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Факультет аеронавігації, електроніки та телекомунікацій
Кафедра аерокосмічних систем управління

ДОПУСТИТИ ДО ЗАХИСТУ
Завідувач кафедри АКСУ
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КВАЛІФІКАЦІЙНА РОБОТА

(ПОЯСНЮВАЛЬНА ЗАПИСКА)

ВИПУСКНИКА ОСВІТНЬОГО СТУПЕНЯ
“БАКАЛАВР”

Тема: «Система управління положенням стержнів атомного реактора»

Виконавець: студент групи СУ-402________________Роман СУПРУНЕЦЬ

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Київ 2023

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QUALIFICATION PAPER

(EXPLANATORY NOTE)

FOR THE ACADEMIC DEGREE OF BACHELOR

”

Title: “ Nuclear Reactor Rods Position Control System”

Submitted by student of group CS-402:__________________Roman SUPRUNETS

Supervised:____Antonina KLIPA

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Kyiv 2023

НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ

Факультет аеронавігації, електроніки та телекомунікацій

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Спеціальність: 151 " Автоматизація та комп̓ютерно-інтегровані технології"

ЗАТВЕРДЖУЮ

Завідувач кафедри АКСУ

_____________ Юрій МЕЛЬНИК

«_____»___________2023 р.

ЗАВДАННЯ

на виконання дипломної роботи

Супрунця Романа Петровича

1. Тема кваліфікаційної роботи: «Система управління положенням стержнів атомного реактора » затверджена наказом ректора від «13» квітня 2023 р. № 507/ст.

2. Термін виконання роботи: з .22.05.2023 по 22.06.2023.

3. Вихідні дані роботи**:** теорія ядерних реакторів та дизайн PID-контроллерів, дизайн котролерів для системи управління положенням стержнів атомного реактора.

4. Зміст пояснювальної записки:

1. Мета ядерного реактора та принцип дії; 2. Огляд теорії ядерних реакторів ; 3. Огляд типів контроллерів ; 4. Розробка PD-контроллера та налаштування параметрів контроллера для системи управління положенням стержнів атомного реактора.

5. Перелік обов’язкового ілюстративного матеріалу:

1. Структурна схема атомного реактора ; 2. Графіки реакції контролерів на одиничний ступінчастий вплив; 3. Графіки реакції систем на одиничний ступінчастий вплив; 4.Графік положення коренів характеристичного рівняння моделі системі на комплексній площині ; 5. Таблиці налаштування параметрів контролерів за методом Зіглера-Ніколса.

6. Календарний план-графік

№ пор.	Завдання	Термін виконання	Відмітка про виконання
1	Отримання завдання	8.05.2023 – 8.05.2023	
2	Формування мети та основних завдань дослідження	09.05.2023 –10.05.2023	
3	Аналіз методів розробки контролерів	11.05.2023 – 22.05.2023	
4	Теоретичний розгляд рішення задачі	23.05-2023 – 26.05.2023	
5	Розробка контролера з бажаними запасами стабільності	27.05.2023-06.06.2023	
6	Підготовка презентації та роздаткового матеріалу	07.06.2023-11.06.2023	

7. Дата видачі завдання: «8» травня 2023 р.

Керівник дипломної роботи ___________________ Антоніна КЛІПА
(підпис керівника)

Завдання прийняв до виконання ___________________ Роман СУПРУНЕЦЬ
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NATIONAL AVIATION UNIVERSITY
Faculty of Aeronavigation, electronics, and Telecommunications
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APPROVED BY
Head of the ACS Department
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"____" __________2023

Qualification Paper Assignment for Graduate Student

Suprunets Roman Petrovych

1. The qualification paper title: "Nuclear Reactor Rods Position Control System." was approved by the Rector's order of “ 13 ” April 2023 № 507/ст.

2. The paper to be completed between: 22.05.2023 and 22.06.2023

3. Initial data for the paper:

Theory of nuclear reactors and design of PID controllers, design of controllers for the nuclear reactor rods position control system.

4. The content of the explanatory note:

1. Purpose of a nuclear reactor and principle of operation; 2. Overview of the theory of nuclear reactors; 3. Overview of types of controllers; 4. Development of PD controller and tuning controller parameters for the nuclear reactor rods position control system.

5. The list of mandatory illustrations:

1. Structural diagram of a nuclear reactor; 2. Graphs of controller's step responses ; 3. Graphs of the system response to a single-step impact; 4. Graph of the position of the roots of the characteristic equation of the system model on the complex plane; 5. Tables for tuning controller parameters by the Ziegler-Nichols method.

6. Timetable

№	Assignment	Dates of completion	Completion mark
1	Receiving the task	08.05.2023 –08.05.2023	
2	Formation of the goal and main tasks of the research	09.05.2023 –10.05.2023	
3	Analysis of controller development methods	14.05.2023 – 22.05.2023	
4	Theoretical consideration of problem solving	23.05-2023 – 26.05.2023	
5	Development of a controller with desired stability margins	27.05.2023-06.06.2023	
6	Preparation of presentation and handout	07.06.2023-11.06.2023	

7. Assignment issue date: “08” May 2023

Qualification paper supervisor ___________________ Antonina KLIPA
(the supervisor’s signature)

Issued task accepted ___________________ Roman SUPRUNETS
(the graduate student’s signature)

РЕФЕРАТ

Текстова частина роботи: 53 с., 23 рис., 2 табл., 9 літературних джерела.

Об’єкт дослідження – Система управління положенням стержнів атомного реактора

Предмет дослідження – Визначення параметрів ПД-контролера для забезпечення найкращих параметрів перехідних процесів системи, похибок та запасів стабільності

Мета роботи – Дослідження теорії ядерного реактора та принципу їх роботи, вивчення типів контролерів та впровадження в систему PD-контролера.

Методи дослідження – Теорія автоматичного управління рухомими об’єктами, математичне моделювання об’єктів, теоретичний аналіз і моделювання програмним забезпеченням MATLAB.

У роботі проведено дослідження принципу роботи ядерного реактора та системи управління положенням стержнів ядерного реактора, дизайн ПД-контролера із заданим запасом стабільності, включення контролера в систему, аналіз перехідних параметрів, стабільності, похибок та запасів стабільності регульованої та нерегульованої системи.

ABSTRACT

Text part of the work: 53 p., 23 fig., 2 table, 9 references.

Object of research - Nuclear Reactor Rods Position Control System

Purpose of the work - Investigation of the theory of the nuclear reactor and the principle of their operation, study of the types of controllers and implementation of the PD-controller into the system.

Subject of the research - Determination of PD-controller parameters to ensure the best parameters of system transients processes, errors and stability margins.

Methods of research - Theory of automatic control of moving objects, mathematical modeling of objects, theoretical analysis and modeling by MATLAB software.

The work carried out a study of the principle of operation of a nuclear reactor and Nuclear Reactor Rods Position Control System, the design of a PD controller with a required stability margin, the inclusion of the controller in the system, the analysis of transient parameters, stability, errors and stability margins of the regulated and system without controller.

CONTENTS

INTRODUCTION

The discovery of nuclear fusion in December 1938 by chemists Otto Hahn and Fritz Strassman was a sign of epochal significance because it opened for humanity new sources of internal energy. It was an important discovery in the first path of the XX century because the World population is growing, as is energy consumption, so fossil fuels could be exhausted by 2050[1].

So the next step was development a such system which can provide safety transformation of the heat energy from fission reaction into electrical. The first usage attempt of nuclear energy was the Manhattan Project 1942–1946, initiated during World War II, brought together leading scientists to develop the first atomic bomb and marked a significant turning point in nuclear research

The Chicago Pile-1 (CP-1), built under Fermi’s leadership, achieved the first controlled nuclear chain reaction in 1942, demonstrating the feasibility of sustained nuclear reactions.The Experimental Breeder Reactor-I (EBR-I), constructed in Idaho in 1951, became the first nuclear reactor to produce electricity. The Shippingport Atomic Power Station, operational in 1957, marked the transition from experimental reactors to commercial-scale nuclear power production. Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR) became the dominant designs for commercial nuclear power plants, offering enhanced safety and efficiency. Liquid Metal Fast Breeder Reactors (LMFBR) were developed to utilize plutonium more effectively and achieve sustainable nuclear fuel cycles. High-temperature gas-cooled reactors (HTGR) utilized helium as a coolant, enabling higher operating temperatures and potential applications such as hydrogen production and process heat.

Nuclear power plants (NPPs) produce about 53% of the country’s electricity. Totally there are four nuclear power plants in Ukraine: Zaporizhzhya, Rivne, South Ukraine, and Khmelnitsky, with 13 power units of WWER-1000 type (water-water energetic reactor) and two power units of PWR-440 type with a total capacity of 13880.

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CHAPTER 1. THEORY OF NUCLEAR REACTORS AND THE PROBLEM STATEMENT

1.1. Main goals of nuclear reactors

Nuclear reactors, at their core, are designed to harness the power of nuclear fission reactions to generate electricity. In the realm of energy production, nuclear technology stands as a prominent contender due to its ability to deliver significant power outputs while minimizing greenhouse gas emissions. This essay aims to delve into the technical aspects of nuclear reactors and elucidate their primary goals from an engineering standpoint.

One of the primary objectives of nuclear reactors is to achieve optimal power generation efficiency. Reactor designs focus on maximizing the conversion of nuclear fuel’s thermal energy into electrical energy. By employing sophisticated heat exchange systems, coolants such as water or liquid metal transfer the thermal energy to a steam generator, where it is converted into high-pressure steam. This steam subsequently drives a turbine connected to an electrical generator, ensuring the efficient extraction and utilization of energy.

Safety lies at the core of every nuclear reactor design. The foremost goal is to prevent accidents and ensure operational integrity throughout the plant’s lifetime. Rigorous safety protocols, comprehensive training programs, and redundant safety systems are implemented to mitigate potential risks. Reactor designs incorporate multiple physical barriers and advanced containment structures to confine radioactive materials and prevent their release into the environment. The aim is to protect plant personnel, the general public, and the environment from the hazards associated with nuclear energy.

Nuclear reactors strive to provide a consistent and reliable supply of electricity to meet the demands of the electrical grid. Reactor designs prioritize high availability, aiming for extended operational periods with minimal downtime.

ACS DEPARTMENT				Explanatory note			
Performed.	R.Suprunets			SECTION 1.THEORY OF NUCLEAR REACTORS AND THE PROBLEM STATEMENT	N..	Page.	Pages
Supervisor	A.Klipa					11	14
Consultant					402		
S. controller.	M. Dyvnych						
Dep. head	Yu. Melnyk						

Scheduled maintenance and refueling outages are carefully planned to minimize disruptions in power generation.

The objective is to ensure a stable and dependable source of electricity, contributing to the overall reliability of the power system and supporting the needs of industries, homes, and businesses.

In the face of global environmental challenges, nuclear reactors play a vital role in reducing greenhouse gas emissions. By displacing fossil fuel-based power plants, nuclear energy mitigates climate change and improves air quality. The objective is to achieve long-term environmental sustainability by providing a low-carbon energy source. Nuclear reactors emit negligible amounts of carbon dioxide during operation, ensuring a minimal carbon footprint. Furthermore, efforts are made to optimize water usage and manage nuclear waste effectively, minimizing the overall environmental impact.

Nuclear reactors serve as a crucial platform for research and development, facilitating innovation in various scientific disciplines. Through continuous exploration, reactor technologies are refined, safety features are enhanced, and operational efficiency is improved. Advanced reactor designs, fuel cycle optimization, and waste management techniques are actively pursued to address sustainability challenges. Research conducted within nuclear reactors also extends to other fields, such as medical isotope production and space exploration, fostering scientific progress and societal advancements.

1.2. Theory of nuclear reactors

Nuclear reactors use a specific type of fuel, usually uranium-235 or plutonium-239, that can undergo a nuclear chain reaction. The fuel is pelletized and assembled into fuel rods. These fuel rods are then arranged into a structured structure known as the reactor core. In the reactor core, fuel atoms undergo a process called nuclear fission. In nuclear fission, neutrons bombard fuel atoms, splitting the atoms into two smaller nuclei, releasing a lot of energy in the process. The process also releases more neutrons, which collide with other fuel atoms and start a chain reaction. As the fuel undergoes nuclear fission, the chain reaction continues, generating a lot of heat. This heat is released from the splitting atoms as kinetic energy. The heat is carried by a coolant, usually water or a gas such as carbon dioxide, that circulates through the reactor core and absorbs heat from the fuel rods. The hot coolant that absorbs heat from the fuel passes through a heat exchanger called a steam generator. In a steam generator, heat is transferred to a secondary coolant, usually water, which surrounds the primary coolant. Due to heat transfer, this secondary coolant is converted to steam at high pressure. The high-pressure steam generated in the steam generator is directed to the turbine. The steam causes the turbine blades to rotate, converting the thermal energy of the steam into mechanical energy. The rotating turbine is connected to a generator, which contains coils in a magnetic field. As the turbine rotates, it spins the rotor of the generator, which creates an electromagnetic field that induces an electric current in the coil. The current generated in the generator is then transmitted along an electrical conductor, forming an electrical circuit. This current is the flow of electrons that make up the electricity produced by the nuclear reactor. It can be transmitted to the electrical grid and distributed in homes, businesses, and industries for a variety of purposes. After passing through the turbine, the steam is condensed back to water by a condenser, which transfers the heat from the steam to a cooling medium, such as water from a nearby river or cooling tower. The condensate is then pumped back into the steam generator to repeat the cycle.

1.3. Nuclear fission and fission energy

Nuclear fission is a reaction in which the nucleus of an atom splits into two or more smaller nuclei. The fission process often produces gamma photons, and releases a very large amount of energy even by the energetic standards of radioactive decay..

Only three nuclides that are stable enough to allow long-term storage, Uranium-233, Uranium-235, and Plutonium-239, can be fissioned by neutrons of all energies from calorific value to millions of electron volts. Among them, Uranium-235 is the only one found in nature. The other two are artificially made from Uranium-238 and Thorium-232.

The energy released during nuclear fission can be calculated by determining the net mass loss of known isotope masses and using the Einstein mass-energy relationship. A simple (but instructive, if less accurate) alternative procedure is as follows. Ignoring the neutrons involved, since their impact on the present calculation is negligible, the fission reaction can be roughly expressed as

Uranium-235 → Fission product A + Fission product B + Energy. (1.1)

In Uranium-235, the mean binding energy per nucleon is about 7.6 MeV (Mega electron volt), as seen in Eq 1.1. So it is possible to write

92 p + 143 n → Uranium-235 + (235 x 7.6) Mev. (1.2)

Upon subtracting the two binding energy expressions, the result is

Uranium-235 → Fission products + 210 Mev. (1.3)

The fission of a single Uranium-235 (or similar) nucleus is thus accompanied by the release of over 200 MeV of energy. This may be compared with about four ev, which are released by the chemical combustion of an atom of Carbon-12. .[2] Hence, the fission of Uranium yields something like 2.5 million times as much energy as the combustion of the same weight of Carbon

So, in comarance, 1 pound of fissile material produces the same energy as 1.400 tons of coal.

Hence, the total energy (200 Mev) available per fission is about 3.2x10-11 watt-sec, so 3.1x1010 fissions are required to release one watt-sec of energy. In other words, fissions at the rate of 3.1x1010 per sec to produce 1 watt of power.

1.4. General Features

In spite of numerous variations in the design and components of nuclear reactor systems, there are nevertheless a number of general features which all such systems possess in common to a greater or lesser extent. In outline Fig 1.1, a reactor consists of an active core in which the fission chain is sustained and in which most of the energy of fission is released as heat. The core contains the nuclear fuel consisting of a fissile nuclide and often a fertile material in addition.

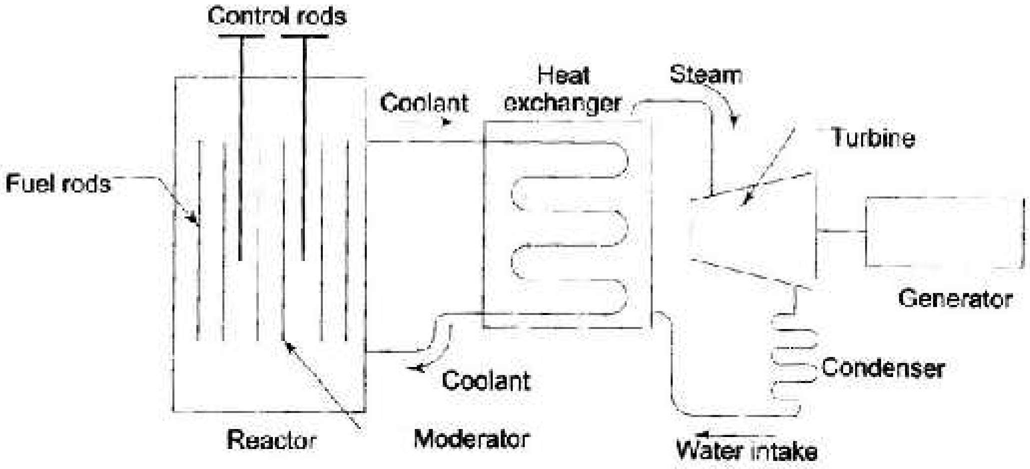

Figure 1.1. Structure diagram of nuclear reactor

If it is desired (as is often the case) that most of the fissions result from the absorption of slow neutrons, there must also be a moderator present. Its function is to slow down the high-energy neutrons liberated in the fission reaction (mainly as a result of elastic scattering reactions). The best moderators are materials consisting of elements of low mass number with little tendency to capture neutrons. Examples are ordinary-Water, Heavy Water (Deuterium Oxide), Beryllium, Beryllium Oxide, Carbon (as graphite), and hydrocarbons. The relative amounts and nature of the fuel and moderator determine the energies of most of the neutrons causing fission.

The core is surrounded by a neutron reflector of a material determined largely by the energy distribution of the neutrons in the reactor. The purpose of the reflector is to decrease the loss of neutrons 27 from the core by scattering back many of those which have escaped. Hence the use of a reflector results in a decrease in the critical mass of the fissile nuclide. If the core contains a moderator to slow down the neutrons, then the same material (or other moderators) can be used in the reflector. On the other hand, when it is required that most of the fissions be caused by neutrons of high energy, the presence of energy-moderating material must be avoided. The reflector then consists of a dense element of high mass number.

The heat generated in the reactor core due to the fissions occurring there is removed by the circulation of a suitable coolant. Among the coolants which have been used or are being considered, liquid Water, liquid Sodium (or Sodium-Potassium alloy), certain organic compounds, and the gasses Air, Carbon Dioxide, and Helium are perhaps of greatest interest. If the energy released in the reactor is to be converted into electrical power, the heat must generally be transferred from the coolant to a working fluid to produce a hot gas. The resulting hot vapor or gas can then be used in a conventional turbine-generator system. In some reactors, water is boiled within the reactor core so that the fission heat is directly utilized to produce steam.

The higher the temperature of the steam or other working fluid, the greater the efficiency for conversion into useful power. Hence in a power reactor, it is desirable to operate at the highest practical temperature. Furthermore, in the interests of the economy, the specific power of the reactor (i.e., the rate of heat generation per unit mass of fissile material) should be large. As far as nuclear considerations are concerned, there are no limits to the attainable temperature or power level of a nuclear reactor. The practical operating conditions are thus determined by engineering limitations rather than by nuclear factors. Heat must be removed from the core at a rate that permits the coolant to attain a high temperature without the development of such thermal stresses and internal temperatures as to cause the reactor to suffer damage.

The rate of heat generation in a reactor core is proportional to the nuclear fission rate. This is determined in a given system by the neutron density (i.e., the number of neutrons per unit volume). Control (including startup) operation at any desired power level and shutdown is thus achieved by varying the neutron density in the core. This is done either by moving rods of a material that readily captures neutrons (i.e., a neutron poison) or by displacing part of the reactor core or reflector. Insertion of a poison (e.g., Cadmium or Boron) results in a decrease in neutron density and hence in the reactor poser. Withdrawal of the poison is accompanied by an increase in both neutron density and power level. Similarly, displacement of a portion of the reflector or of the core may permit neutrons to escape, thus causing a decrease in the neutron density, whereas its replacement will produce an increase in the density [2].

1.5. Reactor Types

Nuclear reactors can be classified in various ways. But the most fundamental distinction is that based on the kinetic energy (or speed) of the neutrons causing most of the fissions in the given reactor.

Nearly all the neutrons liberated in fission have high energies. And so if no moderator is present in the reactor core or reflector, the majority of fissions are produced by fast neutrons. A nuclear reactor in which this is the case is called a **fast reactor**.

The fuel material for such reactors must contain a significant proportion (about 10 percent or more) of a fissile nuclide. The remainder must be a substance of high or intermediate mass number since elements of low mass number would slow down the neutrons. Also, as far as possible, elements must be avoided, which can cause inelastic scattering (and hence slowing down) of neutrons of moderately high energy.

When the fissile nuclide produced is identical to that used to maintain the fission chain, the reactor is called a **breeder**. A fast reactor utilizing Plutonium-239 as the fuel and Uranium-238 as the fertile species can act as a **power breeder** generating power and at the same time producing more Plutonium-239 than is consumed. An analogous fast power-breeder reactor is possible with Uranium-235 and Thorium-232 as fissile and fertile nuclides, respectively. However, it appears that breeding in this system can be achieved in reactors of another type (to be described below) which have some advantages over fast reactors.

It is possible for a fast reactor to employ Uranium-235 as the fissile species to maintain the nuclear chain reaction and Uranium-238 as the fertile material, which is converted into Plutonium-239. Such a converter reactor is not strictly a breeder, even though the quantity of Plutonium-239 produced may exceed that of the Uranium-235 consumed. If the latter situation applies, the reactor is sometimes called a **pseudo-breeder.**

If the reactor core contains a considerable proportion of a moderator, the high energy of the fission neutrons will be rapidly decreased to the thermal region. Most of the fissions in such a reactor (called a **thermal reactor)** will then be caused by thermal (slow) neutrons. Thermal reactors have the advantage over fast reactors in greater flexibility of design. There is a reasonable choice of both moderators and coolants as well as fuel materials. Depending on the nature of the fuel and moderator, a thermal reactor may be quite small or relatively large.

Many thermal reactors include a fertile species so that they are converters. However, in certain circumstances where reactors of compact design are required, the fuel consists of essentially pure Uranium-235. Reactors of this latter type are called **burners** since they consume fissile material without replacing it. [2] Such reactors can only be justified where special situations make their use mandatory (e.g., in a submarine).

1.6. Primary cooling circuits

As stated above, the water in the primary circuits is kept under a constant elevated pressure to avoid boiling. Since the water transfers all the heat from the core and is irradiated, the integrity of this circuit is crucial. Four main components can be distinguished:

1. Reactor vessel: Water flows through the fuel assemblies, which are heated by the nuclear chain reaction.

2. Volume compensator (pressurizer): To keep the water under constant but controlled pressure, the volume compensator regulates the pressure by controlling the

equilibrium between saturated steam and water using electrical heating and relief valves.

3. Steam generator: In the steam generator, the heat from the primary coolant water is used to boil the water in the secondary circuit.

4. Pump: The pump ensures the proper circulation of the water through the circuit. To provide for the continued cooling of the reactor core in emergency situations, the primary cooling is designed with redundancy.

1.7. Secondary circuit and electrical output

The major control objective of a nuclear reactor is to maintain the output power within specified limits. This can be achieved as follows. The nuclear reaction releases energy in the form of heat. This energy is used for the production of steam. The steam is subsequently used to drive a turbine and, in turn, the turbine drives a four generator, which finally produces electric power. The overall picture and schematic diagram are shown in Figure 1.1. The reference signal $r(t)$ corresponds to the desired output power, whereas $y(t)$ is the actual output power. The two signals $r(t)$ and $y(t)$ are compared, and their difference is fed into the control unit. The control unit consists of special rods which, when they move towards the point where the nuclear reaction takes place, result in an increase of the output power $y(t)$, and when they move away, result in a decrease of the output power $y(t)$. When $y(t) > r(t)$, the error $e(t)$ is negative, the rods move away from the point of the nuclear reaction, and the output $y(t)$decreases. When $y(t)> r(t)$, the error $e(t)$ is positive, the rods move towards the point of the nuclear reaction, and the output $y(t)$increases. This way, the power output $r(t)$ follows the desired value $r(t)$.[3]

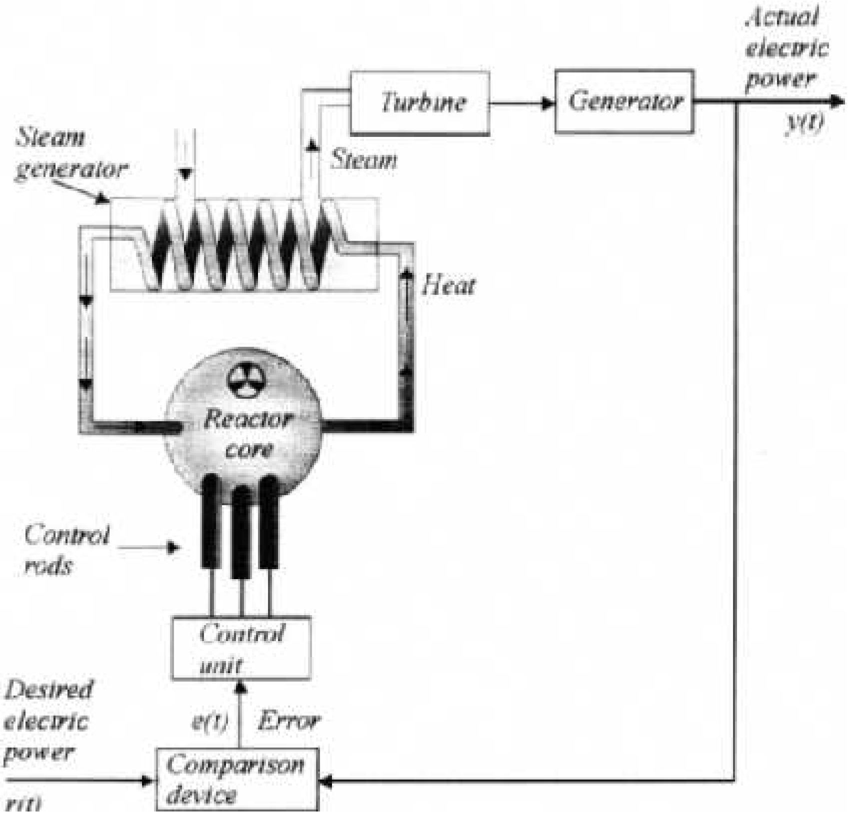

Figure 1.2. Overval picture of nuclear power plant

1.7. Classification of the control rods

Most reactors have rods with different functions or serving different purposes.

- Shim rods are used to bring the reactor approximately to the desired power level when the system is started up. The shim rods must, therefore, have a fairly large reactivity equivalent, the actual amount depending on the particular reactor. Because the rate of increase of reactivity must be closely regulated, the driving mechanism must be such that the shim rods cannot move at high speed during startup.
- Regulating rods are used to bring the reactor up to the operating level and to maintain the power essentially constant. The reactivity equivalent of these rods can be very small, but in general, they must be able to react quickly to changes that affect the reactor.
- The safety rod’s purpose is to shut down the reactor quickly in the moment of an emergency. Safety rods must be capable of moving very rapidly. And their

reactivity equivalent must be appreciably greater than the maximum excess of reactivity built into the reactor. In some reactors, the same rods are used as shim rods and safety rods.

1.8. Control system of nuclear reactor rods position as an object of research and problem statement

The primary purpose of a reactor control system is to ensure uninterrupted and reliable operation in all situations for which the device is designed.

The primary purpose of the reactor control system is to ensure uninterrupted and reliable operation in all situations for which it is designed. It must be able to start the reactor and bring the power output to the desired level, maintain it at that level, and shut down the reactor if necessary. The reactor must be able to shut down when needed. And like any power plant, it must have safeguards in place to prevent damage in the event of an accident. Therefore, the management (or operation) of a nuclear reactor is, in principle, the same as that of a normal power plant. The management (or operation) of a nuclear reactor does not differ in principle from the management of other means of energy production that use fuels such as coal or oil.

An important difference between managing a nuclear reactor and managing other energy converters stems from the nature of the fuel. In reactors built or designed to date, with a few exceptions, the fuel cannot be continuously replaced as it is consumed. Therefore, these reactors must include in their design all the fuel needed to produce a predetermined amount of energy. This can be quite important for mobile reactors used in ship or aircraft engines, for example, as they must be supplied with enough fuel for long periods of continuous operation.

A nuclear reactor cannot be used to release energy continuously unless the critical mass for the particular fuel, shape, etc., is exceeded. For this reason, a power reactor must include extra fuel. And so it must obviously have excess (or built-in) reactivity to an appreciable extent at the time that it commences operation. In addition, other factors, such as the need to override the effect of fission product poisons and of temperature, require that additional reactivity be built into the reactor.

Because of the high reactivity, the neutron flux (or density) and hence the fission rate and the power are capable of an extremely rapid and dangerous increase in a very short time. An essential aspect of reactor control thus lies in the precautions to be taken to prevent an excessive rate of increase in neutron flux when the power level is being raised.

Since the power level of a reactor is virtually proportional to the neutron flux, the obvious basis for reactor control is to vary the effective multiplication of reactivity. If the effective multiplication factor is greater than unity, the reactor is supercritical, and the power level will increase continuously. Upon decreasing the factor to unity so that the reactor is just critical, the power output will remain constant (apart from transient changes) at the level attained at that time.

Finally, by making the reactor subcritical, the power level will be decreased.

There are four main methods that can be used to change the effective breeding ratio: fuel, moderators, reflectors, or the addition or removal of neutron absorbers.

Each of these methods has been used or proposed to control reactors in operation or under construction.

The control procedure involves the introduction or removal of materials such as boron or cadmium that have a large thermal neutron capture cross-section and has been widely used in thermal reactors until now because it is simple and convenient. Bars or strips of boron steel, boron, or cadmium are widely used to control reactors.

The rods can be located inside the core or in a reflector near the core where the thermal neutron flux is high. Due to its high melting point and other useful properties, the element hafnium is used in water-cooled reactors. There is a purpose in using some rare earth oxides in reactors operating at very high temperatures.

Nuclear power plants have two main circuits: cooling and circuit electrical output; that’s why its control unit should keep output power and temperature of heat transfer fluid.

1.9. Conclusion

Nuclear power has become an important player in the global energy space, providing numerous benefits that contribute to economic development, energy security, and environmental sustainability. To summarize the importance of nuclear energy, the following advantages can be highlighted:

Nuclear power is a low-carbon source of energy that plays a vital role in reducing greenhouse gas emissions and combating climate change. Unlike fossil fuel power plants, nuclear reactors produce electricity without emitting carbon dioxide (CO2) and other harmful air pollutants. By generating electricity from nuclear power, countries can significantly reduce their dependence on fossil fuels and contribute to global efforts to mitigate climate change.

Nuclear power plants are a stable and reliable source of energy. They can operate continuously for long periods of time, providing a baseload that meets the constant demand for electricity.

Nuclear power plants are capable of generating significant amounts of electricity. A single nuclear reactor can produce hundreds or even thousands of megawatts of power, providing energy to millions of homes, businesses, and industrial facilities. This ability to generate electricity on a large scale makes nuclear power a valuable contributor to national power systems, contributing to economic growth and industrial development.

The primary fuel for nuclear reactors, Uranium, is relatively abundant in the Earth’s crust.

Nuclear energy provides significant employment opportunities and economic benefits. The construction, operation, and maintenance of nuclear power plants require a skilled workforce, which opens up employment prospects in engineering, construction, research, and other related fields. In addition, nuclear power plants contribute to the development of the local economy by providing a stable source of income and attracting investment in the surrounding communities.

Nuclear energy stimulates technological progress and innovation in various industries. Research and development in nuclear science and engineering have led to breakthroughs in areas such as materials science, radiation therapy in medicine, and nuclear waste management. The development of nuclear energy contributes to scientific progress and technological innovation, which can have broad benefits beyond the energy sector.

CHAPTER 2. DESIGN OF PID-CONTROLLERS

2.1. Types of controllers used with dynamic systems

The additional element called the controller is included in the structure of a system for obtaining the required performance estimates. There are two main kinds of compensation depending on the location of the controller, namely, series and feedback compensations.

2.1.1. Proportional controller

A proportional controller is a form of feedback control. It is the simplest form of continuous control that can be used in closed-loop systems. P-only control minimizes fluctuations in process variables, but it does not always bring the system to the desired set point. It provides a faster response than most other controllers, initially allowing P-only controllers to respond a few seconds faster. However, as the system becomes more complex (i.e., more sophisticated algorithms), response time differences may accumulate, allowing the P-only controller to potentially respond a few minutes faster. While the P-only controller does offer the advantage of faster response times, it does create a deviation from the set point. This deviation is called an offset and is not normally required in the process. The presence of the offset means that the system cannot be maintained at the desired setpoint at a steady state. It is similar to the systematic error in a calibration curve, where there is always a constant set of errors that prevent the line from crossing the origin.

P control linearly correlates the controller output (the drive signal) with the error (the difference between the measured signal and the set point). This P control behavior is mathematically illustrated in equation 2.1, and Figure 2.1 is shown a schematic diagram of a system with transfer functions of plant ( ), controller ( ), and feedback unit ( ).

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S. controller.	M. Dyvnych						
Dep. head	Yu. Melnyk						

( ) = ( ), (2.1)

where ( ) - system input;

-controller gain;

( )-error.

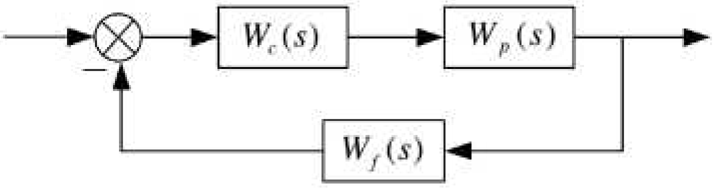

Figure 2.1. System with a proportional controller.

From the above equations, it can be seen that P-only control provides a linear relationship between the system error and the output of the system controller. This type of control provides a signal-based response that adjusts the system to eliminate any oscillations and return the system to a steady state. The inputs to the controller are the set point, signal, and bias voltage. The controller calculates the difference between the set point and the signal (representing the error) and sends this value to the algorithm. Combined with the bias, the algorithm determines what action the controller should take. Figure 2.2 below shows a plot of the P controller output for a step increase in the input at time $_0$. The diagram is exactly the same as the step entry diagram itself.

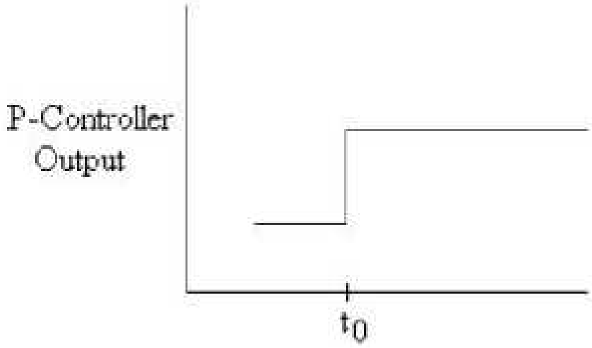

Figure 2.2 P-controller response for step unit.

2.1.2. Integral controller

Integral control is a second form of feedback control. It is often used because it is able to remove any deviations that may exist. Thus, the system returns to both a steady-state and its original setting. A negative error will cause the signal to the system to decrease, while a positive error will cause the signal to increase. However, I-only controllers are much slower in their response time than P-only controllers because they are dependent on more parameters. If it is essential to have no offset in the system, then an I-only controller should be used, but it will require a slower response time. This slower response time can be reduced by combining I-only control with another form, such as P or PD control. I-only controls are often used when measured variables need to remain within a very narrow range and require fine-tuning control. I-controller affects the system by responding to accumulated past errors. The philosophy behind integral control is that deviations will be affected in proportion to the cumulative sum of their magnitude. The key advantage of adding an I-controller to your controller is that it will eliminate the offset. The disadvantages are that it can destabilize the controller, and there is an integrator windup, which increases the time it takes for the controller to make changes.

I-control correlates the controller output to the integral of the error. The integral of the error is taken with respect to time. It is the total error associated over a specified amount of time[4]. (2.2) is shown as a mathematical explanation of integral control.

$$(\quad) = \frac{1}{\quad}\int_0 \quad (\quad) \quad + \quad (\quad_0), \tag{2.2}$$

where - integral controller gain;

$(\quad_0)$ - the controller output integration;

- integration time.

I-only controls work in much the same way as P-only controls. The inputs are again the set point, signal, and bias voltage. Calculate the error again and send this value to the algorithm. However, instead of using a linear relationship to calculate the response, the algorithm now uses an integral to determine which response to take. Once the points are evaluated, a response is sent, and the system adjusts accordingly. Due to the reliance on , the algorithm takes longer to find the correct answer. Figure 2.3 below shows the plot of the I controller output for an input step increase at time $_0$. The plot represents the region below the step input plot.

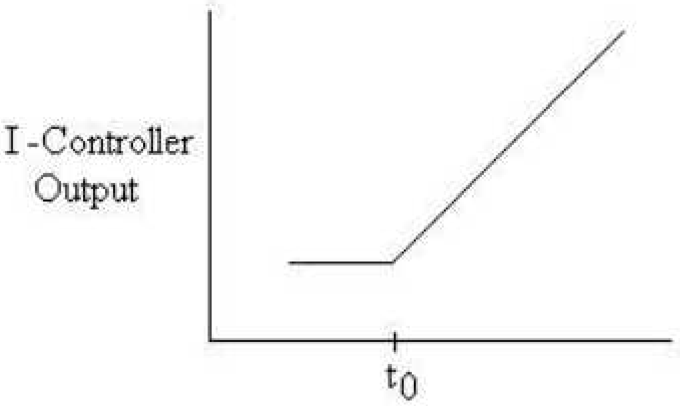

Figure 2.3. I-controller response for step unit.

2.1.3 Differential controller

As the name suggests, differential control action is proportional to the time rate of change of the error signal. Because of its sensitivity to fluctuations in the measured process variable, derivative control is seldom used but is sometimes applied successfully by using a low-pass filter to reduce high-frequency noise in the error signal. Differential controllers are useful in systems where there is a considerable lag time between the control action and its effect on the system output. This time lag can result in an incorrect error term being supplied to the controller, and the system may go into instability. By combining the proportional and differential components of the error term, the controller can anticipate the future changes taking place in the output in addition to the error itself. Thus, a differential controller could help stabilize a closed-loop system. This controller is expressed in the (2.3).[5]

$$(\;) = \;(—), \qquad (2.3)$$

where - derivative time constant.

Mathematically, derivative control is the opposite of integral control. While there are I-only controls, there are no D-only controls. The D control only measures the change in error. D controls do not know where the set point is, so they are often combined with another control method, such as B. Pure P control or PI combination control. D control is typically used in processes where process performance changes rapidly. However, as I control, D control is mathematically more complex than P control. Because a computer algorithm takes longer to compute the derivative or integral than simply linearly relating the input and output variables, adding D control slows down the controller’s response time. Output graph of the D controller with increasing input at time t0

As shown in Figure 2.4 below. As expected, this graph represents the derivation of the step input graph.

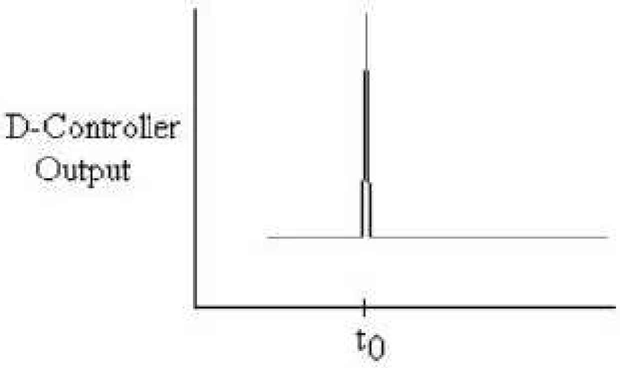

Figure 2.4. D-controller response for step input.

2.1.4 PI-controller

One combination is the PI-control, which lacks the D-control of the PID system. PI control is a form of feedback control. It provides a faster response time than I-only control due to the addition of the proportional action. PI control stops the system from fluctuating, and it is also able to return the system to its set point. Although the response time for PI-controller is faster than the I-only control, it is still up to 50% slower than the P-only control. Therefore, in order to increase response time, PI control is often combined with D-only control. Equation 2.4 shows the mathematical meaning of this controller.

$$(\quad) = \quad (\ (\quad) + \frac{1}{\quad}\int \quad (\quad)\quad) + \quad , \tag{2.4}$$

where - controller gain;

- integration time.

This equation shows that the PI controller behaves like a simplified PID controller with zero derivatives. Alternatively, a PI controller can also be viewed as a combination of P-only and I-only governing equations. The bias term in P-only control is equal to the integral action of I-only control. P-only control is only active when the system is not reaching the set point. When the system is at the set point, the error is zero, and the first term in the equation disappears. The system is then controlled by the I-only part of the controller. If the system deviates from the setpoint again, pure P control is activated. Figure 2.5 below shows a plot of the output signal of the PI controller for a stepwise increase in the input signal at time $_0$. As expected, this chart resembles a qualitative combination of P-only and I-only charts.

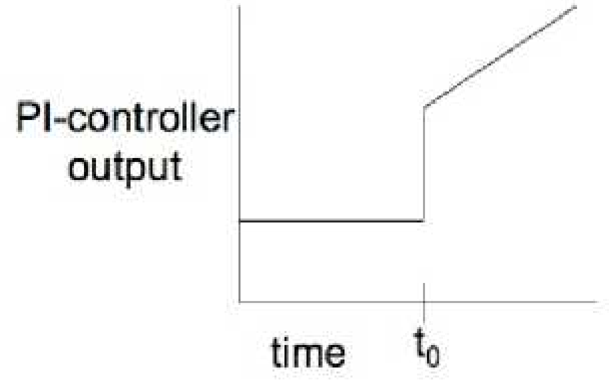

Figure 2.5. PI-controller response to a single step.

2.1.5 PD-controller

Another control combination is PD control, which lacks the I control of the PID system. PD control is a combination of feedforward and feedback control because it acts on current process conditions and predicted process conditions. In PD control, the control output is a linear combination of the error signal and its derivative. PD control involves suppressing fluctuations using proportional control and predicting process errors using derivative control.

As mentioned earlier, PD control relates the controller output to the error and the derivative of the error.

This PD-control behavior is mathematically illustrated in (2.5).

$$(\quad) = \quad (\;(\quad) + \quad —) + \quad . \tag{2.5}$$

This equation shows that the PD controller behaves like a simplified PID controller with zero integral term. Alternatively, a PD controller can also be viewed as a combination of P-only and D-only governing equations. In this control, the purpose of D-only control is to predict the error to increase the stability of the closed-loop system. Due to the lack of an integral term, P-D control is not widely used. Without the integral term, the error in steady-state operation is not minimized. P-D control is typically used in batch pH control loops where there is no need to minimize errors in steady-state operation. In this application, the error is related to the control signal through proportional and derivative terms. Figure 2.6 below shows a plot of the output of the PD controller for a stepwise increase in input at time $_0$. Again, as expected, the chart is a combination of P-only and D-only charts.

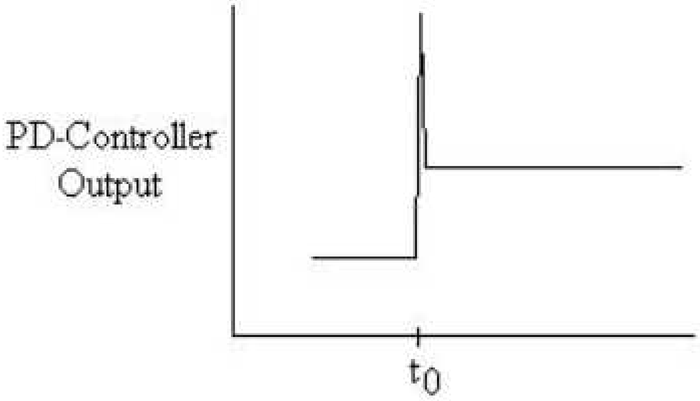

Figure 2.6. PD-controller response for a single step.

2.2. PID-controller structure and its influence on a dynamic system

Proportional-integral-derivative control is a combination of three control methods. PID control is the most commonly used because it combines the advantages of all types of control. These include faster response times from pure P control and reducing zero offset from combined differential and integral controllers. This offset was eliminated by the additional use of the I control. Adding D control greatly improves the response of the controller combination since disturbances in the system are predicted by changes in measurement error. Conversely, the single-use response time is slower than the faster P-only controls, as mentioned earlier. The PID controller, although seemingly the most suitable controller, is also the most expensive. Therefore, it is not used unless the process requires the accuracy and stability of a PID controller. The mathematical meaning of this controllers type is shown in (2.6)

.

$$(\quad) = \quad (\;(\quad) + \frac{1}{\quad}\int \qquad (\quad) \quad + \quad \frac{}{}) + \quad . \tag{2.6}$$

As shown in the above equation, PID control is a combination of all three control types. In this equation, the gain is multiplied by the integral and derivative terms as well as the proportional term because the gain in compound PID control also affects the I and D parts. Due to the use of derivative control, PID control cannot be used for processes with a lot of noise since the noise affects the predictive feedforward aspect. However, PID control is used when the process requires no drift and fast response time. Figure 2.7 below shows a plot of the PID controller output for a stepwise increase in input at time $_{0}$. This graph is similar to a qualitative combination of P-only, I-only, and D-only charts.

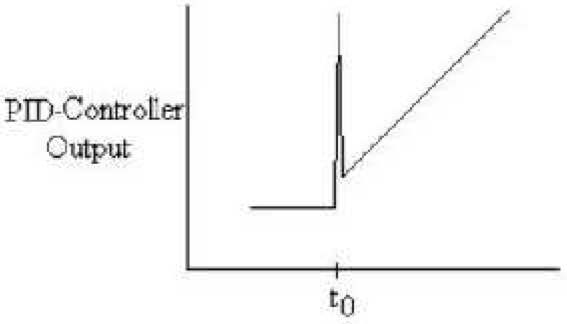

Figure 2.7. PID-controller response to a step function.

2.3. Tuning of PID-controller coefficients by the step response method

Ziegler and Nichols proposed rules Proportional-integral-derivative control is a combination of three control methods. PID control is the most commonly used because it combines the advantages of all types of control. These include faster response times from pure P control and reducing/zero offset from combined differential and integral controllers. This offset was eliminated by the additional use of the I control. Adding D control greatly improves the response of the controller combination since disturbances in the system are predicted by changes in measurement error. Conversely, the single-use response time is slower than the faster P-only controls, as mentioned earlier. The PID controller, although seemingly the most suitable controller, is also the most expensive. Therefore, it is not used unless the process requires the accuracy and stability of a PID controller. The mathematical meaning of this controllers type is shown in (2.7).

.

$$(\quad) = \quad (\quad (\quad) + \frac{1}{\quad}\int \quad (\quad) \quad + \quad \frac{\quad}{\quad}) + \quad . \tag{2.7}$$

As shown in the above equation, PID control is a combination of all three control types. In this equation, the gain is multiplied by the integral and derivative terms as well as the proportional term because the gain in compound PID control also affects the I and D parts. Due to the use of derivative control, PID control cannot be used for processes with a lot of noise since the noise affects the predictive feedforward aspect. However, PID control is used when the process requires no drift and fast response time. Figure 2.8 below shows a plot of the PID controller output for a stepwise increase in input at time $_0$. This graph is similar to a qualitative combination of P-only, I-only, and D-only charts.

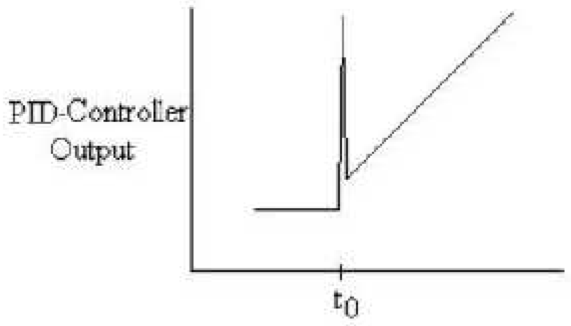

Figure 2.8. PID-controller response to a step function.

For determining values of the proportional gain , integral time , and derivative time , based on the transient response characteristics of a given plant. Such determination of the parameters of PID controllers or tuning of PID controllers can be made by engineers on-site by experiments on the plant.

There are two methods called Ziegler—Nichols tuning rules. In both methods, they aimed at obtaining a 25% maximum overshoot in step response, see Figure 2.9.

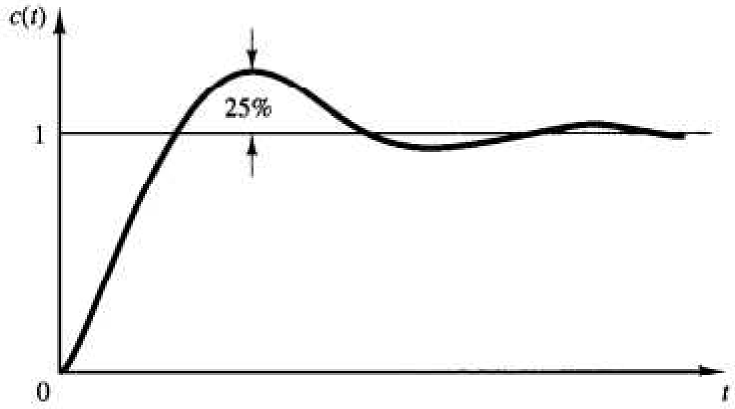

Figure 2.9. 25% overshoot in unit step response.

First method. In the first method, we experimentally obtain the response of the plant to a unit-step input. If the plant involves neither integrator(s) nor dominant complex conjugate poles, then such a unit-step response curve may look like an S-shaped curve, as shown in Figure 2.10. (If the response does not exhibit an S-shaped curve, this method does not apply.) Such step-response curves may be generated experimentally or from a dynamic simulation of the plant.

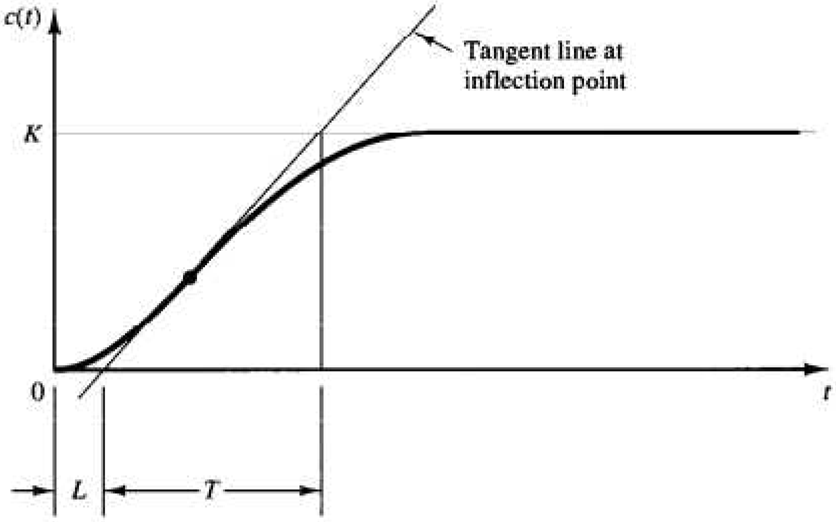

Figure 2.10. S-shaped response curve

The S-shaped curve may be characterized by two constants, delay time L and time constant T. The delay time and time constant are determined by drawing a tangent line at the inflection point of the S-shaped curve and determining the intersections of the tangent line with the time axis and line c(f) = K, as shown in Figure 2.10. The transfer function C(s)/U(s) may then be approximated by a first-order system with a transport lag, as shown in the 2.8.

$$\frac{(\ )}{(\ )} = \frac{-}{+1}, \qquad (2.8)$$

where - the intersection of the tangent line with axis ( );

- delay time;

- time constant.

Ziegler and Nichols' method suggests setting the parameters of a controller according to Table 2.1.

Table 2.1

Type of Controller			
P	—	∞	0
PI	0.9–	$\frac{\ }{0.3}$	0
PID	1.2–	2	0.5

2.4. Tuning of PID-controller coefficients by the frequency response method

Second method. In the second method, we first set = ∞ and = 0. Using the proportional control action only increases from 0 to a critical value of Kcr, where the output first exhibits sustained oscillations. (If the output does not exhibit sustained oscillations for whatever value may take, then this method does not apply.)[6] Thus, the critical gain and the corresponding period are experimentally determined, as shown in Figure 2.11.

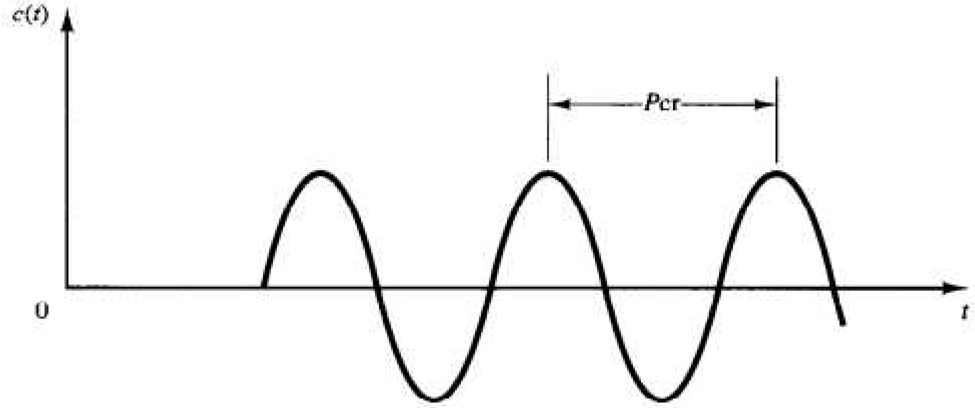

Figure 2.11. Period which depends on critical value

Ziegler and Nichols suggested that we set the values of the parameters according to Table 2.2

Table 2.2

Type of Controller			
P	0.5	∞	0
PI	0.45	$\frac{1}{1.2}$	0
PID	0.6	0.5	0.125

2.5. Conclusion

Proportional-Integral-Derivative (PID) controllers are widely used in control systems to regulate processes and achieve desired setpoints. The implementation of PID controllers can be achieved using various techniques, such as analog electronic circuits, digital microcontrollers, or software-based algorithms. Modern control systems often use digital PID controllers, which allow for precise tuning, adaptive control, and advanced features like feedforward control.

CHAPTER 3. CONTROL SYSTEM DESIGN FOR NUCLEAR REACTOR RODS POSITION

3.1. Analysis of the nuclear reactor rods dynamics without controller

The structure diagram of the system is presented in Fig. 3.1.

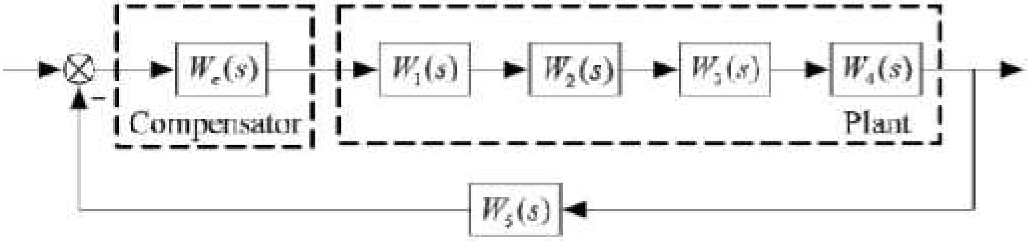

Figure 3.1. Block diagram of nuclear reactor rod position control system

The purpose of this part is the analysis of nuclear reactor dynamics without a compensator unit according to the data in Table 3.1.

Table 3.1

$_1(\ )$	$_2(\ )$	$_3(\ )$	$_4(\ )$	$_5(\ )$	, rad/s		α
2.5	$\frac{4}{(\ +4)}$	0.15	7.5	$\frac{1}{0.15\ +1}$	2	55°	5

The first step is a union of models by a series, parallel, and feedback laws of transfer functions connection.

$$(\ ) = \frac{(\ _1(\ )*\ _2(\ )*\ _3(\ )*\ _4(\ ))}{1+\ _5(\ )*(\ _1(\ )*\ _2(\ )*\ _3(\ )*\ _4(\ ))}. \quad (3.1)$$

After substituting values into (3.1), the transfer function of the uncompensated

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Consultant					402		
S. controller.	M. Dyvnych						
Dep. head	Yu. Melnyk						

system with feedback unit will have the next view:

$$(\ \ ) = \frac{2.5*\frac{4}{(\ \ +4)}*0.15*7.5}{1+\frac{1}{0.15\ \ +1}*2.5*\frac{4}{(\ \ +4)}*0.15*7.5} \Rightarrow \frac{1.688\ \ +11.25}{0.15\ \ ^3+1.6\ \ ^2+4\ \ +11.25}. \qquad (3.2)$$

The next step is defying the stability of the system by defying the zeros and poles of the model of plant (3.2). Zeros and poles are the roots of the nominator polynomial and characteristic equation.

Roots:

$$1.688\ \ \ + 11.25 = 0;$$

$$= -6.6667.$$

Zeros:

$$0.15\ \ \text{\textasciicircum}3 + 1.6\ \ \text{\textasciicircum}2 + 4\ \ \ + 11.25 = 0;$$

$${}_1 = -8.5771 + 0.0000\ \ ;$$

$${}_2 = -1.0448 \pm 2.7663\ \ .$$

Now it is possible to visualize those results to check necessary and sufficient system stability conditions Figure 3.2.

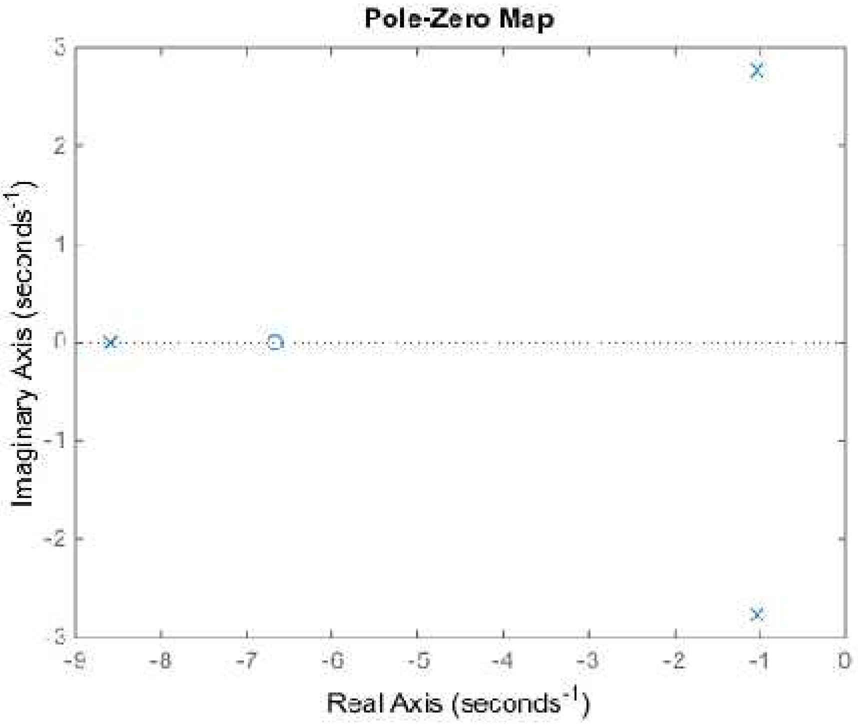

Figure 3.2. Pole-zero map of the system.

According to a necessary and sufficient stability condition, the system is stable if all coefficients of the characteristic equation are positive and roots are placed in the LHP.

To make a conclusion about the possibility of the system to return into an initial state, it’s necessary to make a bode plot in Figure 3.3, simulate the response of the system to a single step in Figure 3.4, and single impulse disturbances.

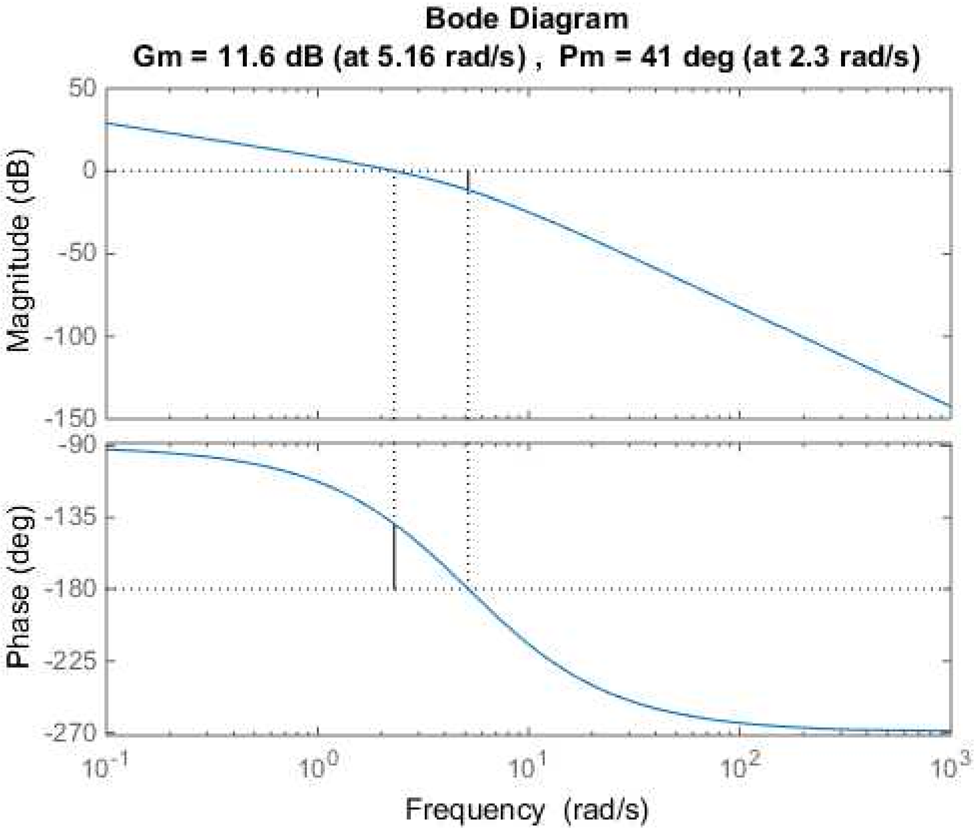

Figure 3.3. Bode plot of the system

As we can see, this system is stable open loop system because all stability margins is positive, in other words magnitude graph crosses the crossover frequency before the phase reached shift in -pi degree.

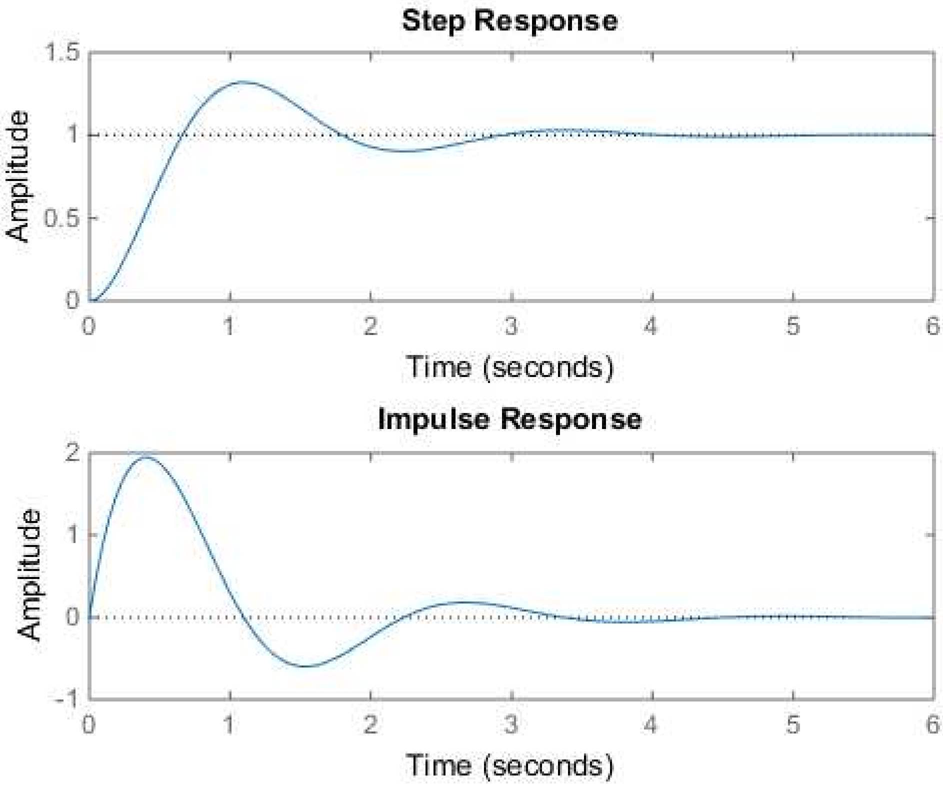

Figure 3.4. Time responses of the system

To get a better understanding of performance estimates, let’s display step response on different graph windows, Figure 3.5.

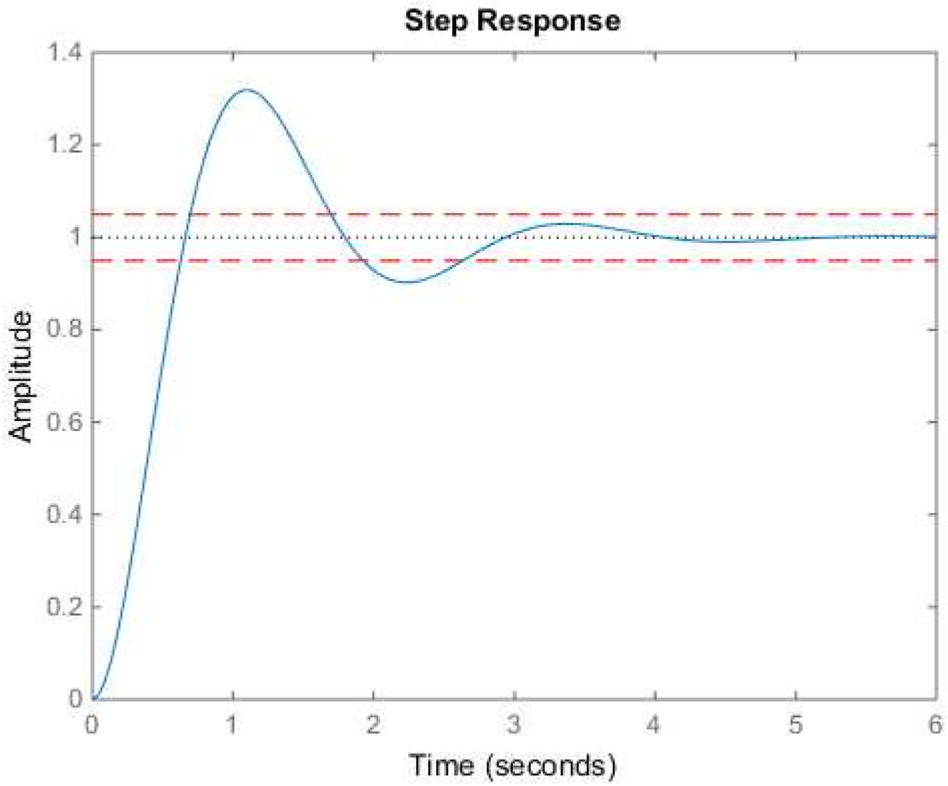

Figure 3.5. Step response of a plane

So, the settling time is 2.6s, the overshoot is 31.9%, the rise time is 0.663s, the delay time is 0.383s, the oscillation factor is 0.78, and the number of oscillations is 2.

The integral quadratic index is equal to 1.48.

3.2 Synthesizing a PD-controller

The transfer function of an ideal PD-controller is:

$$(\quad) = \quad + \quad s. \tag{3.3}$$

A differentiator gain unlimited increase results in an infinite gain at high frequencies. So, in order to restrict the gain at high frequencies, an additional pole is appended in the differential component of the PD-controller.[8] In this case, the transfer function of a real PD-controller can be written as follows:

$$(\quad) = \quad + \frac{}{_0 \quad +1}, \tag{3.4}$$

where $\tau_0$is a very small value (τ_0<<1). If τ_0 is known, so it is necessary to determine two parameters in the synthesis procedure. The synthesis of a PD-controller, first of all, requires the calculation of the phase shift of the controller at a frequency as:

$$\theta = \qquad (\qquad) = -180 \quad + \qquad - \qquad (\qquad) \quad (\qquad); \tag{3.5}$$

$$\theta = -180 + 55 + 116.5651 = 8.2621\ o \quad 0.1442\text{rad}.$$

And the determination of:

$$= \frac{}{|\quad (\quad) \quad (\quad).|}; \tag{3.6}$$

$$= \frac{0.9}{|1.2 \qquad .|} = 0.8214.$$

Then is determined as

$$= \frac{}{|\quad (\quad) \quad (\quad).|}; \tag{3.7}$$

$$= \frac{0.1}{2*|1.2 \qquad |} = 0.0597.$$

Now it is possible to create an ideal and real PID-controller transfer function by substituting coefficients and into a (3.3) and (3.4).

Ideal:

$$(\quad) = 0.8214 + 0.0597s.$$

Real:

$$(\quad) = 0.8214 + \frac{0.0}{0.0 \qquad +1}.$$

The Bode diagram of the designed controller is shown in Figure 3.6

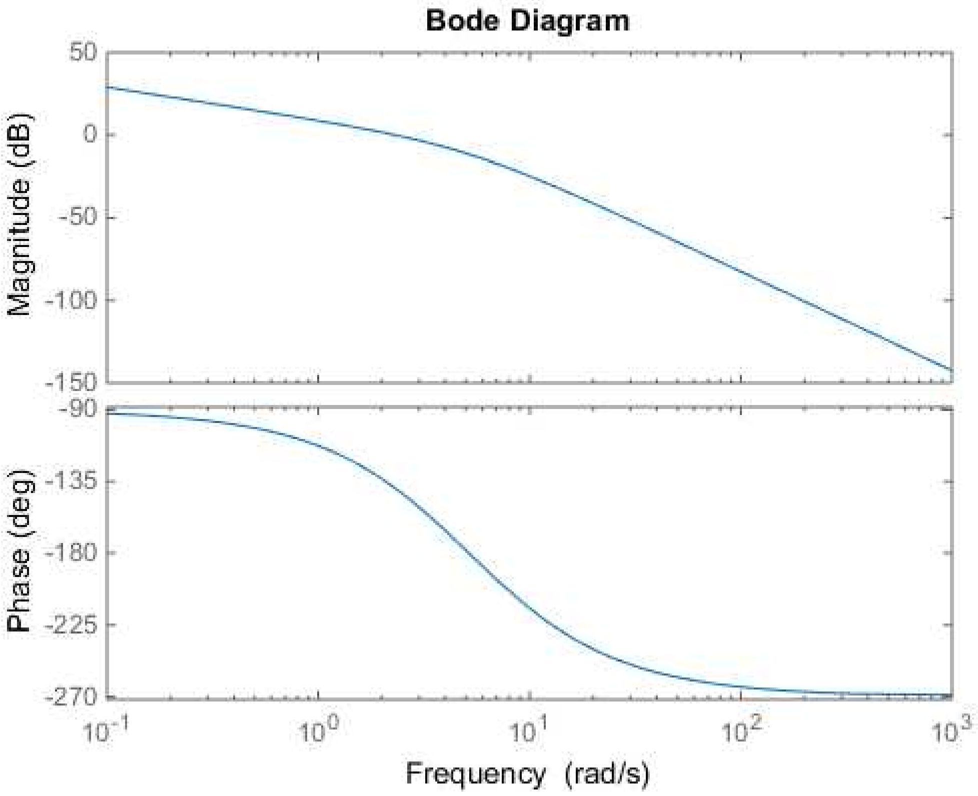

Figure 3.6. Bode plot of a PD-controller

3.3. Analysis of the nuclear reactor rods dynamics with controller

According to the figure 3.2, the compensator is connected in a series way, so the transfer function of the whole system has the next view:

$$= \frac{1234}{1 + 1234 \quad 5}; \qquad (3.7)$$

after substitution:

$$= \frac{0.1008 \quad ^{2} + 2.058 \quad + 9.241}{0.000015 \quad ^{4} + 0.1502 \quad ^{3} + 1.6 \quad ^{2} + 4.672}.$$

To check the stability of the system, it is necessary to check the poles and zeros placement on a complex plane, so Figure 3.7 shows the poles-zeros map.

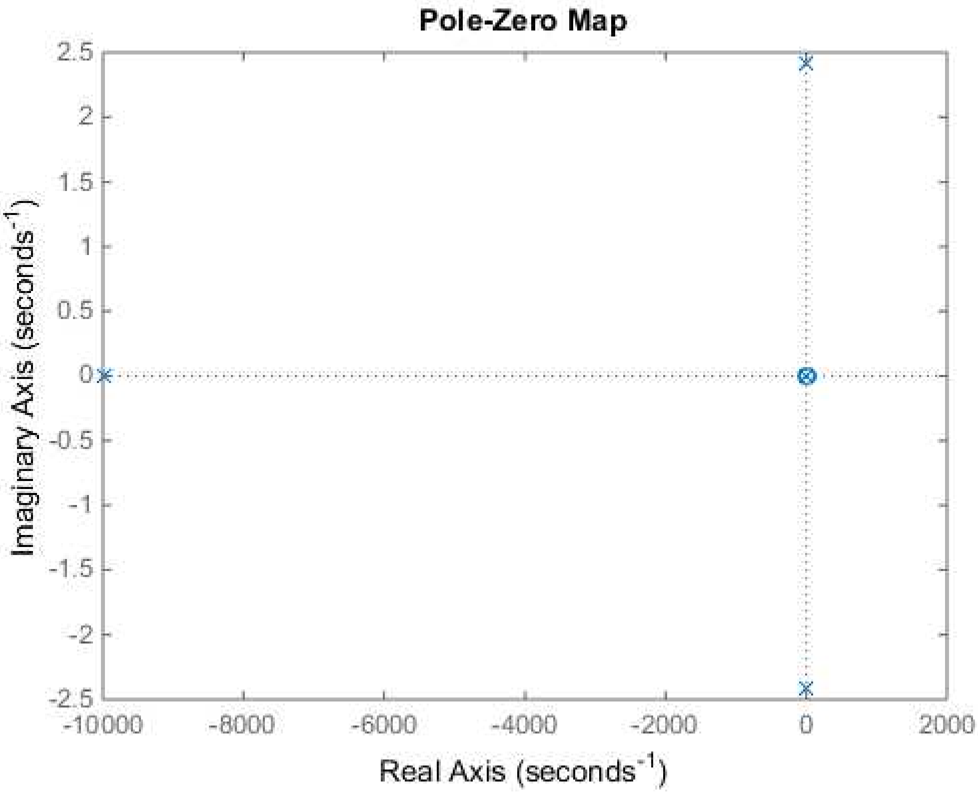

Figure 3.7. Pole zero map of the compensated system

So we have the next result poles are equal to -$-1 * 10^{-4} + 0i$, $-0.000810^{-4} + 0i$, $-0.0002 \pm\ 0.0002i$, and zeros are equal to$-13.7519\ a \qquad - 6.6667$.

According to a necessary and sufficient stability condition, the system is stable if all coefficients of the characteristic equation are positive and roots are placed in the LHP.

To make a conclusion about the possibility of the system to return into an initial state, it’s necessary to make a bode plot Figure 3.8, simulate the response of the system to a single step and single impulse Figure 3.9 disturbances.

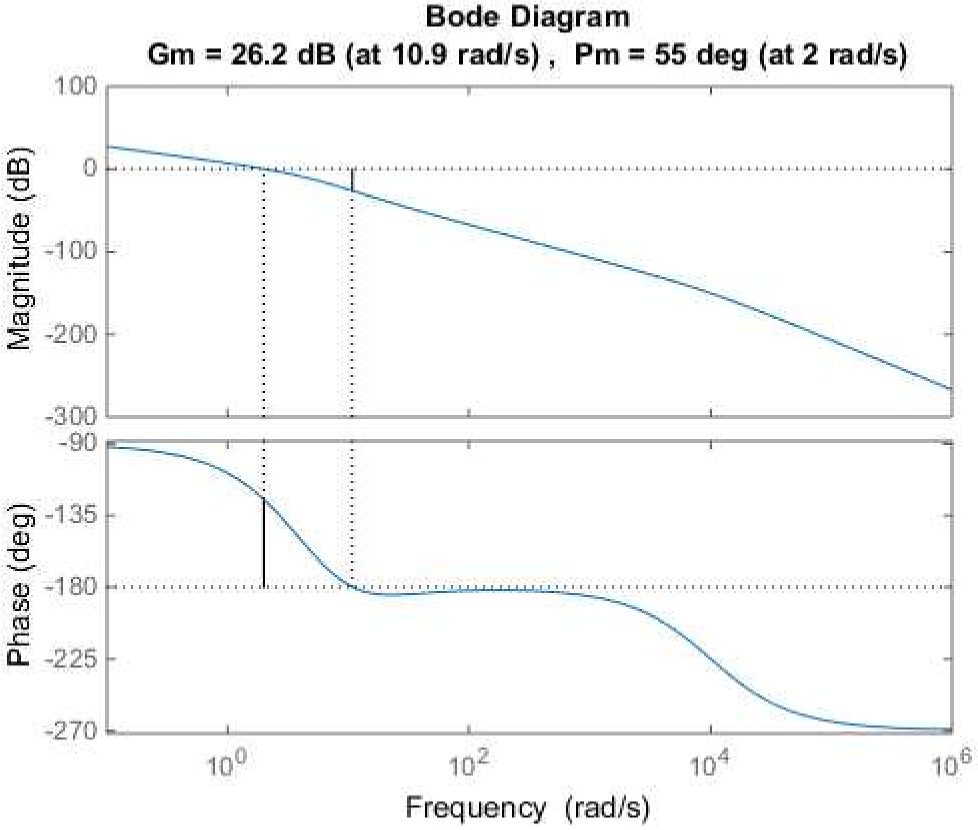

Figure 3.8. Bode plot of the compensated system

Now we can see the difference between compensated and uncompensated systems in the case of stability margins: uncompensated systems have 11.6 dB gain margin and 41° phase margins, in another way in compensated Gm=26.2 dB and Pm= 55°.

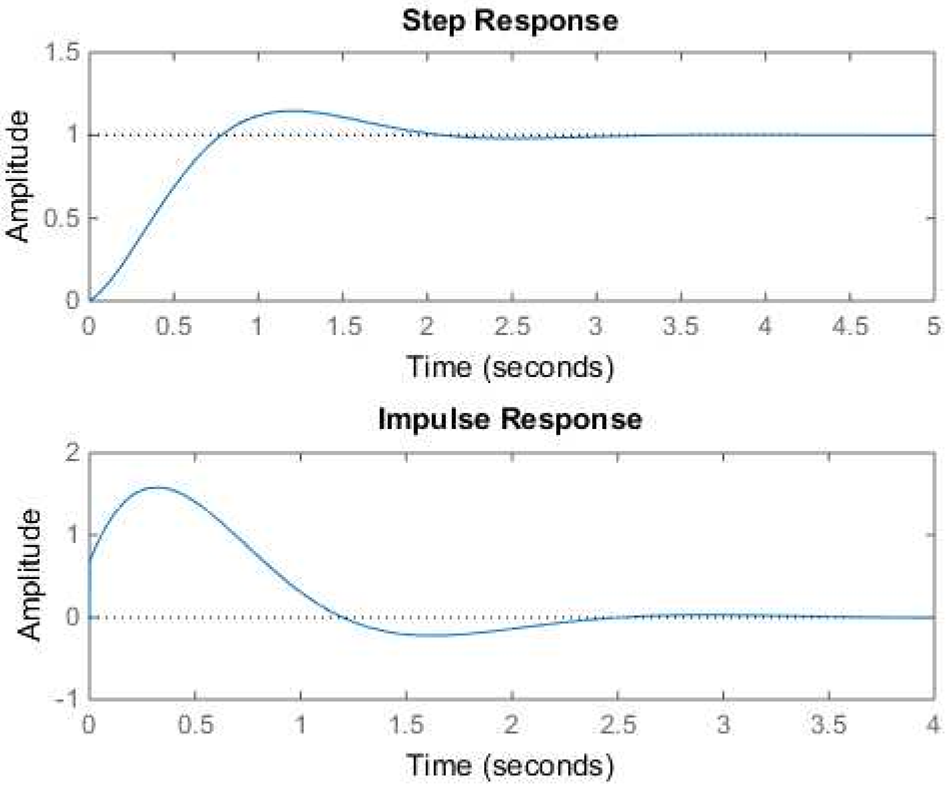

Figure 3.9. Time responses of the compensated system

To get a better understanding of performance estimates, let's display step response on different graph window, Figure 3.10.

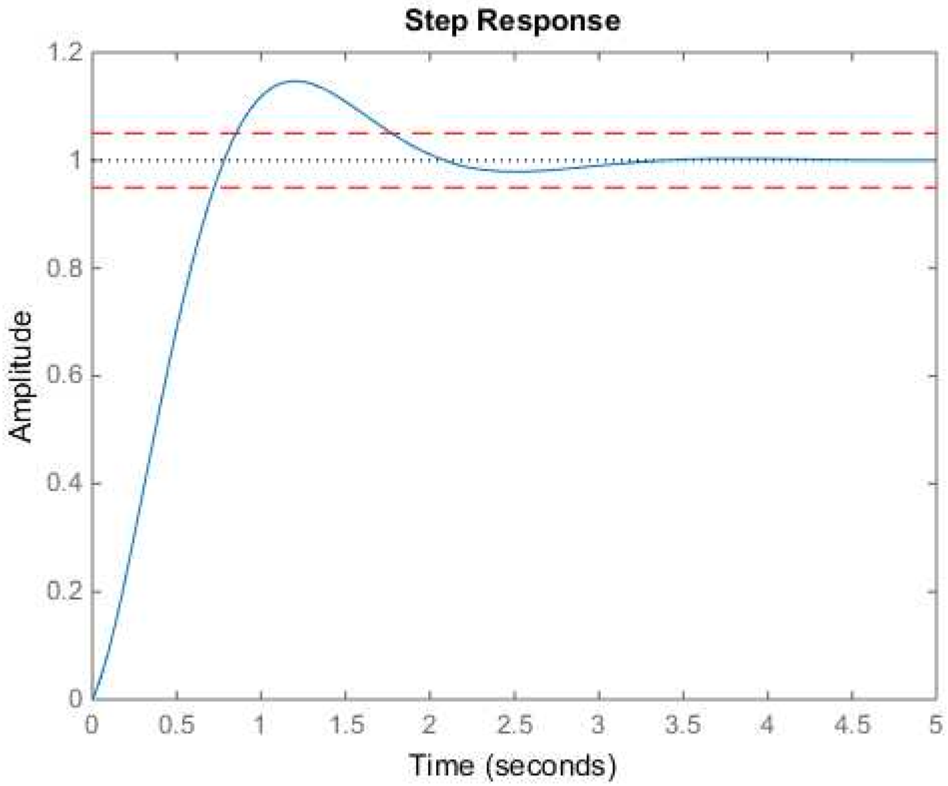

Figure 3.10. Step response of the compensated system

So, the settling time is 1.82s, the overshoot is 15%, the rise time is 0.786s, the delay time is 0.37s, the oscillation factor is 0, and the number of oscillations is 1.

The integral quadratic index is equal to 1.1981.

3.4. Comparison of the uncompensated and compensated nuclear reactor model

To compare the results of compensated by a PD-controller and uncompensated systems, it is necessary to see the behavior to some on a single input, like it was in Figures 3.13 and 3.8, and display them on the one plot Figure 3.11 :

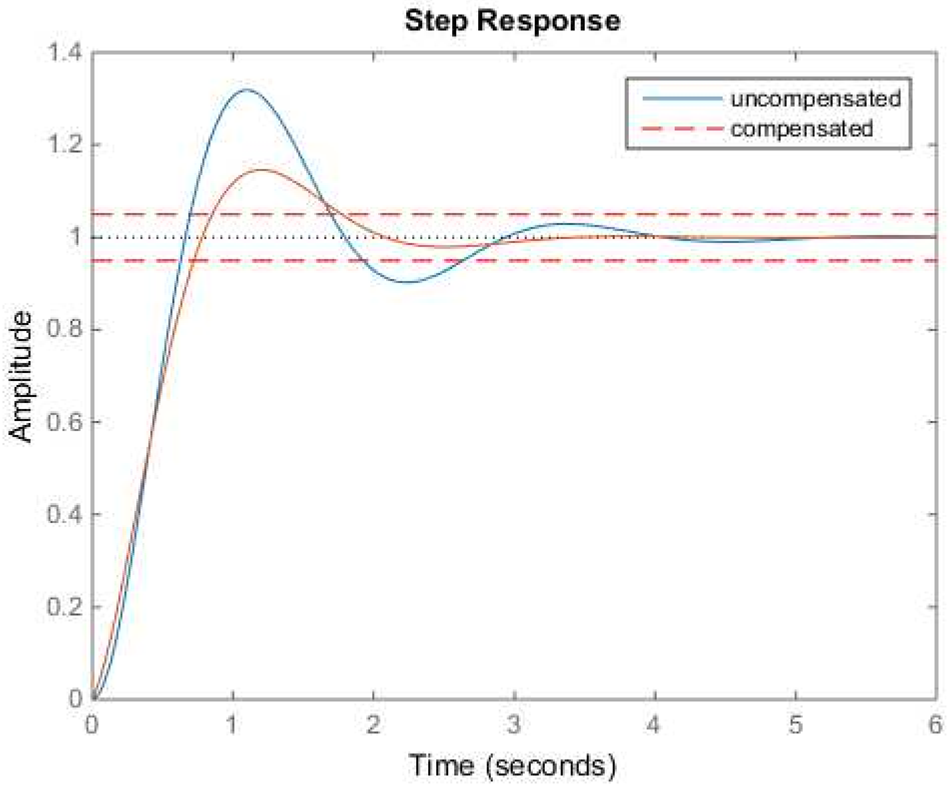

Figure 3.11. Step responses of both systems

At the first look at compensated system performance estimates decreases: the settling time changes from 2.6s to 1.82s and which means that system takes less time to return to an equilibrium state, overshoot from 31.9% become 15% and is caused because amplitude decreasing , rise time and a number of oscillations decreased to 1, oscillation factor become 0, $_2$ changes from 1.48 to 1.1981.

3.5 Conclusion

Application of designed controller improves system in numerous parameters:

stability margins, performance estimates and integral quadratic error. In summary, stability margins assess the robustness of a control system to maintain stability, performance estimates evaluate how well the system meets desired criteria, and integral quadratic error quantifies the cumulative error over time, aiding in the optimization of control system performance. These concepts play a crucial role in control system analysis, design, and tuning

CONCLUSION

It could be possible to say that the controller improve the parameters of those systems, and we look at the performance estimates we can see that the compensated system have much better characteristics also integral quadratic performance index, which shows the integral of the error squared under input signal changes from 1.48 to 1.1981, another moment which should be taken into account that system have higher gain and required stability margins 26.2 dB and 55°, in accordance, this mean that we can give more gain to the system before it gets unstable.

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APENDIX

```
%initial data
s=tf(’s’);
W1=tf([0 2.5],[0 1]);
W2=(4)/(s*(s+4));
W3=tf([0 0.15],[0 1]);
W4=tf([0 7.5],[0 1]);
W5=(1)/(0.15*s+1);
omega=2; alpha=5; tau=0.0001;Pm=55;
% creation model of plant
W1234=W1*W2*W3*W4;
W_fin = feedback(W1234,W5);
W_unc_ol = series(W1234, W5);
% poles and zeros of uncompensated
figure(1)
pzmap(W_fin)
%bode plot
figure(2)
bode(W_unc_ol)
%step and impulse
figure(3)
subplot(2,1,1)
step(W_fin)
subplot(2,1,2)
impulse(W_fin)
%integral quadratic performance index
h2=normh2(W_fin)
% disign of PD controller
[mag, phase] = bode(W_unc_ol,omega),
theta=-pi+Pm/57.296-phase/57.296;
Kp=cos(theta)/mag
Kd=sin(theta)/(omega*mag)
% Creation of transfer function of real PD-controller
Wc=Kp+((Kd*s)/(tau*s+1));
%Connection of controller in the system
W_final=feedback(series(Wc,W1234),W5);
W_cont_plant=series(Wc,series(W1234,W5));
%zeros and poles of compensated system
figure(4)
pzmap(W_final)
%bode plot
figure(5)
bode(W_cont_plant)
```

```
% step and impulse responses of compensated system
figure(6)
subplot(2,1,1)
step(W_final)
subplot(2,1,2)
impulse(W_final)
% integral quadratic performance index of compensated system
h2=normh2(W_final)
%step response of both systems
figure(7)
step(W_fin), hold on, line([0 7],[0.95 0.95],’Color’,’red’,’LineStyle’,’--’),...
   line([0 7],[1.05 1.05],’Color’,’red’,’LineStyle’,’--’),step(W_final), ...
   legend(’uncompensated’,’compensated’)
```