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Steam Temperature Control Based on Modified Active Disturbance Rejection

Master thesis

Study programme: N2612 – Electrical Engineering and Informatics

Study branch: 3906T001 – Mechatronics

Author: **Bc. Nadezhda Ovchinnikova**

Supervisor: Ing. Lukáš Hubka, Ph.D.





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Diplomová práce

Studijní program: N2612 – Electrical Engineering and Informatics

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Autor práce: **Bc. Nadezhda Ovchinnikova**

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2. Make a review of control algorithms used to control this technological part.
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- [2] Hlava, J., Hubka, L., Tuma, L. Multi model predictive control of a power plant heat exchanger network based on gap metric. 2012 16th International Conference on System Theory, Control and Computing, ICSTCC 2012 – Joint Conference Proceedings.
- [3] Opalka, J., Hubka, L., Nonlinear state and unmeasured disturbance estimation for use in power plant superheaters control. (2015) Energy Procedia, 100 (C), pp. 1539-1546.
- [4] Opalka, J., Hubka, L., Nonlinear model predictive control of the steam superheating – Unmeasured disturbance suppression. Proceedings of the 2015 20th International Conference on Process Control, PC 2015, 2015-July, pp. 221-225.
- [5] Sun, L., Hua, Q., Shen, J., Xue, Y., Li, D., Lee, K. Y. Multi-objective optimization for advanced superheater steam temperature control in a 300 MW power plant. Applied Energy, 208, pp. 592-606.

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Abstract

This work is aimed at studying the applicability of active disturbance rejection algorithm and modified active disturbance rejection algorithm for use in controlling the superheated steam temperature in propulsion of thermal power plant. The studies were conducted on the basis of the linearized model of the superheater. The algorithm itself for active disturbance rejection is relevant to study in connection with the possibility of its application for complex technological objects (objects with a large number of parameters). These objects are the superheater, which is part of the superheated steam preparation object, for supplying high-pressure steam to the turbine high-pressure stage. To demonstrate the effectiveness of this algorithm (within the framework of the problem of disturbance rejection) in comparison with the classical PID controller, the results of mathematical modeling are presented. The paper also presents the results of a study of a modified active disturbance rejection method. The need to study this method is due to the high order of the mathematical model of the control object under study. The results of these studies are also given in the work.

Keywords

Active disturbance rejection control, Modify active disturbance rejection control, Superheater, Coal-fired power plant, Steam turbine, Superheated Steam Temperature

Abstrakt

Tato práce je zaměřena na studium využitelnosti algoritmu aktivního odstranění vlivu neměřené poruchy a modifikovaného algoritmu aktivního odstranění vlivu neměřené poruchy aplikovaného na řízení teploty přehřáté páry v tepelné elektrárně. Studie byly prováděny na základě linearizovaného modelu přehříváku. Studium algoritmu aktivního odstranění vlivu neměřené poruchy je relevantní v souvislosti s možností jeho aplikace pro komplexní technologické procesy (procesy/soustavy s velkým počtem parametrů). zde je studovaným objektem přehřívák, který je součástí technologického uzlu přípravy přehřáté páry pro dodávku vysokotlaké páry do vysokotlakého stupně turbíny. Efektivnost obou algoritmů aktivního odstranění vlivu poruchy v porovnání s klasickým PID regulátorem je demonstrována na výsledcích simulací. Podrobnější analýza obou metod je nezbytná zejména v případě, kdy řídíme systém vyššího řádu jako například v případě přehříváku. Výsledky analýzy jsou také v práci uvedeny.

Klíčová slova

Řízení aktivně odstraňující vliv poruchy, Modifikované řízení aktivně odstraňující vliv poruchy, Přehřívák, Uhelná elektrárna, Parní turbína, Teplota přehřáté páry

Contents

List of Abbreviations	8
1 Introduction	9
2 Description of the power plant	11
2.1 Structure of steam turbine.....	12
2.2 Model description of steam superheating.....	16
2.3 Power plant control metods	18
3 Active disturbance rejection control (ADRC).....	22
3.1 ADRC Control Design	22
3.2 Simulation and analysis ADRC.....	26
3.2.1 First-order ADRC	26
3.2.2 Second-order ADRC	29
3.2.3 Alternative performance of the ADRC algorithm	33
3.3 Practical use ADRC.....	35
4 Modified Active disturbance rejection control design for high-order system.....	37
4.1 Analysis and tuning procedure of MADRC	38
4.2 Numerical simulation.....	43
4.3 Cascade control for MADRC-PI and PID-PI	47
5 Conclusion.....	52
References	54

List of Abbreviations

SST	Superheated Steam Temperature
CPP	Coal-fired Power Plant
ADRC	Active Disturbance Rejection Control
MADRC	Modify Active Disturbance Rejection Control
ESO	Extended State Observer
SFCL	State-Feedback Control Law

1 Introduction

Electricity is a modern source of life. It is impossible to imagine the life of a modern person without electricity. Street and office lighting, traffic control, food production, telephone communications and many other aspects of life are almost entirely dependent on electricity. Electricity demand is increased every day. This is not only because of rapid urban development and population increase, but also because of production capacity growth. High-tech production minimizes manual labor, thereby increases the amount of electricity consumed.

Due to the growing demand market, the electricity generation market is developing and is ready to offer the consumer various technologies for obtaining a valuable resource: hydropower, thermal power plants, solar power plants, wind generators, nuclear power plants and so on.

Historically, the largest electricity suppliers have been and remain thermal power plants. The power plant technology that has been tested over the years has proven itself and meets the needs of most consumers.

In second place are hydroelectric power stations. There is a misconception that hydropower is currently not actively developing. This is not true, the vector of hydropower development is not as global as before. Now small generation projects, which are based on water objects - small hydropower plants, are gaining popularity. They allow providing local industrial facilities and small settlements with electricity and relieve the main hydraulic structures (large hydroelectric power plants).

The same tendency is observed on the combined heat and power plants market – it is more relevant nowadays to build small boiler houses for individual subjects. It is also connected with the development of the resource base - liquefied gas is gaining more popularity. Development of nuclear energy is also worth noting. But the pace of nuclear energy development is significantly lower in comparison with other segments. This is due to the significant knowledge-intensive and higher risks. Wind and solar power stations are also gradually entering into consumer life. In addition to large research projects, small solar electrical plants, which can provide energy for subsistence farming, are also gaining popularity.

The overall positive trend in the development of energy market and the availability of alternatives to classical thermal power plants solutions cannot, unfortunately, completely replace them. Therefore, there is the task of improving the performance of classical thermal power plants by automating production. The introduction of control systems will allow detailed investigation of

the power plant technological processes and will provide an opportunity not only to increase the efficiency of the components and assemblies, but also to reduce the costs of their maintenance and repair. Precise control algorithms will ensure comfortable conditions for all devices in real time. All these actions will allow extending the life cycle of expensive and difficult to manufacture the main components of the power plant - steam turbines and power generators.

The steam turbine is driven by the flow of superheated steam and, at the expense of the generator, converts the mechanical energy of rotation into electrical energy. Important parameters when working with superheated steam are its temperature and pressure. In the framework of the thesis will be considered the temperature control of superheated steam. Maintaining a stable temperature of the working environment (superheated steam) during the operation of the steam turbine and reducing sensitivity to disturbances is one of the key tasks of the control system of the propulsion of a thermal power plant. The methods of solving this problem will be discussed in this research work.

The second chapter describes the propulsion of a thermal power plant, its key features, the process of selecting a mathematical model of the superheated steam system, and provides data on the methods studied for controlling the temperature of superheated steam.

The third chapter describes the process of synthesizing the method of active disturbances rejection. The chapter also presents the results of mathematical modeling of the control process and a comparative analysis of methods effectiveness.

The fourth chapter describes the application of the method of modified active disturbances rejection as applied to the problem of controlling the temperature of superheated steam and the results of practical studies of its effectiveness in comparison with the classical control method.

2 Description of the power plant

In the modern world, the energy market is beginning to be actively replenished with new technologies and efficient alternative solutions in the field of electric power generation. Wind generators, solar panels, geothermal sources, tidal hydroelectric power plants, nuclear power plants are no longer distant prospects. These technologies are being more and more implemented not only as experimental systems, but they also create real alternative to classical thermal power plants.

One example is a photovoltaic plant with a total capacity of 290 MW, located in Yuma, Arizona, USA. The structure of the solar power plant includes 5,200,000 solar cells [1]. In the European part of the world, one of the largest solar energy projects is a photovoltaic power plant with a total capacity of 166 MW, located in the commune of Schipkau, Brandenburg, Fig. 2.1 [2]. The largest wind power plant in the world is a project that is implemented in the water area of Liverpool (United Kingdom) - Burbo Bank (capacity 346 MW) [3]. Building a solar power plant at the site of a former quarry was an excellent solution, since recultivating the soil after quarrying would give less benefit, (cultivation of agricultural crops or capital construction in this area would be associated with significant risks).



Figure 2.1 – Solarpark Meuro photovoltaic station



Figure 2.2 – Burbo Bank wind farm

At the moment, progressive technologies cannot act as a full-fledged alternative of traditional power generating complexes. Thermal power plants, which were founded back in 1882, today are the main source of electricity. Years of operating experience did not solve all the problems associated with the optimization and control of power units. Therefore, the study of new, more efficient control algorithms is an urgent task that requires the introduction of modern approaches and the use of advanced computer equipment.

The implementation of advanced control algorithms will not only increase the service life of power plant equipment, but also reduce the amount of fuel resources used in the process (oil, fuel oil, coal, liquefied gas, etc.). This problem is associated with the price rise of classical resources on the market (the development of mining technologies and the reduction of the reserves of readily available minerals inevitably leads to a higher cost of the final resource).

2.1 Structure of steam turbine

The power plant is an important and crucial industrial object. The process of generating electricity is a set of complex technical installations that are able to maintain their performance

under variable consumption load that is associated with uneven daily loads and changes in the internal parameters of the units (pressure, temperature, etc.). The most technically complex and demanding unit of a power plant is its propulsion — a steam turbine and a complementary system for preparing superheated steam.

A simplified scheme of the power plant is shown in Figure 2.3:

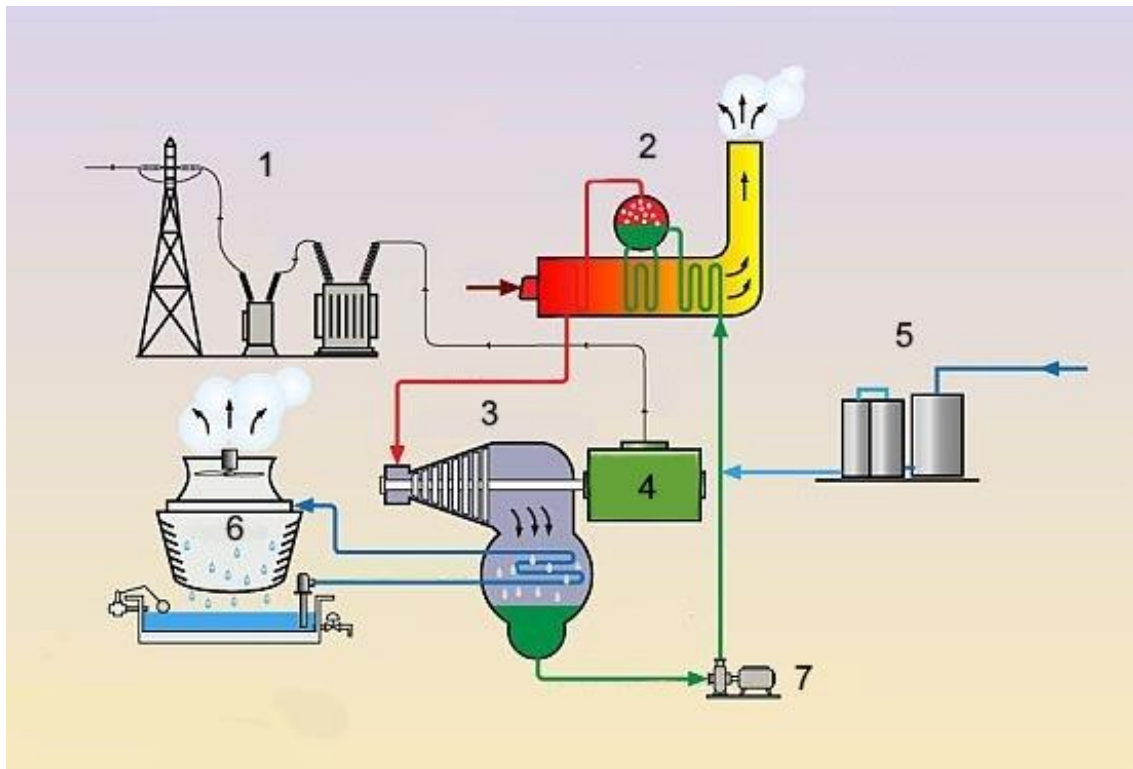


Figure 2.3 – Scheme of operation of the condensing turbine

1 – substation; 2 – boiler unit; 3 – steam turbine; 4 – generator; 5 – water treatment plant;
6 – cooling tower; 7 – circulation pump.

In this diploma thesis, algorithms for controlling the superheat steam temperature (SST) in the power point of the power plant are developed. The enlarged scheme of the propulsion is shown in Figure 2.4:

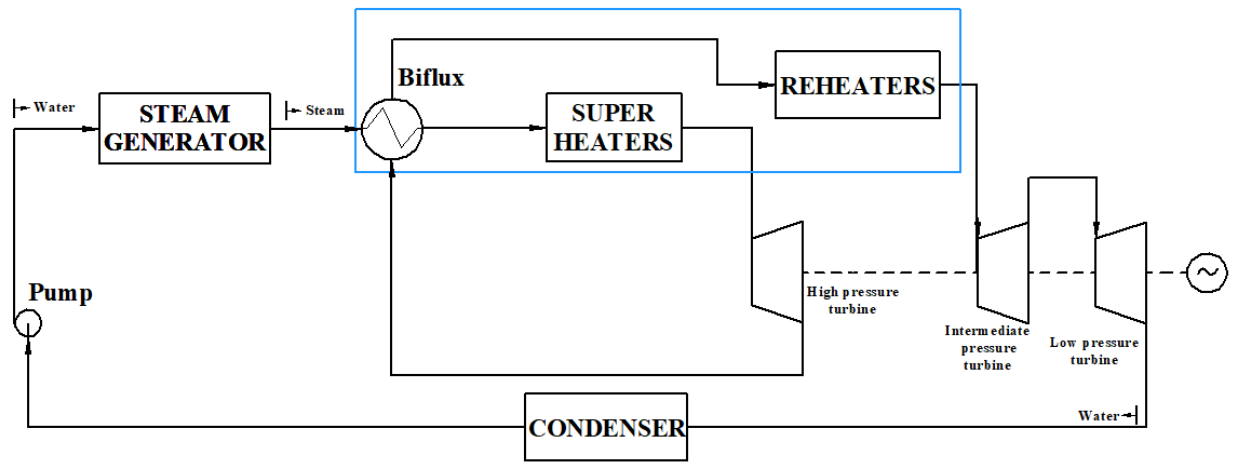


Figure 2.4 – Structure propulsion

Components of the power point which are of particular interest in terms of control, are highlighted with a blue rectangle in Figure 2.4.

Superheater is the superheated steam supply unit to the high pressure component of the turbine.

Reheater is the reheated steam supply unit that is used in the components of medium and low pressure turbine.

Figure 2.5 shows the structure of steam turbine.

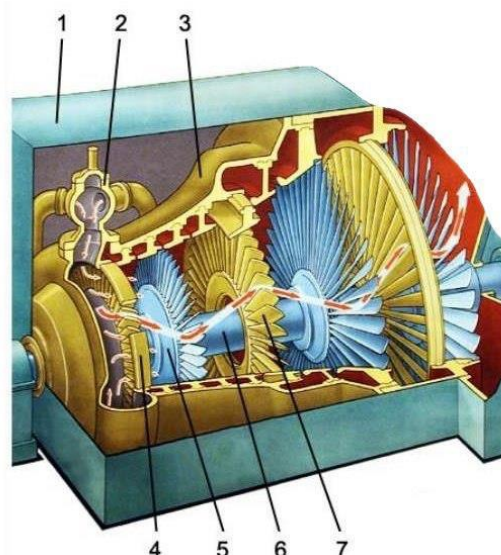


Figure 2.5 – High pressure stage of the turbine

1 – casing; 2 – steam distribution device; 3 – turbine housing; 4 – nozzle apparatus; 5 – rotor disk; 6 – turbine shaft; 7 – stator disk.

The most critical component of the steam turbine is the high pressure component. Its performance largely determines the quality of the entire power plant. Temperature decrease of the steam, which enters the high-pressure component, entails the appearance of water (condensate) in the turbine mechanism, which in turn significantly reduces the efficiency of the entire power plant and leads to the failure of the entire turbine unit. The allowable temperature fluctuation range is about 5 degrees Celsius [4]. Maintaining temperature in the specified range allows keeping the working capacity and efficiency of the mechanism.

It therefore means that the task of maintaining the temperature at the outlet of the superheater (at the entrance to the high pressure stage of the turbine) is extremely important and requires increased attention from development engineers of the control system. In the future, the resulting structure of the control system can be applied to control other temperature circuits inside the propulsion.

More details about the superheated steam supply unit to the high pressure component of a steam turbine can be found in Fig. 2.6.

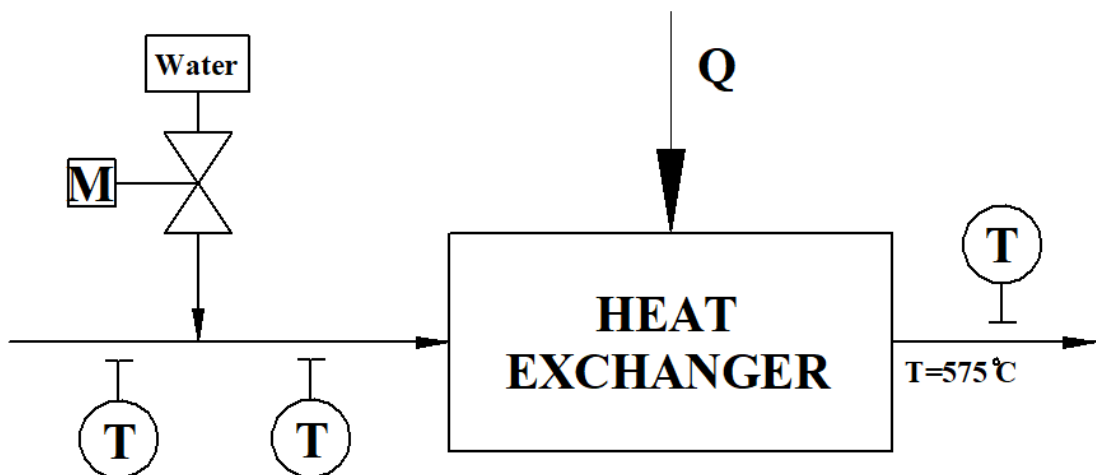


Figure 2.6 – Superheated steam supply unit to the high pressure

A superheater is a device that is designed to superheat steam, that is, raises its temperature above the saturation point. The principle of superheater operation: the incoming flow is first cooled to a certain temperature using a spray valve for supplying water (controlling the degree of valve opening); then, using a heat exchanger, the flow is heated to the required temperature by supplying external heat from the coal boiler of the coal-fired power plant (CPP).

The aforementioned principle of superheater operation identifies the main problems in the development of the control system:

- variation in temperature and pressure feedwater;
- variation in temperature of the external heat flow from the coal boiler of CPP.

These disturbances are random in nature and are categorized as immeasurable. This feature must be taken into account when choosing control methods.

Considering all the physical features of the superheater, two control loops can be distinguished inside it: the first loop is the circuit for maintaining the temperature at the inlet into the superheater by controlling the spray valve; second circuit – loop of temperature control at the superheater outlet with controlling the temperature of the input stream.

Thus, a cascade control system with distinguish of internal and external control loops will be investigated. Also, the system will take into account the influence of active non-measurable perturbations.

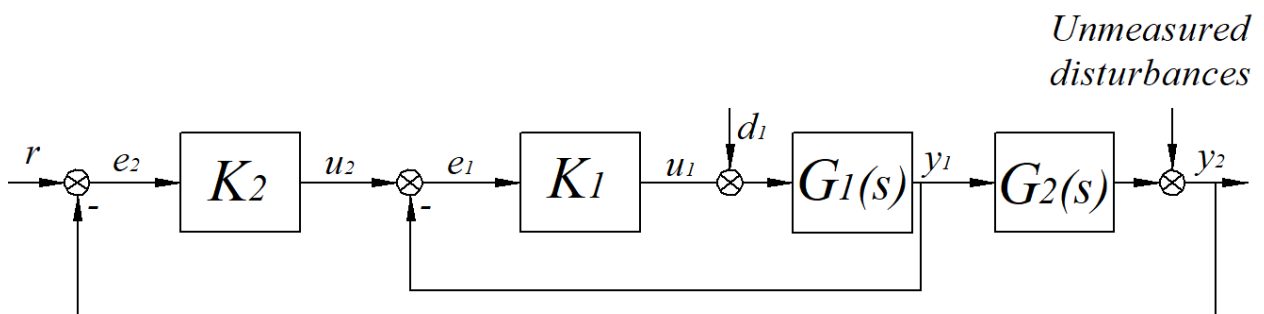


Figure 2.7 – Structure of cascade control of SST

2.2 Model description of steam superheating

Obtaining a mathematical model of a superheater is a complex research task. It is almost impossible to obtain an exact mathematical model of any real physical process.

Multiple factors affecting the behavior of the superheater, create too much non-linearity of physical processes. This task is solvable, the majority of real technological processes and objects are described by non-linear models. This form of description is inconvenient when creating regulators. Therefore, when solving applied problems, the method of transition from a nonlinear model to its linear analogue — linearization — is used. Linearization is carried out in the vicinity

of the selected working point (the point of study of the behavior of the system). The error that occurs when working with a linear analogue of a nonlinear model is called linearization error.

The control algorithms developed for linear models are in most cases suitable for working with nonlinear objects. This possibility is confirmed with practical research and describes the recommended conditions for regulators usage that were obtained based on linear models.

The mathematical model of the superheater can be obtained using various methods, such as: heat balance method [5] [6], finite difference method (multi-objective genetic algorithm) [4], partial differential equations (discretization by dividing the heat exchanger into several control volumes) [7].

Heat balance method is relied on obtaining a mathematical model of the object based on the input and output values of the superheater parameters. This method has limited accuracy and does not take into account all nonlinearities that arise.

Finite difference method (multi-objective genetic algorithm) based on obtaining step responses of a real superheater (operating power plant) with their subsequent analysis and comparison of data from a mathematical model [4]. This method gives a good accuracy and an adequate mathematical model of the superheater. The main disadvantage of this method is its high cost and large work efforts.

In practice, this method was used, for example, in research at the existing 300 MW power plant in Shanxi Province, China [8] to obtain a superheated steam control model. As a result of these studies, an approximated linear model of open-loop transfer functions was obtained:

$$G_1(s) = \frac{-1.726}{(19.775s + 1)^2}, \quad (2.1)$$

$$G_2(s) = \frac{1.474}{(28.774s + 1)^4} \quad (2.2)$$

Partial differential equations (discretization by dividing the heat exchanger into several control volumes), allows getting an adequate model of the superheater and its linear interpretation that was applied in the context of our study [9].

As a result of studying the Euler equations for an isothermal system, that was taken as the basis for obtaining a mathematical model of a heat exchanger, and analyzing temperature processes in a single heat exchanger tube, a mathematical model of the entire heat exchanger was obtained.

In order to apply the obtained mathematical model to study the heat exchanger temperature control algorithms, studies were carried out on the model linearization in the vicinity of the working point. The result of these studies are two transfer functions. $G_1(s)$ and $G_2(s)$, describing the dynamics of processes in the heat exchanger:

$$G_1(s) = \frac{-1.5}{(3s + 1)^2} \quad (2.3)$$

$$G_2(s) = \frac{1.6}{(20s + 1)^6} \quad (2.4)$$

$G_1(s)$ – second-order transfer function describing the process of cooling water before the superheater.

$G_2(s)$ - the transfer function of the sixth-order describing the process of superheater operation..

Taking into account all the features of the mathematical model, the regulator, which is being developed, must provide sufficient robustness in order to minimize the previously described non-measurable perturbations (to solve the problem of maintaining the temperature in a given range).

2.3 Power plant control methods

Power Plant Process Control is a complex task. It consider the following:

- features of the operation of the power plant elements caused by spontaneous changes in the parameters of the working environment, and described as immeasurable perturbations (change in the amount of input heat associated with the nonlinearity of the process of burning coal)
- change in supply (cooling) water pressure;
- control speed of the opening position of the (cooling) water delivery valve.

The problem of automatic control of superheated steam temperature, solved by classical control methods (PID, PI regulators) does not provide the necessary quality of transients. This fact led engineers to begin work on finding new control algorithms that allow solving an extended, more complex problem.

A progressive control method is the model predictive control [10], [11]. This method has been widely used in the control of petrochemical plants and, therefore, has earned attention to the possibility of its usage to control thermal power plants.

The solution of temperature regulation task in a system of multiple heat exchangers is possible to obtain using a predictive control model.

The essence of the predictive control method consists in drawing up the trajectory of the output variable change in a given time interval based on the predictive mathematical model of the control object. The quality of control, in this case, is determined by the accuracy of the mathematical model and the duration of the desired prediction horizon. The prediction horizon is determined by the technological parameters of the object under examination, by studying all possible modes of system operation and transients in it. The optimal selection of qualitative indicators ratio of the transition process and the requirements for the prediction horizon can ensure the proper quality of control processes in the system, taking into account the computational capabilities of the control system.

The generalized structure of the regulatory system based on the predictive control method is depicted in Figure 2.8:

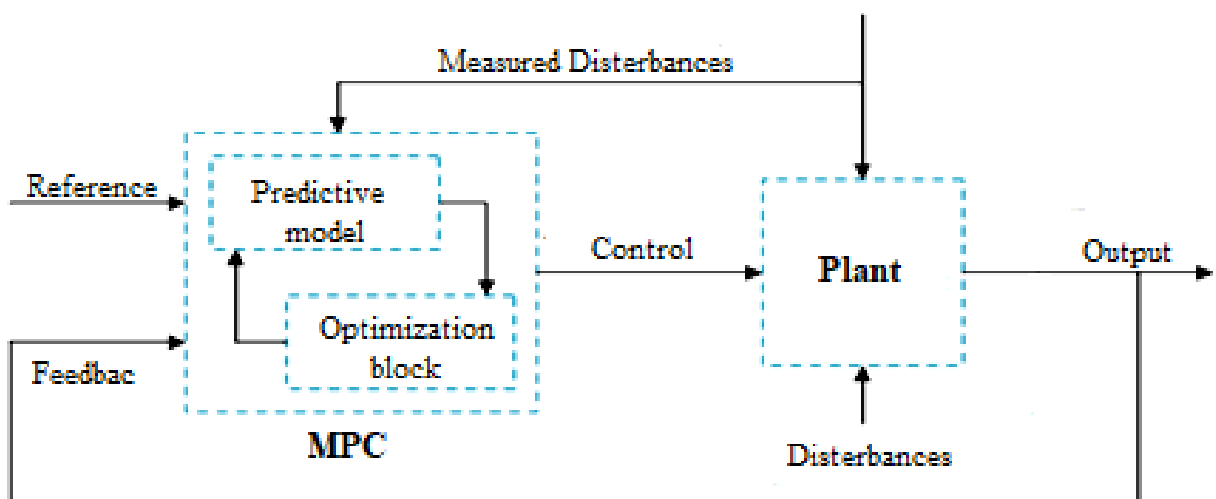


Figure 2.8 – Structure of the regulatory system based on the predictive control method

Unlike classical linear regulators, the model of predictive control takes into account resource constraints, the values of which are determined by the characteristics of real actuators and measuring devices.

Positive experience in solving the problems of controlling the power output of a power plant is presented in a number of research projects.

As an example, the results of the paper "Model predictive control of the thermal power plant generating unit output" are given in [12]. This article is interesting because of its similarity with the article [10] in the applied approach of obtaining a mathematical model of the control object, based on which a mathematical model of the system under study is taken. The non-linear model of the power unit was obtained from the vector equations of balance mass, energy and pulse balance for the elements of the steam boiler, presented in the form of recuperative heat exchangers, as well as from the material balance equations of the steam turbine sections and the equation of its rotational motion. Linear model of power unit is obtained from non-linear model with the help of linearization procedure "in small" range regarding nominal operation mode of power plant and with a number of assumptions.

The main control effect in regulating the power unit is the opening position of the turbine control valve.

Another example of usage predictive control method is the scientific work "Predictive control and adaptive control in the functional subsystems of heat power APCS" [13]. In this paper, studies of the application of the predictive control algorithm for the correction of the PID coefficients of the regulators of real subsystems of a thermal power plant were conducted. The research results have received a practical application in the implementation of control algorithms at the Penza CHP-1.

Studies on the use of predictive models prove the prospects of the research. In the course of the work, the algorithms of classical and modified suppression of active non-measurable perturbations that have similar principles of constructing a control model with a predictive control model (using an observing model and estimating the prediction of the output variable) were studied.

It should be noted that the quality of the control system is determined by the computing power of the controller (during the sampling step, the controller must solve a system of differential equations to predict the control signal). Taking into account the dynamically developing market of computer technology and microprocessor technologies, the introduction of models based on

mathematical modeling of control objects in the field of automated regulation of technological processes using DCS systems is a promising direction in the development of control theory.

In addition to the predictive control model, modern research was conducted for a number of other methods: neuro-PID [14], internal mode control (IMC) [15], self-adaptive PID [16], fractional-order PID [17] and radial basis function PID (RBF) [18]. Advanced control strategies, such as fuzzy logic control [19], fuzzy model predictive control [20], dynamic matrix control (DMC) [21], neuro-fuzzy generalized predictive control (GPC) [22] and predictive control with direct link [23]. The use of these algorithms has a number of significant limitations:

- These control strategies have a greater computational complexity, which makes it difficult to implement them on a distributed control system (DCS) platform.
- Some control strategies are highly dependent on an exact mathematical model of steam superheating, while an exact model of steam superheating is very difficult to obtain, and changes depend on operating modes.

Algorithms that are able to suppress unmeasurable perturbations are less studied. Such methods allow you to control processes with an inaccurate mathematical model and the presence of immeasurable disturbances (the high robustness of such algorithms allows you to implement them when working with real technological objects). Such methods are called – active disturbance rejection control (ADRC) and modify active disturbance rejection control (MADRC). The results of studies of the effectiveness of such algorithms for solving the problem of controlling the temperature of superheated steam supplied to a high-pressure stage of a power plant are given below.

3 Active disturbance rejection control (ADRC)

Active disturbance rejection control is a relatively new method, which has already received recognition as one of the most popular control methods with active disturbance compensation. Jingqing Han first proposed it in the 1990s [24]. ADRC [25] - [28] is an alternative to PID and has established itself as a method with simple implementation and good performance. It is designed specifically for systems that have immeasurable perturbations and uncertainties that can significantly affect the quality of system performance. As mentioned in chapter 2, the superheater relates to this type of object.

ADRC was originally proposed as a combination of a tracking differentiator plus an Extended State Observer (ESO) with a non-linear form. [29]. However, in order to simplify the analysis of the method, the parameterized linear ADRC proposed in [28], which uses linear gains instead of nonlinear gains, will be considered, and setting is just the bandwidth configuration.

This chapter describes the structure of the ADRC, presents its analysis and modeling, and also presents data on the practical application of ADRC.

3.1 ADRC Control Design

Active disturbance rejection control is a control method that has gained popularity in recent years. The main part of the ADRC is extended state observer. The advanced observer is used to estimate the general disturbance of the system and exclude it from the control signal before it affects the system [28].

After compensation of the disturbance, the process takes the form of cascade integrators, on the basis of which the PD/PID controller is developed. Rough model is enough for studies, since all modeling errors are processed as a perturbation (this decision is justified, given the key feature of the ADRC - the ability to process immeasurable perturbations, which include the inaccuracies of the mathematical model of the object under study).

The general structure of the ADRC is shown in Figure 3.1.

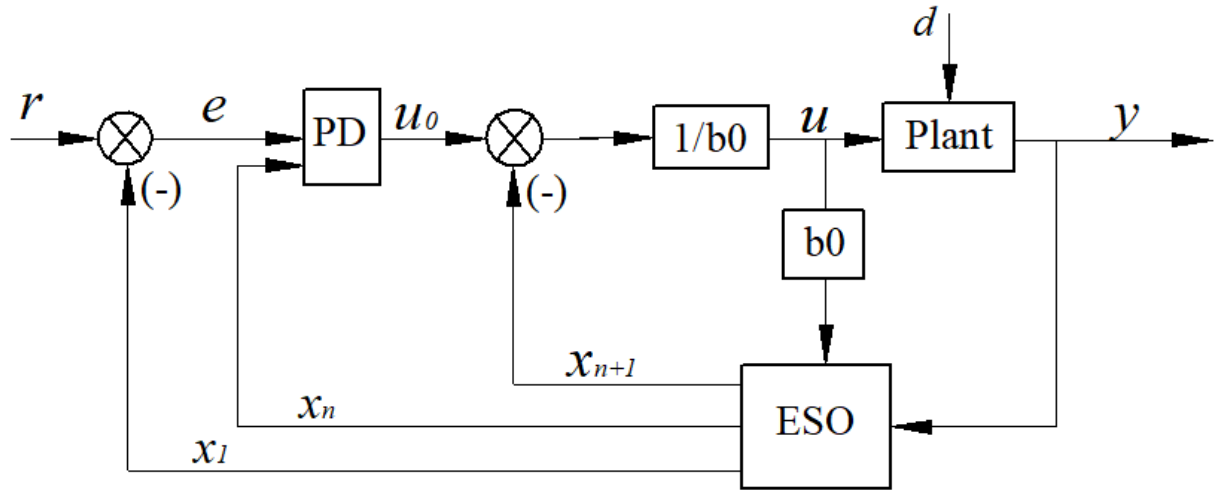


Figure 3.1 – General structure of the ADRC

Consider the n-th order system:

$$y^{(n)} = bu + f(y^{(n-1)}, y^{(n-2)}, \dots, y, u, d) \quad (3.1)$$

where, y is the system output, u – controller output, $b = b_0 + \Delta b$ – a process parameter, with an estimated value b_0 and unknown part Δb , f - a general disturbance, including unknown dynamics and disturbances, d is an external disturbance.

The operation of the ADRC algorithm is based on an estimate of the unknown generalized perturbation (f). For this purpose, an ESO observer is used, which allows, with sufficient for the operation of the algorithm accuracy, to perform approximate estimate task.

If the observer is stable and corresponds to the system, then x_1, x_2, x_n, x_{n+1} will be an accurate estimate $y, \dot{y}, y^{(n-1)}, \dots, f$.

Equation (3.1) can be written:

$$\begin{cases} \dot{x} = Ax + Bu + E\dot{f} \\ y = Cx \end{cases} \quad (3.2)$$

where,

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_n \\ \vdots \\ x_{n+1} \end{bmatrix}$$

$$A = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \\ 0 & 0 & 0 & \cdots & 0 \end{bmatrix}_{(n+1) \times (n+1)} \quad B = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ b_0 \\ 0 \end{bmatrix}_{(n+1) \times 1} \quad E = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix}_{(n+1) \times 1} \quad (3.3)$$

$$C = [1 \ 0 \ 0 \ \cdots \ 0]_{1 \times (n+1)}$$

System of equations for describing an extended observer:

$$\begin{cases} \dot{\hat{x}} = A\hat{x} + Bu + L(y - \hat{y}) \\ \hat{y} = C\hat{x} \end{cases} \quad (3.4)$$

Here, \hat{x} is the estimated state vector x , \hat{y} – is the estimated output of the system y , L – is the gain vector of the observer.

There are several methods for tuning the observer, for example modal [30] or using the bandwidth property [28], where all the A-LC eigenvalues are located in $-\omega_o$. The matrix L has the form:

$$L = \begin{bmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_n \\ \beta_{n+1} \end{bmatrix} = \begin{bmatrix} \omega_o \alpha_1 \\ \omega_o^2 \alpha_2 \\ \vdots \\ \omega_o^n \alpha_n \\ \omega_o^{n+1} \alpha_{n+1} \end{bmatrix} \quad (3.5)$$

$\alpha_i, i = 1, 2, \dots, n + 1$, - are selected such that the characteristic polynomial $s^{n+1} + \alpha_1 s^n + \dots + \alpha_n s + \alpha_{n+1}$ is Hurwitz [28].

Parameter $\omega_o > 0$ - this is the observer bandwidth. Order of it should be one time higher than the system order so that the observer operates and processes disturbances faster. But there are still limitations, for example, a limitation on the sampling rate during practical implementation, as well as high throughput can cause noise.

The well-tuned outputs of ESO \hat{x}_i are close to x_i , then we get:

$$\hat{x}_{n+1} \approx x_{n+1} = f \quad (3.6)$$

From equation (3.6) it follows that the generalized perturbation can be compensated. Therefore, the control law is:

$$u = \frac{u_0 - \hat{x}_{n+1}}{b_0} \quad (3.7)$$

where, u_0 part of the control signal.

Further, equation (3.1) can be written:

$$y^{(n)} = f - \hat{x}_{n+1} + u_0 \approx u_0 \quad (3.8)$$

Control is reduced to setting the PD controller parameter

$$u_0 = k_p(r - \hat{x}_1) - k_{d1}\hat{x}_2 - \dots - k_{dn}\hat{x}_n \quad (3.9)$$

Setting k_i is chosen as $k_i = \omega_c$, where ω_c – is the required frequency of the closed loop [31].

$$k_i = \binom{n-m}{n-m-i+1} \cdot \omega_c^{n-m-i+1}, i = 1, 2, \dots, n-m \quad (3.10)$$

where, n and m – the number of finite poles and zeros of the transfer function of the control object, respectively.

A large regulator bandwidth typically increases the response speed, but, bringing it to the limit, it can also make the system oscillatory or even unstable. Thus, the controller bandwidth is adjusted based on performance and resilience requirements, as well as noise sensitivity.

ADRC benefits

- Easy to set up. Three parameters need configuring for the working of ADRC regulator – b_0, ω_o, ω_c . If it is possible to obtain some data about the system, then b_0 can be calculated (as a rule, b_0 is obtained empirically). ω_o should be chosen about 10 times the value of ω_c of the control object, to ensure the speed of the regulator. Unlike the traditional PID controller, which

has three unbound variables, a non-linear PID and a fuzzy PID (they have even more variables), the ADRC setup is faster and easier.

- Improved compensation. According to research, ESO keeps track well of total perturbations, non-linearities, and uncertainties, so the principle of the ADRC is quite understandable. First, all perturbations are combined into one function - a general perturbation, and then a state observer is added behind the linear part of the object and its order increases. As a result, ESO very well tracks the general disturbance and compensates it from the input side. The entire complex control process turns into simple integration, whereas the PID controller responds poorly to changes in the system output, which increases the control error.
- Practical applicability. To ensure adaptability, the observer must be fast enough (about 10 times higher) compared with the dynamics of the process and the closed loop [30]. But it is important to note that the location of the poles of the observer will be limited by the sampling frequency and the increasing influence of noise on the control action. As long as a good compromise can be found in this regard, the ADRC can be seen as an alternative to solving practical control problems.

3.2 Simulation and analysis ADRC

Simulations are conducted for ADRC first and second-orders to show his control abilities. Since in practice ADRC is most often used for systems of the first and second-orders, their work will be investigated in order to compare the efficiency with respect to the SST model control. There is also another way to implement ADRC, which can improve system performance by changing the feedback control law to reduce the error in estimating the perturbation of the extended state observer.

3.2.1 First-order ADRC

There is a first-order transfer function:

$$F(s) = \frac{Y(s)}{U(s)} = \frac{K}{Ts + 1} \quad T \cdot \dot{y}(t) + y(t) = K \cdot u(t) \quad (3.11)$$

Using equations (3.1) - (3.3), can write the equations for the extended observer:

$$\begin{pmatrix} \hat{x}_1(t) \\ \hat{x}_2(t) \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} \hat{x}_1(t) \\ \hat{x}_2(t) \end{pmatrix} + \begin{pmatrix} b_0 \\ 0 \end{pmatrix} \cdot u(t) + \begin{pmatrix} l_1 \\ l_2 \end{pmatrix} \cdot (y(t) - \hat{x}_1(t)) \quad (3.12)$$

Using equations (3.6) - (3.9), the control law is written as:

$$u(t) = \frac{k_p \cdot (r(t) - \hat{x}_1(t)) - \hat{x}_2(t)}{b_0} \quad (3.13)$$

The structure of the ADRC regulator of the first-order is shown in Fig. 3.2.

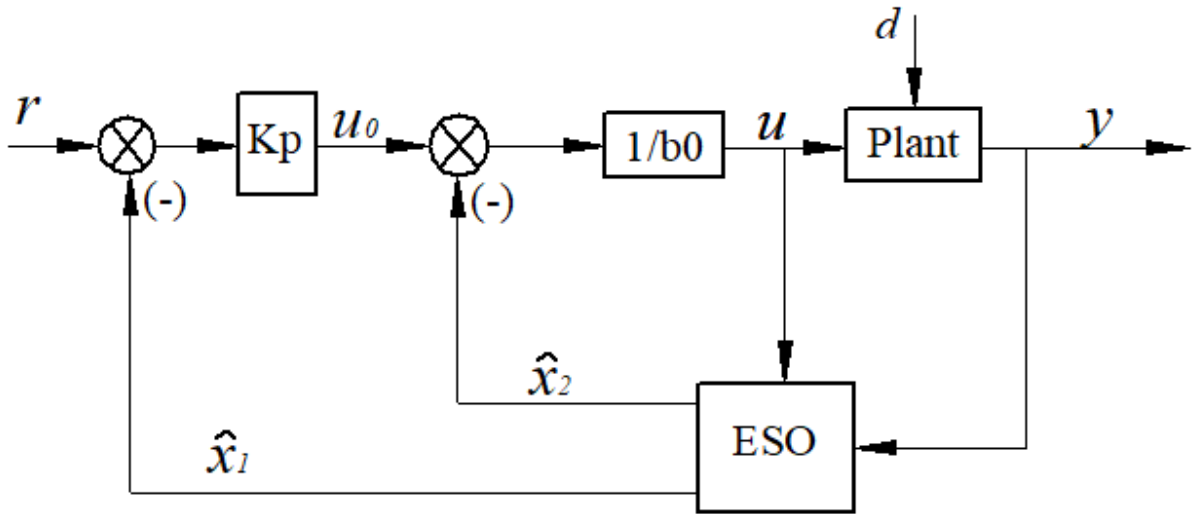


Figure 3.2 – ADRC structure for first-order system

Here, k_p acts on the estimate $\hat{x}_1(t) = \hat{y}(t)$, and not on the output of the system $y(t)$. It shapes out feedback control based on the evaluation. As noted earlier, with the steady work of an observer, there will be similarities with the classical PD. This is described in more detail in section 3.2.4.

Given the widespread use of the PID-type controller in practice, it makes sense to conduct a comparative analysis of the operation of the ADRC controller with the PID controller. The simulation is performed using the Matlab / Simulink environment. For a first-order object model, it is enough to apply the PI controller. Figure (3.3) and (3.4) show closed loop step response with changing parameters of the transfer function of the system, also the control settings for ADRC and PI are designed for identical closed loop dynamics with the same settling time.

$$\text{System transfer function: } F(s) = \frac{K}{T_s s + 1} = \frac{1}{s + 1};$$

Let settling time for a closed loop system, $T_{set} = 1$ s. Estimated value is defined as: $b_0 \approx \frac{K}{T} = 1$. During the experiments it will be fixed. In accordance with the desired time, we calculate the proportional coefficient of the regulator, $k_p \approx \frac{4}{T_{set}} = 4$. The poles of the observer are taken in accordance with equation (3.5), $\beta_1 = -2 \cdot s_{ESO}$, $\beta_2 = s_{ESO}^2$ at $s_{ESO} \approx 10 \cdot s_{CL} = 10 \cdot (-k_p) = -40$.

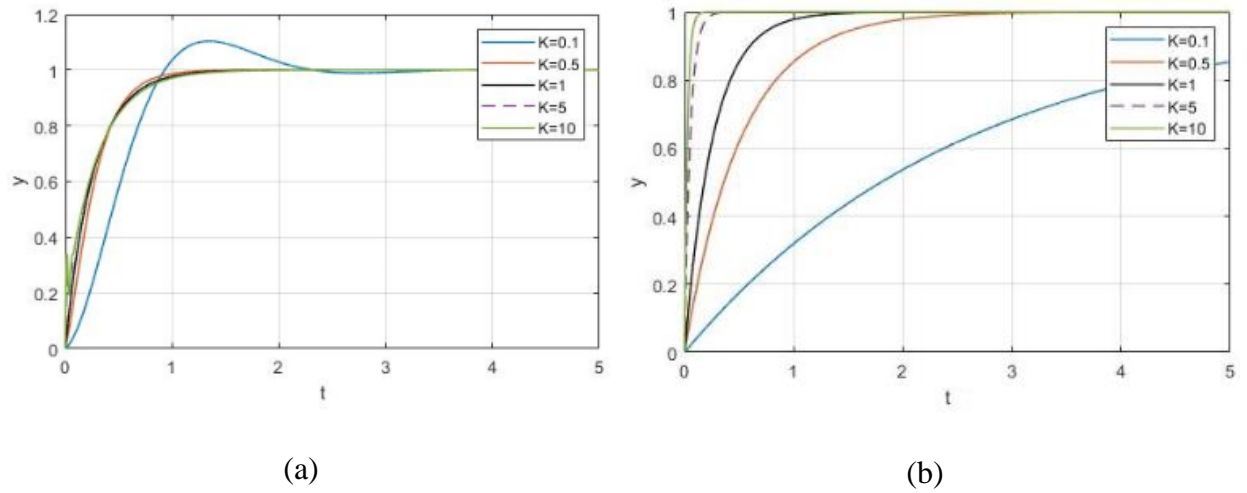


Figure 3.3 – Comparison of ADRC and PI for the first-order system with variable parameter K .
 (a) Variation K , ADRC; (b) Variation K , PI.

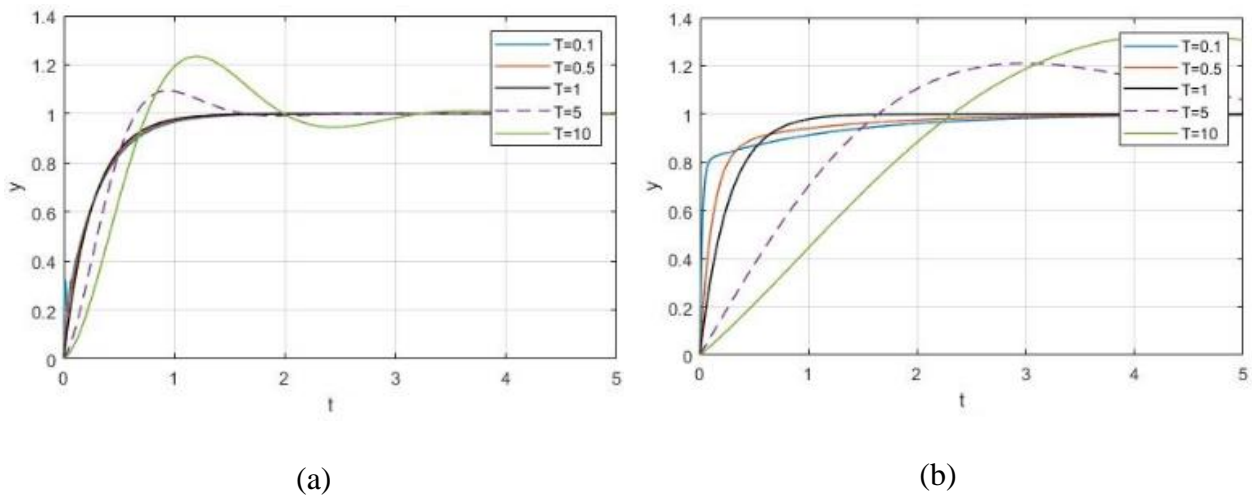


Figure 3.4 – Comparison of ADRC and PI for the first-order system with variable parameter T .
 (a) Variation T , ADRC; (b) Variation T , PI.

We will also analyze the disturbance rejection. To do this, we introduce the input disturbance in the process for the ADRC and PI regulator. In Fig. 3.5 shows closed loop step response. Disturbance is served at time $t=2s$.

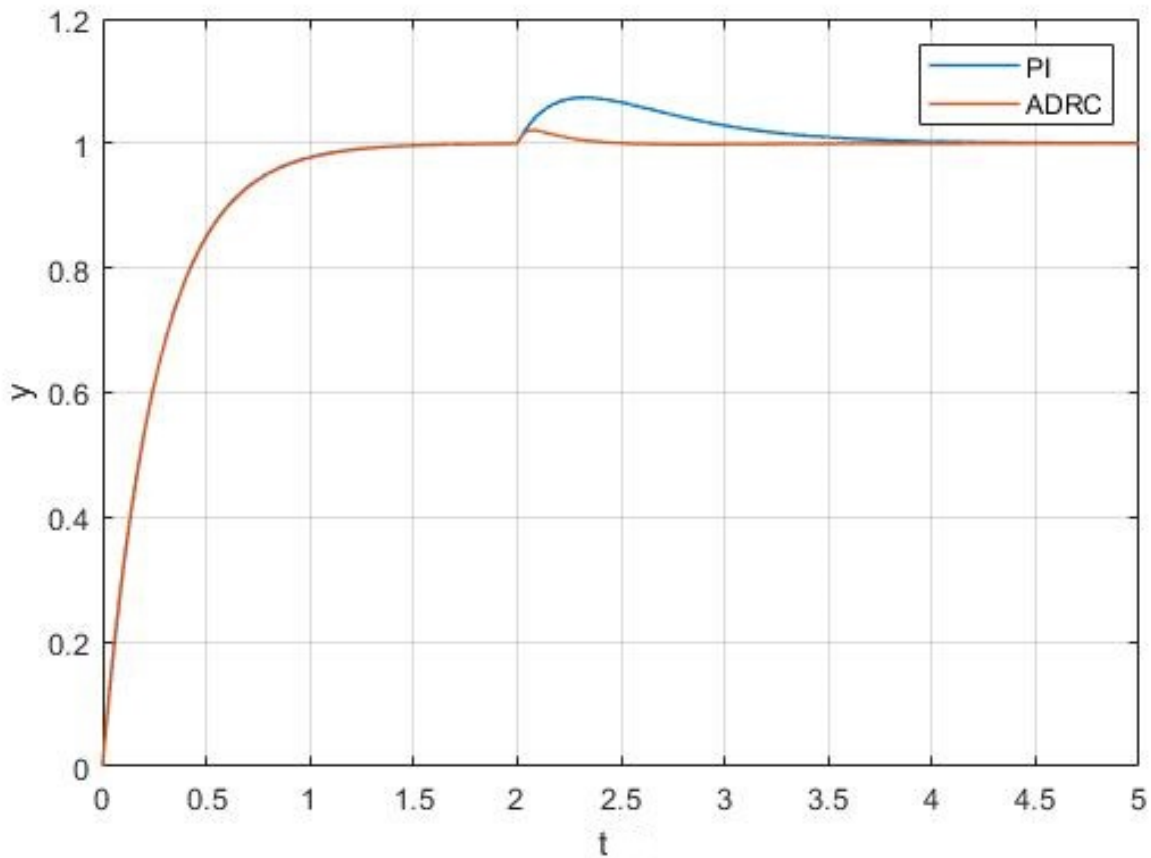


Figure 3.5 – Comparison of ADRC and PI disturbance rejection capabilities for a first-order system.

From Fig. 3.5 shows that the ADRC is better at compensating for disturbances. To get similar results with the PI regulator, it would require more aggressive tuning.

3.2.2 Second-order ADRC

There is a second-order transfer function:

$$F(s) = \frac{Y(s)}{U(s)} = \frac{K}{T^2 s^2 + 2\xi T s + 1} \quad T^2 \cdot \ddot{y}(t) + 2\xi T \dot{y}(t) + y(t) = K \cdot u(t) \quad (3.14)$$

Using equations (3.1) - (3.3), can write the equations for the extended observer second-order:

$$\begin{pmatrix} \hat{x}_1(t) \\ \hat{x}_2(t) \\ \hat{x}_3(t) \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} \hat{x}_1(t) \\ \hat{x}_2(t) \\ \hat{x}_3(t) \end{pmatrix} + \begin{pmatrix} 0 \\ b_0 \\ 0 \end{pmatrix} \cdot u(t) + \begin{pmatrix} l_1 \\ l_2 \\ l_3 \end{pmatrix} \cdot (y(t) - \hat{x}_1(t)) \quad (3.15)$$

Using equations (3.6) - (3.9), the control law is written as:

$$u(t) = \frac{k_p \cdot (r(t) - \hat{x}_1(t)) - k_d \cdot \hat{x}_2(t) - \hat{x}_3(t)}{b_0} \quad (3.16)$$

The structure of the ADRC regulator of the second-order is shown in Fig. 3.6.

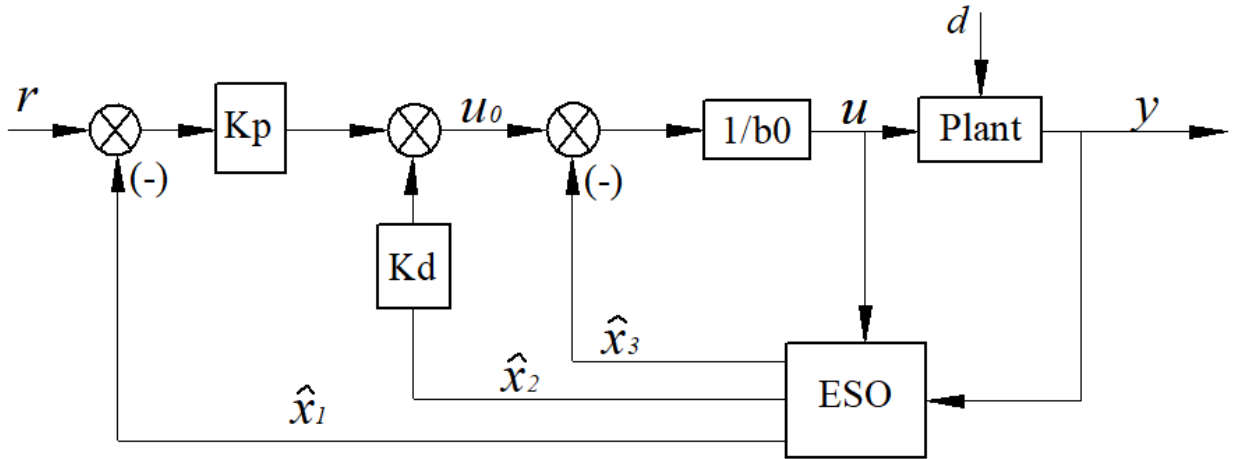


Рисунок 3.6 – Структура ADRC для системы второго порядка

We have PD controller structure. Here, k_p acts on the estimate $\hat{x}_1(t) = \hat{y}(t)$, and k_d acts on the estimate $\hat{x}_2(t) = \dot{\hat{y}}(t)$.

In order to show the advantages of the second-order ADRC, then it was compared with the standard PID controller. For clarity, the controllers are designed for the same closed loop dynamics (the same settling time without overshoot).

$$\text{Second-order system transfer function: } F(s) = \frac{K}{T^2s^2 + 2TDs + 1} = \frac{1}{s^2 + 2s + 1};$$

For the PID controller, use the standard 'PID Controller' block in Simulink, configured to match the closed loop dynamics for the ADRC case.

Let settling time for a closed loop system, $T_{set} = 5$ s, without overshoot. Estimated value is defined as: $b_0 \approx \frac{K}{T^2} = 1$. During the experiments it will be fixed. In accordance with the desired time, we calculate the PD regulator, $k_p \approx \left(\frac{6}{T_{set}}\right)^2 = 1,44$, $k_d \approx \frac{12}{T_{set}} = 2,4$. The poles of the observer are taken in accordance with equation (3.5), $\beta_1 = -2 \cdot s_{ESO}$, $\beta_2 = s_{ESO}^2$ at $s_{ESO} \approx 10 \cdot s_{CL} = 10 \cdot \left(-\frac{6}{T_{set}}\right) = -12$.

In Fig. 3.7 - 3.9 shows the results of modeling a system with varying parameters.

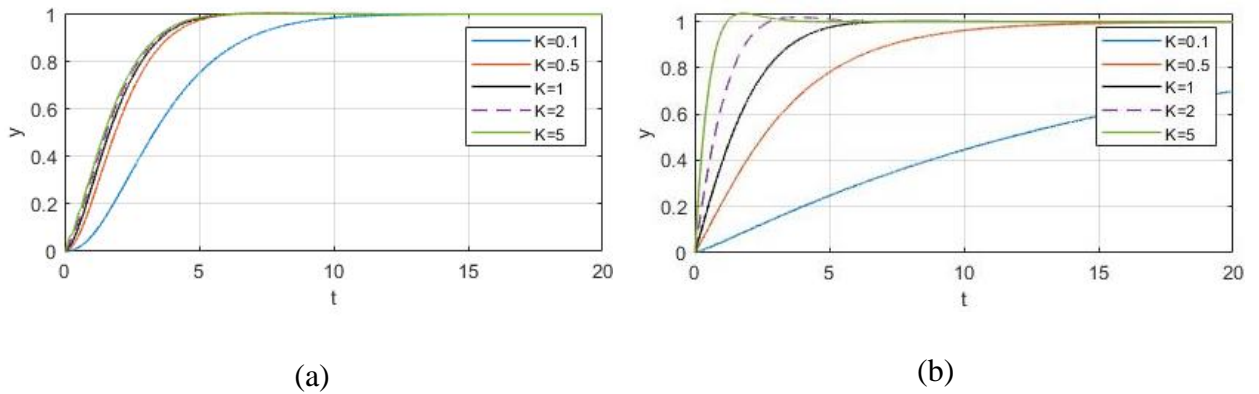


Figure 3.7 – Comparison of ADRC and PID for the second-order system with variable parameter K . (a) Variation K , ADRC; (b) Variation K , PID.

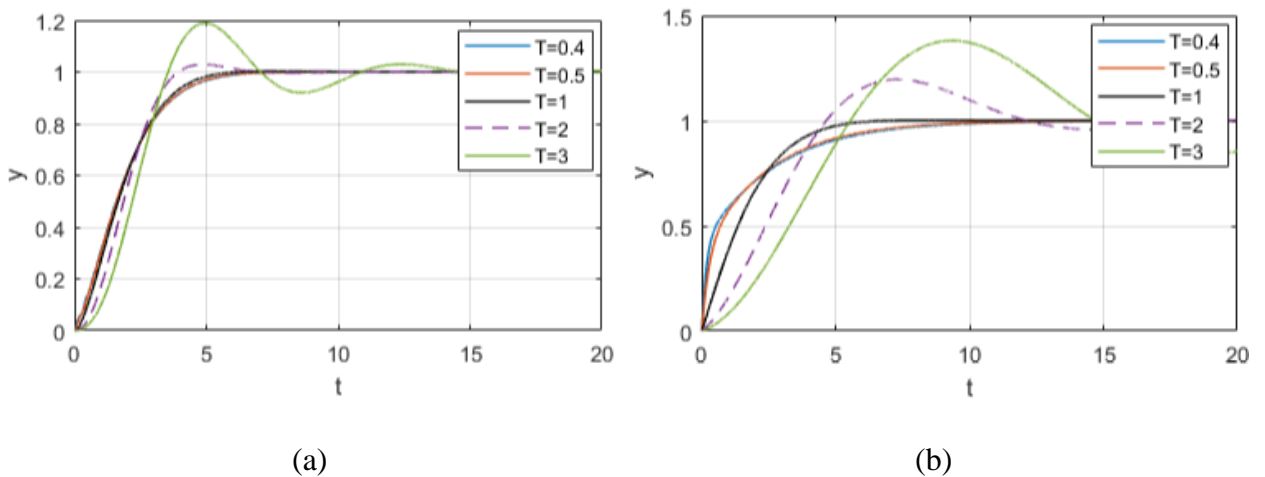


Figure 3.8 – Comparison of ADRC and PID for the second-order system with variable parameter T . (a) Variation T , ADRC; (b) Variation T , PID.

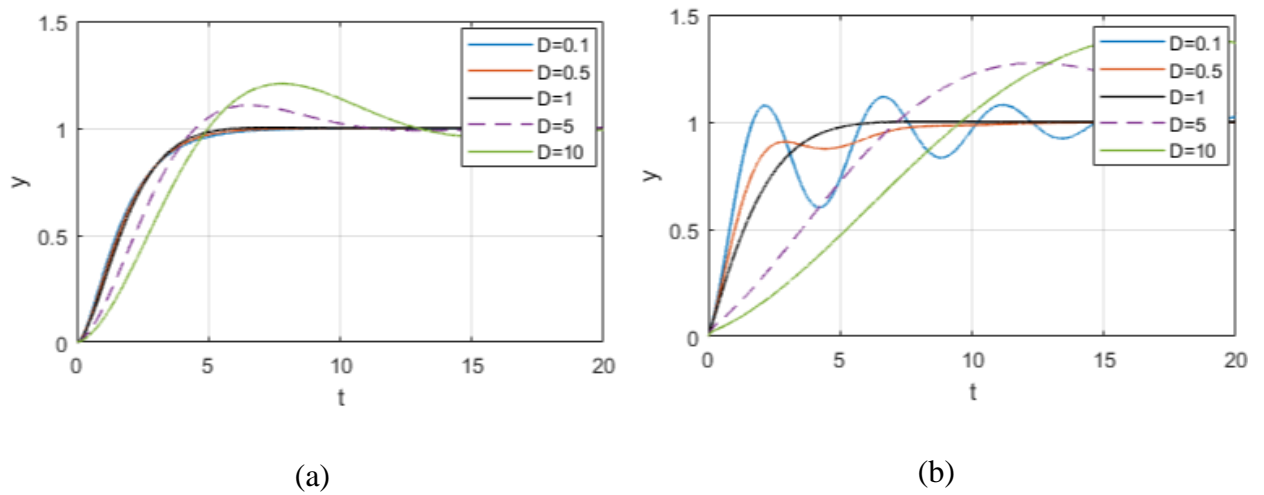


Figure 3.9 – Comparison of ADRC and PID for the second-order system with variable parameter D (damping factor). (a) Variation D , ADRC; (b) Variation D , PID.

According to the simulation results, we can conclude that the ADRC method has better results with a large margin of resistance to changes in parameters than PID.

The following is an analysis of disturbance rejection. In Fig. 3.10 shows the closed loop step response. Disturbance is served at time $t=15s$.

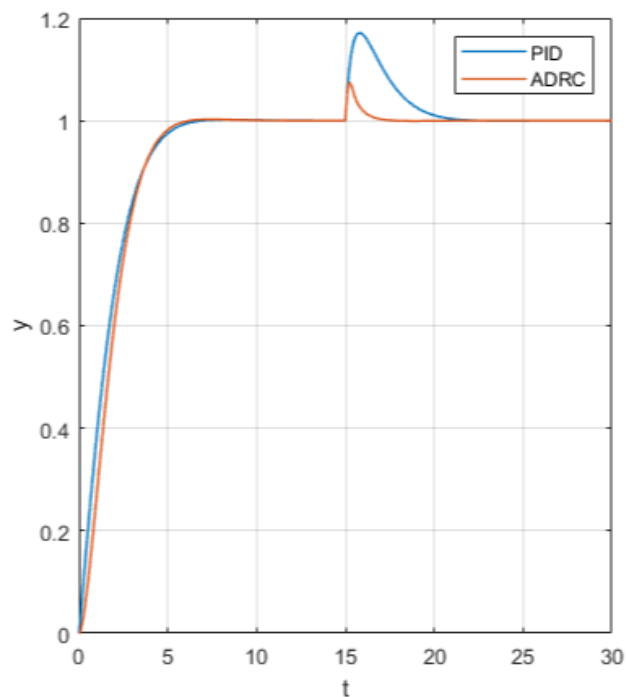


Figure 3.10 – Comparison of ADRC and PID disturbance rejection capabilities for a second-order system.

From Fig. 3.10 shows that the ADRC is better at compensating for disturbances. To get similar results with the PID regulator, it would require a more aggressive tuning, and, as a consequence, applying a filter to the setpoint signal.

3.2.3 Alternative performance of the ADRC algorithm

Subsequently, when applying this algorithm to the non-linear SST control model, a possible improvement would be to apply feedback on the output of the control object (rather than the ESO output estimate) in the control law, in order to reduce part of the negative effect caused by the ESO evaluation error.

As noted earlier, x_1, x_2, x_n, x_{n+1} is an estimate of $y, \dot{y}, y^{(n-1)}, \dots, f$. And, no matter how well the observer works, there is the possibility of an error in the estimation of state variables at the beginning of the control process. It can be reduced by replacing the estimate x_1, x_2, x_n with the output of the system $y, \dot{y}, y^{(n-1)}$. That is, the control law (3.9) is replaced by (3.17).

$$u_0 = k_p(r - y) - k_{d1}\dot{y} - \dots - k_{dn}y^{(n-1)} \quad (3.17)$$

This structure is shown in Fig. 3.11 and Fig. 3.13 for the system of the first and second order, respectively. The simulation results and comparison of different approaches are presented in Fig. 3.12 and Fig. 3.14. The simulation was performed for systems of the first and second orders with transfer functions from section 3.2.2.

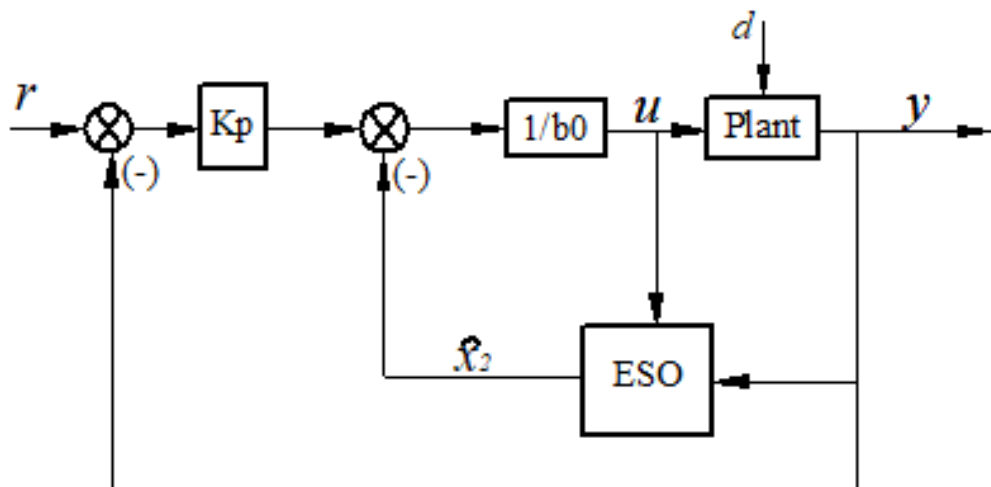


Figure 3.11 – Alternative design of the first-order ADRC.

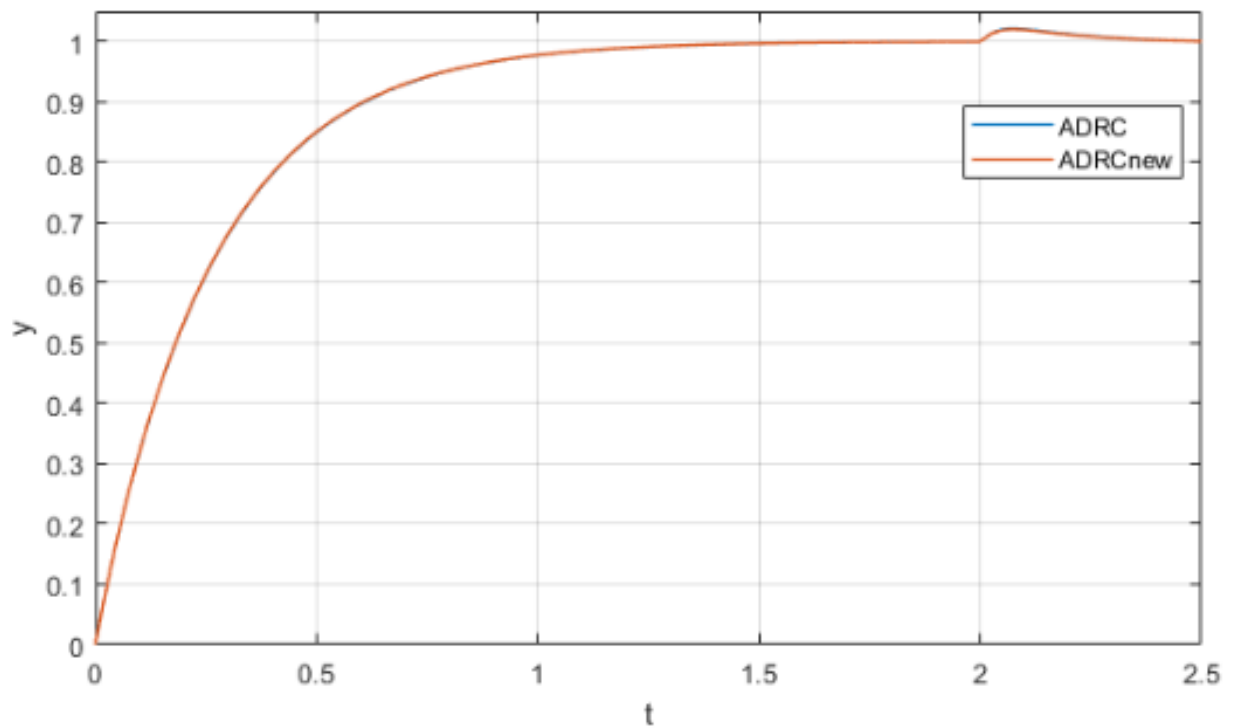


Figure 3.12 – Modeling, according to the classical structure of the ADRC first-order and alternative design.

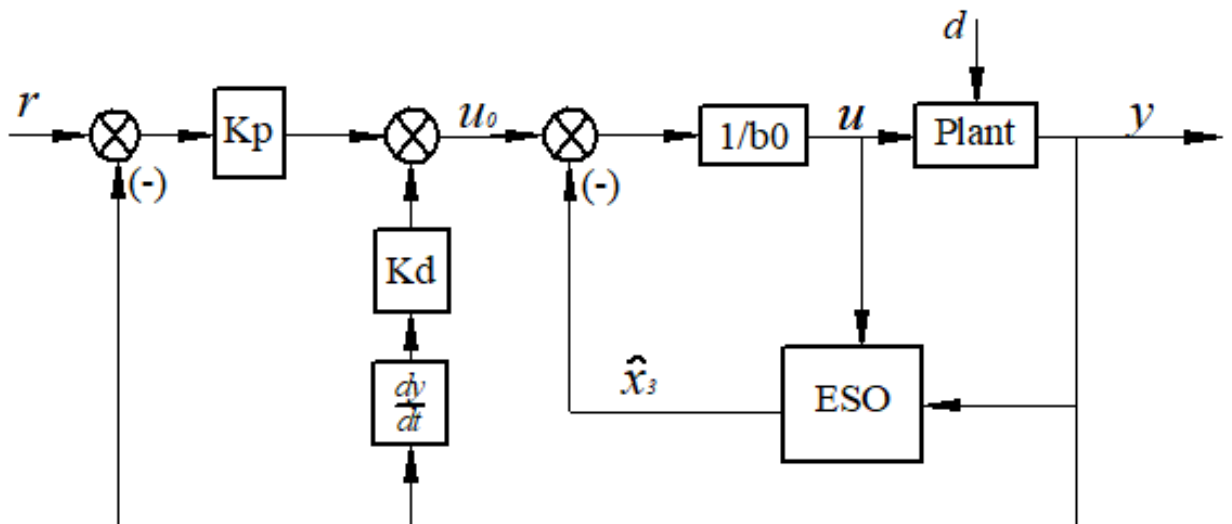


Figure 3.13 – Alternative design of the second-order ADRC.

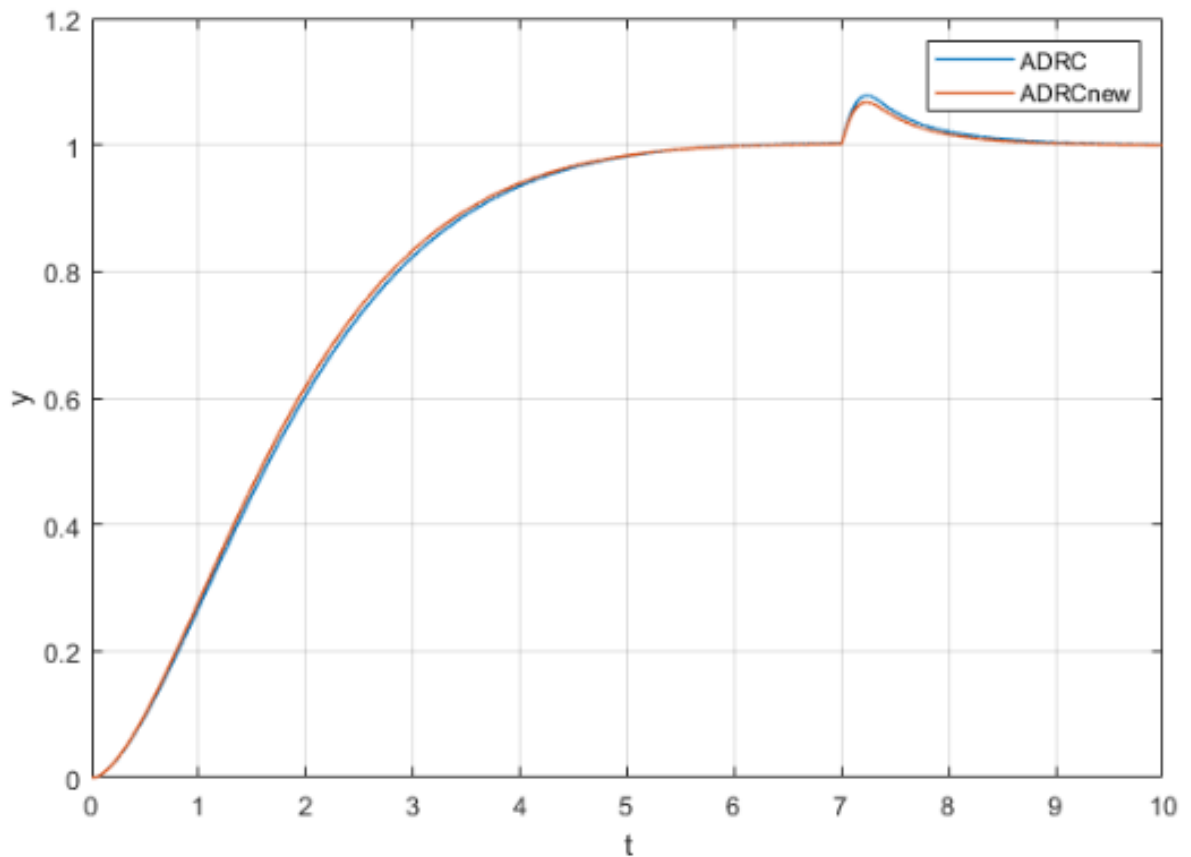


Figure 3.14 – Modeling, according to the classical structure of the ADRC second-order and alternative design.

With this execution of the ADRC algorithm, the effect of an error in estimating the linear part is theoretically avoided. This is more noticeable for the second-order system. Less significant for a first-order system.

3.3 Practical use ADRC

Already today, the ADRC regulator has been widely used in solving applied problems. It is used in such areas as power electronics control [32], [33], motion control [34], voltage and temperature control [35], [36], water pressure management system [37] and others.

Texas Instrument (TI) uses ADRC technology in a new line of motion control chips [38]. SpinTAC Control is an advanced controller based on the ADRC, which actively evaluates and compensates for system interference in real time. Its advantage is in quick and easy tuning (with one coefficient), in comparison with PID.

With regard to the task of flight control, the application of the ADRC method in this area has also been well studied, and thousands of simulation tests have been conducted on various types of aircraft. It is proved that the ADRC can achieve effective management of a complex system in the absence of an exact mathematical model.

4 Modified Active disturbance rejection control design for high-order system

The steam superheating control process is difficult because of its slow dynamics in the part of the superheater due to the high-order system. As noted earlier, the process in the superheater, the steam from which goes directly to the turbine, is described by the transfer function of the sixth-order.

Theoretically, it is possible to make an ADRC with an order that matches the order of the system, but it will have a complex structure and configuration. In [39], it was noted that lower-order ADRC can work well for a higher-order system. Still, it makes sense to look for alternative ways to implement the ADRC algorithm for high-order systems to achieve improved output characteristics.

A study [40] proposed a management strategy for ADRC with a time delay. With this approach, oscillation can occur in the system when the delay time is not specified exactly.

A possible improvement to the ADRC from Chapter 3 is its modification. To speed up the system response, reduce oscillation and the ability to cope with uncertainties, you need to add some compensation to delay the control signal before it enters the ESO.

The block scheme of MADRC is shown in Fig. 4.1.

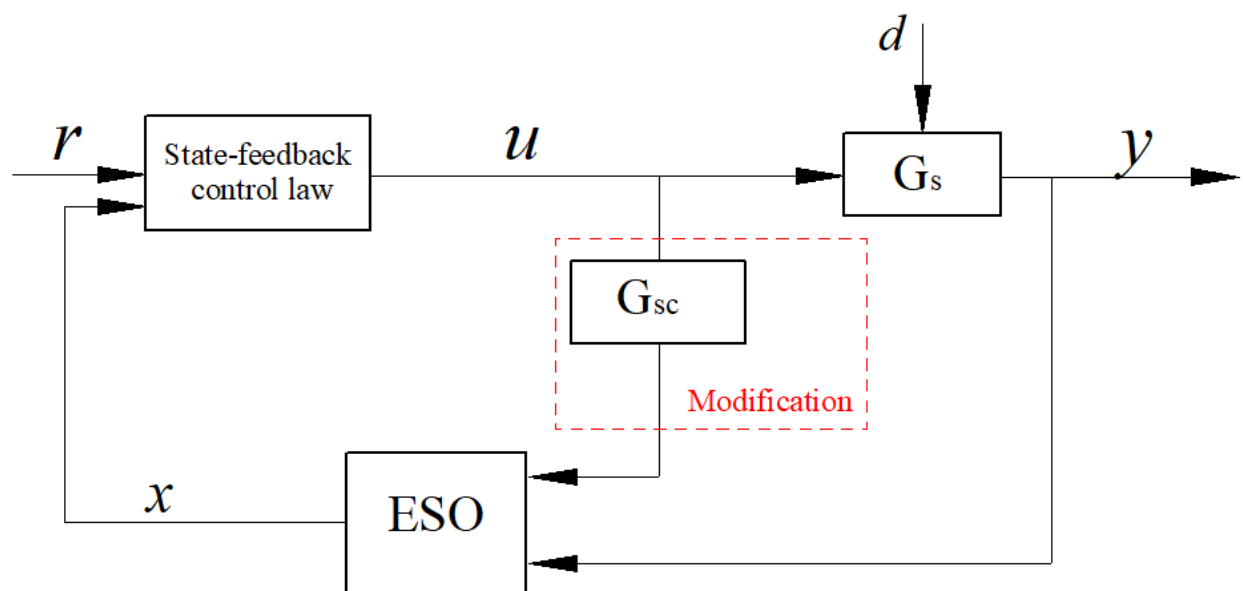


Figure 4.1 – The block scheme of MADRC

A high-order system is defined as:

$$Gs(s) = \frac{K}{(Ts + 1)^n} \quad (4.1)$$

where, K , T and n - gain, time constant and system order respectively, $n \geq 2$.

The transfer function of the compensation part is defined as:

$$Gsc(s) = \frac{1}{(Ts + 1)^{n-1}} \quad (4.2)$$

Due to the fact that the high-order system output is initially delayed due to the dynamic characteristics of the system, the added compensation part can synchronize the control signal and the system output, which is included in the ESO, and allows the ESO to provide more accurate estimates of the high-order system states.

Using equation (3.4), we write equation (4.2) for ESO in MADRC

$$\begin{cases} \dot{\hat{x}} = A\hat{x} + Bu_c + L(y - \hat{y}) \\ \hat{y} = C\hat{x} \end{cases} \quad (4.3)$$

where, u_c – the output of the compensation part and the state-feedback control law (SFCL) coincides with equation (3.7).

4.1 Analysis and tuning procedure of MADRC

The structure of the MADRC differs from the ADRC, respectively, it is necessary to carry out the setup procedure again. We use the SST control system presented in Chapter 2, equation (2.4).

Consider the impact of the parameters of the first-order MADRC on the quality indicators of the closed loop step response. For this, take $b_0 = \frac{2K}{T} \approx 0,1$, the controller bandwidth $\omega_c = 0.06$ and the observer bandwidth should be taken $\omega_0 \approx 100\omega_c = 6$. During the study, only one parameter will be subject to change (the rest remain fixed). This study was conducted for each parameter. The influence of different b_0 , ω_0 and ω_c for the first-order MADRC is presented in Figure 4.2 - Figure 4.4.

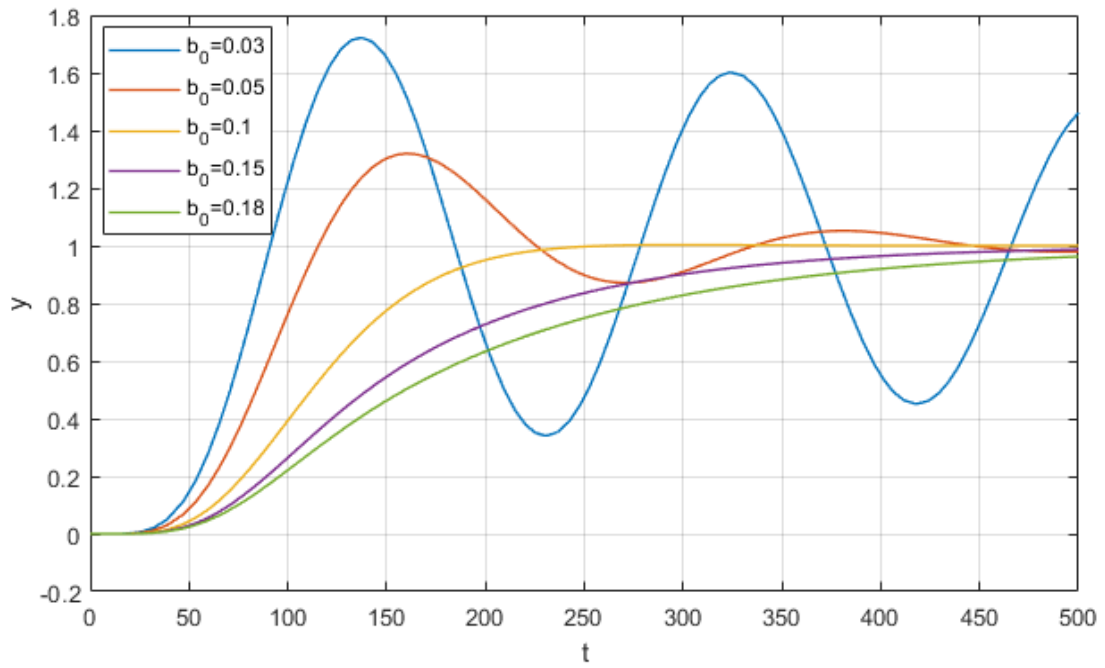


Figure 4.2 – The effect of b_0 on first-order MADRC performance

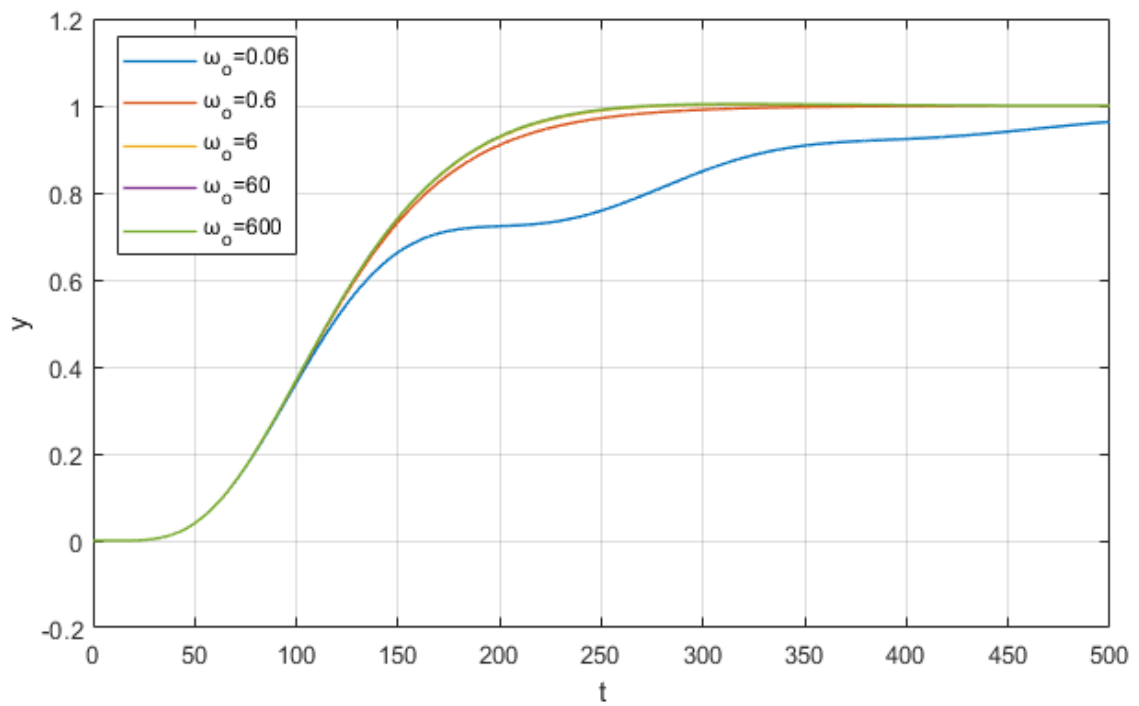


Figure 4.3 – The effect of ω_0 on first-order MADRC performance

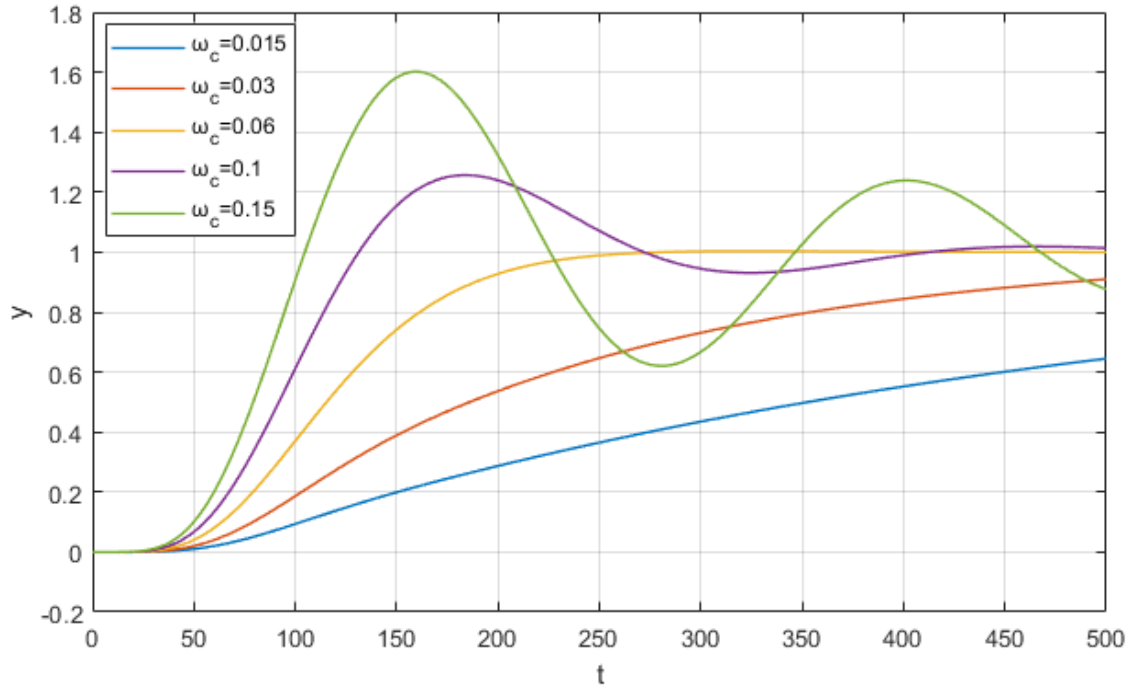


Figure 4.4 – The effect of ω_c on first-order MADRC performance

After analyzing the results, we can conclude that when ω_0 is large enough, with its further increase, its effect on performance stops. The larger ω_0 , the higher the susceptibility to noise [28]. At the same time, too small ω_0 leads to instability of the system. b_0 - is an approximated parameter of the real system, which is associated with $k_p = \omega_c$. b_0 and ω_c have a significant impact on the control.

The following is a practical method for tuning a first-order MADRC:

1. Take $b_0 \approx \left[\frac{2K}{T}, \infty \right)$, then fix it;
2. Choose ω_0 focusing on the ratio $\omega_0 \approx 100\omega_c$, with $\omega_c \approx b_0$. An alternative method is to increase ω_0 with a fixed ω_c until it stops changing the system performance significantly. Then fix ω_0 ;
3. Change ω_c according to the desired characteristics;
4. Adjust $b_0 \approx \omega_c$ for correct results.

Since in practice the use of both first and second-order ADRC is found, similarly, the same analysis can be performed for second-order MADRC. In this case, equation (4.2) can be written as:

$$G_{sc}(s) = \frac{1}{(Ts + 1)^{n-2}} \quad (4.4)$$

Consider the impact of the parameters of the second-order MADRC on the quality indicators of the closed loop step response. For this, take $b_0 = \frac{2K}{T} \approx 0,1$, the controller bandwidth $\omega_c = 0,06$ – here are considered k_p and k_d . The observer bandwidth $\omega_o \approx 100\omega_c = 6$. Similarly to the previous case, one parameter will change, and the rest will be fixed. The influence of different b_0 , ω_o and ω_c for the second-order MADRC is presented in Figure 4.5 – Figure 4.7.

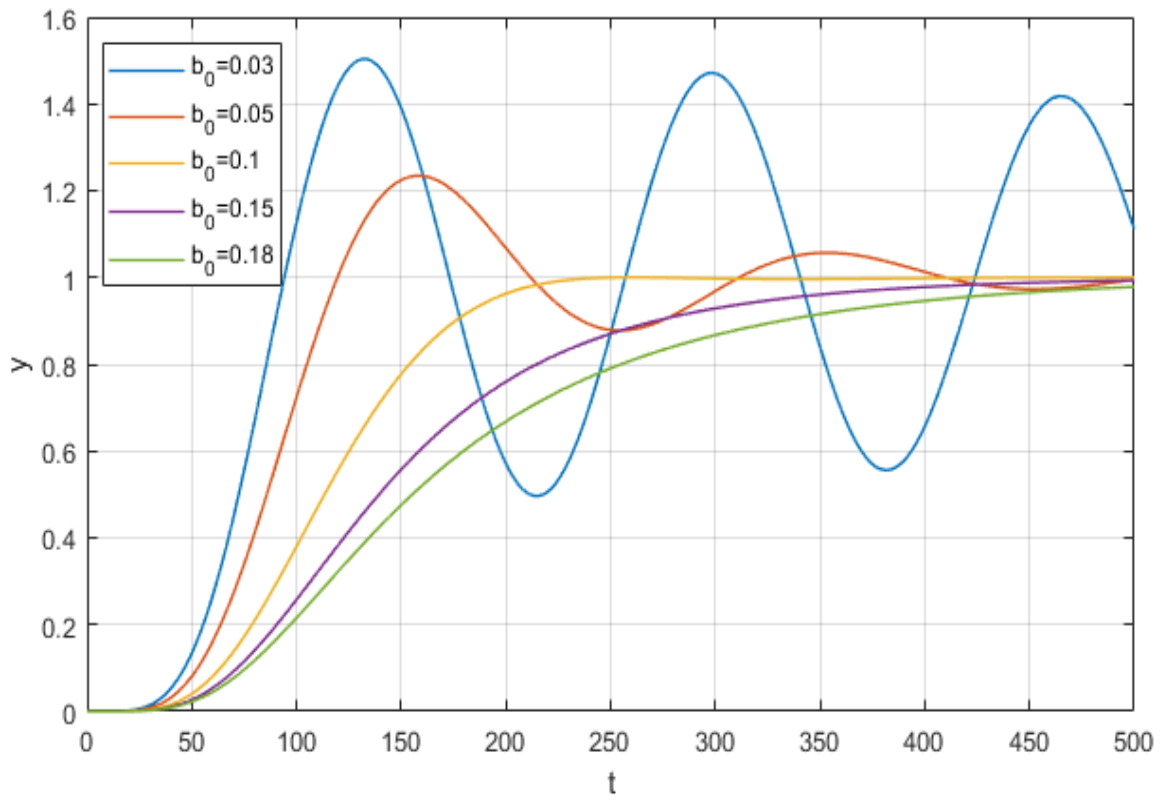


Figure 4.5 – The effect of b_0 on second-order MADRC performance

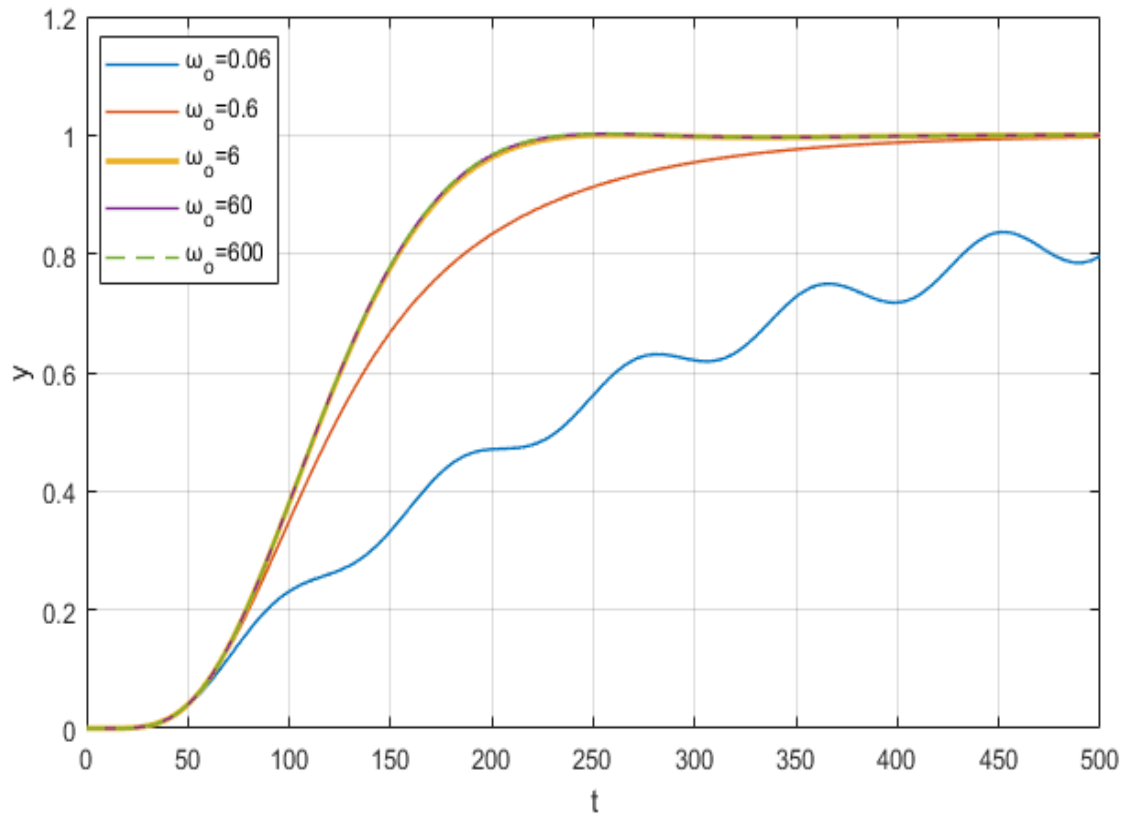


Figure 4.6 – The effect of ω_0 on second-order MADRC performance

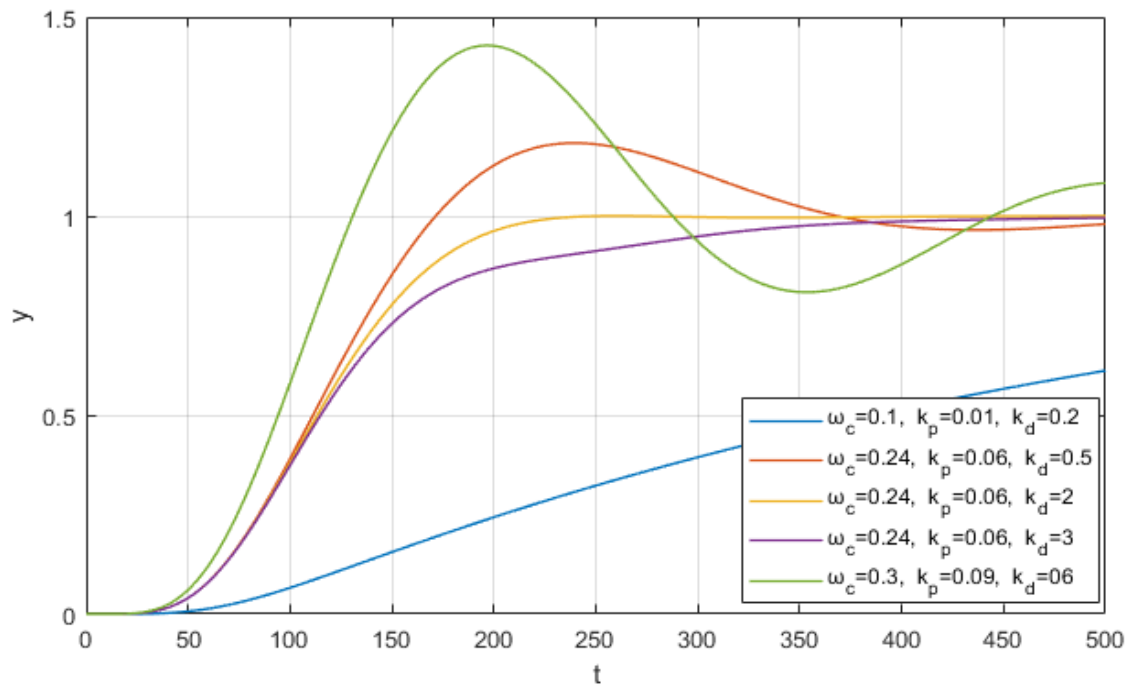


Figure 4.7 – The effect of ω_c on second-order MADRC performance

A practical method for tuning a second-order MADRC:

1. Take $b_0 \approx \left[\frac{2K}{T}, \infty \right)$, then fix it;
2. Choose ω_o focusing on the ratio $\omega_o \approx 100\omega_c$, with $\omega_c \approx b_0$. An alternative method is to increase ω_o with a fixed ω_c until it stops changing the system performance significantly. Then fix ω_o ;
3. Change ω_c according to the desired characteristics, wherein: $\omega_c^2 \approx k_p$, and $k_d \approx (2-10)\omega_c$;
4. Adjust $b_0 \approx \omega_c$ for correct results.

The results are almost identical to the results obtained from the first-order MADRC analysis. Next, we compare its ability to rejection disturbances.

4.2 Numerical simulation

Compare the proposed MADRC with the classical control algorithm - PID. The parameters used for MADRC are taken from section 4.1. System used, equation (2.4):

$$G(s) = \frac{1.6}{(20s + 1)^6}$$

The transfer function for the compensation part of the first-order MADRC and the second-order MADRC is given in equations (4.5) and (4.6) respectively.

$$G_{sc1}(s) = \frac{1.6}{(20s + 1)^5} \tag{4.5}$$

$$G_{sc2}(s) = \frac{1.6}{(20s + 1)^4} \tag{4.6}$$

At a time stamp of 500 s, disturbances are fed into the system. The approximated generalized perturbation function has the form of a third-order transfer function. This is due to the dynamics of the process and the data obtained experimentally from a real power plant. All parameters of the controllers are presented in table 4.1.

Table 4.1 – Controller Parameters

Control method	Parameters
First-order MADRC	$b_0 = 0.1, \omega_0 = 6, \omega_c = 0.06$
Second-order MADRC	$b_0 = 0.1, \omega_0 = 6, k_p = 0.06, k_d = 2$
PID	$k_p = 0.15, k_i = 0.003, k_d = 1.13$

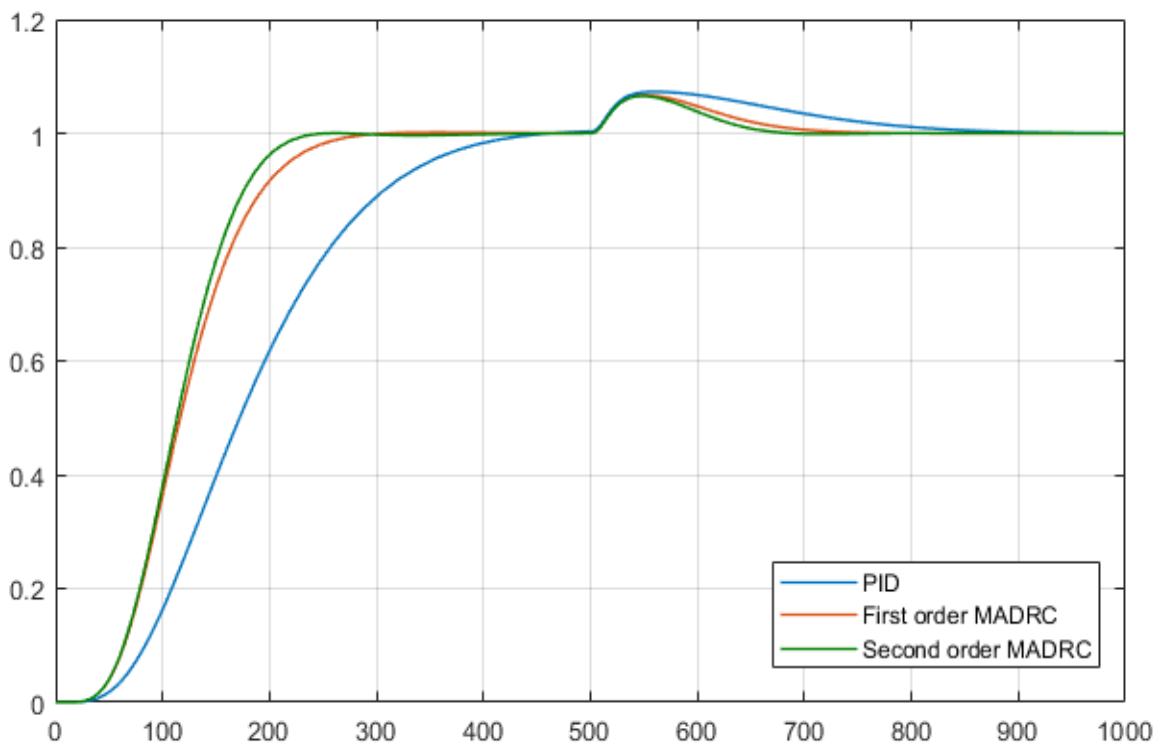


Figure 4.8 – Output characteristics of the original model with different controllers

As noted earlier, the steam superheat system has some uncertainties. Therefore, a high-order system must have robust control. To verify this, experiments were performed with a change in the gain of the original system in the interval $K = (1.1 \dots 2)$ and a change in the time constant in the interval $T = (10 \dots 30)$, while all the parameters of the controllers remain unchanged.

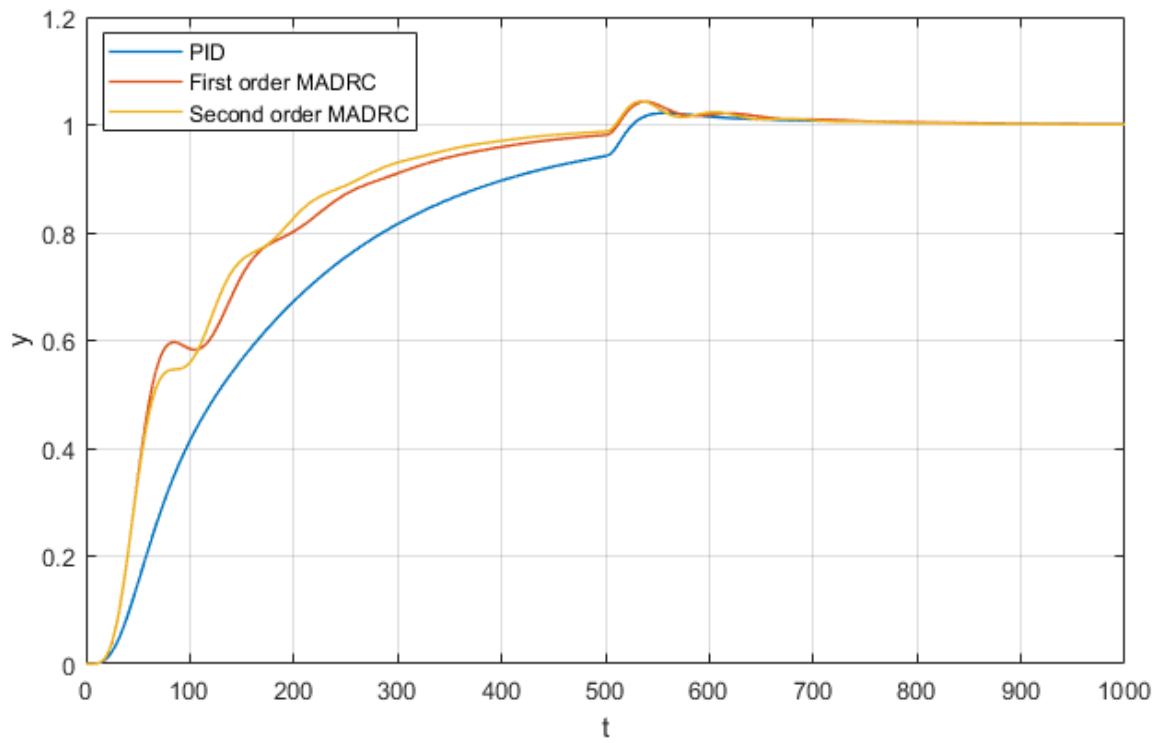


Figure 4.9 – System output characteristics with $T = 10$

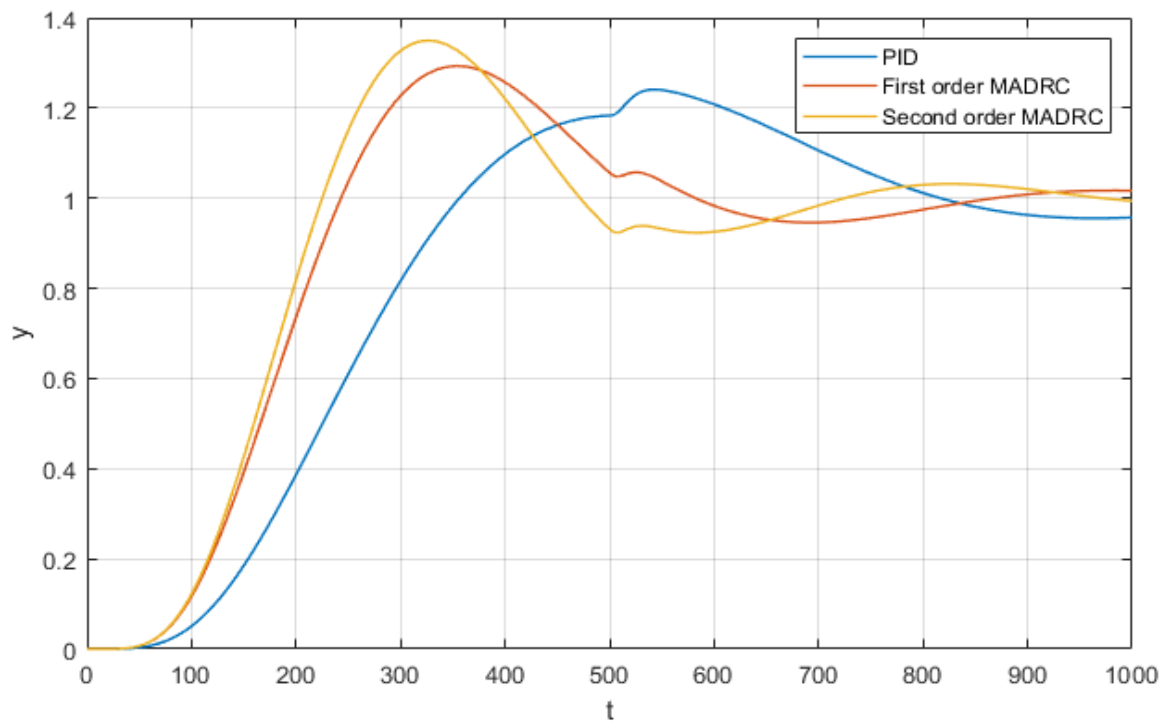


Figure 4.10 – System output characteristics with $T = 30$

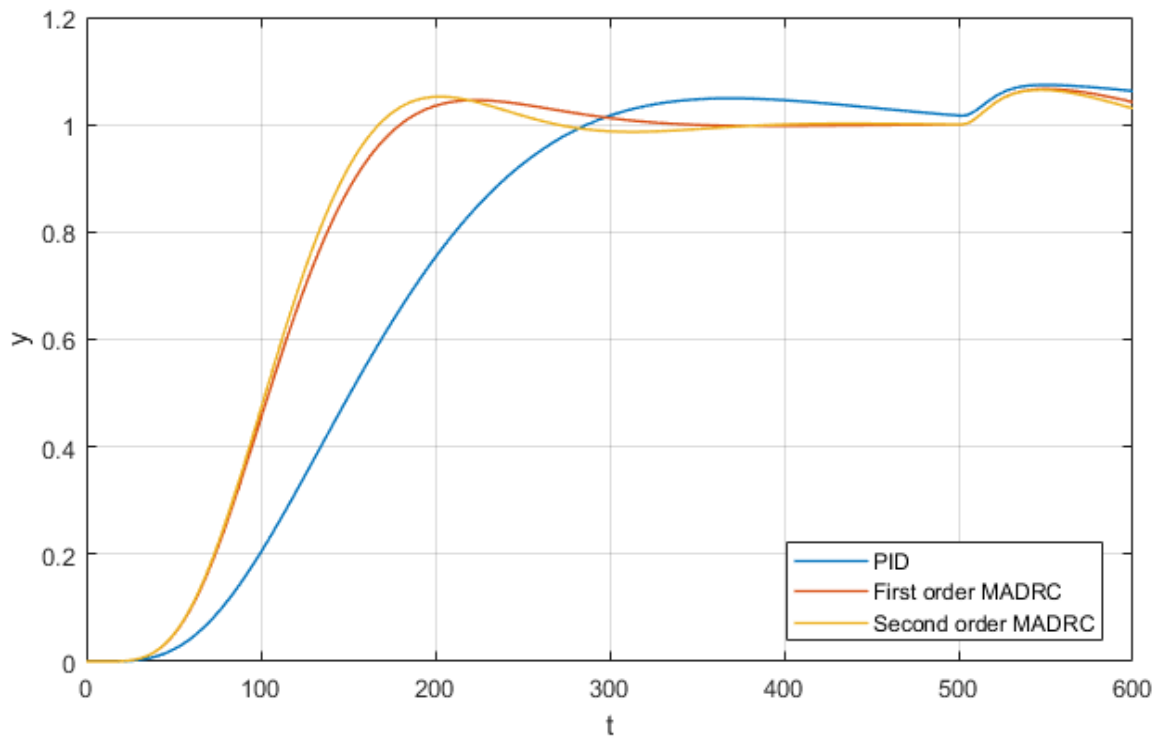


Figure 4.11 – System output characteristics with $K = 2$

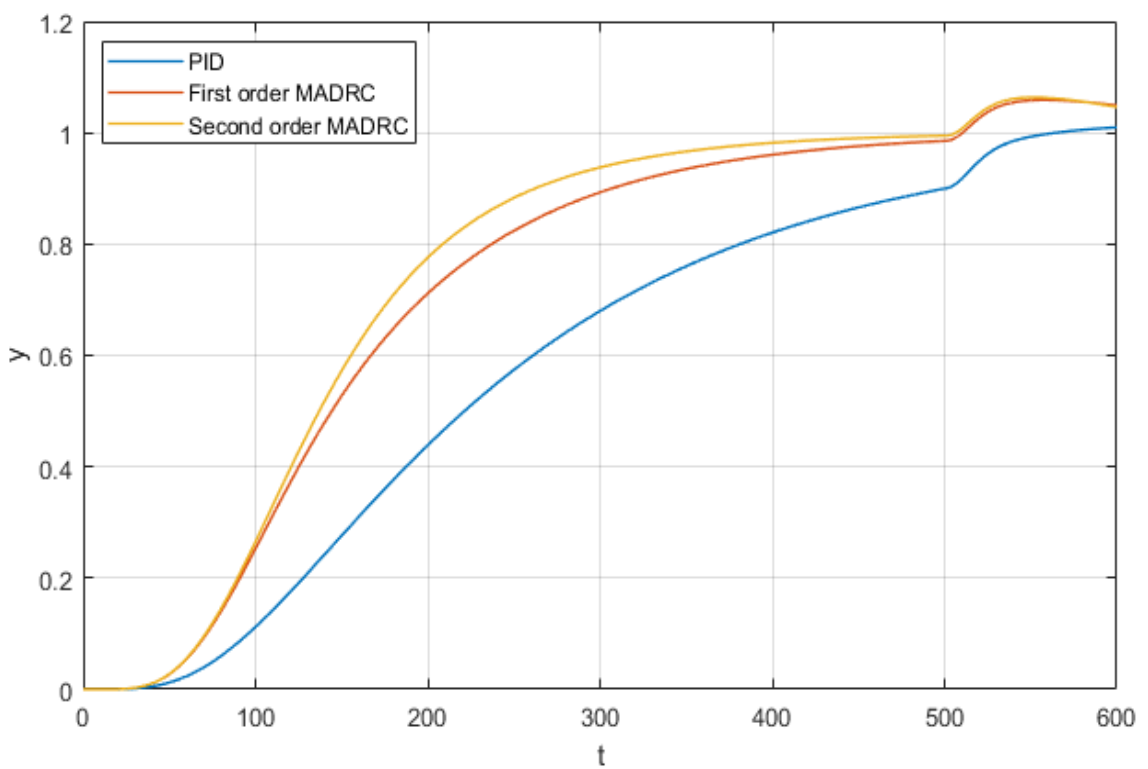


Figure 4.12 – System output characteristics with $K = 1.1$

As can be seen from Fig. 4.9 - 4.12, in some cases, MADRC has better performance in tracking and compensating disturbances, and, therefore, coping with system uncertainties.

MADRC inherits all the advantages of ADRC, and moreover copes with the slow dynamics of a high-order. MADRC does not need an exact mathematical model. Only three parameters are required for adjustment, which can be easily determined.

4.3 Cascade control for MADRC-PI and PID-PI

Based on the theory and research conducted in my thesis, it can be concluded that MADRC is an appropriate control strategy for the steam superheating system, since the SST control system has immeasurable perturbations, slow dynamics and there is no exact mathematical model.

As noted earlier, the SST control system is a cascade control system with internal and external control loops. For the internal circuit, a PI controller is sufficient, since it has a faster dynamics than the external one, and temperature changes caused by disturbances of the internal circuit can be compensated by a superheater (external control loop). The original PID-PI control strategy is presented in Fig. 4.13.

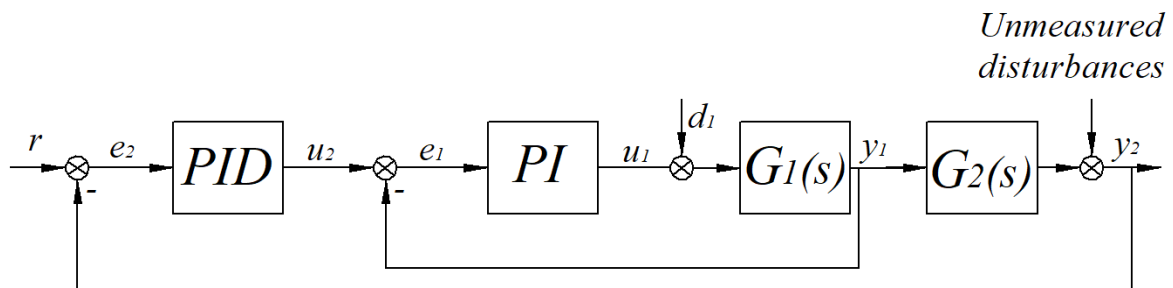


Figure 4.13 – PID-PI cascade control strategy for control SST system

The MADRC-PI cascade control strategy for the SST control system is shown in Figure 4.14. For a comparative analysis of the effectiveness of control systems, let's compare the original strategy with that developed and calculated in Chapter 4 of MADRC.

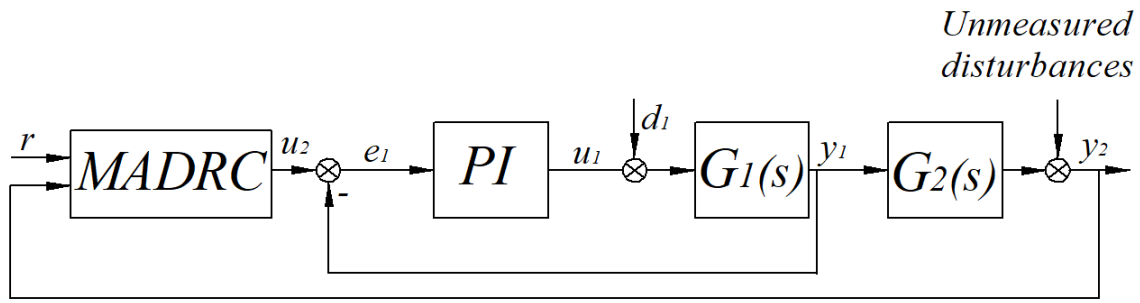


Figure 4.14 – Стратегия управления каскадом MADRC -PI для системы SST

There is some difference in setting up a single control loop and a cascade system. This is due to the "expansion" of the regulatory system. Therefore, it is not possible to transfer the coefficients for the regulators from Table 4.1, since an overshoot occurs. Therefore, it is required to tune the regulator by the method in section 4.1, and the compensation part is still taken $G_{sc1}(s) = \frac{1}{(20s+1)^5}$, $G_{sc2}(s) = \frac{1}{(20s+1)^4}$ for the first and second-order MADRC, respectively. Differences between the object of control and the compensation part can be considered as uncertainty.

All parameters for the simulation control SST at are shown in Table 4.2, and transient characteristics are shown in Figure 4.15. A perturbation is added to the system at the 600 s time mark.

Table 4.2 – Control parameters for the control SST cascade system

Control method	Parameters	Parameters PI ₁
MADRC ₁ – PI ₁	$b_0 = 0.1, \omega_0 = 6,$ $k_p = 0.053$	$k_p = -0.556$ $k_i = -0.126$
MADRC ₂ – PI ₁	$b_0 = 0.1, \omega_0 = 6,$ $k_p = 0.047, k_d = 1.5$	
PID – PI ₁	$k_p = 0.184, k_i = 0.003,$ $k_d = 1$	

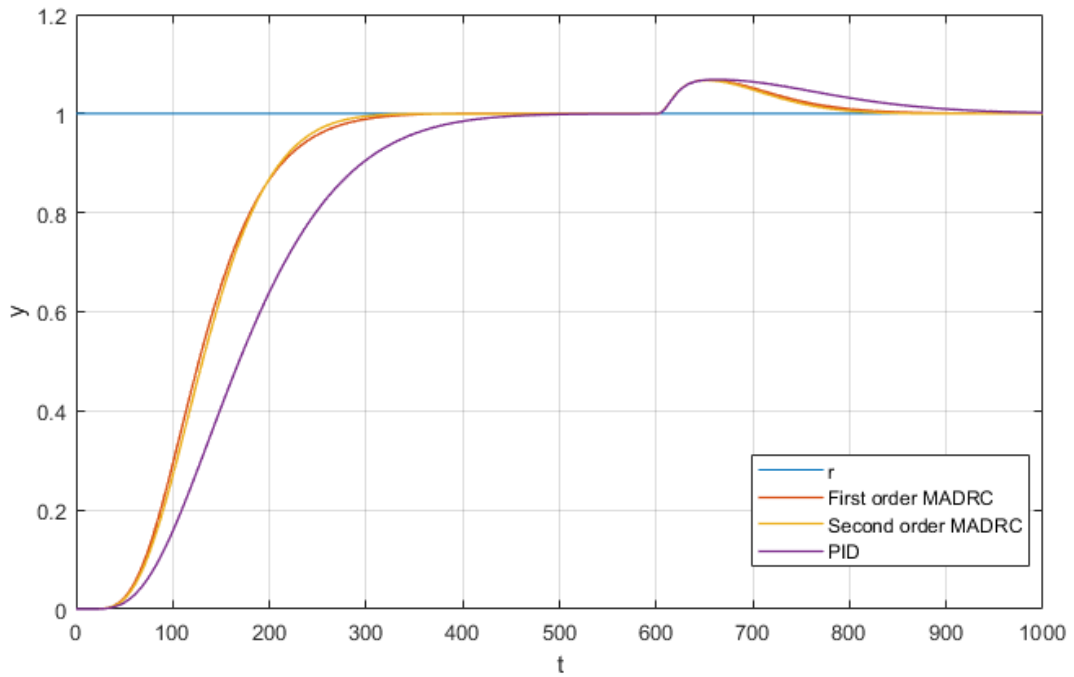


Figure 4.15 – Output characteristics of the control SST system with MADRC-PI and PID-PI

From Fig. 4.15 shows that the regulators MADRC-PI have a slight advantage in control efficiency, and there is also no overshoot, which is very important for SST control. In cascade control under given conditions, the first order MADRC-PI and second order MADRC-PI are almost the same. Therefore, it makes sense to use the first order MADRC scheme for the SST control system (it is a bit simpler in structure and tuning). Figure 4.16 shows the SIMULINK model of cascade control with first-order MADRC. Although the observer, as proved in Chapter 3, works steadily and tracks well, for modeling the error, the output from the object rather than the estimate is used, the possible advantages of this are discussed in section 3.2.3.

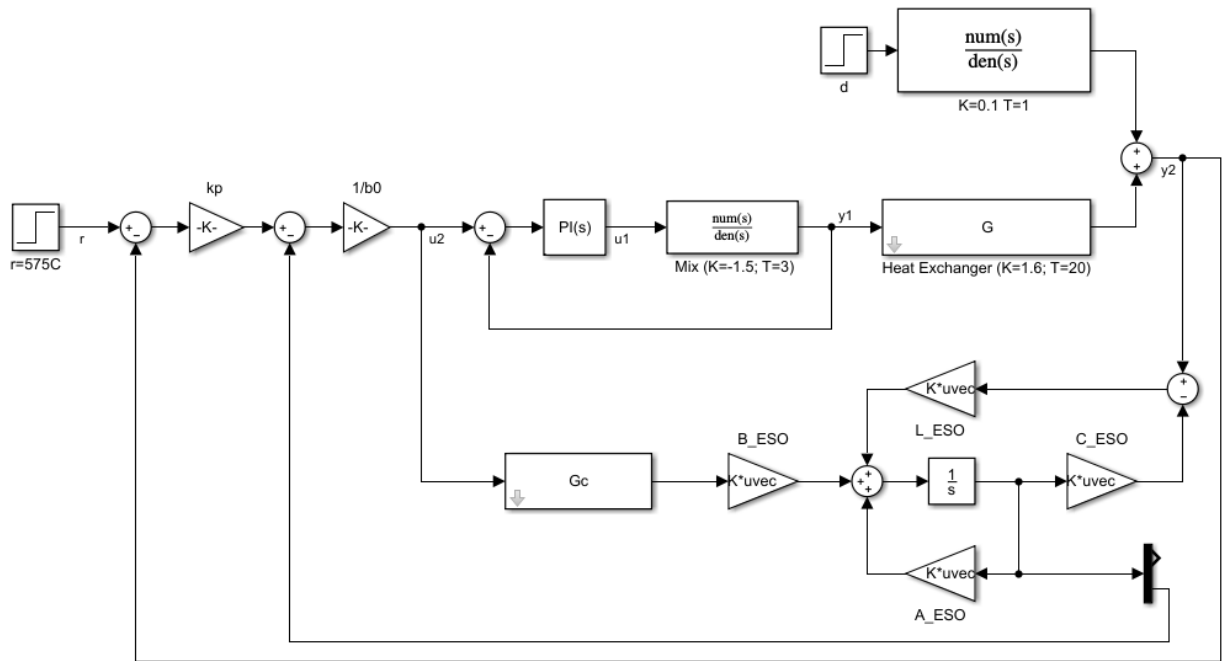


Figure 4.16 – The scheme in SIMULINK first-order MADRC

Next, Figure 4.17 shows the system output and control signal for regular random disturbances with a first-order MADRC-PI and PID-PI (parameters for controllers from Table 4.2).

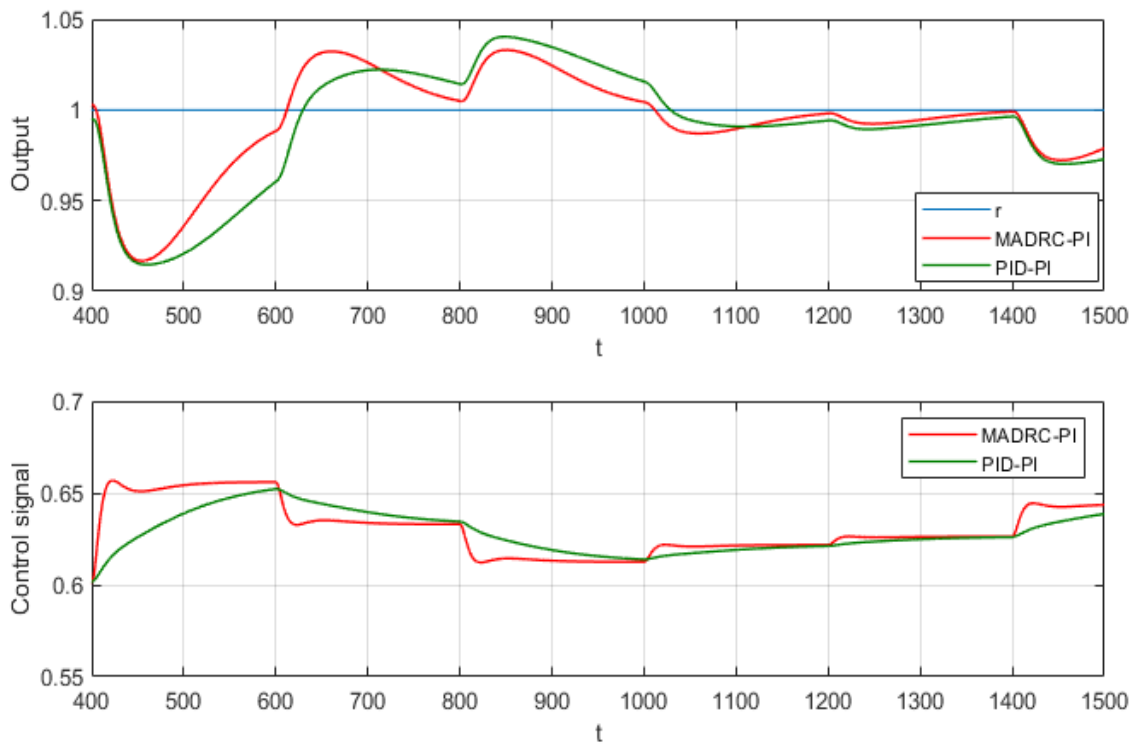


Figure 4.17 – System output and control signal for regular random disturbances

Summing up, as a rule, excessively high temperatures can lead to irreparable damage to the steel pipe, while low temperatures will lead to a decrease in the economic and efficient operation of the power plant. Using the proposed MADRC-based cascade control structure, the effect of disturbances on superheated steam temperature can be compensated more efficiently than using the classical PID-PI cascade. Therefore, due to the proven improved efficiency of the control system, the proposed cascade structure of the MADRC based regulator can make a significant contribution to the development of the energy sector.

5 Conclusion

In the thesis work was considered the possibility of applying the algorithm of active disturbance rejection to the system for controlling the temperature of superheated steam supplied to the high-pressure stage of a steam turbine of a thermal power plant. This makes it possible to reduce the sensitivity of the temperature of superheated steam to external disturbances, which in turn helps to improve the operation of the entire steam turbine mechanism and increase its efficiency.

The structure and principle of operation of the steam turbine are described. This made it possible to identify the main problems with the operation of the steam turbine control system - the temperature oscillation of superheated steam under the action of unmeasurable interference; and justify the need to explore new control algorithms.

Possible approaches to obtaining a mathematical model of a superheater suitable for research are described: heat balance method, finite difference method (multi-objective genetic algorithm), partial differential equations (discretization by dividing the heat exchanger into several control volumes). A linearized model of a high-order superheater was chosen for research.

The ADRC method is considered on the example of first and second order regulators in comparison with PI and PID controllers, respectively. Studies have shown that ADRC has greater robustness and speed in disturbances rejection than PI and PID controllers (when setting up controllers for identical closed loop dynamics with the same settling time).

The procedure for setting up MADRC regulators of the first and second order is described. Comparison of efficiency MADRC regulators of the first and second order with the PID controller has been carried out when working with a mathematical model of a high-order system of superheater. As a result of research, it has been showed that the use of MADRC regulators for a high-order model demonstrates an advantage in terms of the quality of the transition process compared to the PID regulator (including under the influence of disturbances).

The cascade control systems MADRC-PI of the first and second order and PID-PI for the suppression of external disturbances in the control system of the superheated steam area are investigated. The simulation results showed that the MADRC-PI cascade is able to cope with the task of rejected external disturbances, stabilizing the temperature of superheated steam, is more effective in comparison with PID-PI.

Thus, the conducted studies have shown the possibility of using active disturbance rejection algorithms to increase the efficiency of the superheated steam temperature control system (reducing the influence of disturbances on the system operation). In the future, the resulting structures of regulators can be applied to research on real technological objects on the basis of nonlinear models.

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