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FACULTY OF MECHANICAL ENGINEERING
INSTITUTE OF SOLID MECHANICS, MECHATRONICS AND BIOMECHANICS

# DESIGN OF POWER SUPPLY FOR AIRCRAFT MODEL

NÁVRH ZDROJE ELEKTRICKÉ ENERGIE PRO MODEL LETADLA

DIPLOMOVÁ PRÁCE
MASTER'S THESIS

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# ZADÁNÍ DIPLOMOVÉ PRÁCE

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Ředitel ústavu Vám v souladu se zákonem č.111/1998 o vysokých školách a se Studijním a zkušebním řádem VUT v Brně určuje následující téma diplomové práce:

**Návrh zdroje elektrické energie pro model letadla**

v anglickém jazyce:

**Design of Power Supply for Aircraft Model**

Stručná charakteristika problematiky úkolu:

Dálkově ovládané letecké modely, které jsou poháněny spalovacím motorem, musí sebou nést i baterie pro napájení bezdrátového přijímače a řídících servopohonů. Zařazením vhodného generátoru ke spalovacímu motoru získáme nový zdroj elektrické energie pro napájení přijímače i servopohonů a ušetříme tím váhu baterií v modelu letadla.

Cíle diplomové práce:

1. Rešeršní studie zadané problematiky.
2. Porovnání jednotlivých koncepcí konstrukce a návrh vhodné konstrukce.
3. Simulační ověření vhodnosti konstrukce generátoru.
4. Návrh výkonové elektroniky pro model letadla.

Seznam odborné literatury:

Měřička, J., Zoubek, Z.: Obecná teorie elektrického stroje, SNTL, Praha, 1973.

Steingart, D.: Power Sources for Wireless Sensor Networks, Springer, 2009.

Vedoucí diplomové práce: Ing. Zdeněk Hadaš, Ph.D.

Termín odevzdání diplomové práce je stanoven časovým plánem akademického roku 2011/2012.

V Brně, dne 16.11.2011

L.S.

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| prof. Ing. Jindřich Petruška, CSc.<br>Ředitel ústavu | prof. RNDr. Miroslav Doupovec, CSc., dr. h. c.<br>Děkan fakulty |

## Abstract

The Master's thesis you are holding in your hands deals with design of electrical generator for remote control aircraft models powered by combustion engine. Such models are energized by batteries that have to be exchanged after discharge. The motivation of this thesis was to suppress the need for landing in order to recharge the battery packs. The thesis develops several analysis and simulation models for solution of this problem.

## Abstrakt

Diplomová práca, ktorú držíte v rukách, sa zaoberá návrhom elektrického generátoru pre modely lietadiel na diaľkové ovládanie poháňané spaľovacím motorom. Takýmto modelom je dodávaná energia pomocou batérií, ktoré sa musia po vybití vymieňať. Motiváciou tejto práce bolo potlačiť potrebu pristávania za účelom dobíjania batériových paketov. Práca vyvíja niekoľko analýz a simulačných modelov pre riešenie tohto problému.

## Keywords

remote control aircraft model, electrical generator, alternator, axial flux, coils, magnets, dc-dc converter, Simulink

## Kľúčové slová

model lietadla na diaľkové ovládanie, elektrický generátor, alternátor, axiálny magnetický tok, cievky, magnety, dc-dc menič, Simulink

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## Declaration on oath

I, Martin Šrámek, declare on word of honor that I have written this work by myself with cooperation of my supervisor and help of literature stated in References.

Martin Šrámek

# Thanks

First of all, at this place I would like to thank to supervisor of my Master's thesis – Ing. Zdeněk Hadaš, Ph.D. – for valuable advices and help in trouble shooting. Mostly, I thank to God since He is above all, to my family for supporting me during studies and to my friends for holding me tight in difficult situations.

# Contents

# Chapter 1

# Introduction

Without electromechanics we cannot imagine everyday life. It is a wide branch related to a variety of nowadays engineering applications (robotics, computers, car industry, power plants, mechatronic systems, etc). The secret of electromechanical devices is hidden in the transformation between mechanic and electric energy (and vice versa). Another mission of electromechanics is to improve up-to-date approaches and to look for other alternative solutions.

Remote control (RC) aircraft models can be considered as a target for such improvements. Modelers often make their own upgrades that develop the performance of aircrafts. The reason for opening this topic is an interest in improvements and alternative sources of energy. Normally, RC models are supplied by ordinary accumulator batteries which are not immortal. That leads to a quest for other options of power supplies.

The aim of this work is to find a proper replacement for batteries and to design the system with aspect of all particular issues. Design gradually gets through the questions of mechanical shape, magnetic features, electromechanical transformation and electronic circuits. Output of this thesis should be the systems of the same behavior as mentioned batteries but leaving out difficulties with charging and need for landing.

Problematic is studied in 8 chapters in this thesis. Thematically, it might be divided into three parts. The first is a research study that provides a brief view on majority of design aspects used in this work. The second says about known inputs and requirements. It specifies the task and determines the way of technical solution. The last part is the largest and contains all design steps leading to fulfill the assignment.

# Chapter 2

# Research

Remote-controlled aircraft models are supplied by secondary batteries. Their life cycle is quite short and therefore the flight of aircraft is time-limited. Choosing the proper way how to replace this source of energy, we can elongate time period in the air.

This research study serves as a tool for choosing the proper alternative source of electric energy for RC aircraft model. It tells about nowadays approaches and construction solutions, contains several physical principles and gives a brief view on available options. In addition, it describes how to process and store energy in electrical form.

## 2.1 Transformation of electro-mechanical energy

### 2.1.1 Electrical generators

The aim of this thesis is to design a suitable generator that should be placed between prop and fuel engine. It would replace batteries which are necessary for wireless signal receiver (remote control), servomotors and engine ignition. Beside technical realization it is important to consider weight and price of generator.

Hence the basis of task is to get electrical energy from the rotational motion of engine. This provides a generator – source of electrical voltage (current). There are two large groups of electric generators:

- Dynamos – sources of DC voltage
- Alternators – sources of AC voltage

Dynamo as the rotational electrical machine transfers mechanical energy into electrical one in the form of DC voltage. Nowadays, it loses its utilization since it is less effective, less reliable and difficult to maintain. However they are still used in many applications where one requires lower power or low DC voltage source. Compared to alternators, dynamos have got still some disadvantages [1]:

- Complex construction – higher chance of failure
- Possibility of commutator damage – non-ability of high RPM use
- Difficult regulation
- Weight, dimensions, sparkling of commutator

Alternators have found their utilization in car industry. In 1940s they started to dominate over dynamos as their replacement.

### 2.1.2 Physical principle of electrical energy production

As it was said above, electrical generators are used for transformation of mechanical motion into the form of electric voltage or current. Work of such generators is based on Faraday's law of induction which says: '*Electromotive force is induced in any closed circuit when the time change of magnetic flux is present.*' [2]

$$\varepsilon = -\frac{\partial \Phi_B}{\partial t} \tag{2.1}$$

In (2.1) $\varepsilon$ is electromotive force and $\Phi_B$ is magnetic flux of given magnetic field. If the magnetic flux through a coil with *N* turns is changing, a total induced electromotive force or voltage is a sum of these particular voltages. [2]

$$\varepsilon = -N\frac{\partial \Phi_B}{\partial t} \tag{2.2}$$

If a simple coil is pulled in uniform magnetic field (perpendicular to the cross-section of a coil) the voltage induced in coil could be computed as in Equation (2.3). The situation is shown in Figure 2.1.

$$\varepsilon = -N\frac{\partial \Phi_B}{\partial t} = -N\frac{\partial}{\partial t}(BS) = -NBL\frac{\partial x}{\partial t} = NBLv \tag{2.3}$$

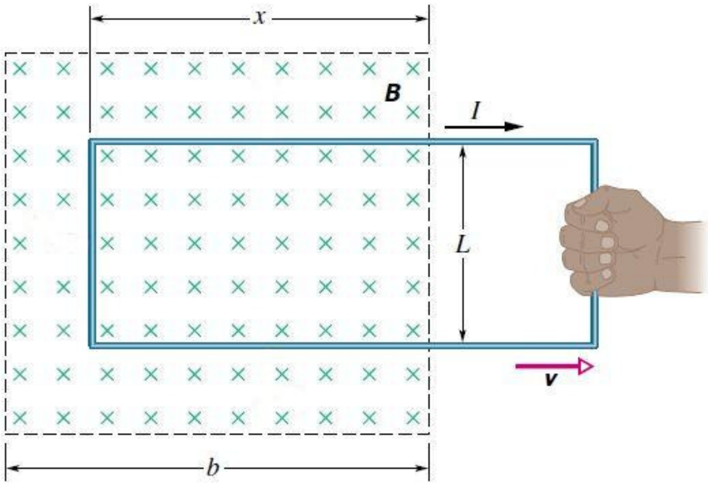


**Figure 2.1: Faraday's law in moving coil [2]**

If *x* is decreased, the magnetic flux descends as well and voltage is expressed with the help of velocity *v*. This equation will be mostly used in this thesis and is a base for next computations.

### 2.1.3 Radial vs. axial flux alternators

According to Chapter 2.1.1 the most suitable choice of electrical generator for our purpose is an alternator. Alternators are mostly used in cars and wind turbines. They produce an alternating current (AC) which has to be rectified into direct current (DC) when charging the batteries. Automotive alternators use mostly a rotor winding energized with direct current (current may vary to allow the control of the output voltage). Alternators in cars work in higher range of rpm depending on engine power (approximately in the range of 1000-7000 rpm). On the other hand, wind turbines use permanent magnet rotors (PM's) and use to work in lower ranges of rpm. Construction of wind turbine and rotational frequency cause several differences from automotive alternators.

**Figure 2.2: Radial flux alternator (used in cars) [3]**

One of the most significant differences is the way of magnetic flux flow. An exploded view of typical automotive alternator is in Figure 2.2. Winding of rotor is placed into slots as well as stator's one. Additionally, an orientation of coils is realized to make magnetic flux flow perpendicular to the axis of rotation. This type of generator is named as so-called radial flux machine.

Axial flux machines are used in applications where it is required by conditions (where a demand for narrow electrical generator is). Further, it brings many advantages in design of magnetic flux flow. It flows parallel to the axis of machine rotation. Such machine can be seen in Figure 2.3.

In general, considering either radial or axial flux generators, magnetic field of PM's (or electromagnets) in rotor has to be parallel to magnetic field of stator coils in order to obtain the highest efficiency. Both, axial and radial may be designed in more realizations (single or double rotor, single or double stator).

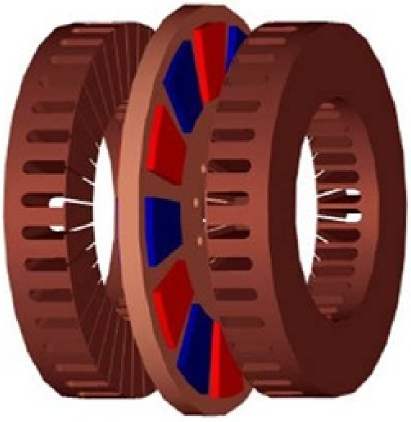

**Figure 2.3: Axial flux alternator [4]**

### 2.1.4 Previous applications and topics

Several applications of similar character are stated in this section. They might be helpful in design of own application as the output of this thesis.

#### 2.1.4.1 Permanent magnet brushless alternator for light combat aircraft

In [5], the design of PM brushless alternator is described. In automotive field, the most common case of alternator construction uses radial-flux oriented rotor. Mentioned optimized design does not tell us anything about the placement of alternator. It relies on a great deal of flexibility in their geometry. Anyways, it brings high requirements to produce 28 V (DC) and 2.5 kW power. It has to operate efficiently over a high-speed range of 6200 rpm to 12500 rpm. Described alternator should serve for emergency purposes when the main generator (30 kVA) fails. It has to supply important dashboard components. The main objective is the design of a minimum volume and good efficient three-phase alternator.

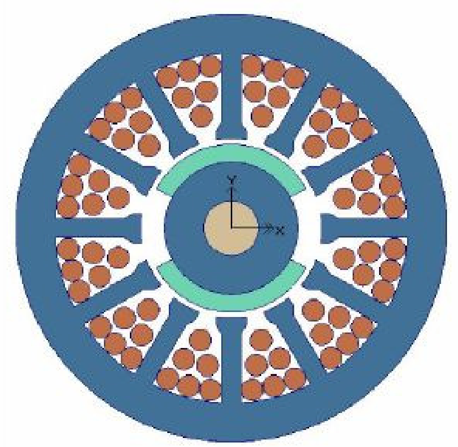


**Figure 2.4: Structure of alternator for light combat aircraft [5]**

The very simple structure design of alternator is displayed in Figure 2.4. Algorithm of design gets through the computations of geometry, flux density and finally power losses and output power. More detailed description of complete design is stated in [5]. The article provides simpler solution of design. Therefore this thesis has gained only inspiration of it.

The other inspirational output is the used electronics (Figure 2.5). Three-phased alternator produces alternating current which is rectified by common diode bridge. The buck converter is added after rectifier. It is simple step-down DC to DC converter that uses two switches (a transistor and a diode), an inductor and a capacitor. Buck converters can be remarkably efficient up to 95% or higher for integrated circuits.

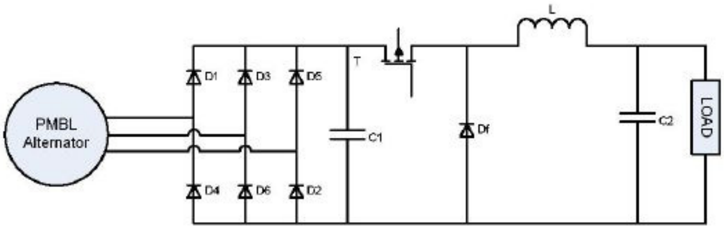


**Figure 2.5: Un-controlled diode rectifier with buck converter [5]**

### 2.1.4.2 Rotor yoke thickness of axial-flux PM generator

Next valuable topic is discussed in [6]. Main subject investigated in this paper is the optimized thickness of the back iron of the permanent magnet. A very small thickness of the rotor yoke reduces the terminal voltage and efficiency and a very large value of it increases the rotor inertia, mechanical problems and cost of machine with no significant improvements of the machine performance characteristics. Hence design of the rotor plays an important role and requires more careful attention.

This topic is addressed to high-speed generators (50 000 rpm). In such case, the design is quite different from designing a conventional low-speed machine. Document contains computations of reluctances, losses and deeper study of magnetic circuit. One of the outputs is the function in Figure 2.6. It shows how flux density varies with changing thickness of yoke.

Nd-Fe-B magnet material is chosen for rotor. As author says, this material is generally the best candidate for use in PM machines. Axial-flux machines are mostly coreless machines without any slots naturally. It causes smaller dimensions of machines. For investigation of magnetic flux density effect, finite elements method (FEM) is used. FEM software in [6] is ANSYS.

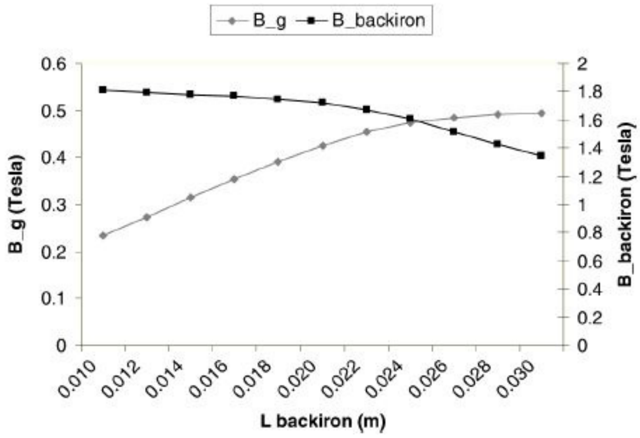


**Figure 2.6: Air gap and back-iron flux densities versus yoke thickness [6]**

### 2.1.4.3 Automotive alternator with integrated switched-mode rectifier

Document [7] presents the design of 42 V Lundell automotive alternator, and determines the main parameters which are important for use with a switched-mode rectifier. Although this alternator works with current field controller (in rotor) it gives an interesting idea of electronic rectifying solution.

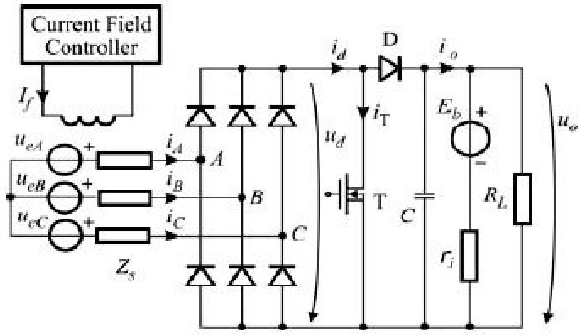


**Figure 2.7: The circuit diagram of power management system [7]**

At low speeds, the switched-mode rectifier operates as a boost converter with a very high commutation frequency. At large speeds, it operates as a normal PWM buck converter. The alternator inductance becomes part of the boost circuit.

### 2.1.4.4 Homemade axial-flux alternator

On the internet, there are many pages with own homemade alternators for wind turbines. One of the manuals for building PM axial-flux turbine is described in [8].

The text is written simply and is aimed for people who like “Do it yourself” applications. Nevertheless, it is quite useful for a brief view on mechanical and electrical design of an axial-flux alternator. Neodymium round magnets are used in rotor again as a key technological development that allows efficient alternators to be built. Round magnets use to be used in smaller alternators. When the machine gets larger, it is often more practical to use rectangular magnets. Rotor consists of two rotor plates what makes so-called double-sided axial-flux PM machine [9]. A right concentrating of magnetic field into air gaps can highly influence the output power of such generator. Final shape of the wind turbine rotor is in Figure 2.8.

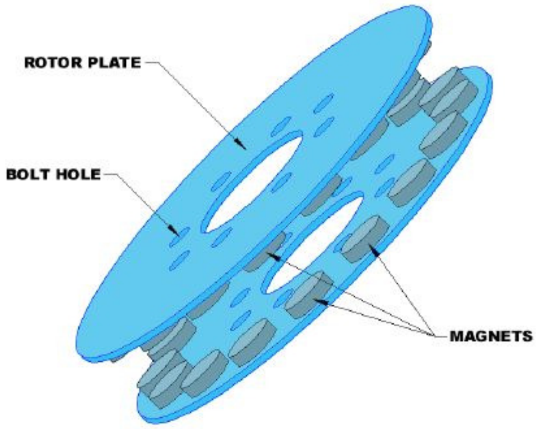


**Figure 2.8: Final shape of wind turbine rotor [8]**

Magnets are attached to rotor plates in order to close magnetic flux lines. Thus the concentration of magnetic field becomes more homogenous. Flux also alternates between north and south poles of magnets. Stator coils are placed between plates so that the direction of flux lines is perpendicular to coil surface and alternator is most efficient.

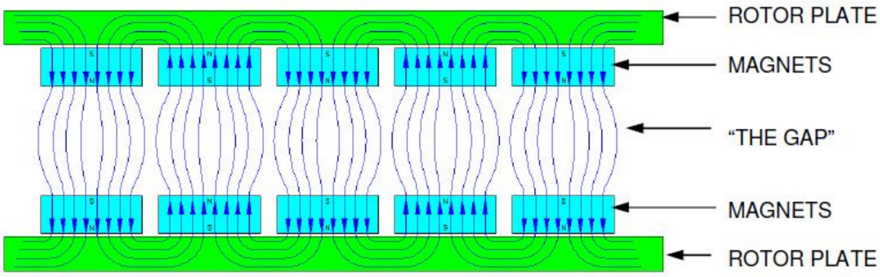


**Figure 2.9: Concentrating the magnetic field [8]**

Wind turbine alternators use to work in lower rpm range. The alternator discussed above is able to produce 50 V at 80 rpm. Practically when connected to a 48 V battery system, it records 600 W at 100 rpm (roughly 12A).

## 2.2 Distribution of electrical energy

After generating an electrical voltage, it is necessary somehow to distribute it to loads. This can be executed by connection to suitable circuit with rechargeable elements.

### 2.2.1 Rectifying

An alternator produces alternating current. Loads are dimensioned to work under direct current. This is a conflict. Usual solution of this issue is the use of suitable rectifier. There are more conceptions of rectifiers that use mostly two approaches: half-wave rectification and full-wave rectification.

Half-wave rectifier produces DC voltage by passing either the positive or negative AC wave and blocking the other half. It is very simple to compose but on the other hand the efficiency of such rectifier is very poor (only a half of input reaches the output). More usual is to use full-wave rectification. It converts the whole of AC input to constant polarity waveform and is more efficient. However, they need more components to be built. The comparison of half-wave and full-wave rectifiers work is described in Figure 2.10.

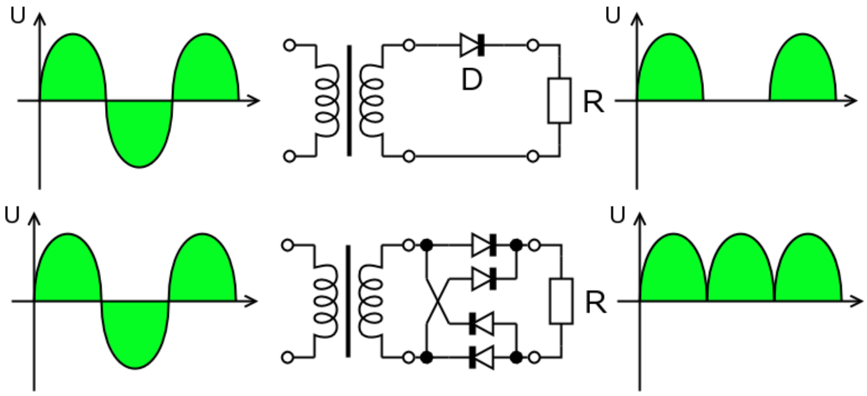


**Figure 2.10: Comparison of half and full-wave rectifier [10]**

Rectifiers bring with themselves many advantages but they cause some peak losses and smoothing too. Normal built-in voltage drop represents 0.6 V for ordinary diodes and approximately 0.3 V for Schottky diodes. When using bridge rectification, this could make significant power losses in low voltage supplies. In addition, although rectifiers transform alternating voltage to DC one, they do not produce a constant voltage. This is often fixed by adding a suitable filter. The simplest way uses just a capacitor connected to DC output of rectifier.

### 2.2.2 DC-DC power converters

A variety of applications, where the wide input voltage range has got to be changed to another voltage value, employs DC-DC converters. They converts unregulated voltage to the regulated one, mostly of constant value. In practice DC-DC converters typically reach efficiency of 70% to 95%. The reason is that they include switched-mode circuits.

There are three basic topologies of such converters: [11]

- Buck converter
- Boost converter
- Buck-boost converter

All of them consist of a switch network (reduces or gains input voltage) and a low-pass filter (removes the high-frequency switching harmonics). Switch network is realized by using semiconductor elements such as diodes and MOSFETs. Typical switching frequency lies in the range 1 kHz to 1MHz, depending on the speed of semiconductor devices. Deeper studies of DC-DC converters can be found in [11] and [23]. However, for good understanding of work, the basic equation is stated here:

$$V_s = \frac{1}{T_s}\int_0^{T_s} v_s(t)dt \tag{2.4}$$

In Equation (2.4), $V_s$ represents average value of the switch output voltage $v_s(t)$. Geometrically, the integral is equal to the area under the signal waveform. Switch voltage waveform of buck converter is pictured below. The switch output voltage $v_s$ is equal to $V_g$ in switch position 1 and equal to zero while the switch is in position 2. Waveform is periodical having period $T_s$ and duty cycle $D$.

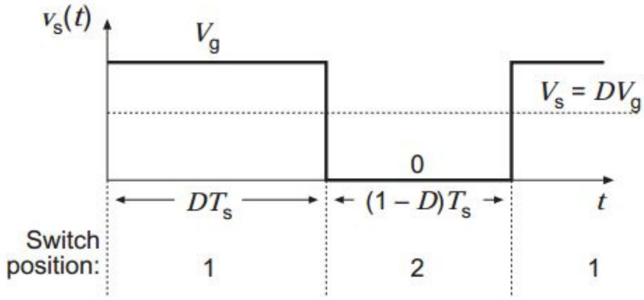


**Figure 2.11: Buck converter output voltage waveform [11]**

Ideally, the converter produces a DC output voltage whose magnitude is controllable via the duty cycle $D$. Thus the conversion ratio $M(D)$ is introduced. It is defined as the ration of the DC output voltage $V$ to the DC input voltage $V_g$ under steady-state conditions.

$$M(D) = \frac{V}{V_g} \tag{1.5}$$

For instance, for the buck converter's DC ratio holds $M(D) = D$. Circuit models of buck and boost converters and their DC conversion ratios are shown in Figure 2.12.

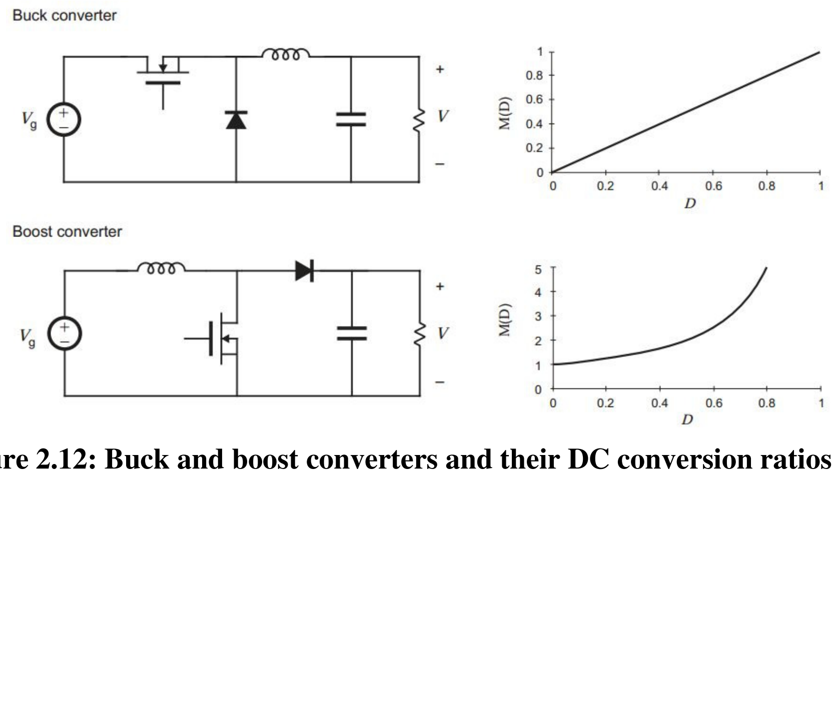


**Figure 2.12: Buck and boost converters and their DC conversion ratios [11]**

### 2.2.3 Energy storage

When a constant DC power is generated it does not remain permanently. Hence it must be stored. Nowadays there are two usable types of electrical energy storage:

- Secondary battery
- Supercapacitor (also called Ultracapacitor)

#### 2.2.3.1 Secondary battery

Usually batteries represent an active element of DC circuit. This thesis deals with an application which assumes battery to be both active and passive component. Accordingly, there are two points of view:

- Battery recharging – battery behaves as a load (passive element)
- Supplying the circuit load – battery behaves as active element

There is a variety of battery types including primary cells (non-rechargeable batteries) and secondary cells (rechargeable batteries). [12] Further, for our application we will assume only rechargeable batteries.

In [13], one can find a comparison of several battery types. They differ from one another mainly in terms of the amount of electrical energy they can store and deliver. Additionally, batteries are described by several features as the gross electrical storage capacity. It is usually specified in milliamp-hours (mAh). Needless to say the stored energy can be delivered at various rates when talking about discharge, and also replaced at various rates during the recharge. These rates are usually specified in terms of the ‘C Rate’, where C is the battery’s nominal capacity in mAh. A discharge rate of 1C means that the battery is discharged at the same rate as its nominal capacity.

| Type (chemistry) | Nominal Cell Volts | Cycle life | Charging time | Maximum discharge rate | Cost |
|---|---|---|---|---|---|
| NiCad | 1.2 | Long | 14-16h (0.1C) or <2h (1C) | High (>2C) | Medium |
| NiMH | 1.2 | Medium | 2-4h | Medium | Higher |
| Li-ion | 3.6 | Long | 3-4h | Med/High (<1C) | Very high |

**Table 2.1: Rechargeable batteries comparison chart**

Several types of quality rechargeable batteries are in Table 2.1. They have many benefits what can reflect on their price. However, they still are not perfect and have some losses in efficiency. Due to internal resistance, one has to put more energy into it during charging that they will ever return to the load during recharging. Usual rule is that 40% of the charging energy is wasted – so to fully charge a battery, it is necessary to provide 140% of its nominal capacity. [13]

Some of chosen detailed information are stated below:

*NiCad batteries* use nickel hydroxide as the positive electrode and cadmium metal/cadmium hydroxide as the negative electrode, with potassium hydroxide as the electrolyte. They have a higher energy density than SLA batteries and that make them popular for powering compact portable equipment: cordless power tools, instruments, radio transceivers, model boats and cars. NiCads duffer form the memory effect and are therefore not really suitable for applications that involve shallow cycling or spending most of their time on a float charger. They can provide very cost-effective energy storage and the longest working life of any of the rechargeable batteries.

*NiMH batteries* are in many ways a development from the NiCad. Like NiCads, NiMH batteries use a nickel/nickel hydroxide positive electrode and potassium hydroxide as the electrolyte. However instead of a cadmium/cadmium hydroxide negative electrode, the NiMH has an electrode made from a hydrogen-storage alloy such as lanthanium-nickel or zirconium-nickel. They have up to 30% higher energy density than NiCads. They are not very satisfied with deep discharge cycles. Another thing is that they dissipate heat during charging, and can only be charged at about half the rate of NiCads. Charging is more complicated and ideally involves temperature sensing. Their typical use is for mobile and cordless phones, portable camcorders and laptop computers.

*Li-ion batteries* are a recent development from lithium primary cell. Lithium is the lightest of all metals and has the highest electromechanical potential, which gives it the possibility of an extremely high energy density. Li-ion batteries have roughly twice the energy density of NiCads. Unlike NiCad and NiMH batteries they are not subject to memory effect and have a relatively low self-discharge rate (about 6% per month). On the other hand Li-ion batteries cannot be trickle or float charged. [13]

#### 2.2.3.2 Supercapacitor

Supercapacitors are capacitors with capacitance values greater than any other capacitor type available today. Capacitance values reach up to 400 Farads in a single standard case size. Supercapacitors are not as volumetrically efficient and are more expensive than batteries but they have the highest capacitive density available today. Hence they can be used for applications ordinary reserved for batteries.

[14] The most significant advantage supercapacitors have over batteries is their ability to be charged and discharged continuously without degrading like batteries do. What makes them different from other capacitor types are the electrodes used. They are based on carbon (nanotube) technology. It creates a very large surface area with an extremely small separation distance. Capacitors consist of two metal electrodes separated by a dielectric material (this

material also affect the performance of capacitor). More about supercapacitor theory can be founf in [14].

The double layers formed on the activated carbon surface can be illustrated as a series of parallel RC circuits.

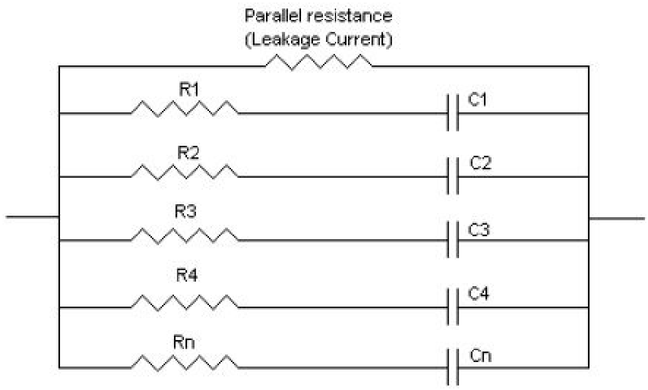


**Figure 2.13: Principle of supercapacitor as series of RC circuits [14]**

When voltage is applied current flows through each of the RC circuits. Supercapacitors can be illustrated similarly to conventional film, ceramic or aluminum electrolytic capacitors. Equivalent circuit is shown in Figure 2.14 as a simplified or first order model of a supercapacitor.

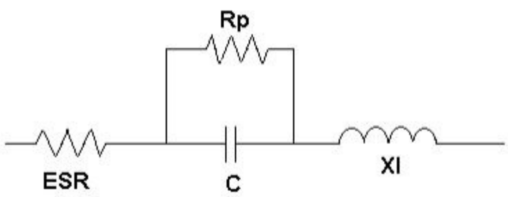


**Figure 2.14: Equivalent circuit of supercapacitor [14]**

Supercapacitors have found their uses in computer systems, UPS systems, power conditioners, welders, inverters, power supplies, cameras, power generators.

# Chapter 3

# Synopsis of tasks

Chapter 3, called Synopsis of tasks, deals with a solution of thesis tasks. According to work requirements, it gives a brief view on general function and summarizes the particular design tasks.

## 3.1 Requirements

Final output of this document should be a complete design of an electrical generator for RC aircraft model (Figure 3.1). It is powered by fuel combustion engine. The current model is equipped with two batteries that have to be carried for supplying the RC receiver and controlled servomotors. Design is orienting on a choice of suitable generator that should be attached to rotor of prop engine and should replace current battery packs. That is why the generator construction plays an important role. Application requires light and simple solution at the same time.

**Figure 3.1: A real view on RC aircraft model**

Assigned task fulfills principles of a complex mechatronic design task. To sum up particular inputs, here is the list of requirement priorities:

- Functionality – avoidance of landing for recharge reasons
- A light weight
- Low prize

## 3.2 Actuation focus

### 3.2.1 Batteries and servomotors

Previously, the model was powered by two battery packs consisting 4 AA batteries each. All components were ordered from [15]. A pack is able to provide 4.8 V output voltage and weighs approximately 130 g. The prize of such pack oscillates around 350 CZK.

Aircraft model uses totally 9 servomotors for flight control. They consume a low current. Current pulses reach 0.55 A. When servo is stopped it takes away 0.5 A. Two types of HITEC servomotors are used. Function goals of servos are listed below:

Servomotors HITEC HS-311:

- 2x ailerons
- 2x landing flaps
- 1x throttle
- 1x hook

Servomotors HITEC HS-755:

- 2x elevator
- 1x rudder

HITEC servos could be purchased for the prize of 300CZK.

### 3.2.2 Combustion engine

Combustion petrol engine ZDZ 80 is used as a prop drive. It weighs 1850 g and the range of rpm is in interval 1200 – 8200 rpm (without a load). It can produce maximal mechanical output power of 5.88 kW. Closer characteristic of ZDZ 80 petrol engine is stated in [16].

Figure 3.1 contains aircraft model with engine placed in a metal frame. It might help in attaching the disc alternator to aircraft model. The only proper place for a disc alternator is then behind a prop. While rotor would be fixed with a driven shaft, stator can be firmly screwed to the mentioned frame. Highlighted position of an alternator is drawn in Figure 3.2.

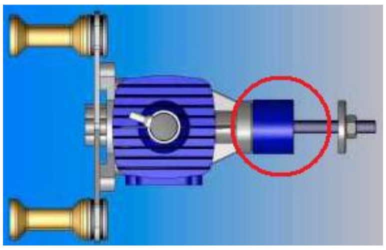

**Figure 3.2: Position for a disc alternator**

## 3.3 Partition of design tasks

After the requirements are summarized, we have to deal with complex mechatronic design. It can be split into several subtasks:

- Mechanical design
- Analysis of magnetic circuit
- Electromechanical transformation analysis
- Simulation modeling of electronic circuit

They are closely related one to another. Thus, the designer has to be aware that if he would change one parameter, it might lead to the change and eventually to malfunction of whole system.

The diagram of complex mechatronic design is depicted below in Figure 3.3:

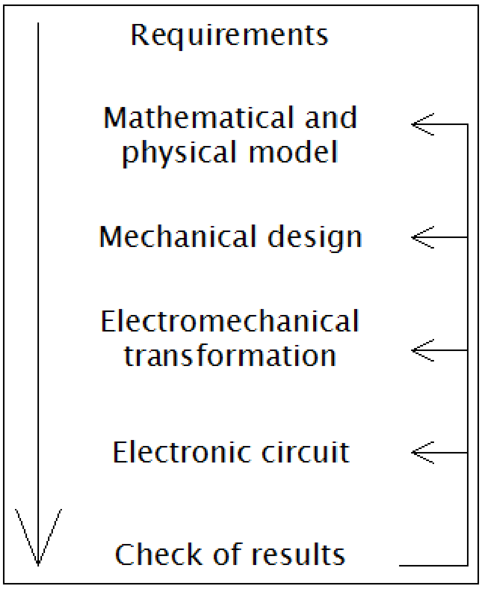


**Figure 3.3: Algorithm of complex mechatronic design**

# Chapter 4

# Mechanical design

## 4.1 Suitable construction

Driven shaft has a diameter of 5 cm. Looking at Figures 3.1 and 3.2, there is around 4 cm of axial place in front of metal frame. Whole geometrical conception has to be done in respect to these parameters and request for the light weight.

According to such requirements everything leads to the choice of single-phase disc-type axial-flux alternator.

## 4.2 Mechanical model

### 4.2.1 Rotor

When thinking of mechatronic approach to design of a system, one has to be aware of the fact that every step deals with a group of following steps. When designing a rotor, we must realize, it is concerned with mechanical structural analysis (deformation in high rpm, choice of material) and magnetic analysis (number of magnets, strength of magnetic field) for instance.

Duty of rotor is to create a variable magnetic field. Rotor is assembled of two significant parts: permanent magnets and a ferromagnetic metal disc. Beside of these two it contains epoxy resin that is used for attaching magnets to iron disc. The simplest choice of material for ferromagnetic metal is iron as a very common candidate. It has a high permeability and confines magnetic flux lines.

Figure below (4.1) shows possible shape of iron disc construction. This part can be manufactured by casting. After shaping, 6 holes are drilled for mounting the rotor to driven shaft. Ordinary M5 metric screws might be used. In general, this part is the support and carries the whole mechanical loading.

**Figure 4.1: Suggested shape of rotor disc**

Figure 4.2 represents disassembled rotor view for better imagination.

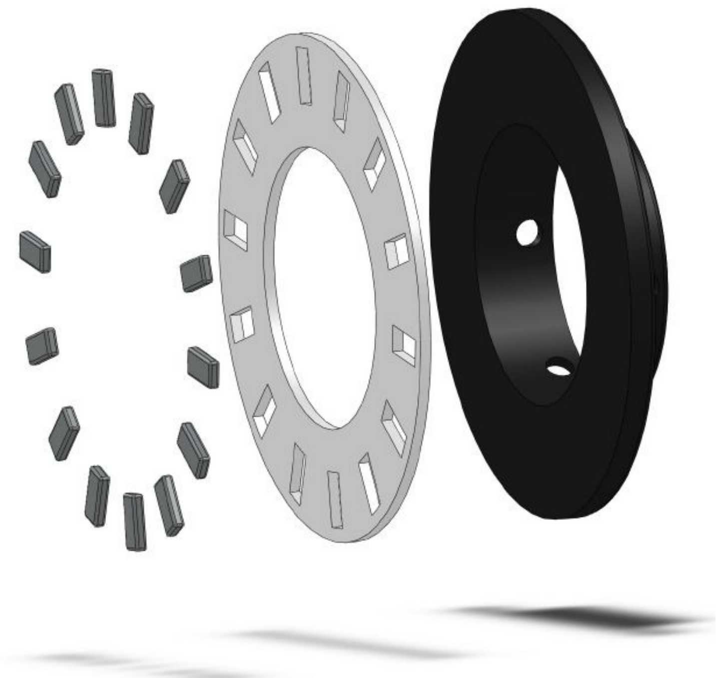

**Figure 4.2: Assembled rotor view**

When a load in form of rpm is applied, the rotor deforms a bit. The influence of this deformation is studied in static structural analysis. It has been done in ANSYS Workbench platform.

Workbench provides a wide scale of materials in tis libraries. For deformation analysis, these materials and characteristics were chosen:

| Part | Material | Density [kg/m$^3$] | Young's Modulus [MPa] | Poisson's Ratio [-] |
|---|---|---|---|---|
| Iron disc | Gray Cast Iron | 7200 | 110000 | 0.28 |
| Epoxy resin | FR-4 Epoxy | 1900 | 5000 | 0.3 |
| Magnets | Nd-Fe-B | 7500 | 160000 | 0.24 |

**Table 4.1: Materials for deformation analysis**

Simulation uses FEM calculations with static structural analysis type. Mechanical APDL solver target is involved. Assuming two steady-state conditions - rotational velocity and fixed support on the inner diameter – auto-scaled view of rotor's total deformation is shown in Figure 4.3. The state of rpm was set to 8200, although if assuming a prop, the engine does not reach such values.

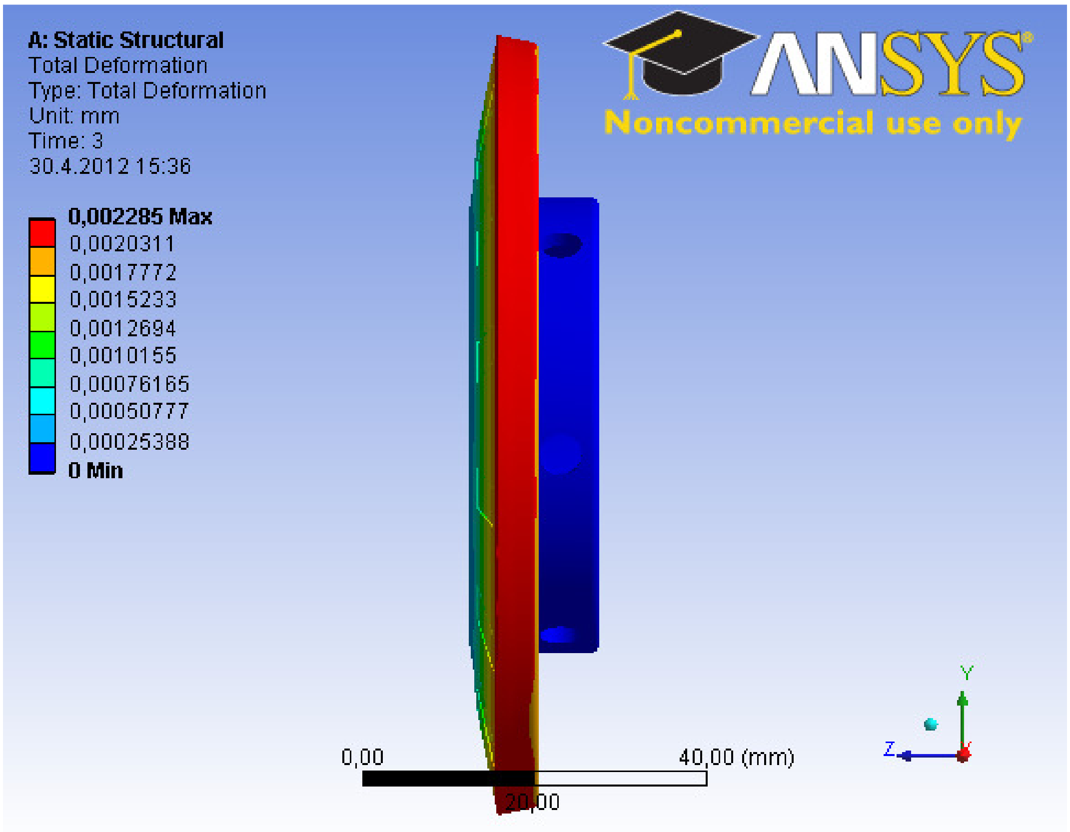


**Figure 4.3: Deformation of iron disc**

Even though there is a deformation on rotor, the value 2.3 µm of displacement is very low and can be neglected. The similar simulation has been done for rotational velocity of 1000 rpm, only for orientation reasons. In this case, maximal displacement reached 0.03 µm.

### 4.2.2 Stator

There are two options for solution of stator. First one assumes a stator compound of coils and a solid that would hold them tight in their positions (epoxy resin). Second one contains extra part – steel laminations. The purpose in this case is to avoid eddy current losses. A disadvantage of this option is that using steel laminations rapidly increases weight of alternator. That is why option without laminations is preferred.

Independently of approach we use, from Figure 3.2 we assume 4 mm of coil length (axial dimension). Coils are sealed in epoxy resin and can be mounted by screwing it to engine frame. An example of stator shape is depicted in Figure 4.4 below. This is only an orientation shape of stator. Final shape assumes coils totally sealed in epoxy resin. Since the epoxy resin can be manufactured as either a good thermal insulator or conductor, and the flying aircraft is flown off very well by air, cooling is secured.

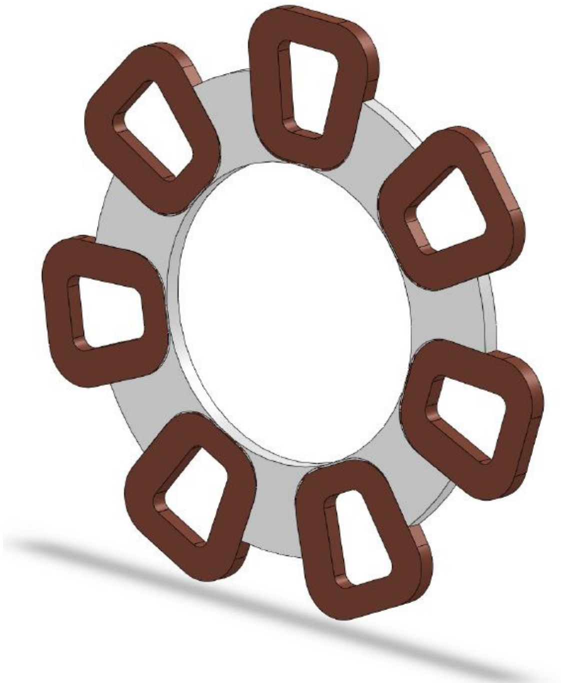

**Figure 4.4: Construction of stator coils**

### 4.2.3 Relative position of magnets and coils

When magnets rotate around coils, it is important to consider the relative position of both. Equation (2.3) is based on fact that if magnetic flux lines close in a single loop, no induced voltage is created since the change of magnetic flux is zero. Hence, designer has to take care of relative positioning magnet and coils. Then he can efficiently take an advantage of magnetic field properties. Axial-flux alternator is designed with 14 PMs and 7 coils. This choice has been done as the most suitable solution with a respect on geometry.

The entire assembly is shown below in a rear axial view. Number of PMs has to be even because the magnet poles are put alternately (magnetic design is discussed later in Chapter 5).

As the rotor turns, magnets of same pole orientation are either in the center of coil core or out of it respectively. So the best efficiency of magnetic field is observed.

**Figure 4.5: Relative position of PMs and coils**

Solved mechanical inputs and outputs are briefly listed in Table 3.1

| Inputs | Value |
|---|---|
| Diameter of driven shaft, *d* | 50 mm |
| Axial space, *k* | 40 mm |
| Outputs | |
| Middle radius of PM position, $r_m$ | 37.5 mm |
| Outer diameter of rotor, *D* | 100 mm |
| Number of magnets, $N_m$ | 14 |
| Number of coils, $N_c$ | 7 |
| Coil radial height, *L* | 15 mm |
| Coil axial length, *l* | 4 mm |
| Air gap, *g* | 1 mm |
| Iron disc thickness, *h* | 4 mm |
| Whole axial dimension, *H* | 22 mm |

**Table 4.2: List of mechanical inputs and outputs**

# Chapter 5

# Analysis of magnetic circuit

As it was said in Chapter 4, the best solution for studied application is PM axial-flux device. The choice of suitable magnets and their impact on magnetic field are discussed in this section.

## 5.1 Magnets

There is a plenty of magnets with variety of magnetic features. Website [17] has been used as a source for choosing the most suitable ones. There are two most widely manufactured types of magnets: ferrite and neodymium magnets (NdFeB). Ferrite magnets are the traditional black we know from office notice boards but their utilization is much boarder (electric motors, magnetic separators, speakers…). However, the NdFeB magnets are currently the strongest permanent magnets. That is why they were chosen in the design, even though they are a bit more expensive.

According to Equation (1.1), amount of induced voltage on the coil clips is proportional to the change of magnetic flux through the coil. It means that the aim of designer is not to create a great magnetic field but to bring up the widest possible difference in magnetic flux. It can be done easily by positioning of magnet poles alternately around the circumference of rotor.

Specifically, neodymium magnets were preferred by having greater residual induction *Br* and coercive force *Hcb*. They are main features of magnetic materials. In addition, there is another characteristic which combines both, so-called B-H curve (or curve of magnetization). Magnetic design uses a fact that relative permeability $\mu_r$ is a function of magnetic field intensity (given by flux density) [18]:

$$\mu_r = \frac{B_r}{H_{cb}\mu_0} \tag{5.1}$$

From general construction studied in Chapter 4, it is clear that magnets will touch an iron disc. The purpose is to focus and close magnetic field in rotor. Assuming ferromagnetic material in rotor and stator, it is a given they would be magnetized. Equation (5.1) is defined from B-H curve shown in Figure 5.1. Residual induction and coercive force are features taken from specific (zero valued) conditions.

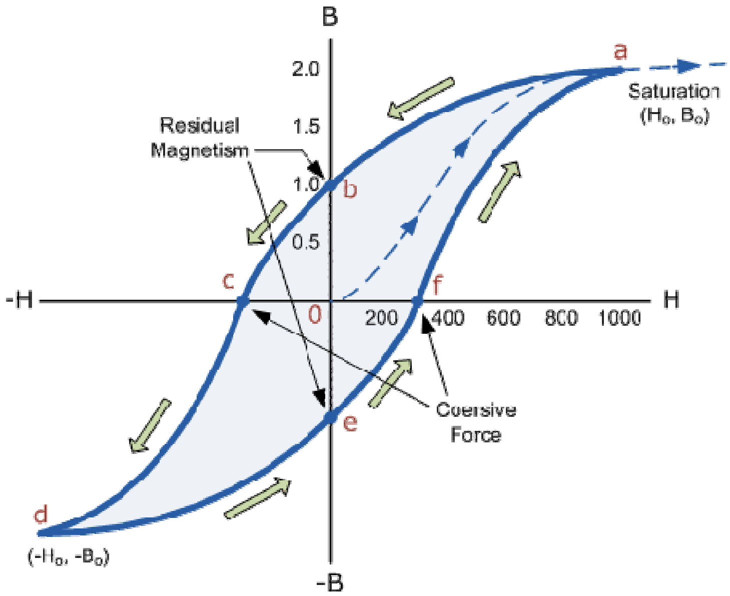


**Figure 5.1: General magnetization curve [18]**

Magnetic analysis of alternator rotor was processed in ANSYS simulation software. Three magnets were investigated and results are shown later. To see how stator steel laminations reduce hysteresis and eddy current losses, there was created a model with and without it. Totally then 6 different models were examined. That produced a serious platform for comparison of different magnet strengths and dimensions. Neodymium magnet specifications are listed in Table 5.1. Values of residual induction and coercive force are mean values of wider range taken from [17]. These values were used in magnetic simulation.

| Number | Dimensions [mm] | Weight [g] | Residual induction [mT] | Coercive force [kA/m] |
|---|---|---|---|---|
| N - 20423 | 15x7.5x5 | 4.22 | 1190 | 895.5 |
| Au - 21034 | 10x5x2 | 0.75 | 1415 | 922.5 |
| N – 20897 | 8x8x4 | 1.92 | 1350 | 922.5 |

**Table 5.1: Examined NdFeB magnets in ANSYS**

First letter in a magnet code means the surface treatment (N means nickel, Au means gold). Magnetic features have a lot to do with mechanical design of rotor. The iron disc must not be too thin because magnetic field would be very concentrated in specific places. On the other hand it should not be thick for weight reasons.

As can be seen from table above the lightest choice as well as the best magnetic features are presented by Au-21034 neodymium magnet. Hence it has been chosen for next design and all pictures below are oriented this only magnet.

If we align position of magnets on circumference we get 2D picture as below. This can help in design. However, it should not make the basis of modeling since the magnetic symmetry is not present as in 3D model. Figure 5.2 shows the view on a focus of magnetic flux lines from top plane of rotor. On the left, simulation has not used steel laminations in stator. On the right side, magnetic simulation with laminations use can be seen.

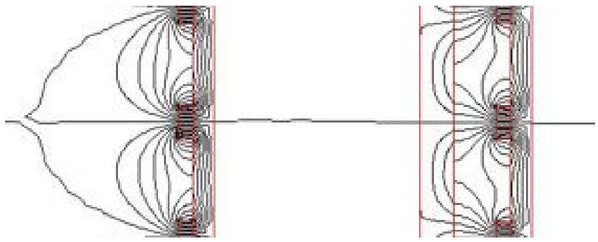

**Figure 5.2: Magnetic flux lines (stator without and with steel laminations)**

Simulation in ANSYS is closely connected to mechanical outfit. A distance between magnets depends on the number of them. The thickness of iron disc behind magnets and the thickness of laminations depend on thickness of magnets and their strength.

## 5.2 FEM magnetic analysis

As it was said, magnetic analysis was done in ANSYS system. Algorithm defining geometry, magnetic characteristics of particular simulated parts of alternator and environment, material features and size of mesh is used.

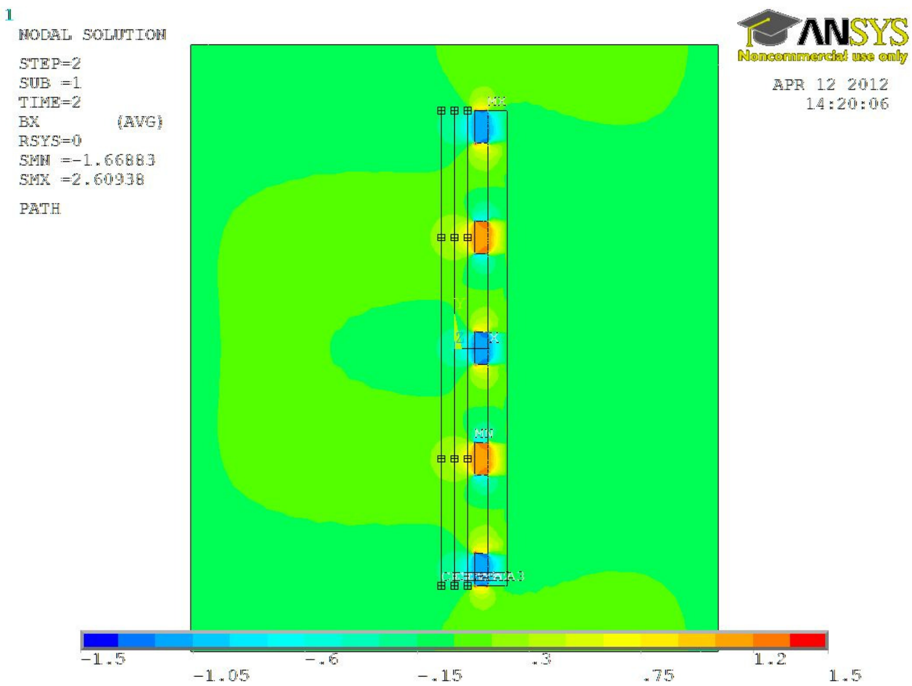


**Figure 5.3: Flux intensity in axial direction contour plot**

The purpose of magnetic models is to determine the flux intensity function across the coil cores. According to rotor construction, we may assume harmonic pass of the flux intensity. In Figure 5.3, one could see how flux intensity in axial direction varies around the circumference. Most important part of magnetic flux intensity is $B_x$ since it enters the simulation calculation in each used software.

Concentration of magnetic field in magnetized iron plays an important role in assuming the thickness of iron disc. It has an impact on losses theory and eddy currents. They influence a thermal behavior. However in our case the thermal fluctuations are not significant since a flying aircraft has a satisfied cooling. To see the overall flux intensity the sum of *Bx* and *By* is plotted below.

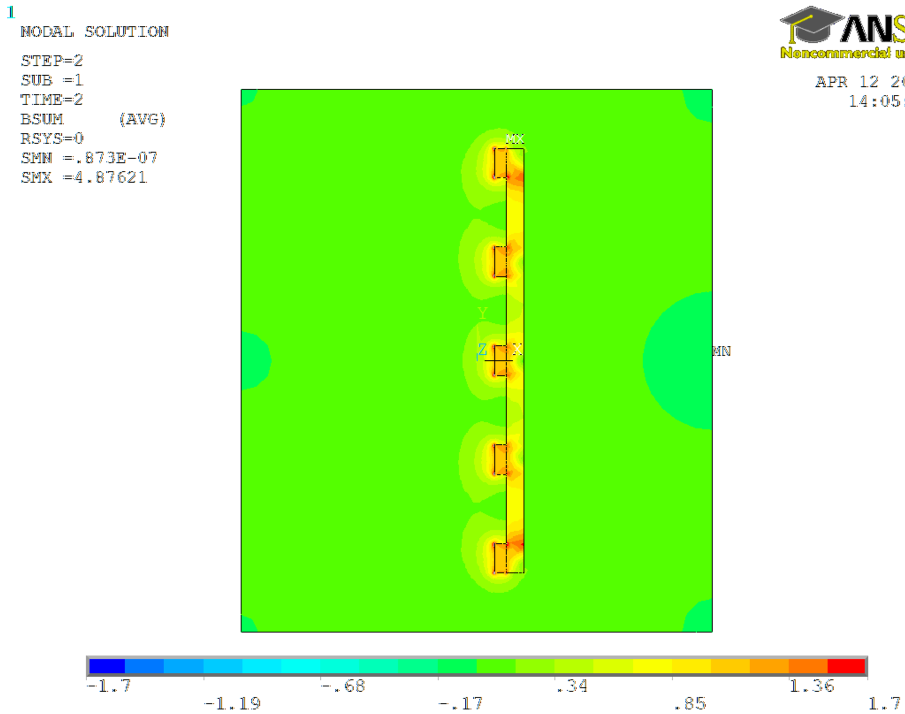


**Figure 5.4: Sum of flux intensities**

Figure 5.5 presents the pass of axial direction flux density. A value of flux density varies with the distance from magnets. Therefore three paths were built in the place where stator coils should lie. They can be seen in Figure 5.3 too. The space for coil packets is 6 mm large. Assuming the 1 mm air gap, the paths are in distance of 1, 3 and 5 mm from magnets. Path data from ANSYS were taken and fed to MATLAB for next simulations.

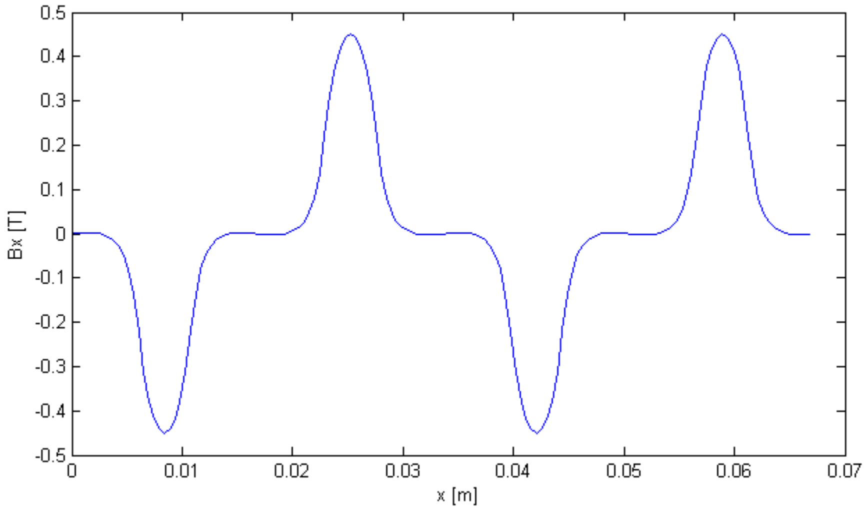


**Figure 5.5: Function of $B_x(x)$**

The reason of three paths use was to create an average value of flux intensity in given point of rotation. In Figure 5.5, the average of flux intensity around the circumference of rotor is drawn. Ripples in the picture represent positions of magnets. The shape of function says about alternating of magnet poles and it repeats around entire rotor.

This algorithm was used for all magnets stated in Table 5.1 so that we obtained data with different “magnet strength”.

# Chapter 6

# Electromechanical transformation analysis

During designing and performing simulations, there were used two approaches to build simulation model. The aim of modeling was to create complex Simulink model that has rpm on the input and constant voltage on the output. First approach can be understood as a partial model for computing output voltage. That is computed by m-file and consequently loaded into Simulink model. Computations are done mainly by using Equation (2.3). The second approach contains whole simulation based on process solved by Simulink. It mostly uses Equation (2.1).

Chapter 6 includes and discusses both approaches.

## 6.1 First approach

Firstly, to compute induced voltage in a coil, the approach described in Paragraph 2.1.2 was used. The approach like this is a bit inconvenient because input in form of rpm is not a part of simulation model however a part of m-file. According to Equation (2.3) holds:

$$U_i = NBLv \tag{6.1}$$

*N* represents the number of turns in a coil, *B* is the magnetic flux and *L* is the height of coil. Actually, here comes a speculation. In Figure 2.1, L is a height of coil however homogenous magnetic field is assumed. In our case, PMs create inhomogeneous magnetic field. Therefore one has to decide which dimension to use. There are two options: dimension of a coil or dimension of a PM. As we know magnetic flux intensity in front of PMs, it would be more correct to put into equation the length of PM. However, Faraday's law of induction says about 'closed' loop through which the flux changes. According to this assumption, the dimension of a coil should be chosen, although including some inaccuracies in magnetic flux density. In addition, as we see from mechanical design the length of PM and the height of a coil is quite similar. Hence we will assume L as a length of a coil. Velocity *v* is then a velocity computed from angular velocity and rpm:

$$v = \omega r_m = \frac{2\pi}{60} n . r_m \tag{6.2}$$

Where $r_m$ is a middle radius of PM placements and n is rpm state. Here is an example: Induced voltage through a coil with 300 turns after passing 2 PMs in rotational frequency 1000 rpm looks as in Figure 6.1.

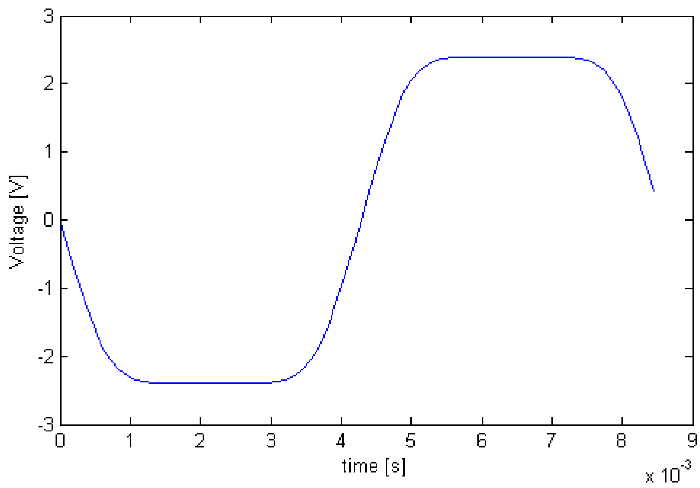


**Figure 6.1: Induced voltage after 2 PMs passing (example situation)**

Ideally, total voltage induced in stator coils would appear on alternator's output terminals. In real, it is not possible. Induced voltage is produced in coils with a certain number of turns and with own magnetic field properties. They are represented by internal resistance and inductance respectively. They cause a voltage drop which makes the terminal voltage to be lower. The relationship between induced and terminal voltage can be computed as:

$$U_o = U_i - X_S I \tag{6.3}$$

Here $U_o$ is terminal voltage, $U_i$ is induced voltage, I is current flowing in circuit and $X_S$ represents a total synchronous impedance of machine. Equation (6.3) is the general formula of synchronous machine model taken from [19]. Graphical configuration can be seen below:

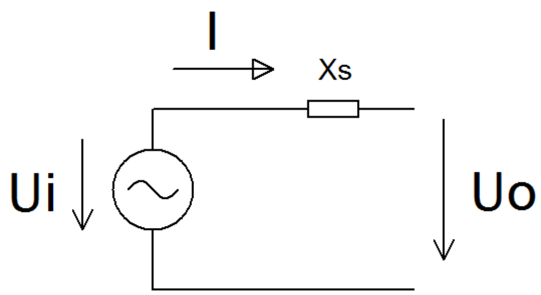


**Figure 6.2: Circuit model of synchronous alternator**

### 6.1.1 Design of coil parameters

A good choice of PMs and proper design of stator coils play an important role, and have a great impact on output voltage. Designer has to deal with this deep connection. Design stated in this paragraph has been used in both approaches.

In synchronous machine model, total synchronous impedance consists of inductive reactance $X_L$ and ohm resistance of stator winding *R*.

Since the electrical simulation is done in SimPowerSystems toolbox – modeling and simulation of electrical power systems – it computes the impedance itself while simulating. However, it is necessary to input inductance of coils L and resistance of winding R. These parameters are determined with a respect to coils geometry and connection.

From mechanical design (Chapter 4), the wire bundle of coil is 6 mm thick and the axial length is 4 mm. The surface of wires cross-section is then 24 mm$^2$. That has to be modified by coefficient of filling $C_f$ (in this electromechanical simulation 0.6). If *N* is the number of turns in a coil, the diameter $d_w$ of a wire is:

$$d_w = \sqrt{\frac{4C_f S_{bundle}}{\pi N}} \tag{6.4}$$

Number of turns in a coil is a parameter that directly influences the output voltage and can be computed by using Equation (6.1). It is good to realize that such calculation is estimation and can be regulated later in a process of simulation.

For instance, estimated number of turns $\widetilde{N}$ for producing the 5 V voltage of a coil, if rotor rotates with 1000 rpm in magnetic field of 0.2 T is then:

$$\widetilde{N} = \frac{U}{BL\omega r_m} = \frac{60.U}{BL2\pi n r_m} = 849 \tag{6.5}$$

Number of turns is related to both computations – coil inductance *L* and coil resistance *R*. In simulation, number of turns is changed as an output voltage optimization. However, in general it is said that the optimal current density of electric conductor is 3 A/mm$^2$. This fact will help as a limit.

Relationship for inductance of coil computation says:

$$L = \frac{\mu N^2 A}{l} \tag{6.6}$$

Here inductance depends on area of coil *A*, length of coil *l* (our axial length) and magnetic feature – permeability of environment $\mu$.

Resistance of coil depends on the length of wire $l_w$ used in coil and cross-section of wire $S_w$. In addition, as a constant value, the wire resistivity is entered to the equation as a parameter of certain conductor material.

$$R = \rho \frac{l_w}{S_w} \tag{6.7}$$

These are the basic parameters of coil that one has to take care of. They are calculated in MATLAB's m-file and sent to Simulink's simulation model. Beside these basic coil parameters, we have to think of the circuit connection. When connecting coils in parallel, the calculation similar to parallel resistor calculation is used [20]:

$$\frac{1}{L_{eq\_par}} = \frac{1}{L_1} + \frac{1}{L_2} + \cdots + \frac{1}{L_n} \tag{6.8}$$

Connection in series is computed as:

$$L_{eq\_ser} = L_1 + L_2 + \cdots + L_n \tag{6.9}$$

Hence, we can significantly change parameters of circuit by suitable choice of connection. Having seven equal coils of 9.7 mH, the equivalent inductance of series connection is 67.9 mH, while parallel connection presents around 1.4 mH. In addition, one is able to obtain results between these two values by suitable combination. Equivalent resistance is computed analogically.

### 6.1.2 Simulation of electromechanical device

For seeing how induced voltage in PM alternator is distributed, the model in Simulink with a help of SimPowerSystems toolbox has been created. Whole electromechanical simulation can be done as it was discussed in Chapter 2 when talking about wind turbines. Figure 6.3 shows how the model is built up. It contains Repeating sequence block which is fed by induced voltage pass calculated in MATLAB main script. Induced voltage is computed for a single coil. Since the connection of coils is in series, the value is gained by 7 (number of stator coils). Coils impedance is represented by ohmic-inductive component that is put behind induced voltage according to circuit model in Figure 6.2. Rectifier block is a subsystem consisting Schotky diodes and filter capacitor is placed for stabilization reasons.

Parameters computed for alternator and used in simulation are listed in Table 6.1 below.

| | |
|---|---|
| Number of turns | 25 |
| Diameter of wire | 0.85 mm |
| Wire corss-section | 0.57 mm$^2$ |
| Single coil inductance | 67.6 µH |
| Single coil resistance | 0.07 Ω |
| Schottky forward voltage | 0.3 V |
| Filter capacitance | 10 mF |

**Table 6.1: Simulation parameters**

In left upper corner of Simulink window, there is a block for graphical user interface. The type of simulation can be set here. For our purposes, the type can be set to “continuous”. However, when the simulation gets more complex the type has to be changed to “discrete” time simulation. It will make the simulation faster and less memory consuming.

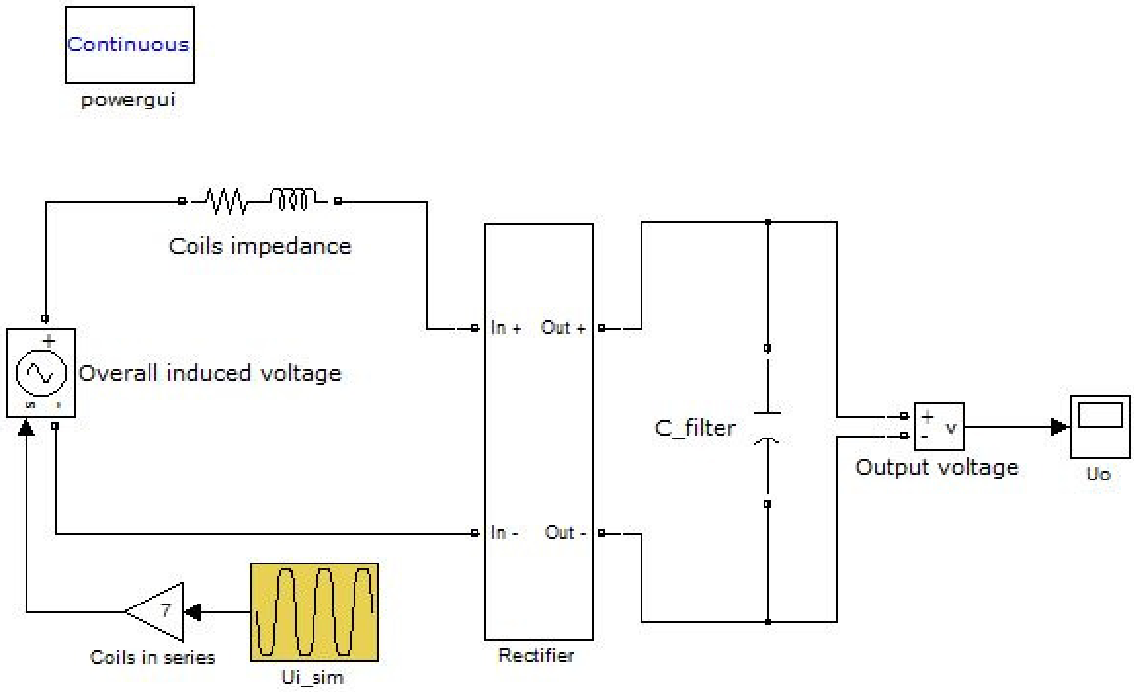


**Figure 6.3: Simulation model of electromechanical transformation (first approach)**

1000 resp. 8000 rpm state are considered as low or high limit of rpm, respectively. In Figure 6.4 below, there is shown voltage at both rpm limits. Output voltage then moves between 0.8 V and 11 V in steady-state. This is quite comfortable range of output voltages for further distribution.

However, the simulation brings several troubles that have to be solved. The amount of current in wires deals with its diameter. In general it is well-known that acceptable current density through the wire is 3 A/mm$^2$. Current in low rpm is not such significant as in the highest limit. At 8000 rpm and with set of mentioned simulation parameters, current impulse reaches 4.74 A. Such current is destructive for wire cross-section of 0.57 mm$^2$.

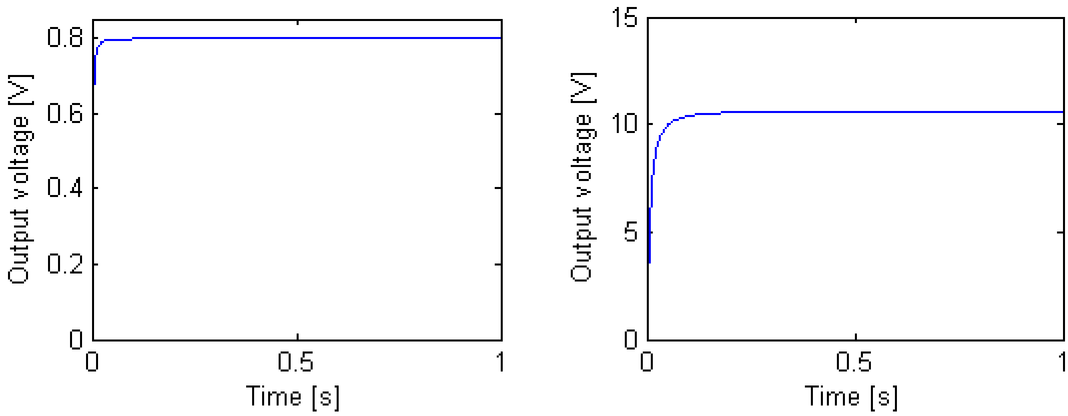


**Figure 6.4: Output voltage at 1000 (left) and 8000 rpm (right)**

In design, many iteration cycles were used to reach sufficient results. First of all, the largest request is asked for output voltage. It should be designed so that we can adjust it by other electronic components as DC-DC converters. Beside the output voltage adjustment, designer has to watch the induced voltage. If there is non-acceptable loss in impedance, the quality of inductive impedance must be changed (most often by the number of turns). Current through the coils can be additionally influenced by the exchange of magnets for weaker or stronger ones.

The pass of induced voltage looks as in Figure 6.5 and 6.6. High rpm state causes voltage of 11.2 V, while in the output there is voltage of 10.7 V. It means that around 0.5 V disappears in inner impedance of alternator. Such loss is not significant, voltage disappears in alternator's inductive impedance.

Inductive impedance is an important part of design. It depends on frequency of voltage signal. The higher is the rotational frequency, the greater is the impact on total inner impedance.

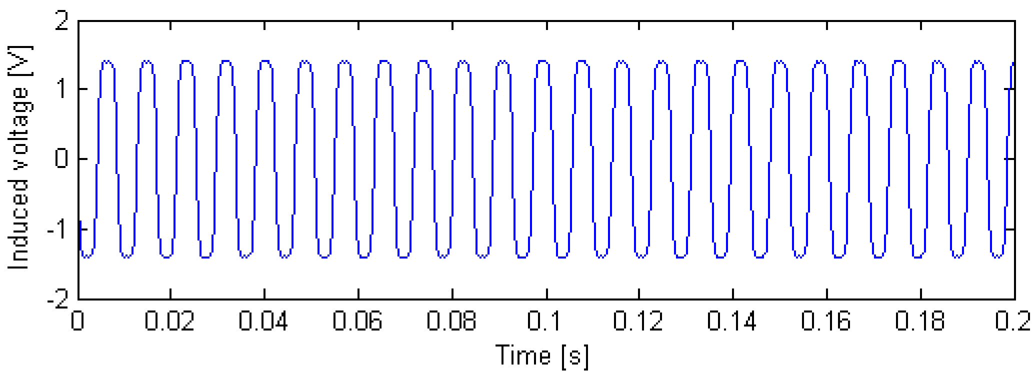


**Figure 6.5: Induced voltage at 1000 rpm**

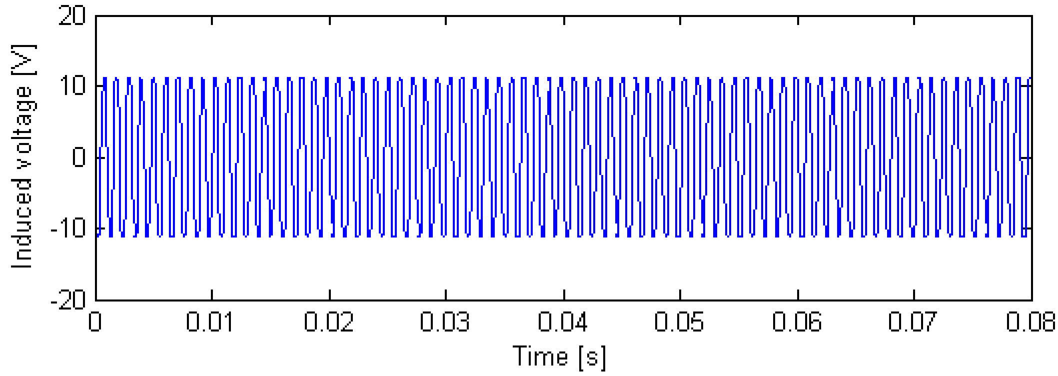


**Figure 6.6: Induced voltage at 8000 rpm**

## 6.2 Second approach

In fact, obtained magnetic data from ANSYS represent function *Bx(x)*, where *Bx* is a magnetic flux density in axial direction and *x* means arc length computed as:

$$x = r_m \varphi \quad (4.2)$$

$\varphi$ is a rotational distance and $r_m$ is a middle radius (it says about placing the magnets).

As it was said in Chapter 2, a voltage through a coil is induced when a magnetic flux changes in time. Assuming a single coil and rotating rotor we get time-variable magnetic field. Induced voltage can then be calculated as:

$$U_i = -\frac{d\Phi(\mathrm{x})}{dt} = -S\frac{d\mathrm{B}(\mathrm{x})}{dt} \quad (4.3)$$

Equation (4.3) above determines induced voltage when the coil cross-section S is constant (as in our case). In this relationship, it can be seen that although magnetic flux intensity depends on arc length it comes through a time derivative. That means magnetic flux intensity has to be determined as a function of time.

Mechanical output of combustion engine is represented by rpm. Rpm state is then input for electromechanical system. Figure 6.7 represents mathematical computation of induced voltage by using Equation (4.3). The principle of repeating sequence block is used. Look-up table has the role to assemble the signal *B(x)* into continuous time signal. This signal is then gained by the number of turns *N* and active magnetic flux area *S*. Finally, time derivative block processes the output signal. That is shown in figures below. Induced voltage is calculated with *N* turns per one coil. Simulation was performed with same parameters as in first approach (see Table 6.1). Figure 6.8 and 6.9 shows output signal of 7 coils in series. Again, induced voltage at both rpm limits is presented.

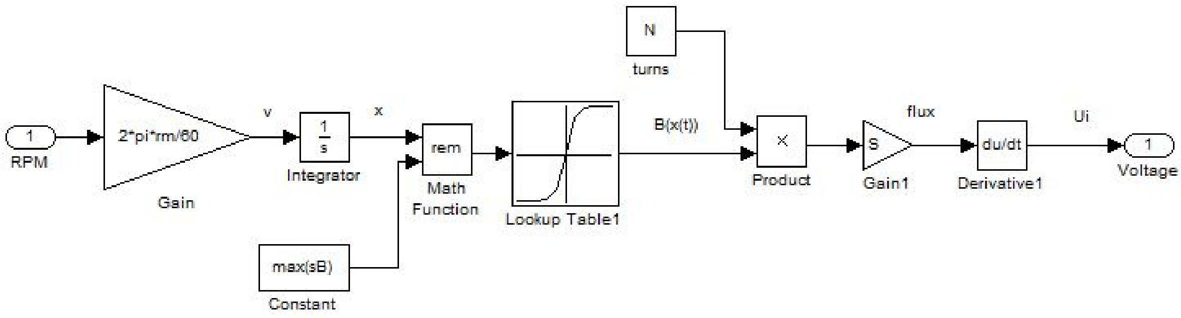


**Figure 6.7: Simulink model of electromechanical system**

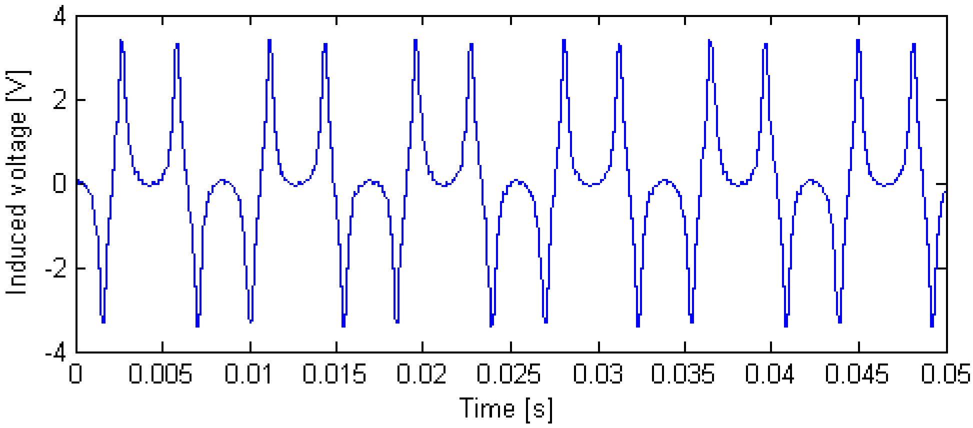


**Figure 6.8: Induced voltage by using second approach at 1000 rpm**

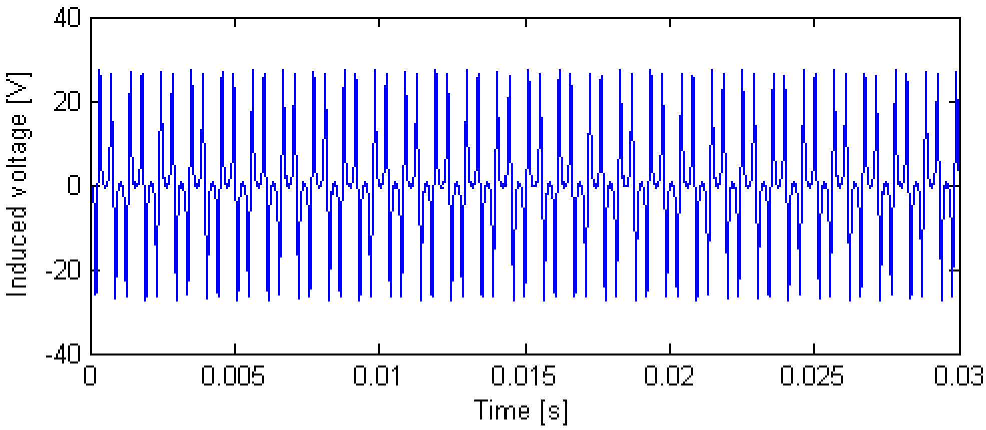


**Figure 6.9: Induced voltage by using second approach at 8000 rpm**

As the rotational frequency changes, the signal frequency and amplitude change too. Pictures above represent derivative in specified time. Main simulation model looks as the one studied in first approach. However, for the complete and brief view, the model of second approach is depicted in Figure 6.10. After passing the rectifier and filter capacitance, the voltage has the shape as in Figure 6.11. There are two passes: output voltage at low limit of 1000 rpm (on the left) and output voltage at high limit of 8000 rpm (on the right).

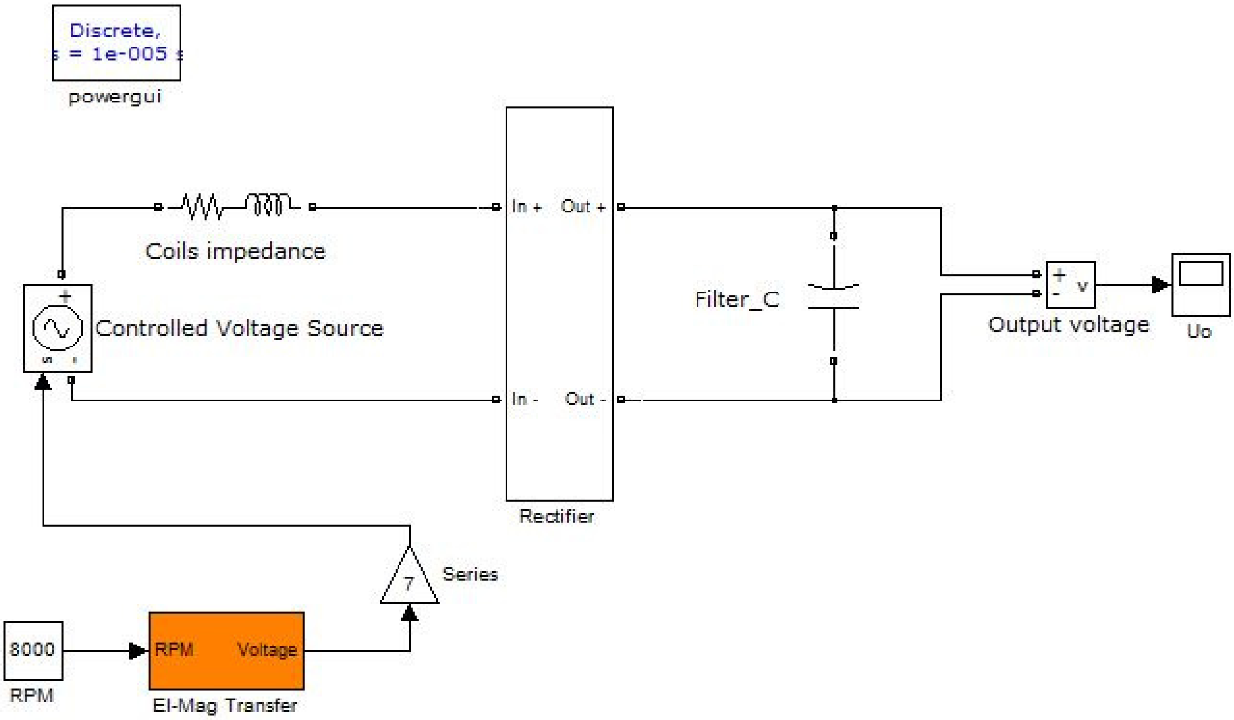


**Figure 6.10: Simulation model of electromechanical transformation (second approach)**

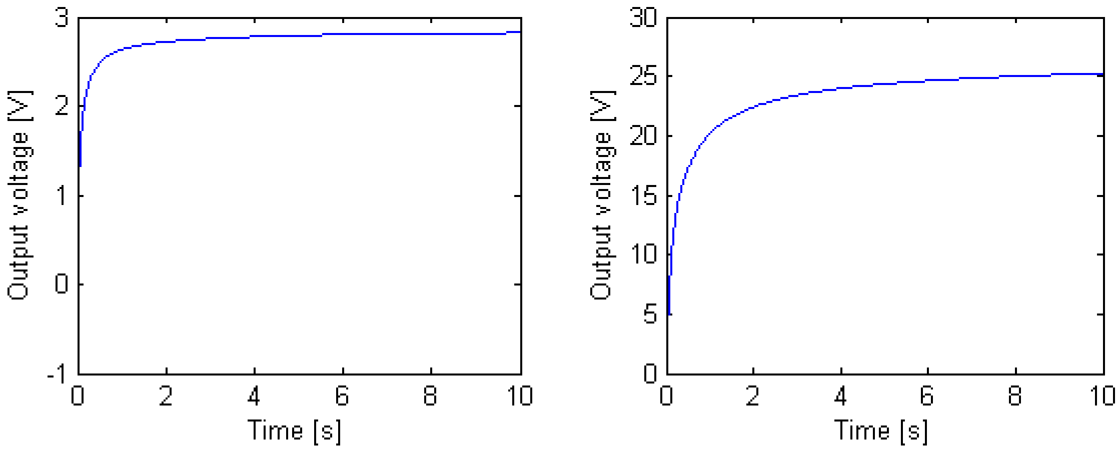


**Figure 6.11: Output voltage of alternator with no load**

Now, as the alternator satisfies the task of good efficiency, the power can be processed further. As a result, simulation model using second approach is assumed since the model is more complex and justifies the overall mechatronic system model.

# Chapter 7

# Simulation modeling of electronic circuit

After electromechanical transformation, the alternator is able to supply certain voltage. This voltage is just a proportional reaction to rotation of prop. If one wants to get the maximum at this state, he has to process the output power in a proper way. Chapter 7 deals with this problem.

## 7.1 Rectifier

In previous chapter, the model of electromechanical transformation contained a subsystem block called ‘Rectifier’. This block has not been discussed yet, because it is the part of electronic circuit.

Rectifier is actually the full-wave bridge studied in Chapter 2. It consists of four diodes placed according to model in Figure 2.10. Subsystem of SimPowerSystems toolbox is shown in Figure 7.1.

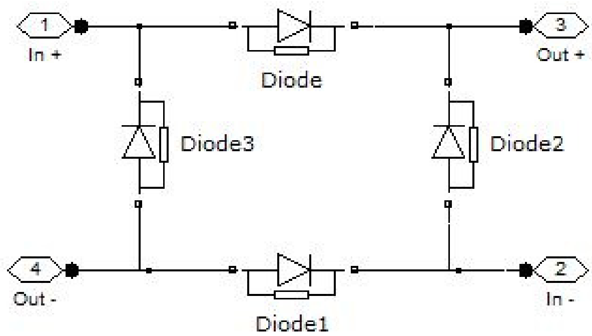


**Figure 7.1: SimPowerSystems subsystem for rectifier**

It might be important to emphasize, this subsystem model does not respect the placing ‘IN ports’ and ‘OUT ports’ as in the main model. However, the position is exchanged. One has to pay an attention which wire is the input and which represents the output.

When talking about a choice of diodes, Schottky diodes were preferred since they have lower forward voltage and better qualities for this application. Normal diodes have voltage drop around 0.6-1.7 V while Schottky diodes reduce a voltage drop to around 0.3 V. In addition, lower voltage also causes higher switching frequency and better system efficiency. On the other hand, Schottky diodes bring several limitations too. [21] A low voltage drop is concerned with low reverse voltage. Often, this value is around 50 V.

STPS2L40U diode was chosen according to available options from [22]. Table 7.1 contains the basic parameters.

| | | |
|---|---|---|
| Reverse voltage | $U_{rrm}$ | 40 V |
| Forward current | $I_f$ | 2 A |
| Forward voltage drop | $U_{fm}$ | 0.34 V |
| Surge non repetitive forward current | $I_{fsm}$ | 75 A |
| Bush | - | SMB |
| Prize | | 8.2 CZK |

**Table 7.1: STPS2L40U Schottky diode parameters**

## 7.2 Current limiter

In process of electromechanical transformation (Chapter 6), the main focus was concentrated on transfer of induced voltage to alternator terminals and power efficiency. However, for the operational reasons is important to watch coil currents too. After placing ammeter to model in Figure 6.10, the initial current of 3.3 A has been detected. Impulse of current is short, it takes approximately 0.02 s (see Figure 7.2). However, since the optimal current density is 3 A/mm$^2$ and wires used in application have cross-section of around 0.6 mm$^2$, the maximum current flow through stator coils should be 1.8 A. For this reason, the current limiter was designed.

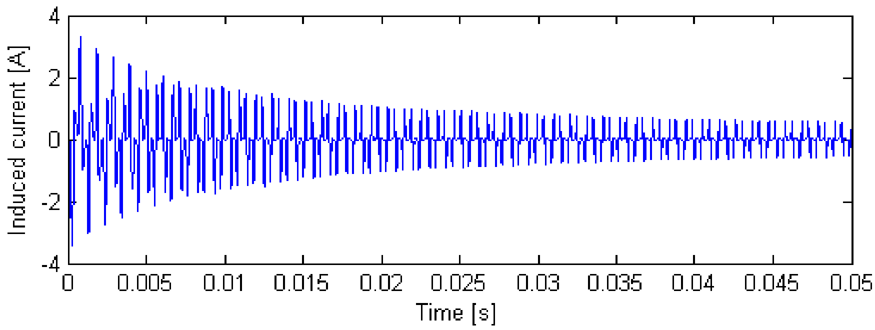


**Figure 7.2: Current flow through coils**

Circuit diagram of current limiter is shown in Figure 7.3. It is not necessary that limiter is not available as single electronic component. It can be easily constructed.

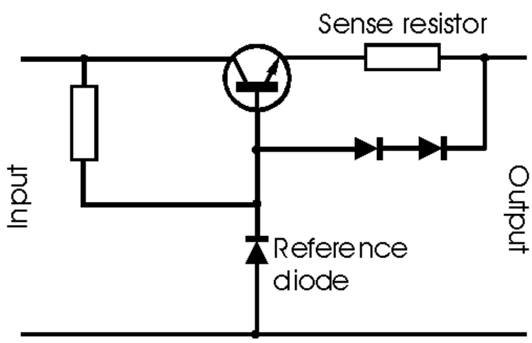


**Figure 7.3: Circuit diagram of current limiter [22]**

According to this diagram taken from [22], the simulation model in Simulink SimPowerSystems was built. Chosen parameters are stated in Table 7.2 below. System was simulated in cycles by changing the values in order to set optimal ones. Again Schottky diodes were chosen as they provide the most comfortable results. Thank to its switching properties and wide utilization, MOSFET transistor was chosen. Resistor qualities were adjusted in order to eliminate large current flows.

| | |
|---|---|
| MOSFET forward voltage | 4V |
| Schotky diode forward voltage | 0.34 V |
| Sense resistor | 1000 kΩ |
| Parallel resistor | 20 Ω |

**Table 7.2: Parameters of current limiter**

The SimPowerSystems model and pass of current modified by limiter are pictured below. Although limiter deletes large current in the beginning, it vertically shifts the pass and current reaches 1.05 A during whole simulation. Previously, after reaching steady-state, induced current was around 54 mA in ripples. That means that limiter brings beside its positive effect some disadvantages. Anyways, the danger of large current impulse disappears by using current limiter.

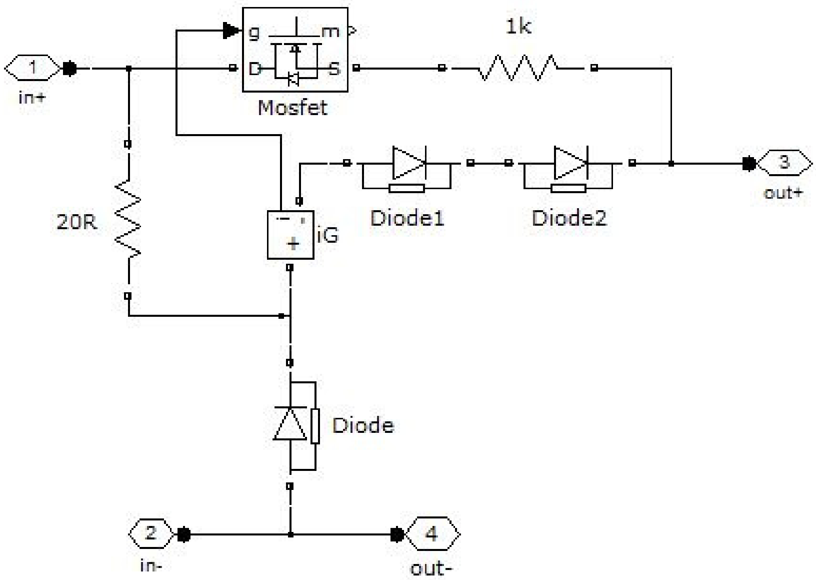


**Figure 7.4: Simulation model of current limiter**

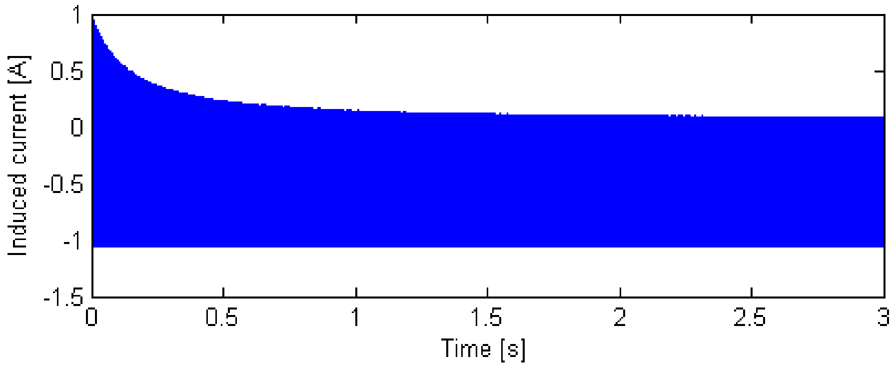


**Figure 7.5: Coil current after using current limiter**

From the other point of view, current of 3.3 A is obtained only in the beginning of process and by using of constant rpm state. In real, this is not possible since combustion engine has its own starting. In other words, it takes a time till the engine gives constant rpm at upper limit and final pass has shape of a slope. In this case, there is no need for current limiter.

## 7.3 DC-DC converter

As the combustion engine works, the rpm state changes and voltage on the output varies too. The aim of alternator is to provide a constant voltage supply. This can be achieved by using a suitable DC-DC converter.

From Figure 6.11 is clear that output voltage moves between approximately 2.7 and 25 V. Servomotors are supplied from 4.8 V battery packs. Assuming the charging of batteries or supercapacitor, output voltage of DC-DC converter should be a bit higher (5V). Hence, the best solution would be to use a converter that is able to work both ways – to increase the input voltage (boost converter) and to decrease it (buck converter). Such converter is called buck-boost converter. The only negative of this converter is that it inverts the polarity of output. There are many other non-inverting topologies but to simplify this task, we will transform alternator voltage and use simple buck converter.

To amplify the voltage, an ideal linear transformer from SimPowerSystems was used. The amplification coefficient $K$ was set to 2.5 so that we obtain the range of 5.5 – 62 V. This voltage is then decreased to desired 5 V.

A short study of DC-DC converters is stated in Chapter 2. In Figure 2.12, one can see the diagram of buck converter. It can be redrawn by using an ideal switch (Figure 7.6).

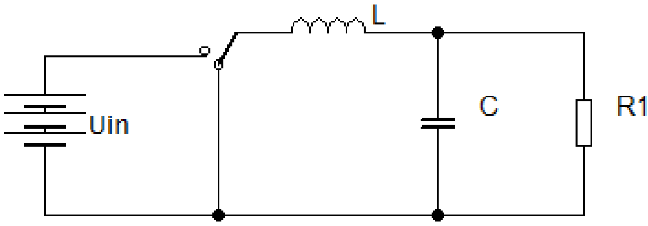


**Figure 7.6: Diagram of buck converter (ideal switch)**

As the switch works, diagram changes into two sub-diagrams representing ‘ON’ and ‘OFF’ status. These states are shown in Figure 7.7.

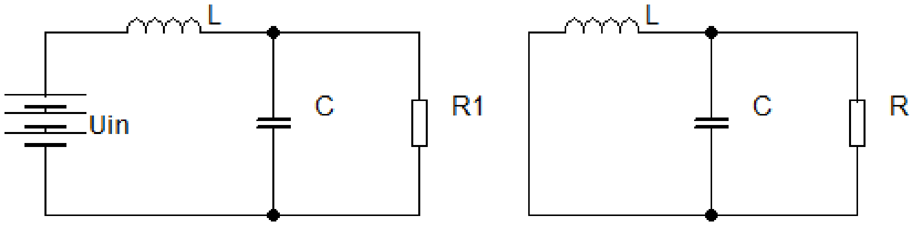


**Figure 7.7: ‘On’ diagram (left) and ‘off’ diagram (right)**

The main idea of converter is to change input voltage by regulating the switching frequency. Each state is represented by own equations for inductor voltage and capacitor current. Assuming internal resistances of capacitor and inductor, we get equations below [23].

‘On’ state:

$$C\frac{du_C}{dt} = i_L - \frac{U_o}{R_C} - i_0 \tag{7.1}$$

$$U_o = u_C + C\frac{du_C}{dt}R_C \tag{7.2}$$

$$L\frac{di_L}{dt} = U_{in} - U_o - R_L i_L \tag{7.3}$$

‘Off’ state:

$$C\frac{du_C}{dt} = i_L - \frac{U_o}{R_C} - i_0 \tag{7.4}$$

$$U_o = u_C + C\frac{du_C}{dt}R_C \tag{7.5}$$

$$L\frac{di_L}{dt} = -U_o - R_L i_L \tag{7.6}$$

These equations were implemented in Simulink. Simulation Equations (7.3) and (7.6) differ only in input voltage. It is represented by switching between input voltage and zero (see Figure 7.8). Parameters of buck converter are listed in Table 7.3.

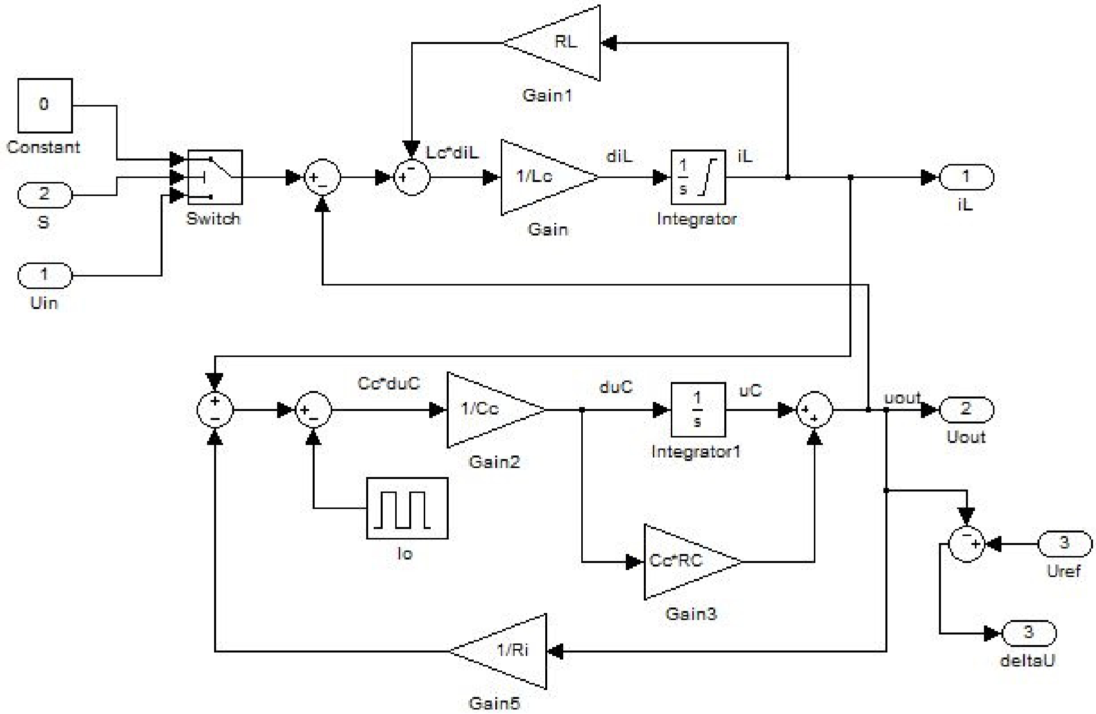


**Figure 7.8: Simulink implementation of used buck converter**

| | |
|---|---|
| Coil inductance *Lc* | 1.7 mH |
| Capacitor *Cc* | 200 μF |
| Coil resistance *RL* | 0.095 Ω |
| Capacitor resistance *RC* | 0.17 Ω |
| Load resistance *Ri* | 10 Ω |

**Table 7.3: Buck converter parameters**

Switching frequency is controlled by pulse width modulation (PWM). Buck converter in Figure 7.8 is a subsystem with three inputs and three outputs. Input and output with the number of 3 represent reference voltage and voltage error respectively. The difference between output voltage and reference voltage is the input for PWM controller. The duty of such controller is to modify the switching according to voltage error. PWM PI controller was built according to [24]. PWM PI subsystem is depicted below.

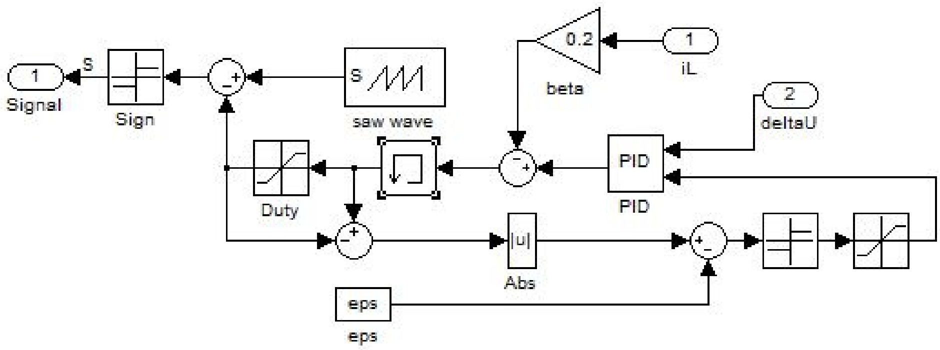


**Figure 7.9: PWM PI controller Simulink implementation**

Parameters of PI regulator and $\beta$ coefficient (represents influence of inductive current) were chosen after iterative simulation and are presented in Table 7.4.

| | |
|---|---|
| Proportional $K_p$ | 7 |
| Integral $K_i$ | 300 |
| Coefficient $\beta$ | 0.2 |
| Switching frequency $F_s$ | 100 kHz |

**Table 7.4: Parameters of PWM PI controller**

Model of closed-loop buck converter placed in system is in Figure 7.10.

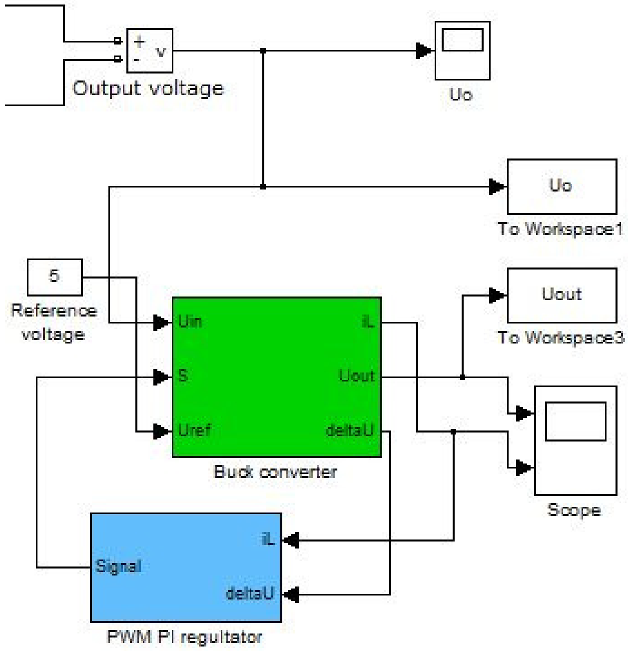


**Figure 7.10: Buck converter with closed-loop**

Finally, the results after passing the voltage through buck converter are stated below. Speed of simulation significantly depends on switching frequency. In addition, the memory of simulation machine did not allow longer simulation times. Hence, the simulation is executed in time interval of 0.4 s. In Figure 7.11, there is a comparison of alternator output voltage and output voltage of converter for 1000 rpm limit. Next picture shows the same for the higher limit of 8000 rpm.

Distortion of output is not significant. Detailed zoom of distortion at 8000 rpm is shown in Figure 7.13.

Reaction of systems on more variable inputs of rpm state is stated in appendices.

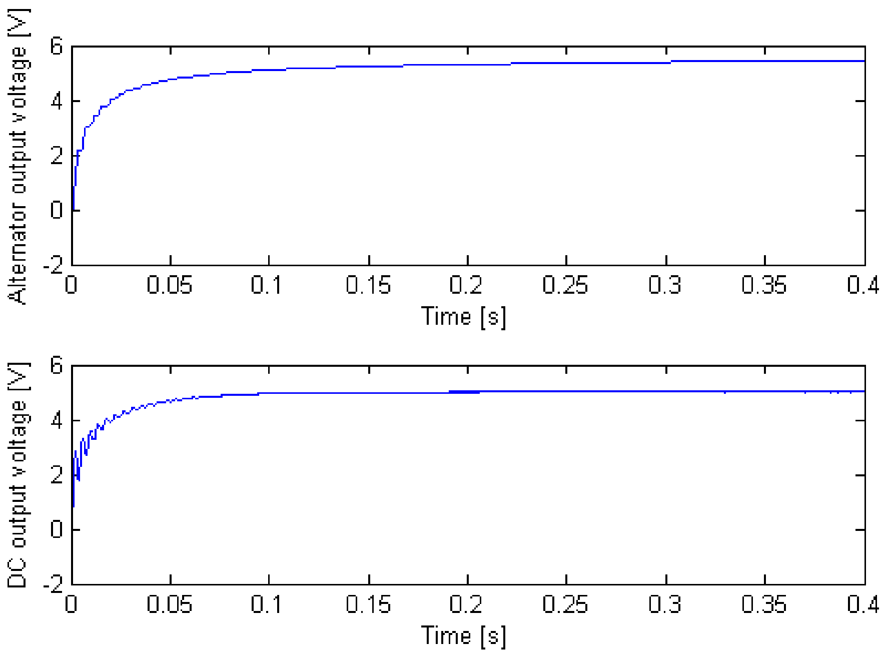


**Figure 7.11: Work of DC-DC buck converter (1000 rpm)**

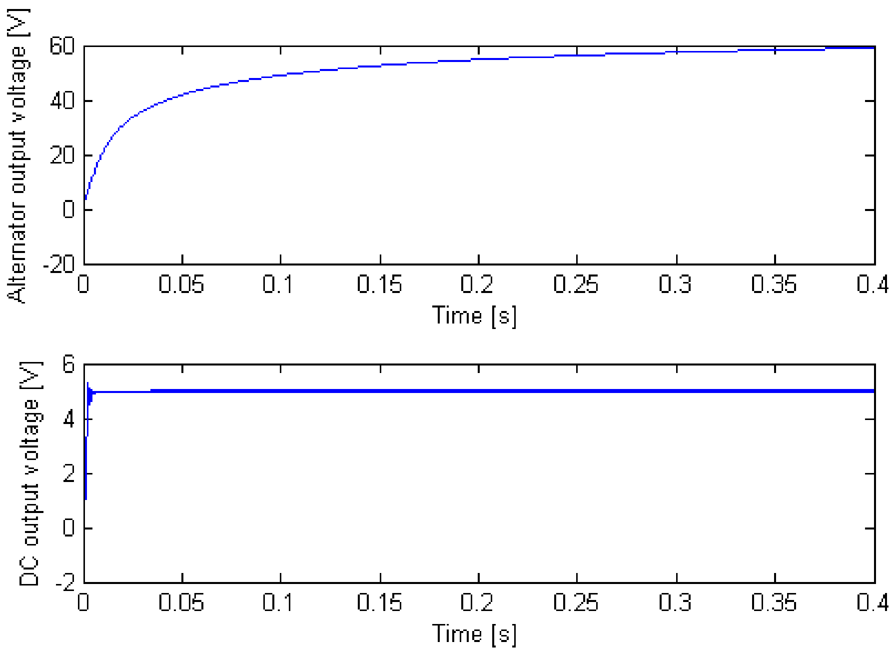


**Figure 7.12: Work of DC-DC buck converter (8000 rpm)**

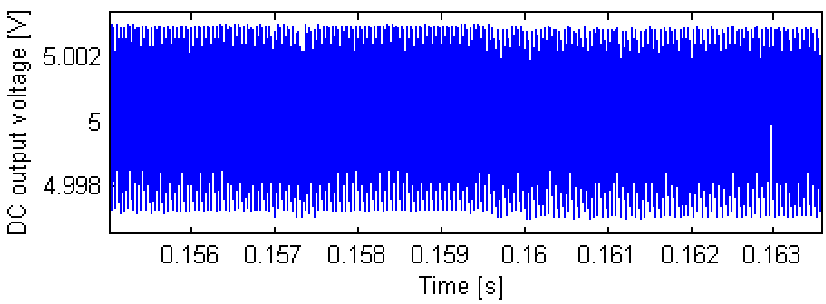


**Figure 7.13: Distortion of converter output**

# Chapter 8

# Conclusion

This work was concerned with the design of electromechanical device able to replace previously used batteries. Chosen device is alternator equipped with rectifier and DC-DC converter (in some cases with the current limiter). In the air, this makes batteries fully replaceable by this device. Hence, the aim has been satisfied however there are still some matters that can be improved in the future.

Here is the list of significant outputs:

- Alternator supplies RC aircraft by constant voltage of 5 V obtained by the transformation of mechanical power. Therefore, it avoids the need for landing and exchange the battery packs.
- According to SolidWorks physical properties of alternator assembly, the weight of whole alternator is almost 300 g. Additionally, there comes the weight of electronics. Expected weight then should be under 400 g.
- Prize of the system depends on production of alternator parts and availability of electronic components. However, overall prize should not be high and the system is affordable.

Although this thesis does not provide the ready product, it studies and simulates all aspects that designer might meet. In the design, various software environments solving their own area were used:

- Mechanical aspect: SolidWorks, ANSYS Workbench
- Magnetic aspect: ANSYS Mechanical APDL with electromagnetic analysis
- Mathematical aspect: MATLAB/Simulink
- Electrical aspect: Simulink/SimPowerSystems toolbox

Time allowed for solution of this task does not permit to solve several matters. Resultant system model consists of physical (SimPowerSystems) and mathematical (Simulink) part. Next step might be the development of complete physical model. In addition, to transform the induced voltage more efficiently, a non-inverting buck-boost converter instead of linear transformer and buck converter can be used. Finally, to store the generated power either a supercapacitor or one of the secondary cell batteries can be added to the circuit.

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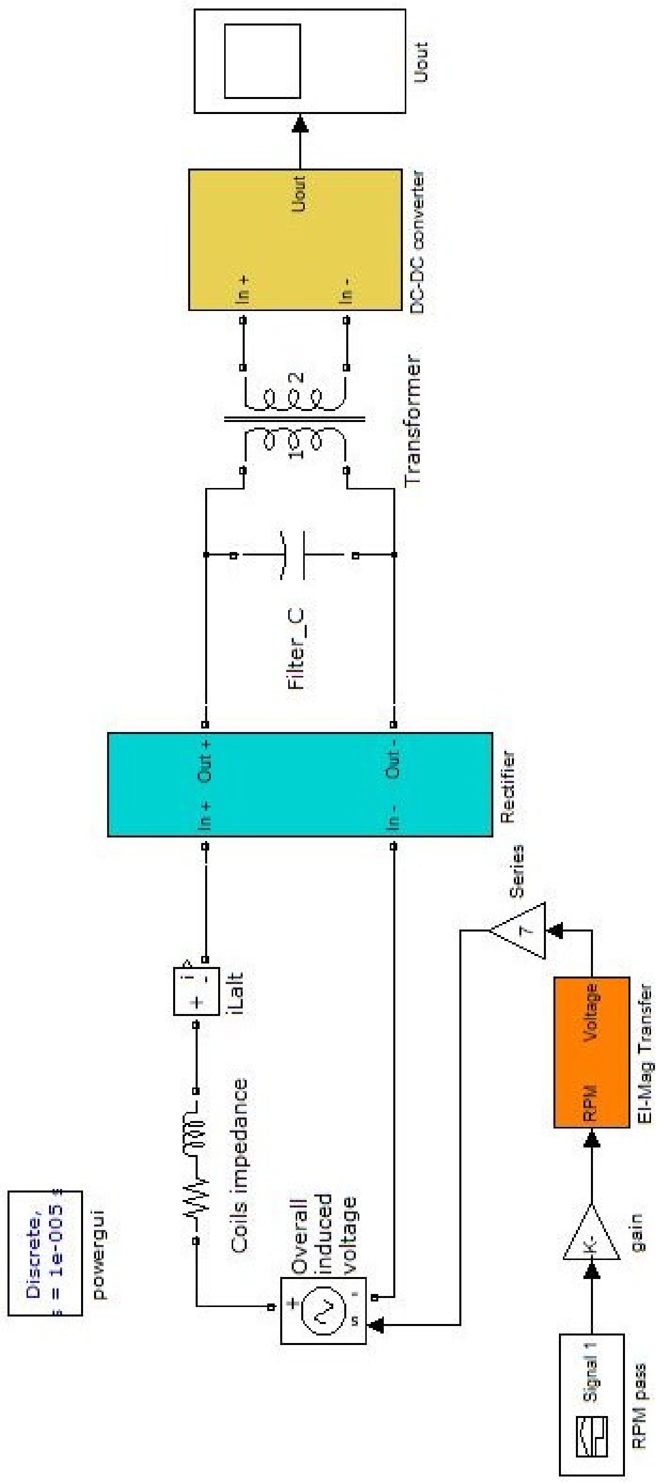
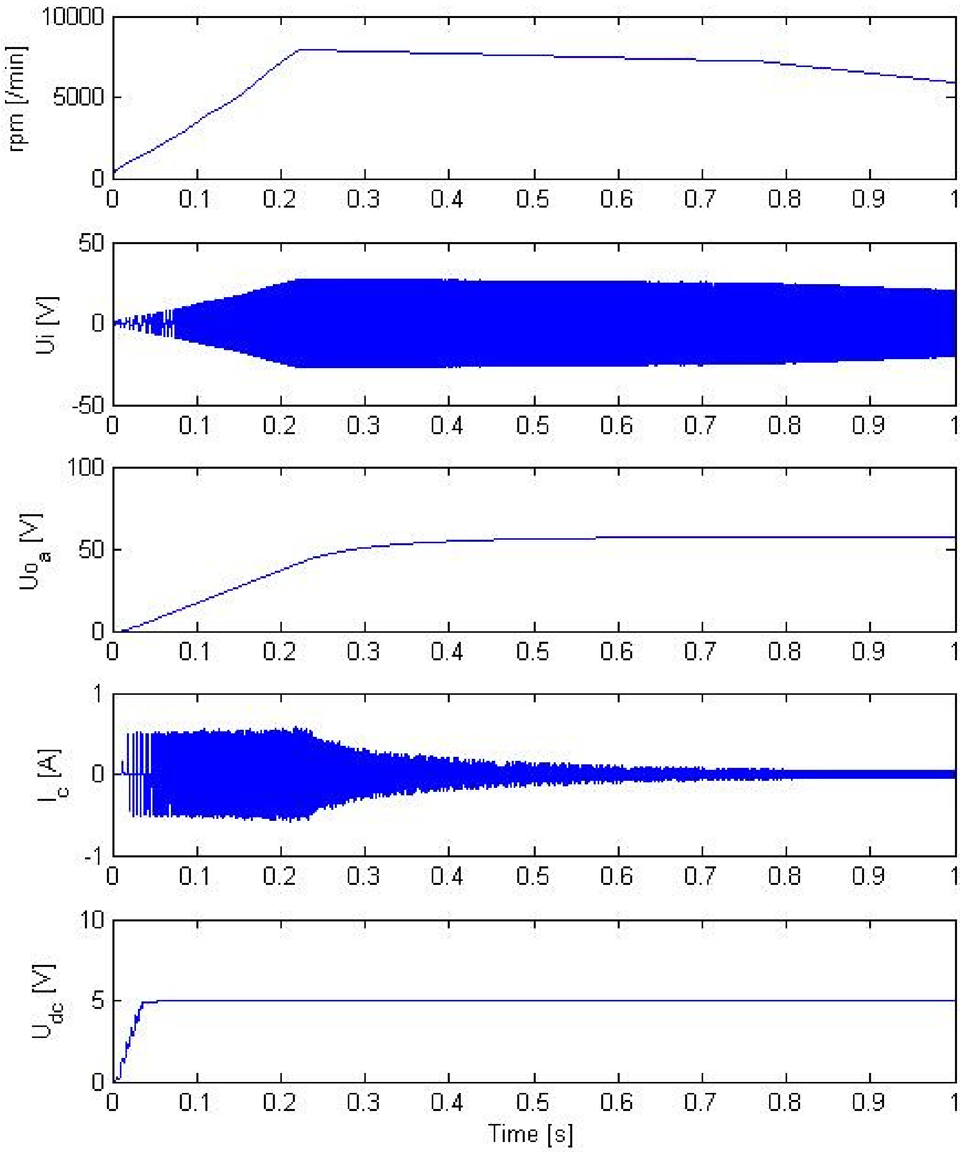
# Appendix A




**Appendix A: Final simulation model in Simulink/SimPowerSystems**

# Appendix B




**Appendix B: Behavior of system in respect to variable input of rpm state.**

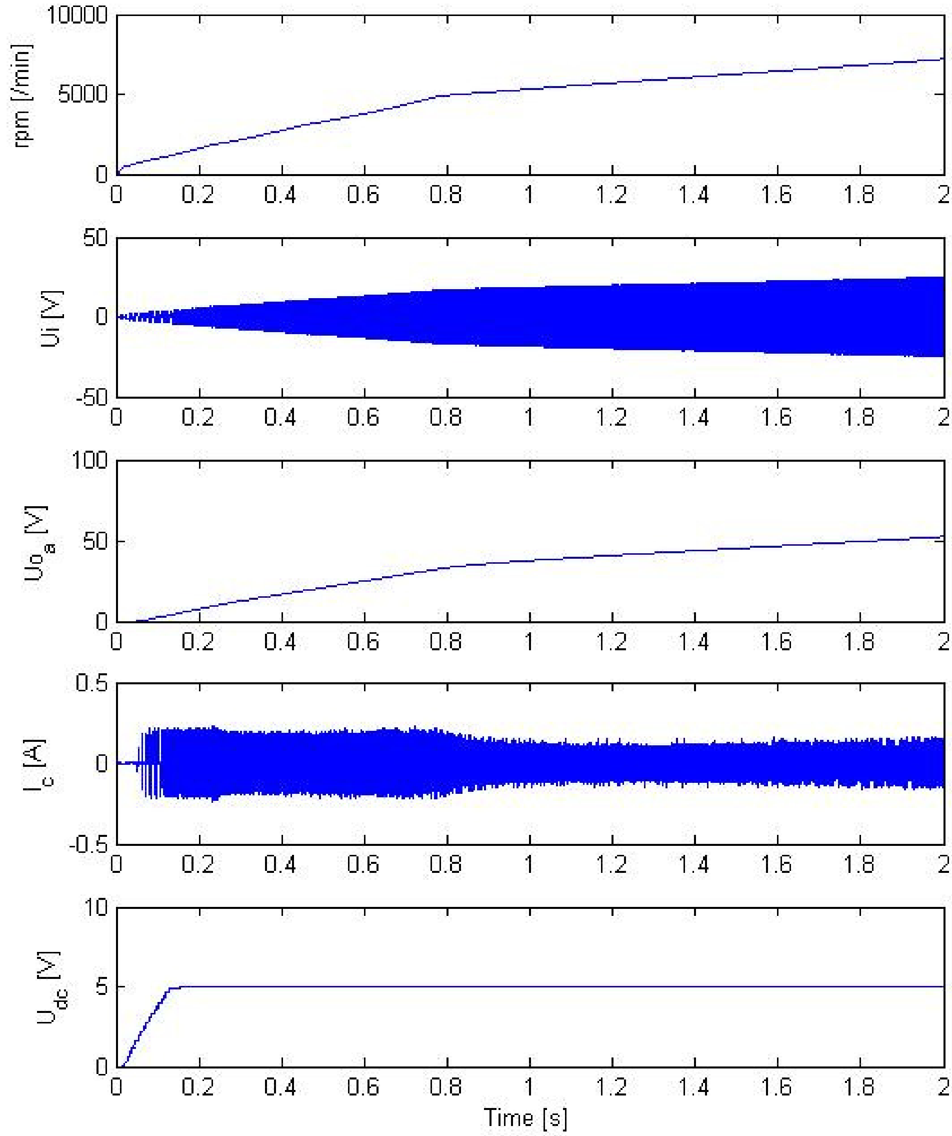
$U_i$ = induced voltage,

$Uo_a$ = output voltage of alternator,

$I_c$ = current through alternator coils,

$U_{dc}$ = DC output voltage

# Appendix C




**Appendix C: Behavior of system in respect to variable input of rpm state.**

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$U_{dc}$ = DC output voltage