    fname = [fname '_' num2str(Nz1) '_' num2str(Nxy1)];
end
if nargin > 9
    fname = [fname '_' num2str(Nz2) '_' num2str(Nxy2)];
```

```
end
if nargin > 11
    fname = [fname '_' num2str(rX)];
end
if nargin > 12
    fname = [fname '_' num2str(rY)];
end
if nargin > 13
    fname = [fname '_' num2str(rZ)];
end
if nargin > 14
    fname = [fname '_' num2str(Wd1)];
end
if nargin > 15
    fname = [fname '_' num2str(Wz1)];
end
if nargin > 16
    fname = [fname '_' num2str(Wxy1)];
end
if nargin > 17
    fname = [fname '_' num2str(Wd2)];
end
if nargin > 18
    fname = [fname '_' num2str(Wz2)];
end
if nargin > 19
    fname = [fname '_' num2str(Wxy2)];
end

% ends with .inp
fname = [fname '.INP'];
fid = fopen(fname , 'w');

% writing title and coil information
fprintf(fid, '** Coil defenition file for use with FASTHENRY **\n');
fprintf(fid, '* Eric Smit\n');
fprintf(fid, '* using simple coil defenitions \n\n');


% making defenitions
% standert unit zize mm, all sizes are in mm
fprintf(fid, '.Units MM\n');
% normelized conductivety and default conductor width and hight
fprintf(fid, '.Defaults sigma=5.8e4\n\n');

%---------------------------------------------------------------
% making the first coil

% text for reference
fprintf(fid, '** first coil defenition\n');
fprintf(fid, '*----------------------------------------\n\n');

% calculations for coil1
Loop1Ofset = -((Nz1-1)/2)*Wz1;

for j = 1:Nxy1
    for i = 1:Nz1
        fprintf(fid, '* coil1 y%d x%d\n', j, i);
        fprintf(fid, '* nodes\n');
```

```
        fprintf(fid, 'NS1Ly%dx%dp1 x=%d y=%d z=%d\n', j,i, (W1/2+((j-
1)*Wz1))*-1 ,  ((L1/2)+((j-1)*Wxy1))*-1       , Loop1Ofset+((i-1)*Wz1));
        fprintf(fid, 'NS1Ly%dx%dp2 x=%d y=%d z=%d\n', j,i,  W1/2+((j-
1)*Wz1)     ,  ((L1/2)+((j-1)*Wxy1))*-1       , Loop1Ofset+((i-1)*Wz1));
        fprintf(fid, 'NS1Ly%dx%dp3 x=%d y=%d z=%d\n', j,i,  W1/2+((j-
1)*Wz1)     ,   (L1/2)+((j-1)*Wxy1)           , Loop1Ofset+((i-1)*Wz1));
        fprintf(fid, 'NS1Ly%dx%dp4 x=%d y=%d z=%d\n', j,i, (W1/2+((j-
1)*Wz1))*-1 ,   (L1/2)+((j-1)*Wxy1)           , Loop1Ofset+((i-1)*Wz1));
        fprintf(fid, 'NS1Ly%dx%dp5 x=%d y=%d z=%d\n', j,i, (W1/2+((j-
1)*Wz1))*-1 , (((L1/2)+((j-1)*Wxy1))*-1)+0.01 , Loop1Ofset+((i-1)*Wz1));
        fprintf(fid, '* segments\n');
        fprintf(fid, 'ES1Ly%dx%dp1 NS1Ly%dx%dp1 NS1Ly%dx%dp2 w=%d h=%d\n',
j,i,j,i,j,i,Wd1,Wd1);
        fprintf(fid, 'ES1Ly%dx%dp2 NS1Ly%dx%dp2 NS1Ly%dx%dp3 w=%d h=%d\n',
j,i,j,i,j,i,Wd1,Wd1);
        fprintf(fid, 'ES1Ly%dx%dp3 NS1Ly%dx%dp3 NS1Ly%dx%dp4 w=%d h=%d\n',
j,i,j,i,j,i,Wd1,Wd1);
        fprintf(fid, 'ES1Ly%dx%dp4 NS1Ly%dx%dp4 NS1Ly%dx%dp5 w=%d h=%d\n',
j,i,j,i,j,i,Wd1,Wd1);
        fprintf(fid, '\n');
    end

        fprintf(fid, '* connecting loops%d\n', j);
    for i = 1:(Nz1-1)
        fprintf(fid, '.equiv NS1Ly%dx%dp5 NS1Ly%dx%dp1\n', j,i+((mod(j,2)-
1)*-1), j,i+(mod(j,2)));
    end
    fprintf(fid, '\n');
end

fprintf(fid, '* connecting loop series\n');
for j = 1:Nxy1-1
    fprintf(fid, '.equiv NS1Ly%dx%dp5 NS1Ly%dx%dp1\n', j,1+(mod(j,2)*(Nz1-
1)), j+1,1+(mod(j,2)*(Nz1-1)));
end
fprintf(fid, '\n');
fprintf(fid, '* defining output\n');
fprintf(fid, '.external NS1Ly1x1p1 NS1Ly%dx%dp5\n\n', Nxy1, 1+((Nz1-
1)*mod(Nxy1,2)));

% text for reference
fprintf(fid, '** first coil end\n');
fprintf(fid, '*----------------------------------------\n\n');

%--------------------------------------------------------------
% making the second coil

%--------------------------------------------------------------
% making the second coil

% text for reference
fprintf(fid, '** second defenition\n');
fprintf(fid, '*----------------------------------------\n\n');

% calculations for coil2
Loop2Ofset = -((Nz2-1)/2)*Wz2;
% en dit word lagge


for j = 1:Nxy2
```

```
    for i = 1:Nz2
        fprintf(fid, '* coil2 y%d x%d\n', j, i);
        fprintf(fid, '* nodes\n');
        fprintf(fid, 'NS2Ly%dx%dp1 x=%d y=%d z=%d\n', j,i, X+(W2/2+((j-
1)*Wz2))*-1 , Y+ ((L2/2)+((j-1)*Wxy2))*-1       , Z+Loop2Ofset+((i-
1)*Wz2));
        fprintf(fid, 'NS2Ly%dx%dp2 x=%d y=%d z=%d\n', j,i, X+ W2/2+((j-
1)*Wz2)     , Y+ ((L2/2)+((j-1)*Wxy2))*-1       , Z+Loop2Ofset+((i-
1)*Wz2));
        fprintf(fid, 'NS2Ly%dx%dp3 x=%d y=%d z=%d\n', j,i, X+ W2/2+((j-
1)*Wz2)     , Y+  (L2/2)+((j-1)*Wxy2)           , Z+Loop2Ofset+((i-
1)*Wz2));
        fprintf(fid, 'NS2Ly%dx%dp4 x=%d y=%d z=%d\n', j,i, X+(W2/2+((j-
1)*Wz2))*-1 , Y+  (L2/2)+((j-1)*Wxy2)           , Z+Loop2Ofset+((i-
1)*Wz2));
        fprintf(fid, 'NS2Ly%dx%dp5 x=%d y=%d z=%d\n', j,i, X+(W2/2+((j-
1)*Wz2))*-1 , Y+(((L2/2)+((j-1)*Wxy2))*-1)+0.01 , Z+Loop2Ofset+((i-
1)*Wz2));
        fprintf(fid, '* segments\n');
        fprintf(fid, 'ES2Ly%dx%dp1 NS2Ly%dx%dp1 NS2Ly%dx%dp2 w=%d h=%d\n',
j,i,j,i,j,i,Wd2,Wd2);
        fprintf(fid, 'ES2Ly%dx%dp2 NS2Ly%dx%dp2 NS2Ly%dx%dp3 w=%d h=%d\n',
j,i,j,i,j,i,Wd2,Wd2);
        fprintf(fid, 'ES2Ly%dx%dp3 NS2Ly%dx%dp3 NS2Ly%dx%dp4 w=%d h=%d\n',
j,i,j,i,j,i,Wd2,Wd2);
        fprintf(fid, 'ES2Ly%dx%dp4 NS2Ly%dx%dp4 NS2Ly%dx%dp5 w=%d h=%d\n',
j,i,j,i,j,i,Wd2,Wd2);
        fprintf(fid, '\n');
    end

        fprintf(fid, '* connecting loops%d\n', j);
    for i = 1:(Nz2-1)
        fprintf(fid, '.equiv NS2Ly%dx%dp5 NS2Ly%dx%dp1\n', j,i+((mod(j,2)-
1)*-1), j,i+(mod(j,2)));
    end
    fprintf(fid, '\n');
end

fprintf(fid, '* connecting loop series\n');
for j = 1:Nxy2-1
    fprintf(fid, '.equiv NS2Ly%dx%dp5 NS2Ly%dx%dp1\n', j,1+(mod(j,2)*(Nz2-
1)), j+1,1+(mod(j,2)*(Nz2-1)));
end
fprintf(fid, '\n');
fprintf(fid, '* defining output\n');
fprintf(fid, '.external NS2Ly1x1p1 NS2Ly%dx%dp5\n\n', Nxy2, 1+((Nz2-
1)*mod(Nxy2,2)));

% text for reference
fprintf(fid, '** second coil end\n');
fprintf(fid, '*----------------------------------------\n\n');

%--------------------------------------------------------------
% making the end defenitions

% defining the frequency range
fprintf(fid, '.freq fmin=1e5 fmax=1e5 ndec=1\n\n');

% ending file
fprintf(fid, '.end\n\n');
```

```
%closing file
%State = fclose (fid);


% State = 'Ok';

end
```

Appendix-D: Slicap

Slicap stands for Symbolic Linear Circuit Analysis Program. Slicap is an online solver made by Montagne Design & Consultancy and is free to use. The program can show symbolic, numeric and graphical representations of electrical circuits. The program uses nodal input of the circuit. For every circuit a nodal representation like in Figure 1 are made.

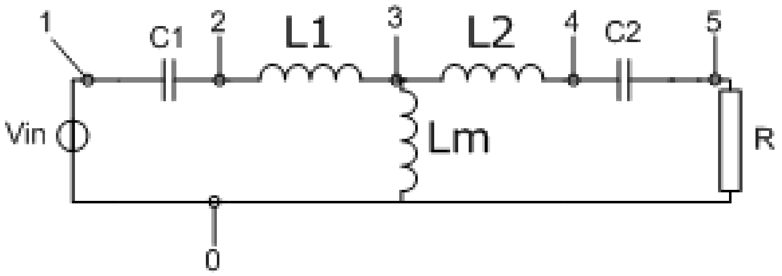


Figure 1 nodal circuit

```
Basic inductive coupling
V_in 1 0 V_s
C_1 1 2 C_cor
C_2 4 5 C_cor
L_1 2 3 L_sigma
L_2 3 4 L_sigma
L_3 3 0 L_m
R_1 5 0 R_l
.s V_in
.v 5 0
.p V_s sin(100000*s)
.p C_cor 25.33n
.p L 0.1m
.p x 0.1
.p L_m L*x
.p L_sigma L*(1-x)
.p R_l 1
.symbolic gain laplace
.symbolic gain matrix
.symbolic gain fourier
.numeric gain pz
.plot gain pz
.plot gain step .t 0m 0.3m
.plot GAIN DB .f 10000 1000000
.end
```

The text above is a Slicap input file. To make the bode plots the numeric gain pole zero (pz) is used. For every variation in coupling and resistance a new file needs to be created. Excel is used to make the drawings of the bode plots. By making a frequency sweep for both the magnitude and phase. The equations are taken from a document of the Massachusetts institute of technology.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF MECHANICAL ENGINEERING
2.14 Analysis and Design of Feedback Control Systems
Understanding Poles and Zeros

Magnitude is calculated as:

$$\left|H\left(j\omega\right)\right| = K\frac{\prod_{i=1}^{m}\left|j\omega - z_i\right|}{\prod_{i=1}^{n}\left|j\omega - p_i\right|} \tag{1}$$

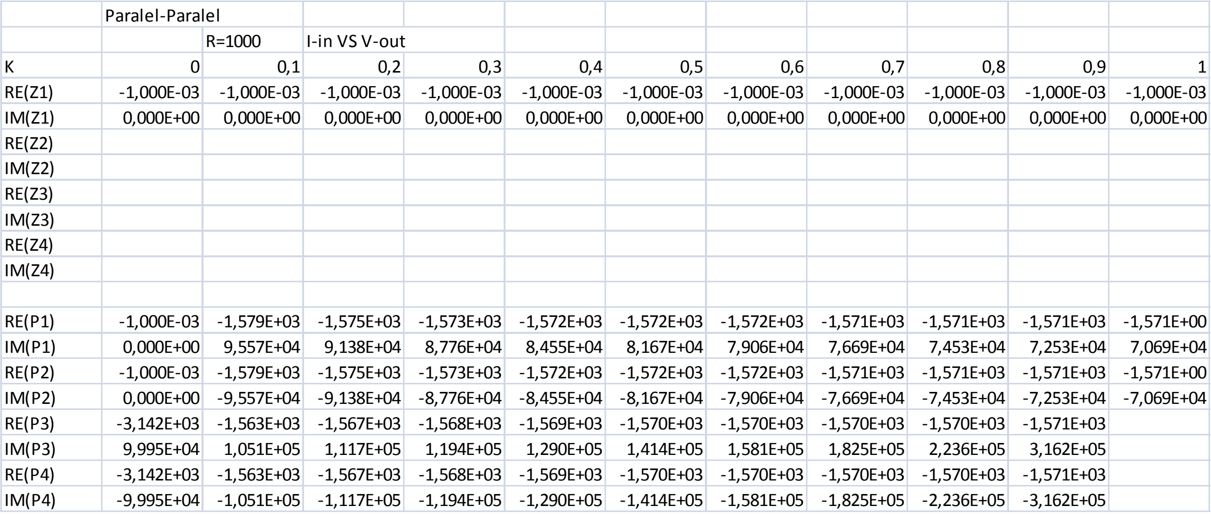
Phase is calculated as:

$$\angle H\left(j\omega\right) = \sum_{i=1}^{m}\angle\left(j\omega - z_i\right) - \sum_{i=1}^{n}\angle\left(j\omega - p_i\right) \tag{2}$$

Where z_i are the zeros and p_i are the poles of the circuit. K the gain factor which is not used in the figures and set to 1. m and n are the number of zeros and poles respectively. For the magnitude both axes are put in logarithmic scale the phase uses only logarithmic scale for the frequency.

Input part of excel

Table 1 the poles represented in excel for the parallel-parallel 1000Ohm circuit



	Paralel-Paralel										
		R=1000	I-in VS V-out								
K	0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1
RE(Z1)	-1,000E-03	-1,000E-03	-1,000E-03	-1,000E-03	-1,000E-03	-1,000E-03	-1,000E-03	-1,000E-03	-1,000E-03	-1,000E-03	-1,000E-03
IM(Z1)	0,000E+00	0,000E+00	0,000E+00	0,000E+00	0,000E+00	0,000E+00	0,000E+00	0,000E+00	0,000E+00	0,000E+00	0,000E+00
RE(Z2)											
IM(Z2)											
RE(Z3)											
IM(Z3)											
RE(Z4)											
IM(Z4)											
RE(P1)	-1,000E-03	-1,579E+03	-1,575E+03	-1,573E+03	-1,572E+03	-1,572E+03	-1,572E+03	-1,571E+03	-1,571E+03	-1,571E+03	-1,571E+00
IM(P1)	0,000E+00	9,557E+04	9,138E+04	8,776E+04	8,455E+04	8,167E+04	7,906E+04	7,669E+04	7,453E+04	7,253E+04	7,069E+04
RE(P2)	-1,000E-03	-1,579E+03	-1,575E+03	-1,573E+03	-1,572E+03	-1,572E+03	-1,572E+03	-1,571E+03	-1,571E+03	-1,571E+03	-1,571E+00
IM(P2)	0,000E+00	-9,557E+04	-9,138E+04	-8,776E+04	-8,455E+04	-8,167E+04	-7,906E+04	-7,669E+04	-7,453E+04	-7,253E+04	-7,069E+04
RE(P3)	-3,142E+03	-1,563E+03	-1,567E+03	-1,568E+03	-1,569E+03	-1,570E+03	-1,570E+03	-1,570E+03	-1,570E+03	-1,571E+03	
IM(P3)	9,995E+04	1,051E+05	1,117E+05	1,194E+05	1,290E+05	1,414E+05	1,581E+05	1,825E+05	2,236E+05	3,162E+05	
RE(P4)	-3,142E+03	-1,563E+03	-1,567E+03	-1,568E+03	-1,569E+03	-1,570E+03	-1,570E+03	-1,570E+03	-1,570E+03	-1,571E+03	
IM(P4)	-9,995E+04	-1,051E+05	-1,117E+05	-1,194E+05	-1,290E+05	-1,414E+05	-1,581E+05	-1,825E+05	-2,236E+05	-3,162E+05	

The top row shows the coupling factors used. These files were created for every circuit. the results of excel files are in Appendix-F.

Appendix-E: Matlab Simulink

The completed circuit was simulated using Matlab Simulink. The following figures show the simulink files.

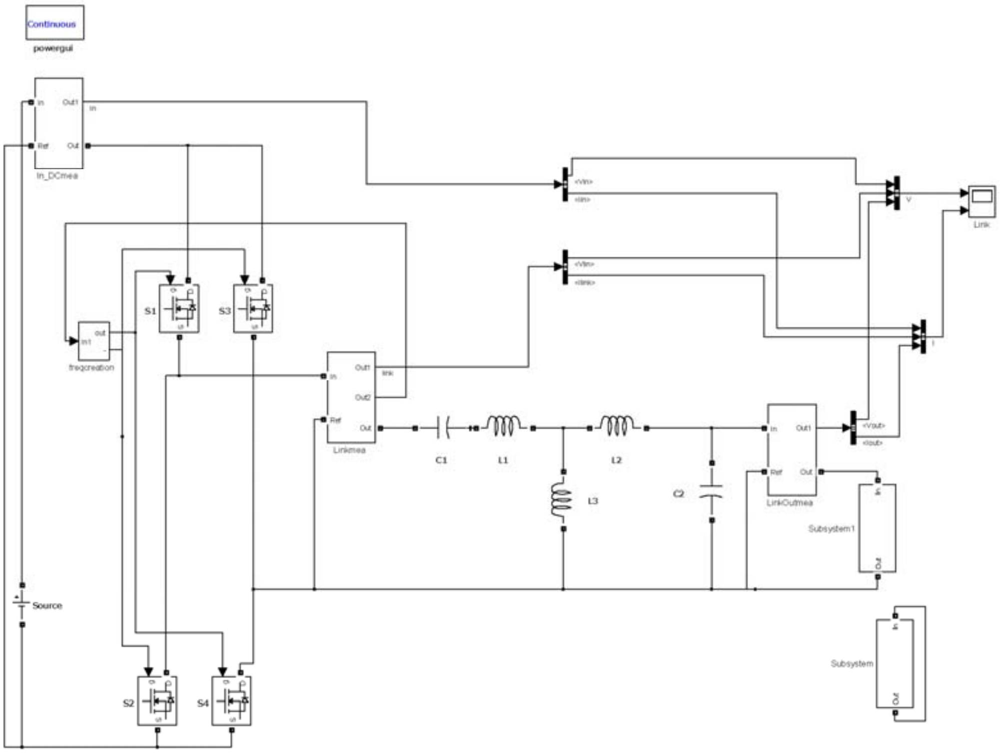


Figure 1 Top level, with H-bridge, link components and scope

Figure 2 voltage and current measurements

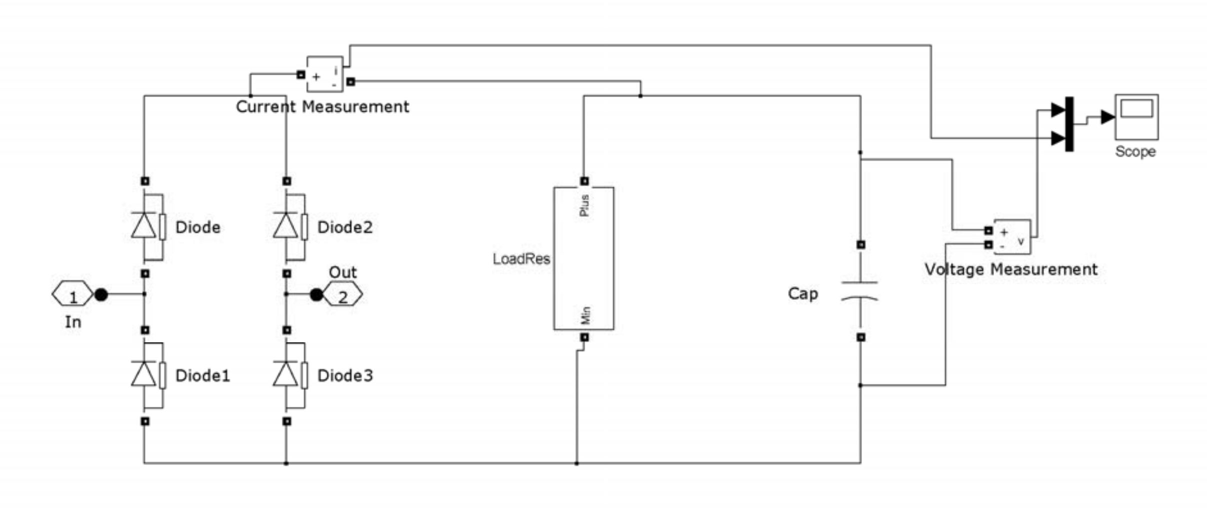


Figure 3 load configuration, Diode Bridge, cap and output measurement

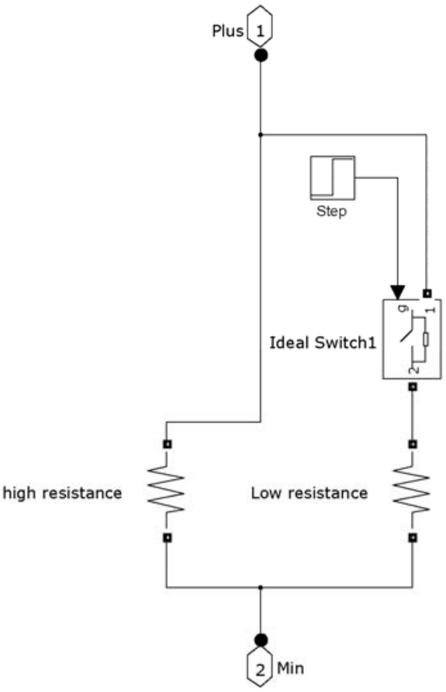


Figure 4 load switch, high or low resistance

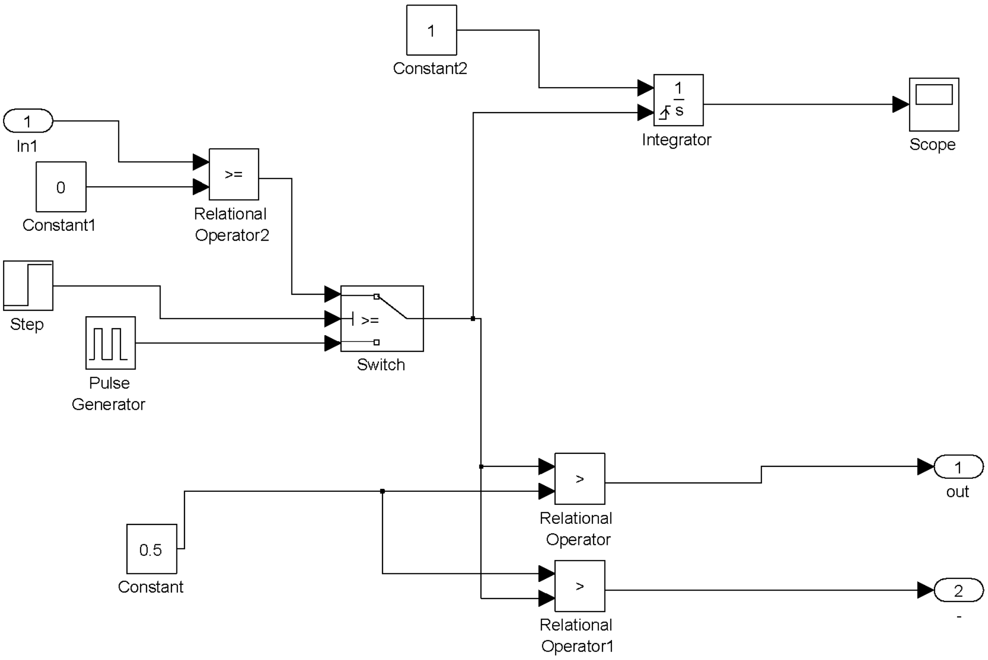


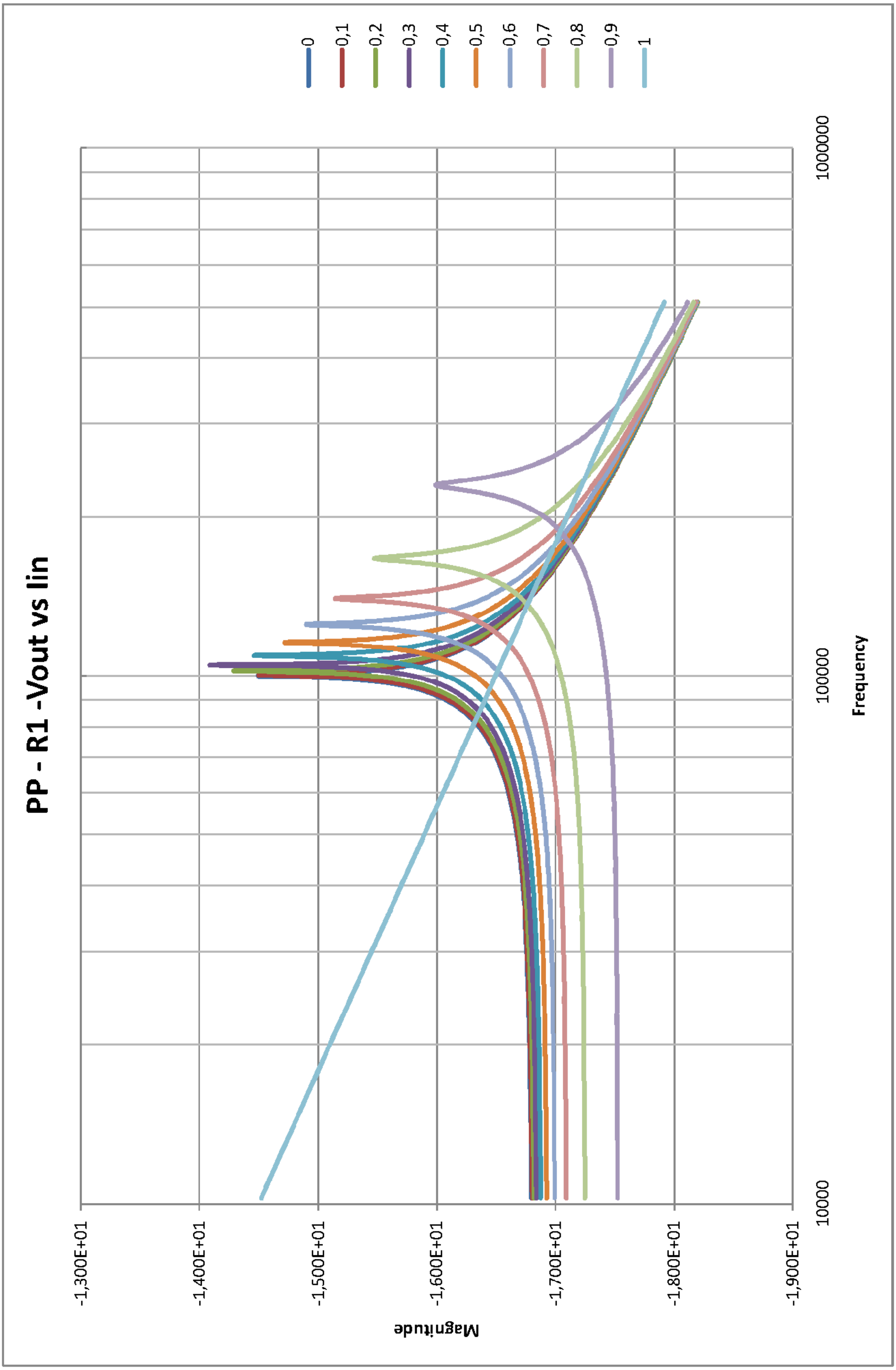
Figure 5 mosfet control circuit, and an integrator to show the frequency of the system.

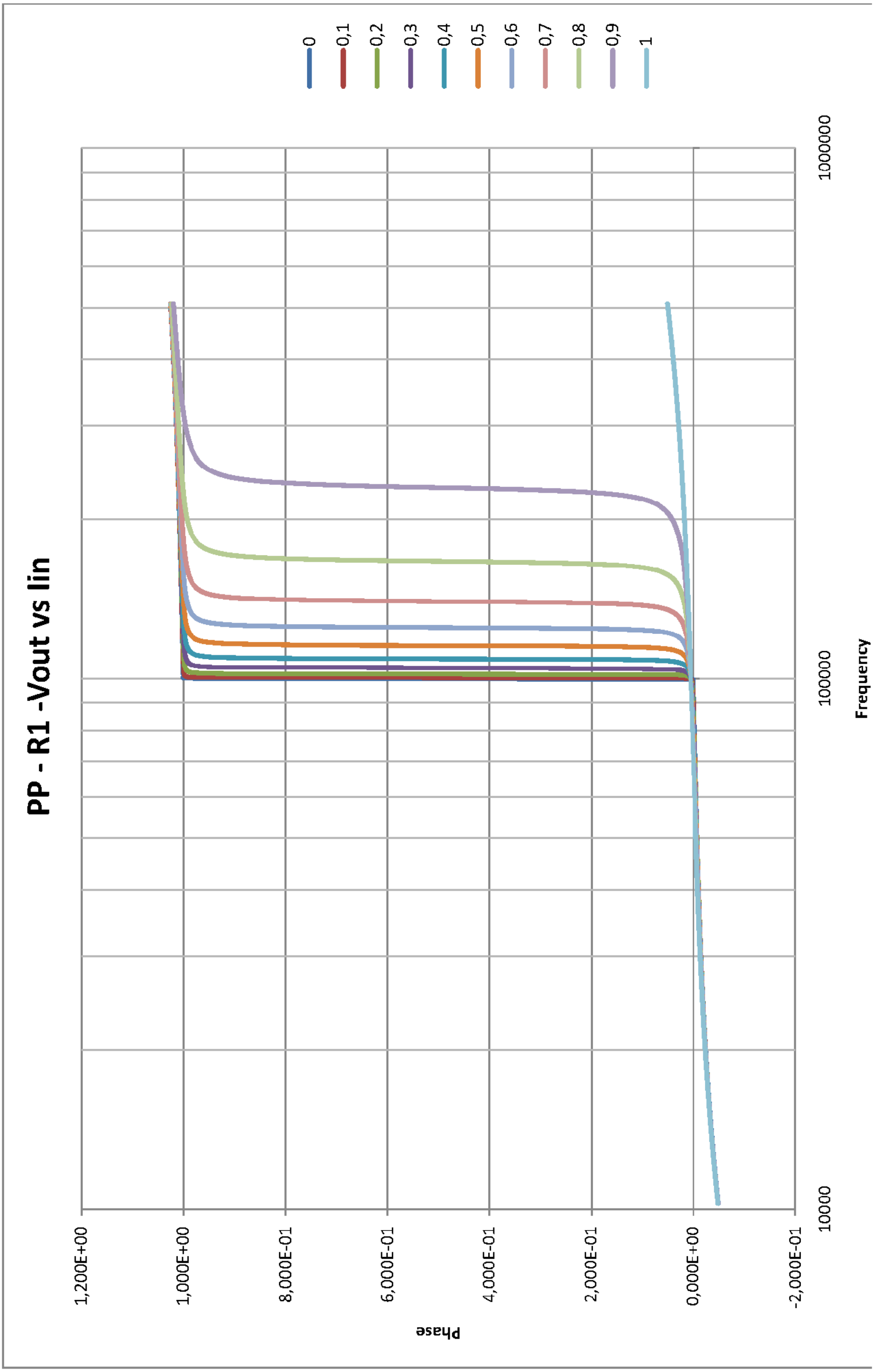
Appendix-F: Large bode plots

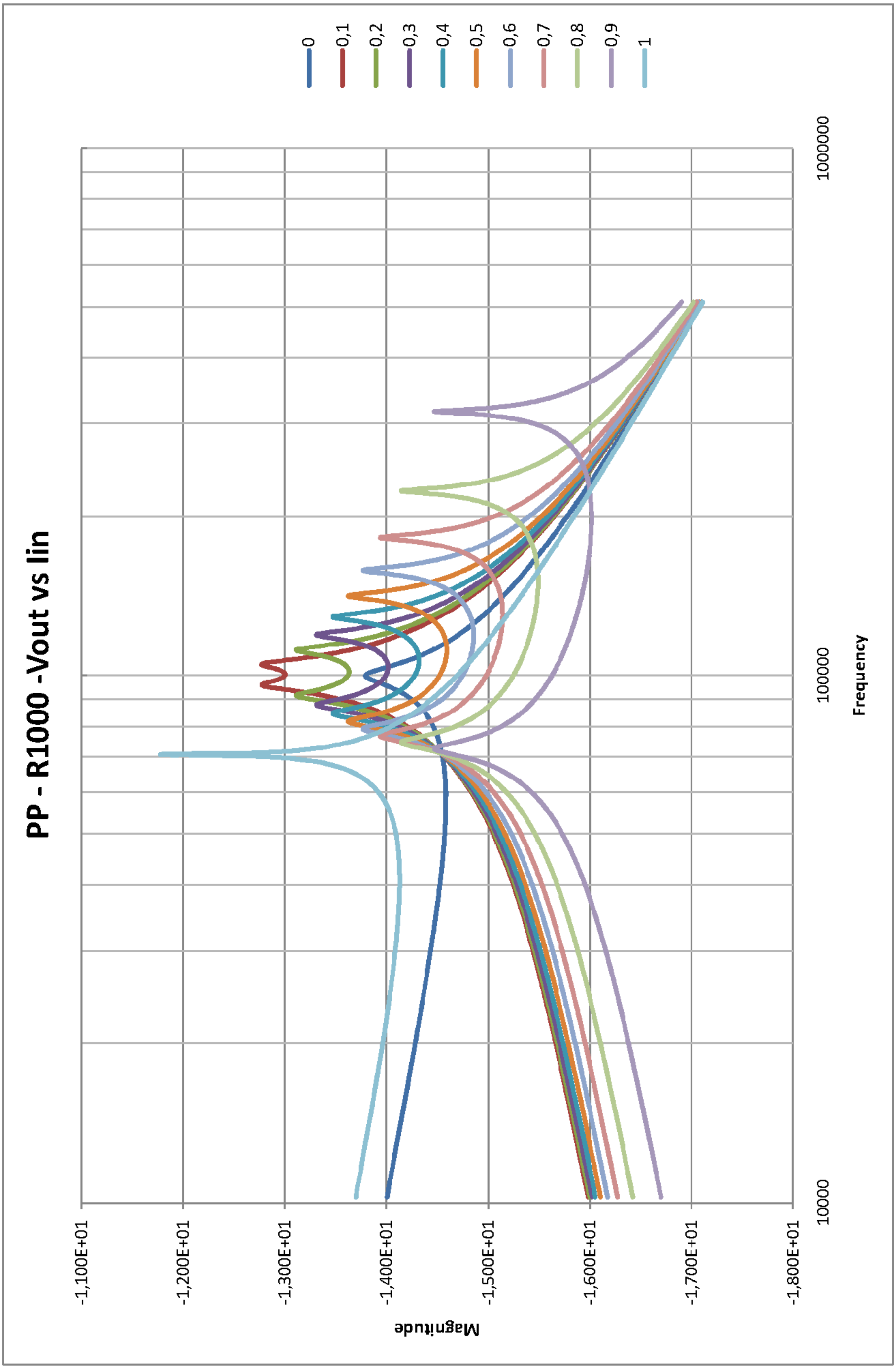
This appendix provides larger bode plots where the ones in chapter 5 are unreadable.

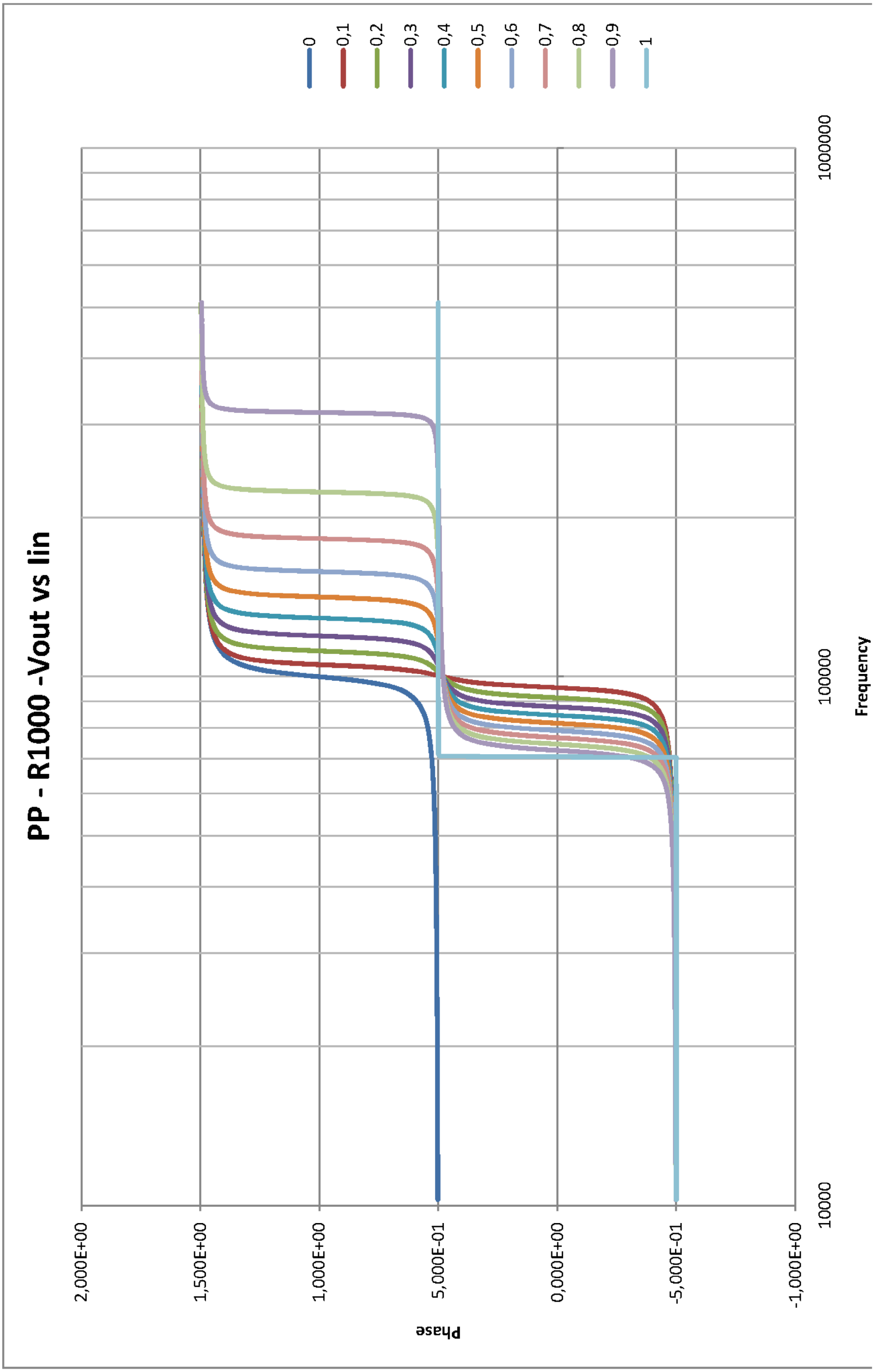
Parallel to parallel circuit is on pages 84 to 87.
Parallel to series circuit is on pages 88 to 91.
Series to parallel circuit is on pages 92 to 95.
Series to series circuit is on pages 96 to 99.

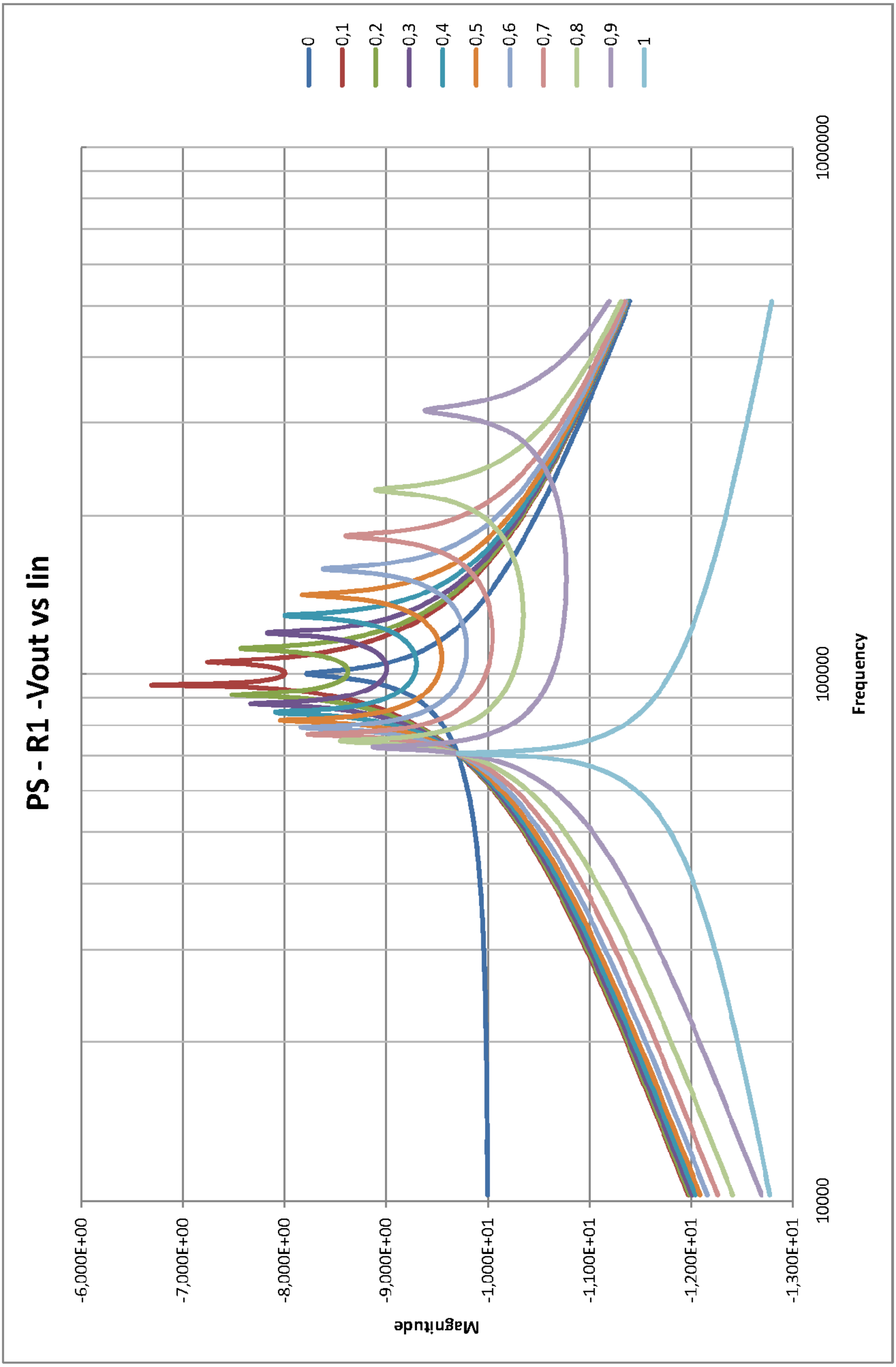
In all circuits first the low resistance magnitude, then the low resistance phase, then the high resistance magnitude and then the high resistance phase is displayed.

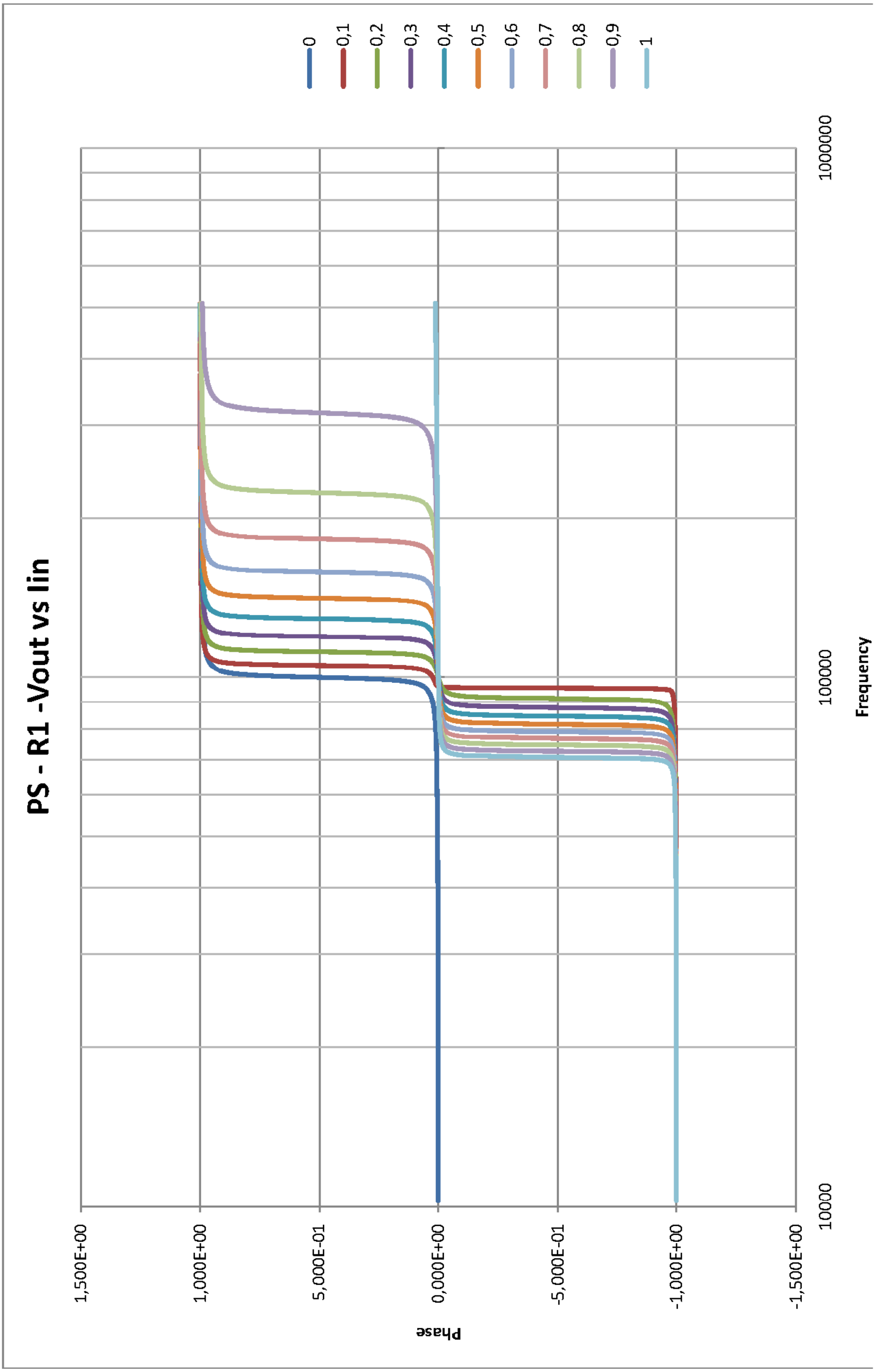

PP - R1 -Vout vs Iin
Magnitude
-1,300E+01
-1,400E+01
-1,500E+01
-1,600E+01
-1,700E+01
-1,800E+01
-1,900E+01
Frequency
10000
100000
1000000
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1

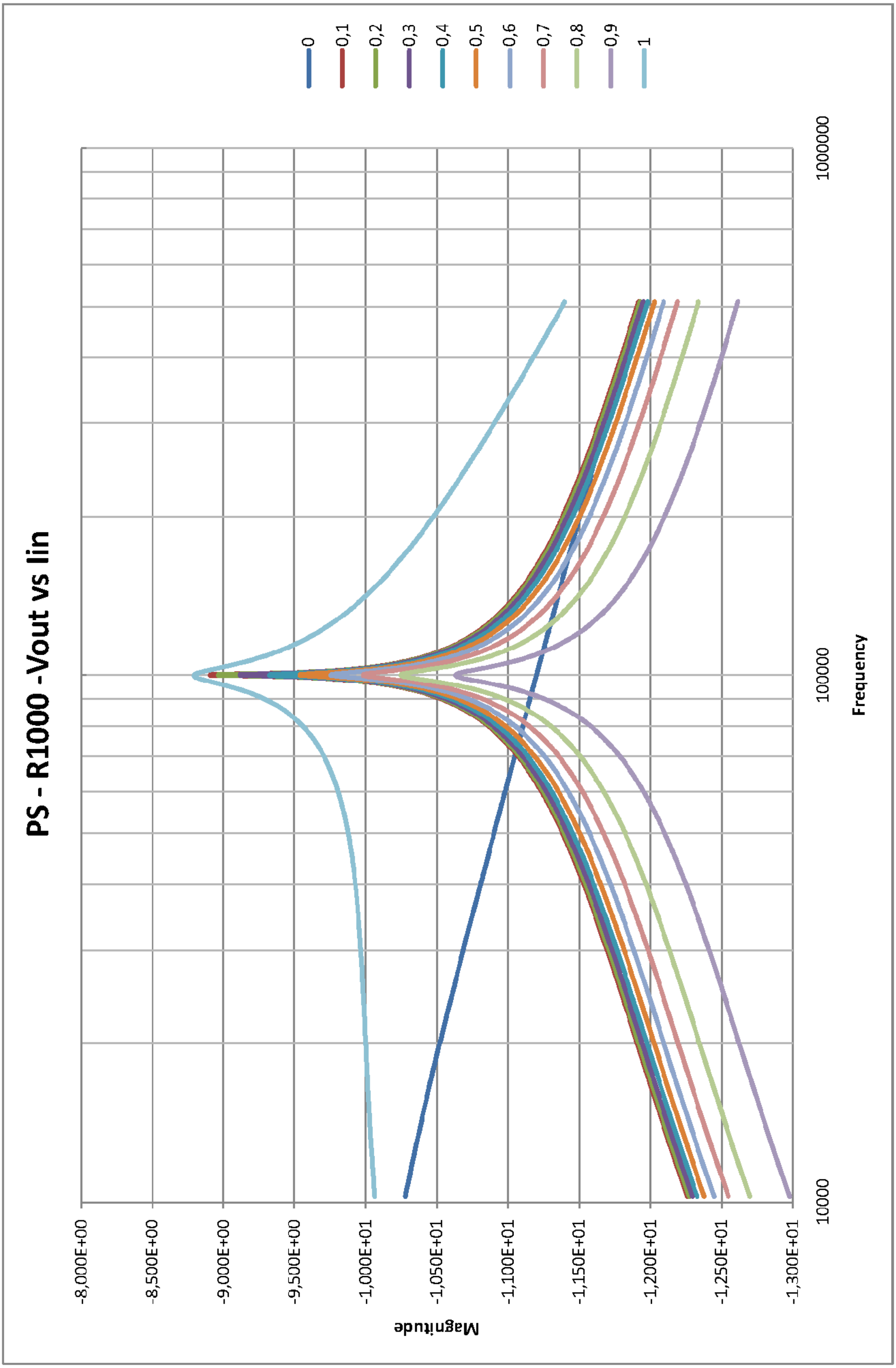

PP - R1 -Vout vs Iin
Phase
Frequency
1,200E+00
1,000E+00
8,000E-01
6,000E-01
4,000E-01
2,000E-01
0,000E+00
-2,000E-01
10000
100000
1000000
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1

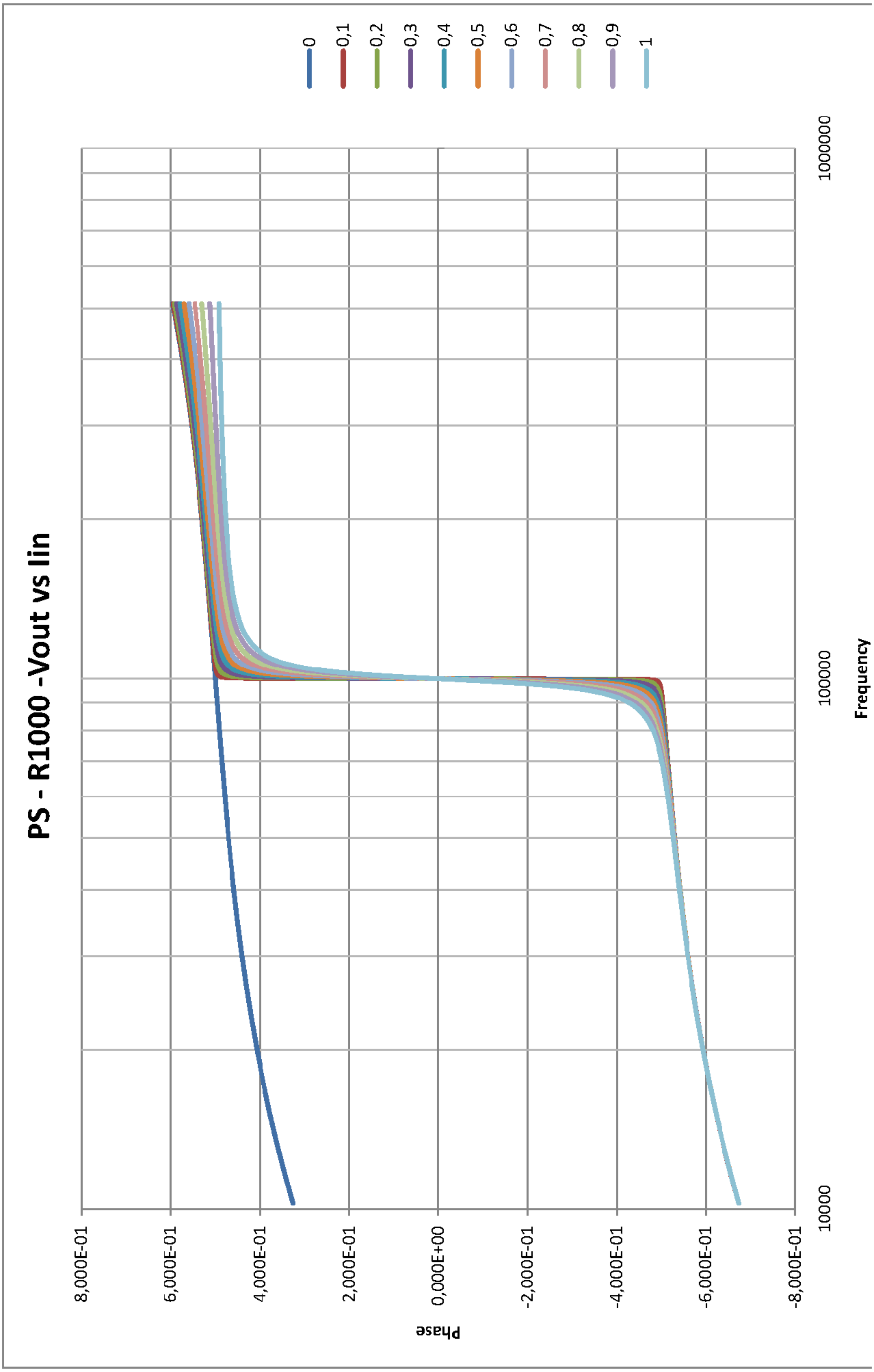

PP - R1000 -Vout vs lin
Magnitude
-1,100E+01
-1,200E+01
-1,300E+01
-1,400E+01
-1,500E+01
-1,600E+01
-1,700E+01
-1,800E+01
Frequency
10000
100000
1000000
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1

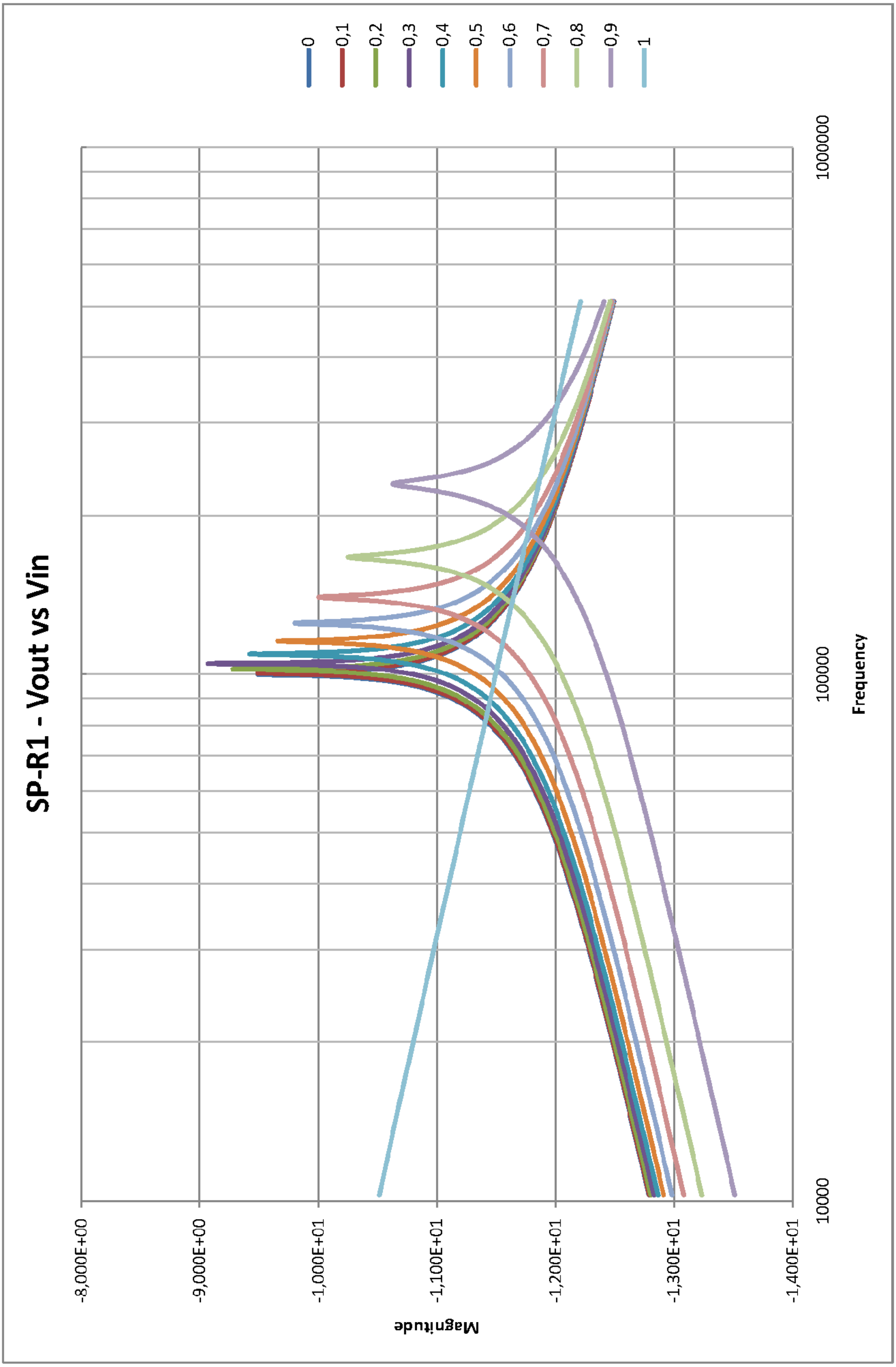

PP - R1000 -Vout vs Iin
Phase
2,000E+00
1,500E+00
1,000E+00
5,000E-01
0,000E+00
-5,000E-01
-1,000E+00
Frequency
10000
100000
1000000
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1

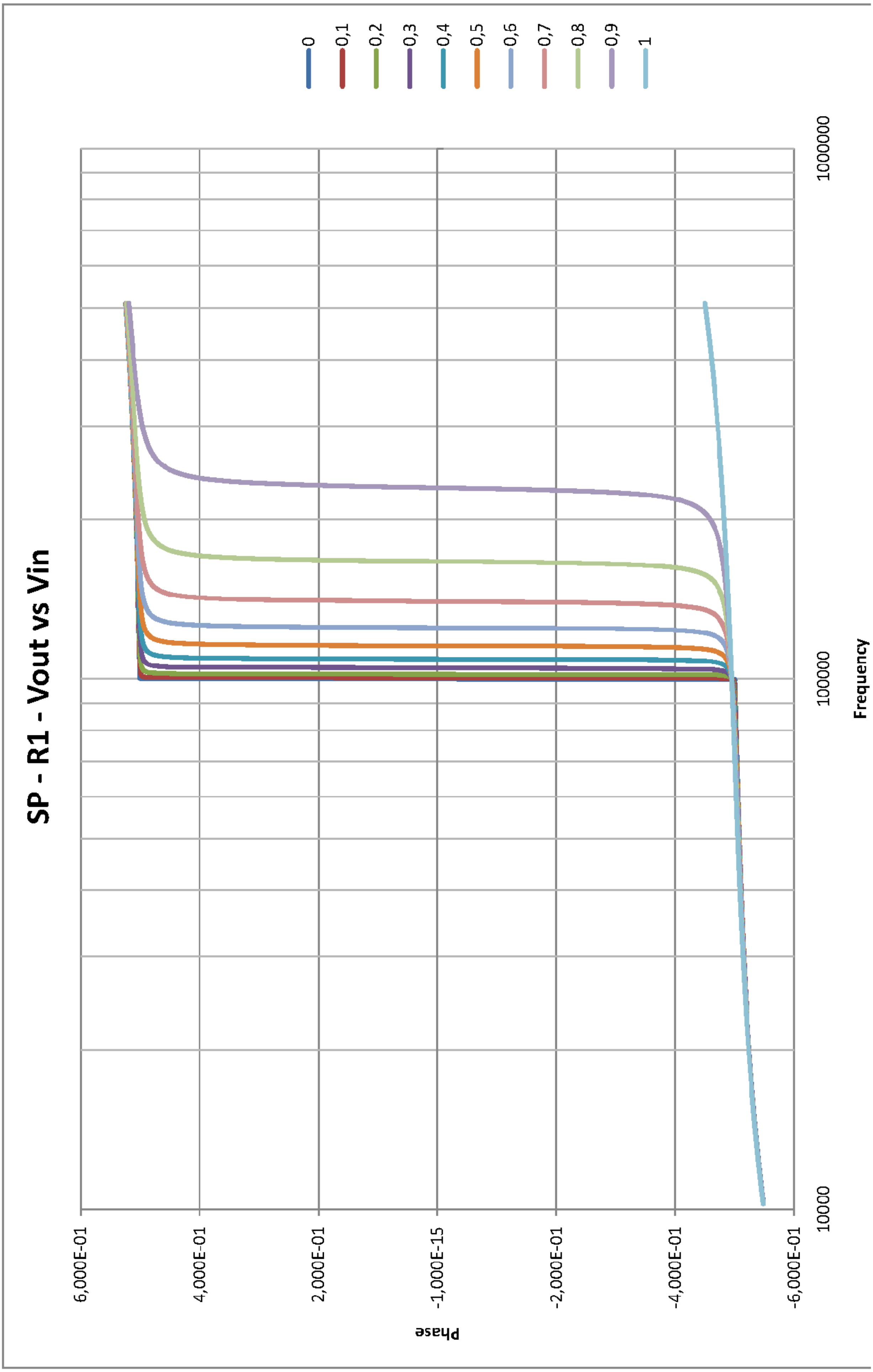

PS - R1 -Vout vs Iin
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1
Magnitude
-6,000E+00
-7,000E+00
-8,000E+00
-9,000E+00
-1,000E+01
-1,100E+01
-1,200E+01
-1,300E+01
Frequency
10000
100000
1000000

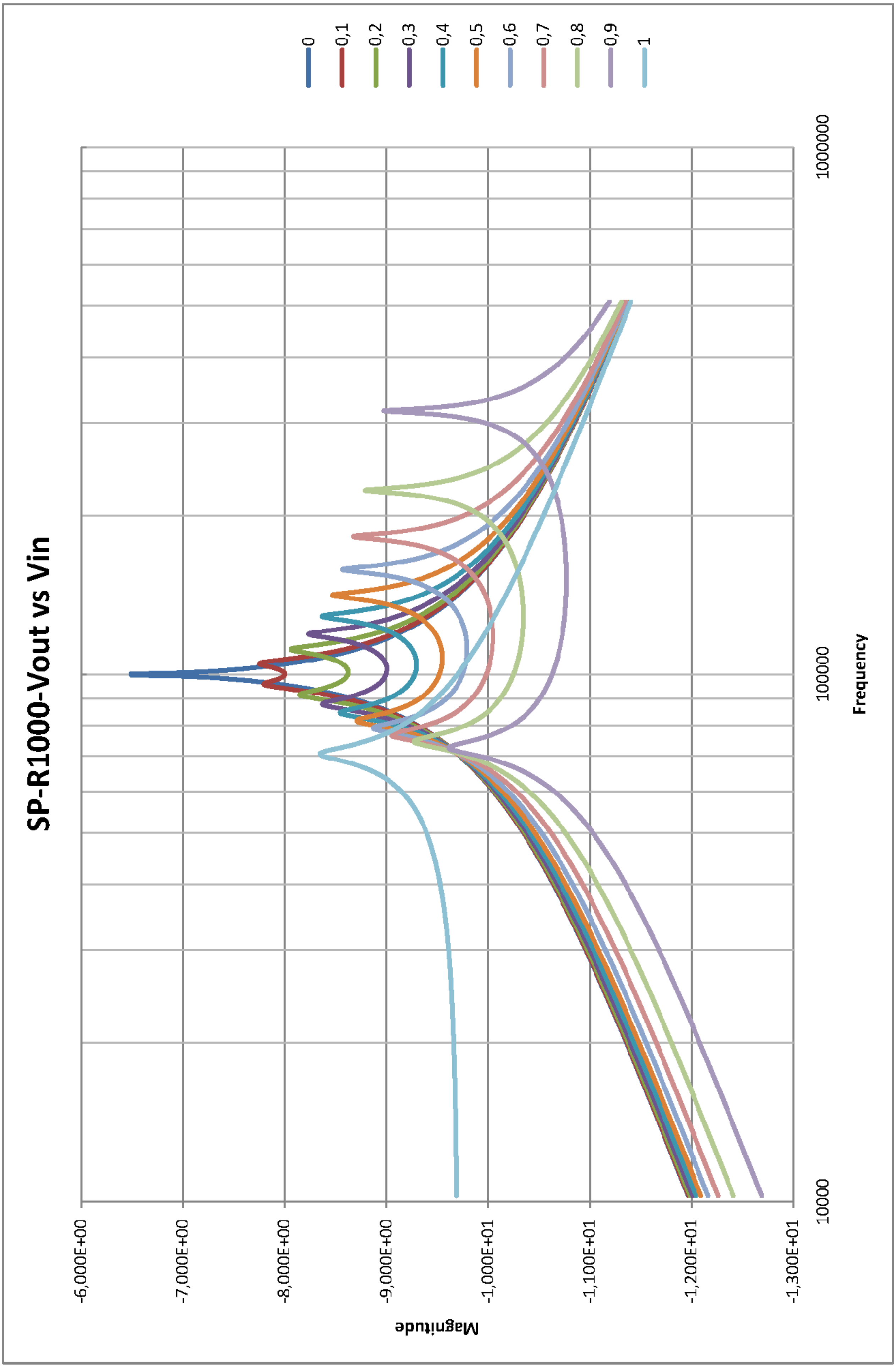

PS - R1 -Vout vs Iin
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1
Phase
1,500E+00
1,000E+00
5,000E-01
0,000E+00
-5,000E-01
-1,000E+00
-1,500E+00
Frequency
10000
100000
1000000

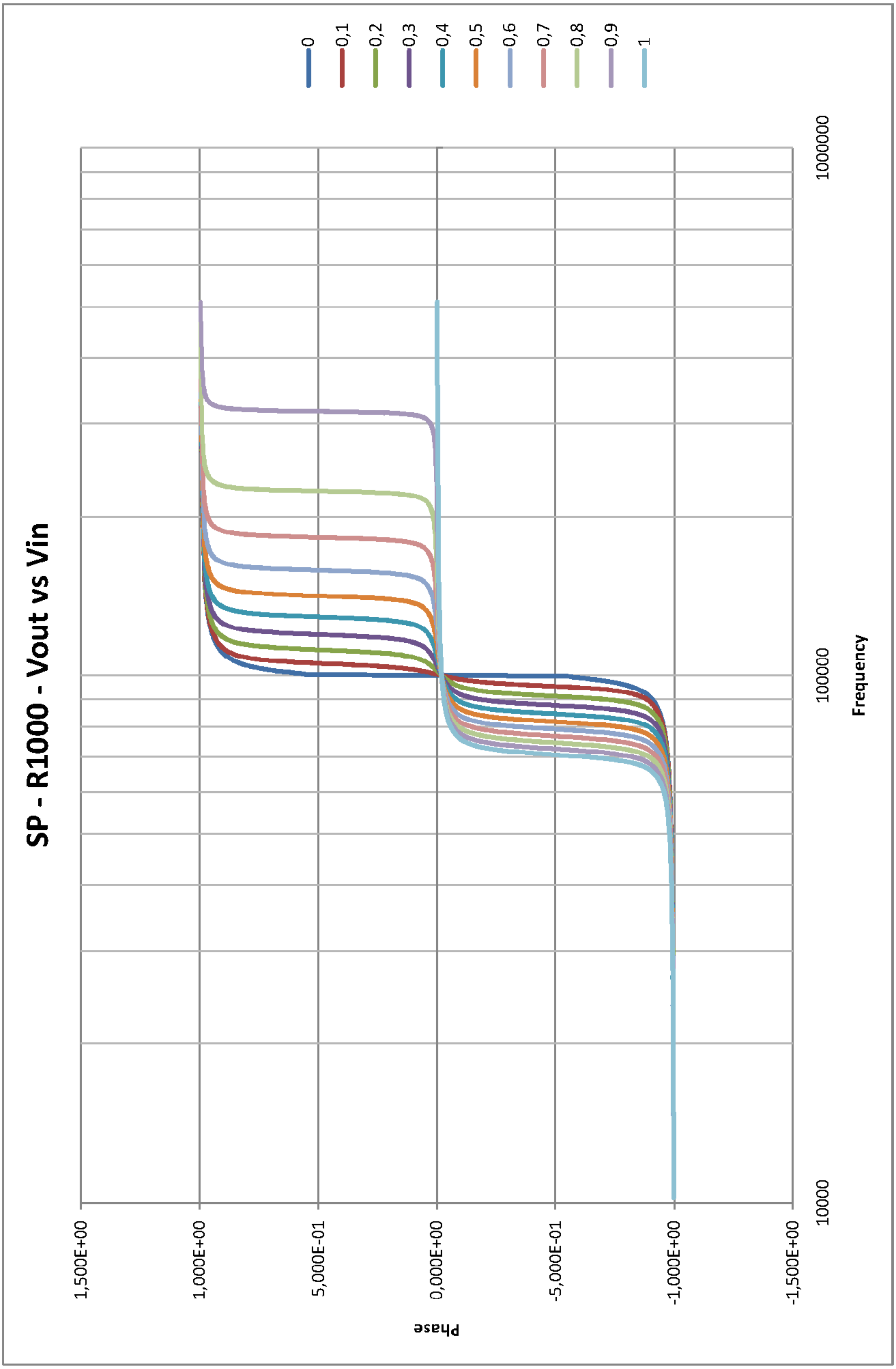

PS - R1000 -Vout vs Iin
Magnitude
Frequency
-8,000E+00
-8,500E+00
-9,000E+00
-9,500E+00
-1,000E+01
-1,050E+01
-1,100E+01
-1,150E+01
-1,200E+01
-1,250E+01
-1,300E+01
10000
100000
1000000
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1

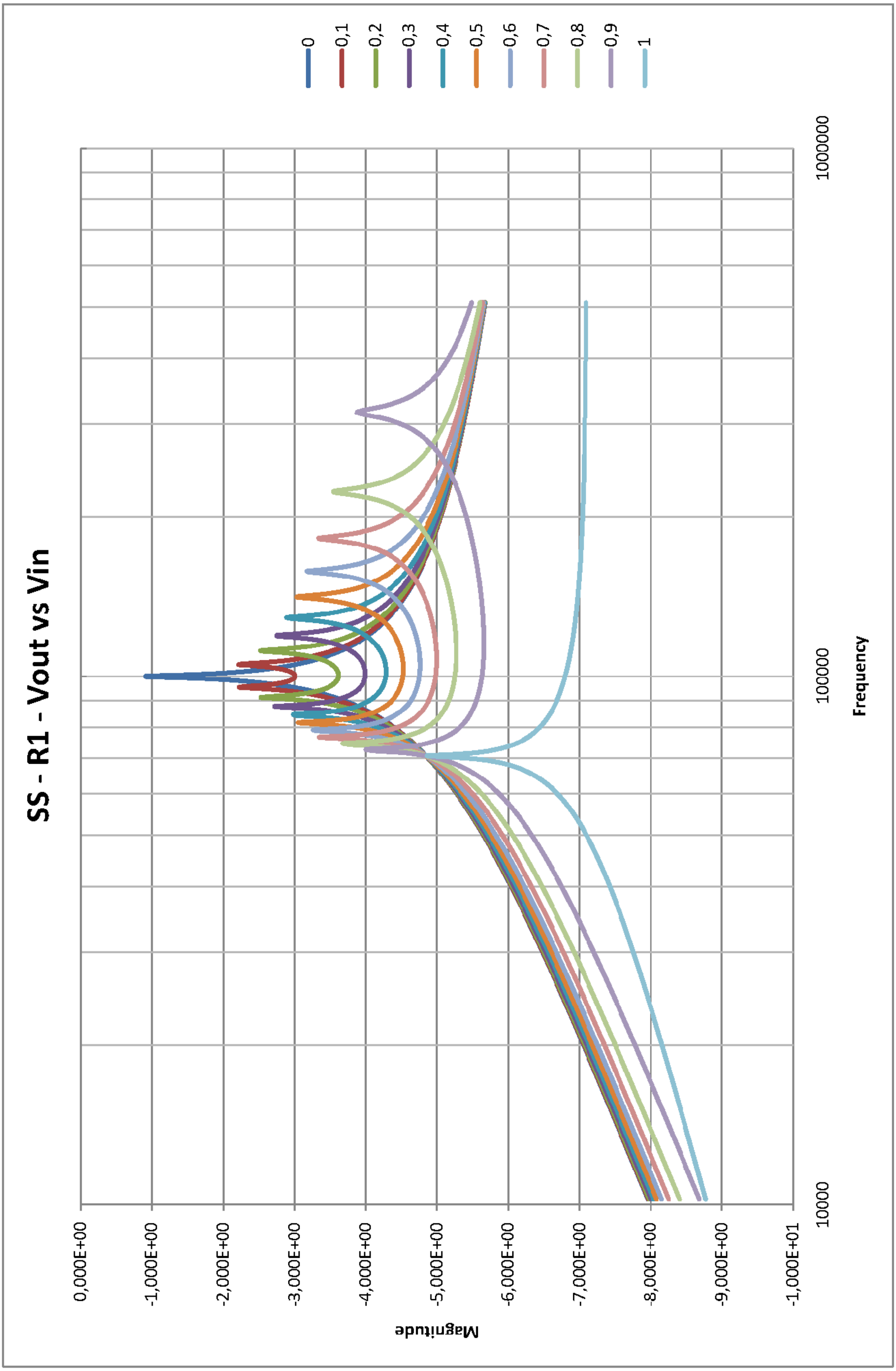

PS - R1000 -Vout vs Iin
Phase
8,000E-01
6,000E-01
4,000E-01
2,000E-01
0,000E+00
-2,000E-01
-4,000E-01
-6,000E-01
-8,000E-01
Frequency
10000
100000
1000000
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1

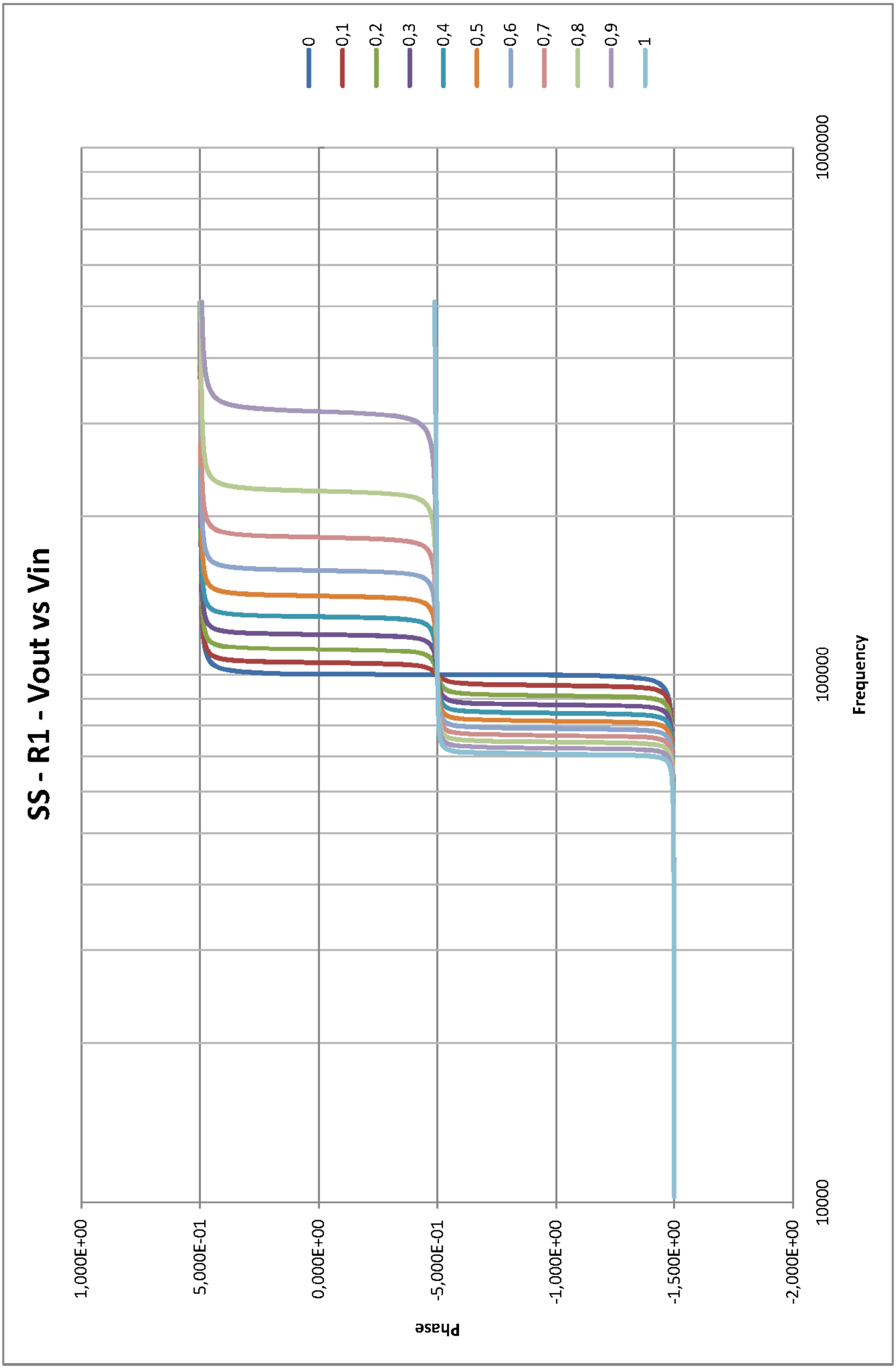

SP-R1 - Vout vs Vin
Magnitude
-8,000E+00
-9,000E+00
-1,000E+01
-1,100E+01
-1,200E+01
-1,300E+01
-1,400E+01
Frequency
10000
100000
1000000
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1

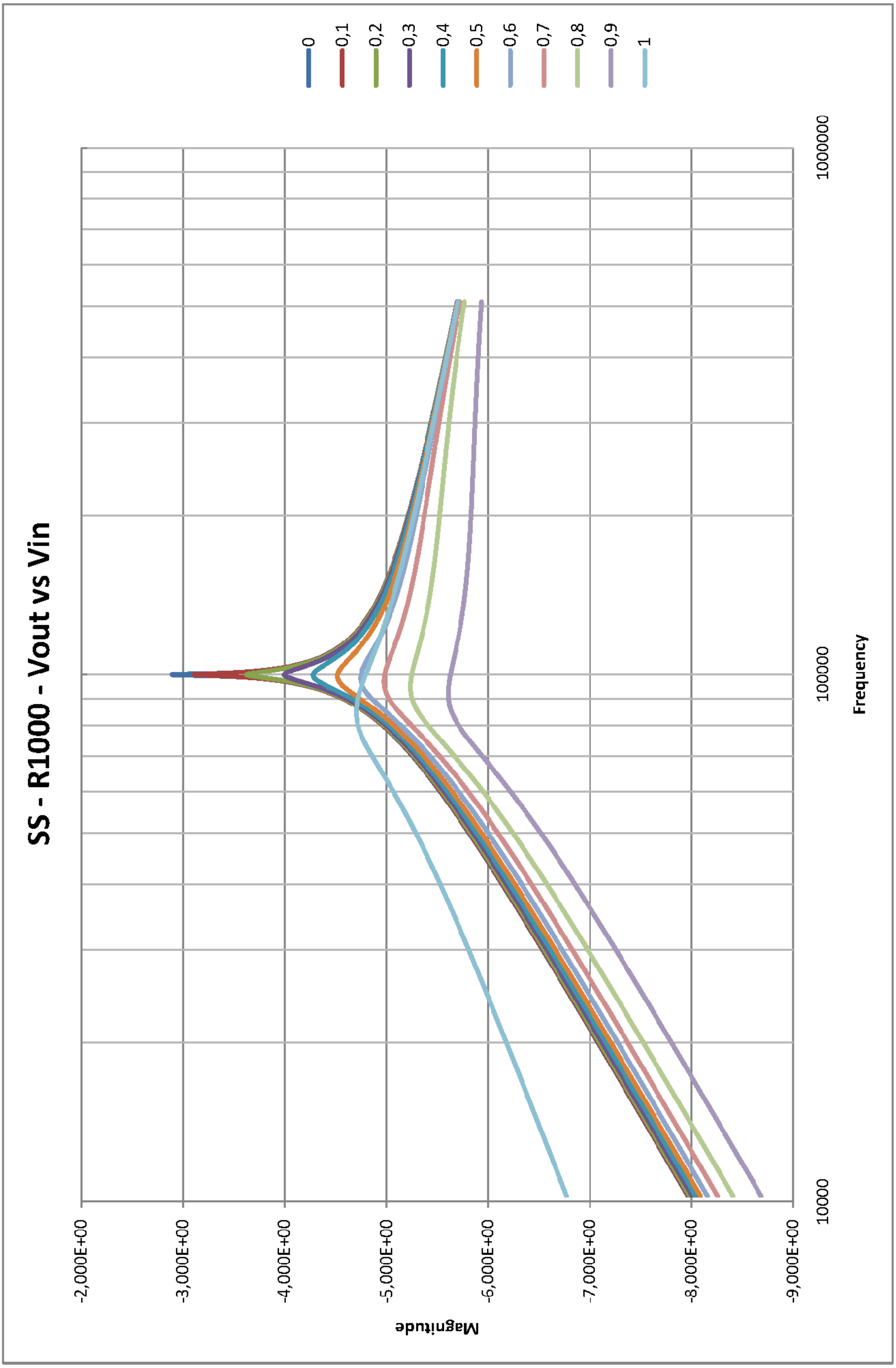

SP - R1 - Vout vs Vin
Phase
6,000E-01
4,000E-01
2,000E-01
-1,000E-15
-2,000E-01
-4,000E-01
-6,000E-01
Frequency
10000
100000
1000000
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1

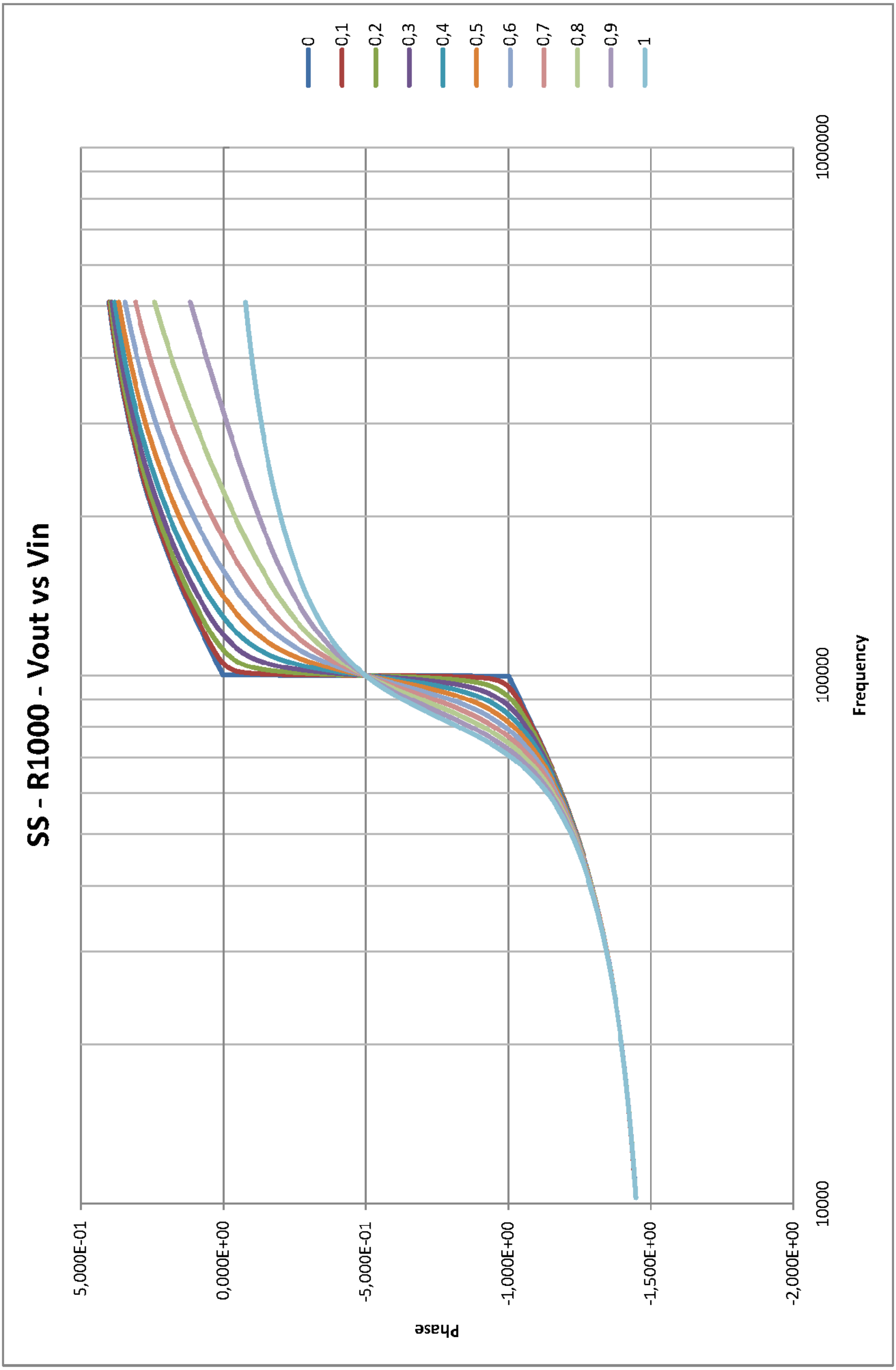

SP-R1000-Vout vs Vin
Magnitude
-6,000E+00
-7,000E+00
-8,000E+00
-9,000E+00
-1,000E+01
-1,100E+01
-1,200E+01
-1,300E+01
Frequency
10000
100000
1000000
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1


SP - R1000 - Vout vs Vin
Phase
1,500E+00
1,000E+00
5,000E-01
0,000E+00
-5,000E-01
-1,000E+00
-1,500E+00
Frequency
10000
100000
1000000
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1


SS - R1 - Vout vs Vin
Magnitude
0,000E+00
-1,000E+00
-2,000E+00
-3,000E+00
-4,000E+00
-5,000E+00
-6,000E+00
-7,000E+00
-8,000E+00
-9,000E+00
-1,000E+01
Frequency
10000
100000
1000000
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1


SS - R1 - Vout vs Vin
Phase
1,000E+00
5,000E-01
0,000E+00
-5,000E-01
-1,000E+00
-1,500E+00
-2,000E+00
Frequency
10000
100000
1000000
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1


SS - R1000 - Vout vs Vin
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1
-2,000E+00
-3,000E+00
-4,000E+00
-5,000E+00
-6,000E+00
-7,000E+00
-8,000E+00
-9,000E+00
Magnitude
10000
100000
1000000
Frequency


SS - R1000 - Vout vs Vin
Phase
5,000E-01
0,000E+00
-5,000E-01
-1,000E+00
-1,500E+00
-2,000E+00
Frequency
10000
100000
1000000
0
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1