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Algorithm for optimal voltage level at Krasíkov substation operating reactive power equipment available.

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To life, to work in a way that I could study abroad and complete one of my life goals. This experience has enriched me as a person and opened the door to new opportunities.

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To the ones that were and are not anymore, thanks for everything. This is also for you.

Declaration

I hereby declare that this master's thesis is the product of my own independent work and that I have clearly stated all information sources used in the thesis according to Methodological Instruction No.1/2009 – "On maintaining ethical principles when working on a university final project, CTU in Prague".

V Praze, 20. May 2022

Abstract

Voltage control of the network is a key point for Electric Power Systems. Load variations, network disturbances, and protection issues affect the performance of the network, and it is the duty of the dispatcher to adjust the network values to maintain the voltage margins. The following work presents the implementation of a primary and secondary regulation analysis for Substation Krasikov, a pilot node of the Czech Transmission system, with the inclusion of a Variable Shunt Reactor (VSR), the main Busbar. The conjunction of both controllers will produce a controlling algorithm to adjust the voltage in the pilot node and allow the operation of the VSR. Finally, some changes in the algorithm are discussed to adjust in a better way the setpoint in the voltage control.

Keywords: Modelling, Voltage control, Reactive Compensation, AVR, VSR, Stateflow, Matlab/Simulink

Supervisor: Ing. Martin Pistora
ČEPS a.s.

Abstrakt

Řízení napětí sítě je pro Electric Power Systems klíčovým bodem. Změny zatížení, rušení sítě a problémy s ochranou ovlivňují výkon sítě a je povinností dispečera upravit hodnoty sítě tak, aby byly zachovány napěťové rezervy. Následující práce představuje implementaci analýzy primární a sekundární regulace pro rozvodnu Krasikov, pilotní uzel České přenosové soustavy, se zahrnutím Variable Shunt Reactor (VSR), hlavní přípojnice. Spojení obou regulátorů vytvoří řídicí algoritmus pro úpravu napětí v pilotním uzlu a umožní provoz VSR. Nakonec jsou diskutovány některé změny v algoritmu, aby se lépe upravila požadovaná hodnota v řízení napětí.

Klíčová slova: Modelování, řízení napětí, reaktivní kompenzace, AVR, VSR, Stateflow, Matlab/Simulink

Překlad názvu: Algoritmus pro optimální nastavení napětí pomocí jalového výkonu v rozvodně Krasíkov

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Chapter 1

Introduction

ČEPS is the company, within the Czech Republic, in charge of the operation of the transmission network. As a system operator controls the available network elements to handle reactive power injection for regulating the voltage in an operating range to reduce losses, stable state, or some disturbance that can occur. To do it, ČEPS network divides the transmission network into pilot nodes, divided into "non interactive regions" to control the voltage from the inside up to the complete electrical system.

The strategy used is well known in many literatures and applied widely, with some approaching differences. The primary, secondary, and tertiary regulations are part of ČEPS dispatching center. Where the calculations define the voltage reference in the pilot nodes or internal nodes, if possible, with the tertiary regulation, which is a global optimizator of the network according to the network constraints. Then, this voltage reference acts in the secondary regulation where all the machines of the region meets the voltage reference. Finally, for local disturbances or uncontrolled machines, the primary control acts directly on the setpoint of the excitation field of the synchronous machine to adjust Voltage terminals and influence the network.

The analysis bases on the Q/V characteristics in the reactive power sources. For synchronous machines, a change in the excitation field of the machine can change the internal angle between the voltage field and the voltage terminal, adjusting the reactive power of the machine without losing Active Power Capabilities. For a Variable shunt reactor, the change of the inductance by the tap modification varies the voltage level in the connection point. To research about this features and their applications within the network, modeling process is a key point. All the network elements can be expressed as an equivalent circuit, sharing the same base values, allowing the analysis as a simple electrical network circuit. This approach allows electrical engineers to investigate about network conditions using engineering simulation tools. This thesis uses Matlab/Simulink and its library Specialized Power Systems to visualize the response of the network under tested circumstances.

Therefore, the study starts with an overview of ČEPS controlling techniques, with more interest in the secondary and primary regulation, the subject of interest in this research. Then, it covers the description of the Krasikov Substation elements (Synchronous machines, VSR, Transformers) and the equations behind to model the system in Matlab/Simulink. The equations and base values parameters pass the formulation of the Primary and Secondary control of Krasikov Substation and for the VSR. Finally, simulation results are presented and an improval technique is discussed for the whole system.

The simulation trends show that the model process respects the reactive power limits, and the voltage regulation technique applies under different situations. Although there are more standardized ways to formulate a Secondary regulation, the method used allows the system to follow the voltage reference. The VSR works as expected, it regulates Krasikov Busbar and does not influence the states of the synchronous machines. The optimization applied works more on the contribution of the system to speed up the process of regulations due to the machine's capability and time constants, but future works can improve the setpoint of the voltage reference by any optimization technique.

Chapter 2

Voltage Control in the Czech Transmission system and Substation Krasíkov

2.1 Voltage Control principle in the Czech Transmission System

Voltage Control is one of the essential operating tasks of system operators and power utilities to keep the voltage within an allowable range for high-quality customer services [12]. The change of power loads connected to the grid affects the voltage profile. System operators in dispatching centers handle reactive power injection for controlling voltage within an established operating range to reduce power losses and assure the correct functioning of loads connected to the grid. With the integration of new technologies and efficiency standards, customers require precision to maintain voltage within the predefined limits. On the interface where transmission and distribution systems interact (i.e., at voltage level 110 kV), predefined voltage values are upon agreement of the two operators (typically within ± 10 % of the nominal value) [12].

Traditionally, there are four methods to regulate distribution system voltage used by voltage management services, including [12]:

- On-load tap changing transformers (OLTC).
- Shunt capacitors banks (and reactors) switching.

- Synchronous and static compensators.
- Generating unit excitation systems.

Voltage control problem, connected with voltage stability issues, is a critical power system security issue. Instability appears when a disturbance, increase in load demand, or change in system condition causes a progressive and uncontrollable drop-in voltage. The local character of the voltage level, the diversity of the control means, and the interaction between them make voltage control particularly complex [12]. The Czech Power network system works with the Voltage and Reactive power (U&Q) control principle like other European countries. The primary task in the Czech Republic Transmission System is to keep the voltage within the permitted limits and provide a safe and economical operation [1].

The structure of the voltage and reactive power control is a three-level hierarchical structure explained in Figure 2.1.

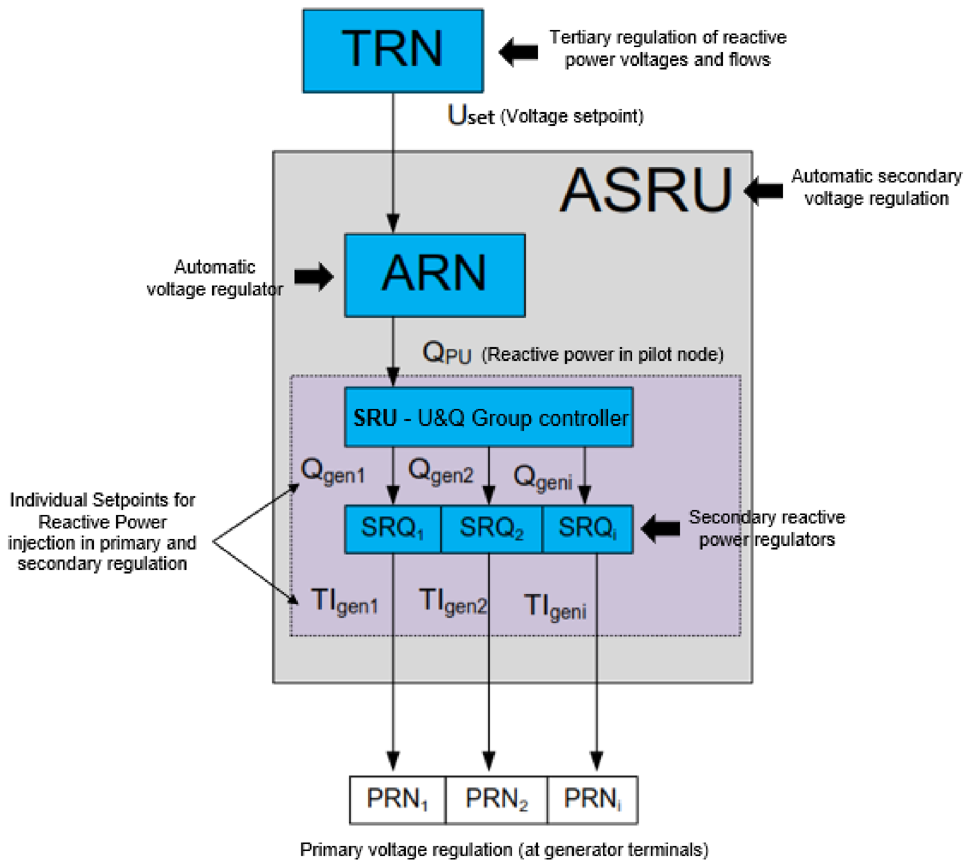


Figure 2.1: U & Q control hierarchy [1]

The voltage of the network is mainly affected by the voltage maintained in the pilot nodes [1]. The network divides into non-interactive zones where generators and other compensatory means helps to control the voltage's value in the central bus called Pilot Node. For this purpose, the control system divides as follows:

1. **Tertiary regulation of reactive power voltages and flows (TRN):** TRN performs a mathematical calculation to optimize the voltage over the whole transmission system, providing ASRU optimal settings every three minutes or when the dispatcher requires, the objective function used by TRN is to minimize active power loss while respecting all assigned constraint limits and maintaining sufficient reserves of reactive power sources in case of network failures.

2. **Automatic secondary voltage regulation (ASRU):** The ASRU controls the equipment in charge of the voltage compensation entering the values from TRN recommendations from the ČEPS dispatching center, supporting the voltage on the transmission system using the Automatic Voltage Regulation (ARN) to respond to the deviation of the actual voltage from the input at the pilot node, and determining the required reactive power at individual compensation equipment (generators, static and synchronous compensators, reactors, OLTC). U & Q controllers (SRU) ensure a proportional distribution of the required reactive power from ARN according to the available range to individual equipment. Finally, the Secondary reactive power controller (SRQ) responds to the deviation of the actual reactive power to the specified SRU value.

3. **Primary voltage regulator (PRN):** The PRN regulates the voltage at the generator terminals responding to the deviation of the actual voltage with the specified voltage from the SRQ at the generator terminals. The PRN controls the magnitude of the excitation winding and thus the magnitude of the reactive power respecting the under and overexcitation limits determined by certified PQ diagrams. In block exclusion from ASRU (SRU-locally), the PRN does not receive any commands from SRQ and responds only to the terminal voltage deviation [1].

The process through levels defined in equipment gets clear in Figure 2.2. The scope of this study is in the zone marked by the green box.

ČEPS delivered the current control parameters and voltage regulators at the PRN level and SQR units to elaborate on this thesis. Therefore, the main framework is the analysis of the operation of the compensating equipment available and the estimation to choose a proper algorithm with

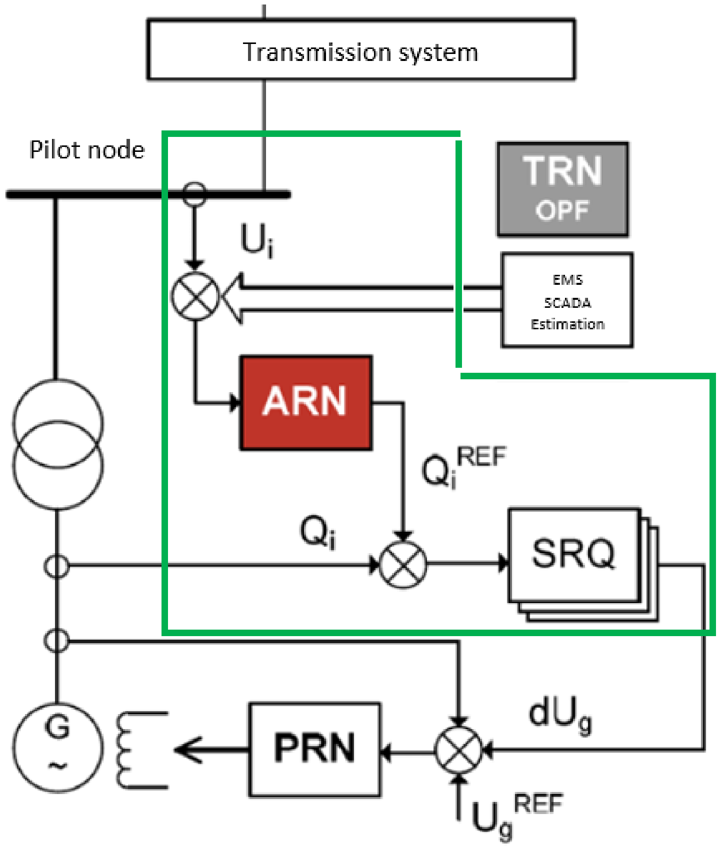


Figure 2.2: Control structure in the pilot node [1]

the capability of optimization to produce the values for SQR from the ARN system considering the limits and the methodology applied by ČEPS.

2.2 Description and Software representation of Substation Krasíkov

The case study is Substation Krasíkov, a pilot node in the Czech Power network system. Figure 2.3 shows its representation from the ČEPS dispatching center with the components connected at different voltage levels.

Substation Krasíkov is a double bus system at Transmission Level that connects five power lines and three step-down Transformers. Four of these lines direct to different locations (V_401 Týnec, V_402 Prosenice, V_453 Neznášov, and V_458 Horní Životice). At the same time, V_457 joins the Pump Storage Hydrohidraulic Power Station with two Turbines that can

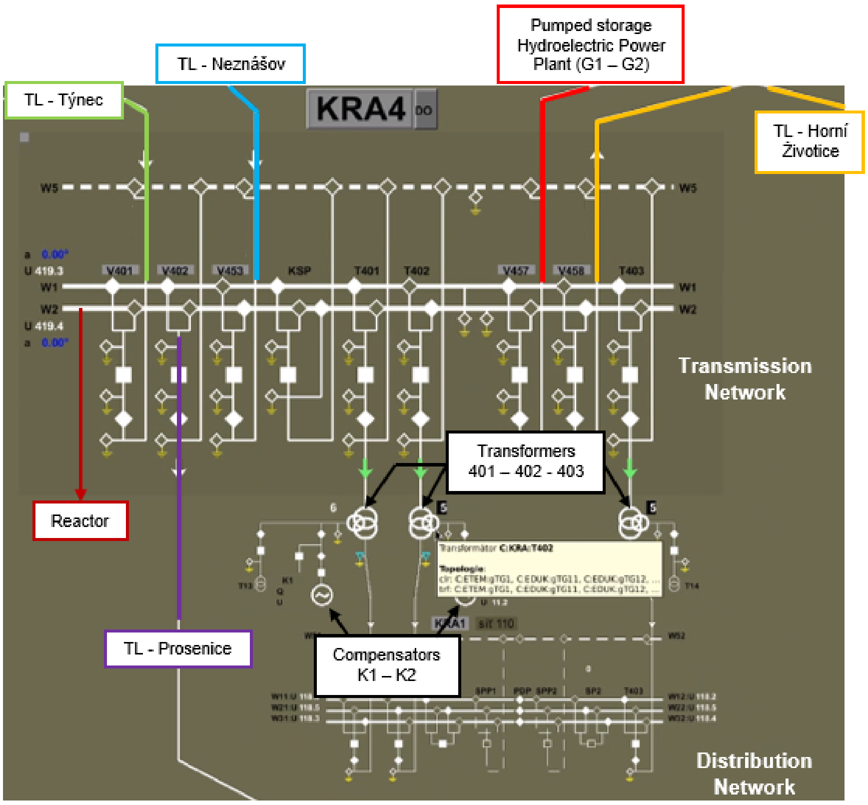


Figure 2.3: ČEPS operation center representation of Krasikov Substation

function as Synchronous Generators (G1 and G2) and Pumps connected through two step-up two winding Transformers (T1 and T2). Figure 2.4 displays a simple model enough for the Power Station overview. Finally, a variable shunt reactor (VSR) will be present directly in the main busbar. The three step-down three winding Transformers (T401, T402, and T403) produce a 110 kV Distribution Network. There are two reactive compensators in the tertiary winding composed of two synchronous condensers.

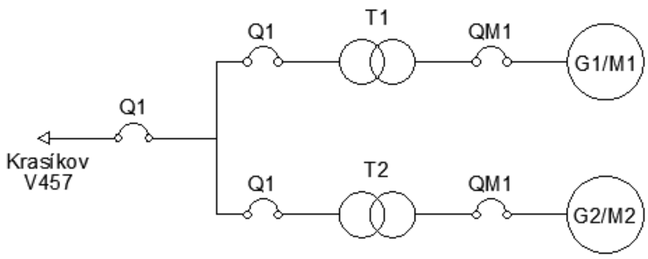


Figure 2.4: Pump Storage Hydrohidraulic Power Station

To analyze the substation operation with the compensation equipment to propose an algorithm method, a mathematical modeling process stands in specialized software. The study develops in Matlab/Simulink using the Specialized Power Systems and Stateflow libraries, adequately representing the substation's elements and the interaction with the algorithm actions. A non-disclosure agreement protects the modeling data of the equipment delivered for this study. The data includes the parameters required for Matlab to model the power lines, compensation devices, generators, transformers, and the certified PQ diagrams limiting reactive injection in addition with some assumptions necessary to simplify and complete equipment parameters. An m. file gathers all the model parameters, calculations and control values used within the simulation. Table 1 summarizes the primary information of the equipment of Substation Krasíkov for modeling, including the simplification mentioned.

Item	Description	Abbr.	Type	Voltage	Power	Q limits
1	Generators	G1/G2	Synchronous machine	22 kV	355 MVA	131/ -42 MVAR
2	Condensers	K1/K2	Synchronous machine	10.5 kV	125 MVA	110.59/ -55.28 MVAR
3	Two winding Transformers	T1/T2	Ynd1	420/ 22 kV	360 MVA	
4	Three winding Transformers	T401/ T402/ T403	Y/Y/D	420/ 110/ 10.5 kV	350 MVA	
5	Variable Shunt Reactor	VSR	OLTC	420 kV	60/120 MVA	
6	Power Line	V_457	59.8 km	400 kV		
7	Transmission Network			400 kV	15118 MVA	

Table 2.1: Primary data of Substation Krasíkov equipment

Chapter 3

Substation Krasíkov Mathematical Model

3.1 Synchronous Machines

Substation Krasíkov presents four synchronous machines: two generators and two condensers. The generators are two Hydro turbines located in the Pump Storage. The turbine head includes the generators' composing elements, and the water flows through the blades moving the turbine's shaft for electricity production. Furthermore, the two condensers are in Substation Krasíkov, where two small motors run the machine's shafts to adjust the speed, and the network's control pursues the reactive compensation. The theoretical principles and the development of the equations describing synchronous machines and their excitation systems are available in many references [5] [13] [14]. The interest of this chapter consists in understanding the synchronous machine in different operational modes, the role of the excitation system in reactive power compensation capability, and the application of the mathematical model using the available data to input in Matlab/Simulink elements for Synchronous machines and Excitation systems. ČEPS provided machine and excitation parameters for modeling. Although a disclosure agreement protects the data, the mathematical model will detail the constants selected. The mathematical model is the same for all machines, and the difference stands in the command mode within the simulation. The mathematical models for the synchronous machine and the excitation system are available in Matlab/Simulink based on the IEEE criteria design.

3.1.1 Operational Modes

The synchronous machine can operate as a generator, motor, or compensator. Figure 3.1 displays the different arrangments of the machine for this study, and its main interactive elements [15]:

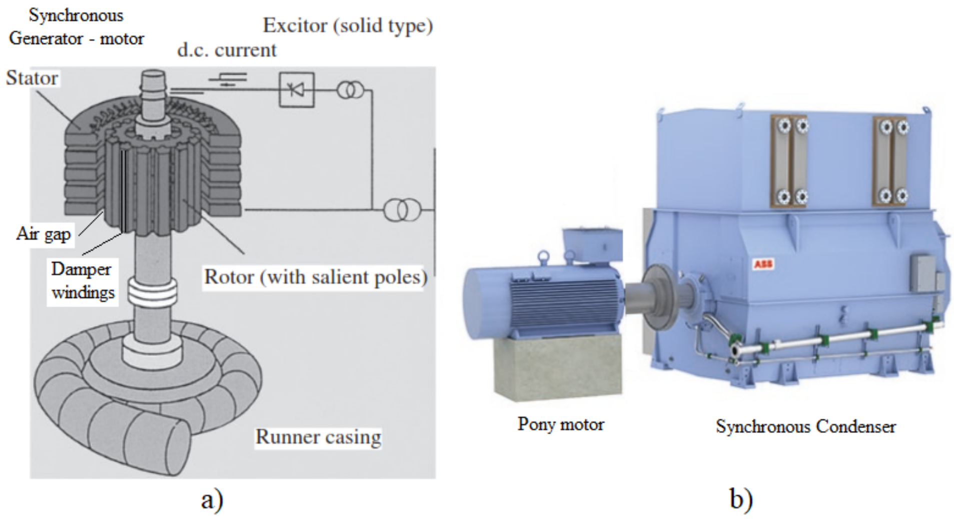


Figure 3.1: Synchronous Machine composition: a) Generator - motor for pumping up station [2] b) Condenser and pony motor [3]

- **Stator:** Stationary magnetic composed of core and windings, which operate on an AC power supply.
- **Rotor:** Consist of rotating active parts, where the exciter magnetizes the field-pole winding with direct current. From nominal speed, rotor construction divides into round rotor (high speed) and salient pole (low speed) configurations. Generators and compensators in this study are salient poles due to the availability of the data.
- **Exciter:** This attachment supplies magnetizing current to the field winding. Modern exciters are of the rotating brushless type with no collector rings or brushes.
- **Damper winding**: A set of bars integrated into the rotor allows the machine to self-start like a squirrel-cage induction motor and protection to clear faults.
- **Air gap:** It is the space between the stator and the rotor

The machine receives the name synchronous because its rotational speed is the synchronous speed. This value is constant and calculated from the following relation

$$n = \frac{60f}{p},$$

where

n = Synchronous speed [RPM],

f = Frequency from the Network [Hz],

p = Number of pole's pair in the rotor.

Stator and rotor fields must rotate at the same speed for steady operation[5].

As a **generator**, an external mechanism moves the machine rotor shaft and the rotor's magnetic field up to the synchronous speed. The flux variation in time between the stator and rotor magnetic fields induces an electromagnetic force in the stator. When **motor**, the nominal voltage on the stator produces currents that generate a rotational magnetic field, and with coordination with the motor's start-up method, the rotor can reach synchronism speed. At **Condenser**, a small motor drives the machine rotor shaft to synchronous speed. Then, the excitation system controls the injection or absorption of reactive power to the network.

3.1.2 Reactive Power Capability

The excitation system provides direct current to the synchronous machine field winding. Excitation systems regulate the power system's performance by controlling the synchronous machine's voltage and reactive power flow, enhancing the synchronous machine's protection functions due to its reactive power capability to improve stability [5]. The critical prevention is to avoid excessive heating and loss of excitation. The armature and field current limits reduce RI^2 power losses according to its rated MVA, applied voltage, and power factor rating. At the same time, the machine design restricts the underexcited action (lead power factor) due to the increase of the leakage flux at the end region in the stator. The reactive capability curve, shown in Figure 3.2, expresses the synchronous machine restraining considerations for improving efficiency and excitation systems implementation.

IEEE[4] explains in Figure 3.3 the representation of the synchronous machine excitation systems for power system studies.

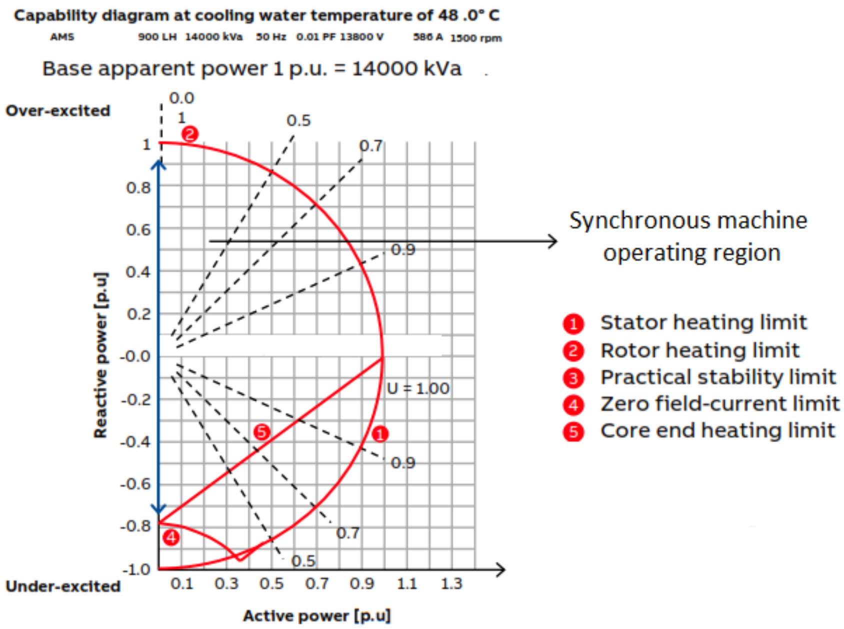


Figure 3.2: Reactive Capability curve for 140 MVA Synchronous Machine [3]

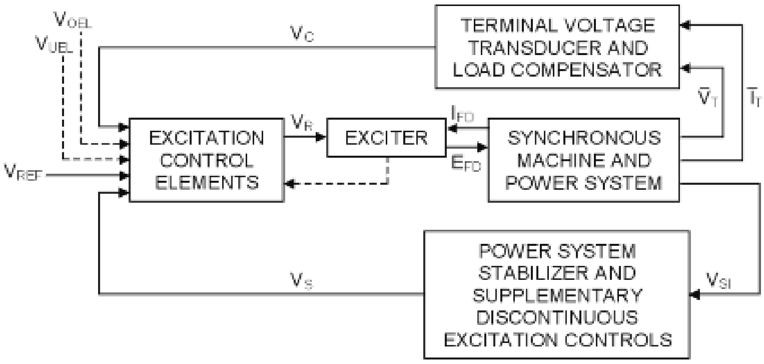


Figure 3.3: Synchronous machine excitation representation [4]

- **Exciter:** Provides DC power to the synchronous machine field winding.
- **Excitation Control Elements:** Processes and amplifies input control signals to a level and form appropriate for exciter control.
- **Limiters and protective circuits:** The control and protective functions ensure the exciter and synchronous machine works within the capability limits. Standard functions are the V/f protection, field-current limitation, over and under excitation threshold, and terminal voltage limiter.
- **Transducer and load compensator:** Sense generator terminal voltage, rectifies and filters it to dc quantity for the control loop. When the voltage terminal is remote, load compensation is possible.

- **Power System Stabilizer:** Provides an additional input signal to the regulator to damp power system oscillations.

The selection of the appropriate excitation system comes from the excitation power source, and its classification is[4]:

- **DC excitation systems:** Utilizes a direct current generator with a commutator as the source of excitation system power.
- **AC excitation systems:** Use an alternator and either stationary or rotating rectifiers to produce the direct current needed for the synchronous machine field.
- **ST excitation systems:** Excitation power supplies through transformers or auxiliary generator windings and rectifiers

The excitation system commands the generator to work as a reactive power source in the generator. The objective is to meet reactive power demand inside over and underexcitation limits, respecting the voltage limits (usually between -5% and +5%), with a possibility of a short time overload capability. While, in the Condenser, even if its losses are considerable, its power factor is near zero, allowing it to fully deliver or absorb reactive power, respecting the same limits as in the generator. The excitation system can automatically run overexcited at high loads and underexcited at light loads. However, in the condenser case, its amount of supplied/absorbed reactive power will depend on the operating voltage setpoint value [16]. Excitation systems combine OEL and UEL in their composition to protect the machine in boundary situations, as explained in 3.1.

OEL (Overexcitation limit)	UEL (Underexcitation limit)
Allow overexcitation for a defined time-overload period	Prevent overheating and loss of synchronism
Reduce excitation to a safe level	Boost voltage in the excitation

Table 3.1: Over and Under excitation Limit principles

OEL uses the field winding temperature, current limiters, exciter field current, and voltage to measure overexcitation conditions. The allowed overexcitation period may be fixed or vary inversely with the excitation level. The excitation level may be reduced instantaneously, ramping or stepping down the reference set point, or transferring control from the AVR to a lower manually controlled field voltage set point. The UEL typically senses either a combination of voltage and current of the synchronous machine or a combination of real and reactive power. The UEL output is either a summing junction to add to the voltage control or an HV gate to override the action of the voltage regulator. Its limiting characteristics rely on the circular diagram of the machine [4]. The aim of this study is the examination of different voltage values in the Substation Krasíkov busbar. Therefore, the simulation will maintain a constant active power in generators and compensators to meet the reactive power behavior specified alongside the data delivered by ČEPS for the excitation system with the OEL and UEL included.

3.1.3 Generator and Condensers mathematical model

The idea for the mathematical model starts with the Schematic from the Figure 3.4 showing the machine's physical configuration to the equivalent model in Matlab/Simulink. The stator has three windings (phases a, b, c) arranged electrically by 120° symmetrically. The stator windings can be multiple poles, but its internal organization keeps the principle. The rotor has two axes of mechanically rectangular symmetry: the d-axis or direct axis and the q-axis or quadrature axis. The direct axis is centered magnetically in the center of the north pole, and the quadrature axis is 90 electrical degrees ahead of the d-axis, as illustrated in IEEE standard definition. The rotor circuits comprise field and damper windings divided in both axes [5] [2].

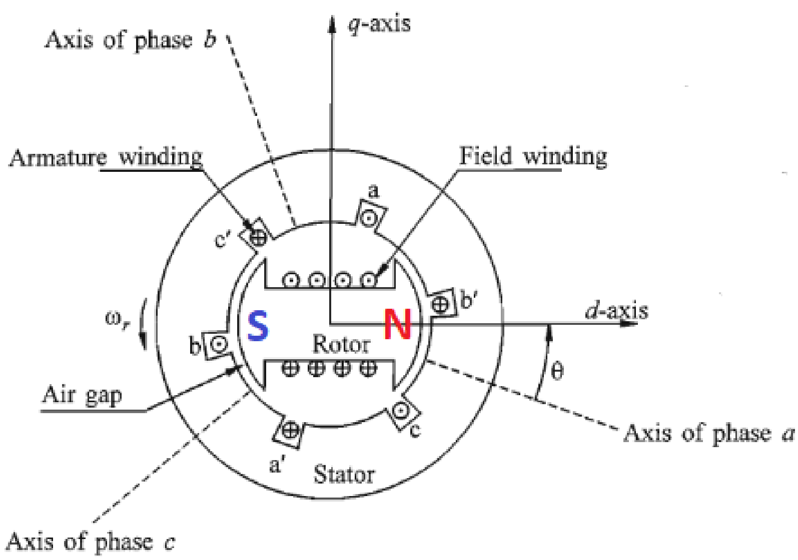


Figure 3.4: Synchronous machine Schematic [5]

The angle theta is the leading difference between the d-axis with the phase a winding positions in the direction of the rotation affecting the magnetic characteristics between stator and rotor, introducing a considerable solving complexity. Park's transformation simplifies the problem. It replaces the three stator windings a, b, c with three fictitious rotor windings called d, q, and 0 (rotor coordinates system). The windings disposed of in the d-axis and q-axis are rotating together with the rotor, and there are no mutual couplings between them. The 0-axis is independent of the d-axis and q-axis since zero sequence currents flow through it only in unbalanced conditions. The main advantage of the Park transformation is that all windings are stationary to each other. Therefore, the magnetic characteristics of self and mutual inductances are constant in time [16].

The presented equation system below sums up the physical response in the synchronous machine's flux linkage, voltage, and currents between stator and rotor windings, and it is the mathematical model utilized in Matlab/Simulink from IEEE standard 1110-2002 [17]:

$$
\begin{aligned}
V_d &= -i_d R_s - w\psi_q + \frac{d\psi_d}{dt} \\
V_q &= -i_q R_s - w\psi_d + \frac{d\psi_q}{dt} \\
V_{fd} &= \frac{d\psi_{fd}}{dt} + R_{fd} i_{fd} \\
V_0 &= -i_0 R_0 + \frac{d\psi_0}{dt} \\
0 &= \frac{d\psi_{kd}}{dt} + R_{kd} i_{kd} \\
0 &= \frac{d\psi_{kq1}}{dt} + R_{kq1} i_{kq1} \\
0 &= \frac{d\psi_{kq2}}{dt} + R_{kq2} i_{kq2}
\end{aligned}
\tag{3.1}
$$

$$
\begin{bmatrix} \psi_d \\ \psi_{kd} \\ \psi_{fd} \end{bmatrix} = \begin{bmatrix} L_{md} + L_l & L_{md} & L_{md} \\ L_{md} & L_{kd} + L_{f1d} + L_{md} & L_{f1d} + L_{md} \\ L_{md} & L_{f1d} + L_{md} & L_{fd} + L_{f1d} + L_{md} \end{bmatrix} \begin{bmatrix} -i_d \\ i_{kd} \\ i_{fd} \end{bmatrix}
$$

$$
\begin{bmatrix} \psi_q \\ \psi_{kq1} \\ \psi_{kq2} \end{bmatrix} = \begin{bmatrix} L_{mq} + L_l & L_{mq} & L_{mq} \\ L_{mq} & L_{mq} + L_{kq1} & L_{mq} \\ L_{mq} & L_{mq} & L_{mq} + L_{kq2} \end{bmatrix} \begin{bmatrix} -i_q \\ i_{kq1} \\ i_{kq2} \end{bmatrix}
$$

$\psi_d, V_d, i_d =$ Winding flux linkage, voltage and current in stator d-axis

$\psi_q, V_q, i_q =$ Winding flux linkage, voltage and current in stator q-axis

V_0, i_0 = Voltage and current in stator 0-axis

$\psi_{fd}, V_{fd}, i_{fd}$ = Flux linkage, voltage and current in field winding

ψ_{kd1}, i_{kd1} = Flux linkage and current in d-axis damper winding

$\psi_{kq1,2}, i_{kq1,2}$ = Flux linkage and current in q-axis damper winding

$R_s, R_0, R_{fd}, R_{kd}, R_{kd}, R_{kq1,2}$ = Stator, zero, field, d-axis damper, q-axis damper winding resistance

L_{md}, L_{mq} = d and q axis stator to rotor mutual inductance

L_{fd} = Field winding leakage inductance

L_l = Stator leakage inductance (both d- and q- axis)

L_{fld} = Differential leakage between armature and field windings

$L_{kd}, L_{kq1,2}$ = d and q axis damper winding leakage inductance

w = Angular frequency ($2\pi f$)

Eq 3.1 covers the whole dynamics in the machine. However, to examine voltage regulation, upcoming assumptions and working conditions will rule the resulting study:

- The model develops using the Park transformation with two axes 90 electrical degrees apart, simplifying the flux-current relationship in two independent networks.
- The synchronous machine simulation will work in balanced conditions neglecting the zero-sequence component.
- The stator windings are sinusoidally distributed along the air gap as far as the mutual effects with the rotor are concerned.
- Model examination discards magnetic hysteresis.
- Magnetic saturation effects are negligible to achieve decomposition of the fluxes into d and q axes.
- The model commonly outlines other current paths in the rotor, such as damper windings on the direct and quadrature axes. Albeit Equation 3.1 names two damper circuits, a pole salient synchronous machine consists of only one. Nevertheless, analyzing voltage stability with reactive power supply does not include Damper-circuit effects.

Equations 3.1 are the fundamentals for the Synchronous machines models in the Specialized Power System package. There are three synchronous machines models: Simplified, Fundamental, and Standard model shown in Figure 3.5. The Simplified model describes the electrical system for each phase consisting of a voltage source in series with an RL impedance implementing the internal impedance of the machine. The Fundamental and Standard models define the synchronous machine as a sixth-order state-space model, described in Eq 3.1, representing the machine's electrical part, considering the dynamics of the stator, field, and damper windings in the equivalent circuit of the model in the rotor reference frame (qd frame), with all rotor parameters and electrical quantities viewed from the stator [6]. The mechanical approach is the same for the three models. This work discards the Simplified model to examine the dynamics during the voltage regulation and its effect on the generators and compensators.

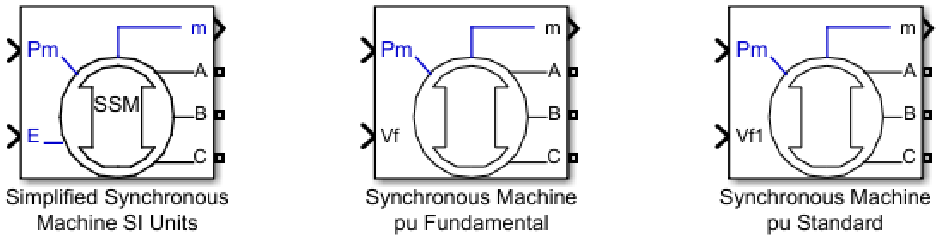


Figure 3.5: Synchronous machine models in Simulink [6]

The difference between the fundamental and standard parameters is that the fundamental parameters determine the electrical characteristics of the synchronous generator relating to the stator and rotor terminal quantities; in contrast, the standard parameters outline the synchronous machine's electrical characteristics in the form of effective inductances or reactances seen from the machine terminals. Consequently, standard characteristics reflect sustained transient and sub-transient conditions, and the corresponding time constants determine the decay rate of currents and voltages [16]. The simulation chooses generators and condensers in the Standard Parameters per unit values synchronous machine to compare the course of transient signals and the easiness of their calculation. The standard parameters used by Matlab/Simulink and present in the system of Equations 3.1 are:

- L_l **Armature Leakage inductance:** Its estimation comes from the manufacturer at the design stage.
- $L_d = L_{md} + L_l$ **Direct Axis Synchronous Inductance:** Ascertained by an open-circuit test or steady-state shortcircuit test
- $L_q = L_{mq} + L_l$ **Quadrature Axis Synchronous Inductance:** Discovered after a slip test.

- **The d-axis and q-axis open-circuit sub-transient time constant T"d0 and Tq"0:** characterizes the initial decay of the transients in the d-axis and q-axis variables immediately after a disturbance in the synchronous machine with the stator winding open-circuited.
- **The d-axis open circuit transient time constant Td'0:** Distinguishes the decay of transients in the d-axis after the sub-transient period prior to the steady-state with the stator winding open-circuited.
- The sub-transient and transient short circuit time constants, as well as the armature time constant (Td", Td', Ta), are not required.

The change in the inductances appears from the variation in the pathway of the magnetic flux of the machine in steady-state, transient, and sub-transient conditions. When a disturbance occurs, the machine tries to maintain the flux linkage between the rotor and armature as before the fault. The magnetic flux produced by the armature winding cannot pass through the rotor instead uses the damper and field winding loops. During the sub-transient operation, the magnetic flux forms a loop between the iron of the armature and the air gap beyond the rotor. In the transient, the magnetic flux passes through the leakage paths and flux in the iron of the armature. Finally, the magnetic flux covers direct and quadrature inductances in the steady-state [13]. According to the classic theory, the inductances on synchronous machines are:

$$
\begin{aligned}
L'_d &= L_l + \frac{L_{md}L_{fd}}{L_{md}+L_{fd}} \\
L''_d &= L_l + \frac{L_{md}L_{fd}L_d}{L_{md}L_{fd}+L_{md}L_d+L_{fd}L_d} \\
L''_q &= L_l + \frac{L_{mq}+L_{kq1}}{L_{mq}+L_{kq1}} \\
T'_{d0} &= \frac{L_{md}+L_{fd}}{R_{fd}} \\
T''_{d0} &= \frac{1}{R_{kd1}}(L_{kd1}+\frac{L_{md}L_{fd}}{L_{md}+L_{fd}}) \\
T''_{q0} &= \frac{L_{mq}L_{kq1}}{R_{kq1}}
\end{aligned}
\tag{3.2}
$$

The expressed information, the parameters shared by ČEPS, and some necessary assumptions are practical for calculating the input data for the standard parameters used in the Generators' Matlab/Simulink Synchronous machine block. The information for the Synchronous Condenser is not clear, and to simplify the process, the machine parameters and excitation system data adapts from the Generator's data are the reference with a correction according to the engine's dimensions, and the standard parameters come from reported data in the bibliography for synchronous condensers.

3.1.4 Excitation System model

From ČEPS information the ST1A Static Excitation System is the closest approximation for the Synchronous generators. All components in these systems are static or stationary. The power supply is from the main generator through a transformer to step down the voltage regulated by a controlled rectifier. This kind of excitation system is known as a bus-fed or transformed-fed static system. The generators using such excitation systems perform better when connected to a robust power system [16].

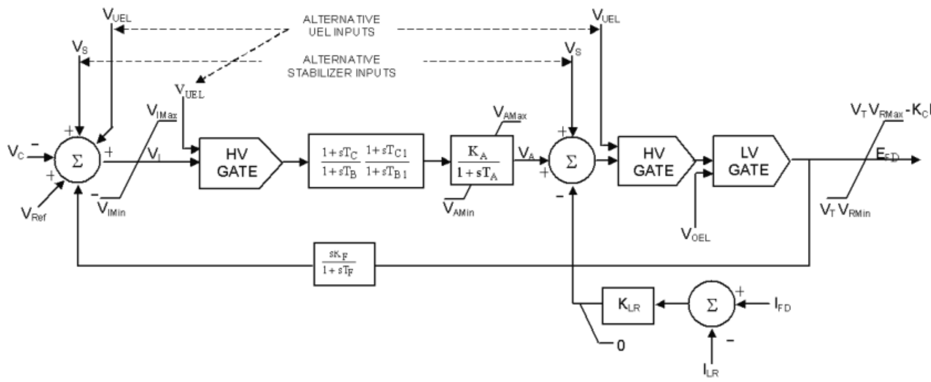


Figure 3.6: Type ST1A - Potential source controlled rectifier exciter [4]

There are no explicit equations to follow more than the IEEE definitions for excitation systems [4] represented in Figure 3.6. To merge Synchronous Generators and Condensers technology, both machines should follow the same model. However, during the modeling and testing process of the simulation, the implementation showed two main problems the results:

- The ST1A reduction/increasetransient gain in the forward path with T_B and T_C or T_{B1} and T_{C1} shown in Figure 3.6 changes drastically the value of the excitation voltage when the data provided by ČEPS specify these parameters equal to zero.
- The Voltage Terminal V_T influences the E_{FD} output within the saturation block described in 3.6.

Therefore, to adjust properly the model according to the granted parameters by ČEPS. The Excitation System chosen for both machines that complies the expected results is the Alternator supplied rectifier excitation system AC4C as shown in Figure 3.7. The purpose is the same, provide DC field voltage using a rotating or stationary rectifiers. The study case approximates to the second case. AC4C excitation system allows us not to deal with the problems noted previously and basically reduces to a voltage regulator gain with its inherent excitation system time constant are K_A and T_A limited by the Rectifier loading factor when specified.

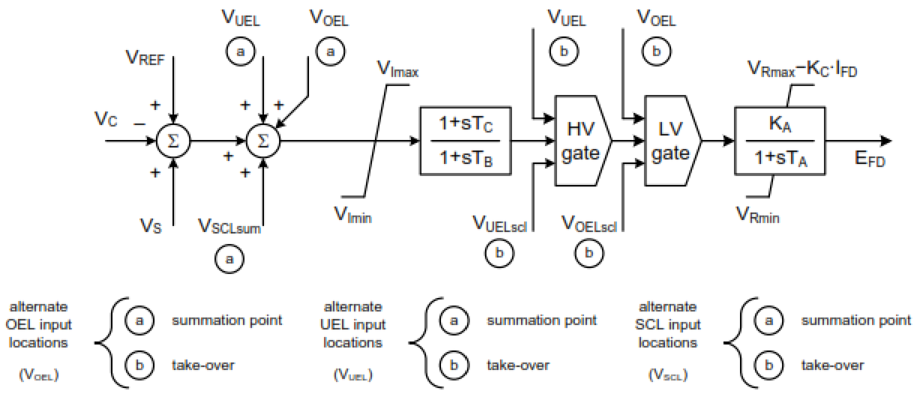


Figure 3.7: Type AC4C - Alternator - supplied controlled rectifier exciter [4]

Finally, the excitation system must include the voltage limits to protect them from Over and Under excitations issues. ČEPS provided the Under and Over excitation limits from all the synchronous machines involved. Therefore, simulation must respect these values. AC4C excitation system shows in the Figure 3.8 shows two options possible: Adding V_{UEL} and V_{OEL} signals to the reference value for the excitation system or with HV or LV selection gate. The option chosen for this analysis is the first one, adapted from [16], the simulation compares the actual reactive power with the limit reactive powers provided by ČEPS integrating the error with an integration time To and Tu. Both integrators are limited with 0 in one of the extremes. The point is to reduce or increase the reference value according to the issue raised.

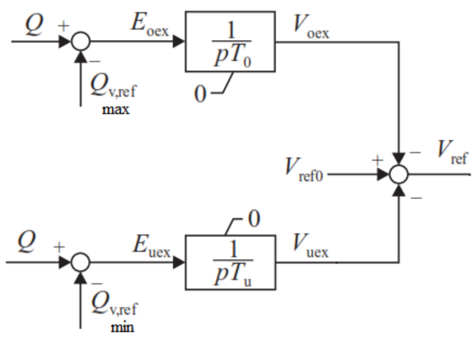


Figure 3.8: Limit Functions for Synchronous Machines [16]

3.2 Transformers

Substation Krasikov locates two types of transformers: Two and Three Windings. The first ones are in the Pump Storage to step up voltage generated in the Hydro Turbines. The others are near Substation Krasikov busbar to step down the voltage for the distribution system and the condensers.

3.2.1 Operational background

The electromagnetic origins are the same for all devices, Faraday's law principle for electromagnetic induction [11]. Transformers are static devices that induce mutual coupling between circuits to transfer energy from one circuit to another. The Figure 3.9 displays its structure, and internal composition, which is available in detail in any cited references [2] [5]. A transformer usually consists of two or more coupled windings on a magnetic iron core. Each phase of a power transformer typically has a pair of windings (primary and secondary) linked by a magnetic circuit or core.

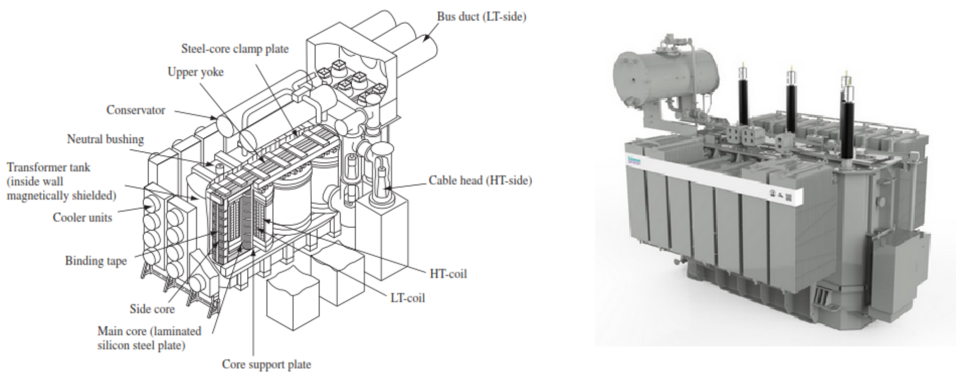


Figure 3.9: Three - phase transformer structure [2]

The most common power transformers connections are Wye, Delta, and Zigzag. The scope of research is Wye and Delta connection. Wye connection can be grounded (Yg), and Delta connection can be D1 and D11 (30° lagging and leading, respectively). The introduction of the notation is for the primary (Y or D) and the secondary (y or d) winding. The number next to the letter is an integer between 0 and 12. It indicates the position of the low-voltage positive-sequence voltage phasor on a clock display when the high-voltage positive-sequence voltage phasor is at 12:00 [18].

Transformers are a source of voltage regulation itself. Power transformers with tap changers can control voltage, phase angle, or both. The tap changer may be on or off-load. Off-load type has a limited range from ± (2.5 to 5), while the advantage in On-load is that the regulation is more extensive and connected to the network [11]. Transformers in the analysis do not include regulation tap changer regulation. However, transformers near Substation Krasikov busbar assist with its third windings connected in delta to stabilize the voltage, in this case, with the condensers installation.

3.2.2 Two and Three windings Transformers model

Previous concepts assist in quickly understanding the relationships between the winding turns and voltage and currents. However, transformers modeling in practice demands attention on [11]:

- **Magnetizing current:** Transformer's magnetic resistance is not zero, then not all flux produced by the primary stays in the core. The flux outside the core is the leakage flux. The primary winding draws a small excitation current from the source, called magnetizing current, and sets up an alternating magnetomotive force and flux in the core. Depending on the magnetic reluctance of the core, a large part of the flux will flow in the core, link both windings, and induce an EMF in each winding according to the connection of the transformer.
- **Leakage and Mutual Inductances:** The magnetic permeability of an iron core in a real transformer is not infinite. Therefore not all the flux produces by the primary winding links to the secondary winding. A small part of the flux linking each winding, the leakage flux of that winding, does not link to other windings and closes through the air, so the transformer possesses leakage reactance in each winding.
- **Core and Load losses:** Eddy current and hysteresis core losses appear in the transformer. Eddy currents circulate within the core steel produced due to induced voltage. The successive reversal of flux in the magnetic circuit causes Hysteresis losses. The load losses represent the losses in the transformer that result from the flow of load currents in the windings comprising the dc resistance, eddy current, and the stray losses in the windings and elsewhere in the transformer tank.

Short-circuit and open-circuit tests give the input data for modeling. This information, remitted by ČEPS, stands for the practice situation stated above, and it is valid for single and three-phase transformers. Power transformers in Substation Krasikov are three-phase core-type transformers. The core has three legs surrounded by each winding. The magnetic circuit connection permits each phase flux to return through the other two phases, expecting a zero excitation current [11]. Table 3.2 summarizes the used formulas for the data calculation input for the Transformer from ČEPS data.

Type	Parameters in Per Unit
Windings leakage impedance (z)	$z = V_{SC[pu]}$ $V_{SC[pu]}$ = Short Circuit Voltage in p.u.
Load losses equivalent resistance (r)	$r = \frac{P_{SC[kW]}}{MVA_{SCTest[MVA]}*1000}$ $P_{SC[kW]}$ = Short Circuit Active Power $S_{SCTest[MVA]}$ = Short Circuit Apparent Power
Windings leakage reactance (x)	$x = \sqrt{z^2 - r^2}$
Magnetizing branch admittance (y)	$y = \|g + jb\| = \%I_{exc}/100$ $\%I_{exc}$ = Excitation current in p.u.
No Load losses equivalent conductance(g)	$g = \frac{P_{NL[kW]}}{MVA_{NLTest[MVA]}*1000}$ $P_{NL[kW]}$ = No Load Active Power $S_{NLTest[MVA]}$ = No Load Apparent Power
Magnetizing branch susceptance (b)	$b = -\sqrt{y^2 - g^2}$

Table 3.2: Formulas for Transformer generic modeling parameters [11]

Matlab/Simulink's library owns the two and three windings transformers subjects of study as shown in Figure 3.21. Equations from the table 3.2 uncover the data for the transformers required for the Matlab/Simulink block.

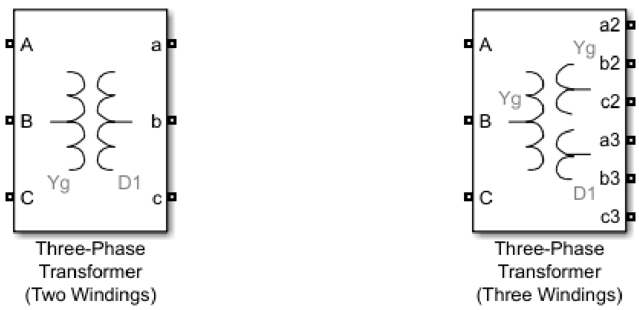


Figure 3.10: Two and Three windings Transformers block in Matlab/Simulink [6]

3.3 Variable Shunt Reactor

Substation Krasikov implements in its main busbar a Variable Shunt Reactor from 60/120 MVA. Similar to Figure 3.11, a reactor and a transformer are similar in their construction, but a three-phase shunt reactor has only three bushings for voltage.

Figure 3.11: Variable Shunt Reactor [7]

3.3.1 Operation within Network

There are two main applications for shunt reactors. Stabilization of the voltage by counterpoising the capacitive charging effect on long transmission lines and voltage control switching its reactive power capability to keep the voltage value within limits during different load conditions. Figure 3.12 portrays the situation when the load changes affect the terminal voltage, and the reactor modifies its reactive consumption to compensate for these effects. The case subject is the reactor connected to the Substation Krasikov busbar.

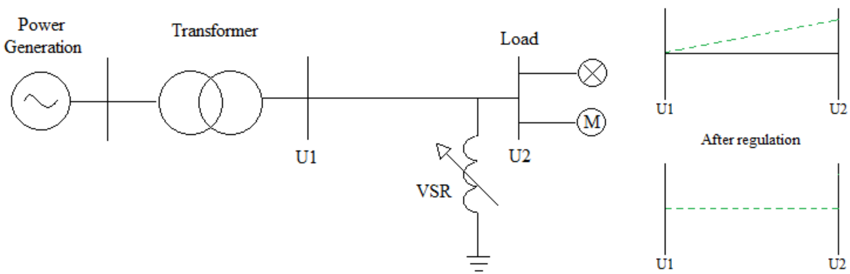


Figure 3.12: Variable Shunt Reactor Effect on Voltage

Technology implied for the construction of the reactors is available in particular in [8]. However, Figure 3.13 shows the design principle of the active part for reactive injection of the variable shunt reactor. The regulating winding is outside the primary winding around the core limb, and the high voltage inlet to the primary winding could be either a yoke entrance or a central entrance to the winding.

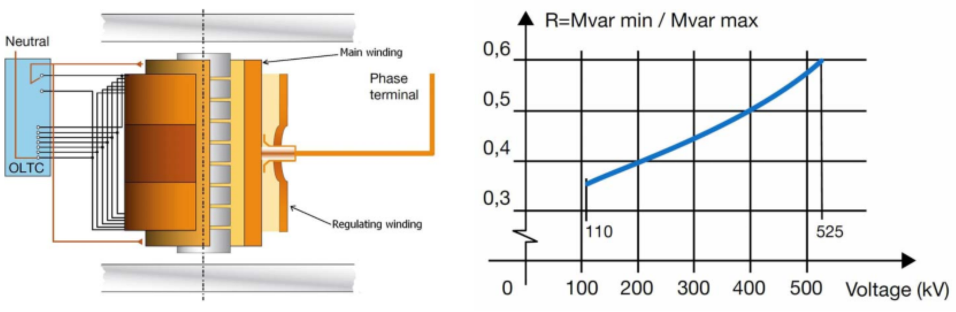


Figure 3.13: Design principle of the active part of the variable shunt reactor[8]

The maximum regulation range is a function of voltage and is generally around a factor 2 at 400 kV. The regulating winding in a VSR is electrically much longer than a regulating winding used in transformer application. The feasible regulation range depends on the voltage rating of the reactor, as shown in Figure 3.13. There are three possible regulating types available for variable shunt reactors as for power transformers:

1. Linear regulation
2. Coarse/fine regulation
3. Plus/minus regulation

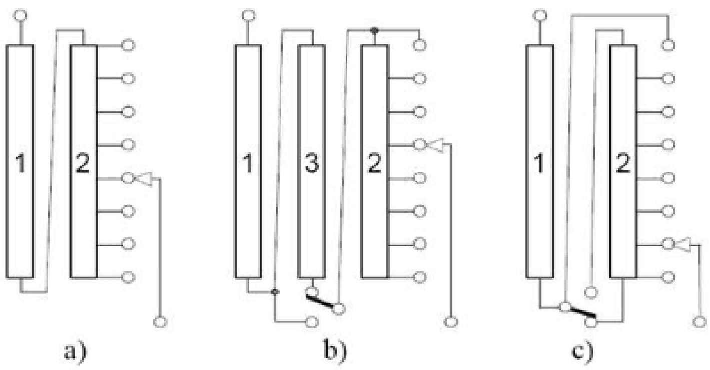


Figure 3.14: Variable shunt reactor different types[8]

Figure 3.14 illustrates the three winding arrangements corresponding to these three regulation types. Winding 1 is the principal, and windings 2 and

3 are the regulating ones. Variable shunt reactors applications rarely use a linear setup. The choice of coarse/fine or plus/minus regulation depends mainly on the loss evaluation given by the customer. In the last position of the minus tap appears the maximum power rating and the highest current. In this tap location, the primary winding connection in b) is advantageous to minimize the losses. Although, c) increment losses because tap changer connects all the winding to go between extremes is chosen due to lower manufacturing costs. Therefore, at high loss evaluations and voltages equal to or less than 400 kV, such as this study, a yoke entry with a coarse/fine regulation is used.

The tap changer is in charge of controlling the variable shunt reactor. Because interrupting the supply is usually unacceptable for a power transformer, On-Load tap changing mechanisms are preferred. OLTC may be mechanical or electronic. Mechanical tap changers are the more common type of mechanical OLTC has two parts: a tap selector to select the tap positions and a diverter to transfer the current from one tap position to another. During tap changing, neither the load current interrupt nor the taps short-circuit. An impedance, resistor, or reactor joins between the taps during the changeover fastly to avoid overheating. Power springs are wound up, usually by a low power motor, and then rapidly released to affect the changeover.

3.3.2 Variable Shunt Reactor model

The variable shunt reactor connects/disconnects electrical turns in the reactor to fix its reactive power consumption, according to these equations:

$$
\begin{gathered}
Q_R \approx \frac{V^2}{X_R} \\
Rlosses \approx 0.2\% Q_R
\end{gathered}
\tag{3.3}
$$

Q_R = Reactive Power from Reactor

V = Voltage applied on the Reactor

X_R = Inductive Reactance

$Rlosses$ = Power losses equivalent

Inductance depends on the electric turns in the reactor, less numbers of electric turns correspond to the maximum reactive power rating and vice versa. The tap changer controls the inductance value and, consequently, the reactive power injected by the VSR. In Matlab/Simulink, there is not a specific model for a variable shunt reactor. Therefore, to build the reactor, the study joins three variable inductance per phase Y-connected in series with a variable resistor representing the power losses. A lookup table gives the inductance value according to the tap setpoint coming from the control of the VSR delaying by 5 seconds the action of each tap step's for stabilization. The control of the equipment comes from a state flow algorithm design, to operate in manual (tap setpoint is defined by user) or auto mode (the algorithm checks the voltage in Krasikov Busbar and move the tap setpoint to compensate the voltage up to its maximum possible ± 2 MVAR). Figure 3.15 shows the schematic of the VSR. ČEPS data provided the complete information on the variable shunt reactor for Substation Krasíkov, where the most valuable for the research is the reactive power and the position of the OLTC. The simulation represents the reactive value in the variable shunt reactor according to the tap setpoint and the OLTC mechanism action and control already described.

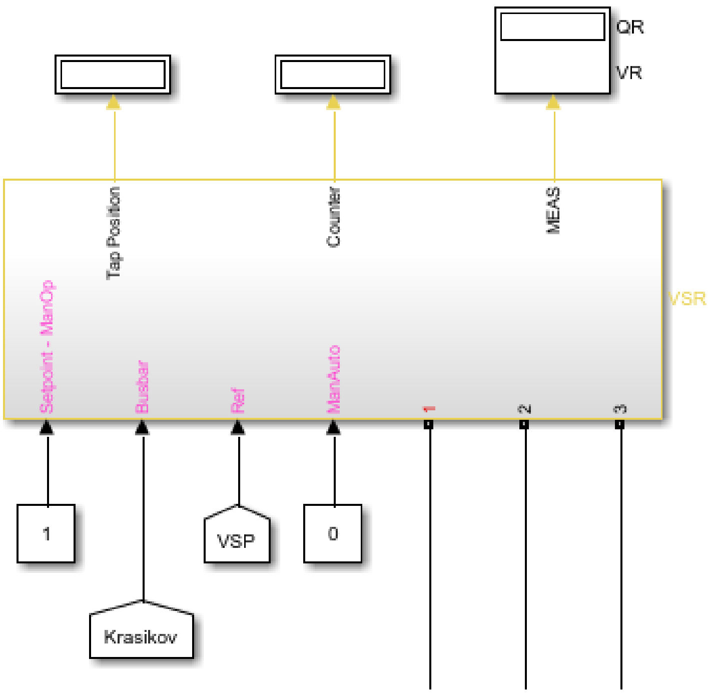


Figure 3.15: Variable shunt reactor representation

3.4 Network Elements

The remaining network elements for the model are the Overhead Lines between the Pump Storage and Substation Krasíkov and the 400 kV Transmission electric network, which can comprehend overhead lines, transformers, electrical loads, represented as a Voltage Source with a series Equivalent Impedance.

3.4.1 Overhead Lines

The overhead line transfers the Electrical power from generating station to consumers. Four parameters characterize a transmission line shown in Figure 3.16 equivalent per each phase:

- **Series Resistance (R):** Represents the conductor resistivity from manufacturers' tables.
- **Shunt Conductance (G):** Leakage currents along insulator strings and corona between the phases and ground.
- **Series Inductance (L):** Magnetic field outcome from the spacing and the geometry between the overhead lines.
- **Shunt Capacitance (C):** Outlines the charging and discharging in the conductors due to alternating voltages.

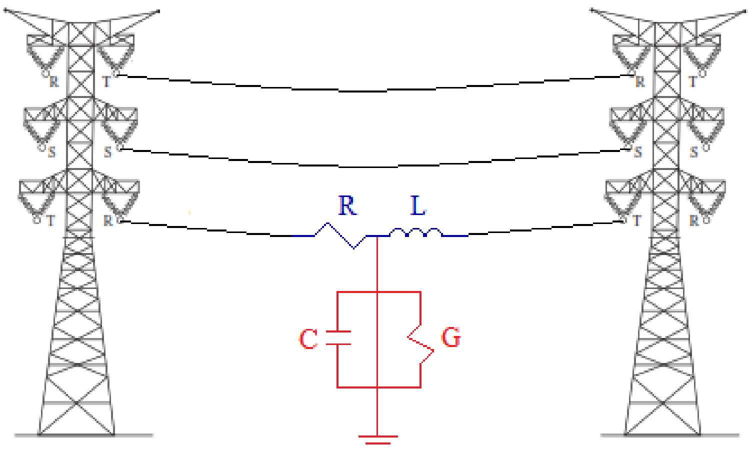


Figure 3.16: Overhead Lines Parameter Representation

The equations and the principles behind the performance of the overhead lines are in [5] [2]. Modeling considers the line length:

- **Short:** Lines < 80 km. They have negligible shunt capacitance. Its scheme reduces the series impedance ($Z = R + jwL$).
- **Medium and Long:** For lines between 80 and 200 km and lines longer than 200 km, respectively. The overhead line adapts to the π equivalent circuit. However, the line divides into many π circuits of shorter lengths for long overhead lines.

From ČEPS data, it is recognizable that the overhead line in focus is less than 80 km, and the parameters received are the positive and zero sequences of the resistance (R), reactance ($X = wL$), and susceptance ($B = wC$). As the line is short, the model discards the susceptance (capacitance component).

3.4.2 Transmission Electric Network

A balanced three-phase network can become a per-phase equivalent circuit using a single line diagram for the purpose of visualization and electrical system analysis. From IEC guidelines, power grids reduce to a Single Phase Voltage source and an impedance in series calculated from the short circuit power, voltage, and X/R ratio between active and inductive characteristics as presented in Equations 3.4.

$$\begin{aligned} X_{TS} &= \frac{(V_{TS}^2)}{MVA_{SC}} \\ R_{TS} &= X_{TS}/XR \end{aligned} \tag{3.4}$$

X_{TS}, R_{TS} = Equivalent Impedance components

V_{TS} = Transmission Voltage

MVA_{SC} = Shortcircuit Power

XR = Reactive component ratio

3.5 Matlab/Simulink Representation

Although ČEPS provided all the information, the disclosure agreement protects the data joined in the .m file. Nevertheless, the following section will describe the information applied to the equipment modeled in Matlab/Simulink simulation.

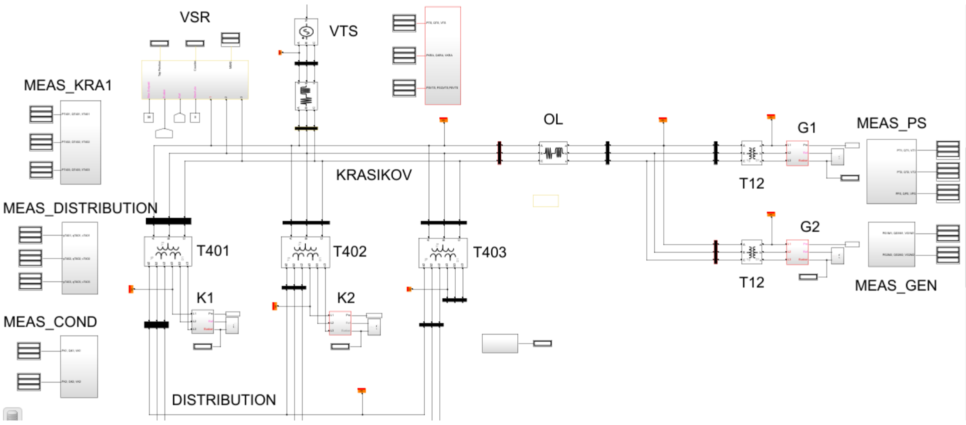


Figure 3.17: Substation Krasikov in Matlab/Simulink Model

3.5.1 355 MVA - 22 kV - Synchronous Generator and Excitation System

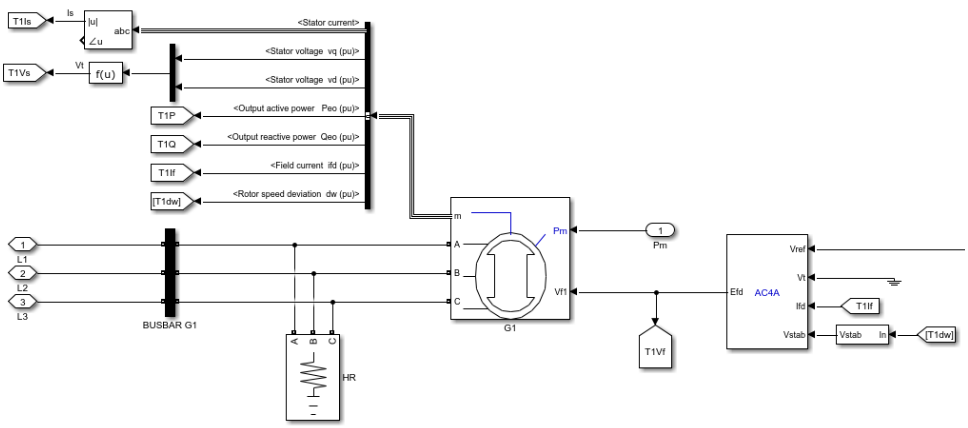


Figure 3.18: Synchronous Generator Model in Matlab/Simulink

Synchronous Generator

Table 3.3 shows the provided, assumed and calculated values for the Synchronous Generators. The assumption of $X_l(pu)$, $X''_q(pu)$, $R_s(pu)$, $H(s)$, $T'_{do}(s)$, $T''_{do}(s)$, $T''_{qo}(s)$ preceed from [5] while $X''_q(pu)$, and $T'_{do}(s)$ are the result of Equations 3.2.

Synchronous Generator Parameters G1 and G2	
Nominal Apparent Power (Pn)	355 MVA
Frequency (fn)	50 Hz
Nominal Voltage (Vn)	22 kV
Speed (p())	polesg
Direct axis reactance (X_d)	Xdg (pu)
Quadrature axis reactance (X_q)	Xqg (pu)
Transient direct axis reactance (X'_d)	X1dg (pu)
Sub - transient direct axis reactance (X''_d)	X2dg (pu)
Negative sequence reactance	X2g (pu)
Assumed and Calculated Parameters	
Stator Resistance (R_s)	0 (pu)
Leakage Reactance (X_l)	0.15 (pu)
Quadrature Sub - transient Reactance (X''_q)	0.28 (pu)
Transient direct axis time constant (T'_{do})	14.17 (s)
Sub - transient direct axis time constant (T''_{do})	0.05 (s)
Sub - transient direct axis time constant (T''_{qo})	0.09 (s)
Inertia constant (H)	4 (s)

Table 3.3: Synchronous Generator Parameters Table

Generator Excitation System

For the Synchronous Generator Excitation System, Table 3.4 shows the used data.

Excitation System Parameters	
Excitation Voltage (Rated Power Generator)	Vfflg (V)
Excitation Current (Rated Power Generator)	Ifflg (A)
Excitation Voltage (no load Generator)	Vfnlg (V)
Excitation Current (no load Generator)	Vfnlg (A)
AC4C Excitation System	
Low-pass filter constant	20 (ms)
Voltage regulator Gain and Time constant	Kag/Tag(s)
Voltage regulator input limits	-10/+10 (pu)
Voltage regulator output limits	VRgmin/max (pu)
Transient gain reduction lead and lag time constants	0 (s)
Rectifier loading factor	Kc (pu)

Table 3.4: Synchronous Generator Excitation System Parameters Table

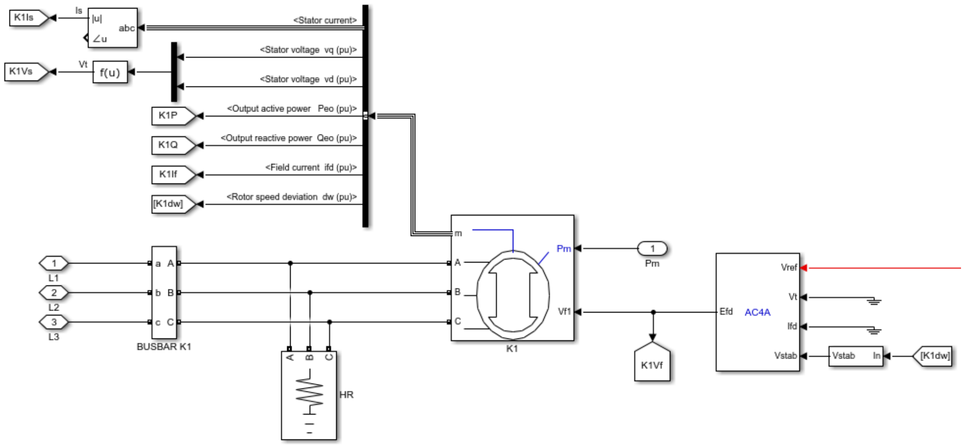


Figure 3.19: Synchronous Condenser Model in Matlab/Simulink

3.5.2 125 MVA - 10.5 kV - Synchronous Condenser and Excitation System

Synchronous Condenser

As explained before, the Synchronous Condenser bases on the Synchronous Generator, where the main difference is the power rating, dimensioned approximately to 30% of the Synchronous Generator in accordance to ČEPS. Therefore, the Nominal Apparent Power (Pn) and Nominal Voltage (Vn) are adjusted as nearest as the real equipment, the remainder machine constants come from a few poles synchronous machine using [16] as a reference. Table 3.5 shows the expressed values.

Synchronous Condenser Parameters K1 and K2	
Nominal Apparent Power (Pn)	125 MVA
Frequency (fn)	50 Hz
Nominal Voltage (Vn)	10.5 kV
Speed (p())	1800 rpm
Stator Resistance (R_s)	0 (pu)
Leakage Reactance (X_l)	0.15 (pu)
Direct axis reactance (X_d)	2.2 pu
Quadrature axis reactance (X_q)	1.15 pu
Transient direct axis reactance (X'_d)	0.55 pu
Sub - transient direct axis reactance (X''_d)	0.40 pu
Sub - transient quadrature axis reactance ($X"_q$)	0.40 pu
Negative sequence reactance	0.20 pu
Transient direct axis time constant (T'_{do})	3.27 (s)
Sub - transient direct axis time constant (T''_{do})	0.035 (s)
Sub - transient direct axis time constant (T''_{qo})	0.035 (s)
Inertia constant (H)	1.5 (s)

Table 3.5: Synchronous Condenser Parameters Table

Condenser Excitation System

The excitation system parameters are adjusted to the machine's rating. However, from the initial information, voltage regulator from gain, time constant, and output limits are different. Table 3.6 shows the data available.

Excitation System Parameters	
Excitation Voltage (Rated Power Generator)	Vfflg/3 (V)
Excitation Current (Rated Power Generator)	Ifflg/3 (A)
Excitation Voltage (no load Generator)	Vfnlg (V)/3
Excitation Current (no load Generator)	Vfnlg (A)/3
AC4C Excitation System	
Low-pass filter constant	20 (ms)
Voltage regulator Gain and Time constant	Kac/Tac(s)
Voltage regulator input limits	-10/+10 (pu)
Voltage regulator output limits	VRcmin/max (pu)
Transient gain reduction lead and lag time constants	0 (s)
Rectifier loading factor	0 (pu)

Table 3.6: Synchronous Condenser Excitation System Parameters Table

Besides the data described for both models, Figures 3.18 and 3.19 additionally comprenhends the following:

- Simulation adds an HR resistor, need it by Matlab/Simulink, because of the elements interconnected are controlled current sources managed by the equations presented previously

- The bus of signals represents all the relevant measurements from the Synchronous Machine to monitoring the simulation
- The excitation system does not required the Vt signal, Vref leads the regulation using a PID controller for Primary Regulation
- The Power System Stabilizer is standard. However, the impact is not that significant due to this research focusing more in Q/V than P/f changes.

3.5.3 22/440 kV - Two Winding Transformer

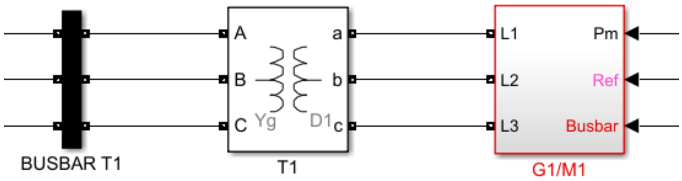


Figure 3.20: Two windings Transformers Model in Matlab/Simulink

Table 3.7 gathers the nameplate and test values delivered by ČEPS from the two windings transformers. From Table 3.2, the formulas allow us to find the resistance windings (r), leakage reactance windings (x), and the no-load losses equivalent conductance (g) of the core, representing the transformer's equivalent circuit. However, Matlab/Simulink transformer's block requires the values per winding except for the power losses of the transformer. Thus, to find each values, [11] propose the following Equations 3.5 to input values for the simulation:

$$\begin{aligned} R1(pu) = R2(pu) = T12r = r/2 \\ L1(pu) = L2(pu) = T12x = x/2 \\ Rm(pu) = 1/b \\ Lm(pu) = 0 \end{aligned} \tag{3.5}$$

Two Windings Transformer Parameters T1, T2	
Nominal Apparent Power (Pn)	St12 (MVA)
Frequency (fn)	50 Hz
Primary Winding Voltage (V1)	420 kV
Secondary Winding Voltage (V2)	22 kV
Short Circuit and Open Circuit Data	
Test Base Power	St12 (MVA)
No load losses	Po12 (kW)
Load losses	Pk12 (kW)
Short Circuit test voltage	uk12 (pu)

Table 3.7: Two Windings Transformer Parameters Table

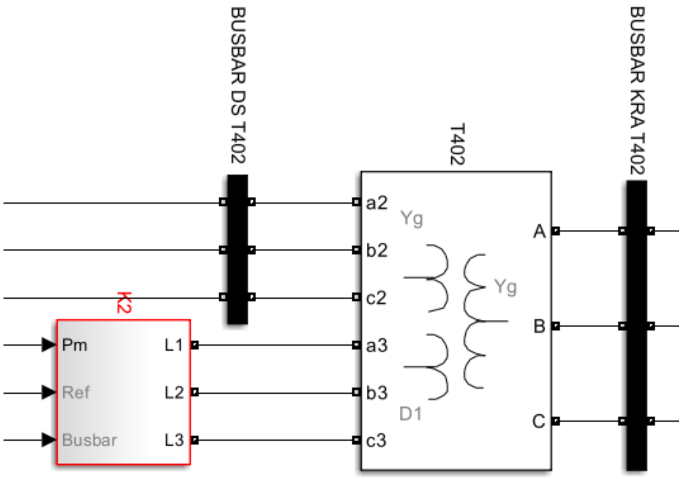


Figure 3.21: Three windings Transformers Model in Matlab/Simulink

3.5.4 420/220/10.5 kV - Three Winding Transformer

Section 3.2 about transformers theory describes parameters and calculations for transformers between two windings. The difference between the three windings case is that the data comprehends the combination between each winding. Therefore, Table 3.8 lists the nameplate and test values delivered by ČEPS between the three windings transformers. As the same case of the two winding transformer Matlab/Simulink transformer's block requires the values per winding except for the power losses of the transformer. Thus, to find each values, [11] propose a transformation described in Equations 3.6 to input values for the simulation:

$$\begin{aligned} Z1(pu) &= \frac{Z_{12} + Z_{13} - Z_{23}}{2} \\ Z2(pu) &= \frac{Z_{12} - Z_{13} + Z_{23}}{2} \\ Z3(pu) &= \frac{-Z_{12} + Z_{13} + Z_{23}}{2} \\ Rm(pu) &= 1/Tb \\ Lm(pu) &= 0 \end{aligned} \tag{3.6}$$

Three Windings Transformer Parameters T401, T402, T403	
Nominal Apparent Power Primary and Secondary Windings (Pn)	St40x1 (MVA)
Nominal Apparent Power Terciary Winding	St40x3 (MVA)
Frequency (fn)	50 Hz
Primary Winding Voltage (V1)	420 kV
Secondary Winding Voltage (V2)	22 kV
Terciary Winding Voltage (V3)	10.5 kV
Short Circuit and Open Circuit Data	
Test Base Power Primary Winding	St40x1 (MVA)
Test Base Power Secondary and Terciary Winding	St40x3 (MVA)
No load losses	Po (kW)
Load losses Primary - Secondary Windings	Pk12 (kW)
Load losses Primary - Terciary Windings	Pk13 (kW)
Load losses Secondary - Terciary Windings	Pk23 (kW)
Short Circuit Test voltage Primary - Terciary Windings	uk12 (pu)
Short Circuit Test voltage Primary - Terciary Windings	uk13 (pu)
Short Circuit Test voltage Secondary - Terciary Windings	uk23 (pu)

Table 3.8: Three Windings Transformer Parameters Table

3.5.5 60/120 MVAR - Variable Shunt Reactor in Simulink

For the VSR, ČEPS provided the rated reactive power at each step. Each step means a different level of inductive reactance. To simulate it, the variable inductor in the Figure 3.22 recieves the inductance value, calculated using the Equations 3.3 from the .m file, and according to each tap as shown:

```
l = [];
```

```
for i = 1:length(MVAR)
    l(i) = (400^2)/(2*fn*pi*MVAR(i));
end

Inductance = transpose(l);
```

A Lookup Table associates the values from the tap position and the inductance in the simulation for the Variable Shunt Reactor. The power losses depend on the variable resistor value, their value correspond to 2% of the inductance reactance. To control of the VSR, the simulation implements a state machine using Stateflow Tool from Matlab. The reason to implement the control with Stateflow is the advantage that allows the simulation to work between the discrete environment need it for the solution of the differential equations, the core of all the elements of System Power Systems, and the combinatorial and sequential decision logic running the VSR's state machine according to the input conditions in the network.

To explain the control of the VSR, the algorithm divides into 4 sections:

1. **On/Off Transition:** The system activates with the OnOff signal, as shown in Figure 3.23

   - All the VSR variables will initialize.
   - Close the circuit breaker.
   - Check if the VSR is in Manual or Auto Mode.
   - Set up the VSR tap and counter to 1 and produce a 5 sec delay to go to Stand by State

   In the case of disconnection (OnOff $= 0$), the variable Out activates after the system checks if the tap is in the initial position. If the tap is out of this position, the system first positions to the initial position, and then the system proceeds to open the breaker.

2. **Manual Function:** This section of the algorithm fundaments in the difference between the Setpoint and the Tap position as presented in Figure 3.24

   - System checks that the Setpoint is within the tap range. Outside this range, system indicates that there is an error and informs the user to check the Setpoint.
   - After Setpoint validation, the control checks the difference between the Setpoint and the Tap position before a tap change. If the tap needs to increase or decrease, control delays each tap change in five seconds for stabilization.

- Finally, when the Tap reaches the Setpoint, the system checks if the Tap had reached some of the limits and informs the user about this situation. If not, the control comes back to the Stand by State.

3. **Auto Function:**

   - As illustrated in Figure 3.25, system checks two conditions:
     a. VSR operation enabled by the central control proposed with the signal VSREN. The premise is that the VSR should support voltage compensation when the Synchronous Machines have reached their available reactive power to extend VSR lifetime.
     b. The Error value should be outside the error limits, this study proposes this solution to prevent ups and downs operations around the Setpoint, with the calculation of this errors limits based on the capability of the 2 MVARs per step of the VSR in the network. The error is defined by the following formula:

$$Error = \frac{Vref - Busbar}{Vref} \tag{3.7}$$

Vref: Voltage Setpoint for Krasikov Busbar (pu)
Busbar: Krasikov Busbar Voltage (pu)

   When both conditions are met, the system starts a 10 secs delay to check if the read voltage difference is a transient or a permanent condition

   - Negative error indicates the Krasikov Busbar needs more reactive power to reach the Setpoint. The VSR starts to change the tap until reaching the minimum error possible. VSR works in the same way when the error is positive but reduces the tap. Each tap change is delayed by five seconds for stabilization
   - Before every tap change, the system checks if the error is still out of range and if VSREn is still On. The control works up to error compensation within its range or up to the max/min limit of the VSR. When VSR reaches the limit, the system informs the user. If the tap is within the range, control comes back to the Stand by State.

4. **Locked State:** The Locked State blocks the VSR operation, basically due to Setpoint being out of range or when the VSR needs to change the tap up, and the tap is already at its maximum or vice versa. To exit this State, the control should check the following:

```
% Condition 1

if Manual && SPOutOfRange
```

```
      if Setpoint < TapMax + 1 && Setpoint > TapMin - 1
         Go to StandBy Mode
   end

   %Condition 2

   if LimitReached
      if Manual
         if Tap == TapMax && Setpoint != TapMax
            Go to StandBy Mode
         elseif Tap == TapMin && Setpoint != TapMin
            Go to StandBy Mode
      elseif Auto
         if Error > Errormin && Tap == TapMax
            Go to StandBy Mode
         elseif Tap < Erromax && Tap == TapMin
            Go to StandBy Mode
   end
```

Important note: When there is a change between the auto or manual mode, the systems do not interrupt the five delay seconds count. After the count finishes, systems comebacks to the Stand by Mode and checks the conditions according to the function selected.

3.5.6 V457 - OL Pump Storage to Krasikov Busbar

The overhead line image in Matlab/Simulink is a series RL circuit, as illustrated in Figure 3.26, filled with the positive sequence values (r1TL and x1TL).

3.5.7 400 kV Network Equivalent Circuit

The Three-Phase Source, illustrated in Figure 3.27, implements a three-phase voltage source connected in series with a R-L impedance specified by the source inductive short-circuit level and X/R ratio using equations 3.4

3.5.8 Measuring Circuits

Finally, in the Specialized Power Systems library, there is the option to include a Three-Phase V-I Measurements. The advantage of this tool is the reading of the Three-Phase Voltage and Current. Using the positive sequence analyzers for Power and Voltage, the simulation shows the Active, Reactive Power, and voltage magnitude by displays or scopes for the signals trends.

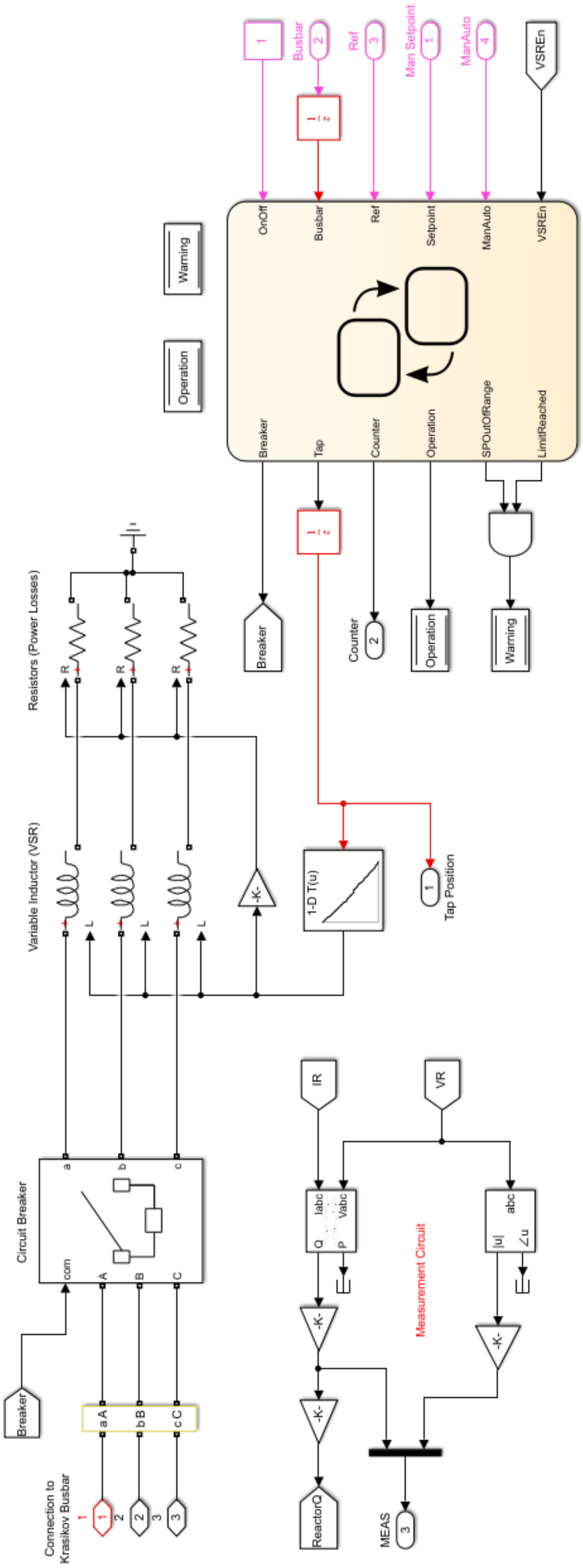


Figure 3.22: Variable shunt reactor model

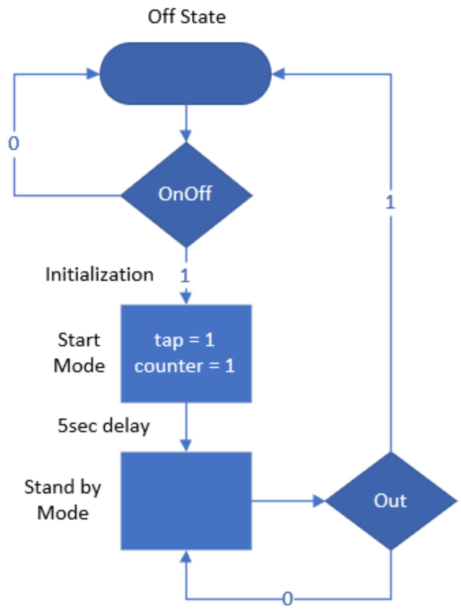


Figure 3.23: On Off algorithm

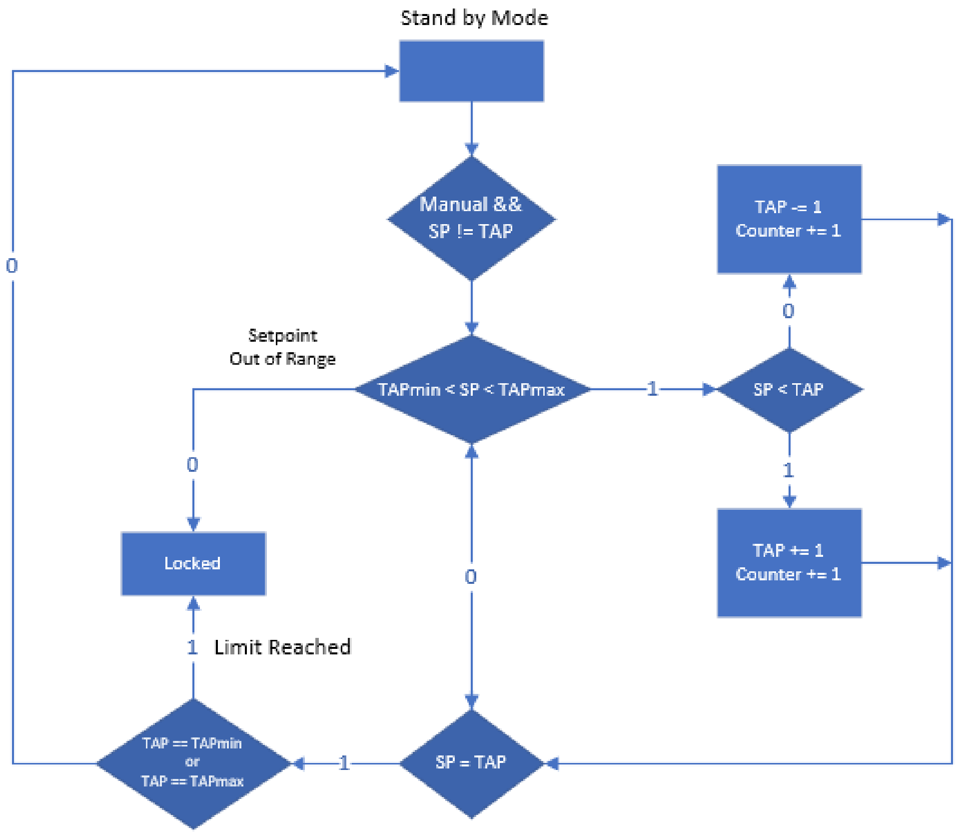


Figure 3.24: Manual function algorithm

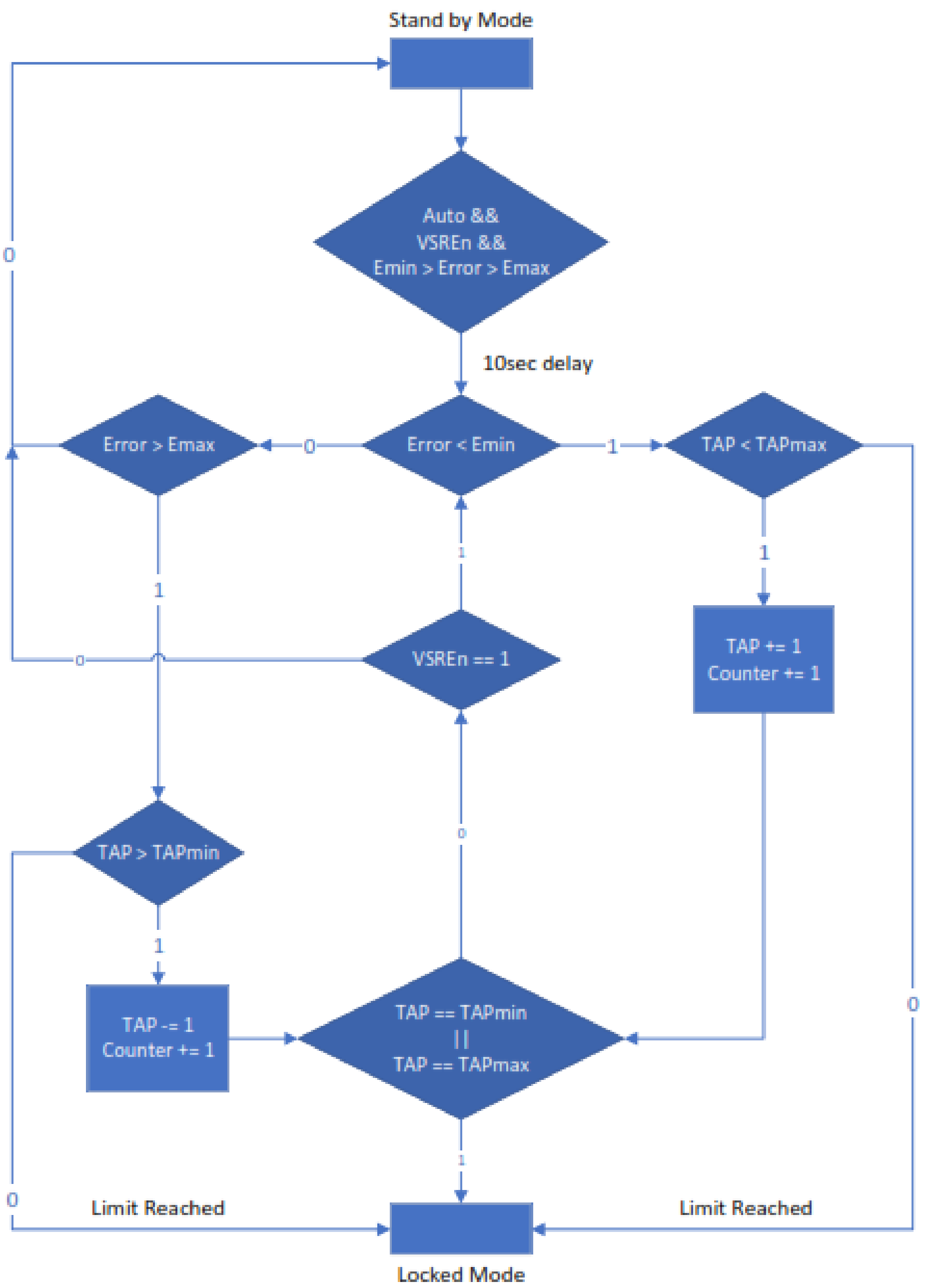


Figure 3.25: Auto Mode algorithm

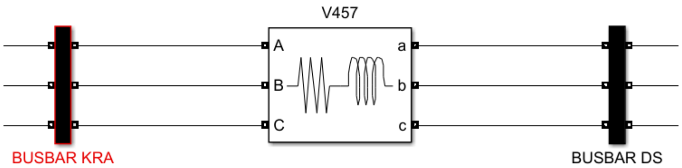


Figure 3.26: Overhead Line Model Matlab/Simulink

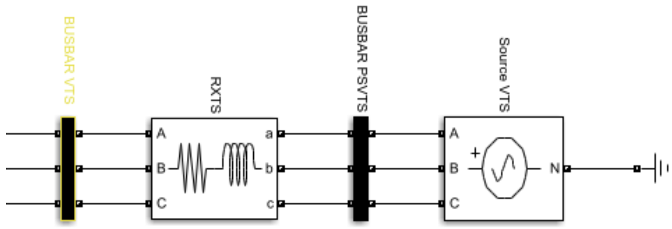


Figure 3.27: Transmission Network Model in Matlab/Simulink

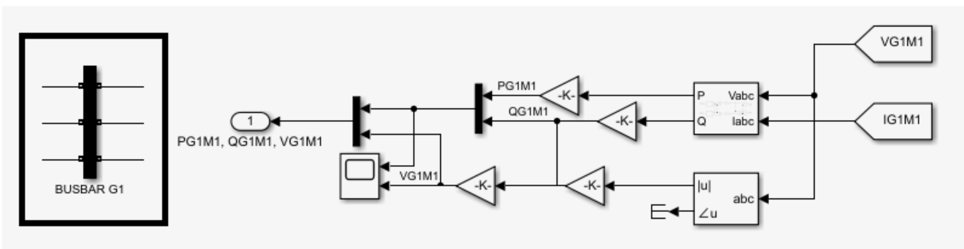


Figure 3.28: Power measuring circuts in Matlab/Simulink

Chapter 4

Operation and control of reactive power sources in Substation Krasíkov

4.1 Primary and Secondary Voltage regulation

As explained initially, ČEPS within the Czech Transmission Network performs the control of the network elements using the Primary, Secondary and Tertiary regulations already explained. The Primary regulation focus on the direct control of generators and compensators estimating the voltage reference from the synchronous machine terminals. When the secondary regulation activates, the system estimates the voltage reference for all the machines in the pilot node region with the restrictions of the controlled elements. From ČEPS perspective, the secondary and tertiary control is global. It counts the network's constraints from machines or loads, the restriction in the other pilot nodes, and optimization requirements from a technical and economic perspective. However, the investigation in this thesis focuses only in Krasikov pilot node and the interaction of the neighbor nodes as follows.

4.1.1 Primary regulation

For the primary regulation, control actions base on local measurements and aim to bring out the voltage at the setpoint value automatically. The dynamics characterized by a dominant time constant up to one second produce a high-speed regulation [16]. The AVR (Automatic Voltage Regulator) performs the primary regulation for the Synchronous Generators and Condensers for Krasikov Substation. The AVR controls the voltage terminal adjusting the field excitation voltage. Following ČEPS guidelines, a PID regulator produces a fast response up to any difference between the reference and busbar voltage (pu) values.

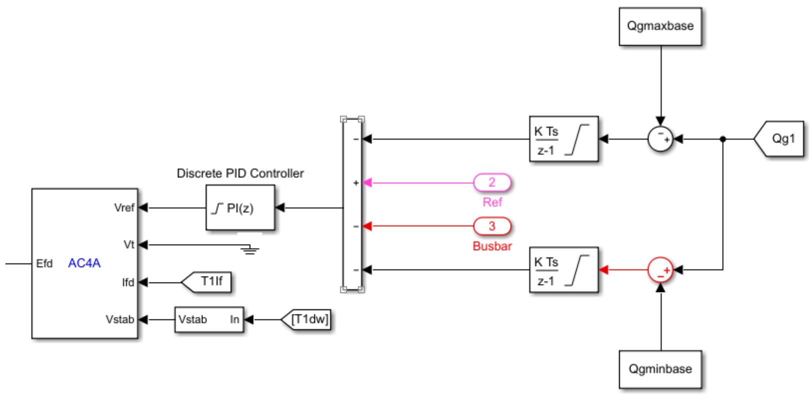


Figure 4.1: Generator Primary Regulation

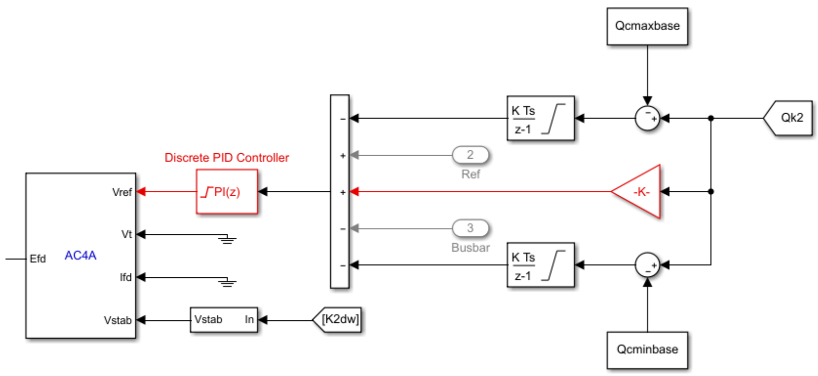


Figure 4.2: Condenser Primary Regulation

Figure 4.1 and 4.2 shows the implemented control for the synchronous machines. The excitation system is capable of managing the machine's voltage terminal, yet in this application, Vt is grounded. There is no affectation in control because of the simplicity from the AC4C in Matlab/Simulink. Vt is a feedback signal to compare with the reference. However, the primary regulation works on the AC4C regulator with the PID response as input, respecting the regulator's limits and the inherit time constant showing the expected performance. Data shows that the regulator of the generators is faster than in the condensers. Thus, the PID controller for the Condenser is slower than the Generator. Using SISOTool from Matlab/Simulink is possible to see the answer of the PID response according to the Generator and Condenser Open Loop as shown in Figure 4.3

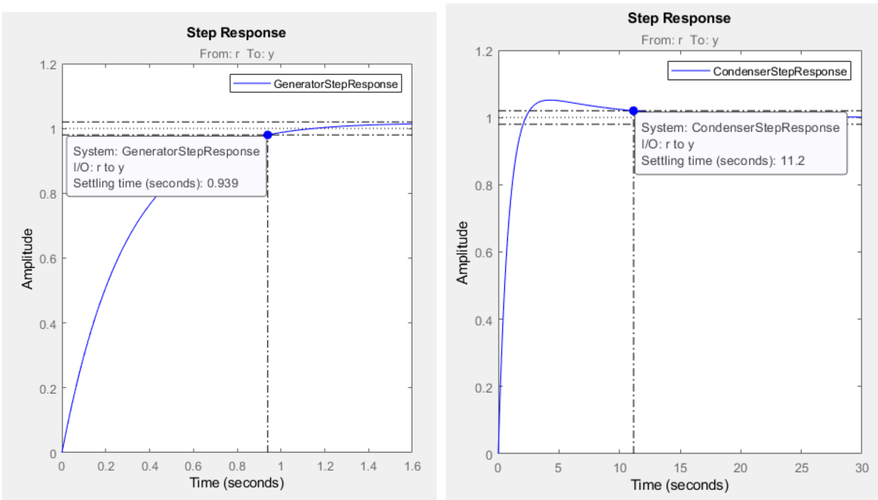


Figure 4.3: Primary Regulation Step Response for Generators and Condensers

The primary regulation includes the OEL and UEL protections working on the excitation voltage as shown in 4.1 and 4.2. The reference value can be the excitation current. Nevertheless, ČEPS kindly delivered the reports on the reactive capability of the synchronous machines. Consequently, this study chooses to compare the reactive of the synchronous machines with these values, everything in each machine pu values. The protection acts as explained:

- OEL: The integral regulator generates a negative signal reducing the excitation voltage when machine's reactive power is greater than the limit threshold. The advantage of this integrator is that it allows a certain transient overload based on the slow transient thermal phenomena. (For Generators Tlim = 10 s, For condensers = 5 s)
- UEL: In this case, the integral regulator generates a positive signal increasing the excitation voltage when machine's reactive power is greater than the limit threshold. The time constant is small with the objective not to allow loss of synchronism. (For Generators Tlim = 10 s, For condensers = 5 s)

Finally, but not least, the simulation test shows that when regulating the excitation voltage of the condensers with the Krasikov Busbar. The voltage in the condenser terminals can reach low values leading to a loss of synchronism. [16] explains this situation: The variations of the reactive power, the voltage drop in a portion of the step-up transformer is completely offset, setting the controlled voltage as the V_{HV} at the HV terminals of the transformer, instead of the voltage at the generator terminals. In practice, and as seen in during simulation tests, this situation corresponds to an unstable operating point. To overcome this issue, the primary control includes a positive compounding factor as indicated in Equation (4.1)

$$V = Vref + \alpha_c Q \tag{4.1}$$

The compounding factor is less than half of the reactance of the step up transformer. In this case, the compensator is located between the tertiary and the primary terminal. Therefore $\alpha_c = T401x13/2$.

4.1.2 Secondary regulation

The Secondary regulation's main objective is to maintain the voltage level in main transmission buses controlling the available reactive power resources in normal operation or when some disturbance happens. The voltage control applies on a small amount of grid buses, the most important ones, each of them able to determine the voltages in the surrounding buses in its area of influence. Therefore, the transmission network splits into "theoretically noninteracting areas" within which the voltage control occurs in the main bus called Pilot Nodes [16]. The pilot node voltage regulation consists in a PI closed loop control for the pilot node comparing the pilot node set point with the pilot node voltage's measurement in the busbar and determining the reactive power level of all the generating units contributing to the total reactive power required.

There is a hierarchy between primary and secondary regulation, as marked, primary regulation faces local perturbations and allows a high-speed control. For the second level, secondary regulation sets up the reactive power levels slower and monitors the network variations. For ČEPS the time of secondary regulation acceptable is between 100 - 120 s. For network operators like ČEPS, the control include OLTC tap changers. However, for this study, the OLTC is not analyzed. Only the VSR reactive power variation is part of the study. Although a central secondary regulation is possible, this research chooses to analyze the area of interest and finds the PI controllers from the equations of the substation Krasikov as an electrical network based on inductances shown in Figure 4.4. The equations discard the resistive components, and the magnetizing circuits of the transformers discard due to simplicity as well as lower impact in the analysis.

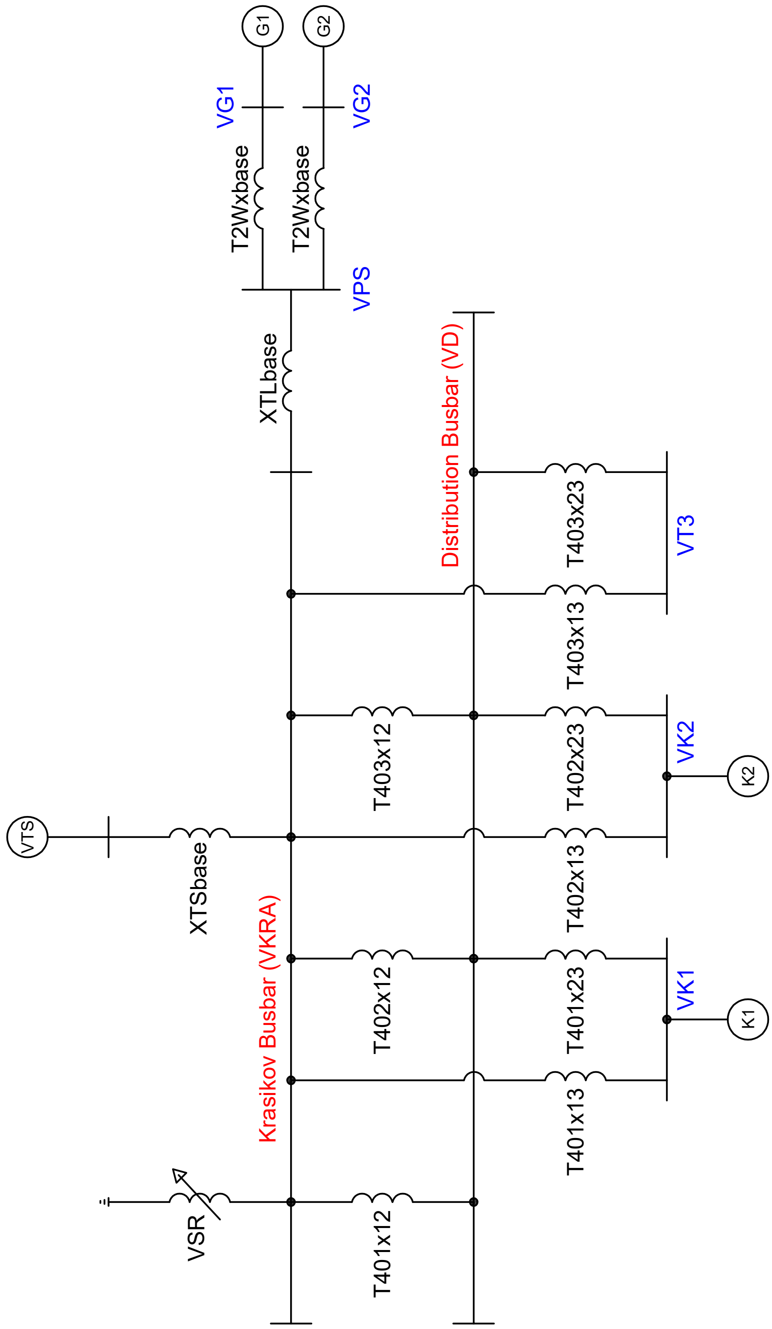


Figure 4.4: Krasikov Substation Circui

To analyze the network as a circuit, elements must be in per unit values of the circuit, some of them differ from the values input in the Matlab/Simulink elements. The values used are per unit in the elements base, while the values need it for the formulation are the per unit values of the network. The base selected is baseMVA = 100 MVA with a Voltage basekV = 400 kV. The transformations happen in the initialization process with the .m file

```
baseMVA = 100*10^6;
basekV = 400*10^3;

factorkV = ((400*10^3)/basekV)^2;

%Two windings Transformer base values
factorT2w = baseMVA/St12;
T12xbase = T12x*factorT2w*factorkV;

%This transformation applies to all the Three - Phase Transformers
%T40x windings Transformer base values
T401z1 = (T401uk12 + T401uk13 - T401uk23)/2;
T401z2 = (T401uk12 - T401uk13 + T401uk23)/2;
T401z3 = (-T401uk12 + T401uk13 + T401uk23)/2;

T401z12 = (T401z1*T401z2 + T401z1*T401z3 + T401z2*T401z3)/T401z3;
T401z23 = (T401z1*T401z2 + T401z1*T401z3 + T401z2*T401z3)/T401z1;
T401z13 = (T401z1*T401z2 + T401z1*T401z3 + T401z2*T401z3)/T401z2;

T401x12base = T401z12*factorT3w1*factorkV;
T401x23base = T401z23*factorT3w1;
T401x13base = T401z13*factorT3w1*factorkV;

% Transmission Line Parameters
ZTL = (basekV^2)/baseMVA;
r1TLbase = r1TL/ZTL;
x1TLbase = x1TL/ZTL;

% Network equivalent
ZNE = (basekV^2)/baseMVA;
XTSbase = XTS/ZNE;
RTSbase = RTS/ZNE;

%Reactor
Qreactor = MVAR(i)/baseMVA; % Tapmin < i < Tapmax
```

The analysis of the circuit stands in equation (4.2). To develop the formula, we start with the relationship between the reactive power and the voltage magnitudes difference between two electrical points:

$$Q = \frac{V_1^2 - V_1 V_2 cos(\delta_2 - \delta_1)}{X}$$

Assumption 1. $\Delta P = 0$ (machines works as reactive compensators)

$$Q = \frac{V_1^2 - V_1 V_2}{X}$$

Assumption 2. $V_{10} \approx V_{20}$ (system works near the operating point)

$$\Delta Q = \frac{V_{10}(\Delta V_1 - \Delta V_2)}{X} \tag{4.2}$$

To study all the circuit, we can apply Equation 4.2 from now on, divided in zones. Then, for the pump storage, we have Equations 4.3, 4.4, 4.5:

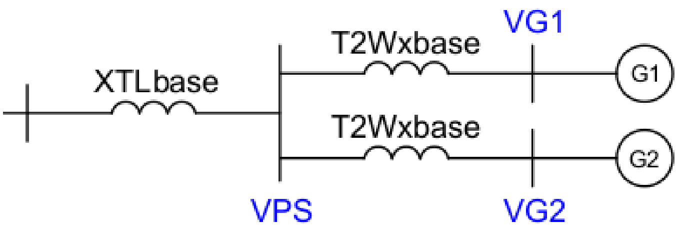


Figure 4.5: Pump Storage Circuit

$$Q_{G1} + Q_{G2} = \frac{V_{KRA(0)}}{x_{TLbase}}(V_{DS} - V_{KRA}) \tag{4.3}$$

$$Q_{G1} = \frac{V_{KRA(0)}}{x_{T2Wxbase}}(V_{G1} - V_{DS}) \tag{4.4}$$

$$Q_{G2} = \frac{V_{KRA(0)}}{x_{T2Wxbase}}(V_{G2} - V_{DS}) \tag{4.5}$$

To find a relationship between the Voltage and Reactive Power of each generator from regarding Krasikov Busbar, replacing V_{DS} from Equation 4.3 in Equations 4.4 and 4.5:

$$\frac{x_{T2Wxbase}}{V_{KRA(0)}}Q_{G1} = V_{G1} - Q_{G1}\frac{x_{TLbase}}{V_{KRA(0)}} - Q_{G2}\frac{x_{TLbase}}{V_{KRA(0)}} - V_{KRA}$$

$$\frac{x_{T2Wxbase}}{V_{KRA(0)}}Q_{G2} = V_{G2} - Q_{G1}\frac{x_{TLbase}}{V_{KRA(0)}} - Q_{G2}\frac{x_{TLbase}}{V_{KRA(0)}} - V_{KRA}$$

$$V_{G1} - V_{KRA} = \frac{x_{T2Wbase} + x_{TLbase}}{V_{KRA(0)}}Q_{G1} + \frac{x_{TLbase}}{V_{KRA(0)}}Q_{G2} \tag{4.6}$$

$$V_{G2} - V_{KRA} = \frac{x_{TLbase}}{V_{KRA(0)}}Q_{G1} + \frac{x_{T2Wbase} + x_{TLbase}}{V_{KRA(0)}}Q_{G2} \tag{4.7}$$

To continue the formulation for the condenser connected to the Krasikov Busbar by the three windings transformer and we have a valid relationship:

$$Q_{13} = Q_{23} + Q_3 \tag{4.8}$$

$$\begin{aligned} Q_{13} &= \frac{V_{KRA(0)}}{x_{T401x13base}}(V_{KRA} - V_K) \\ Q_{23} &= \frac{V_{KRA(0)}}{x_{T401x23base}}(V_D - V_K) \\ Q_3 &= Q_K \end{aligned} \tag{4.9}$$

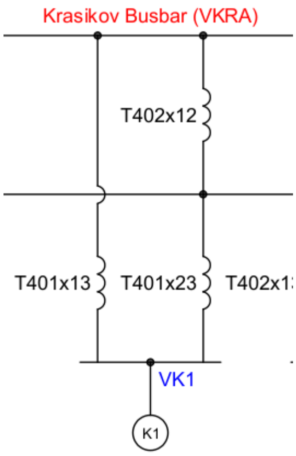


Figure 4.6: Transformer and Condenser Circuit

Replacing Equations (4.9) in (4.8), we find an expresion for each condenser:

$$Q_K = \frac{V_{KRA(0)}}{x_{T401x13base}}(V_{KRA} - V_K) - \frac{V_{KRA(0)}}{x_{T401x23base}}(V_D - V_K) \tag{4.10}$$

Applying (4.10) to each condenser, we obtain:

$$\begin{gathered} \frac{x_{T401x13base}x_{T401x23base}}{V_{KRA(0)}(x_{T401x13base} - x_{T401x23base})}Q_{K1} = V_{K1} \\ - \frac{x_{T401x13base}}{x_{T401x13base} - x_{T401x23base}}V_D + \frac{x_{T401x23base}}{x_{T401x13base} - x_{T401x23base}}V_{KRA} \end{gathered} \tag{4.11}$$

$$\begin{gathered} \frac{x_{T402x13base}x_{T402x23base}}{V_{KRA(0)}(x_{T402x13base} - x_{T402x23base})}Q_{K2} = V_{K2} \\ - \frac{x_{T402x13base}}{x_{T402x13base} - x_{T402x23base}}V_D + \frac{x_{T402x23base}}{x_{T402x13base} - x_{T402x23base}}V_{KRA} \end{gathered} \tag{4.12}$$

With Equations (4.6), (4.7), (4.11), (4.12), its possible to formalize a equation involving the synchronous machines voltages and reactive power, transmission and distribution voltage, and Kraskiov Busbar:

$$[\Delta V - [B_1][V_{KRA}] - [B_2][V_D]] = [A]\Delta Q, \tag{4.13}$$

where

$$A = \begin{bmatrix} \frac{x_{12}+x_{TL}}{V_{KRA(0)}} & \frac{x_{TL}}{V_{KRA(0)}} & 0 & 0 \\ \frac{x_{TL}}{V_{KRA(0)}} & \frac{x_{12}+x_{TL}}{V_{KRA(0)}} & 0 & 0 \\ 0 & 0 & \frac{xT401_{13}xT401_{23}}{V_{KRA(0)}(xT401_{13}-xT401_{23})} & 0 \\ 0 & 0 & 0 & \frac{xT402_{13}xT402_{23}}{V_{KRA(0)}(xT402_{13}-xT402_{23})} \end{bmatrix}, \tag{4.14}$$

$$B_1 = \begin{bmatrix} 1 \\ 1 \\ \frac{xT401_{23}}{xT401_{13}-xT401_{23}} \\ \frac{xT402_{23}}{xT402_{321}-xT402_{23}} \end{bmatrix}, \quad B_2 = \begin{bmatrix} 0 \\ 0 \\ \frac{xT401_{13}}{xT401_{13}-xT401_{23}} \\ \frac{xT402_{13}}{xT402_{13}+xT402_{23}} \end{bmatrix}. \tag{4.15}$$

All the reactive contributions in Krasikov Busbar compose of

$$\sum Q = Q_{G1} + Q_{G2} + QW1_{T401} + QW1_{T402}.$$

where $QW1_{T401}$ and $QW1_{T402}$ are the reactive power from the primary of the transformer, where Equation (4.8) applies. Finally, to approximate the voltage changes in Krasikov Busbar

$$\sum Q + Q_{T403} - Q_{Reactor} = \frac{V_{K(0)}}{x_{TS}}(V_{KRA} - V_{TS}). \tag{4.16}$$

To form the control loop for the PID controllers, Equation (4.13) helps to find the reactive power required

$$\Delta Q = [\Delta V * A^{-1} - [B_1 * A^{-1}][V_{KRA}] - [B_2 * A^{-1}][V_D]]. \tag{4.17}$$

The term $\Delta V * A^{-1}$ is the voltage from the synchronous machines, due to difference in the time frames between the secondary and the primary regulation. Primary regulation is faster, then the control can replace the term by an integrator with a time constant of 5 s. The time is sufficient to expect the change of the reactive power of each machine. Then, to find the PID parameters, we come back to the equations developed before. To calculate the proportional element, we consider that $\Delta t = 0^+$, the reactive variation is faster than the voltage perturbance. Therefore, for the generators individual compensation will be

$$V_{G1} - \cancelto{0}{V_{KRA}} = \frac{x_{T2Wbase} + x_{TLbase}}{V_{KRA(0)}} Q_{G1} + \frac{x_{TLbase}}{V_{KRA(0)}} Q_{G2},$$
$$KP_G = \frac{\Delta Q_{G1}}{\Delta V_{G1}} = \frac{\Delta Q_{G1}}{\Delta V_{G1}} = \frac{V_{KRA(0)}}{x_{T2Wbase} + x_{TLbase}}. \tag{4.18}$$

For the condenser, individual compensation will be

$$Q_K = \frac{V_{KRA(0)}}{x_{T401x13base}} (\cancelto{0}{V_{KRA}} - V_K) + \frac{V_{KRA(0)}}{x_{T401x23base}} (\cancelto{0}{V_D} - V_K),$$

$$KP_{K1} = \frac{\Delta Q_{G1}}{\Delta V_{G1}} = V_{KRA(0)} \frac{x_{T401x13base} x_{T401x23base}}{x_{T401x13base} - x_{T401x23base}}, \tag{4.19}$$

$$KP_{K2} = \frac{\Delta Q_{G2}}{\Delta V_{G2}} = V_{KRA(0)} \frac{x_{T402x13base} x_{T402x23base}}{x_{T402x13base} - x_{T402x23base}}. \tag{4.20}$$

Finally, the integral component is a stable condition in Krasikov Busbar after a change from the Transmission Voltage. For this, the assumption is that each machine covers the whole disturbance

$$Q + \cancelto{0}{Q_{T403}} - \cancelto{0}{Q_{Reactor}} = \frac{V_{KRA(0)}}{x_{TS}} (V_{KRA} - V_{TS}),$$
$$(\cancelto{0}{\Delta V_{ref}} - \Delta V_{KRA})(KP + \frac{KI}{s}) = \frac{V_{KRA(0)}}{x_{TS}} (\Delta V_{KRA} - \cancelto{0}{\Delta V_{TS}}).$$

Then, replacing KP from Equations (4.18), (4.19), (4.20), and setting the integration pole for $s = -\frac{1}{T_s}$ with a stabilzation time for the control loop $T_s = 50s$,

$$KI_G = V_{KRA(0)} \left(\frac{1}{x_{T2Wxbase} - x_{TLxbase}} + \frac{1}{x_{TS}} \right),$$
$$KI_{K1} = V_{KRA(0)} \left(\frac{x_{T401x13base} x_{T401x23base}}{x_{T401x13base} - x_{T401x23base}} + \frac{1}{x_{TS}} \right),$$
$$KI_{K2} = V_{KRA(0)} \left(\frac{x_{T402x13base} x_{T402x23base}}{x_{T402x13base} - x_{T402x23base}} + \frac{1}{x_{TS}} \right).$$

PID generators have the option of saturating the outputs. Thus, to create a proper reactive power level, the controllers limit its output according to the max or min reactive power possible in pu values. The only difference for the condenser outputs is the compounding factor in the analysis. If not, the control will not reach the maximum compensation possible.

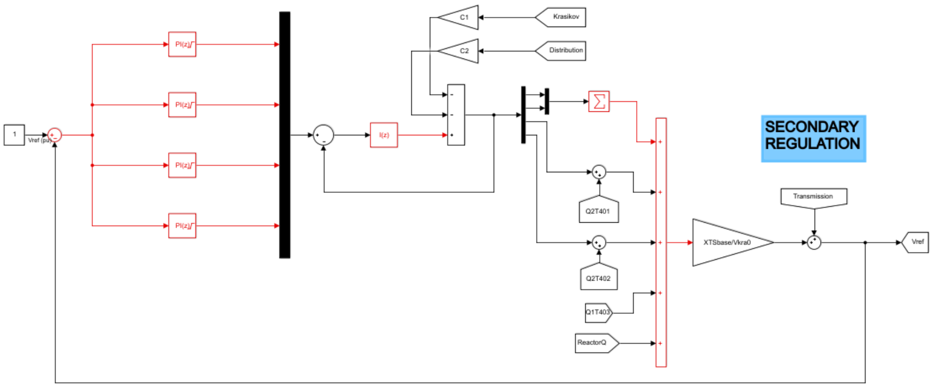


Figure 4.7: Secondary Regulation in Matlab/SImulink Model

4.1.3 VSR Operation within the Network

The VSR within the simulation will work in Auto Mode. The key point is to detect when the reactive power sources are saturated in their limits. To do it, the signal generates, as Figure 4.8 explains, the Interval signals produce a true signal when the reactive powers of the machines are within the interval. The or gate and not gates allows to only have a positive signal when all the signals are out of the range. The bistable sets the signals and waits for the reset. The resets produce when all the signals are positive through the gate.

Finally, it is important to point out that the control works direct in Krasikov busbar, Equation (4.16) joins all the reactive powers. As the synchronous machines are not contributing and without any sudden changes in the surrounding voltages as part of the static analysis

$$
\begin{aligned}
Q_{Reactor} = & -\frac{V_{KRA(0)}}{x_{TS}}(V_{KRA} - \cancelto{0}{V_{TS}}) \\
& - V_{KRA(0)}\left(\frac{1}{x_{T401x12}} + \frac{1}{x_{T401x12}} + \frac{1}{x_{T401x12}}\right)(V_{KRA} - \cancelto{0}{V_D}).
\end{aligned}
$$

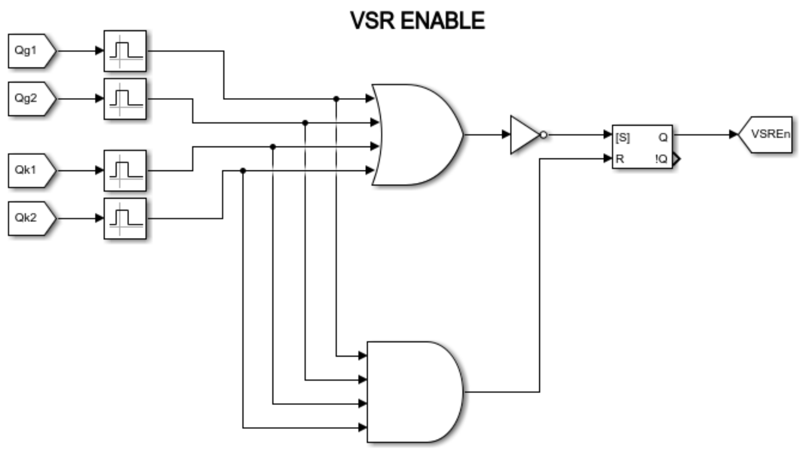


Figure 4.8: VSR Enable Signal

With ± 2 MVARs with a maximum of 60 MVARs of regulation

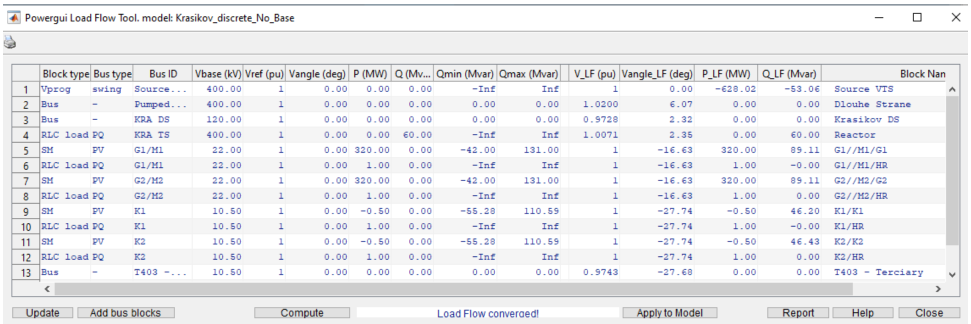
$$\Delta V = -0.0001(pu) \tag{4.21}$$

Therefore, the min and max error comes from Equation (4.21). The Error signal from Equation (3.7) compares with the value presented.

4.2 Algorithm for optimal use of reactive power sources in Substation Krasíkov

The implicit function of the algorithm comes with the secondary regulation. Therefore, to test the model the simulation starts with a Power flow estimation by the Specialized Power System PowerGui tool.

Its clear that the Krasikov Busbar is the pilot node and in a Power flow analysis should be the "swing bus". However, for Matlab/Simulink only voltage source can be programmed as a swing bus. It is possible to install a source in Krasikov Busbar and run the simulation, but test shows that any change in the voltage its consumed by the equivalent power sources and the effect of the synchronous machine is not appreciable. Therefore, Transmission System Power Source is the swing bus, the generators and condensers are PV buses and the rest are PQ buses. As seen in the Figure 4.9, the Power flow converges and this values will be input automatically by Matlab/Simulink in order to initialize the model.



	Block type	Bus type	Bus ID	Vbase (kV)	Vref (pu)	Vangle (deg)	P (MW)	Q (Mv...	Qmin (Mvar)	Qmax (Mvar)	V_LF (pu)	Vangle_LF (deg)	P_LF (MW)	Q_LF (Mvar)	Block Nan
1	Vprog	swing	Source...	400.00	1	0.00	0.00	0.00	-Inf	Inf	1	0.00	-628.02	-53.06	Source VTS
2	Bus	-	Pumped...	400.00	1	0.00	0.00	0.00	0.00	0.00	1.0200	6.07	0.00	0.00	Dlouhe Strane
3	Bus	-	KRA DS	120.00	1	0.00	0.00	0.00	0.00	0.00	0.9728	2.32	0.00	0.00	Krasikov DS
4	RLC load	PQ	KRA TS	400.00	1	0.00	0.00	60.00	-Inf	Inf	1.0071	2.35	0.00	60.00	Reactor
5	SM	PV	G1/M1	22.00	1	0.00	320.00	0.00	-42.00	131.00	1	-16.63	320.00	89.11	G1//M1/G1
6	RLC load	PQ	G1/M1	22.00	1	0.00	1.00	0.00	-Inf	Inf	1	-16.63	1.00	-0.00	G1//M1/HR
7	SM	PV	G2/M2	22.00	1	0.00	320.00	0.00	-42.00	131.00	1	-16.63	320.00	89.11	G2//M2/G2
8	RLC load	PQ	G2/M2	22.00	1	0.00	1.00	0.00	-Inf	Inf	1	-16.63	1.00	0.00	G2//M2/HR
9	SM	PV	K1	10.50	1	0.00	-0.50	0.00	-55.28	110.59	1	-27.74	-0.50	46.20	K1/K1
10	RLC load	PQ	K1	10.50	1	0.00	1.00	0.00	-Inf	Inf	1	-27.74	1.00	-0.00	K1/HR
11	SM	PV	K2	10.50	1	0.00	-0.50	0.00	-55.28	110.59	1	-27.74	-0.50	46.43	K2/K2
12	RLC load	PQ	K2	10.50	1	0.00	1.00	0.00	-Inf	Inf	1	-27.74	1.00	0.00	K2/HR
13	Bus	-	T403 -...	10.50	1	0.00	0.00	0.00	0.00	0.00	0.9743	-27.68	0.00	0.00	T403 - Terciary

Figure 4.9: Substation Krasikov Power Flow Results

Transmission Network Disturbance: VTS = 0.005 (pu) Step. To check the algorithm implemented, the simulation will produce a transmission network disturbance. Figures 4.10 and 4.11 show the system response to a rising step in the transmission system.

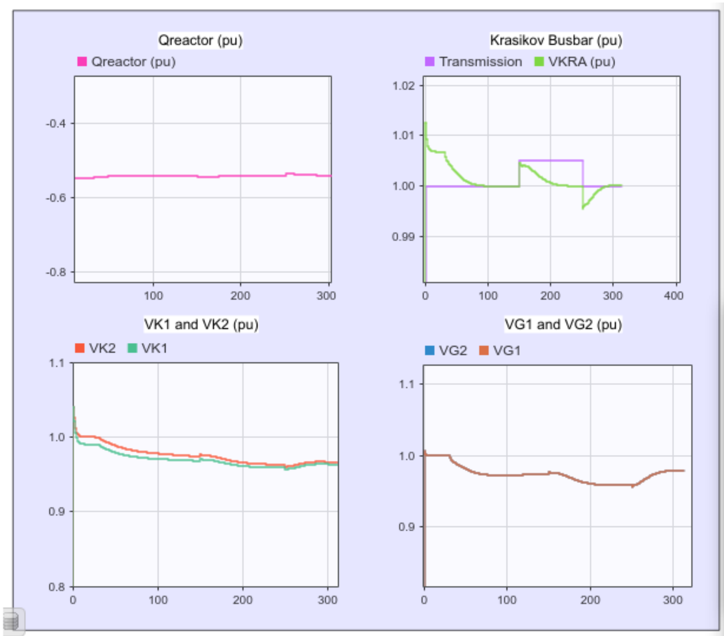


Figure 4.10: Transmission Signal Variation - Voltage Response

The setpoint of the reference voltage of the system is 1 (pu) through the whole process. Initially, the system starts with the initial values setting the voltage around 1.007 (pu) as Power Flow indicates. After 30 seconds the system changes from primary regulation to secondary regulation. The output of the PID control loop is the new reference and its compared with Krasikov Busbar. At that moment, the system adjust the voltage to 1 (pu) and at t = 150 - 250 s the step occurs. From Figure 4.10 two points are clear:

- Regulation system works in order to mantain the reference voltage for

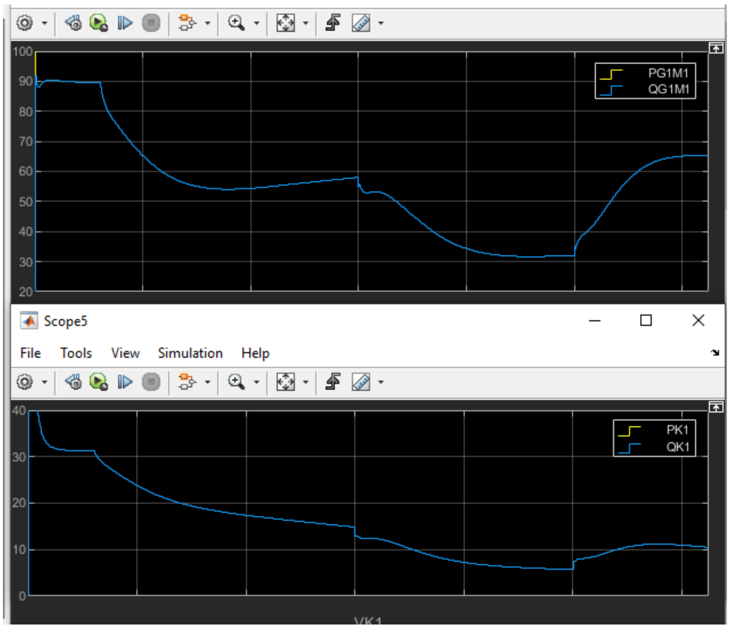


Figure 4.11: Transmission Signal Variation - Reactive Power Response

Krasikov Busbar. This voltage can be input automatically or manual.

- VSR doesnot work unless the machines are not saturated.

Figure 4.11 shows the Reactive Power response to the Transmission network disturbance. The graph allows us to know the compensating effect in the Krasikov pilot node:

$$\frac{\sum Q}{V_{KRA}} = \frac{26*2+10*2}{baseMVA*0.004}$$
$$\frac{\Delta Q}{V_{KRA}} = 180(pu)$$

From Equation 4.16, the theoretical value = 150 (pu). The difference can be counted in the reactive losses of the system.

VSR regulation. As reflected in the theoretical part, the regulation is approximately around -0.0001 (pu) voltage change with one step variation. For the 60 MVARs step in total, the VSR adds 0.18 MVAR/kV in Krasikov Substation.

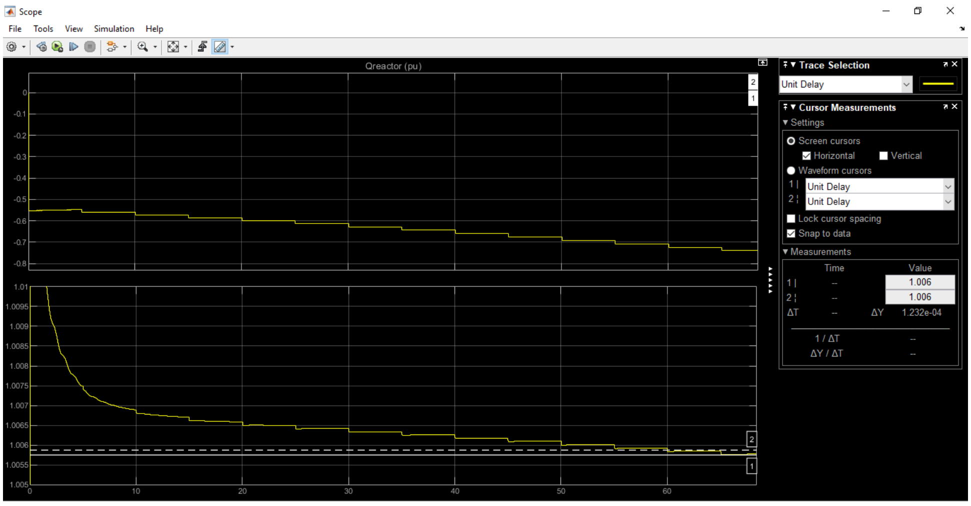


Figure 4.12: Voltage effect in Krasikov Busbar

4.3 Optimal tuning of the algorithm

The system shows addecuate resuls. However, its clear that the system is only driven by the network capabilities witouth counting the reactive power sources capabilities. For this previous equations will include two factors ($\alpha_{gen} = \frac{Q_G}{\sum Q} and \alpha_{con} = \frac{Q_K}{\sum Q}$) proportionally to the machines capabilities. The results are the following:

System improves in the following:

- Regulation is faster, due to the inmediate intervetion of the G1 reactive power. There is around 30 seconds of difference between the generator and condenser in reaching limit points.
- VSR works as required when both machines saturate. The VSR starts to work and helps Krasikov substation to reach the setpoint. VSR doesnot move its setpoint when system starts to recuperate by the PID actions.
- In this case, the $\frac{\Delta Q}{V_{KRA}} = 170(pu)$ similar to the results obtained before.

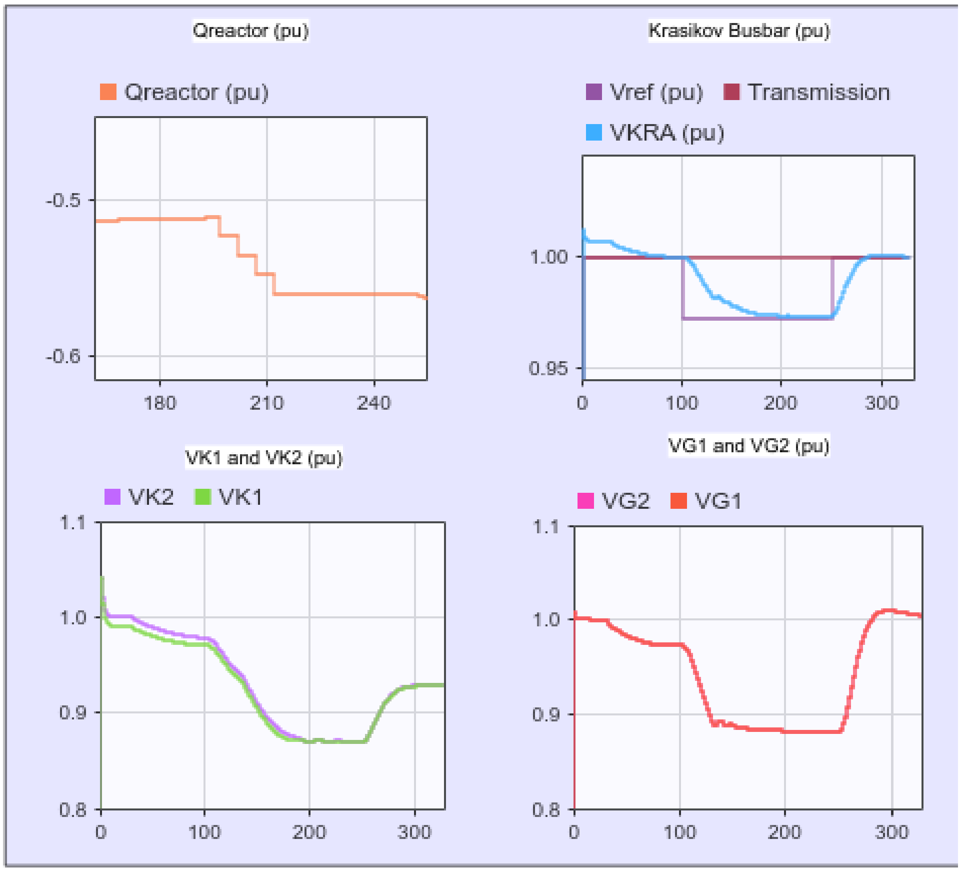


Figure 4.13: Voltage variation after reference change

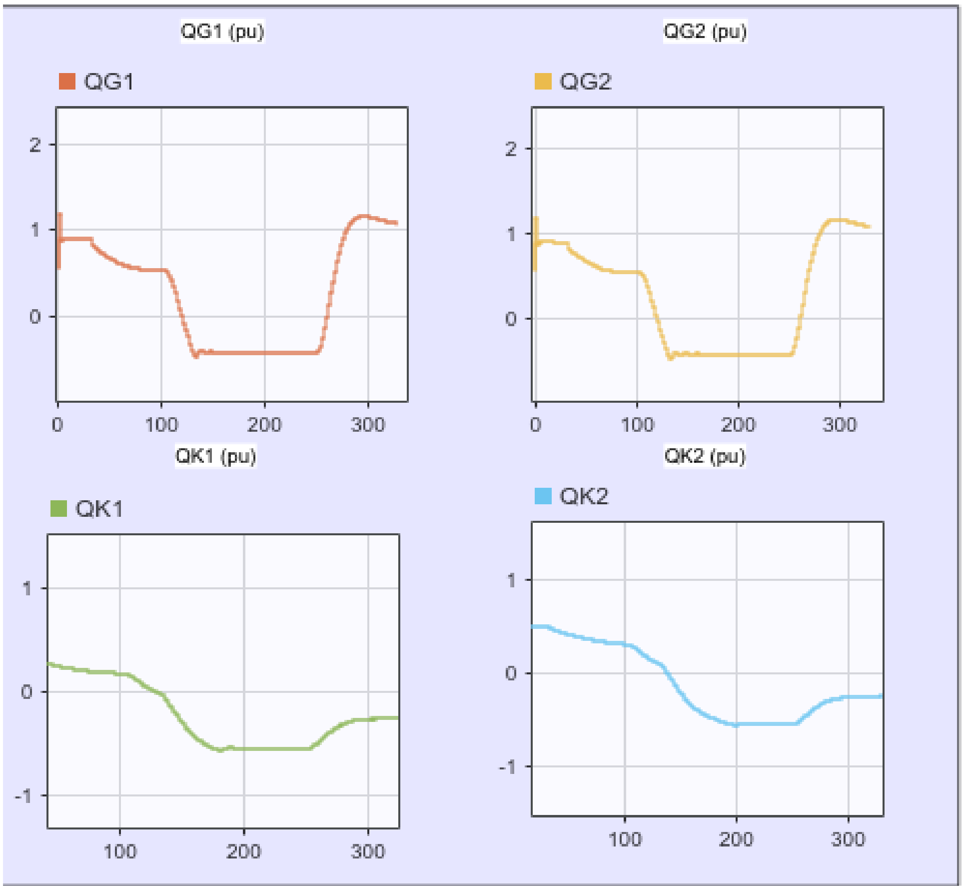


Figure 4.14: Reactive Power variation after reference change

Chapter 5

Recommendations and Conclusions

- Simulation results shows the Q/V characteristics in the synchronous machines. When the control is dimensioned properly according to its capabilities, the reactive power injected by these elements proportions stability to the network under disturbances. Similarly, reactive power compensators like the VSR analyzed in this research helps to maintain the voltage within the limits when its required. It's true that the control can be more flexible and help the system to reduce the reactive load in the generators or compensators. However, the focus of the study is more as a back up of the current regulation

- The Primary and Secondary regulation are powerful tools for the control of electrical networks. The analysis is based on the nature of the elements interconnected and can be applied to more extend networks. The primary control is vital to extend generators lifetime and the secondary regulation helps to estimate the relationship between the change of MVARs and kV. In our study, with the MVAbase = 100 MVA and basekV = 400 kV, this constant is up to 180 MVAR/kV. Its truth that the optimization process can be improved for further work into a more sophisticated analysis based on different techniques. However, to understand the regulation in Krasikov Busbar, the proposal on this thesis is clear

- The operation of the VSR shows the expected. The support to Krasikov Busbar in the case of exhausting all the reactive power available by the synchronous machines. The Stateflow machines, works smoothly for this implementations of state machines to control machines or electric power system elements. The effect on the regulation is tested, and it has always to take in count the delay of the nature of the inductance.

Appendix A

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MASTER'S THESIS ASSIGNMENT

CTU
CZECH TECHNICAL UNIVERSITY IN PRAGUE

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Specialisation: **Electrical Power Engineering**

II. Master's thesis details

Master's thesis title in English:

Algorithm for optimal voltage level at Krasíkov substation operating reactive power equipment available.

Master's thesis title in Czech:

Algoritmus pro optimální nastavení napětí pomocí jalového výkonu v rozvodně Krasíkov

Guidelines:

1. Describe voltage control in the Czech transmission system and substation Krasíkov
2. Create a model of substation Krasíkov and reactive power sources connected to it
3. Create an algorithm for optimal use of reactive power sources to control voltage in substation Krasíkov
4. Find an optimal tuning of the algorithm
5. Based on the above, draw recommendations for voltage control algorithm in substation Krasíkov

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Praha: České vysoké učení technické, 2011, ISBN 978-80-01-04940-2

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Date of master's thesis assignment: **25.02.2021** Deadline for master's thesis submission: **20.05.2022**

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