Lappeenranta University of Technology
School of Energy Systems
Master’s Degree Programme in Electrical Engineering

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DESIGN OF A POWER-ELECTRONIC PROTECTION DEVICE FOR A DIRECT-ON-LINE BRUSHLESS EXCITATION SYNCHRONOUS MACHINE

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ABSTRACT

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Design of a power-electronic protection device for a direct-on-line brushless excitation synchronous machine

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The graduation paper deals with a design of an overvoltage protection device for a synchronous machine with brushless excitation. The synchronous machine system comprises a 5 MVA salient-pole main synchronous motor, an outer-pole synchronous auxiliary excitation machine and a rotating diode bridge, placed on the shaft.

The main goal is to produce a reliable, autonomous and efficient overvoltage protection device that protects both the field winding of the main machine and the rotating diode bridge from excessive voltage induced in the field winding of the main machine during Direct On Line (DOL) start.

The main method of the design is modelling and simulation of the main synchronous machine, protection device and their interaction in MatLab Simulink computing environment.

As a result, a parametrized model for an overvoltage protection device is produced and its proper functioning is proven to sufficient degree. The model is simplified at some degree and a number of issues remain unsolved, such as gate circuitry and discretization issues.

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Lappeenranta, June 2019 Aleksei Antoniuk

Abbreviations. denotations and symbols

AC — Alternating Current

DC — Direct Current

EMF — Electromotive force

DOL — Direct On Line

EESM — Electrically Excited Synchronous Machine

In this particular paper, a number of expressions are approximately interchangeable:

Excitation winding ≈ Field winding

F	Force, N
Q	Charge, C
v	Velocity, m/s
B	magnetic flux density, T
l	Length, m
i	Electric current, A
t	Time, s
e	Electromotive force, V
Ψ (or ψ)	Magnetic flux linkage, Vs
U	Voltage, V
ω	Angular velocity, rad/s
Ω	Mechanical velocity, rad/s or rpm
p	Number of pole pairs
s	Slip
r	Radius, m
f	Frequency, Hz
Z	Impedance, Ω
S	Apparent power, VA
T	Torque, Nm
R	Resistance, Ohm
L	Inductance, H
J	Inertia, kgm^2
k_r	Reduction factor
θ_r	Rotor position angle, rad

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1. INTRODUCTION

The whole system of electrical energy generation is still strongly based on rotating electrical machines. Synchronous generators are a primary supply of the world's electrical energy. On the other hand, synchronous motors are widely used in high power and/or precision demanding applications. Thus, development of this machine type is very important. In this paper, overvoltage protection of the field winding of a high-power brushless excitation synchronous machine with Direct On Line (DOL) starting is considered.

A DOL synchronous motor is turned on by supplying full mains three-phase voltage to its stator winding. This voltage generates an EMF in both damper and field windings in the rotor. This induced AC voltage can be very high for a short period of time when the rotor speed is low. Since in brushless excitation the main machine field winding is fed via a rectifier, mounted on a rotating shaft, the induced AC voltage threatens the insulation integrity and the semiconductors of the rectifiers by applying a high reverse biasing voltage to them. For this reason, an overvoltage protection device is designed.

The need of this particular design is industry originated. Above all, higher efficiency and intelligence is desired for this device.

The goal of this paper is to design an overvoltage protection device for a Direct-On-Line brushless excitation synchronous machine system.

The following objectives are formulated:

1. Investigate the process of excessive voltages emergence during DOL start of a brushless synchronous machine;
2. Consider the features and requirements for an overvoltage protection device followed by a design proposition;
3. Model and simulate the system, comprising both synchronous machine and overvoltage protection device, using the tools of MatLab Simulink environment.

1.1 Introduction to synchronous machine

Synchronous machine is one of two fundamental types of AC machines, along with asynchronous machine (or induction motor). Both of them utilize a rotating magnetic field to convert electrical energy into mechanical energy or vice versa. In these machines, rotating magnetic field is produced by feeding a spatially distributed windings inside the machine with, usually, a three-phase current system, or, rotating a source of the magnetic field inside the machine. The main difference between the asynchronous machine and synchronous machine, as the names suggest, is that the rotor of a synchronous machine rotates synchronously with the common magnetic field, while the rotor of an asynchronous machine either lags or leads it.

In steady-state motoring mode, a synchronous motor rotor rotates synchronously with the common magnetic field, created by the machine’s stationary part called stator, or armature and the rotor. In a normal inner rotor assembly, there is a three-phase winding in the external stator, inserted in stator slots, located on the inner surface of the armature. This winding, when fed by a three-phase voltage system, creates a rotating magnetic field. In turn, the rotor interacts with this field, creating torque. Unlike an asynchronous machine, in a synchronous machine the rotor is excited separately, not by the same three-phase voltage system, connected to the stator. The rotating part of the machine, called rotor, can be implemented in several different basic ways: as a cylindrical non-salient-pole rotor, as a salient-pole rotor with electrically excited magnetic poles, as a synchronous reluctance machine rotor that utilizes reluctance torque, or as a permanent magnet rotor, in which the rotor current linkage is created by permanent magnets.

In generator mode, the share of the magnetic field created by the rotor using one of the ways, mentioned above, the machine is driven by an external torque, applied to the shaft, that in turn has the rotor active parts attached on it. Thus, a magnetic field, rotating inside the machine, is created. This field induces voltages in the three-phase stator winding and, if the outputs of the stator winding are connected to a load, currents start to flow. The frequency of this voltage is strictly defined by the rotating speed of the rotor and the number of poles of the machine. This voltage is AC and can be easily distributed using transformers.

Some of the advantages, that make AC machines ubiquitously used, are:

1) AC machines manufactured for higher power ratings, can be made smaller and lighter than DC machines. This leads to lower material expenses;
2) They are usually more reliable and require less maintenance than DC machines;

3) AC machines can operate with widely varying loads, maintaining their constant speed and stable torque because of their stiff speed-toque curve;
4) They operate more easily at higher speeds (over 3000 or 3600 rpm) while DC machine's speed may be limited by commutator and brushes mechanical endurance;
5) Speed-controlled AC drives require a lower amount of apparent power at start than a drive, based on direct current machine and thyristor bridge. Though, this is correct for speed-controlled drives, not for Direct-On-Line drives. which are considered in this paper;
6) A feature of regenerative braking, provided by alternating current machines, is extremely relevant in electric vehicles today, as well as in other applications.

Moreover, synchronous machines particularly:

1) Can provide precise constant speed;
2) Can have extremely high efficiency (up to 99% in large machines);
3) Can deliver active as well as reactive power (controllable power factor), providing reactive power correction in the grid.

Nevertheless, some difficulties relate to synchronous machine application, for example:

1) AC machines usually require more complicated speed and torque control algorithms and equipment;
2) According to Minnesota Electric Technology (2016), Inc., "DC technology is more cost effective than AC in general for lower horsepower applications" (Why use DC motors instead of AC motors?, para. 3)

The ability of motors to convert electrical energy into mechanical energy is based on the interaction between magnetic field and electric currents. The Lorentz force equation can be expressed verbally as follows. A force d$\boldsymbol{F}$ acts on a charge dQ moving at velocity $\boldsymbol{v}$ through a current-carrying conductor of length d$\boldsymbol{l}$ subjected to a magnetic flux density $\boldsymbol{B}$. In equation form (Pyrhönen et al., 2016, p. 19),

$$\mathrm{d}\boldsymbol{F} = \mathrm{d}Q\boldsymbol{v} \times \boldsymbol{B} = \mathrm{d}Q\frac{\mathrm{d}\boldsymbol{l}}{\mathrm{d}t} \times \boldsymbol{B} = \frac{\mathrm{d}Q}{\mathrm{d}t}\mathrm{d}\boldsymbol{l} \times \boldsymbol{B} = i\mathrm{d}\boldsymbol{l} \times \boldsymbol{B} \tag{1.1}$$

On the other hand, generators can convert mechanical energy into electrical energy according to Faraday's law of induction. It states that "the electromotive force around a closed path is equal to the negative of the time rate of change of the magnetic flux enclosed by the path". In simple words, a changing magnetic field induces an EMF across a conductor. This EMF is given by the rate of change of the magnetic flux (Wikipedia, 2019, Faraday's law of induction, para. 2):

$$e = -\frac{\mathrm{d}\Psi_{\mathrm{B}}}{\mathrm{d}t} \tag{1.2}$$

where e is the electromotive force (EMF) and Ψ_{B} is the magnetic flux linkage.

There are a lot of types of synchronous machines, but in this paper, taking into account the system under consideration, we devote our attention to salient pole electrically excited synchronous machine. This machine is illustrated schematically with vector diagrams on Figure 1.1.

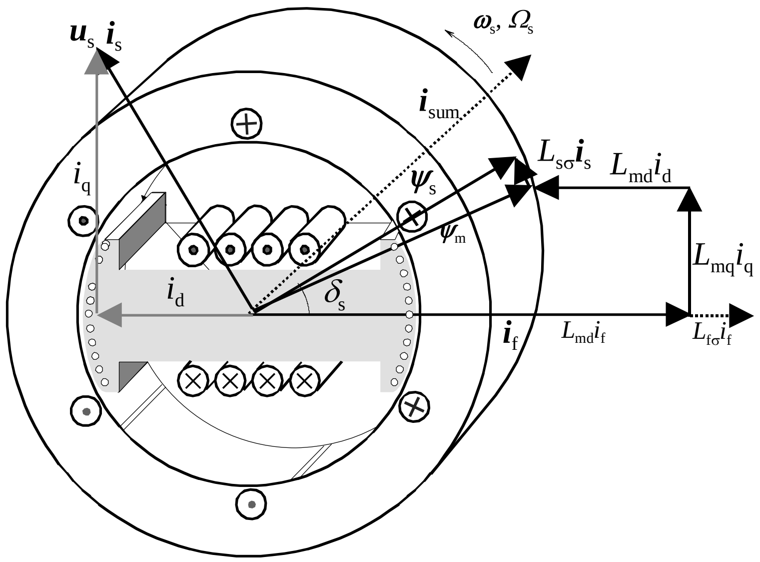

Figure 1.1 – Salient pole synchronous machine with vector diagrams for steady-state counter-clockwise motoring: stator voltage $\boldsymbol{u}_s$, stator current $\boldsymbol{i}_s$, field-winding current $\boldsymbol{i}_f$, vector sum of currents $\boldsymbol{i}_{sum}$, stator flux linkage $\boldsymbol{\psi}_s$, and air-gap flux linkage $\boldsymbol{\psi}_m$. Reproduced with permission of John Wiley & Sons Ltd. (Pyrhönen et al., 2016, p. 192).

In order to get an idea of the model of a synchronous machine, it is worth to indicate the following:

1) In AC machines theory, a space vector concept is used. It summarizes a three-phase voltage system in a way that the resulting single complex vector is rotating in space. Space vector approach significantly simplifies the mathematical description of an AC machine.
2) Lorenz law, that is mentioned above, also describes the torque production in a synchronous machine. The “magnetic flux part” now is mainly on the rotor, though the overall magnetic flux of the system, that takes the armature reaction into account, must be considered. On the contrary, the “current” part is now in the stator, which is alternating in a way to produce continuous rotation.
3) Synchronous machine is modelled in the rotor reference frame because this approach eliminates magnetizing inductance variation caused by machine’s rotor anisotropy. Thus, inductances in the equations of the model are constant coefficients

As you can see in the diagram, power factor is influenced by the flux linkage component created by the field winding, meaning that the angle between the stator current and the voltage is controllable by the rotor excitation current.

1.2 The concept of brushless excitation for a synchronous machine

One of the main disadvantages of DC machines is the unavoidable use of an electromechanical commutator. There are also so-called Brushless DC motors, but strictly speaking, they are pretty much synchronous motors, not DC motors. These BLDCs are powered by DC electricity via an inverter or switching power supply. The idea of an electromechanical commutator is to deliver the electric power from a stationary part of the device to a rotating one. Usually, a commutator includes carbon brushes, that are applied to metal plates on a rotating machine part. These brushes happen to be unreliable for several reasons. First of all, they are subject to mechanical wear. Commutators also produce sparks, that degenerate the brushes thermally and create fire hazard.

Squirrel cage induction motors are free from a commutator in their construction because the machine is magnetized by the only stator voltage. But induction motors have many flaws, e. g., low power factor. Synchronous machine rotor initially assumes the presence of slip-rings, but there are solutions that allow us to get rid of the slip-rings.

An example of a brushless excitation system for a synchronous machine is presented on Figure 1.2.

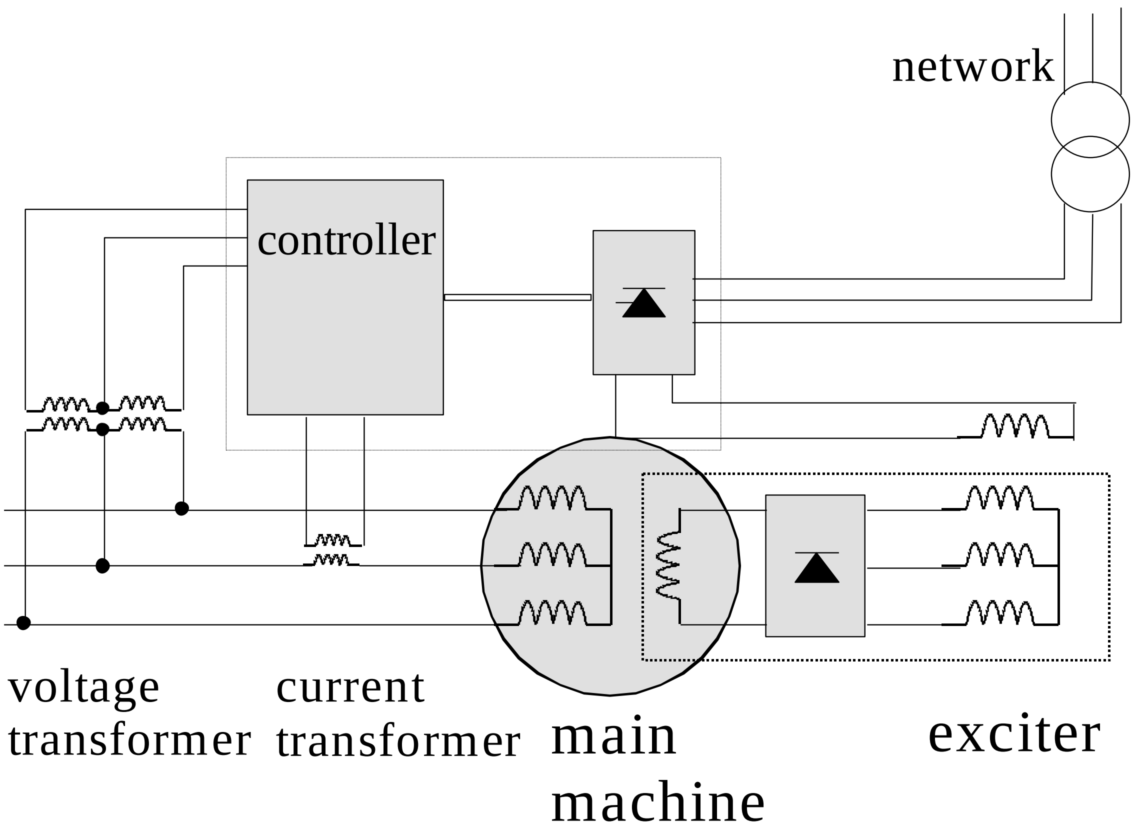

Figure 1.2 – Brushless excitation system for a synchronous machine. Reproduced with permission of John Wiley & Sons Ltd. (Pyrhönen et al., 2016, p. 293)

The idea of this system is to mount an auxiliary AC machine on the shaft of the main machine. The auxiliary machine is an outer pole synchronous machine, meaning that its own field winding is placed on the stationary part of the machine. There are e. g. three-phase windings, located in the rotor of this machine. When the common shaft is rotating, the flux of the auxiliary machine is penetrating the three-phase windings, generating three-phase voltage system in rotor. This voltage is rectified by a rectifier, placed on the same shaft, and then fed to the field winding of the main machine. In DOL start the initial acceleration of the main machine is provided by the damper winding, that allows to start a synchronous machine as an induction motor.

Thus, the energy for the magnetization of the main machine is transferred by the auxiliary machine using mechanical energy and electromagnetic induction. The excitation voltage is controlled by the controller in the case of an electric drive. The excitation machine power is small related to the power of the main machine.

In this way, a brushless solution is offered. The rectifier rotates with the rotor and a thyristor bridge that feeds the excitation (auxiliary) machine is capable of temporarily applying also a high negative voltage to the field winding to reduce electric current, if the machine's load state drops abruptly and there is a need to drive the excitation machine field winding current fast to a lower value (Pyrhönen et al., 2016, p. 292).

This solution is connected with a number of difficulties:

1) The shaft must be designed in such a way that it enables placing a rectifier and conducting wires on (or in) it, taking into account that the shaft is rotating rapidly;
2) You have to utilize an additional electrical machine, that leads to additional costs;
3) The field winding current is altered via the times constants of two machines. This may limit the dynamical performance of the machine.
4) In the case of Direct-On-Line start with damper windings, high voltages are induced in the field winding of the main machine, which may harm the diode bridge, applying a high reverse biasing voltage to the diodes, or even break the insulation of the windings.

The fourth issue in this list is the topic under consideration in this particular paper. Let us have a closer look at this phenomenon.

Initially, the electrical angular speed of the rotor $\omega_r = 0$ ($\omega_r = p\Omega_r$). Direct-On-Line start implies that full nominal terminal voltage is applied to the machine at a single moment of time. This voltage instantly creates a strong changing magnetic field, penetrating the rotor. Thus, an EMF is induced in both damper and field windings. The configuration of a damper winding in a synchronous machine is not exactly the same as of the induction motor squirrel-cage. The former is anisotropic on the d- and q-axes, unlike the latter, having different inductances on the d- and q-axes. Nevertheless, it is possible to approximate the EMF in the damper winding of a synchronous machine using the equation for a squirrel cage. According to the Lorenz force, voltages, induced in the rotor bars are:

$$e_{\mathrm{r,bar}}(x) = s\omega_{\mathrm{s}} r_{\mathrm{r}} l B_{\delta}(x) \tag{1.3}$$

where $e_{\mathrm{r,bar}}(x)$ is voltage, induced in a bar x, $s = (\omega_{\mathrm{s}} - \omega_{\mathrm{r}})/\omega_{\mathrm{s}}$ – per-unit slip that expresses the difference between the synchronous speed and rotor speed, r_{r} is the rotor radius, l is the length of the squirrel cage bars, $B_{\delta}(x)$ is the flux density, penetrating the bar x (Pyrhönen et al., 2016, p. 375). Consequently, the current starts to flow in the rotor, creating its own magnetic field. As a result, electromagnetic torque is produced, and the rotor accelerates.

In turn, the way how an EMF is induced in the field winding is similar to the process in damper winding. But the calculations are complicated because of the specific spatial distribution of the field winding. Moreover, the fact, that damper windings in this situation act like a Faraday's cage for the field winding, must be taken into account. According to the Lenz's law, "the direction of the current induced in a conductor by a changing magnetic field is such that the magnetic field created by the induced current opposes the initial changing magnetic field" (Wikipedia, 2019, Lenz's law, para. 1). Thus, the resulting flux, that reaches the field windings is smaller than it would be in the absence of damper windings.

According to equation (1.3), the EMF is directly proportional to the slip. It means that the EMF reaches its maximum at $\omega_{\mathrm{r}} = 0$, decreasing with acceleration. Thus, it is possible to predict the behavior of the EMF. This voltage is at its maximum amplitude at zero speed, going down as soon as the rotor gains speed and the voltage reaches zero at synchronous speed. Also, this voltage is an AC voltage because the rotor is rotating more slowly than the common magnetic field having the stator frequency, allowing it to change its direction through the rotor multiple times during the acceleration. The frequency of this voltage is also decreasing as soon as the rotor gains speed and reaches zero at synchronous speed.

1.3 Brushless excitation system description

The brushless excitation system under consideration is depicted in Figure 1.3.

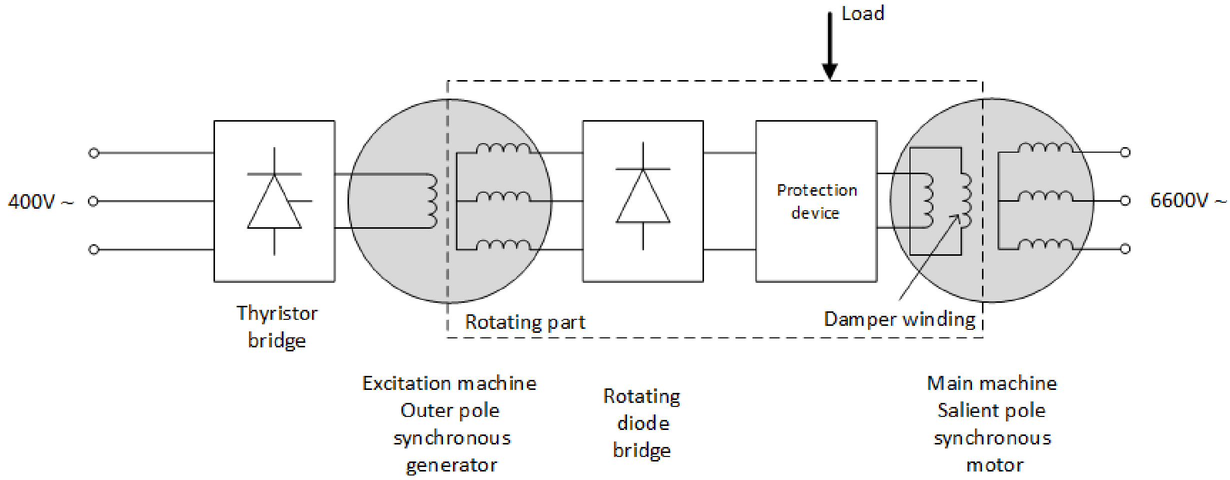

Figure 1.3 – The diagram of the brushless synchronous machine system under consideration

The main machine under study is an electrically excited synchronous salient-pole motor. The example machine used has 11 pole pairs; its stator is connected in wye and its nominal power is 5 MVA. Its nameplate parameters at the nominal point, are listed in Table 1.1.

Table 1.1 – Nameplate parameters of the main machine at the nominal point

Output power, kW	4875
Terminal voltage, V	6600
Stator current, A	438
Power factor	1
Rotational speed, rpm	327,27
Frequency, Hz	60
Field winding DC voltage, V	81.5
Field winding DC current, A	191

A field winding is a single-phase DC winding, and it does not have the same number of winding turns as the stator. The field-winding current must be referred to the stator d-axis equivalent circuit, since the two-axis equivalent circuits are fundamental for the modelling of a synchronous machine. This referring is described by the quantity named referring factor or reduction factor k_r.

The per-unit values are obtained by dividing each dimension with a base value. Typical per-unit values for motor control are derived using the following base values (Pyrhönen et al., 2016, p. 32):

- peak value for rated stator phase current $\hat{\imath}_N$
- peak value for rated stator phase voltage $\hat{u}_N$

- rated angular frequency $\omega_\mathrm{n} = 2\pi f_\mathrm{sN}$
- rated flux linkage, corresponding also to the rated angular velocity $\hat{\psi}_\mathrm{N}$
- rated impedance Z_N
- time in which 1 radian in electrical degrees $t_\mathrm{N} = 1$ rad / ω_N is travelled at a rated angular frequency. Relative time τ is thus measured as an angle $\tau = \omega_\mathrm{N} t$
- apparent power S_N corresponding to rated current and voltage
- rated torque T_N corresponding to rated power and frequency

Based on the Table 1.1, the base values for the machine under consideration are calculated as follows:

- The base value for current is $I_\mathrm{b} = \hat{\imath}_\mathrm{N} = \sqrt{2} I_\mathrm{N} = \sqrt{2} \times 438\ \mathrm{A} = 619.43\ \mathrm{A}$;
- The base value for voltage is $U_\mathrm{b} = \hat{u}_\mathrm{N} = \sqrt{2}\frac{U_\mathrm{N}}{\sqrt{3}} = \sqrt{2} \times \frac{6600\ \mathrm{V}}{\sqrt{3}} = 5388.88\ \mathrm{V}$;
- Angular frequency is $\omega_n = 2\pi f_\mathrm{sN} = 2 \times 3.14 \times 60 = 377\ \mathrm{rad/s}$;
- The base value for flux linkage is $\psi_\mathrm{b} = \hat{\psi}_\mathrm{N} = \frac{\hat{u}_\mathrm{N}}{\omega_\mathrm{N}} = \frac{\sqrt{2}\times 6600\ \mathrm{V}}{\sqrt{3}\times 377\ \mathrm{rad/s}} = 14.3\ \mathrm{Vs}$;
- The impedance base value is $Z_\mathrm{b} = Z_\mathrm{N} = \frac{\hat{u}_\mathrm{N}}{\hat{\imath}_\mathrm{N}} = \frac{6600\ \mathrm{V}}{\sqrt{3}\times 438\ \mathrm{A}} = 8.7\ \Omega$;
- The base value for inductance is $L_\mathrm{b} = L_\mathrm{N} = \frac{\hat{u}_\mathrm{N}}{\omega_\mathrm{N}\hat{\imath}_\mathrm{N}} = \frac{6600\ \mathrm{V}}{\sqrt{3}\times 377\ \mathrm{rad/s}\times 438\ \mathrm{A}} = 0.023\ \mathrm{H}$;
- The apparent power base value is $S_\mathrm{b} = S_\mathrm{N} = \frac{3}{2}\hat{\imath}_\mathrm{N}\hat{u}_\mathrm{N} = \sqrt{3} I_\mathrm{N} U_\mathrm{N} = \sqrt{3} \times 438\ \mathrm{A} \times 6600\ \mathrm{V} \approx$ 5 MVA (Pyrhönen et al., 2016, p. 32);
- And, finally, the base value for torque is $T_\mathrm{b} = \frac{p 3 \hat{\imath}_\mathrm{N}\hat{u}_\mathrm{N}}{2\omega_\mathrm{N}} = \frac{p\sqrt{3} I_\mathrm{N} U_\mathrm{N}}{\omega_\mathrm{N}} = \frac{11\times\sqrt{3}\times 6600\ \mathrm{V}\times 438\ \mathrm{A}}{377\ \mathrm{rad/s}} =$ 146093 Nm, where p is a number of pole pairs.

Initially, the parameters of the motor in per-unit values, referred to stator at 75 Celsius were received. Using the base values, SI values can be derived from per-unit values. Summarized parameters are listed in Table 1.2.

Table 1.2 – A summary of the main machine parameters.

Parameter	Per-unit value	SI value
Stator resistance $R_{s,\ pu}$	0.0047	$R_s = R_{s,pu}Z_b = 0.0047 \times 8.7\ \Omega = 0.04\ \mathrm{Ohm}$
Stator leakage inductance $L_{s\sigma.\ pu}$	0.1410	$L_{s\sigma} = L_{s\sigma,pu}L_b = 0.141 \times 0.023\ \mathrm{H} = 3.24\ \mathrm{mH}$
Direct axis magnetizing inductance $L_{md,\ pu}$	0.9660	$L_{md} = L_{md,pu}L_b = 0.966 \times 0.023\ \mathrm{H} = 22.2\ \mathrm{mH}$
Quadrature axis magnetizing inductance $L_{mq,\ pu}$	0.4792	$L_{mq} = L_{mq,pu}L_b = 0.4792 \times 0.023\ \mathrm{H} = 11\ \mathrm{mH}$
Excitation winding leakage inductance $L_{f\sigma,\ pu}$	0.2310	$L_{f\sigma} = L_{f\sigma,pu}L_b = 0.231 \times 0.023\ \mathrm{H} = 5.3\ \mathrm{mH}$
Excitation winding resistance $R_{f,\ pu}$	0.0010	$R_f = R_{f,pu}Z_b = 0.001 \times 8.7\ \Omega = 8.7\ \mathrm{mOhm}$
d-axis damper winding leakage inductance $L_{D\sigma,\ pu}$	0.0455	$L_{D\sigma} = L_{D\sigma,pu}L_b = 0.0455 \times 0.023\ \mathrm{H} = 1\ \mathrm{mH}$
d-axis damper winding resistance $R_{D,\ pu}$	0.0261	$R_D = R_{D,pu}Z_b = 0.0047 \times 8.7\ \Omega = 41\ \mathrm{mOhm}$
q-axis damper winding leakage inductance $L_{Q\sigma,\ pu}$	0.0595	$L_{Q\sigma} = L_{Q\sigma,pu}L_b = 0.0595 \times 0.023\ \mathrm{H} = 1.37\ \mathrm{mH}$
q-axis damper winding resistance $R_{Q,\ pu}$	0.0198	$R_Q = R_{Q,pu}Z_b = 0.0198 \times 8.7\ \Omega = 0.17\ \mathrm{Ohm}$
Rotor inertia J, kg·m^2	–	9576
Reduction factor from rotor to stator k_r	3.8905	–

The parameters for the excitation machine were not received. Fortunately, in the context of this paper, the excitation machine parameters are not necessary to make a proper analysis and design. Although they would be very useful in order to cover all possible issues.

The protection system is designed to be started in a way, described as follows:

1) First, full terminal three-phase voltage system is supplied to the stator, while the excitation machine remains non-excited. Acceleration is provided by two torques, produced in a salient pole synchronous machine in the absence of excitation current — damper windings torque and reluctance torque. The former accelerates the synchronous machine as an asynchronous machine, while the latter is produced because of the difference between d- and q-axis inductances and oscillates. There is also a torque, created by the currents, induced in the field winding, but the simulation results in Chapter 3 show that this currents actually decelerates the rotor;
2) Next, as soon as the main machine reaches its synchronous speed, the excitation machine is excited, producing excitation voltage and, consequently, current for the main machine;
3) Finally, mechanical load is connected to the shaft of the main machine.

To conclude, the information, presented in this chapter will be directly used to figure out the requirements and features of the protection device, as well as to model and simulate the brushless excitation system in MatLab Simulimk in further chapters.

2. PROTECTION DEVICE DESIGN

2.1 Formulation of the device requirements

In general, the goal of this paper is to design a power-electronic protection device that will provide a reliable protection against excessive AC voltage, induced in the excitation winding of an electrically excited synchronous machine with brushless excitation. In order to figure out the requirements and features for this device, the structure of the system and parameters of the machine under consideration are taken into account and analyzed:

1) In the particular machine arrangement, considered in this paper, the main machine's field winding is supplied with current supplied by the excitation machine through a diode bridge. The use of a diode bridge is justified by the fact that the use of controlled rectifier is restricted, since the rotor is rotating. Fortunately, it is possible to control the excitation current of the main machine by controlling the excitation current of the excitation machine via a thyristor bridge, depicted in Figure 1.3.
2) Insulation protection must be provided as well as diode bridge protection, since the excitation winding is also not designed to withstand excessive voltages of such amplitude.
3) It can be stated that the device must be designed for short periods of activation, since excessive voltages only appear during starting of the machine. Theoretically, these excessive voltages may appear during so called alternator paralleling, but the machine considered in this paper is designed to work in motoring mode. Nevertheless, an all-case protection is preferred.
4) The device must be autonomous as much as possible, since its maintenance is complicated because of its location on a rotating part of the machine. Additionally, the structure of the device must be simple to increase its reliability.
5) The size of the device should be small enough to be mounted on the rotor, since the volume reserved for extra equipment on the rotor is limited.
6) False activation of the device should be considered and excluded because it can lead to a failure of the machine, overheating and to an emergency situation in general.
7) The device should consume as less energy as possible to avoid efficiency loss and overheating while the device is either activated or not.
8) The device and its mounting must be mechanically resilient in order to withstand centrifugal forces during the rotation of the rotor.

In this way, the requirements for the device can be summarized as follows:

1) Specific protection for a diode bridge;

2) Insulation protection;
3) Design for short periods of activation;
4) Autonomous, compact and simple design;
5) Reliable activation and reset mechanism;
6) Low energy consumption;
7) Mechanical resiliency;

2.2 Proposed design

The proposed design is based on an outdated US patent by the name of "Overvoltage protection circuit for synchronous machine rotor" patented by Lewis E. Unnewehr in 1986 (US Patent No. US4594632A, 1986).

The structure of the device is shown on Figure 2.1.

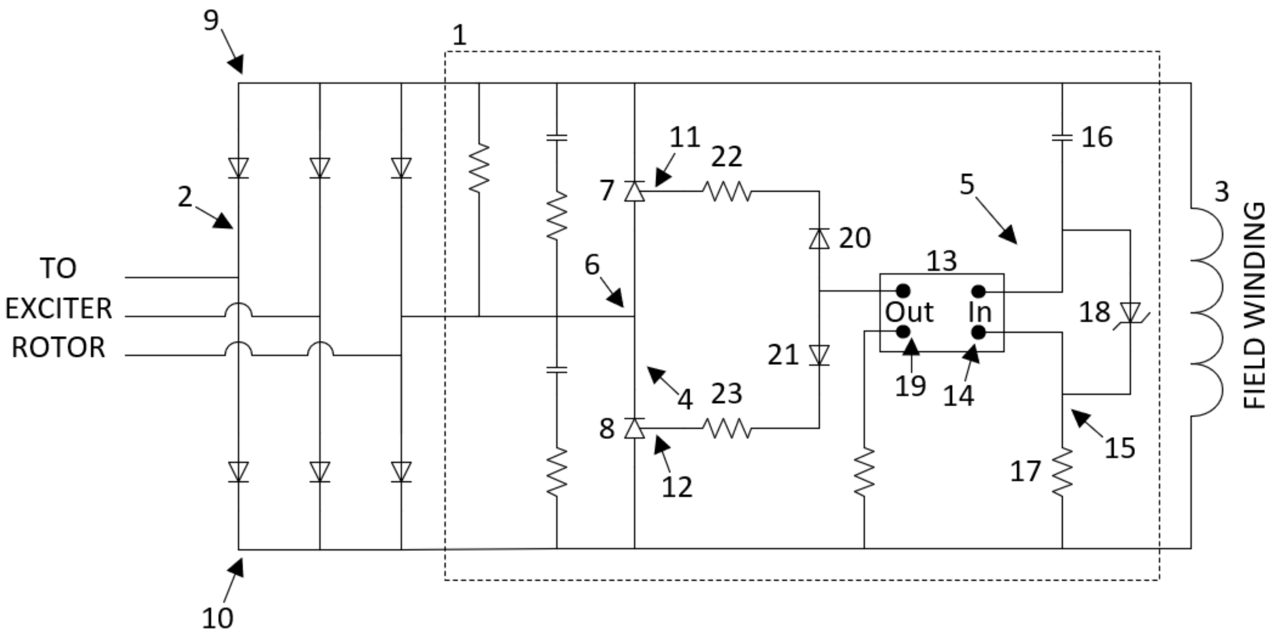

Figure 2.1 – Initial protection device electrical circuit design.

The idea of this device is to provide a low impedance bypass path for excessive AC voltage, induced in the excitation winding of the main machine. In other words, we short-circuit the excitation winding, thus removing the voltage from the rectifier.

The device, that protects the field winding, insulation and a rectifier against an excessive AC voltage, is presented in detail in Figure 2.1 with number **1**. It is connected between the main machine field winding **3** and the rectifier **2.**

The main parts and functions of the circuit for overvoltage protection are:

1) A triggerable current conducting circuit **4**, which provides a low resistance path for an excessive voltage induced in the field winding that is inverse relatively to the rectifier;
2) A voltage sensing circuit **5**, which indicates an excessive voltage induced in the field winding and effects triggering of the current conducting circuit in response to such sensing;
3) A reset mechanism denoted with number **6**, which is responsible for resetting of the current conducting circuit after the latter has been activated and the excessively high inverse voltage that otherwise could be dangerous to the rectifier has ceased.

The triggerable bypass circuit consists of a pair of series-connected triggerable thyristors **7** and **8** connected in parallel with the rectifier and the field winding between the negative and positive buses **9** and **10** respectively. The thyristors have corresponding gate electrodes **11** and **12**, on which a gate input signal might be got to trigger conduction in the thyristors when forward biased. The thyristors would be forward biased, as it is seen from the schematic circuit diagram of Figure 2.1, when reverse biasing by an inverse voltage is happening at the rectifier, meaning that the electric potential of the bus **10** is positive with respect to the more negative bus **9**.

The overvoltage detection circuit **5** incorporates a sensor generally assigned **13** whose output can yield only two distinct states: one when the voltage to the input **14** is below a predefined value and a second when the voltage to the input **14** is above such predefined value. In the favored variant of implementation, the sensor **13** is a solid-state relay (SSR).

There are several types of solid-state relays based on switching property. The classification is as follows:

1) Instant ON SSR. This relay type instantly switches its output on when the activation input voltage is reached;
2) Zero Switching SSR. In this type of a relay, in order to switch the load on, not only the input control voltage should reach the threshold value, but also the load AC voltage must hit zero value.
3) Peak Switching SSR. The switching of a Peak Switching SSR happens when the input control voltage reaches the required value AND output AC voltage hits its next peak
4) Analog Switching SSR. In analog switching relay, the relay's switching depends on the amplitude of the AC load voltage. (Electrical Technology, n. d., Solid State Relay (SSR), para. 5.2).

In the overvoltage protection device, considered in this paper, an **Instant ON solid-state relay** must be utilized because excessive voltage must be removed as soon as possible in order to protect the insulation and the diode bridge.

The other part of the overvoltage sensing circuit is an input circuit 1**5** which is connected between the buses **9** and **10** across the field winding. It provides an electrical input to the solid-state relay and determines the magnitude of the induced voltage in the field winding that would activate the solid-state relay, switching its output on. This, in turn, provides the thyristor gates with the signals that switches them to conductive mode. The input circuit comprises of a capacitor **16**, resistor **17**, and voltage limiting device **18**, preferably a Zener diode. The purpose of the resistor **17** and capacitor **16** is to determine the voltage level, at which the solid-state relay will supply the gates of the thyristors with voltage pulse sufficient to activate them. These tuning components may be adjustable, if needed for the particular purpose.

A Zener diode is a type of diode that allows current to flow not only from its anode to its cathode, but also in the reverse direction, when the Zener voltage is reached (Wikipedia, 2019, Zener diode, para. 1). The Zener diode **18** provides two functions:

1) Polarity sensitivity. When the Zener diode is forward biased, the input voltage of the solid-state relay cannot reach the threshold value that activates it;
2) Voltage limiting. When the Zener diode is reverse biased, it limits the maximum voltage applied to the solid-state relay input.

When the rectifier is forward biased, it is capable of conducting the excessive induced voltage from the field winding by itself. In this way, the Zener diode is forward biased, which leads to an inactive state of both the solid-state relay and triggerable current conducting circuit, or in other words, its stand-by operation

On the other hand, when the rectifier is also reverse biased, the Zener diode is also reverse biased. This, if the threshold voltage is reached, leads to the activation of the solid-state relay, so the voltage becomes supplied to the gates of the thyristors, opening a low resistance path for the induced voltage signal, inverse to the rectifier.

The connection between the solid-state relay output **19** and the gates the thyristors is provided by two symmetrical gate circuits, each comprising diodes **20**, **21** and resistors **22**, **23**, respectively.

In standby mode, this protective device does not have any significant effect on the shape of the rectified voltage applied to the field winding by the rectifier because of high resistance of the device circuitry, capacitor blocking effect and/or the reverse biasing of the thyristors. The voltage, that may be induced in the excitation winding of the main machine by the field, created by the stator during starting, is AC and its amplitude may exceed the peak inverse voltage of the diodes in the rectifier.

When such induced voltage is negative, that is the electric potential of the bus **9** is relatively negative with respect to the bus **10**, "a voltage develops across the Zener diode **18** at a rate determined by the time constant of the input circuit **15** and is applied to the input **14** of the solid state relay **13** causing the latter to complete a circuit coupling the positive signal from the bus **10** through the gate circuits as gate input signals to the thyristors. The thyristors then also are forward biased and become triggered to conduction. Thus, the thyristors provide a bypass circuit for such voltage that is inverse to the rectifier. When the induced voltage in the field winding reverses polarity, the thyristors are reverse biased and automatically are commutated to a non-conductive stand-by condition. The positive induced voltage in the field winding, though, can be conducted by the diodes in the rectifier, which then are forward biased" (US Patent No. US4594632A, 1986)

In the situation when the rotor of the auxiliary excitation machine becomes energized, supplying the excitation winding with voltage, while induced voltage has not attenuated at full and thyristors are still conductive, the current will start to flow through thyristors, thus undesirably shorting the excitation machines rotor winding. But, because of the reset mechanism, the thyristors are going to stay conductive only for one period of unrectified phase voltage from the exciter, since the thyristors will be closed then by negative voltage from one of the phases. After that, thyristors will stay turned off since the voltage from the exciter would not exceed the threshold voltage of the sensor.

The nominal power and, consequently, the size of the thyristors employed in this device must be relatively high enough in order to withstand the induced currents for short periods of time. However, these currents are relatively low because of the fact that the induced voltage is alternating and the inductance of the field winding is very high. In this way, the current does not have time to reach high values. As for the other elements of the circuit, they are not subject to high voltages and, therefore, may be small in size, which is important when placed on a rotating shaft

2.3 Constructional issues

The fact that the protection device under development must be mounted on a rotating shaft implies some difficulties to deal with. First of all, the placements of the device and the device itself should meet the following requirements:

1) There is limited area on the shaft to place the device. The device must be compact enough to be properly mounted on the shaft;
2) The device is electrically connected with both main machine's and exciter machine's rotor windings. Thus, when choosing a location to place the device, the possibility to connect it reliably to both windings must be considered.

3) Generally, any mass, mounted on a rotating shaft, and the shaft itself is subject to centrifugal forces. These forces are proportional to the angular speed of the shaft, the mass of an object and the distance from the axis of rotation. Thus, the protection device and its mounting must be mechanically resilient enough to withstand centrifugal forces.
4) Any mass, asymmetrically connected to the shaft, shifts its center of mass, that leads to vibration of the shaft during rotation. Thus, the device must be placed and designed in a way that this shift is minimized in order to avoid this disbalance.

In this paper, no thorough analysis of the mechanical aspects of the design is made since mechanical engineering is not an area of specialization of the author. Nonetheless, some words can and must be addressed to this problem. A solution for the mounting of the device is offered and depicted in Figure 2.2.

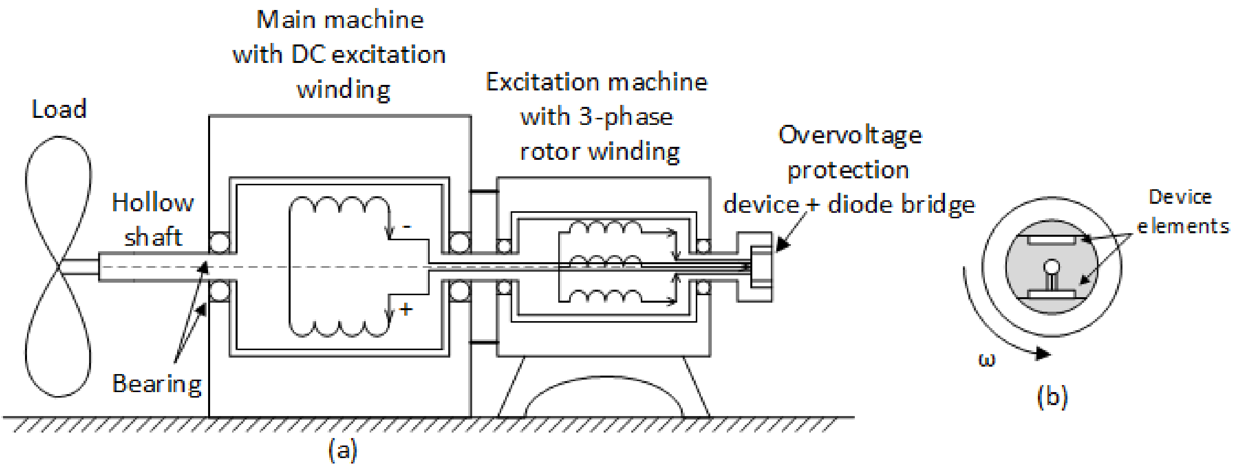

Figure 2.2 – A conceptual diagram of a mounting solution in section (a) and in frontal view (b) (Dimensions are arbitrary and not in scale).

As it can be seen in Figure 2.2, the idea is to take out the device to the end of a hollow shaft and place it as close as possible to the axis of rotation on the inner surface of the shaft. In this way, the following problems are solved to some extent:

1) Such mounting solution provides enough place for the device, while the hollow shaft acts as a space for wires;
2) Both the device and wiring are placed close to the axis of rotation, which leads to a decrease of both centrifugal forces and induced currents, since both of them are proportional to the distance from the axis of rotation;
3) The device is placed in such a way that its mass is balanced as much as possible related to the axis of rotation. Thus, the shift of the center of mass and, consequently, vibration, is minimized;
4) Carrying the device to the end of the shaft provides access for maintenance.

3. MatLab modelling and simulation of the system

3.1 Synchronous machine model

A synchronous machine model that was used in this paper is presented in Figure 3.1.

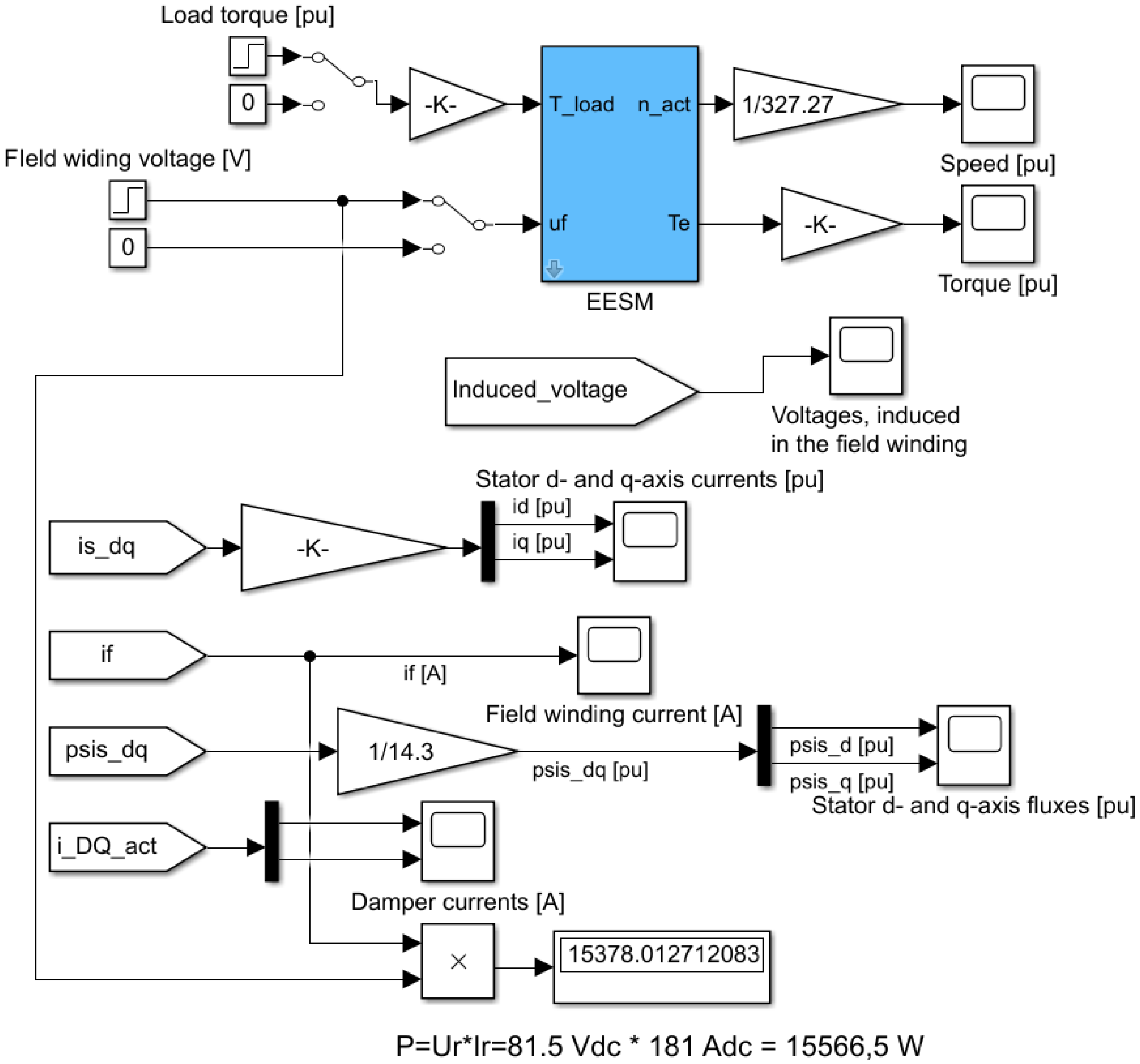

Figure 3.1 – Top level of the model with inputs, outputs and observation tools

The model is multileveled with a masked EESM model. Further levels, as well as EESM model parameters, are presented in appendices A-F.

The model is based on an Electrically Excited Synchronous Machine equivalent circuit in dq-axes, illustrated in Figure 3.2.

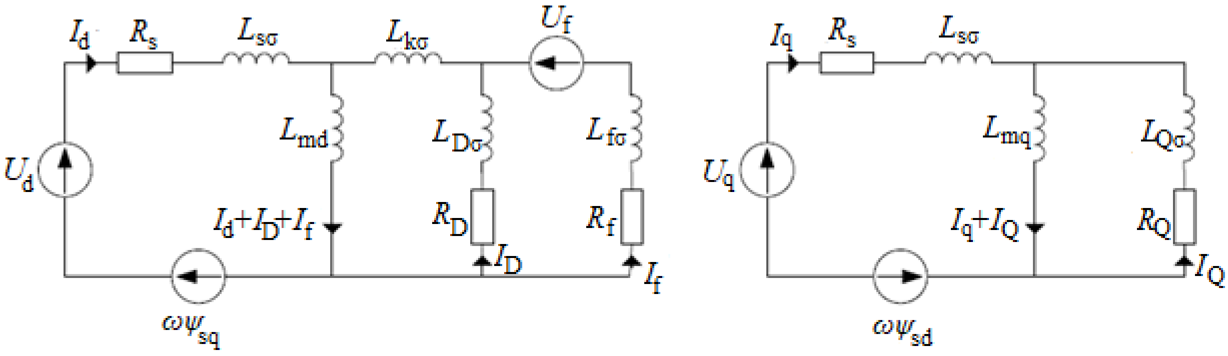

Figure 3.2 – Equivalent circuit of the electrically excited synchronous motor (Pyrhönen, O., 1998)

In Figure 3.2, the following denominations are used: U_d, U_q – stator voltages in d- and q-axis respectively; I_d , I_q – stator currents in d- and q-axis respectively; I_D, I_Q – rotor currents in d- and q-axis respectively; U_f, i_f – excitation voltage and current respectively; R_s, R_D, R_Q, R_f – stator winding, damper winding in d- and q-axis, field winding resistances respectively; $L_{s\sigma}$, $L_{D\sigma}$, $L_{Q\sigma}$, $L_{f\sigma}$– stator winding, damper windings in d- and q-axis, field winding leakage inductances respectively; L_{md}, L_{mq} – magnetizing inductances in d- and q-axis respectively.

Based on the equivalent circuit, the voltage dq-axes model of the EESM is (Mirlenko, A, 2017):

$$\boldsymbol{u}_{\mathrm{d}} = R_{\mathrm{s}}\boldsymbol{i}_{\mathrm{d}} + \frac{\mathrm{d}}{\mathrm{dt}}\boldsymbol{\psi}_{\mathrm{d}} - \boldsymbol{\omega}\boldsymbol{\psi}_{\mathrm{q}} \tag{3.1}$$

$$\boldsymbol{u}_{\mathrm{q}} = R_{\mathrm{s}}\boldsymbol{i}_{\mathrm{q}} + \frac{\mathrm{d}}{\mathrm{dt}}\boldsymbol{\psi}_{\mathrm{q}} - \boldsymbol{\omega}\boldsymbol{\psi}_{\mathrm{d}} \tag{3.2}$$

$$0 = R_{\mathrm{D}}\boldsymbol{i}_{\mathrm{D}} + \frac{\mathrm{d}}{\mathrm{dt}}\boldsymbol{\psi}_{\mathrm{D}} \tag{3.3}$$

$$0 = R_{\mathrm{Q}}\boldsymbol{i}_{\mathrm{Q}} + \frac{\mathrm{d}}{\mathrm{dt}}\boldsymbol{\psi}_{\mathrm{Q}} \tag{3.4}$$

$$\boldsymbol{u}_{\mathrm{f}} = R_{\mathrm{f}}\boldsymbol{i}_{\mathrm{f}} + \frac{\mathrm{d}}{\mathrm{dt}}\boldsymbol{\psi}_{\mathrm{f}} \tag{3.5}$$

Equations (3.1 – 3.2) are the expressions of the stator voltage d- and q-parts; the d- and q-axis damper windings are expressed by equations (3.3 – 3.4); the rotor field winding equation is given by equation (3.5). The machine currents can be written as:

$$i_{\mathrm{d}} = \frac{C}{A}\psi_{\mathrm{d}} - \frac{D}{A}\psi_{\mathrm{D}} - \frac{E}{\mathrm{A}}\psi_{\mathrm{f}} \tag{3.6}$$

$$i_{\mathrm{q}} = \frac{L_{\mathrm{Q}}}{B}\psi_{\mathrm{d}} - \frac{L_{\mathrm{mq}}}{B}\psi_{\mathrm{Q}} \tag{3.7}$$

$$i_{\mathrm{D}} = \frac{F}{A}\psi_{\mathrm{D}} - \frac{H}{A}\psi_{\mathrm{f}} - \frac{D}{\mathrm{A}}\psi_{\mathrm{d}} \tag{3.8}$$

$$i_{\mathrm{Q}} = \frac{L_{\mathrm{q}}}{B}\psi_{\mathrm{Q}} - \frac{L_{\mathrm{mq}}}{B}\psi_{\mathrm{q}} \tag{3.9}$$

$$i_{\mathrm{f}} = \frac{G}{A}\psi_{\mathrm{f}} - \frac{H}{A}\psi_{\mathrm{D}} - \frac{E}{\mathrm{A}}\psi_{\mathrm{d}} \tag{3.10}$$

where ψ_{d}, ψ_{q} – stator flux linkage in d- and q-axis respectively; ψ_{D}, ψ_{Q} – damper winding flux linkage in d- and q-axis respectively; ψ_{f} – field winding flux linkage.

The coefficients in (2.6 - 2.10) are substituted with the calculated inductances:

$$A = L_{\mathrm{D}}L_{\mathrm{f}}L_{\mathrm{d}} - L_{\mathrm{md}}^2(L_{\mathrm{D}} + L_{\mathrm{f}} + L_{\mathrm{d}} - 2L_{\mathrm{md}}) \tag{3.11}$$

$$B = L_{\mathrm{q}}L_{\mathrm{Q}} - L_{\mathrm{mq}}^2 \tag{3.12}$$

$$C = L_{\mathrm{D}}L_{\mathrm{f}} - L_{\mathrm{md}}^2 \tag{3.13}$$

$$D = L_{\mathrm{md}}L_{\mathrm{f}} - L_{\mathrm{md}}^2 \tag{3.14}$$

$$E = L_{\mathrm{md}}L_{\mathrm{D}} - L_{\mathrm{md}}^2 \tag{3.15}$$

$$F = L_{\mathrm{f}}L_{\mathrm{d}} - L_{\mathrm{md}}^2 \tag{3.16}$$

$$G = L_{\mathrm{D}}L_{\mathrm{d}} - L_{\mathrm{md}}^2 \tag{3.17}$$

$$H = L_{\mathrm{md}}L_{\mathrm{d}} - L_{\mathrm{md}}^2 \tag{3.18}$$

where L_{md} and L_{mq} - d-axis and q-axis magnetizing inductances respectively; L_{d} and L_{D} - d-axis stator and rotor inductances respectively; L_{q} and L_{Q} - q-axis stator and rotor inductances respectively; L_{f} – field (excitation) inductance.

The electrically excited synchronous motor current model equations are the following:

$$|\boldsymbol{\psi}_{\mathrm{s}}| = \sqrt{\boldsymbol{\psi}_{\mathrm{d}}^2 + \boldsymbol{\psi}_{\mathrm{q}}^2} \tag{3.19}$$

$$\boldsymbol{\psi}_{\mathrm{d}} = L_{\mathrm{s}\sigma}\boldsymbol{i}_{\mathrm{d}} + L_{\mathbf{md}}(\boldsymbol{i}_{\mathrm{d}}+\boldsymbol{i}_{\mathrm{D}}+\boldsymbol{i}_{\mathrm{f}}) \tag{3.20}$$

$$\boldsymbol{\psi}_{\mathbf{q}} = L_{\mathrm{s}\sigma}\boldsymbol{i}_{\mathbf{q}} + L_{\mathbf{mq}}(\boldsymbol{i}_{\mathrm{q}}+\boldsymbol{i}_{\mathrm{Q}}) \tag{3.21}$$

$$\boldsymbol{\psi}_{\mathrm{md}} = L_{\mathbf{md}}(\boldsymbol{i}_{\mathrm{d}}+\boldsymbol{i}_{\mathrm{D}}+\boldsymbol{i}_{\mathrm{f}}) \tag{3.22}$$

$$\boldsymbol{\psi}_{\mathrm{mq}} = L_{\mathbf{mq}}(\boldsymbol{i}_{\mathrm{q}}+\boldsymbol{i}_{\mathrm{Q}}) \tag{3.23}$$

Stator voltages in the rotor reference frame are obtained using series Park and Clarke transformations, also called direct-quadrature-zero transformation. This transformation, first, recalculates three-phase voltage on two orthogonal axes α and β, and then, fixes this system of axes to a rotating rotor. In this way, the magnetizing inductance of the machine is no longer dependent on the rotor position, that significantly simplifies the calculations. The equations for the Clarke transformation, or Alpha-beta transformation are:

$$u_\alpha = \frac{2u_a - u_b - u_c}{3} \tag{3.24}$$

$$u_\beta = \frac{u_b - u_c}{\sqrt{3}} \tag{3.25}$$

where u_a, u_b and u_c are conditionally the first, second and third instantaneous phase voltages. and then, moving to the Park transformation:

$$u_d = u_\alpha \cos(\theta_r) + u_\beta \sin(\theta_r) \tag{3.26}$$

$$u_q = u_\beta \cos(\theta_r) - u_\alpha \sin(\theta_r) \tag{3.27}$$

where θ_r is the rotor position angle.

The discretized voltage model of EESM can be described with the following equations (Mirlenko, A, 2017):

$$\Delta\psi_d = \frac{T_s}{2}\left[\Delta u_d - R_s\left(\frac{C}{A}\Delta\psi_d - \frac{D}{A}\Delta\psi_D - \frac{E}{A}\Delta\psi_f\right) - \Delta\omega\Delta\psi_q\right] \tag{3.28}$$

$$\Delta\psi_q = \frac{T_s}{2}\left[\Delta u_q - R_s\left(-\frac{L_Q}{B}\Delta\psi_q - \frac{L_{mq}}{B}\Delta\psi_Q\right) - \Delta\omega\Delta\psi_d\right] \tag{3.29}$$

$$\Delta\psi_D = \frac{T_s}{2}\left[-R_D\left(\frac{F}{A}\Delta\psi_D - \frac{H}{A}\Delta\psi_f - \frac{D}{A}\Delta\psi_d\right)\right] \tag{3.30}$$

$$\Delta\psi_Q = \frac{T_s}{2}\left[-R_Q\left(\frac{L_Q}{B}\Delta\psi_Q - \frac{L_{mq}}{B}\Delta\psi_q\right)\right] \tag{3.31}$$

$$\Delta\psi_f = \frac{T_s}{2}\left[\Delta u_f - R_f\left(\frac{G}{A}\Delta\psi_f - \frac{H}{A}\Delta\psi_D - \frac{E}{A}\Delta\psi_d\right)\right] \tag{3.32}$$

Electromagnetic torque, produced in a synchronous machine, in space-vector representation, is expressed as follows:

$$T_e = \frac{3}{2}p\boldsymbol{\psi}_s \times \boldsymbol{i}_s \tag{3.33}$$

where p is the number of pole pairs, $\boldsymbol{\psi}_s$ – stator flux linkage space vector, $\boldsymbol{i}_s$ – stator current space vector. In terms of values, referred to rotor reference frame (dq-frame), equation (3.33) can be rewritten as:

$$T_s = \frac{3}{2}p(\boldsymbol{\psi}_d\boldsymbol{i}_q - \boldsymbol{\psi}_q\boldsymbol{i}_d) \tag{3.34}$$

The synchronous motor mechanical part is described with the equation:

$$\omega_r = \int \frac{T_e - T_{load}}{J} \tag{3.35}$$

where ω_r – rotor angular speed; T_e and T_load – electromagnetic and load torque respectively; J – inertia of the rotor.

In order to run a simulation, nominal load torque is calculated as follows (Niiranen J, 2000):

$$T_\mathrm{l} = \frac{p\sqrt{3}U_N I_N}{\omega_N} = \frac{11 \times \sqrt{3} \times 6600\ \mathrm{V} \times 438\ \mathrm{A}}{2 \times \pi \times 60\ \mathrm{rad/s}} = 146096.6\ \mathrm{Nm} \tag{3.36}$$

where p is the number of pole pairs, U_N is stator nominal RMS phase-to-phase voltage, I_N is stator nominal RMS current and ω_N is angular frequency. Since excitation winding parameters are referred to the stator, the field windings voltage is chosen in accordance with energy principle — the energy, consumed by the referred to stator excitation winding must be equal to the energy, consumed by the real excitation winding.

The simulation was performed with sampling time T_s = 100 μs for 10 seconds. As it was mentioned in Chapter 1, the machine is started in a sequence: first, full stator voltage is fed, next on the 4$^{\mathrm{th}}$ second excitation winding is excited and finally, on the 6$^{\mathrm{th}}$ second load is connected to the shaft. The results are presented on Figures 3.3 – 3.4.

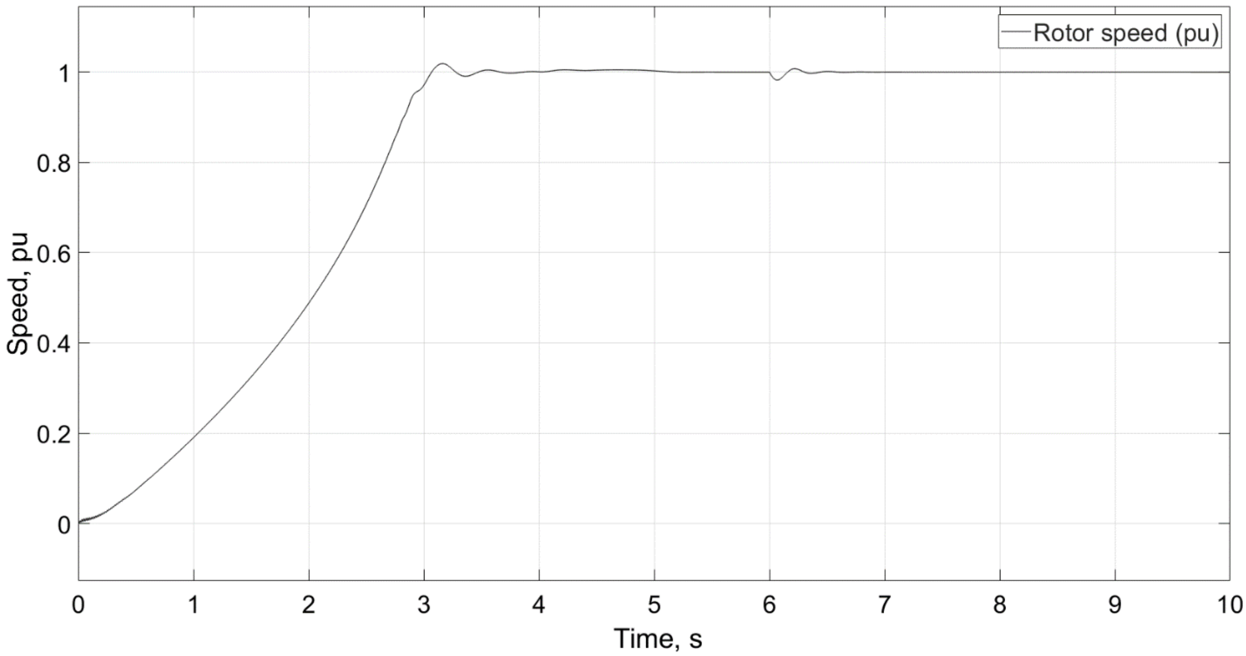

Figure 3.3 – Rotor speed with nominal load and excitation current (1 pu corresponds to 327.27 rpm).

As it is seen in Figure 3.3, the synchronous motor successfully reaches its synchronous speed and maintains it under the nominal load. Initial acceleration without excitation happens with the damper windings torque and reluctance torque.

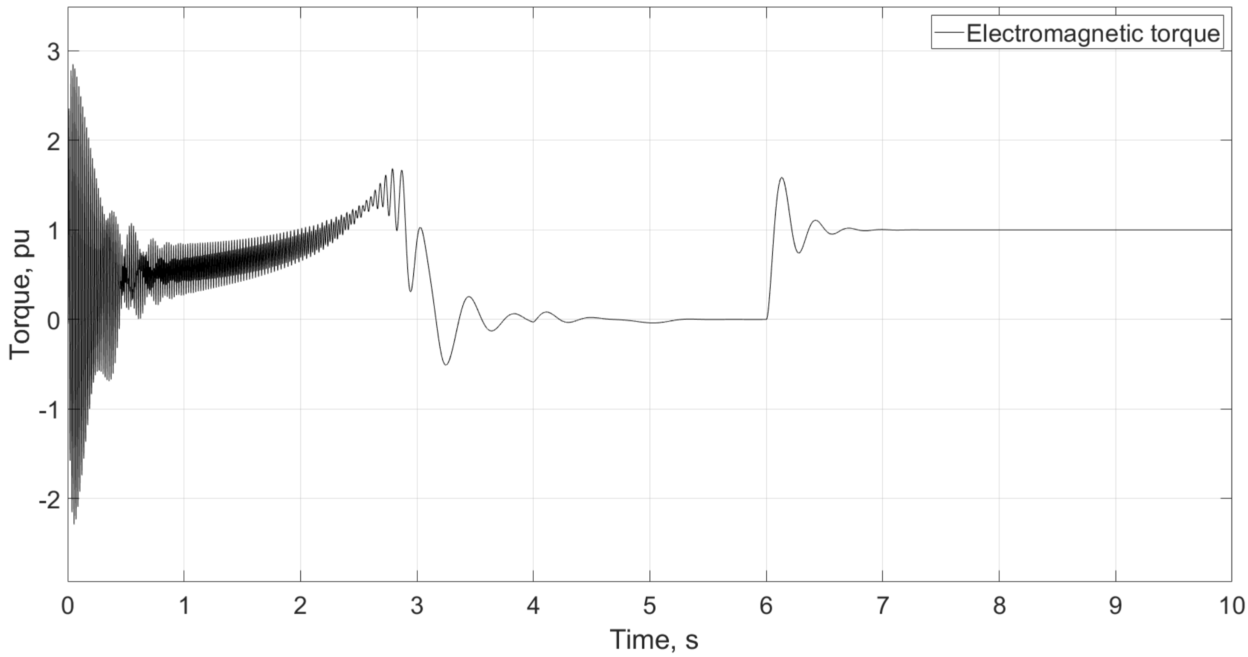

Figure 3.4 – DOL starting to no-load, excitation and applying nominal load and excitation current (1 pu corresponds to 145096.6 Nm).

In order to calculate the voltage, induced in the excitation winding, the equation, that describes the dependence between flux and voltage, is used (Wikipedia, 2018, Flux linkage, para. 2):

$$e = \frac{\mathrm{d}\psi}{\mathrm{d}t} \tag{3.37}$$

where e is the voltage across the device, or the potential difference between the two terminals and ψ is the winding's flux linkage.

Of course, if the excitation winding forms a closed loop, current will start to flow in it when any voltage is induced. According to the Lenz's law, as it was said in Chapter 1, "the direction of the current induced in a conductor by a changing magnetic field is such that the magnetic field created by the induced current opposes the initial changing magnetic field" (Wikipedia, 2019, Lenz's law, para. 1). But the voltage from which we protect the excitation winding is induced in such a direction that the reverse biases the rectifier diodes. In this way, we can assume the excitation winding as an open circuit.

In this way, the induced voltage is calculated simply taking a time derivative of the excitation winding flux linkage and setting the excitation winding resistance in the model to infinity. Next, the load torque and the excitation voltage are set to zero. The same sampling time was utilized during this simulation.

The results are shown on Figures 3.5-3.6.

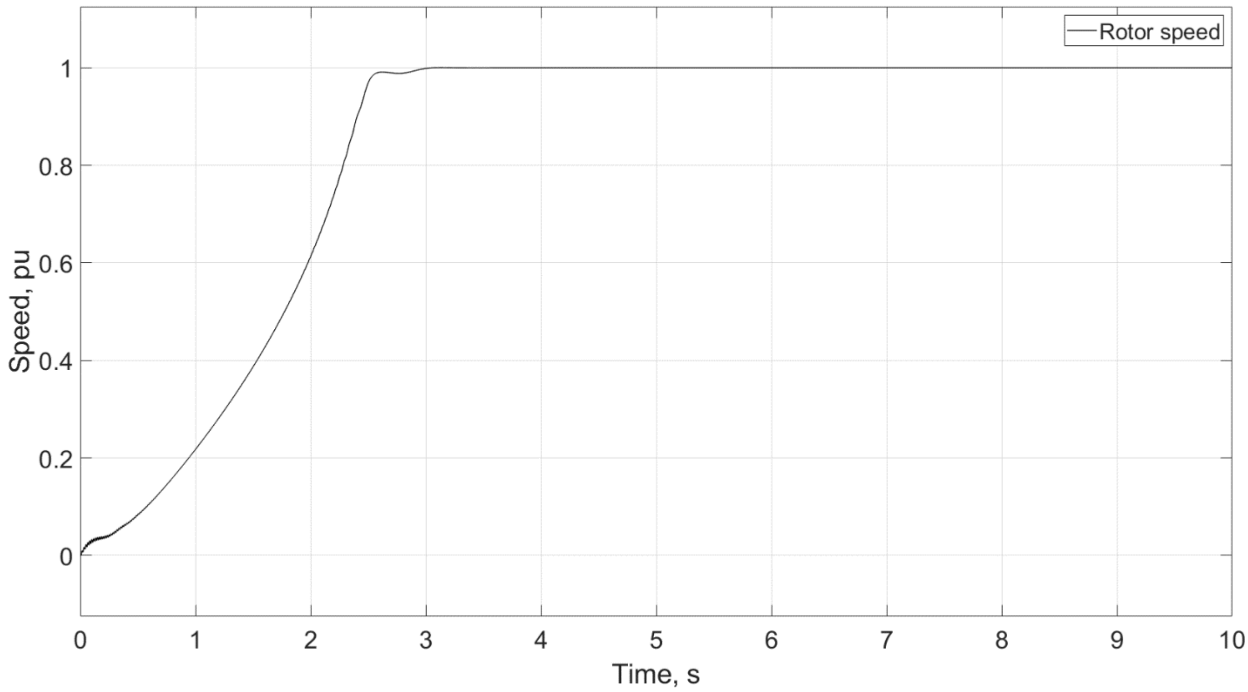

Figure 3.5 – Rotor speed with zero load and turned off, open circuit excitation winding (1 pu corresponds to 327.27 rpm).

As it can be seen in Figure 3.5, the machine reaches its synchronous speed even faster probably because of the absence of the oscillating torque, created by the field winding current, that is placed in the stator field that is rotating much faster than the rotor.

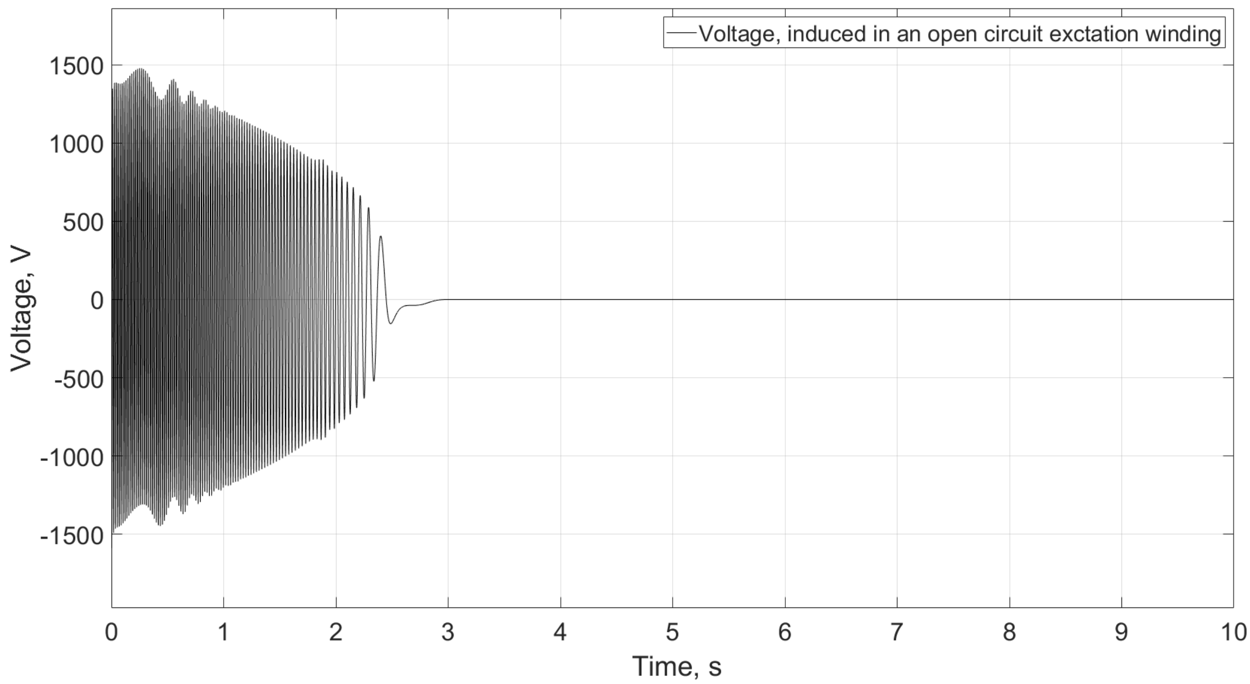

Figure 3.6 – Voltage, induced in an open circuit excitation winding.

As it can be seen in Figure 3.6, the voltage is extremely high, compared to the nominal excitation winding voltage U_f=81.4 Volts. This voltage also behaves as it was predicted in Chapter 1 — it is AC and reaches its maximum at $t \approx 0$, then decreases as soon as the machine accelerates. In reality, only negative half-waves of this voltage meet an open circuit in the excitation windings, but this fact, as far as the author is concerned, should not change the situation significantly, but is still worth considering.

At this point, when the induced voltage is proven to be dangerous for the excitation winding, we proceed to modelling and simulation of the protection device.

3.2 Protection device model

An overvoltage protection device model in MatLab produced on the basis of the design presented in Chapter 2 is shown in Figure 3.7.

The excitation machine is represented as an ideal three-phase voltage source with zero impedance. In reality, the excitation machine's rotor three-phase winding has a certain value of resistance and inductance, but they can be omitted because of the following reason: considering the flow of the induced voltages, they would not create a significant voltage drop across the windings and, hence, significant current in it. In the case of positive (forward to diodes) half-waves of the induced AC voltage, they are shorted through the diode bridge, on the other hand, negative (backward to diodes) half-waves of the induced AC voltage are shorted through thyristors. Nevertheless, the inductance of the excitation machine's rotor three-phase winding would affect the speed of rise of the current in the main machine's excitation winding. Excitation winding voltage value takes diode bridge voltage drop into account.

Next, a diode bridge is introduced. Excitation machine's three-phase winding is connected to a diode bridge, mounted on a rotating shaft. For the sake of simulation, there is a connector that provides excitation turn-on either at the start on the simulation or on the 3th second (when induced voltage is removed). Regarding diode bridge diodes, a piecewise linear model of a diode was used. It describes I-U curve of a diode as two straight lines — low conductance below opening voltage and high conductance above opening voltage. In reality, I-U curve of a diode is exponential, but in the light of this work, piecewise linear model is accurate enough. Forward voltage of each diode is $\underline{U}_{fd}$ = 1.3 V and on-state resistance is R_{on} = 3 mOhm. The latter is chosen in order to maintain approximately nominal voltage drop U_{fd} = 1.3 V across the diode under nominal field winding current. In practice, the diodes are chosen based on their nominal current and maximum reverse voltage. Maximum reverse voltage is discussed further in this chapter.

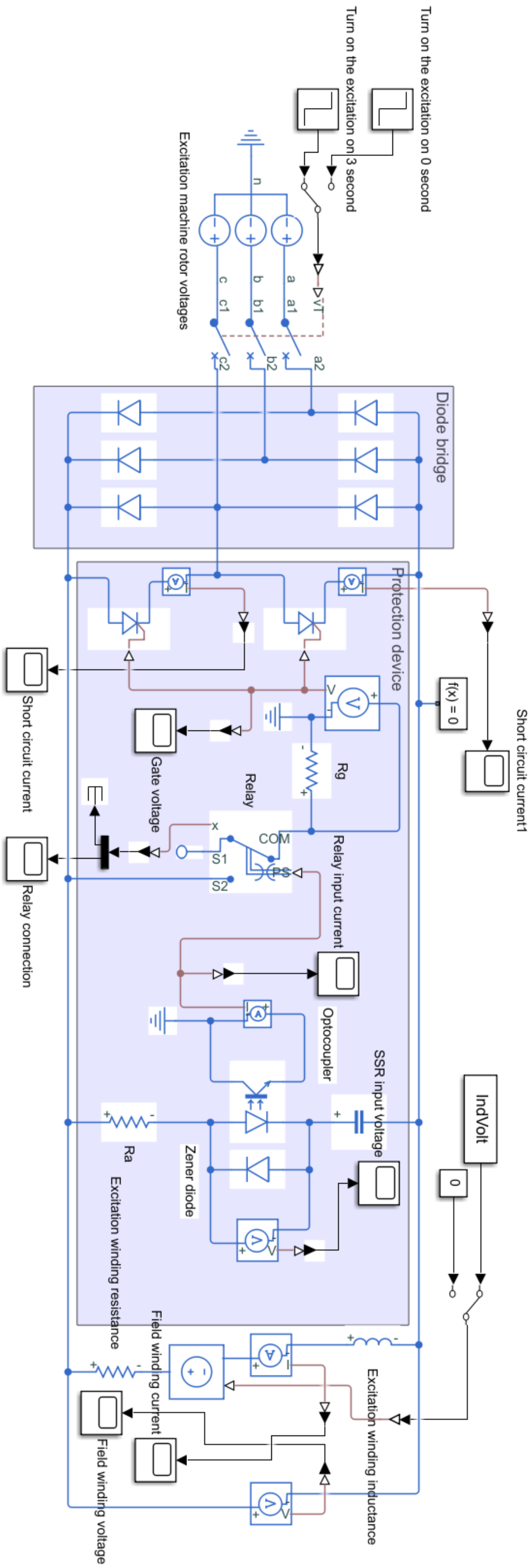

Figure 3.7 – A protection device model

Moving to the protection device, as it was said in Chapter 2, it consists of two main parts — the voltage sensing circuit and the bypass triggerable circuit. In turn, the voltage sensing circuit comprises the solid-state relay with its input circuit.

The input circuit is designed to react to AC voltage exceeding U_{trig} = 400 V. Trigger voltage $\underline{U}_{trig}$ has such a value to ensure decent dynamics of the main synchronous machine, the excitation winding must have a large voltage margin. Voltage of value up to 400 V may be supplied to the main machine's excitation winding in order to change the field current rapidly. Thus, this voltage is chosen as a trigger voltage for the protection device, as well as maximum rectifiers' reverse voltage.

A Zener diode has Zener voltage U_z = 1.8 V and forward voltage U_{fdz} = 0.9 V. When forward biased, the Zener diode limits the input voltage of the solid-state relay to 0.9 V and when reverse biased, limits it to 1.8 V, which is exactly a trigger voltage of the solid-state relay. The voltage drop across the relay input and its input current is adjusted using a high resistance of value R_a = 26.75 kOhm. There is also a capacitor installed in series with the resistor R_a and LED in order to block DC current during normal operation and reduce losses.

Unfortunately, a pre-made model for a solid-state relay was not found in MatLab. Thus, the solid-state relay is represented with an optocoupler and a relay block. Optocoupler LED lights when optocoupler input current reaches I_{LED} = 30 mA. Normally, relay common terminal (COM) is connected to the terminal S1. When LED is on, the relay connects terminal S2 to a common terminal instead.

Regarding bypass triggerable circuit, it comprises two thyristors and gate circuitry. Due to, probably, lack of the author's knowledge in either electronics or MatLab environment, or both, some problems with gate circuitry modelling were encountered. Is this paper, gate circuitry is simplified. When the relay connects terminal S2 to a common terminal, voltage develops across the resistance of R_g = 100 kOhm. Voltage sensor indicates this voltage and sends it to the thyristors' gate inputs.

The thyristors are also modelled with a piecewise linear model. They have the same voltage drop and equivalent on resistance as the diode bridge in order to balance the current, created by induced voltage. There are two of them in order to provide a reset mechanism. Reset mechanism is simply a point between thyristors, connected to a phase of excitation machine rotor winding. If the main machine is excited before the moment, when induced voltage disappear, thyristors will short the excitation voltage only for a one half-period of voltage. Then, they will be closed by negative voltage on the first thyristor cathode. Anyway, it is strongly not recommended to excite the machine until induced voltage is fully removed.

The main machines excitation winding resistance and inductance should be calculated using the referring factor and PU-parameters of the main synchronous machine. In a synchronous machine model, PU values for field winding resistance and leakage inductance describe the parameters of equivalent three-phase field winding. Resistance of an equivalent three-phase field winding is calculated as follows:

$$R'_{\mathrm{f3ph}} = R_{\mathrm{f,pu}} Z_{\mathrm{b}} = 0.001 \times 8.7\ \Omega = 8.7\ \mathrm{mOhm} \tag{3.38}$$

Resistance of the real one-phase DC winding is calculated with the following equation (Pyrhönen et al., 2016, p. 224):

$$R_{\mathrm{fDC}} = 3R'_{\mathrm{f3ph}} k_{\mathrm{ri}}^2 = 3 \times 8.7\ \mathrm{mOhm} \times\ 3.8905^2 = 0.395\ \mathrm{Ohm} \tag{3.39}$$

The inductance is calculated as follows:

$$L_{\mathrm{f,pu}} = L'_{\mathrm{f\sigma,pu}} + L_{\mathrm{md,pu}} = 0.966 + 0.231 = 1.197 \tag{3.40}$$

$$L_{\mathrm{f}} = L_{\mathrm{f,pu}} L_{\mathrm{b}} = 1.197 \times 0.023\ \mathrm{H} = 27.5\ \mathrm{mH} \tag{3.41}$$

These inductance and resistance are set as field winding inductance and resistance in the protection device model.

Due to discretization issues and the switching nature of the protection device model, protection device was simulated separately from the EESM model with variable step. Instead, induced voltage plot is saved to workspace beforehand as timeseries with sampling time T_s = 100 µs and supplied to the model through “From Workspace” Simulink block.

3.3 Protection device simulation results

To begin, the model was simulated in order to tune the sensor circuit to react to voltage above 400 V. To do so, first, a 400 V DC voltage from rectifier is supplied to the field winding. The simulation results are presented in Figures 3.8-3.9

As it can be seen in Figures 3.8-3.9, the thyristors are turned off under this voltage, negligible current flows through the thyristors and full voltage is supplied to the field winding.

If a voltage above 400 V is supplied to the field winding, the sensor must react to it and short the winding through the thyristors. The results of the simulation with the value of voltage of 410 V supplied from the rectifier are presented in Figures 3.10-3.11.

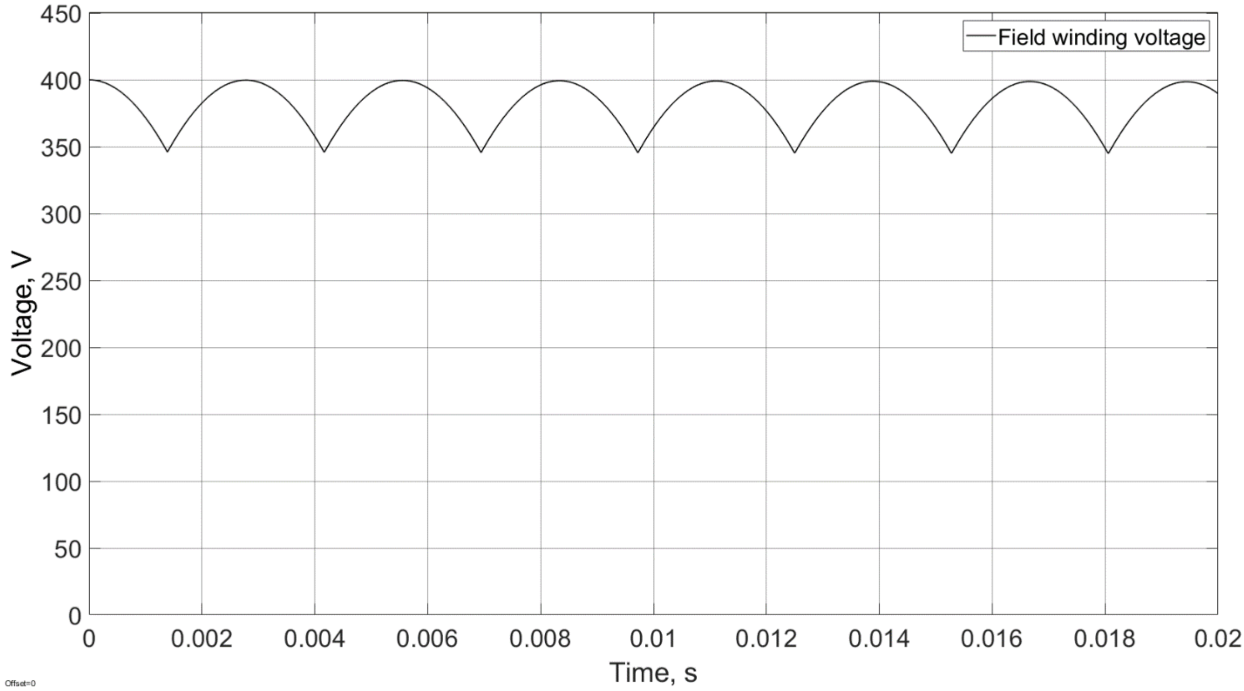

Figure 3.8 – Field winding voltage under 400 V DC input rectifier voltage

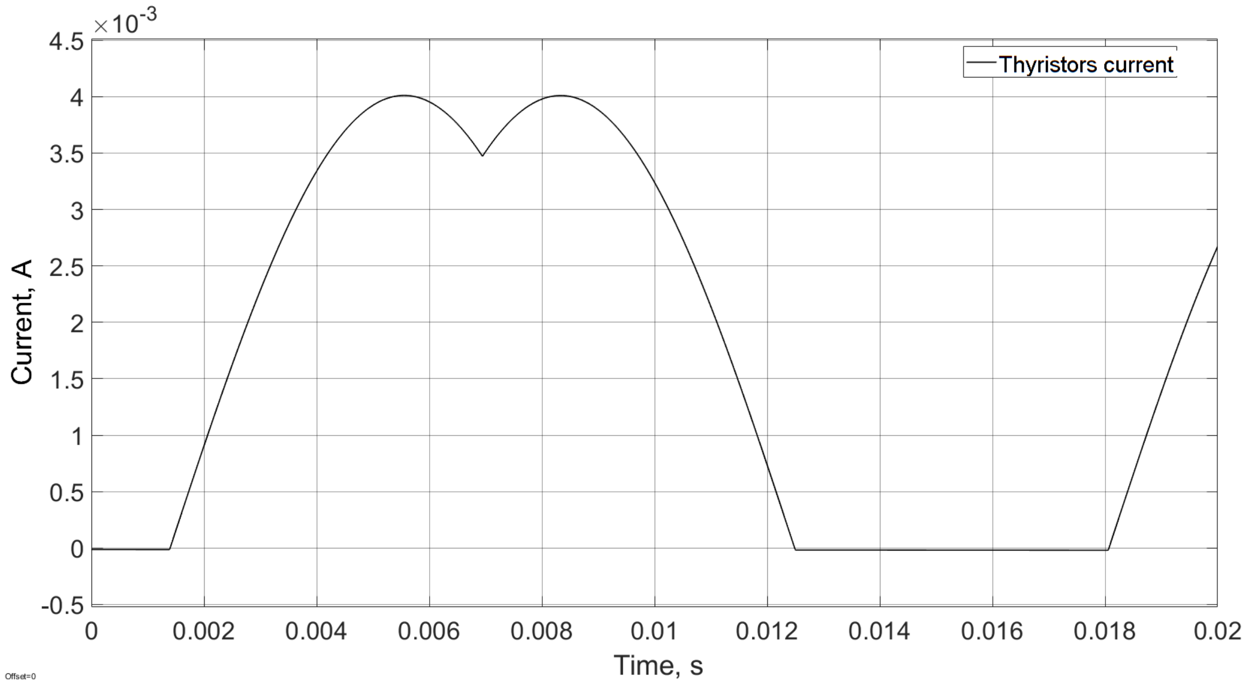

Figure 3.9 – Thyristors current under 400 V DC input rectifier voltage

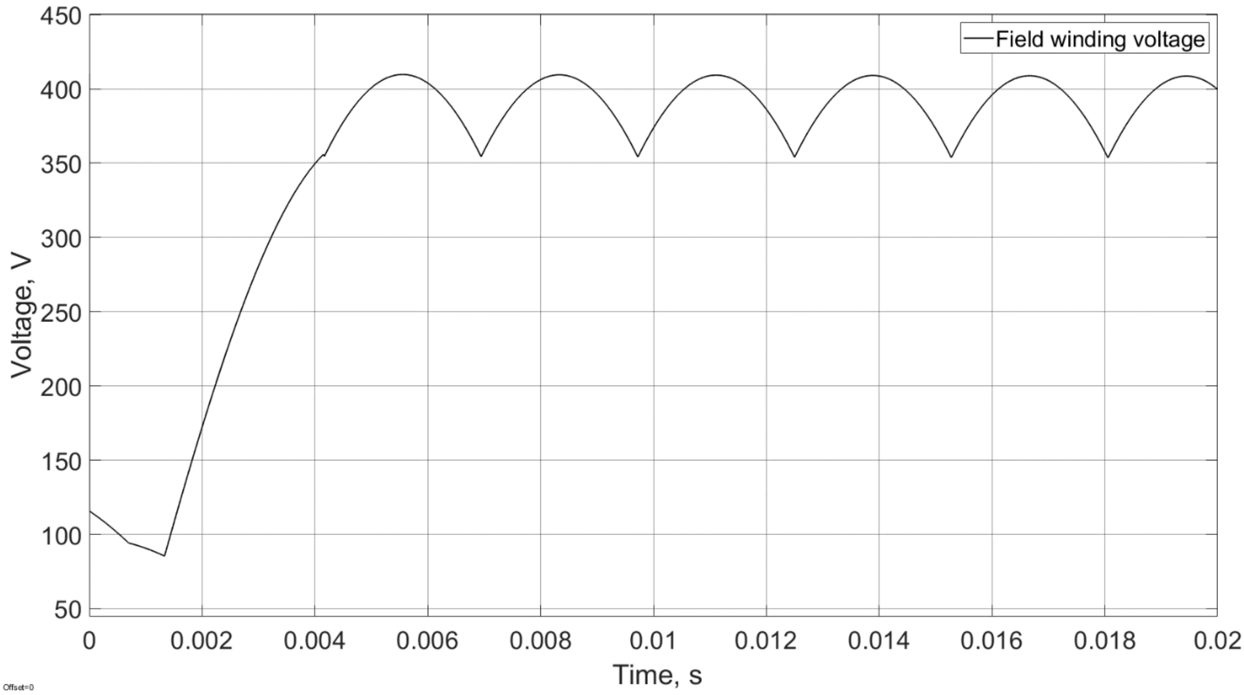

Figure 3.10 – Field winding voltage with 410 V DC input rectifier voltage

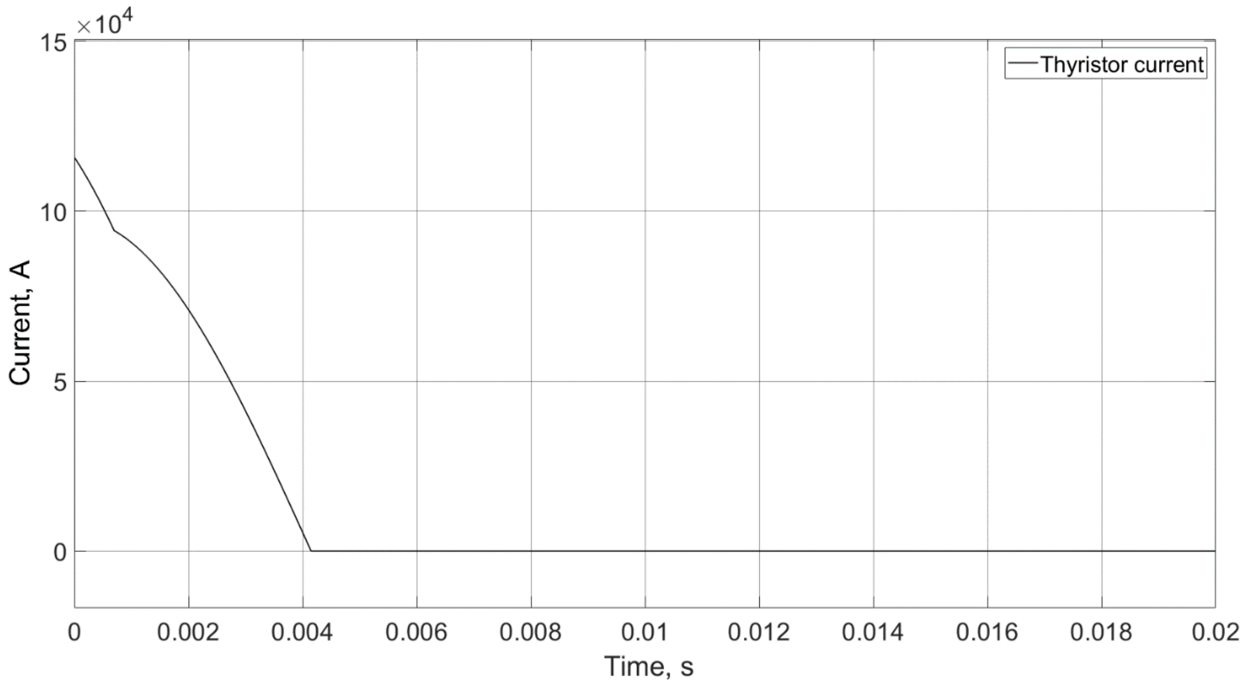

Figure 3.11 – Top thyristor current with 410 V DC input rectifier voltage

As it is seen in Figures 3.10-3.11, thyristors were successfully opened during the simulation. Top thyristor conducted the current until negative voltage was reached on a phase to which it is connected. Then, neither of them was opened because blocking conductor was already charged. Thus, sensing current was reduced below the activation level. The thyristor current is extremely high, but in reality, it will be much lower because of the inductance of the excitation machine rotor winding. Nevertheless, as it was said before, appearance of this current is must be avoided if possible.

Finally, the protection circuit was tested on the voltage, induced by stator in the field winding of the main machine. This time, as it was said in Chapter 1, nominal field winding voltage $U_f \approx 81.5$ from the auxiliary machine is supplied on the 3rd second of simulation, after induced voltage is completely attenuated. The results are presented in Figures 3.12-3.16.

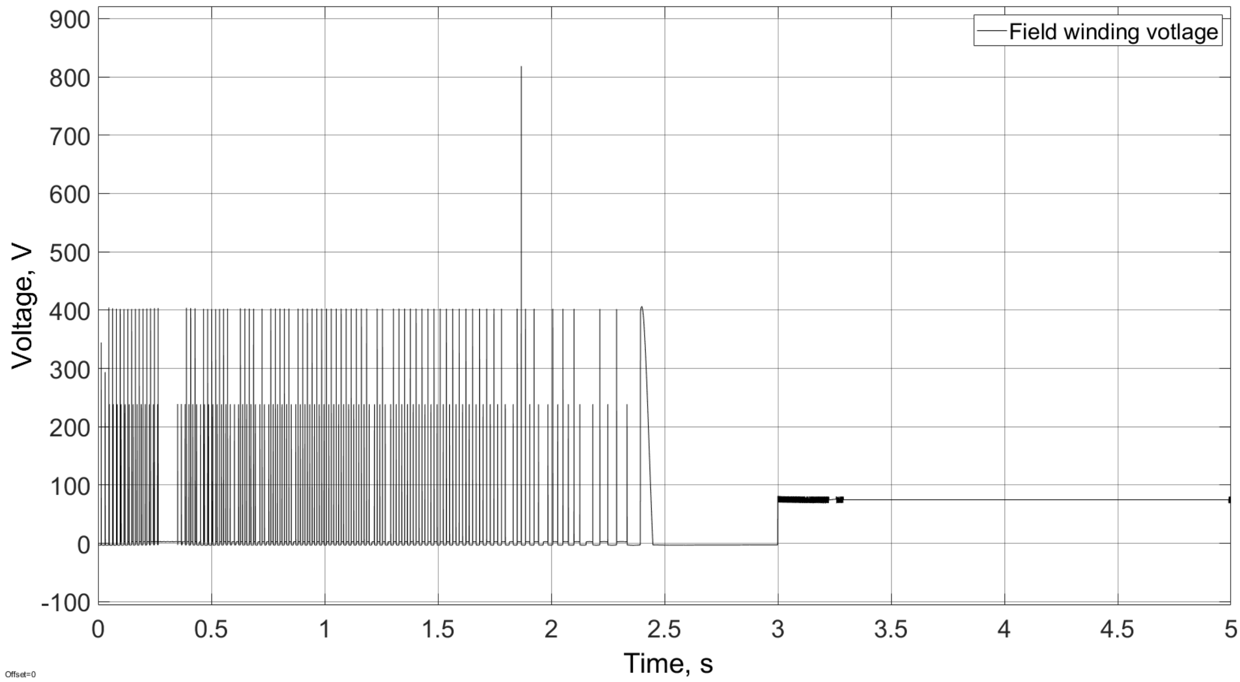

Figure 3.12 – Field winding voltage under induced voltage during DOL start

Figure 3.12 shows that the induced voltage on the diode bridge is now restricted to 400 V. There is a surge of 800 V on the plot, but the author's experience suggests that this surge is probably a result of the discrete nature of the simulation in the MatLab environment. Its width is negligibly small, equal to one sampling time period. After the excitation machine is turned on, the pulsating voltage smooths out at some moment of simulation, but it is certainly because of the variable step of simulation and does not change the whole picture. If we zoom in the plot, that is done on Figure 3.13, we can see that, excluding 400 V surges, that occur until the sensing circuit responds to the voltage, both negative and positive voltage drop is approximately equal to 2.6 V, which equals to the voltage drop, defined by the properties of the diode bridge diodes and thyristors.

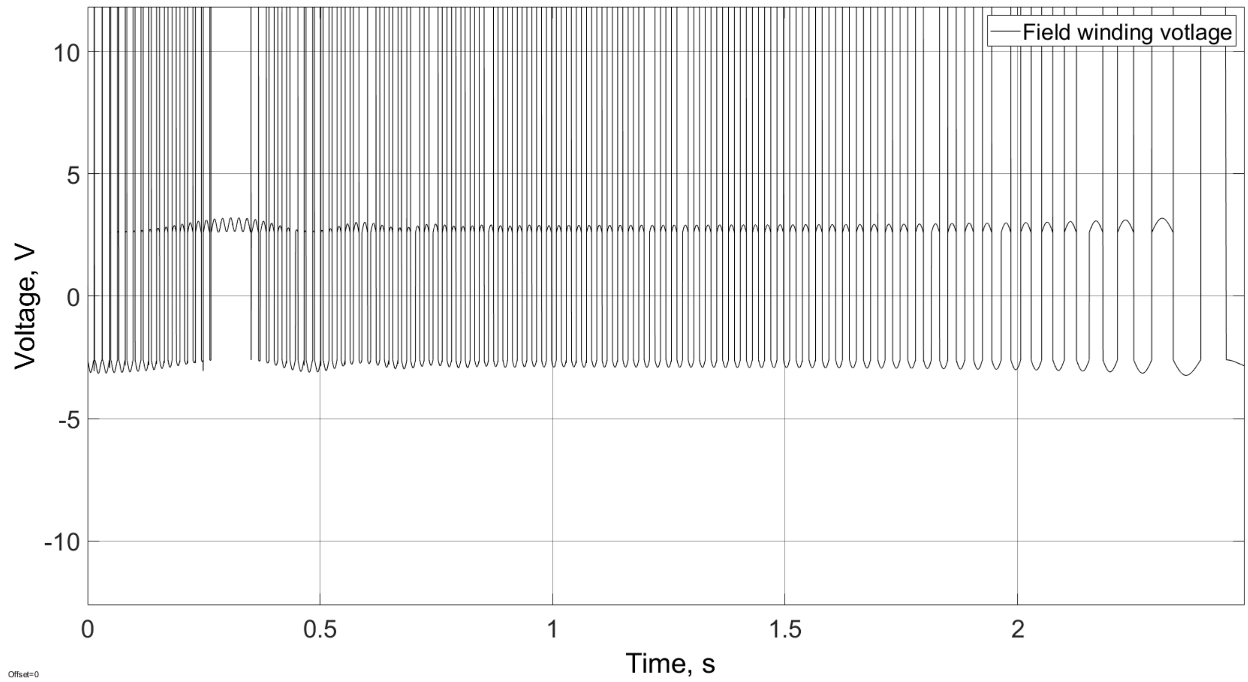

Figure 3.13 – Field winding voltage under induced voltage, zoomed.

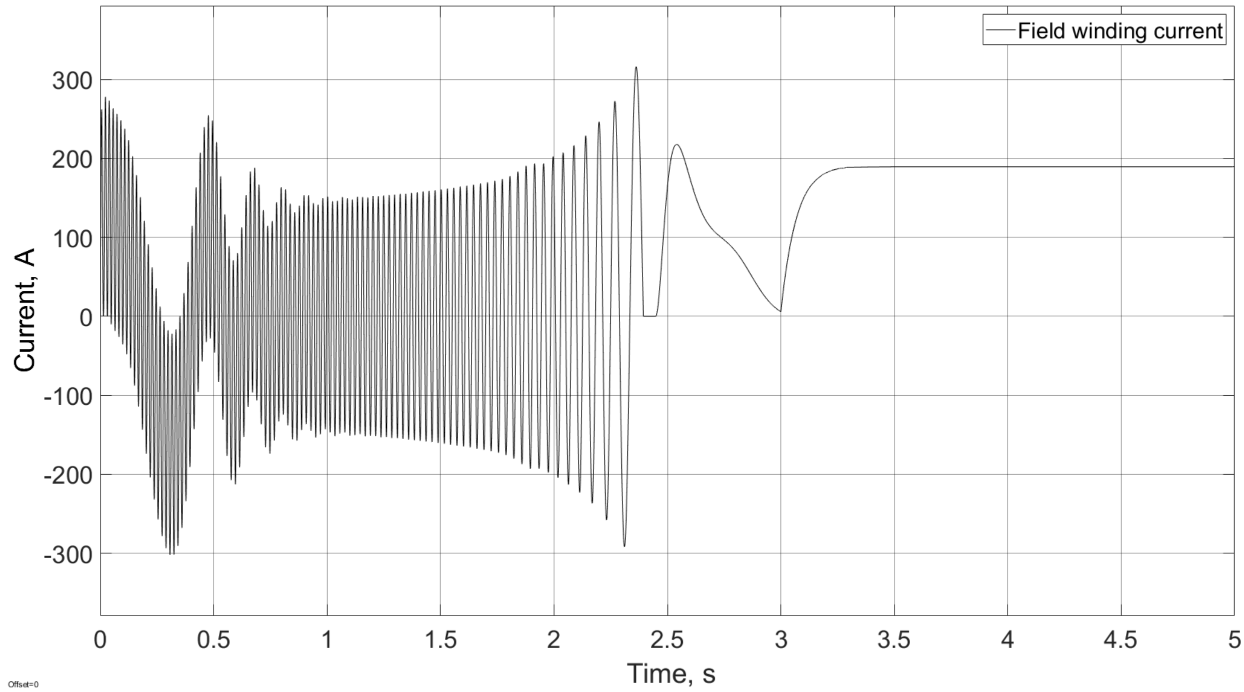

Figure 3.14 – Field winding current under induced voltage

Despite the fact that such a high voltage is shorted through such a small resistance, the current does not reach any relatively huge values as one can expect. The current is not high because the fact that main machine's excitation winding is highly inductive and resists the change of current in it. Moreover, the fact that induced voltage is alternating also makes the current smaller.

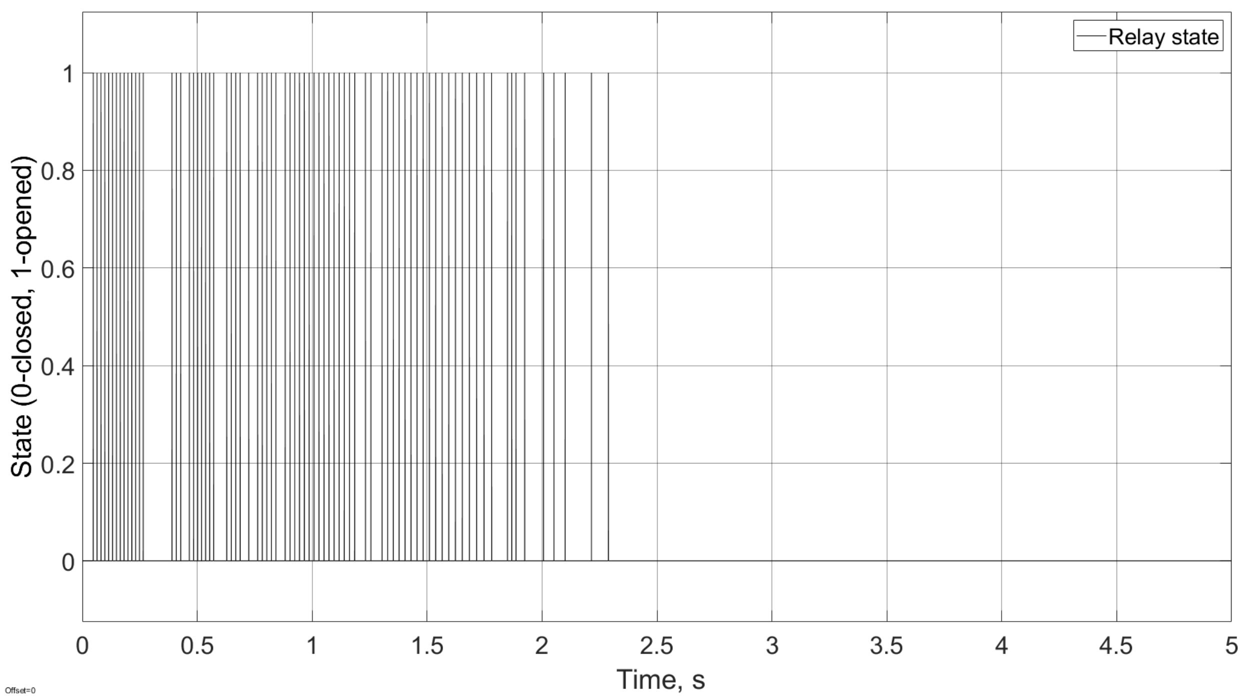

Figure 3.15 – Relay state plot (0-closed, 1-opened) under induced voltage

As it can be seen in Figure 3.15, the relay successfully switches the voltage to gate inputs, consequently turning the thyristors on. There are moments when the current continues to flow only through diodes for more than one period of induced voltage. This happens because of two facts: First, the induced voltage is not perfectly balanced and, second, excitation windings inductance resists the change of current in it and accumulates electromagnetic energy. Together, this creates time intervals, when the voltage with opposing sign happens to be not enough to reverse the current, already accumulated in the winding.

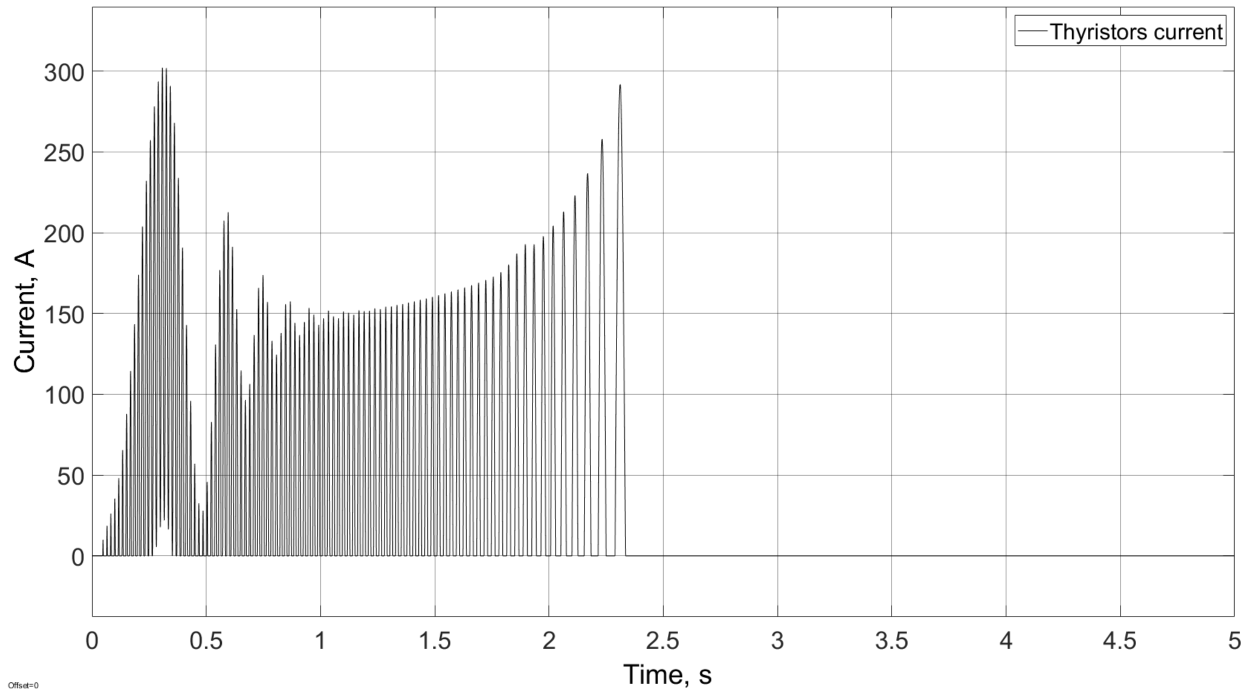

Figure 3.16 – Thyristors current under induced voltage

As it is seen in Figure 3.16, current successfully stops flowing through thyristors when induced voltage reverses polarity.

Two important notices must be made regarding this particular simulation:

1) The thyristors gate circuitry in this model is artificial to in some sense and does not ideally represents the real circuitry, that would be utilized in a real device. It needs further development in order to consider all issues that can connected with it, for example, as it was found out during simulation trials, problems with a proper gate current for thyristors opening.
2) In reality, the main synchronous machine is dependent on the protection device operation — when current, created by induced voltage, flows through excitations winding, it affects the acceleration of the machine. But, as it was shown in the beginning of this chapter, this effect is not significant. Nevertheless, in order to produce a proper model of the whole system, interconnection between the machine and the protection device should established.
3) In order to simplify the simulation, some devices in the model are also simplified, for example, as it was said before, a piecewise linear model was used for the semiconductor devices. Thus, a thorough examination of the device under development should include as much specific features of real devices as possible.

Conclusion

During the work done in this paper, an overvoltage protection device for a brushless excitation high power synchronous machine was analyzed. The following objectives were achieved:

1) Brushless excitation for a synchronous machine was introduced and discussed in the context of the topic under consideration;
2) The process of inducing voltage in the excitation winding of a synchronous machine during DOL start is investigated;
3) The features that the protection device should possess for this particular synchronous machine case are outlined;
4) A solution for a protection device is proposed and described in detail;
5) A model for the electrically excited synchronous machine under consideration is made and its operation is simulated in MatLab;
6) A model of the protection device, based on the proposed design, is derived in MatLab, tuned and tested;
7) The model's behavior is tested in application against voltage, induced in a synchronous machine, and its effectiveness is proven.

The majority of problems, encountered during this particular design were connected with the complexity of the system in general, its switching nature and discrete nature of MatLab environment calculations. Some devices' models were simplified, yet this should not have had a significant impact on the design in whole. Some weak points and further development direction can be stated:

1) The gate circuitry of thyristors is simplified because of simulation problems encountered during modelling. It does not represent the real circuits that must be used in a device at full, yet a general idea of them is presented in the paper. Anyway, more thorough consideration of this issue is needed.
2) The interdependence between the protection device and the main synchronous machine is not provided, yet it is proven that this interdependence should not significantly affect the operation. Still, it is recommended to be taken into account.
3) In general, more proper analysis of MatLab simulation algorithms, as well as more precise representation of protection device components is recommended and yet to be done.
4) It is recommended for sake of further development of the device to make a low power prototype of the device and test it in laboratory environment, for example, on sinusoidal voltage at least. This experiment might be very informative and may reveal the applicability and effectiveness of the concept at some degree.

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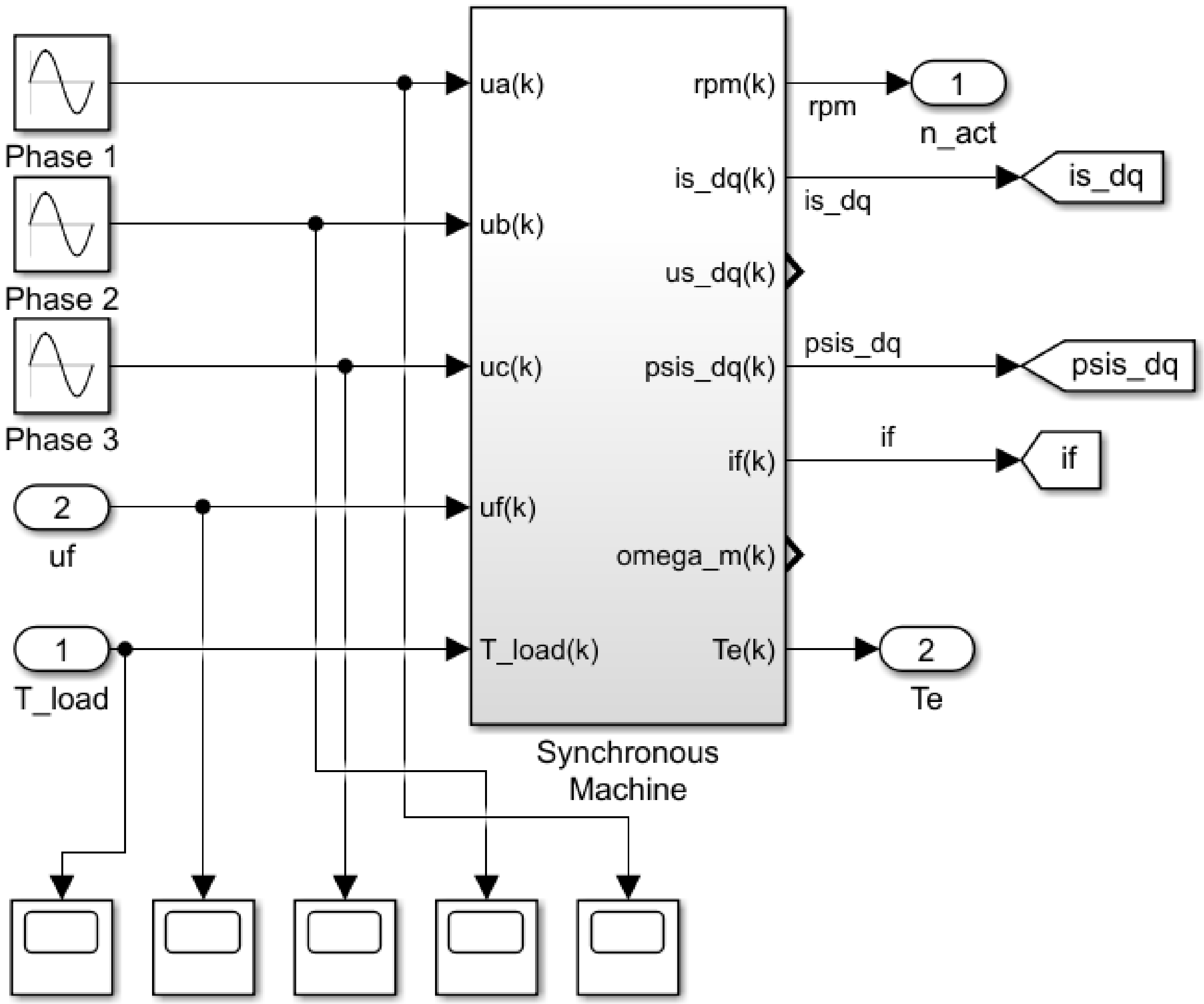
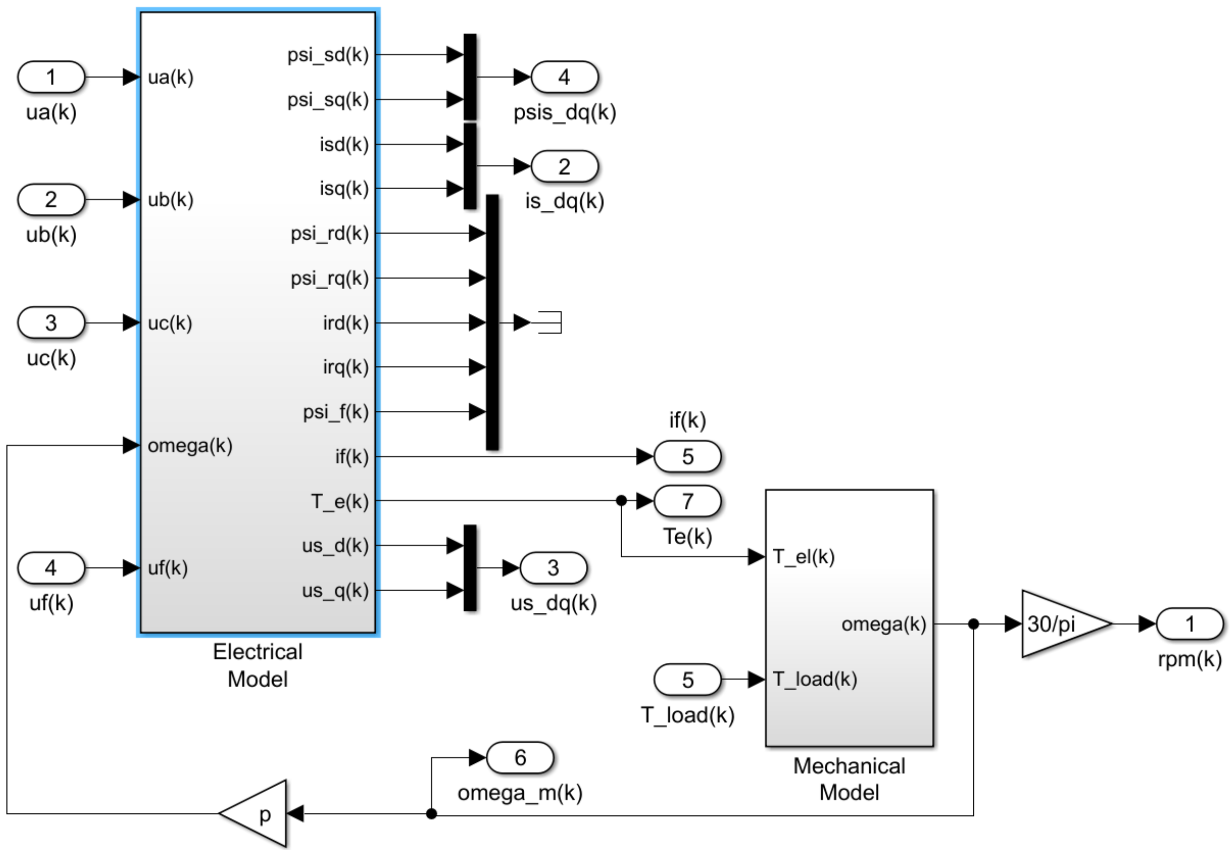
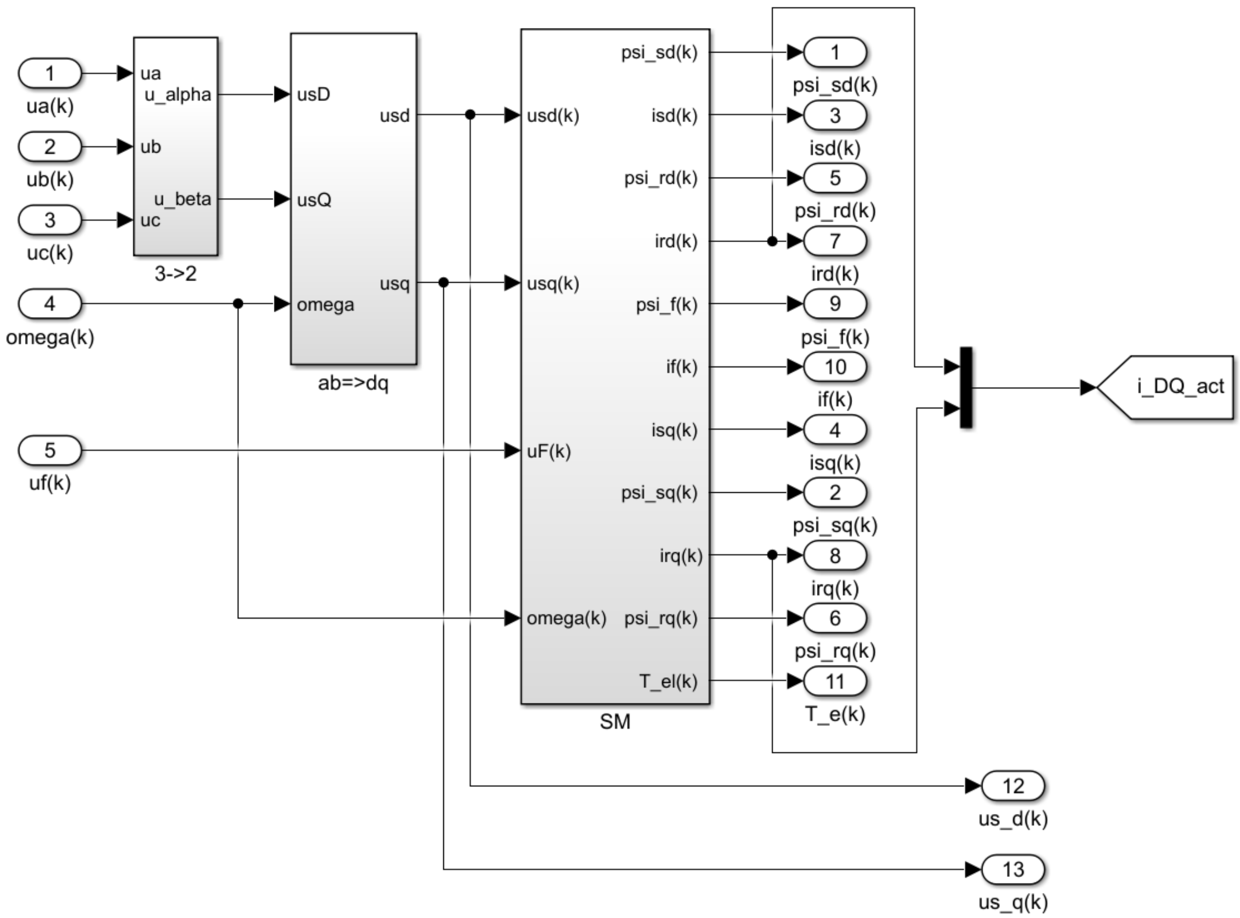
Appendices



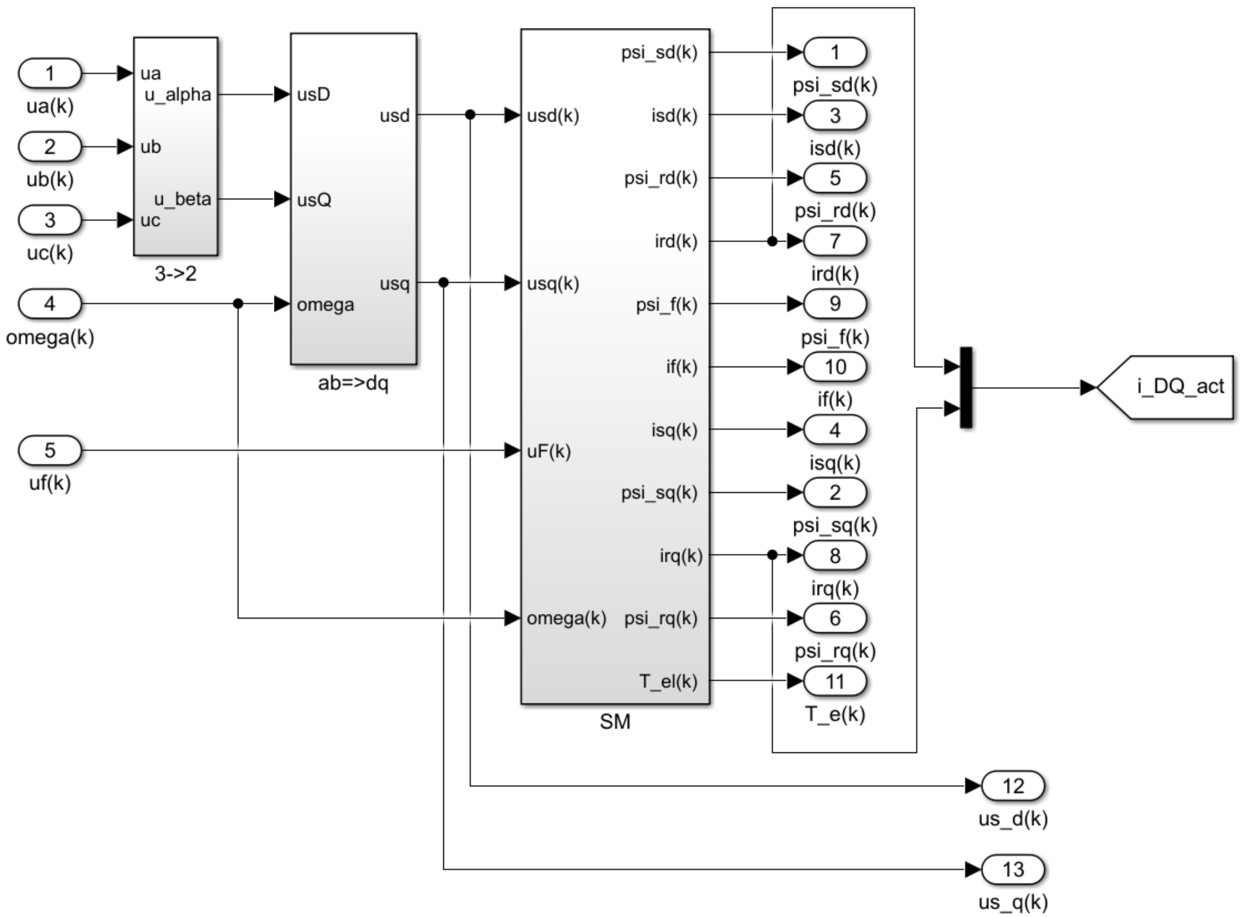
Appendix A – Second level of the EESM model with phase voltages.



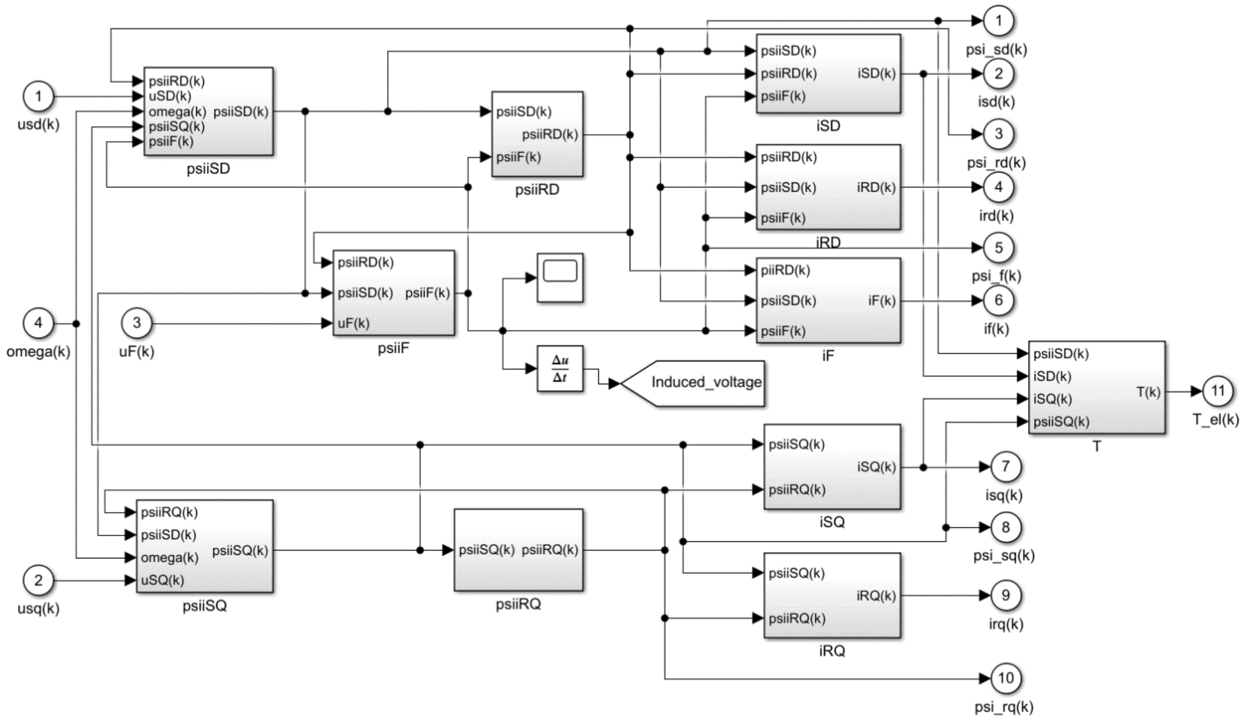
Appendix B – Third level of the EESM model with separated electrical and mechanical model.



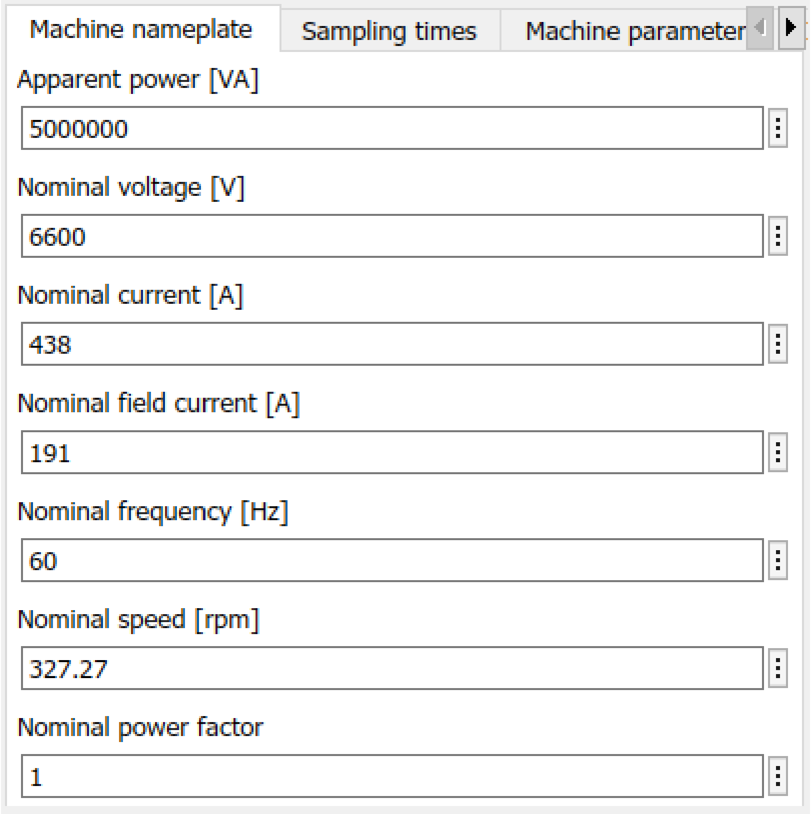
Appendix B – Third level of the EESM model with separated electrical and mechanical model.



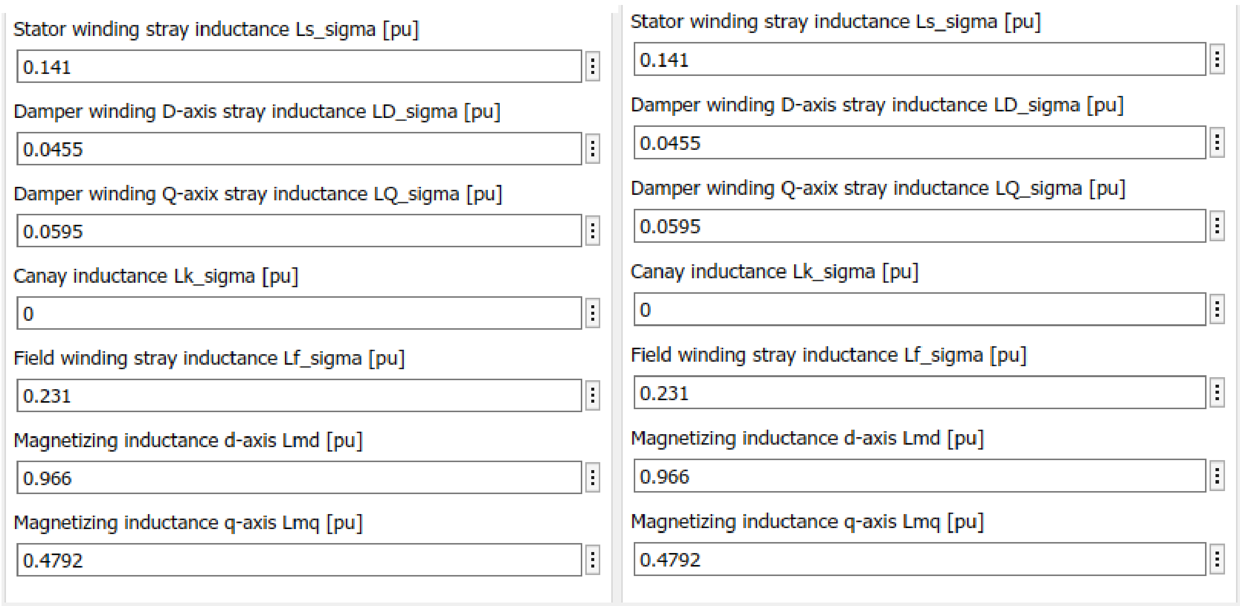
Appendix C – Fourth level of the EESM model with axes transformations.



Appendix D – Bottom level of the EESM model with fluxes and currents calculations.



Appendix E – Machine nameplate parameters of the synchronous machine under consideration.



Appendix F – Machine parameters of the synchronous machine under consideration.