Critical Study, Modeling, and Improvement of the Excitation System for a 200 MVAR Generator / NOOR 1

by

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Abstract

This project focuses on the critical study and modeling of the Automatic Voltage Regulator (AVR) within a solar power generation plant. The report begins by providing an overview of the electrical network structure and exploring the concept of deregulation, followed by a superficial analysis of service and system philosophies concerning security during static, dynamic, and transient states.

The core of the study delves into the three levels of voltage and frequency regulation, with a particular emphasis on the level 1 voltage regulation at the plant's output. A critical examination of the currently utilized AVR is conducted, followed by its modeling using Simulink to analyze its performance and efficiency.

The findings highlight the significance of advancing to level 2 regulation at the plant, as the current setup only performs primary regulation, with secondary regulation being manually operated. This transition is crucial for enhancing the plant's operational reliability and efficiency. The results of the modeling and analysis provide valuable insights into potential improvements for the plant's voltage regulation system.

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List of Abbreviations

- **AVR**: Automatic Voltage Regulator
- **FACTS**: Flexible AC Transmission Systems
- **PSS**: Power System Stabilizer

Chapter 1

Introduction

1.1 Presentation of the Host Organization

1.1.1 Presentation of the Companies

In this section, we will present the Noor Ouarzazate projects and the host organization, MASEN, including its history, missions, and organizational structure. We will then describe the BOOT projects and the PPA (Power Purchase Agreement) that governs the relationship between MASEN and the project company. Additionally, we will discuss the role of the Engineering and Performance entity within MASEN in ensuring compliance with contractual requirements.

MASEN

masen
force inépuisable de développement

The agency is a Moroccan private company with public capital, established in March 2010 to implement the Moroccan solar plan. Its purpose is to develop solar power plants and support the deployment of a solar ecosystem in Morocco through an integrated approach. Since its inception, it has been led by Mustapha Bakkoury, who serves as the Chairman of the Executive Board.

ACWA Power

It is a Saudi company specializing in the development and operation of power plants and water desalination units. The company invests in solar energy (photovoltaic PV), concentrated solar power (CSP), geothermal energy, and clean coal. The Saudi company has taken over the contracts for all phases of the NOOR (1, 2, and 3) project in Ouarzazate, which operate using CSP technology. The company is currently present in eleven countries across the Middle East, North Africa, Turkey, as well as South Africa and Southeast Asia.

NOMAC

NOMAC (First Operation and Maintenance Company) is a global enterprise responsible for providing operation and maintenance services across a range of sites. Established in 2005 with its own administration, governance, and financial objectives, NOMAC is a subsidiary of the Saudi group ACWA Power. ACWA Power is a developer, investor, owner, and operator of numerous power projects, including PV and CSP, in various countries.

NOMAC consists of a team of managers, technicians, and engineers from various fields who manage and maintain electricity production at several international solar, wind, and water desalination plants, adhering to all safety and environmental standards. NOMAC won the bid to manage and operate the NOOR Ouarzazate CSP solar project, which is overseen by the Moroccan Solar Energy Agency (MASEN).

Through its operation, maintenance, and performance analysis services, which prioritize operator safety and environmental compliance, NOMAC ensures the smooth functioning of the NOOR complex to generate and sell electricity to MASEN according to the agreement signed in November 2012. This project is structured under a BOOT (Build, Own, Operate, Transfer) model.

Safety is the top priority at NOMAC. Consequently, the management strategy is based on a set of rules that place paramount importance on Health, Safety, and Environment (HSE) and emphasizes proactive measures to manage any risks effectively.

- NOMAC Group Policy : NOMAC is a closely integrated group of operational divisions and subsidiaries. The group's policy includes a commitment to development, human capital safety, an integrated management system, an enterprise resource planning system, and a risk management system.

  NOMAC implements the FIRST safety policy and conducts ongoing safety training for all personnel. It also ensures that all elevators, lifting chains, and hoist panels are periodically tested and certified for safe use.

  NOMAC's health and safety management system is certified under OHSAS 18001 (2007). The company minimizes environmental impact by rigorously applying mitigation and monitoring plans, and ensuring that each staff member's responsibilities are clearly defined. In this regard, NOMAC's operations are also certified according to ISO 14001 (2004).

- Organizational Chart of the Company :

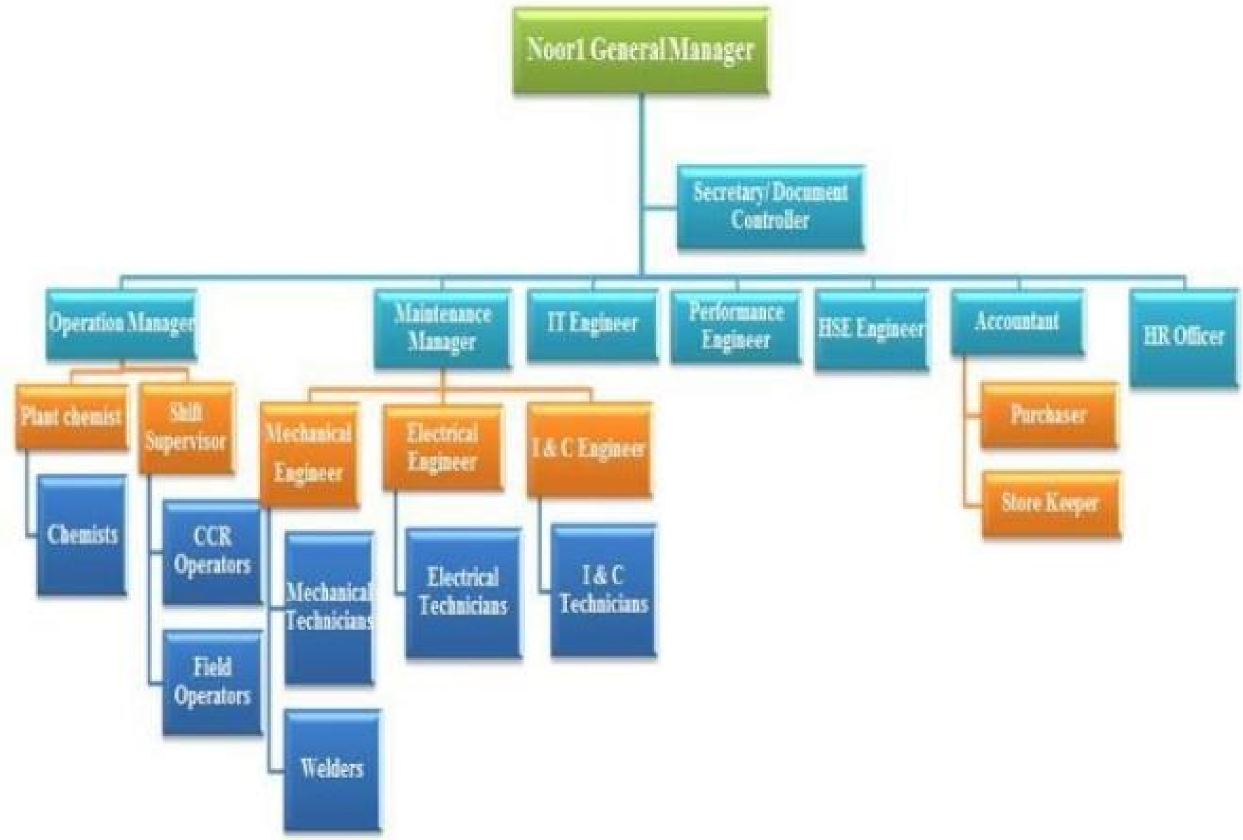

Figure 1.1: Organizational Chart of the Company

1.1.2 General Overview of the Noor Ouarzazate Site

Noor 1

The first plant of the solar complex was inaugurated in February 2016, after 3 years of construction work. It is named NOOR1. Chosen for its exceptional sunshine, with nearly 320 days of sun, the site covers an area of approximately 480 hectares, equivalent to 600 football fields. This first phase of the project involves the operation of a solar thermal power plant (CSP) based on parabolic mirror technology that concentrates sunlight onto pipes where the heat transfer fluid circulates to be heated. This type of plant extends production hours beyond sunset, as it is equipped with a 3-hour heat storage capacity in molten salts.

Figure 1.2: NOOR 1

Noor 2

The NOOR2 solar plant will use the same technology as NOOR1 but will feature more parabolic trough collectors. Spanning an area of 680 hectares, it will be able to produce an electrical power of 200 MW, with an 8-hour storage capacity. NOOR2 is still under construction and will only be operational in 2018.

Figure 1.3: NOOR 2

Noor 3

A new technology will underpin the third phase of the project: NOOR3 will use solar thermal tower technology. This involves a solar tower that captures concentrated sunlight to generate steam, which then drives a turbine to produce electricity. This plant will have a power output of 200 MW and an 8-hour storage capacity.

Figure 1.4: NOOR 3

Noor 4

NOOR IV is the fourth phase of the NOOR solar complex in Ouarzazate, Morocco. It employs photovoltaic (PV) technology to convert sunlight directly into electricity. With a total installed capacity of 72 MW, NOOR IV plays a crucial role in enhancing the complex's contribution to clean, renewable energy. This reduces reliance on fossil fuels and lowers greenhouse gas emissions. Featuring thousands of solar panels, this PV plant efficiently captures solar energy and is a vital component of Morocco's strategy to diversify its energy portfolio and advance environmental sustainability.

Figure 1.5: NOOR 4

1.2 Description of Noor 1

1.2.1 The Solar Field

Operation

- The primary role of this system is to receive the cold HTF from the main pumps at a temperature of 293°C and heat it up to 393°C using solar radiation.

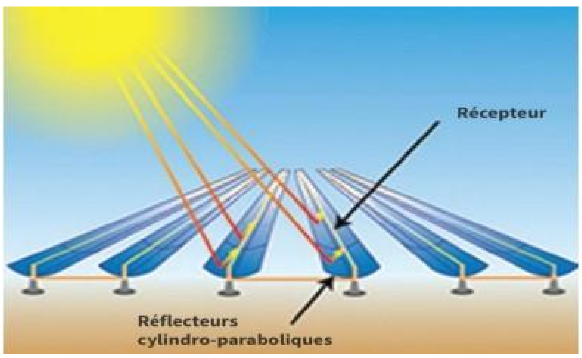

Figure 1.6: The Solar Field

- On an area of approximately 480 hectares, there are about 500,000 solar mirrors. The solar field system of the NOOR1 solar plant consists of 400 SENERTROUGH2 loops connected in parallel, forming 14 subfields. Additionally, the system includes cold and hot HTF collectors, which are responsible for distributing and collecting the fluid to the power block.
- This solar field contains 7 platforms, each comprising a number of fields, totaling 14 ”subfields.”

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Main Equipment

The main equipment in the solar field includes parabolic trough collectors, receiver tubes, and supporting structures. These components are crucial for capturing and concentrating solar energy effectively.

Mirror Cleaning System

The mirror cleaning system ensures that the parabolic trough collectors maintain optimal performance by removing dust and debris that can reduce their efficiency. This system uses a combination of water and mechanical brushes to clean the mirrors.

1.2.2 HTF Circuit

Heat-Transfer Fluid (HTF)

The heat-transfer fluid (HTF) used in Noor 1 is designed to efficiently transfer heat from the solar collectors to the steam generation system. The HTF is typically a synthetic oil with high thermal stability.

HTF Expansion System

The HTF expansion system manages the thermal expansion of the fluid as it heats up. This system includes expansion tanks and associated controls to accommodate changes in fluid volume and maintain system pressure.

Main HTF Pumps

The main HTF pumps circulate the heat-transfer fluid throughout the solar field and into the heat exchangers. These pumps are critical for maintaining the flow and pressure of the HTF.

1.2.3 Water Circuit

PTA (Power Turbine Auxiliary)

The PTA system assists in controlling the operation of the turbine and ensuring stable power generation. It provides additional support and regulation to the turbine's performance.

Water-Steam Circuit

The water-steam circuit manages the conversion of heat from the HTF into steam. It includes heat exchangers, steam generators, and other components necessary for efficient steam production.

Condensation System

The condensation system cools and condenses the steam back into water after it has passed through the turbine. This system is essential for recycling water and maintaining efficient operation.

Steam Generation System (SGS)

The steam generation system converts the heat-transfer fluid's thermal energy into steam. This process involves heat exchangers and other equipment to ensure effective steam production.

Steam Turbine

The steam turbine converts the thermal energy of the steam into mechanical energy, which is then used to generate electricity. It is a key component of the power generation process.

1.2.4 Nitrogen Production System (PSA)

Local Production from Air

The PSA (Pressure Swing Adsorption) system produces nitrogen locally from the air, using adsorption technology to separate nitrogen from other gases.

Production from Purchased Liquid Nitrogen

In addition to local production, the plant also uses purchased liquid nitrogen as a backup or supplementary source for its operations.

Role of Nitrogen in the Plant

Nitrogen is used in various processes within the plant, including purging, inerting, and cooling applications. Its role is critical in maintaining safe and efficient operations.

1.2.5 Thermal Storage System

Main Equipment

The thermal storage system includes equipment such as storage tanks and heat exchangers that store and release thermal energy. This system helps to manage the plant's energy supply and demand.

Modes of Operation

The thermal storage system operates in different modes to balance energy production and consumption. It can store excess thermal energy during peak production and release it during periods of lower solar availability.

Detection Method for HTF Leaks in Salts

Methods for detecting leaks of heat-transfer fluid (HTF) in thermal storage salts include monitoring systems and leak detection sensors to ensure system integrity and safety.

1.2.6 Electrical Distribution

Alternator

The alternator generates electrical power from the mechanical energy produced by the steam turbine. It is a crucial component for converting the turbine's output into usable electrical energy.

Main Transformer

The main transformer steps up the voltage of the generated electricity to match the transmission grid requirements. It ensures efficient distribution of electrical power from the plant.

Auxiliary Transformer

The auxiliary transformer provides additional voltage regulation and power supply for auxiliary systems within the plant, supporting its overall operation.

Chapter 2

Electrical Grids - Critical Infrastructure

2.1 Reliability and Security of Electrical Grids

Reliability in electrical grids refers to the system's ability to meet power demands within the rated capacities of equipment and voltage limits, accounting for both planned and unplanned outages. Grid operations involve frequent changes in operating conditions. Events such as equipment failures, outages, or load modifications can cause disruptions in the system's state, sometimes leading to critical situations. While some emergencies can be resolved using conventional tools, others may require load shedding as the only solution. In extreme cases, grid stability and integrity are threatened, posing long-term reliability issues.

To manage such risks, operators rely on the ”N-1” security criterion, which ensures that the loss of a single grid element (e.g., line, transformer, or generator) does not compromise the overall system. If this criterion is met, the system can recover without triggering a defense plan, thanks to automatic controls and protections.

In deregulated environments, ensuring grid security can become more challenging, as some stakeholders might prioritize short-term profits over long-term system stability. Grid operators must therefore work to ensure that all participants follow strict standards to maintain system security.

2.2 Events That Changed the Philosophy of Electrical Systems in Terms of Security

Several major events have significantly influenced the approach to security in electrical systems, reshaping how systems are managed and protected:

2.2.1 The 2003 North American Blackout

One of the most severe power outages in history occurred in August 2003, affecting 50 million people across the U.S. and Canada. This event highlighted the vulnerabilities in the transmission network, specifically the lack of coordination and failure in the grid's protection mechanisms. As a result, it emphasized the importance of real-time monitoring, better communication between operators, and the need for more stringent reliability standards to prevent cascading failures in the grid.

2.2.2 The 2012 India Blackout

The largest blackout ever recorded took place in July 2012, affecting 620 million people in India. The event underscored the fragility of large interconnected systems, where a single failure can trigger massive outages. It prompted changes in grid management practices, especially around load forecasting, balancing supply and demand, and improving the infrastructure to handle such large-scale disturbances.

2.2.3 The Enron Scandal and California Energy Crisis

The manipulation of the energy market by Enron during the California energy crisis in the early 2000s caused a reevaluation of regulatory oversight and the importance of transparency in energy trading. It showed how profit-driven strategies could jeopardize grid stability and security, leading to new policies and reforms to ensure fair practices in energy markets.

These events have collectively influenced the modern philosophy of electrical system security, reinforcing the need for robust, adaptive, and coordinated approaches to both technical infrastructure and market operations.

Enron's Strategies

Enron, a major electricity wholesaler and service provider, exploited loopholes in California's deregulated electricity market to create an artificial shortage and profit from the ensuing energy crisis. The company's sole focus was to generate profits through market and economic manipulation, employing various dubious strategies. Some of these strategies were:

- ”Fat Boy” This strategy involved overstating electricity demand, allowing Enron to be paid for electricity it did not deliver. It manipulated the market by creating a fictitious demand to inflate prices artificially.

- ”Get Shorty” Enron traders sold electricity they did not own, betting that prices would drop, enabling them to buy electricity at lower rates and profit from the difference. This was essentially a form of market speculation that disrupted the supply-demand balance.

- ”Ricochet” Enron exported electricity from California to out-of-state entities, only to re-import it at higher prices. This created an artificial scarcity in California, driving prices up while Enron capitalized on the inflated rates.

- ”Load Shift” Enron deliberately overestimated electricity demand in Northern California and underestimated it in the South. This created a fake congestion problem in the north, driving up prices, while the lower estimated demand in the south decreased prices. Enron then positioned itself to transfer the ”excess” load from north to south, profiting from the imbalance it created.

- ”Death Star” Through this strategy, Enron was paid for relieving congestion on the grid, but in reality, they simply shifted energy around without actually reducing any congestion. This allowed the company to profit from non-existent services.

  These strategies were technically legal, as they did not violate the specific wording of the laws in place. However, they clearly manipulated market rules for Enron’s financial gain at the expense of consumers, contributing to power shortages and price spikes in California. This scandal led to a reassessment of regulatory policies to ensure the stability and fairness of energy markets.

2.3 New Philosophy of System Services in Terms of Security

In response to evolving challenges and the increasing complexity of electrical grids, the philosophy surrounding system services has shifted towards a more integrated and proactive approach to security. This new philosophy emphasizes several key principles to ensure grid reliability, stability, and security, especially in the face of modern threats and demands.

2.3.1 Proactive Risk Management

The traditional reactive approach to addressing grid failures has been replaced by a proactive risk management strategy. This involves identifying potential risks before they become critical and implementing preventative measures. Grid operators are now focusing on predictive maintenance, real-time monitoring, and advanced analytics to detect early signs of system stress or malfunction. This helps reduce the likelihood of cascading failures that could lead to widespread outages.

2.3.2 Enhanced Resilience

Resilience has become a cornerstone of modern grid security philosophy. Resilient systems are designed to withstand and quickly recover from disruptions, whether caused by natural disasters, cyber-attacks, or equipment failure. This involves building redundancy into critical infrastructure, ensuring diverse energy sources (such as renewable energy integration), and implementing flexible operational strategies that allow the grid to adapt to changing conditions in real time.

2.3.3 Decentralization and Distributed Generation

The shift towards decentralization is a key element in improving grid security. Traditional centralized power generation, where large power plants supply energy to vast areas, is being complemented by distributed generation sources like solar panels, wind turbines, and energy storage systems. This reduces the strain on transmission networks and provides multiple points of power supply, making the grid more robust against localized failures.

2.3.4 Advanced Automation and Smart Grid Technologies

Modern grids are increasingly adopting automation and smart grid technologies to enhance security. These technologies allow for real-time monitoring and control of electrical systems, enabling rapid response to disturbances. Automated systems can detect anomalies and reroute power to prevent disruptions, improving the overall security and efficiency of the grid. The use of AI and machine learning further enhances these capabilities by predicting potential issues and optimizing grid operations.

2.3.5 Cybersecurity

With the digitalization of grid infrastructure, cybersecurity has become a critical aspect of system security. Power grids are now highly dependent on digital control systems, making them vulnerable to cyber-attacks. The new philosophy places significant emphasis on securing these systems through the implementation of robust cybersecurity protocols, encryption, and frequent system audits to safeguard against potential breaches that could compromise grid stability.

2.3.6 International and Cross-Sector Collaboration

The interconnected nature of modern power systems means that grid security can no longer be managed in isolation. International cooperation and cross-sector collaboration are essential to ensuring grid stability, particularly in regions where energy transfers across borders are common. Grid operators and regulators are working together to establish common standards and protocols for grid security, ensuring that all parties adhere to best practices and can respond quickly to regional or global threats.

2.3.7 Conclusion

The new philosophy of system services in terms of security reflects a more holistic, forward-thinking approach that leverages technology, decentralization, and collaboration to create a more secure and resilient grid. This transformation is driven by the need to adapt to new risks such as cyber threats, climate change, and the growing integration of renewable energy, ensuring that the electrical grid remains reliable and capable of meeting future energy demands.

Chapter 3

Identification and Analysis of Producer Performance

3.1 Network planning

The analysis of how a production facility impacts the electrical system is based on established principles used in network planning. It involves examining and quantifying the effects of the installation on the electrical grid through various technical criteria. The goal is to determine any necessary adjustments to ensure the system's performance remains within acceptable dynamic limits **Legifrance1999**.

The core idea is that every new connection or operational change in a production unit alters the dynamic state of the grid. The system operator must thoroughly analyze and correct these changes to prevent any negative impact and, ideally, create positive outcomes.

A typical approach involves analyzing the transient behavior of electrical parameters within the production facility's influence zone. This transient state is regulated by various control devices such as Automatic Voltage Regulators (AVR), governors (GOVER), Power System Stabilizers (PSS), and Flexible AC Transmission Systems (FACTS), located at interconnection substations. Proper coordination of these regulatory devices ensures the electrical and mechanical parameters remain within the system's operating standards.

Correct tuning of control gains and time constants allows for shorter transient periods, reduced variation gradients, and limited overshoot values, all of which should not exceed the equipment's design limits. Additionally, well-designed control devices minimize dead zones, which is essential for overall grid stability and security.

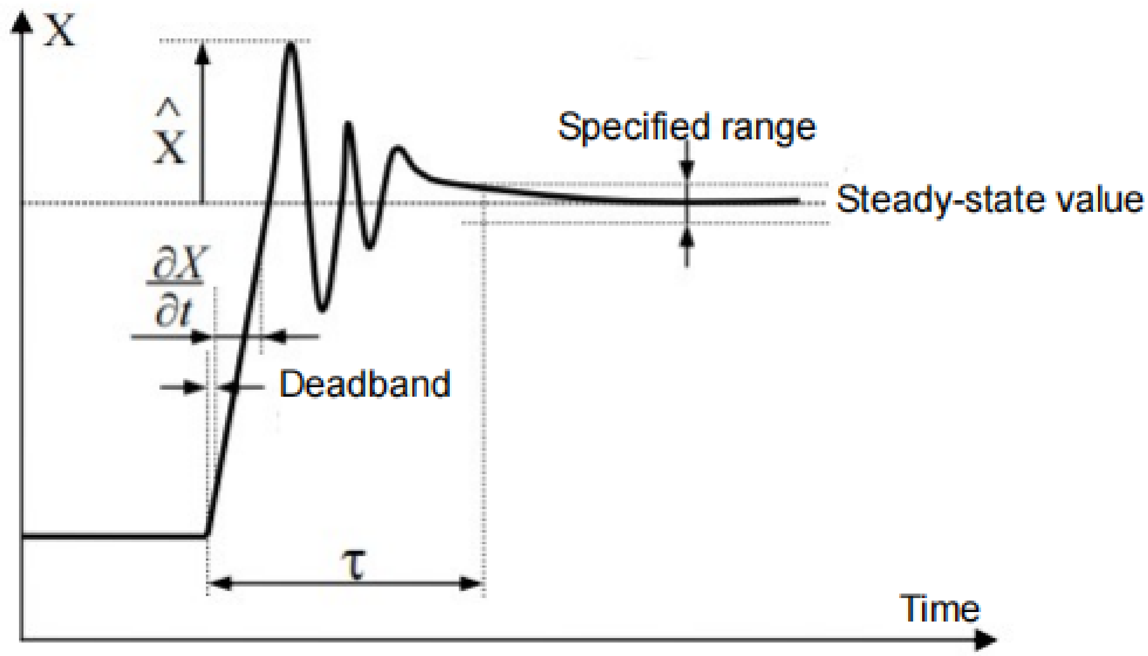


Figure 3.1: Transient performance

The performance of a production facility forms part of the producer's contractual obligations to the system operator. These obligations, unless stated otherwise, must be maintained for the facility's entire lifespan. In deregulated markets, producers may face economic temptations to ignore these commitments, making it necessary for grid operators to employ various measures to ensure that system service obligations are met.

Currently, in most countries, system operators reserve the right to conduct additional studies (either through physical testing or simulations) to verify compliance with performance standards

Legifrance1999, **UCTE2003**, **Transelectrica2004**, **Caiso2000**. Producers are required to report any parameter changes that might affect the performance of their production equipment. To this end, producers must implement monitoring and review procedures to ensure ongoing compliance with contractual standards.

3.1.1 Performance checks are categorized into three types:

- Initial conformity verification: This is the first performance check carried out when the installation is connected to the grid, before its first commissioning. It focuses on the construction provisions that allow access to the network. These include: minimum characteristics that must be respected in terms of voltage, frequency, supply quality, and behavior under normal and disturbed conditions (stability), as well as the performance of frequency-power and voltage settings. Some performances, such as generator stability during short circuits, cannot be tested through trials or measurements and must instead be analyzed through simulations. At the system operator's request, the validity of these simulations, especially the modeling, may be verified using appropriate tests or measurements.

- Permanent operational checks: These checks focus primarily on the voltage, active and reactive power supplied and absorbed by the production units.

- Non-permanent operational checks: These can be scheduled, periodic, contextual (end of works, post-incident, deviation from contractually agreed connection conditions, etc.), or random. They concern, in particular, the verification of the sustainability of construction characteristics, especially for connection structures and their protection systems, auxiliary services, stability, islanding performance, and participation in network restoration. The list and practical modalities of the required checks, which can evolve over time depending on the system operators' needs, are detailed in the connection agreements. The producer must provide the system operator with prior agreement on the conditions for conducting any tests that may cause non-compliance with electrical system safety regulations.

In cases where non-conformity in the producer's installation is identified, two scenarios may occur:

- If the system operator believes that these faults could significantly impact the safety of the electrical system and/or the safety of people and property, they may require the producer to disconnect their installation and declare it unavailable.

In this chapter, we will present the system services related to the safety of electrical networks and identify the connections between producer performance and the associated regulation parameters. We will then describe the current practices of network operators in monitoring the performance of independent producers.

- If the system operator believes that these faults do not significantly affect the safety of the electrical system or the safety of people and property, they may request the producer to bring their installation back into compliance according to the procedures outlined in the operating agreement. If performance issues persist after this compliance procedure, the producer must report the new performance levels of their installation and specify the timeframe within which the initial contractual performance levels will be restored.

3.2 Voltage and Reactive Power Control

Voltage control is achieved through the management of reactive power production, consumption, and transit within the electrical network. Alternators are the primary means of adjusting voltage on the production side. Voltage regulation is organized hierarchically as follows:

- Primary Regulation: Controls voltage at the nodes where producers are connected.
- Secondary Regulation: Adjusts voltage in various areas of the network by modifying the reactive power setpoints of generators.
- Tertiary Regulation: Optimizes the dispatch of reactive power based on economic criteria.

3.2.1 Primary Voltage Regulation

One of the generally mandatory system services for all production units is the injection or withdrawal of reactive power to maintain network voltage levels within specified standards. A producer providing voltage support must be continuously monitored by automatic voltage regulators for the entire duration of the service request. These regulators must maintain the established voltage levels at the nodes where the alternators are connected.

The following diagram illustrates the principle of voltage regulation:

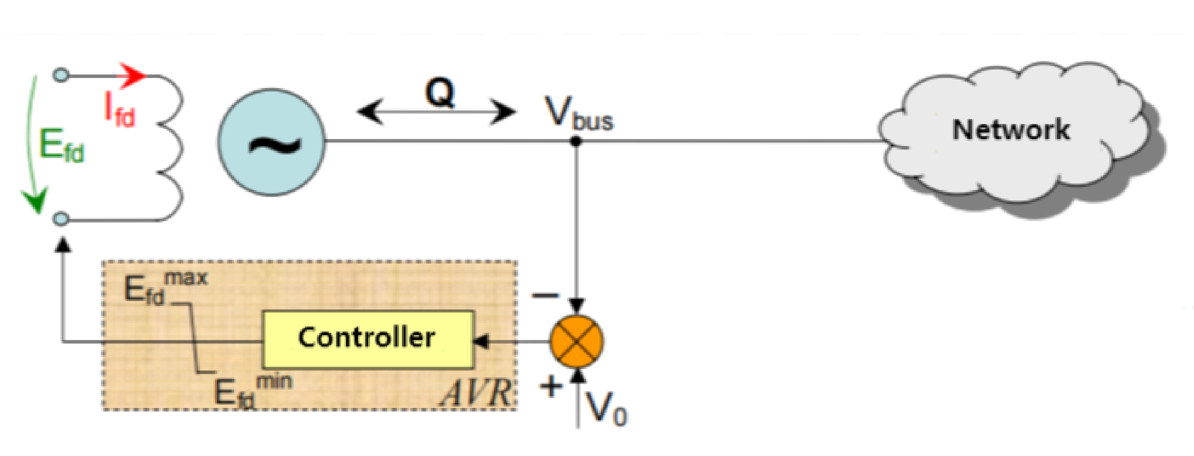


Figure 3.2: Voltage contol

- Q: Reactive power absorbed or injected
- I_{fa}: Excitation current
- E_{fa}: Excitation voltage
- V_{o}: Setpoint voltage
- V_{bus}: Voltage at the generator terminals

The voltage measured at the generator terminals is compared to the reference value, and the difference is sent to the AVR. The controller processes and amplifies this difference to control the excitation. It must ensure the dynamic performance of the production unit, such as rise time, transient duration, response time, deadband, etc. To guarantee stability in the control-command scheme, the excitation requires a stabilization loop, which is not shown in Figure 3.2 and consists of a feedback-type compensation. At the output of the controller, there is a limiter block that operates in overexcited mode to deliver reactive power, taking into account the machine's structural limitations and the excitation circuit. If the voltage at the generator terminals is below the reference value, the controller instructs the generator to increase the voltage at its terminals. Conversely, if the generator voltage exceeds the reference value, the controller directs the generator to operate in underexcited mode, absorbing reactive power and thereby reducing the generator voltage. The response time of the primary voltage regulation ranges from a few tenths of a second to several seconds.

Some grid operators require producers to locally supply a sufficient amount of reactive power to compensate for voltage drops in the lines caused by the flow of reactive power in the system [Caiso, 2000 - 1]. The most critical issue in voltage control by producers is the management of the reactive power reserve. The reactive power reserve is not a measurable quantity, nor is it a dynamic quantity per se, but it is used dynamically. In the following, we will identify the positioning of this reserve within the physical generator system and the voltage regulation loop.

The automatic voltage regulator (AVR) controls the excitation current or the excitation voltage (both are proportional, with the excitation winding resistance providing the proportionality). At the output of the AVR, the machine's excitation voltage is limited both lower and higher, mainly due to structural limitations.

Assuming the operating point at the time of analysis is $(E_{\text{fd\_oper}}, Q_{\text{oper}})$, we can conclude that the available reactive power reserve is the difference between the maximum acceptable reactive power from a structural standpoint that could be produced and the operational value of the reactive power:

$$\text{Reactive power reserve} = Q_{\text{genmax}} - Q_{\text{oper}} \tag{3.1}$$

The producer can participate in the system service of voltage – reactive power control exclusively with this reserve and nothing more. In the opposite sense, the same reasoning applies: the maximum

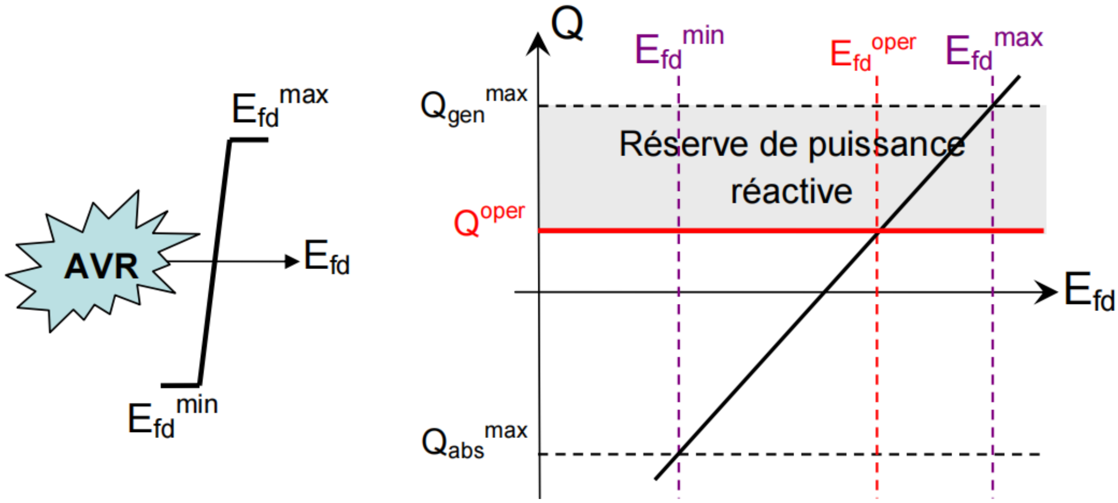


Figure 3.3: Identification of the reactive power reserve

amount of reactive power that can be absorbed is given by the difference between the operational value of reactive power at the time of analysis and the limit power given by the manufacturer:

$$\text{Reactive power absorption reserve} = Q_{\text{oper}} - Q_{\text{absmax}}. \tag{3.2}$$

One of the questions that arises is: does any producer have a specific interest in intentionally reducing the reactive power reserve? The answer is yes, and we will demonstrate below what their reasons and constraints could be.

The active power-reactive power characteristic of a generator. There are three constructive limits:

- Thermal limit of the excitation inductor
- Thermal limit for the armature
- Thermal limit for the magnetic core

Various boundary operating conditions can push the power system to its minimum reactive power reserves. For instance, a temporary loss of an overloaded transmission line increases power flows on adjacent lines, raising line currents and reactive power losses. This, in turn, increases the system's demand for reactive power, leading to a drop in nodal voltages. While this voltage drop typically

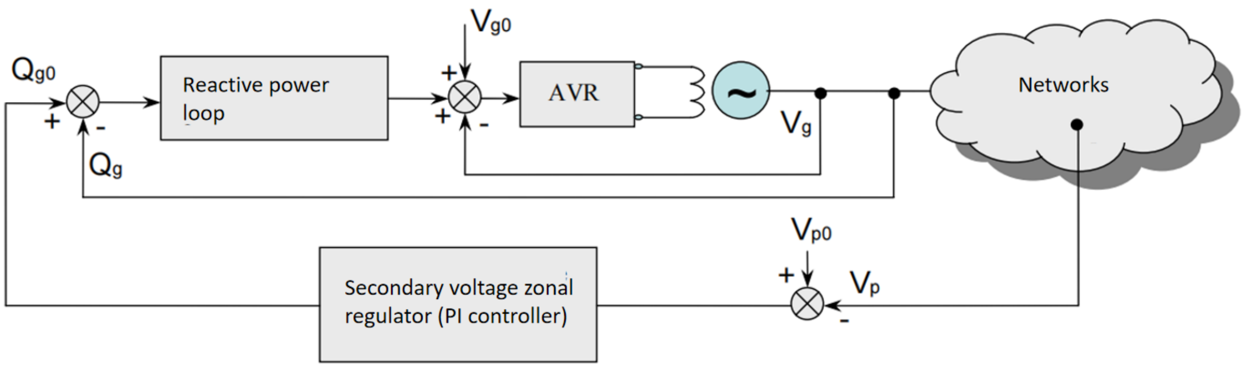


Figure 3.4: Secondary Voltage Regulation loops

stabilizes power flows by reducing load demand, generator voltage regulators respond by boosting excitation currents to inject more reactive power and restore voltage levels. This increased power flow raises line and transformer currents, worsening voltage drops. On-load tap-changing transformers exacerbate this effect, further depleting the system's reactive power reserves. As generation units approach their current limits (excitation, armature, magnetic core), they lose the ability to provide reactive power, rendering their voltage regulation ineffective. At this point, the risk of voltage collapse becomes imminent. Adequate reactive power reserves and adherence to required reserve levels by producers are critical. While deviations from these requirements may not always cause immediate harm, under unfavorable conditions, they can significantly compromise the overall network security.

European technical requirements **Arrêté1999**, **UCTE2003**, **Transelectrica2004** demand that producers maintain a reactive power availability of about 45% of the maximum active power of the production facility and be able to absorb up to 20% of the maximum active power. When the active power of the installation depends on the external temperature, the value of the installation's maximum power is taken at the considered temperature. When the installation has multiple units, and not all of them are running, the values of the reactive power reserves are based on the maximum power of the units that are operating.

3.2.2 Secondary Voltage Regulation

The secondary voltage regulation occurs at the regional level and complements primary regulation to enhance voltage stability. The grid operator determines setpoint voltages at pilot nodes (nodes with the highest short-circuit power in a given region) through technical-economic optimization calculations (tertiary regulation). Secondary regulation establishes new reactive power setpoints for generating units to ensure that the voltages at the pilot nodes align with the optimized calculations. This type of regulation will be the focus of our improvement section. A schematic diagram of the secondary voltage regulation is provided in the following figure:3.4

Principle of secondary voltage regulation.

The difference between the voltage measured at the pilot node (V_{p}) and the setpoint voltage for the pilot node (V_{p0}) is processed and amplified by the zonal secondary voltage regulator. Its output, Q_{g0}, is then compared with the reactive power at the connection point of the synchronous machine (Q_{g}). The reactive power difference represents the voltage setpoint correction for the primary voltage regulation (AVR).

The secondary voltage regulation is provided by producers qualified for this system service, utilizing reactive power reserves. The regulation's time constants are significantly longer (on the order of several minutes) compared to primary voltage regulation.

3.2.3 tertiary voltage regulation

The tertiary voltage regulation optimizes the management of reactive power on a global network scale, considering techno-economic criteria. Unlike primary and secondary regulation, which operate locally or regionally, tertiary regulation aims to coordinate all available reactive power resources to ensure long-term system stability while minimizing operating costs.

This regulation is based on optimization calculations that define voltage and reactive power setpoints for critical nodes in the network. It mainly intervenes when other levels of regulation are unable to maintain voltage stability, particularly in the event of overload or large-scale disturbances. Tertiary regulation seeks to redistribute reactive power production based on the capacity of different generation units, while also taking into account economic constraints such as network losses and production costs.

In summary, tertiary voltage regulation optimizes the dispatching of reactive resources across the network, ensuring effective management of power flows to maintain electrical system stability while minimizing costs.

3.3 Introduction to Frequency Regulation

Frequency regulation is one of the fundamental pillars to ensure the stability and quality of an electrical grid. In an interconnected network, frequency must remain stable around a nominal value (generally 50 Hz or 60 Hz) to ensure the synchronization of generators and the continuity of energy supply.

Any frequency deviation from the nominal value is often the consequence of an imbalance between active power production and consumption. When demand exceeds production, frequency decreases; conversely, if production is in excess, frequency increases. Therefore, effective frequency regulation is crucial to avoid issues like power outages or generator disconnections.

3.3.1 Concept of Network Speed Stasis

Speed stasis (or stasis) is a key parameter in frequency regulation. It represents the sensitivity of the network frequency to load variations, defined as the percentage change in frequency relative to the change in active power. Formally, it can be expressed by the following relationship:

$$S = \frac{\Delta f}{f_n} \times 100 \quad \text{for } \Delta P \tag{3.3}$$

where:

- S is the speed stasis in percentage,
- Δf is the frequency change,
- f_n is the nominal frequency of the grid,
- ΔP is the change in active power.

A high stasis indicates that the network can withstand larger power variations without experiencing significant frequency fluctuations. In practice, each generator in a network has a stasis that determines its automatic response to frequency changes. Generators with lower stasis contribute more significantly to frequency regulation.

3.3.2 Load Damping Rate

The load damping rate is another critical factor in frequency regulation. It measures the network's ability to dampen frequency oscillations after a disturbance. When electricity demand changes suddenly (e.g., during the startup or shutdown of a large load), frequency may oscillate before returning to its stable state.

The damping rate depends on several elements, including:

- The nature of the loads: Some loads (like motors) have an inertial response that helps stabilize frequency.
- The characteristics of the generators: The faster the generators react, the quicker frequency oscillations are dampened.
- Secondary and tertiary regulation systems: They intervene to adjust active power settings to dampen oscillations over the long term.

The damping rate ξ can be represented by the ratio between the system's ability to dissipate the energy of oscillations and the tendency to continue those oscillations. A low damping rate will lead to prolonged oscillations, while a high damping rate will ensure a rapid return to equilibrium.

3.3.3 Effects of Frequency Disturbances

Frequency disturbances in an electrical grid can be caused by:

- Imbalances between production and consumption.
- Loss of large generators or significant transmission lines.
- Rapid changes in demand, such as during peak consumption.

These disturbances can have serious consequences for network stability. If frequency drops below a critical threshold, automatic load shedding may be triggered to prevent blackouts.

3.3.4 Conclusion

Frequency regulation is a delicate operation that relies on the network's ability to maintain a stable balance between active power production and consumption. The concepts of speed stasis and damping rate play a fundamental role in this regulation by defining the automatic response of generators to load variations and ensuring the damping of frequency oscillations. These parameters must be optimized to guarantee the stability and reliability of the electrical network.

3.3.5 Frequency Regulation Methods

Frequency regulation is essential for maintaining the balance between electricity production and consumption. The stability of frequency in an electrical network depends on the ability to adjust production according to variations in demand. A stable frequency is crucial for the reliable and safe operation of electrical equipment and interconnected systems.

Importance of Frequency Regulation

1. **Network Stability**: A stable frequency prevents undesirable oscillations that can lead to equipment disconnections, power outages, or even blackouts.
2. **Equipment Protection**: Frequency regulation protects sensitive equipment by maintaining optimal operating conditions.
3. **Production Optimization**: Good regulation maximizes the use of energy production resources, especially renewable sources, while minimizing energy costs.
4. **Regulatory Compliance**: Network operators must comply with specific standards to ensure the reliability and safety of the electrical system.

Frequency Regulation Methods

1. **Primary Regulation**
   - **Description**: This is provided by synchronous generators that automatically adjust their production in response to frequency variations. When a frequency drop is detected, these generators increase their active power production.
   - **Operation**: The speed control system of the generators modifies the energy flow based on the measured frequency. This method reacts quickly, within seconds.
   - **Importance**: It serves as the first line of defense against frequency variations, allowing for immediate response.
2. **Secondary Regulation**
   - **Description**: This is performed by centralized control systems that adjust production levels to return frequency to its nominal value after a disturbance.
   - **Operation**: Secondary regulators monitor the frequency and command adjustments to generators to compensate for persistent imbalances.
   - **Importance**: It eliminates frequency errors after primary regulation has done its job.

3. **Tertiary Regulation**

    - **Description**: This concerns the long-term optimization of production and resource planning to respond to load fluctuations over a longer period.
    - **Operation**: It involves manual adjustments and dispatching decisions to ensure long-term balance.
    - **Importance**: It is essential for managing seasonal variations and predictable changes in demand.

Standards to Comply With

Network managers and operators must adhere to various standards to ensure the reliability and safety of electrical systems:

1. **Frequency Standards**:

    - Generally, frequency must remain within a range of ± 0.2 Hz of the nominal value. For a nominal frequency of 50 Hz, this means the frequency must be maintained between 49.8 Hz and 50.2 Hz.

2. **Generator Response Standards**:

    - Generators must be able to reach their full capacity within a few minutes after a disturbance. Specific requirements may vary according to local regulations.

3. **Response Time Standards**:

    - Regulation systems must respond within specified time frames. For example, primary regulation must react within 10 seconds of a disturbance, while secondary regulation must take over within a few minutes.

4. **Reliability Standards**:

    - Network operators must follow reliability standards that include requirements for generator availability, emergency plans, and regular testing of regulation systems.

Conclusion

Frequency regulation is essential for the proper functioning of an electrical network. Primary, secondary, and tertiary regulation methods each play a vital role in balancing production and consumption. Adhering to established standards is crucial to ensure the stability, safety, and efficiency of the electrical system.

3.4 Dominant Regulators: AVR, PSS, and FACTS

Regulators play a crucial role in managing the stability of frequency and voltage in an electrical network. Among them, the Automatic Voltage Regulator (AVR), the Power System Stabilizer (PSS), and Flexible AC Transmission Systems (FACTS) devices are the most commonly used. Each of these regulators has specific functions that contribute to the reliability of the network.

3.4.1 Automatic Voltage Regulator (AVR)

Description: The AVR is a device that automatically regulates the output voltage of a generator or alternator. It adjusts the amount of excitation current supplied to the rotor of the generator to maintain a stable output voltage.

Operation:

- The AVR measures the output voltage of the generator and compares it to a reference value.
- If the measured voltage differs from the reference, the AVR adjusts the excitation current, either increasing or decreasing the power supplied to the rotor to compensate for this difference.
- This stabilizes the voltage during load variations.

Importance:

- The AVR helps maintain network stability by preventing voltage fluctuations that can damage equipment and cause disruptions in energy consumption.

3.4.2 Power System Stabilizer (PSS)

Description: The PSS is a device designed to enhance the dynamic stability of an electrical system by mitigating oscillations that occur during load or production variations.

Operation:

- The PSS uses frequency, power, and voltage signals to detect oscillations.
- It provides feedback control to the generator's excitation system to quickly adjust the generated power in response to detected oscillations.
- This is achieved through phase and amplitude control, which helps stabilize the system.

Importance:

- The PSS is essential for improving the network's resilience to disturbances, ensuring a quick response to oscillations and contributing to the overall reliability of the network.

3.4.3 Flexible AC Transmission Systems (FACTS)

Description: FACTS devices are power electronics systems that allow for the control and optimization of energy flow in an electrical network. They enhance the flexibility and capacity of the network to respond to load variations.

Operation:

- FACTS includes devices such as Static Var Compensators (SVC) and Static Synchronous Compensators (STATCOM).

- They adjust voltage and power flow by injecting or absorbing reactive energy into the network.
- This maintains stable voltage and improves the power transfer capacity of transmission lines.

Importance:

- FACTS enhance frequency stability and energy quality by allowing dynamic control of network conditions, which is particularly crucial during the integration of renewable energy sources.

3.4.4 Conclusion

Regulators such as AVR, PSS, and FACTS devices play complementary roles in managing the stability of frequency and voltage in an electrical network. By ensuring precise and responsive control, these devices contribute to providing reliable and quality electrical supply while facilitating the integration of renewable energy sources and meeting the growing energy consumption demands.

3.5 Mathematical Models of Regulators

Mathematical models are essential for analyzing and designing systems for frequency and active power regulation. These models allow for the simulation of electrical system behavior and the prediction of responses to various operating conditions. Below, we present the relevant equations and models for frequency regulation and active power control.

3.5.1 Frequency Regulation Model

The frequency regulation model of a generator can be represented by the following equation:

$$\Delta f = \frac{P_m - P_e}{2H}$$

where:

- Δf: Frequency variation (Hz)
- P_m: Mechanical power supplied to the generator (MW)
- P_e: Electrical power delivered by the generator (MW)
- H: Inertia constant of the generator (s)

This equation indicates that the frequency variation is proportional to the difference between mechanical and electrical power, inversely related to the generator's inertia constant.

3.5.2 Speed Control Model

The speed control model of a synchronous generator can be expressed by the following equation:

$$\frac{d\omega}{dt} = \frac{1}{2H}(P_m - P_e - D(\omega - \omega_0))$$

where:

- ω: Angular speed of the generator (rad/s)
- D: Friction or damping coefficient ($\mathrm{N \cdot m \cdot s}$)
- ω_0: Nominal speed of the generator (rad/s)

This equation models the effect of speed control on the dynamics of the generator and the impact of mechanical and electrical power on its speed.

3.5.3 AVR Regulation Model

The AVR model can be represented by the following equations:

$$\Delta V = K_{AVR} \cdot (V_{ref} - V)$$

where:

- ΔV: Voltage variation (V)
- K_{AVR}: AVR gain
- V_{ref}: Reference voltage (V)
- V: Measured voltage (V)

The AVR adjusts the output voltage based on the difference between the reference voltage and the measured voltage.

3.5.4 Power System Stabilizer (PSS) Model

The PSS can be modeled by the following equation:

$$\Delta P_{ss} = K_{PSS} \cdot \Delta\omega$$

where:

- ΔP_{ss}: Variation of power supplied by the PSS (MW)
- K_{PSS}: PSS gain
- $\Delta\omega$: Frequency variation (Hz)

This equation shows how the PSS contributes to frequency regulation by adjusting the power supplied by the generator based on frequency variation.

3.5.5 FACTS Systems Model

FACTS devices can be modeled by the following equation:

$$Q = B \cdot (V^2) + Q_{load}$$

where:

- Q: Reactive power injected or absorbed (MVAr)
- B: Line conductance (S)
- V: Voltage in the line (kV)
- Q_{load}: Reactive power of the load (MVAr)

This equation illustrates how FACTS adjust reactive power to stabilize voltage in the network.

namic response of regulation systems under various operating conditions and disturbances.

3.5.6 Conclusion

Mathematical models are crucial for understanding and optimizing frequency and active power regulation in electrical networks. By using appropriate equations, it is possible to simulate the behaviors of regulators and predict system responses, contributing to a more effective and reliable management of the electrical network.

Chapter 4

Modeling and simulation of the AC7B AVR

4.1 Introduction to AVR Modeling

The Automatic Voltage Regulator (AVR) plays a crucial role in voltage regulation within electrical systems. By maintaining a stable voltage, the AVR not only protects equipment but also improves the quality of energy supplied to consumers. Its ability to respond quickly to load variations and network disturbances makes it an indispensable element in power plants, especially those using renewable energy sources such as solar energy.

The mathematical modeling of the AVR allows for the analysis of its dynamic behavior and the design of appropriate control strategies. By understanding the underlying principles of its operation, it becomes possible to optimize its performance and ensure an effective response to the demands of the electrical grid. This chapter will focus on the general modeling of the AVR, describing its technical characteristics, and then concentrating on the specific model of the AC7B AVR. A simulation carried out in Simulink will illustrate the results and provide valuable insights into the regulator's performance.

4.2 General Mathematical Modeling of an AVR

The mathematical modeling of an Automatic Voltage Regulator (AVR) is based on a series of equations that describe its operation and interactions with the electrical grid. This modeling aims to capture the dynamic behavior of the AVR to predict its response to load variations and disturbances. Here are the main elements to consider in general modeling:

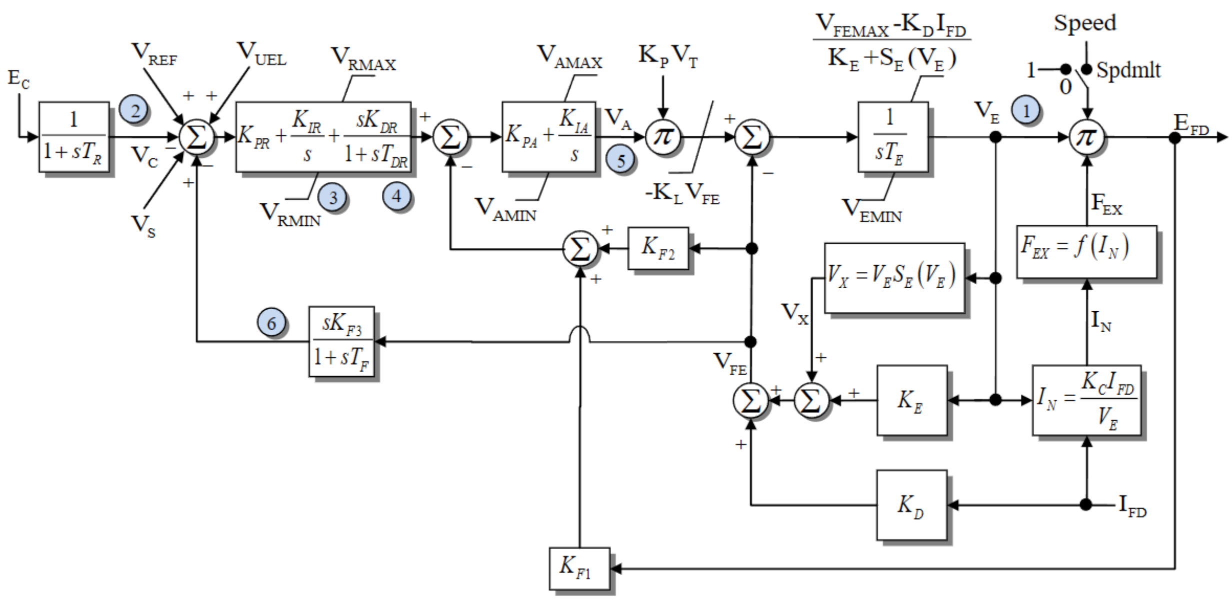


Figure 4.1: AVR regulates voltage control loops

4.2.1 Fundamental Equations

The AVR regulates voltage using several control loops. The main equations governing the behavior of an AVR include:

Output Voltage Equation:

$$V_{out} = V_{ref} + K \cdot (V_{set} - V_{out}) \tag{4.1}$$

Where:

- V_{out} is the output voltage of the AVR.

- V_{ref} is the reference voltage.
- K is the controller gain.
- V_{set} is the set voltage.

Voltage Error Equation:

$$E = V_{set} - V_{out} \tag{4.2}$$

This equation quantifies the error between the set voltage and the output voltage.

4.2.2 Dynamic Model

To model the dynamic behavior of an AVR, a state-space model is generally used to describe the relationships between inputs and outputs:

State Equations:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ U \end{bmatrix} \tag{4.3}$$

Where:

- x_1 represents the state of the voltage.
- x_2 represents the state of the current.
- A, B, C, D are matrices describing the system dynamics.
- U is the input voltage to the regulator.

4.2.3 Transfer Function

The transfer function of an AVR relates the output to the input as a function of frequency. For a simple AVR, the transfer function can be expressed as follows:

$$H(s) = \frac{V_{out}(s)}{V_{set}(s)} = \frac{K}{T_s \cdot s + 1} \tag{4.4}$$

Where:

- T_s is the system time constant.
- s is the Laplace variable.

This function allows analyzing the frequency response of the AVR and determining its stability.

4.2.4 Modeling AVR Components

The AVR consists of several components, whose dynamics can be modeled. For example:

- **Amplifier:** The behavior of the amplifier can be modeled by a voltage gain and input/output impedance.
- **Voltage Sensor:** The sensor provides feedback on the output voltage, and its model may include a delay to account for response times.
- **Control System:** PID (Proportional-Integral-Derivative) controllers can be used to adjust the output based on the voltage error, which can be modeled by:

  $$U(s) = K_p E(s) + \frac{K_i}{s} E(s) + K_d s E(s) \tag{4.5}$$

  Where K_p, K_i, K_d are the proportional, integral, and derivative gains, respectively.

4.3 Technical Characteristics of the AVR

The technical characteristics of an Automatic Voltage Regulator (AVR) are essential for understanding its operation and performance in an electrical system. Here are the main characteristics that influence the design and application of AVRs:

4.3.1 Operating Range

The operating range of an AVR is defined by the input and output voltage it can effectively regulate. This includes:

- **Input Voltage ($\mathbf{V_{in}}$):** The range of input voltage accepted by the AVR, which can vary depending on system specifications.
- **Output Voltage ($\mathbf{V_{out}}$):** The target output voltage, often specified as a nominal voltage that the AVR must maintain.

4.3.2 Dynamic Response

The dynamic response of an AVR is a measure of its ability to react quickly to load variations or disturbances. This characteristic is generally evaluated in terms of:

- **Rise Time ($\mathbf{t_r}$):** The time required for the output voltage to reach a certain percentage of its final value after a change.
- **Settling Time ($\mathbf{t_s}$):** The time it takes for the output voltage to stabilize within an acceptable band after a change.
- **Overshoot:** The amount by which the output voltage exceeds its target value before stabilizing.

4.3.3 Gain and Accuracy

The gain of the AVR is a critical factor influencing its performance. This includes:

- **Voltage Gain (K):** The ratio of the change in output voltage to the change in input voltage. A high gain allows for a faster response.
- **Accuracy:** The ability of the AVR to maintain the output voltage at a constant level despite load variations. This accuracy is often expressed as a percentage of the maximum allowable error.

4.3.4 Robustness and Reliability

The robustness and reliability of an AVR are essential to ensure continuous operation under varied conditions. This includes:

- **Overload Protection:** The ability of the AVR to handle overload conditions without failure.
- **Environmental Conditions:** The ability to operate in varied environments, including extreme temperatures, humidity, and dust.
- **Lifespan:** The longevity of the AVR under normal operating conditions.

4.3.5 Control Characteristics

The types of controllers used in AVRs also influence their performance. This can include:

- **PID Controller:** Used to adjust the output based on the voltage error. The proportional, integral, and derivative gains must be carefully selected to optimize the response.
- **Advanced Controllers:** Some AVRs incorporate advanced control algorithms, such as adaptive or fuzzy controllers, to improve performance under variable conditions.

4.3.6 Communication Interfaces

With the evolution of technology, modern AVRs may include communication interfaces that allow for:

- **Remote Monitoring:** AVRs can be equipped with communication modules to transmit performance and status data to maintenance personnel.
- **Integration with SCADA Systems:** The ability to integrate the AVR into a Supervisory Control and Data Acquisition (SCADA) system for centralized management.

4.4 SIMOTION D and SIMOTION S120 Controllers

4.4.1 Introduction to SIMOTION D and SIMOTION S120 Controllers

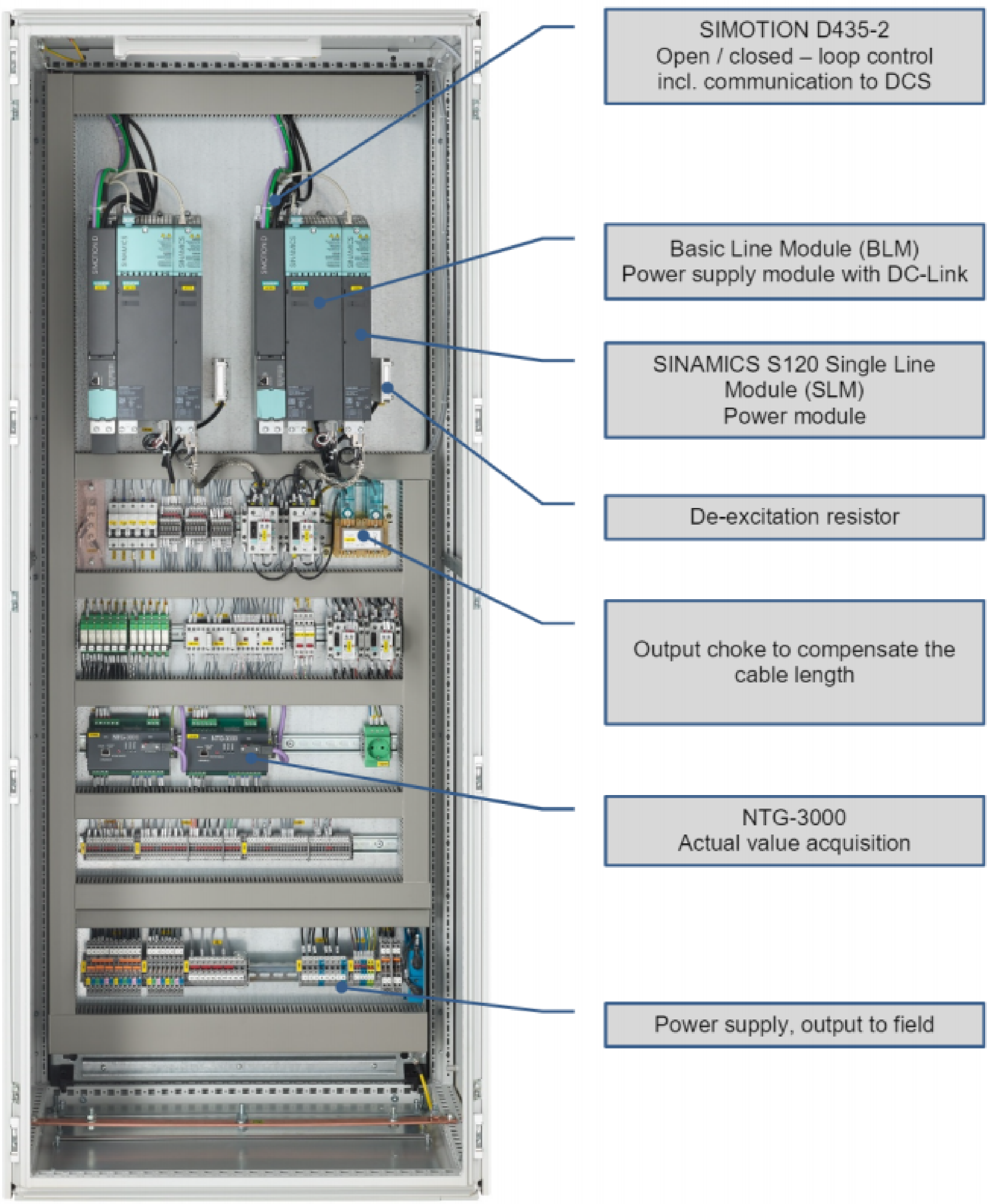


Figure 4.2: SIMOTION D and SIMOTION S120

The SIMOTION D and SIMOTION S120 controllers are advanced control solutions designed for automation applications, particularly in the field of electrical and power control systems.

SIMOTION D:

SIMOTION D is an integrated control system that combines motion control and regulation functionalities. It is ideal for applications requiring high precision and flexibility in controlling complex processes.

- **Features:**
  - Real-time motion control with advanced programming capabilities.
  - Easy integration with other systems and components, facilitating implementation in complex architectures.
  - Ability to handle multiple tasks simultaneously, ensuring optimal operation in dynamic environments.

SIMOTION S120:

SIMOTION S120 is a servo motor control system that offers exceptional regulation performance. It is often used in industrial applications where precise speed and torque control are required.

- **Features:**
  - Innovative motor control technology, providing high responsiveness and regulation precision.
  - Various communication interfaces for easy integration into different systems.
  - Advanced diagnostic capabilities to monitor motor status and optimize performance.

4.4.2 Communication Methods

Communication between the SIMOTION D and S120 controllers and the AVR is crucial for ensuring smooth and efficient operation. The main communication methods include:

PROFIBUS and PROFINET:

These are standardized communication protocols in industrial automation. They enable fast and reliable communication between controllers and other devices.

- PROFIBUS is a protocol based on fieldbus technology, while PROFINET uses Ethernet for faster communications and real-time data exchange.

EtherCAT:

Another Ethernet-based communication protocol that offers very fast response times. EtherCAT is particularly suitable for applications requiring synchronous process control.

Modbus:

An older, but still widely used communication protocol that allows communication between controllers and field devices.

4.4.3 Reasons for Controller Redundancy

The redundancy of SIMOTION D and S120 controllers in the AVR system is implemented for several important reasons:

Increased Reliability:

By using two controllers, the system can continue to operate even if one controller fails. This is essential for ensuring service continuity, especially in critical environments such as power plants.

Easier Maintenance:

Redundancy allows maintenance operations to be performed on one controller while the other continues to operate, minimizing service interruptions.

Improved Performance:

The two controllers can work together to distribute the processing load and improve response times. This can be particularly beneficial in situations where quick decisions are necessary.

Enhanced Safety:

In sensitive applications, having a redundant system increases safety by reducing the risk of total system failure.

4.5 Specifications of the AC7B AVR

4.5.1 Operating Range

The operating range of the AC7B AVR defines the conditions under which it can maintain effective voltage regulation. The specifications include:

Input Voltage:

- Typical operating range: 200 to 480 V AC, allowing flexibility for different types of generators and networks.
- Ability to handle input voltage variations without compromising performance.

Output Voltage:

- Nominal voltage: generally 400 V AC, with acceptable tolerances depending on specific network requirements.
- Ability to adjust the output voltage according to load conditions and network needs.

4.5.2 Dynamic Response

The dynamic response of the AC7B AVR is crucial for its performance in changing environments. The specifications include:

Rise Time:

- Typical time: 200 ms to reach 95% of the final value after a sudden load change.

Settling Time:

- Time to stabilize within an acceptance band: generally 500 ms, ensuring a quick response after disturbances.

Overshoot:

- Maximum overshoot: 5%, ensuring that the output voltage does not significantly exceed the set value, which could be problematic for sensitive equipment.

4.5.3 Robustness

The robustness of the AC7B AVR ensures reliable operation under various conditions. The specifications include:

Overload Protection:

- The AVR is designed to withstand temporary overload conditions, with built-in protection mechanisms to prevent damage.

Environmental Conditions:

- Operating temperature: from -20°C to +60°C, allowing use in varied environments.

- Protection against humidity and dust, compliant with IP54 standards, ensuring reliable operation even in harsh environments.

Lifespan:

- Designed for an operational lifespan of at least 10 years, with minimal maintenance.

4.5.4 Comparison with Other Types of Regulators

AVR vs. RST (Rotor Speed Regulator)

- **AVR:** Primarily used for voltage regulation in electrical systems. Responds quickly to load variations and maintains stable voltage.
- **RST:** Designed for motor speed regulation. Less effective for voltage regulation but better suited for motor control applications.

AVR vs. PSS (Power System Stabilizer)

- **AVR:** Focuses on voltage control, ensuring short-term stability. May not be sufficient for long-term system stabilization.
- **PSS:** Adds a control layer to stabilize frequency and improve the system's dynamic response. Complements the AVR by enhancing overall grid stability.

AVR vs. Static Voltage Regulators (SVR)

- **AVR:** Uses feedback loops to adjust voltage, offering effective dynamic response.
- **SVR:** Uses regulation methods based on static components, which can result in slower response times. Often more expensive and complex to implement than AVRs.

4.6 Mathematical Modeling of the AC7B AVR

The mathematical modeling of the AC7B AVR must consider the complex interactions between the AVR, the PSS, and the electrical grid, while integrating limiters to ensure safe and reliable operation.

4.6.1 AC7B AVR Model

The AC7B AVR adjusts the output voltage based on the voltage error, representing the difference between the desired voltage and the actual voltage. Here are the key equations:

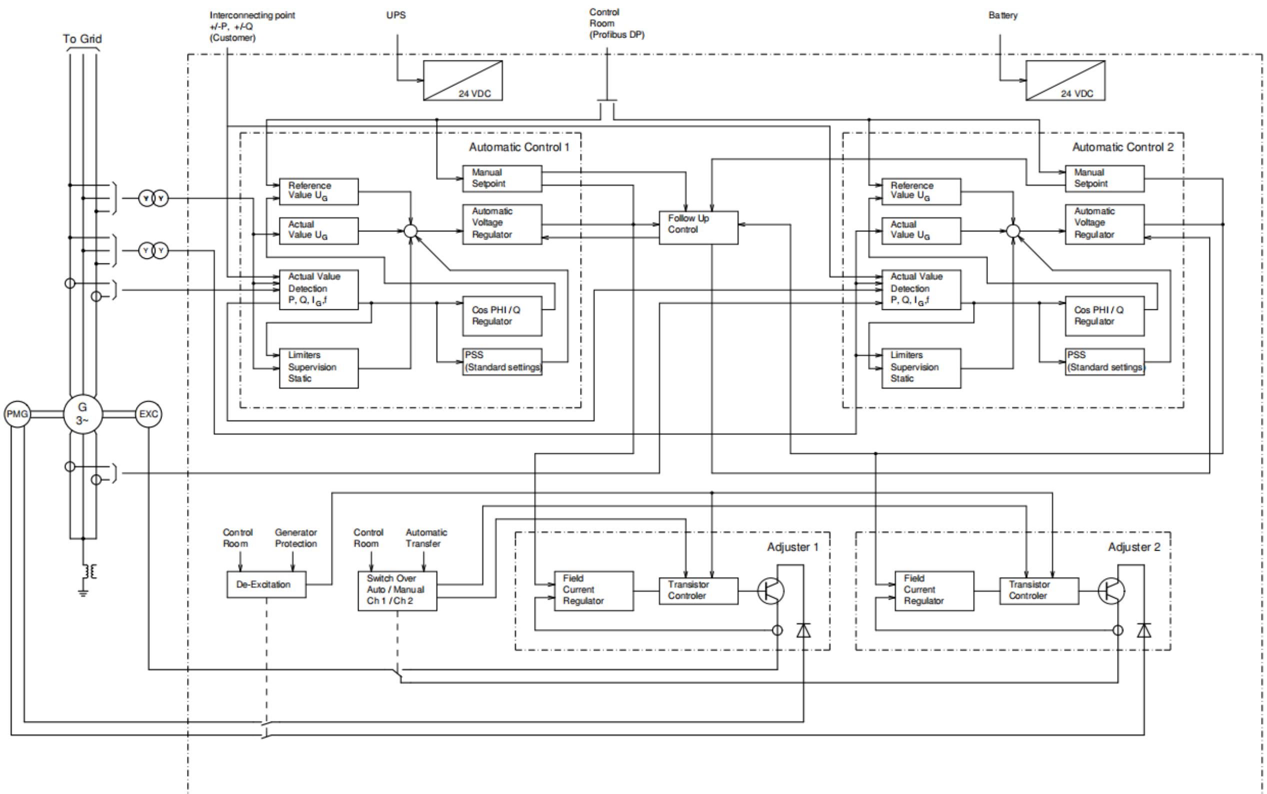


Figure 4.3: AC7B AVR Model

System Variables:

- $V_{setpoint}$: Desired setpoint voltage.
- V_{out}: Actual output voltage.

- $\Delta V = V_{setpoint} - V_{out}$: Voltage error.

Dynamic Equation of the AVR:

$$\frac{dV_{out}}{dt} = K_{AVR} \cdot \Delta V - D_{AVR} \cdot V_{out} \tag{4.6}$$

where:

- K_{AVR} is the regulator gain,
- D_{AVR} represents the damping term.

4.6.2 Integration of the PSS

The PSS is used to improve the system's dynamic response by providing an excitation signal that accounts for frequency and power variations. The equations for the PSS are:

PSS Variables:

- $P_{measured}$: Measured active power.
- ω: Measured frequency.

PSS Equation:

$$PSS_{output} = K_{PSS} \cdot (\Delta\omega) + T_{PSS} \cdot P_{measured} \tag{4.7}$$

where:

- K_{PSS} is the PSS gain,
- T_{PSS} is the PSS response time.

4.6.3 Overall AVR Equation with PSS

The interaction between the AVR and the PSS can be formulated as follows:

$$\frac{dV_{out}}{dt} = K_{AVR} \cdot (V_{setpoint} - V_{out} + PSS_{output}) - D_{AVR} \cdot V_{out} \tag{4.8}$$

4.6.4 Connectivity with the Electrical Grid

The dynamics of the electrical grid can be modeled by the following equation:

$$P_{load} = V_{out} \cdot I_{load} \tag{4.9}$$

where:

- P_{load} is the load power,
- I_{load} is the load current.

4.6.5 Limiters

Limiters are essential to protect the system from undesirable operating conditions. Several types of limiters can be integrated into the model:

Output Voltage Limiter: Ensures that the output voltage does not exceed a maximum value to protect equipment.

$$V_{out\_lim} = \min(V_{out}, V_{max}) \tag{4.10}$$

Excitation Signal Limiter: Restricts the excitation signal to prevent alternator overload.

$$E_{exc\_lim} = \max(E_{exc\_min}, \min(E_{exc}, E_{exc\_max})) \tag{4.11}$$

where:

- E_{exc} is the excitation signal calculated by the AVR,
- E_{exc_min} and E_{exc_max} are the minimum and maximum limits of the excitation signal.

4.6.6 System of Differential Equations

The complete model of the AC7B AVR with PSS and limiters can be represented by the following system of differential equations:

$$\frac{dV_{out}}{dt} = K_{AVR} \cdot (V_{setpoint} - V_{out} + PSS_{output}) - D_{AVR} \cdot V_{out} \tag{4.12}$$

$$PSS_{output} = K_{PSS} \cdot (\Delta\omega) + T_{PSS} \cdot P_{measured} \tag{4.13}$$

$$P_{load} = V_{out} \cdot I_{load} \tag{4.14}$$

$$V_{out\_lim} = \min(V_{out}, V_{max}) \tag{4.15}$$

$$E_{exc\_lim} = \max(E_{exc\_min}, \min(E_{exc}, E_{exc\_max})) \tag{4.16}$$

Simulation with Simulink

In this section, we present the Simulink model used for the simulation and the resulting output curves.

The Simulink model shown in Figure 4.4 represents the dynamic behavior of the AVR system. The inputs to the system are assumed to be constant, and the absence of disturbances allows us to observe how the voltage stabilizes to a per-unit value shortly after the startup of the power plant.

As shown in Figure 4.6, the voltage stabilizes to a per-unit value after a short period. Comparing these results with real simulations conducted by the manufacturer in Figure 4.7 , we observe a similarity between the results, confirming the accuracy of our model.

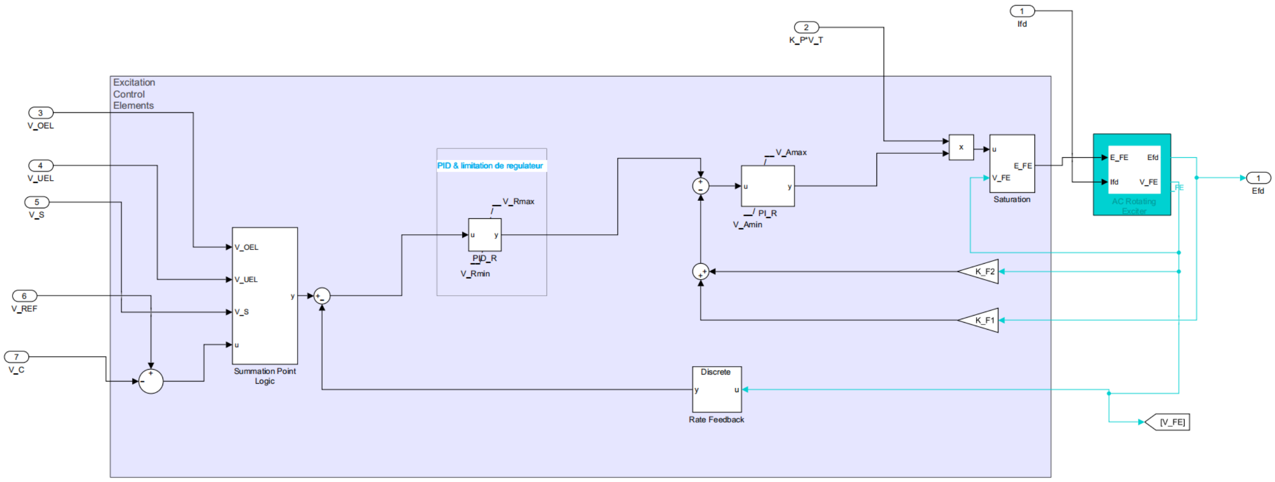


Figure 4.4: Simulink model of the AVR system

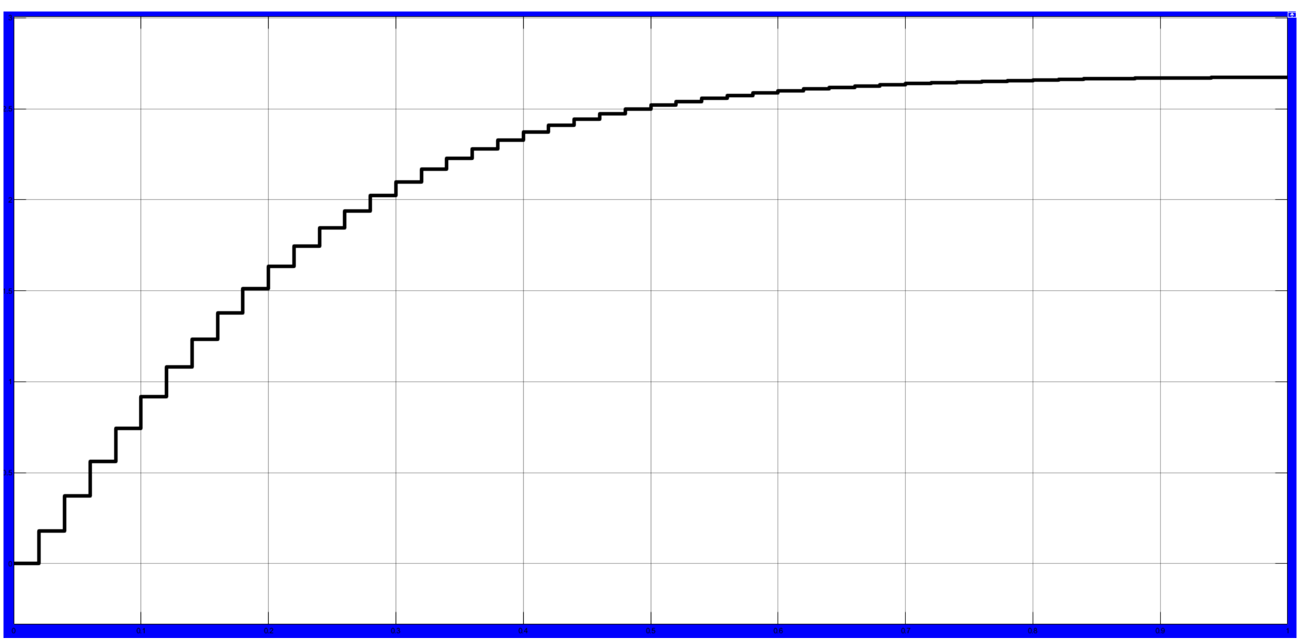


Figure 4.5: Output voltage stabilization curve 1s

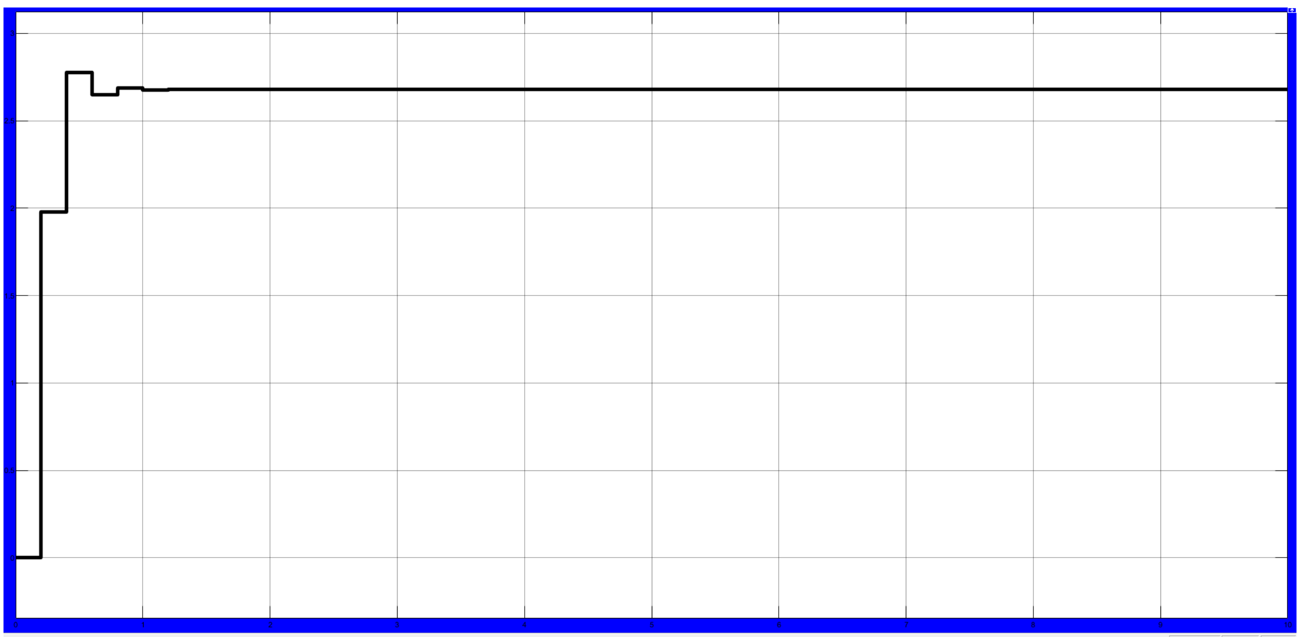


Figure 4.6: Output voltage stabilization curve 60 s

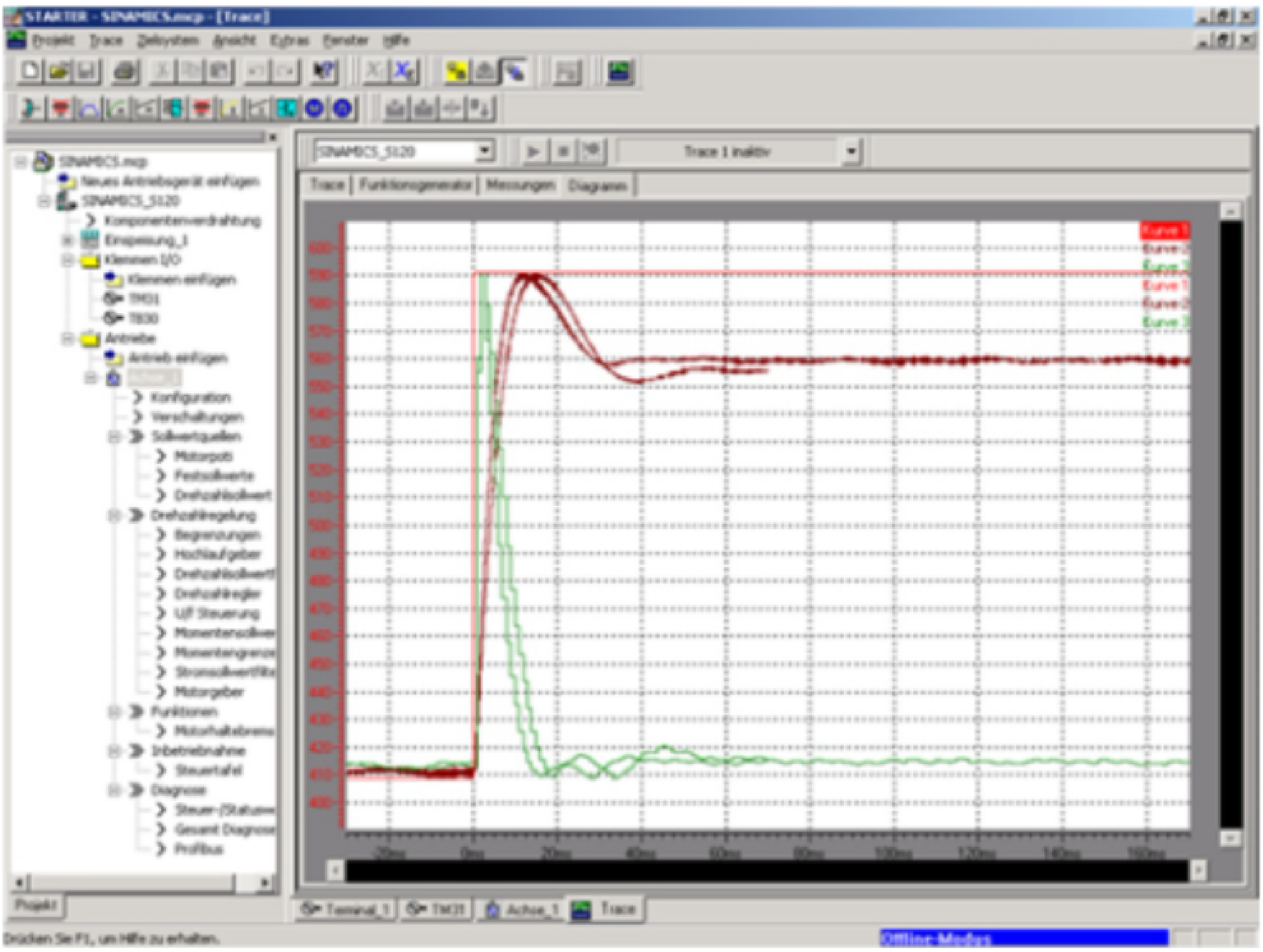


Figure 4.7: real simulations conducted by the manufacturer

Chapter 5

The implementation of secondary voltage regulation at the power plant level

5.1 Introduction

In this chapter, we will examine the implementation of secondary voltage regulation at the power plant level, using the existing AVR. We will also analyze the economic implications, safety impacts, and additional benefits for the company.

5.2 Implementation of Secondary Regulation

Secondary voltage regulation is essential for maintaining the stability of the electrical grid. In our case, we will leverage the existing AVR to effectively manage voltage and reactive power. Communication between the dispatch office and operators is primarily done by phone, which requires a well-defined process:

5.3 Mathematical Model: Estimation of Reactive Power Needs

5.3.1 Parameters

- Q_{needed}: Required reactive power (in VAR)
- P_{load}: Total active power of the load (in W)
- ϕ_{target}: Desired target phase angle (in radians)
- $Q_{current}$: Currently supplied reactive power (in VAR)

5.3.2 Formula

The estimation of reactive power needs can be formulated by the following equation:

$$Q_{needed} = P_{load} \cdot \tan(\phi_{target}) - Q_{current} \tag{5.1}$$

5.3.3 Calculation Steps

Identification of Active Power (P_{load}):

$$P_{load} = \sum_{i=1}^{n} P_i \tag{5.2}$$

where P_i is the active power of each load i and n is the total number of loads.

Selection of Target Phase Angle (ϕ_{target}): Choose a ϕ_{target} based on the desired power factor. For example, for a power factor of 0.95:

$$\phi_{target} = \cos^{-1}(0.95) \tag{5.3}$$

Calculation of Required Reactive Power (Q_{needed}): Using the given formula to calculate Q_{needed}:

$$Q_{needed} = P_{load} \cdot \tan(\phi_{target}) - Q_{current} \tag{5.4}$$

5.3.4 Interpretation of Results

- If $Q_{needed} > 0$: This indicates a need for additional reactive power, requiring the installation of compensation devices.
- If $Q_{needed} \leq 0$: This means the supplied reactive power is sufficient to keep the system within desired limits.

5.3.5 Numerical Example

Data:

- $P_{load} = 1000\,W$
- $\phi_{target} = 0.95$
- $Q_{current} = 300\,VAR$

Calculations:

- Calculation of ϕ_{target}:

$$\phi_{target} = \cos^{-1}(0.95) \approx 0.316\,radians \tag{5.5}$$

- Calculation of Q_{needed}:

$$Q_{needed} = 1000 \cdot \tan(0.316) - 300 \tag{5.6}$$

- Final Calculation:

$$Q_{needed} \approx 1000 \cdot 0.329 - 300 \approx 329 - 300 = 29\,VAR \tag{5.7}$$

5.3.6 Conclusion

The mathematical model effectively estimates the reactive power needs of an electrical system. Using this model, engineers can make informed decisions regarding reactive power compensation in the grid.

5.4 Mathematical Model: Real-Time Adjustment of AVR Parameters to Respond to Demand Variations

5.4.1 Introduction

The real-time adjustment of AVR (Automatic Voltage Regulator) parameters is crucial for ensuring effective voltage regulation, especially in the presence of demand variations. This process involves modifying the gains and regulation coefficients based on changes in load and operating conditions.

5.4.2 Parameters to Adjust

- K_v: Voltage regulation gain
- K_i: Integration gain for dynamic response control
- K_d: Derivative gain to improve stability
- V_{set}: Desired reference voltage
- $V_{measured}$: Measured voltage at the AVR output
- P_{load}: Active power of the load (in W)

5.4.3 Mathematical Model

The control model can be expressed by the following equation:

$$V_{error} = V_{set} - V_{measured} \tag{5.8}$$

AVR control can be achieved using a PID (Proportional, Integral, Derivative) approach:

$$V_{control} = K_v \cdot V_{error} + K_i \cdot \int V_{error}\, dt + K_d \cdot \frac{dV_{error}}{dt} \tag{5.9}$$

5.4.4 Real-Time Adjustment

To adjust the AVR parameters in real-time based on demand variations:

Voltage Measurement:

- Continuously monitor the measured voltage $V_{measured}$.

Demand Estimation:

- Estimate the demand P_{load} from sensors and load analysis.

Parameter Adjustment:

- Use adaptive control logic to adjust K_v, K_i, and K_d:

$$K_v(t) = K_{v,0} + \Delta K_v \cdot f(P_{load}) \tag{5.10}$$

$$K_i(t) = K_{i,0} + \Delta K_i \cdot g(P_{load}) \tag{5.11}$$

$$K_d(t) = K_{d,0} + \Delta K_d \cdot h(P_{load}) \tag{5.12}$$

where $K_{v,0}$, $K_{i,0}$, and $K_{d,0}$ are the base values, and f, g, h are functions that determine how the gains change based on P_{load}.

5.4.5 Performance Analysis

Stability:

- Evaluate system stability by monitoring the voltage response after parameter adjustments.
- Analyze oscillations and response time to ensure the system remains stable.

Efficiency:

- Assess the efficiency of parameter adjustments by comparing $V_{measured}$ and V_{set} values before and after adjustment.
- Calculate the time required to reach a steady state.

Impact on the Grid:

- Analyze how AVR adjustments affect the overall electrical grid, particularly in terms of voltage quality and reactive power.

5.5 Mathematical Model: Use of the Existing AVR

5.5.1 Introduction

The use of the existing AVR for voltage and reactive power regulation involves intelligent integration with the dispatching system. This requires proper configuration of the AVR to receive and execute instructions sent by dispatching, while ensuring effective communication protocols.

5.5.2 AVR Configuration

Receiving Instructions: The AVR must be configured to receive input signals from the dispatching system. This may include:

- Desired reference voltage (V_{set}).
- Adjustments for reactive power to supply or absorb (Q_{adjust}).

Voltage Control: The configuration of the AVR can be expressed by the following model:

$$V_{measured} = f(V_{set}, Q_{adjust}) \tag{5.13}$$

where f represents the functional relationship between the measured voltage, the reference voltage, and the reactive power adjustment.

5.5.3 Communication Protocols

Transmission Protocol: A communication protocol such as Modbus, DNP3, or IEC 61850 can be used to ensure efficient data transmission. Messages should include information on:

- Reference voltage (V_{set}).
- Required adjustments for reactive power (Q_{adjust}).
- Current voltage measurements ($V_{measured}$).

Establishing Communication Channels: Reliable communication channels must be established between the AVR and dispatching. This can be achieved using wired or wireless networks, depending on specific needs. Communication latency should be minimized to ensure real-time adjustments.

5.5.4 Communication Performance Analysis

Transmission Efficiency:

- Measure the time required for instructions sent by dispatching to reach the AVR.
- Evaluate the accuracy of transmitted data by comparing the sent values with those measured by the AVR.

Reliability:

- Assess system reliability by measuring the error rate in data transmission.
- Implement redundancy mechanisms to ensure instructions are not lost or misinterpreted.

5.5.5 Conclusion

Using the existing AVR with clear instructions from dispatching allows for dynamic regulation of voltage and reactive power. With proper configuration and effective communication protocols, the AVR can quickly respond to the needs of the electrical grid, ensuring optimal performance.

5.6 Estimation of Desired Results

5.6.1 Introduction

Estimating the desired results when implementing the existing AVR for voltage and reactive power regulation is essential to evaluate the system's effectiveness. These results can be measured in terms of AVR performance, power quality, and economic impact.

5.6.2 Estimation Objectives

Voltage Stability:

- **Objective:** Maintain the output voltage within acceptable limits (e.g., ± 5
- **Estimation:** Analyze the variations in the measured voltage compared to the reference voltage. The voltage is expected to remain stable even with load fluctuations.

Power Factor Improvement:

- **Objective:** Increase the system's power factor to a desired level (e.g., 0.95).
- **Estimation:** Measure the power factor before and after implementing AVR adjustments. Significant improvement is expected due to reactive power compensation.

Reduction of Energy Losses:

- **Objective:** Reduce energy losses due to reactive currents.
- **Estimation:** Evaluate the decrease in losses by comparing values before and after implementation. A reduction in losses of around 10-20

Reduction of Voltage Oscillations:

- **Objective:** Minimize voltage oscillations due to rapid load variations.
- **Estimation:** Analyze the AVR's response to sudden demand changes. The goal is to achieve rapid damping and voltage stabilization.

Operational Efficiency:

- **Objective:** Improve the overall efficiency of the energy management system.

- **Estimation:** Evaluate the AVR's response time to dispatching instructions. Adjustments are expected to be made in real-time with minimal latency.

5.6.3 Economic Impact

Energy Cost Savings:

- **Estimation:** Calculate potential savings on electricity bills due to improved power factor and reduced losses. Savings of 5-15

Reduction of Penalty Costs:

- **Estimation:** Evaluate the reduction in penalties related to a low power factor. This can result in a significant decrease in overhead costs.

Return on Investment (ROI):

- **Estimation:** Assess the ROI on the AVR implementation and necessary modifications. A positive ROI is expected within 1 to 3 years.

5.6.4 Conclusion

Estimating the desired results provides a framework to evaluate the effectiveness of the existing AVR in regulating voltage and reactive power. By achieving the defined objectives, significant improvements in the electrical grid's performance and notable economic benefits for the company can be expected.

5.7 Economic Analysis of Using Secondary Regulation

5.7.1 Introduction

Implementing secondary voltage regulation in a power plant has significant economic implications. This economic analysis aims to evaluate the costs and benefits associated with using secondary regulation, considering potential savings, necessary investments, and long-term benefits.

5.7.2 Implementation Costs

a. Equipment Costs

- **AVR Upgrade:**
  - Acquisition and installation cost: €50,000.
  - Cost of sensors and communication equipment: €20,000.
- **Total equipment cost:**

$$\text{Total cost} = 50,000 + 20,000 = 70,000\,€ \tag{5.14}$$

b. Operating Costs

- Maintenance costs: Estimated at €2,000 per year.
- Personnel costs: Estimated at €10,000 per year for training and management.
- **Total annual operating cost:**

$$\text{Total operating cost} = 2,000 + 10,000 = 12,000\,€ \text{ per year} \tag{5.15}$$

5.7.3 Economic Benefits

a. Energy Cost Savings

- **Power Factor Improvement:**
  - Assume a 10
  - Annual electricity cost before improvement: €200,000.
  - **Annual energy cost savings:**

$$\text{Savings} = 0.10 \times 200,000 = 20,000\,€ \tag{5.16}$$

b. Penalty Cost Reduction

- **Penalties related to low power factor:**
  - Assume penalties for low power factor were €15,000 per year before implementation.
  - With improvement, these penalties are reduced to €3,000 per year.
  - **Annual penalty savings:**

$$\text{Penalty savings} = 15,000 - 3,000 = 12,000\,€ \tag{5.17}$$

c. Total Annual Savings

$$\text{Total savings} = 20,000 + 12,000 = 32,000\,€ \text{ per year} \tag{5.18}$$

5.7.4 Return on Investment (ROI)

To evaluate the profitability of implementing secondary regulation, we calculate the ROI over a period of 5 years.

Total costs over 5 years:

$$\text{Total costs} = 70,000 + (12,000 \times 5) = 70,000 + 60,000 = 130,000 \,€ \tag{5.19}$$

Total benefits over 5 years:

$$\text{Total benefits} = 32,000 \times 5 = 160,000 \,€ \tag{5.20}$$

ROI:

$$ROI = \frac{\text{Total benefits} - \text{Total costs}}{\text{Total costs}} \times 100 \tag{5.21}$$

$$ROI = \frac{160,000 - 130,000}{130,000} \times 100 \approx 23.08\% \tag{5.22}$$

5.7.5 Conclusion

The economic analysis of using secondary regulation shows that the benefits outweigh the implementation and operating costs. With an ROI of approximately 23.08% over five years, implementing secondary voltage regulation proves to be an economically viable decision. These savings and improvements in energy management will contribute to the company's long-term sustainability and profitability.

5.8 Impact on Network Security Level

5.8.1 Introduction

Implementing secondary voltage regulation has a significant impact on the security level of electrical networks. By improving reactive power management and voltage stability, this regulation helps reduce the risk of network failures and ensures a reliable power supply.

5.8.2 Improvement of Network Stability

Reduction of Voltage Fluctuations:

- Secondary regulation helps maintain voltage within acceptable limits, reducing the risk of fluctuations that can damage equipment or cause power outages.
- Stable voltage helps protect devices connected to the network, extending their lifespan and reducing maintenance costs.

Optimal Reactive Power Management:

- Reactive power regulation helps compensate for imbalances in the network, reducing the risks of instability and overvoltage.
- By maintaining an optimal power factor, the network becomes less susceptible to failures caused by unbalanced loads.

5.8.3 Reduction of Failure Risks

Prevention of Sudden Failures:

- An effective regulation system can quickly detect and respond to load and voltage variations, preventing sudden failures.
- Secondary regulation ensures a rapid response to disruptive events, minimizing impacts on the network.

Enhanced Protection Systems:

- Integrating the AVR with advanced protection systems allows anticipation and reaction to abnormal conditions, enhancing network security.
- This includes using protection relays that rely on real-time data to act quickly when needed.

5.8.4 Reliability Analysis

Improvement of Energy Supplier Reliability:

- With effective regulation, the quality of supplied energy improves, strengthening consumer and business confidence in the energy supplier.
- Reliable power supply is essential for sensitive industries and critical applications.

Risk Assessments:

- Implementing secondary regulation allows for more accurate risk assessments, identifying potential vulnerabilities and critical points in the network.
- This enables proactive measures to enhance network security.

5.9 Conclusion

Secondary voltage regulation, integrated into the electrical system using the AVR, plays a crucial role in improving the stability, reliability, and security of modern electrical networks. Through the analysis of various aspects of this regulation, we have identified significant benefits both technically and economically.

5.9.1 Improvement of Network Performance

- **Voltage Stability:** Regulation helps maintain voltage within optimal limits, minimizing fluctuations and the risk of outages. This results in a notable improvement in the quality of supplied energy.

5.9.2 Resource Optimization

- By integrating dynamic reactive power management, the company can optimize resource utilization, thereby reducing energy losses and operating costs.

5.9.3 Strategic and Environmental Benefits

- Beyond technical advantages, the implementation of secondary regulation enhances the company's brand image, providing a competitive edge. Additionally, it contributes to reducing the carbon footprint, aligning the company with sustainability goals.

5.9.4 Economic Analysis

- Financial estimates show that optimizing energy management can generate significant savings while enabling access to subsidies and incentives, contributing to better profitability.

5.9.5 Security Enhancement

- Secondary regulation also improves network security by providing a rapid response to load variations and abnormal conditions, thereby enhancing the reliability of the electrical system.

In summary, adopting secondary voltage regulation is not only a technical necessity but also a strategic opportunity for companies aiming to improve operational efficiency, strengthen market position, and contribute to a sustainable energy future. The results of this study clearly show that investments in advanced regulation systems translate into tangible long-term benefits for both the company and the broader community.

Chapter 6

Conclusion and Perspectives

6.1 Summary of Results

In this PFA, we explored the modeling of the Automatic Voltage Regulator (AVR), particularly the AC7B model, and conducted a simulation with Simulink to analyze its performance. The mathematical modeling helped understand the dynamic operation of the AVR and its interactions with other components of the electrical system, notably the Power System Stabilizer (PSS). The simulation revealed that the AVR is capable of maintaining the output voltage within acceptable limits, even in the face of load variations.

Following this modeling and simulation, we addressed the transition to secondary regulation, which allows for dynamic management of voltage and reactive power. This shift towards more sophisticated regulation represents a significant advancement in the management of electrical networks, enhancing their reliability and efficiency.

6.2 Research Contributions

This study contributes to the existing literature on voltage regulation systems by providing detailed models and performance analyses. The results highlight the importance of the AVR in managing modern electrical networks and provide a solid foundation for future research in dynamic regulation.

6.3 Study Limitations

Despite the promising results, this study has certain limitations. For instance, the AVR modeling was conducted under ideal conditions, without considering real system disturbances. Additionally, the Simulink simulation was limited by initial assumptions and necessary simplifications to make the model manageable. These factors may influence the results and should be considered in future studies.

6.4 Future Perspectives

To further research on voltage regulation, several avenues can be explored:

Model Improvements: Develop more complex models that integrate nonlinear elements and dynamic behaviors to better reflect the reality of electrical networks.

Practical Case Studies: Conduct case studies on real installations to evaluate the effectiveness of secondary regulation under real conditions.

6.5 Final Conclusion

In conclusion, the modeling of the AVR and the simulation conducted with Simulink demonstrated the crucial importance of these devices in managing modern electrical networks. The transition to secondary regulation, although complex, offers considerable advantages in terms of stability and efficiency. This work paves the way for future research that can deepen and broaden our understanding of regulation systems in an ever-evolving energy context.

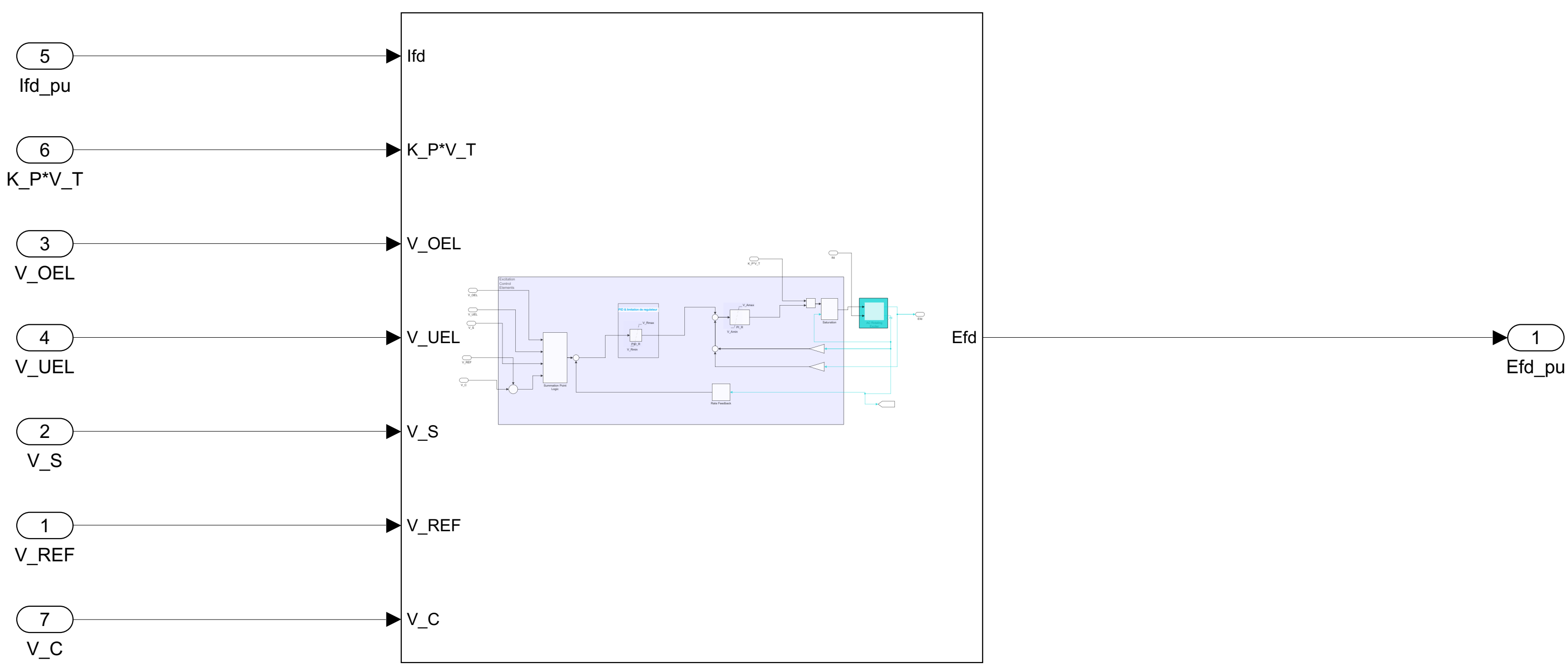
References

Here are some useful references:

- Exciter AC7B and ESAC7B
- IEEE Recommended Practice for Excitation System
- SIMOTION D
- SIMOTION 120

Appendices

Block of our simulation done in Simulink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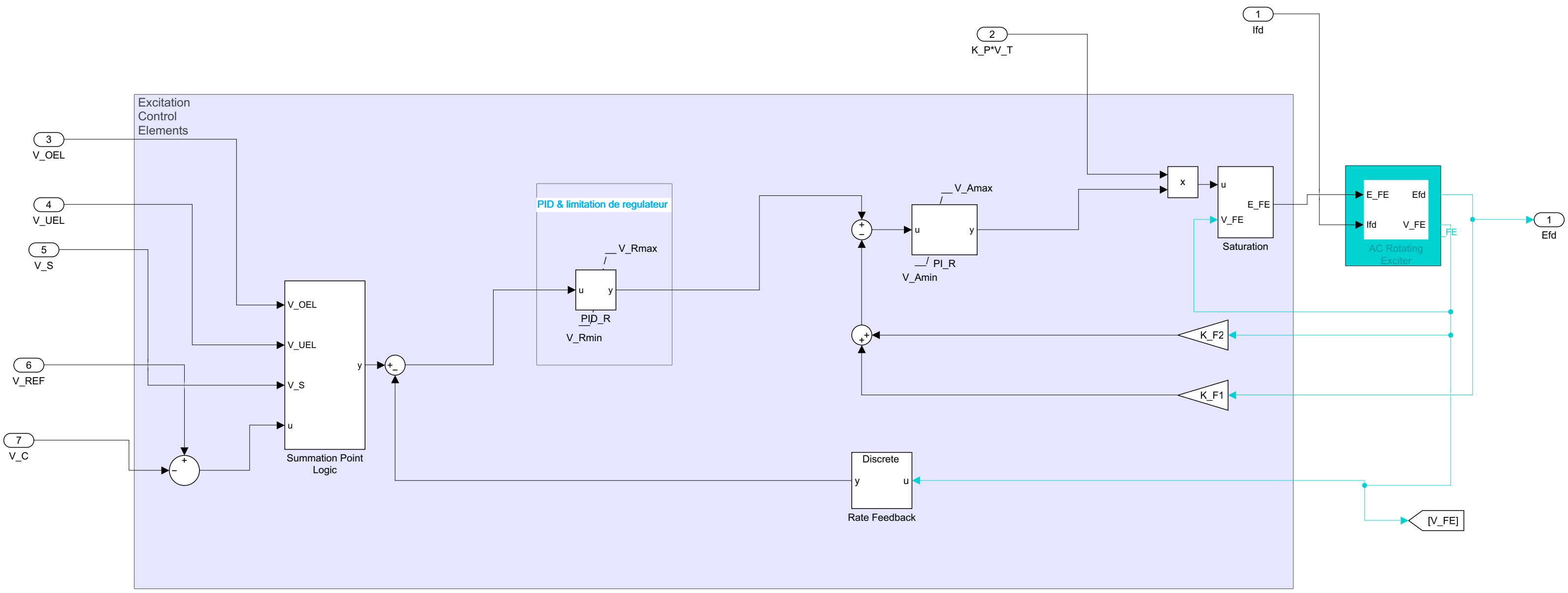

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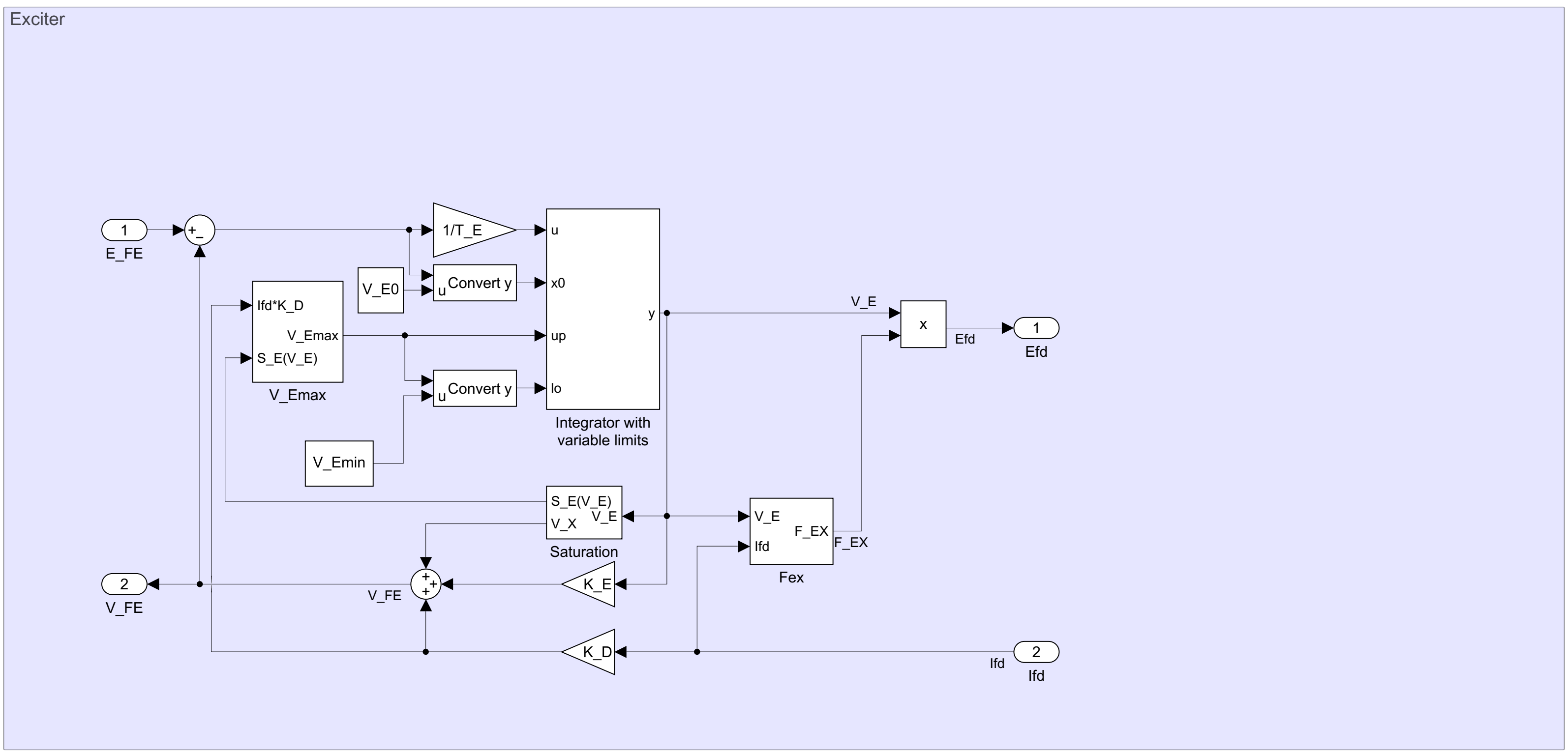
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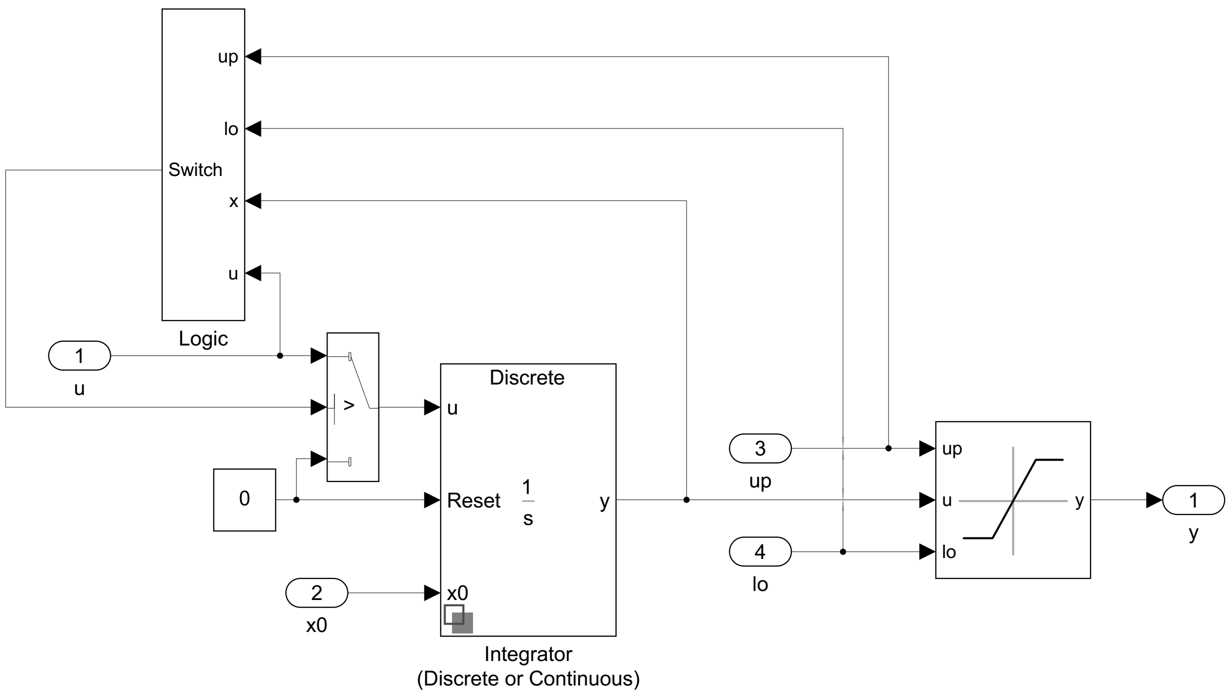

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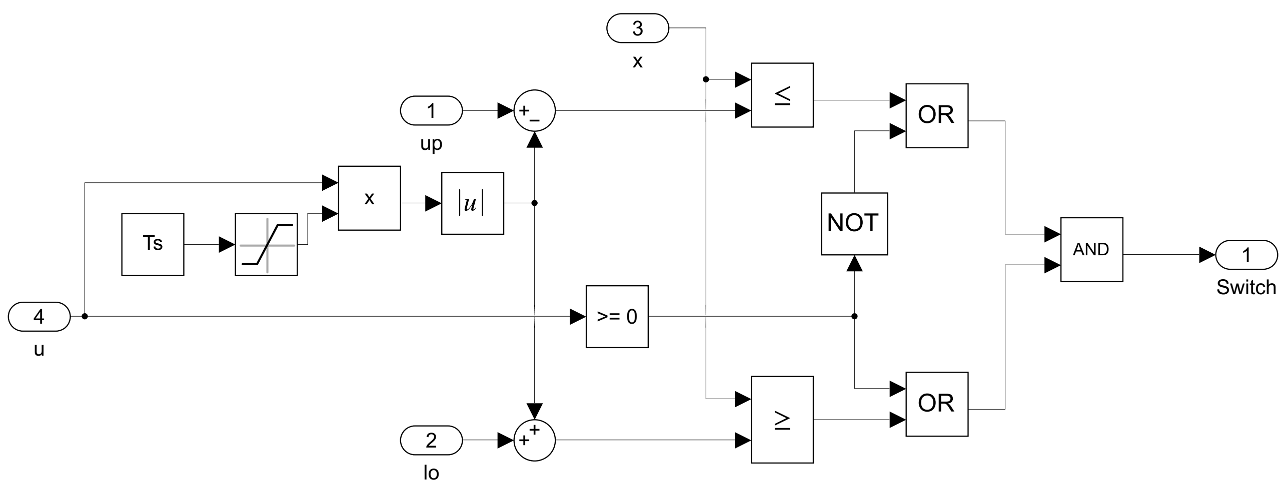

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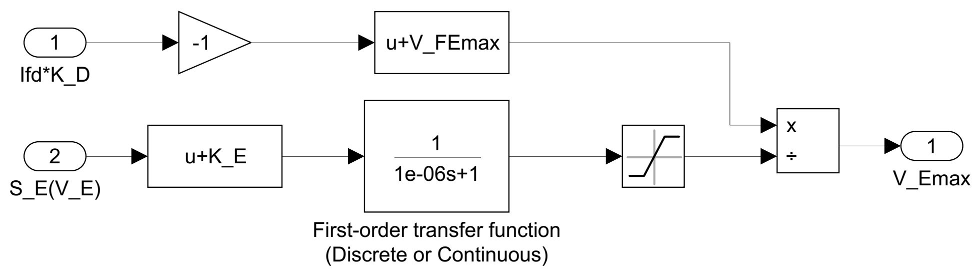
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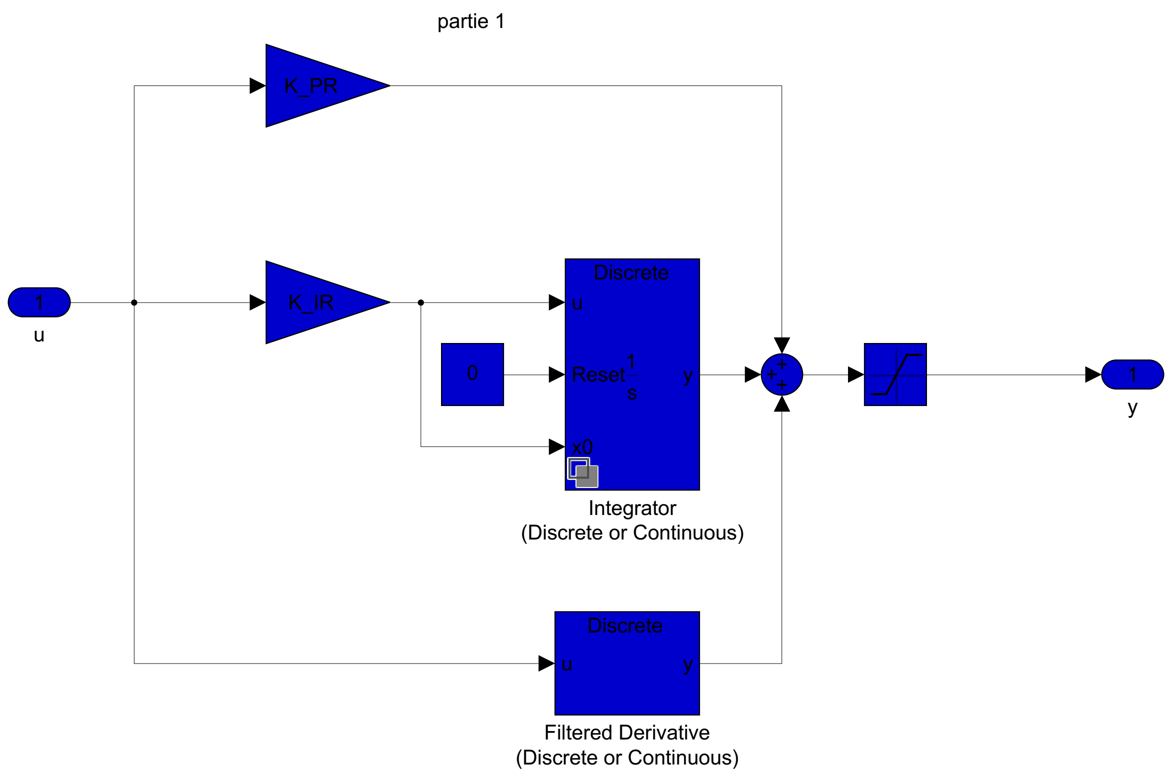
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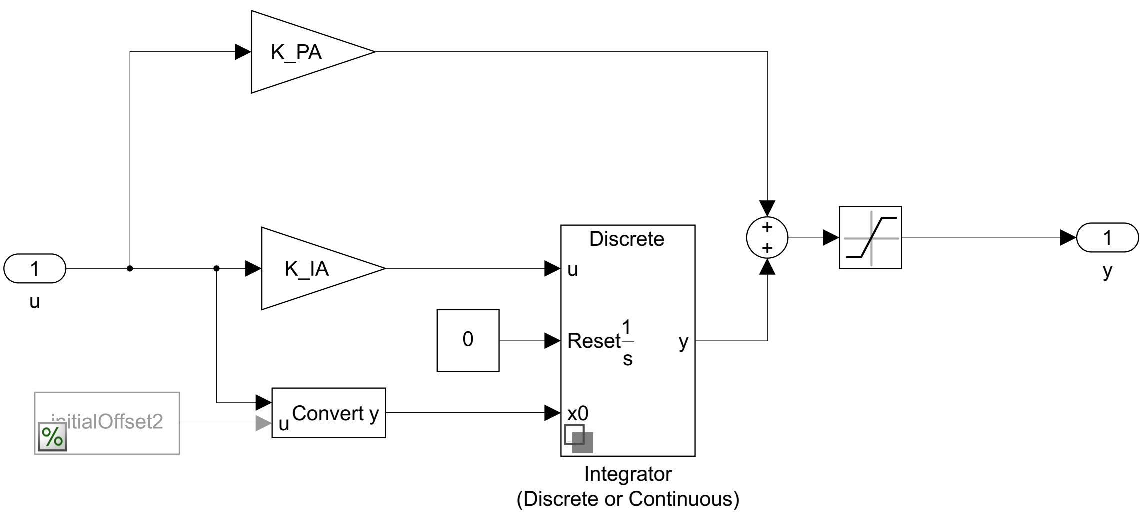
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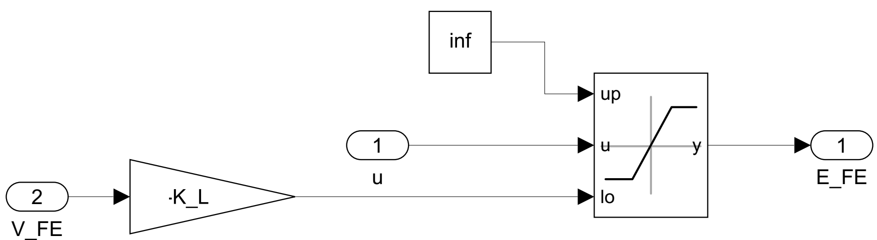

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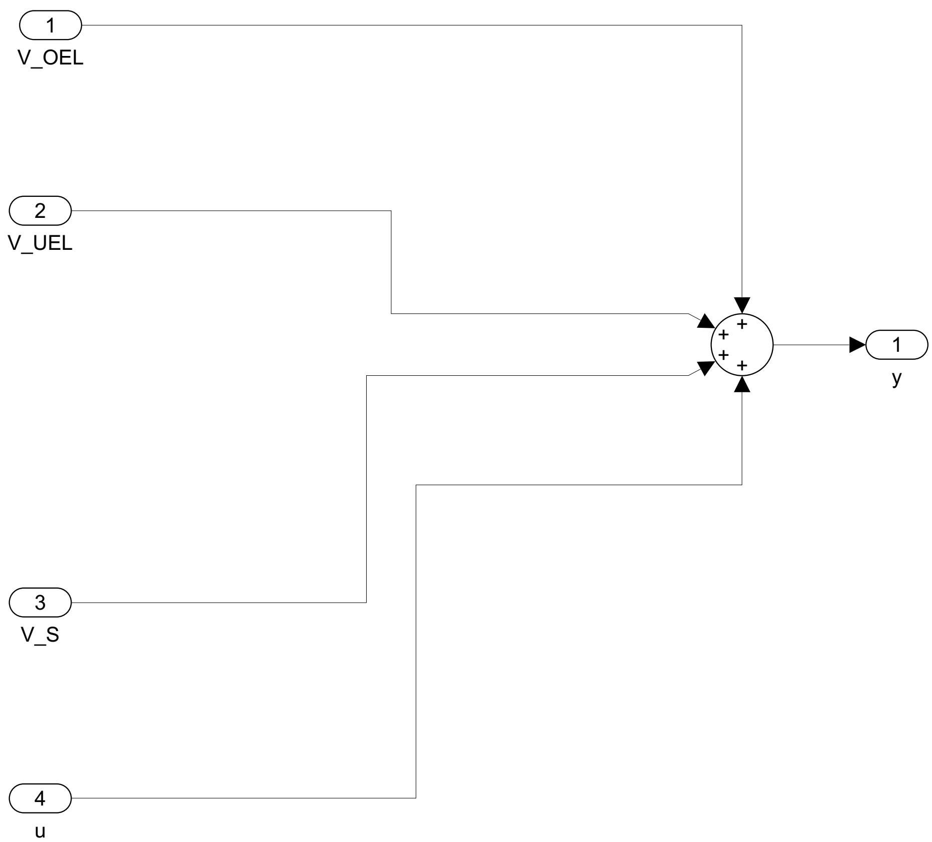

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