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Improved Controller For a Thermal Power Plant

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Man is still the most extraordinary computer of all.

John F. Kennedy

21 May 1963

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I want to express my thanks to My supervisor Dr. BENTARZI for his assistance, his wisdom ideas, effort and suggestions during the realization of this project. I extend my gratitude to all INELEC’s teachers for
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Dedication

With gratitude and sincere, I dedicate this modest work to
My Parents, the case of my existence and success
My dear sister, my brothers and all my family
To All my friends and all who know me.
All those I Like …

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ملخص

إن عدد المنشآت المتعلقة بمحطات توليد الطاقة الحرارية قد انخفض، ولكن بالرغم من هذا فانها لا تزال توفر حوالي 65% من الانتاج العالمي للطاقة، حاليا ازداد الاهتمام بهذا نظرا لانخفاض مردوديتها وكذا الكميات الهائلة من الطاقة، الضائعة. لهذا فان التربين تحتاج إلى طاقة مكافئة لتعويض هذا الضياع. تخفيض هذه الأخيرة سيؤدي إلى تقليص نسبة التلوث وتقليص كلفة الانتاج.

البخار وسيلة لنقل الطاقة من المحرق إلى التربينة. هذا العامل يجب أن يؤخذ بعين الاعتبار بالاضافة إلى الضغط والحرارة، مثل هذا النوع من المنشآت صعب المراقبة والتحكم نظرا لتعدد المتغيرات والطبيعة اللاخطية لها طرق التحكم التقليدية ليست قادرة على التحكم الكلي مع ذلك لهذا فان العمل يقدم طرق جديدة لاستعمال الفازي لوجيك من أجل تحديد نقاط التحكم المثالية بطريقة أوتوماتيكية باستعمال ماتلاب 7.

الكلمات المفتاحية: بمحطات توليد الطاقة الحرارية، تمثيل رياضي، التوربين، الفازي لوجيك، التحكم ب أ د، التحكم الفازي باستعمال الربح النسبي والتكاملي.

Résumé

Le nombre de construction des nouvelles stations d’énergie thermique est relativement réduit. Cependant, 65% de l’énergie mondiale est produite par ces stations.
Dernièrement, plus d’importance a été donné a ces stations vis-à-vis la détérioration de leur efficacité qui est très bas ainsi qu’une importante perte de l’énergie thermique peut être réalisé. Pour générer la quantité nécessaire de l’énergie électrique. La turbine a besoin d’une équivalente quantité de l’énergie thermique pour remplacer les pertes. Minimisant ces derniers va introduire une réduction de la pollution ainsi que les couts de production.

La vapeur constitue un véhicule qui transporte l’énergie de la chambre de combustion vers l’arbre de la turbine. La quantité de vapeur n’est pas le seul paramètre à déterminer, la température et la pression doivent être aussi prise en considération pour une valeur donnée de l’énergie.

Les stations d’énergie thermique sont difficiles à contrôler a cause des non linéarités du système variant dans le temps. Les techniques de commande classique ne sont pas très approprié a cause du changement de la demande, la difficulté de trouver le bon model du system ou de faire des bons mesures sur leurs dynamiques.

Ce travaille présente une nouvelle méthode de commande des stations en utilisant la logique floue, la stratégie de commande est basée sur la détermination automatique des points de fonctionnement optimales nécessaire pour la régulation. Ce travail aussi présente l’utilisation de simulateur de stations thermique, en utilisant Matlab-Simulink version 7.

Mots clés: Station d’energie thermique, Modilisation, Turbine, Boiler, logic floue, commande PID, commande floue avec gain proportional et integral.

ABSTRACT

The number of construction of a new thermal power plant is relatively reduced. However, thermal power plants account for approximately 65% of the world’s power supply. Recently, there have been concerns regarding the deterioration in the efficiency of existing thermal power plants. The efficiency of such type of power plant is very low and great amount of loss in thermal energy may be noticed. In order to generate a required electrical energy, the turbine needs an equivalent amount of thermal energy in addition to the loss. Minimizing the loss leads to a reduction of pollutant in the environment as well as production cost. Steam is merely a vehicle which transports the energy from the burners to the turbine shaft. The flow of steam is not only the parameter that should be determined, but also the temperature and pressure must be taken into consideration for a given value of power.

However, thermal power plant is difficult to be controlled accurately due to the non-linear time varying behavior of the system. The conventional control techniques are unsuitable for it, because load demand changes, process modeling is difficult and lack of suitable measurement of plants’ dynamics.

This work presents a new approach for controlling both boiler and steam turbine of thermal power plant using Distributed Control System associated with Artificial Iintelligence such as Fuzzy logic. The control strategy is based on supervisor level using Fuzzy logic that is required to determine automatically the optimal process set points of regulations level. Besides, this work describes thermal power plant simulator developed by Matlab-Simulink.

Key words: Thermal Power plant, Modeling, Turbine controller, Boiler, Fuzzy logic, PID controller, Fuzzy gain proportional and integral controller.

Chapter I

INTRODUCTION

I.1- Introduction

In the increasingly competitive modern world, the industry faces new challenges of improving productivity and reducing costs. The continuing increase in demand for electric power, unanticipated delays in new generating capacity additions, and the trend toward larger generating stations and larger interconnections are among the many factors which gives a great importance to thermal power plants in order to strength the response capability of the power system and providing reliable and efficient electric service.

The world isn't steady-state, it's dynamic. Market and operating conditions in today's thermal power plants are constantly changing with a staggering number of variables to juggle. Basic regulatory control systems are designed to keep a plant at established control setpoints; however, they are not able to determine the optimal setpoints necessary for maximum advantage in today's highly competitive power generation environment. The more dynamic and complex the plant's operation, the more difficult this optimization becomes –involving many simultaneous operating and regulatory constraints along with real-time fluctuations in prices, costs, and equipment degradation. But within this complexity are significant profit-enhancing opportunities, waiting to be unlocked by a system that can take your basic control to a higher level of performance.

While the competitive advantages that can be realized with optimal setpoints are considerable, the secret of true plant optimization goes further. Simply delivering optimal setpoints to your operators for manual implementation is impractical they would need to make multiple setpoint changes every three to five minutes, while simultaneously ensuring that power and steam generation meet contractual and regulatory requirements, irrespective of host load and steam demands.

Thermal power plant is difficult to be controlled accurately due to the non-linear time varying behavior of the system. Due to load demand change, process modeling difficulties and lack of suitable measurement of plants dynamics make most of the conventional control techniques unsuitable, objectives are left in the hands of a human operator.

In order to overcome these difficulties, engineers have realized new controllers that incorporate human experience using artificial intelligence such as Fuzzy logic. These controllers are simples and lead to efficient solutions which give a human like quality [1],[2].

I.2 -HISTORICAL DEVELOPMENT OF ELECTRIC POWER

Power plants have developed for supplying electricity to the modern world, since a century and half ago. Although other types of energy have been used around the world, however, electricity is the most versatile form for widespread distributed energy. The power plants generate electrical energy after that it will be distributed to consumers through a transmission grid [3].

People first used muscle energy to gather food and build shelters. Muscle energy was used to grind grain with stones, chop wood with hand axes, and propel oar-powered ships. In many instances in history, conquered people became slaves and provided muscle energy for their conquerors.

Stones, axes, and oars are examples of tools that were developed to make muscle energy more effective. Water wheels and windmills replaced muscle power for grinding grain as long ago as 100 B.C.E. Wind and sails replaced muscle energy and oar-powered ships. Early electric power stations were driven by wind and flowing water, and were built where wind and flowing water were available.

Furnaces use heat to melt rock that contains metals such as copper, tin, iron, and uranium. Copper and tin were the first metals melted, and they could be combined to form bronze.

I.3.STEAM-GENERATED POWER

Heating water generates steam, which is used in steam engines for converting thermal energy into mechanical energy. Early steam engines drove a piston that was placed between condensing steam and air, as illustrated in Fig.1.1. When steam condenses, it occupies less volume and creates a partial vacuum. The air on the other side of the piston expands and can push the piston. By alternately injecting steam and letting it condense, the piston can be made to move in an oscillating linear motion.

English inventor Thomas Newcomen invented the steam engine in 1705 and built the first practical steam engine in 1712. Newcomen's steam engine was used to pump water from flooded coal mines. Steam condensation was induced in Newcomen's steam engine by spraying cold water into the chamber containing steam. The resulting condensation created the partial vacuum that allowed air to push the piston. Aweight attached to the rod used gravity to pull the piston back as steam once again entered the left-hand chamber, as shown in Fig.I.1.

Scottish engineer James Watt improved the efficiency of the steam engine by introducing the use of a separate vessel for collecting and condensing the expelled steam. Watt's assistant, William Murdock, developed a gear system design in 1781 that enabled the steam engine to produce circular motion. The ability to produce circular motion made it possible for steam engines to provide the power needed to turn wheels. Steam engines could be placed on platforms attached to wheels to provide power for transportation. Thus, this technology has been needed to develop steam-driven locomotives, paddle wheel boats, and ships with steam-driven propellers. Furthermore, steam engines did not have to be built near a particular fuel source.

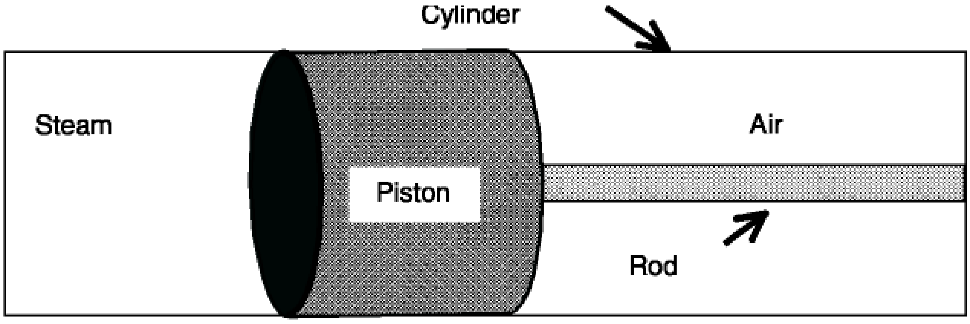

Figure I.1. Schematic of a simple steam engine.

I.4.ENERGY: TECHNOLOGY AND THE FUTUR TRENDS

Steam-generated power was an environmentally dirty source of power that was developed. Burning biomass, such as wood, or fossil fuel, such as coal, typically produced the heat needed to generate steam. Biomass and fossil fuels were also used in the home. Attempts to meet energy demand by burning primarily wood in sixteenth-century Britain led to deforestation and the search for a new fuel source . Fossil fuel in the form of coal became the fuel of choice in Britain and other industrialized nations. Coal gas, which is primarily methane, was burned in nineteenth-century homes.

The demand for energy had grown considerably by the nineteenth century. Energy for cooking food and heating and lighting homes was provided by burning wood, oil, or candles. The oil was obtained from such sources as surface seepages or whale blubber. Steam-generated power plants could only serve consumers in the immediate vicinity
of the power plant. A source of power was needed that could be transmitted to distant consumers.

In 1882, Thomas Edison was operating a first power plant in New York City. Edison’s plant generated direct current electricity at a voltage of 110 V. Nations around the world soon adopted the use of electricity. In 1889, a megawatt electric power station was operating in London, England. Industries began to switch from generating their own power to buying power from a power generating company.

But, a fundamental inefficiency was present in Edison’s approach to electric power generation.

I.5.GROWTH OF THE ELECTRIC POWER INDUSTRY

The power industry started out as a set of independently owned power companies. Because of the large amounts of money needed to build an efficient and comprehensive electric power infrastructure, the growth of the power industry required the consolidation of the smaller power companies into a set of fewer but larger power companies. The larger, regulated power-generating companies became public utilities that could afford to build regional electric power transmission grids. The ability to function more effectively at larger scales is an example of an economy of scale. Utility companies were able to generate and distribute more power at lower cost by building larger power plants and transmission grids.

The load on a utility is the demand for electrical power. Utilities need to have power plants that can meet three types of loads: base load, intermediate or cycling load, and peak load. The base load is the minimum base-line demand that must be met in a 24-hour day. Intermediate load is the demand that is required for several hours each day and tends to increase or decrease slowly. Peak load is the maximum demand that must be met in a 24-hour day.Electric power for small towns and rural communities was an expensive extension of the power transmission grid that required special support.

I.6. ELECTRIC POWER GENERATION

The first commercial-scale power plants were hydroelectric plants. The primary energy source (the energy that is used to operate an electricity-generating power plant) for a hydroelectric plant is water flow. Today, most electricity is generated by one of the following primary energy sources: coal, natural gas, oil, or nuclear power. Table I.1 presents the consumption of primary energy in the year 1999 as a percentage of total primary energy consumption in the world for a selection of primary energy types. The table is based on statistics maintained at a website by the Energy Information Administration (EIA), United States Department of Energy. The statistics have been considered approximately. They are quoted here because the EIA is a standard source of energy information that is widely referenced. The statistics give us an idea of the relative importance of different primary energy sources. Fossil fuels were clearly the dominant primary energy source at the end of the twentieth century. Electric energy, however, is the most versatile source of energy for running the twenty-first century world, and much of the primary energy is consumed in the generation of electric energy.

Table I.1: Primary energy consumption in 1999 by energy type [4]

Primary energy type	**Total world energy consumption**
Oil	39.9%
Natural gas	22.8%
Coal	22.2%
Hydroelectric	7.2%
Nuclear	6.6%
Geothermal, solar, wind and wood	0.7%

Chapter II

THERMAL POWER PLANT

Modern thermal power plants can generate power from 125 MW to 1000 MW. Any thermal power plant consists of a fuel storing system, boiler, turbine, generator, transformer, water handling, emission control system and other complementary accessories. All these units are managed in such a way to generate, regulate electricity and ensure a good product to the consumer.

A thermal power plant produces electricity starting from an energy source. This source can be natural gas, oils, nuclear or even solar energy. This energy source transforms the fluid, usually water, to a vapor. This vapor enters a turbine at high pressure and turns its shaft, which, by the way, turns the shaft of an alternator. The turbine transforms thermal energy into a mechanical one, and the generator transform this mechanical energy into electrical energy.

To turn on the turbine, the pressure of the vapor at the output has to be lower than that of the input. This is done by condensing the vapor downstream in the turbine using a cold source like water. The condensed water is always used as the source of the vapor; which makes a closed thermodynamic cycle.

There are different types of thermal plants: flammable, nuclear, solar and geothermal. In this chapter, the thermal power plants will be described such as located at CAP-DJINET.

II.1.POWER PLANT EFFICIENCY

The operational strategy of electric power plants was traditionally based upon the concept of generating electric power with a reliability and little regard for fuel economy, since fuel was cheap and abundant. However, since the sixties, due to the world economic crisis which gave rise to the oil crisis of the seventies, the utility industry began to show more interest for a deeper understanding of their own power plants with the objective of improving their economic behavior**.**
In the fossil-fired power plant, high-pressure and high temperature boilers are used for generation of electric power large capacity. Also, steam temperature deviation must be kept

within + - 5% in order to maintain boiler operating efficiency and equipment life time as well as to ensure safety. This control performance is depended on air flow and fuel flow.

Energy in general, and electricity in particular, plays a vital role in improving the standard
of life. A good example for thermal power plant can be from India, it has abundant proven reserves of coal of about 95 billion tonnes (Ministry of Coal, 2006) and thus coal-based thermal power plants dominate source-wise mix with 55%
installed capacity of a total of about 1,24,000 MWe (Ministry of Power, 2006). The power plants in India are coal-based operating on sub-critical steam conditions.
The indigenous coal used is of low grade with mineral matter content as high as 45%. In order to address increasing electricity demand and concern for environmental safety it is imperative to install power plants based on advanced coal technologies which are (more) energy efficient, environmentally acceptable, and economically viable. Energy and exergy analysis provides insight into losses in various components of a power generating system. Unlike energy, exergy is not generally conserved but is destroyed. So, the majority of the causes of irreversibilities like heat transfer through a finite temperature difference, chemical reactions, friction, and mixing are accounted by exergy analysis (Cengel and Boles, 2004). Rosen (2001) has compared the performance of operating coal-fired and nuclear steam power plant located in Canada of unit size of approximately 500 MWe using a process-simulator, Aspen Plus. Chew (2003) reviewed the sensitivity of supercritical steam plant cycle performance to operating conditions. Recently, Bugge et al. (2006) have presented the status and perspectives for the AD700 technology which involves the development of a coal-fired power plant with steam temperature of 700oC. The plant efficiencies of old power plants are still around 30% based on lower heating value (LHV) of fuel and modern subcritical cycles (500 MWe unit size) have attained efficiencies of about 35 - 38% (LHV). Further improvement in plant efficiency can be achieved by using supercritical steam conditions. Enhanced efficiency results in reduced emission of CO2 / unit kWh. The first supercritical coal fired power plant have being installed at with unit size of capacity 660 MWe (NTPC annual report, 2006)

II.2. CAP-DJINET POWER PLANT [5]

CAP-DJINET power plant that belongs to SONALGAZ Company is located in the front of the sea in CAP-DJINET, BOUMERDES. It has been made by the Austro-German companies: SIEMENS-KWU-SGP which was in charge of the study and the supervision of the plant's construction. Another company, Spanish (DRAGARDOS), has installed the pipelines and water pumping unit that pumps water from the sea. In addition, the Algerian companies such as ENCC, ETTERKIB, BATIMETAL, GENISIDER, INERGA, SNLB, PROSIDER, ENATUB, SNIC, GTP, SONATRAM, and SOGEP were contributed in the construction of CAP-DJINET power plant.

CAP-DJINET power plant contains 4 thermal-vapor units with a capacity of about 176 MW each, and a total of 706 MW. Generally amount of 672MW is transmitted to the network and power of 32MW is consumed internally in the plant. A boiler that serves the plant consumes 40,000 Nm^3 gas per hour when operating at full load. This gas is pipelined from HASSI R'MEL.

II.3. UNIT DESCRIPTION

Fuel (gas) is fed into the boiler where it is burned in order to heat water and rise its temperature to 540°C (1000F) in order to produce steam that has a pressure of about 160 bar in the boiler. When it enters the turbine, the steam is at a pressure level between 138 to 140 bar. The steam spreads through the turbine that consists of rows of blades attached to a shaft. The steam moves the blades of the turbine, which in turn rotates the shaft of a generator. The rotation of the generator induces alternating current in the windings of the stator. To ensure that the alternating current is maintained at the constant frequency (50 Hertz), both turbine and generator rotate at a constant speed (3000 rpm). The produced output voltage (15.5 kV) will be transformed to 6 kV by step-down transformer for internal use, and to 220 kV by a step-up transformer, in order to ensure efficient transmission over the entire network. A simple schematic of CAP-DJINET thermal Power Plant is shown in Fig.II.I

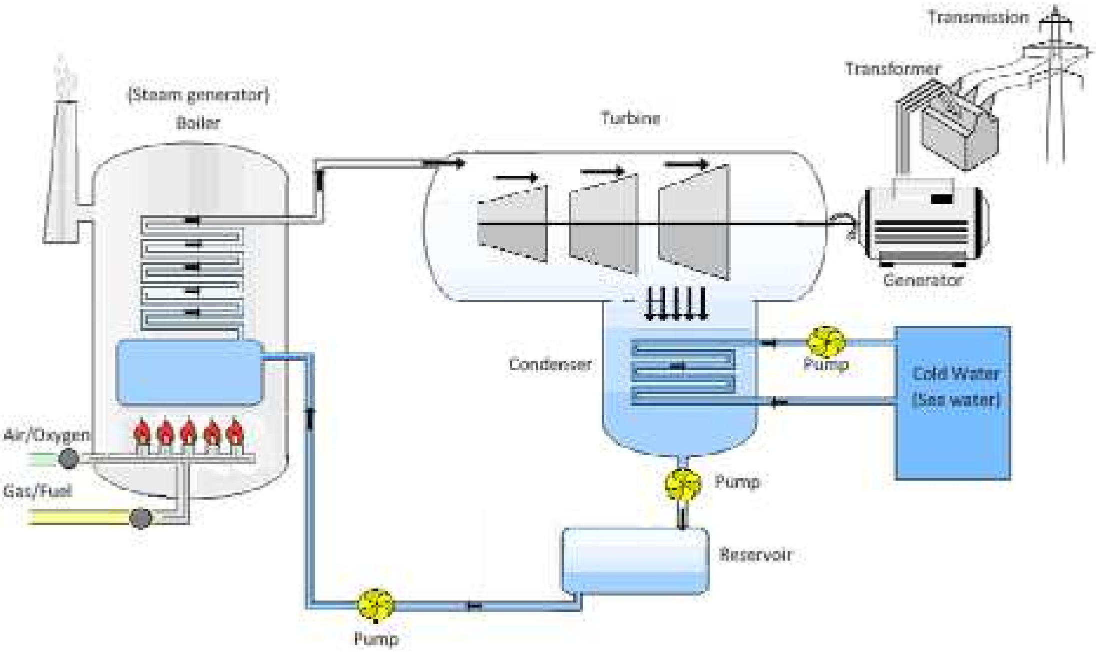

Figure II.1 Simplified schematic diagram of a thermal power plant.

The production of electricity in the power plant of CAP-DJINET starts from the thermal energy and takes different transformations. These transformations occur in different units which are mainly:

- boiler
- steam turbine
- synchronous generator
- transformer
- condenser

II.3.1. Steam generator (Boiler)

A boiler (usually called a steam generator) is a closed vessel in which water flows in transporting tubes. This water is heated under high pressure and transformed into steam that turns the group-turbine-generator. The type of boiler used in the Cap-Djinet power plant is the drum one, which means a large drum is used as a reservoir for fluid (no extracting pumps are used to feed back the water into furnace chamber). In the boiler, the steam attains a temperature of 540° and a pressure of 160 bars.

II.3.2. Steam turbine

The steam turbine is a mechanical device that converts thermal energy from pressurized steam into useful mechanical energy to rotate the shaft of a generator.

The turbine makes use of the fact that steam attains a high velocity, when passing through a small opening. The attained velocity during expansion depends on the initial and final heat content of the steam. This difference in heat content represents the heat energy converted into kinetic energy during the process. The steam turbine is composed of high pressure (HP), medium pressure (MP), and low pressure (LP) cores. All these units turn at a speed of 3000 TR/MIN.

To start the turbine, the electro-hydraulic motor is switched on in order to have an initial speed of 150 TPM (2.5s-1) and the safety valves are opened. After that, the speed controller is selected by the main controller until the set point or speed of 2820 TPM (47s-1) is reached. When speed of 2820 TPM is reached; the synchronizer varies the speed set point from 2820 TPM to 3180 TPM (53s-1) until the group is synchronized with the network at a speed of 3000 TPM (50Hz) and the alternator is coupled with the network. Hence, the group starts to deliver power to the network.

At that time, the selector takes the control by selecting the appropriate controller. Since a speed of 50Hz is reached, the selector selects the power controller that controls the generated power according to the network need (depending on the load). The pressure controller is selected in case of pressure drop that is not recovered by the boiler in a desirable time.

To stop the turbo-alternator group, the group is desynchronized from the network. The valves are closed by the speed controller until a speed of 210 TPM (3.5s-1) is reached. Hence, the electro-hydraulic motor starts. When the valves are totally closed, safety valves close, and the electro-hydraulic motor keep working until the turbine cools. The complete flow chart of the turbine operation is shown in Fig.II.2

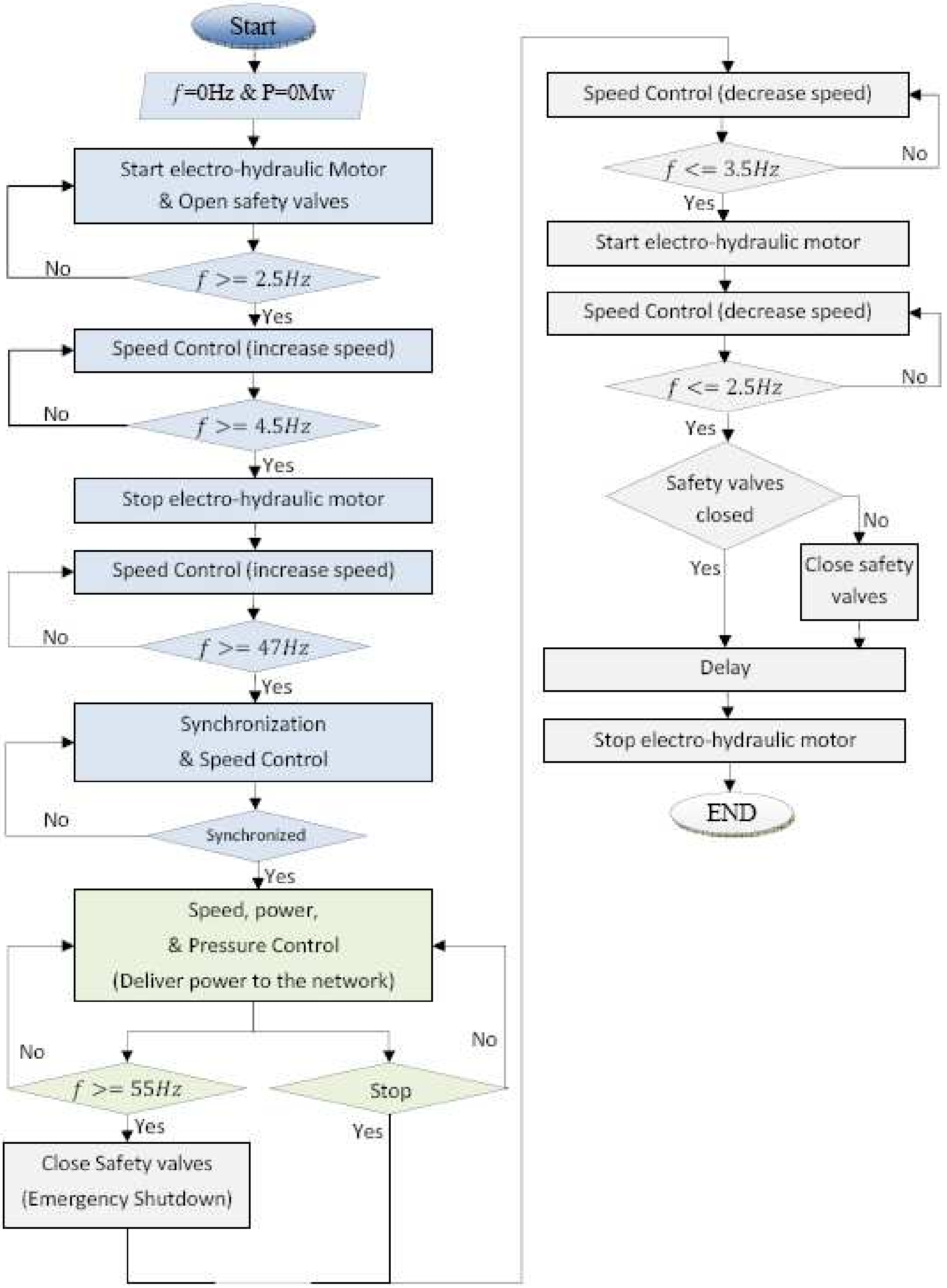

Figure II.2 Flow chart of turbine operation

II.3.3. Synchronous generator

A synchronous generator (alternator) converts mechanical energy to electrical one with an alternating current (AC). It consists of two essential elements: the stator and the rotor. A direct current (DC) is applied to the rotor winding to produce a magnetic field. By the rotation of the rotor (the rotation of the magnetic field), a three-phase voltage is induced in the stator windings. The parameters of the generated voltage are: apparent power of 220 MVA, power of 176 MW, voltage of 15500 V±10%, current of 8165 A, and a frequency of 50 Hz.

Each group in CAP-DJINET contains three alternators as shown in Fig.II.3.

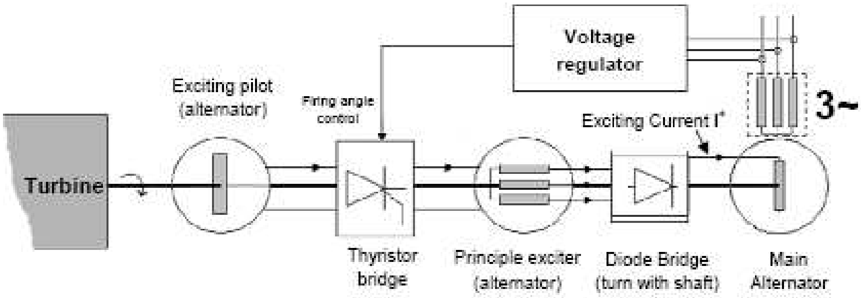

Figure II.3: Schematic diagram of the synchronous generator.

The turbine turns the exciting pilot which contains a natural magnet's rotor. This alternator generates a current at the stator which is converted to DC current by the thyristor bridge. The voltage regulator controls the RMS of the DC current by changing the firing angle. After that, the DC current is transferred to the rotor of the principle exciter. The principle exciter generates an AC current that is converted into a DC current through the use of Diode Bridge. This DC current is transferred to the rotor of the main alternator which is called the exciting current. The main alternator generates a three phase current with a voltage that depends on the exciting current.

II.3.4. Condenser

A condenser is a heat-exchange system, mounted at the outlet of the low pressure core of the steam turbine to condense steam. The condenser increases the efficiency of the turbines. From the bottom of the condenser, powerful pumps recycle the condensed steam (water) back to the feed water heaters for reusing it again. The heat absorbed by the circulation cooling water in the condenser tubes must also be removed to maintain the ability of the water to cool as it circulates. A proper operation of the condenser requires access to a large amount of water; therefore, the sea water is used.

It has been proved that the efficiency can be improved, when feeding back heated water; the gas consumption is much lower than that for a cold distilled water.

II.3.5. Heaters

Heater are the main elements of the Rankin cycle. Their role is to gradually heat up both the water coming from the condenser and the one extracted from high and intermediate pressure parts of the turbine.

II.3.6. Transformer

There are two main transformers, the step down transformer that converts the 15.5 kV to 6 kV for internal uses, and the step-up transformer that converts the voltage from 15.5 kV to 220 kV (see Fig.II.4). This will decrease the current, which in turn reduce energy loss and hence ensure efficient transmission over the network.

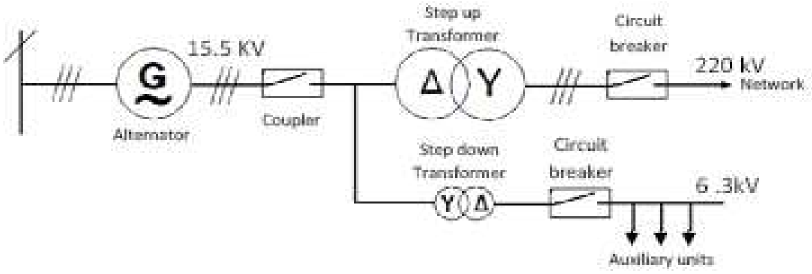

Figure II.4: Alternator connection to the network.

II.3.7.Steam Plant (Rankin) cycle

The Rankin cycle is the most widely used cycle for electric power generation as shown in Fig.II.5. The steam cycle is based on dry saturated steam being supplied by a boiler to the turbine. The steam from the turbine exhausts to a condenser, from which the condensed steam is pumped back into the boiler passing through heaters.

Higher plant efficiency is obtained if the steam is initially superheated, and this means that less steam and less fuel are required for a specific output. Heaters are often used in large utility plants because they give additional steam energy to the low-pressure portion of the turbine; thus, increasing the overall plant efficiency.

By adding regenerative feed water heating, the Rankin cycle is improved significantly. This is done by extracting steam from different stages of the turbine

(three extractions from high pressure core, two from medium pressure core, and one from the condenser) to heat the fed-back water as it is pumped from the condenser to the boiler to complete the cycle.

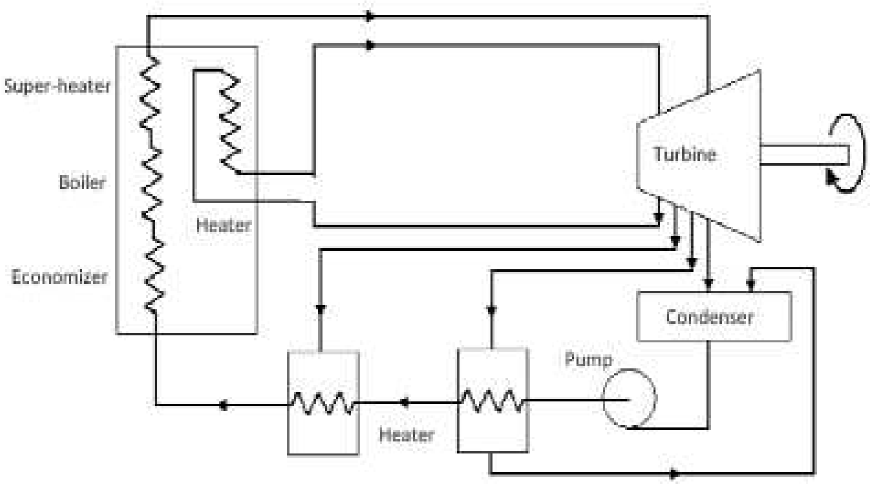

Figure II.5: Schematic diagram of the Rankin cycle

II.4- OVER ALL PLANT PRESENTATION

Figure II.6 shows the overall thermal power plant construction, and the main components with the auxiliary equipments.

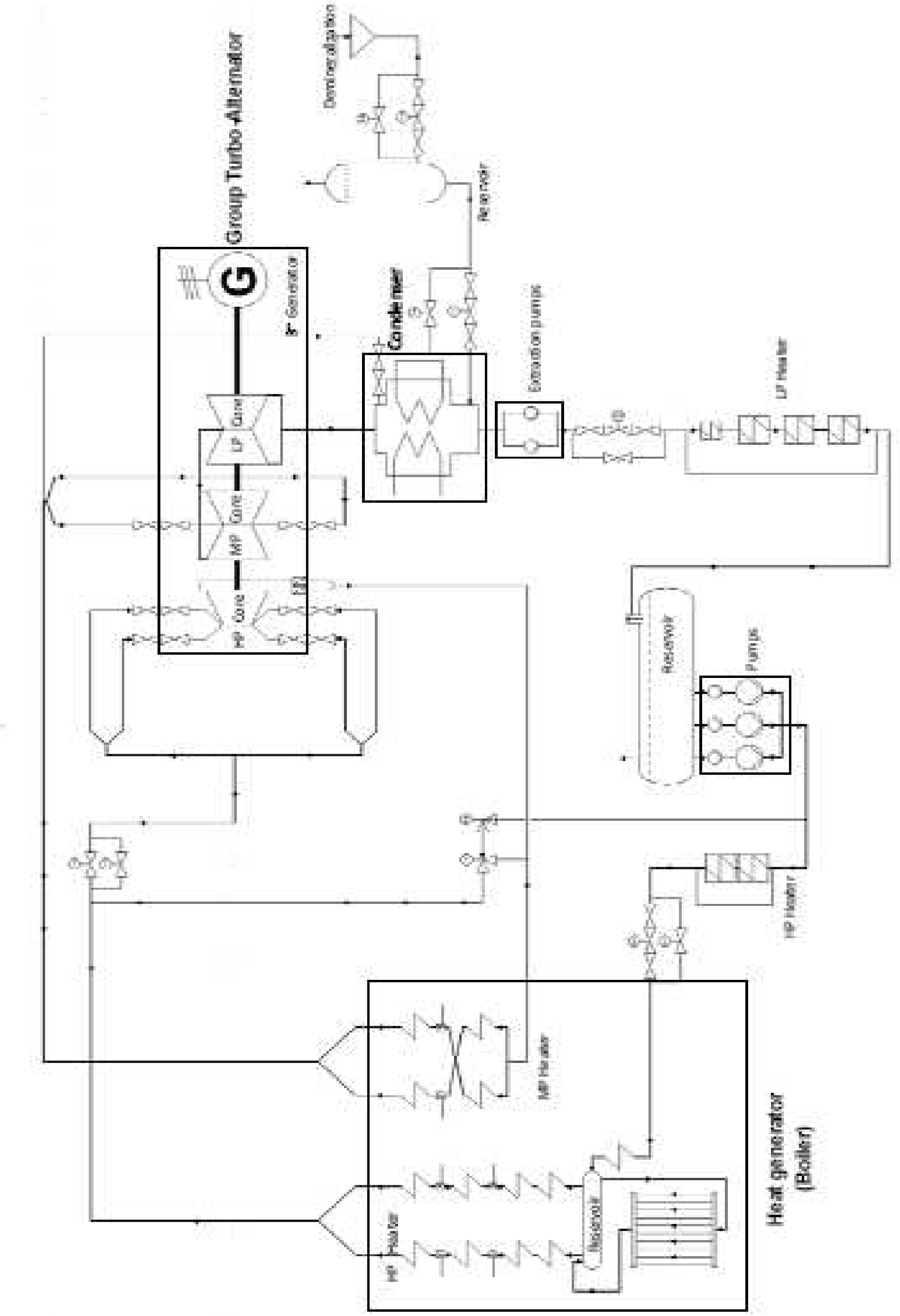

Figure II.6: Overall power plant schematic diagram.

Chapter III

FUZZY LOGIC

Nowadays, instead of conventional control techniques, modern control techniques have been implemented in many industrial plants. In this study, a fuzzy logic-based control technique to regulate the turbine output of a 176 MW thermal power plant has been carried out. For comparison purpose, a conventional proportional, integral and derivative (PID), a fuzzy logic (FL) and a fuzzy gain scheduled proportional and integral (FGPI) controllers have been applied to the power plant.

III.1 THEORY

III.1.1 Fuzzy Sets

This section summarizes the basic concepts and notations of fuzzy set theory and fuzzy logic that will be needed in the following sections. Since research on the subject has been underway for over 30 years it is difficult to cover all aspects of developments in this area. A detailed treatment of the subject may be found in references [6], (Zadeh,1965), (Zadeh,1973) and (Zimmermann, 1985).The idea of fuzzy sets is introduced by the way of an example. Let X be the range of temperature values known as the universe of discourse (or more simply universe) and its elements be denoted as x. Let A be a set of high temperature values that are at least 30°C and $f_A(x)$ be the function called the characteristic function of A.

$$f_A(x) : X \to 0,1 \tag{III.1}$$

Where

$f_A(x) = 1$ if $x \in A$.

$f_A(x) = 0$ if $x \notin A$

This set maps universe X to a set of two elements. For any element x of universe X, the characteristic function $f_A(x)$ is equal to 1 if x is ($\geq 30C$) belonging to set A, and is equal to 0 if x is (< 30°C) not belonging to set A. A is commonly known as a classical or crisp set which has a "clear-cut" boundary. The characteristic function $f_A(x)$ is shown in Fig.III.1. It describes the crisp set of all temperature values greater than or equal to 30°C.

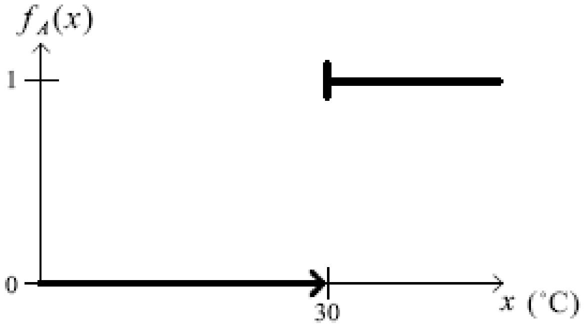

Fig. III.1 Characteristic function $f_A(x)$ *of all temperature values greater than or equal to 30°C.*

In a crisp set, the almost identical elements like the temperature values of 29.9°C and 30.1°C are treated as being completely different. On the other hand, a fuzzy set is a set with a vague boundary. Each value of temperature is associated with a degree of membership. A degree of membership may assume values between 0 and 1. That is, the transition from "belonging to a set" to "not belonging to a set" is gradual. A fuzzy set A of universe X is defined by $\mu_A(x)$ called the membership function (MF) of x in A.

$$\mu_A(x) : X \rightarrow [0,1] \qquad \text{(III.2)}$$

Where

$\mu_A(x) = 1$ if x is totally in A,

$\mu_A(x) = 0$ if x is not in A at all,

$0 < \mu_A(x) < 1$ if x is partly in A.

Figure III.2 shows the membership function $\mu_A(x)$ of all temperature values, e.g. the temperature

25°C with a value of 0.7. This means the temperature of 25°C corresponds to the property “high temperature” with a membership degree of 0.7 on a scale from 0 to 1. The closer the membership degree is to 1 the more strongly x satisfies the property “high temperature”.

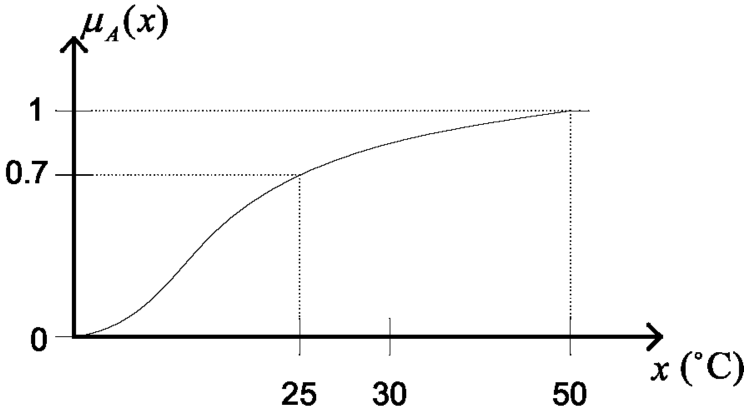

Figure III.2: The membership function $\mu_A(x)$ of all temperature values.

Obviously the definition of a fuzzy set is a natural extension of the definition of a classical set in which the characteristic function is permitted to have continuous values between 0 and 1. If the value of the membership function $\mu_A(x)$ is restricted to either 0 or 1, then A is reduced to a classical set, and $\mu_A(x)$ is the characteristic function of A.

III.1.2.Linguistic Variables and Linguistic Values

The following simple example serves as an introduction to the concept of linguistic variables and linguistic values.

In everyday communication, we often use short sentences, which give the same information as longer ones. When we say that "the weather is too hot" we actually mean that "the weather's temperature belongs to the too hot (very high) category." Even if we knew that the temperature is exactly 42°C, in everyday communication we

prefer saying that "the weather is too hot," as we would assume that there is a common understanding what a very high temperature in weather terms means.

The term temperature may attain two different values: numerical (42°C) and linguistic (too hot).

Variables, for which values are words or sentences, rather than numbers, are called linguistic variables. In this example, the variable temperature may have linguistic values such as very high (too hot), high, medium, low, and very low. This is why linguistic values are sometimes referred to as fuzzy sets.

A fuzzy set is uniquely specified by its membership function. To describe membership functions more specifically, the nomenclature used in the literature (Jang, 1997) will be followed.

-Support

The support of a fuzzy set *A* is the set of all points *x* in *X* such that $\mu_A(x) > 0$

$$\text{Support}\quad (A) = \{x / \mu_A(x) > 0\} \qquad \text{(III.3)}$$

-Core

The core of a fuzzy set *A* is the set of all points *x* in *X* such that $\mu_A(x) = 1$

$$\text{Core}\,(A) = \{x / \mu_A(x) = 1\} \qquad \text{(III.4)}$$

-Normality

A fuzzy set *A* is normal if its core is non-empty. In other words, we can always find a point

$$x \in X \ \text{ such that } \mu_A(x) = 1 \qquad \text{(III.5)}$$

-Crossover points

A crossover point of a fuzzy set *A* is a point $x \in X$ at which $\mu_A(x) = 0.5$

$$crossover(A) = \{x / \mu_A(x) = 0.5\} \qquad \text{(III.6)}$$

-Fuzzy singleton

A fuzzy set whose support is a single point in *X* with $\mu_A(x) = 1$ is called a fuzzy singleton

Corresponding to the ordinary set operations, i.e., union, intersection and complement, fuzzy sets have similar operations, which were initially defined by

Zadeh[1]. These fuzzy sets operations are containment (or subset), union (or disjunction), intersection (or conjunction), complement (or negation), Cartesian product and co-product,

As mentioned earlier, a fuzzy set is completely characterized by its MF. A more convenient way to define a MF is to express it as a mathematical formula.

III.2. Types of Membership Functions

Eight types of membership function (MF) will be described. They are bell MF, triangular MF, Gaussian MF, two-sided Gaussian MF, pi-shaped MF, product of two sigmoidal MFs, difference between two sigmoidal MFs, and trapezoidal MF.

III.2.1.The triangular MF

The triangular MF is expressed as:

$$f(x,a,b,c)=\begin{Bmatrix} 0, x\le a \\ \dfrac{x-a}{b-a}, a\le x\le b \\ \dfrac{c-x}{c-b}, b\le x\le c \\ 0, c\le x \end{Bmatrix}, \qquad \text{(III.7)}$$

where the parameters *a, b* and *c* describe the shape of the triangular MF.

III.2.2.Trapezoidal MF

Trapezoidal MF is expressed as:

$$f(x,a,b,c,d)=\begin{Bmatrix} 0, x\le a \\ \dfrac{x-a}{b-a}, a\le x\le b \\ 1, b\le x\le c \\ \dfrac{d-x}{d-c}, c\le x\le d \\ 0, d\le x \end{Bmatrix}, \qquad \text{(III.8)}$$

where the shape of the trapezoidal MF is decided by the parameters *a, b, c* and *d.*

III.2.3.Gaussian MF

For the Gaussian MF, the expression is:

$$f\left(x,c,\sigma\right)=e^{-\frac{(x-c)^2}{2\sigma^2}}, \tag{III.9}$$

where the parameters c and σ decide the shape of the Gaussian MF.

III.2.4.The two-sided Gaussian MF

The two-sided Gaussian MF is expressed as:

$$f(x,c_1,c_2,\sigma_1,\sigma_2)=\left\{\begin{matrix} e^{-\frac{(x-c_1)^2}{2\sigma_1^2}},x\leq c_1 \\ 1,c_1\leq x\leq c_2 \\ e^{-\frac{(x-c_2)^2}{2\sigma_2^2}},c_2\leq x \end{matrix}\right\}, \tag{III.10}$$

where the shape is decided by the parameters σ_1,c_1 and σ_2,c_2 which correspond to the widths and centers of the left and right half Gaussian functions.

III.2.5.Bell-shaped MF

The bell-shaped MF, is expressed as:

$$f(x,a,b,c)=\frac{1}{1+\left|\frac{x-c}{a}\right|^{2b}}, \tag{III.11}$$

where the parameters *a*, *b*, and *c* describe the shape of bell-shaped MF.

The product of two sigmoidal MFs is expressed as:

$$f(x,a_1,c_1,a_2,c_2)=\frac{1}{(1+e^{-a_1(x-c_1)})(1+e^{-a_2(x-c_2)})} \tag{III.12}$$

where the parameters a_1,c_1,a_2,c_2 describe the shapes of two sigmoid MFs

The difference between two sigmoidal MFs is expressed as:

$$f(x,a_1,c_1,a_2,c_2)=\left|\frac{1}{(1+e^{-a_1(x-c_1)})}-\frac{1}{(1+e^{-a_2(x-c_2)})}\right| \qquad \text{(III.13)}$$

where the parameters a_1, c_1, a_2, c_2 describe the shapes of two sigmoid MFs

The pi-shaped MF is the product of *Z* shape and *S* shape functions. It is expressed as:

$$f(x,a,c)=\begin{Bmatrix} S(x,c-a,c), x\le c \\ Z(x,c,c+a), x>c \end{Bmatrix}, \qquad \text{(III.14)}$$

where *c* is the centre and a (> 0) is the spread on each side of the MF.

III.3.FUZZY RULES

III.3.1. if-then Rules

The goal of fuzzy systems is to mimic a human operator's action or to make humanlike decisions by using the knowledge about a target system (without knowing its model).

This is achieved with fuzzy if-then rules (also known as fuzzy rules, fuzzy implications, or fuzzy conditional statements. For example If *x is A then y is B*

where *x and y* are linguistic variables; *A and B* are linguistic values determined by fuzzy sets on (ranges of possible values) universe of discourses *X and Y*, respectively.

Often the *if* part of the rule *"x is A"* is called the antecedent or premise part and the then part of the rule *"y is B"* is called the consequence or conclusion part.

Due to their concise form, fuzzy if-then rules are often employed to capture the imprecise modes of reasoning that play an important role in the human ability to make decision in an environment of uncertainty and imprecision.

The following examples describe the difference between classical and fuzzy rules

A classical *if-then* rule uses binary logic, for example,

Rule: 1

If the temperature is ≥ 30°C *then* the weather is hot
Rule: 2
if the temperature is < 20°C *then* the weather is cold

In this example the linguistic variable temperature can have any numerical value between 0 and 50°C, but the linguistic variable weather can only take either value hot or cold. In other words, classical rules are expressed in the true or false form.

A fuzzy if-then rule of the above example can be expressed as:
Rule: 1
if the temperature is high *then* the weather is hot
Rule: 2
if the temperature is low *then* the weather is cold

Here the linguistic variable temperature also has the range (universe of discourse) between 0 and 50°C, but this range includes fuzzy sets, such as low, medium, and high. The linguistic variable weather may include fuzzy sets as cold, warm and hot. Thus fuzzy rules relate to fuzzy sets.

Another form of fuzzy if-then rule, proposed by (Takagi, 1983), has fuzzy sets involved only in the premise part. The consequent part of Takagi-Sugeno (TS for short) fuzzy if-then rule is a real-valued function of the input variables instead of a fuzzy set. A TS fuzzy if-then can be expressed in the following general form:

$$if\ x_1 \text{ is } A_{1,} \text{ and } x_n \text{ is } A_n \text{ , } then\ \ y = f(x_1, x_2, ..., x_n)\text{ ,} \qquad \text{(III.14)}$$

where $f()$ is a real-valued function.

III.3.2.Fuzzy Reasoning

Fuzzy reasoning, also known as approximate reasoning, is an inference (inferencing is the process of reasoning about a particular state of the underlying system, using all available knowledge to produce a best estimate of the output) procedure that derives conclusions from a set of fuzzy if-then rules and known facts. Before describing fuzzy reasoning, we need to understand the concept behind the compositional rule of inference, which can be found in (Zadeh, 1973).

Several types of fuzzy reasoning have been used in the literature, a sample of these can be found in (Lee, 1990). In general, the process of fuzzy reasoning can be divided into four steps:

III.3.3.Degree of compatibility

Compare the known facts with the antecedents of fuzzy rules to find the degrees of compatibility with respect to each antecedent MF.

III.3.4.Firing Strength

Combine degrees of compatibility with respect to antecedent MFs in a rule using fuzzy AND (intersection) or OR (union) operators to form a firing strength that indicates the degree to which the antecedent part of the rule is satisfied.

III.3.5.Qualified (induced) consequent MFs

Apply the firing strength to the consequent MF of a rule to generate a qualified consequent MF.

III.3.6.Overall output MF

Aggregate all the qualified consequent MFs to obtain an overall output MF.

III.4.Fuzzy Inference Systems

The fuzzy inference system is a popular computing framework based on the concepts of fuzzy set theory, fuzzy if-then rules, and fuzzy reasoning (Jang, 1997). It has found successful applications in a wide variety of fields such as automatic control, data classification, decision analysis, expert systems, time series prediction, robotics, and pattern recognition (Jamshidi, 1997). Because of its multidisciplinary nature, the fuzzy inference system is known by numerous other names, such as fuzzy expert system (Kandel, 1992), fuzzy model (Sugeno, 1988), fuzzy associative memory (Kosko, 1991), and simply fuzzy system.

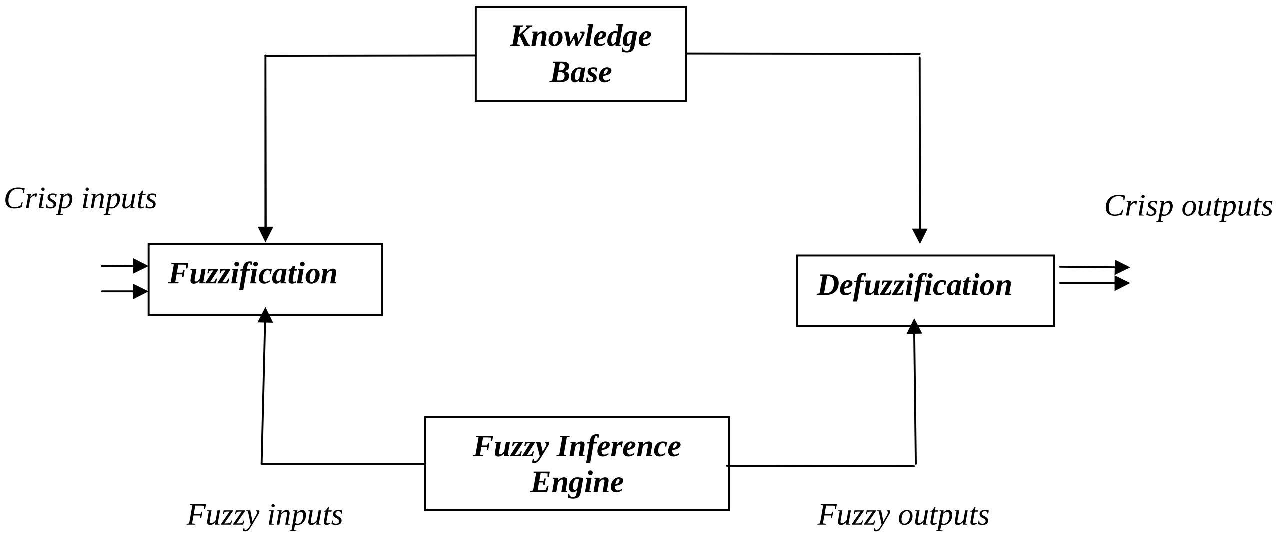

Figure III.3: The basic components of a fuzzy inference system

A fuzzy inference system (FIS) consists of four functional blocks as shown in Figure III.3.

Fuzzification:

transforms the crisp inputs into degrees of match with linguistic values.

Knowledge base:

consists of a rule base and a database. A rule base contains a number of fuzzy *if-then* rules. A database defines the MFs of the fuzzy sets used in the fuzzy rules.

Fuzzy inference engine:

performs the inference operations on the rules.

Defuzzification:

It transforms the fuzzy results of the inference into a crisp output.

As indicated in Fig. III.3, the FIS can be envisioned as involving a knowledge base and a processing stage (consisting of fuzzification, fuzzy inference engine and defuzzication stages).

The knowledge base provides MFs and fuzzy rules needed for the process. In the processing stage, numerical crisp variables are the input of the system. These variables are passed

through a fuzzification stage where they are transformed to linguistic variables, which become the fuzzy input for the fuzzy inference engine. This fuzzy input is transformed by the rules of the fuzzy inference engine to fuzzy output.

The linguistic results are then changed by a defuzzication stage into numerical values that become the output of the system.

Depending on the types of fuzzy reasoning and fuzzy if-then rules employed, a fuzzy inference system can be classified into three types: The

Tsukamoto-type FIS (Tsukamoto, 1979), Mamdani-type FIS (Mamdani, 1975) and Takagi-Sugeno-type FIS (Sugeno, 1988). An in depth analysis of each of these fuzzy inference systems can be found in (Jang, 1997).

Chapter IV

POWER PLANT MODELING

The dynamic behavior of industrial plants heavily depends on disturbances and in particular on changes in operating point. This is particularly the case for thermal power plants. Such plants represent from the control engineering point of view a time-variant and nonlinear multivariable process with strong interactions. Therefore, they are very difficult to control them [7][8].

Power plants have some inputs and outputs. The main input variables of a thermal power plant are fuel flow, feed water, injection water and air. The outputs of the system are electrical power, steam pressure, steam temperature, and combustion gas as shown in Fig.IV.1. Some of the inputs and outputs are more important than the others since these are adequate for modeling the power plant. These are Fuel feed and feed water flow as the inputs, and the electrical power as the outputs illustrated in Fig. IV.1,[9].

Power plant is a multivariable dynamic system. Most of the thermal power plants have been controlled by conventional controller techniques, especially conventional PID or PI controllers for many years since these controllers are easy to implement on systems due to their simple structures. However, changing the power demands, quality differences of the Fuel and contamination of the boiler heating surfaces are problem for controlling the system outputs with conventional controllers. In addition, although there is a reduced mathematical model of a power plant, it is usually non-linear, time-variant and governed by strong cross-coupling of the input variables. All these problems are removed by using advanced control techniques [10]. One of the major techniques is fuzzy logic control. There have been many improvements in the theory of this controller design during the last decades. Consequently, this technique has been widely used in power plants [11], [12].

In this work, three different control techniques have been applied to regulate the power output of the thermal power plant comparatively [13]. These techniques are a PID controller, a fuzzy logic controller (FLC) and a fuzzy gain scheduled PI controller (FGPI).

V.1. SYSTEM MODELING

The investigated plant represents a 706 MW combinational block consisting of a generator/steam turbine unit providing 672MW electrical power [18] due to a fuel fired once-through boiler with live steam at 140 bar and 535°C.

.The power plant consists of boiler, turbine and generator. The boiler can be modeled by a strongly coupled multivariable system. This makes it very interesting from a control engineering point of view. In the boiler, the chemical energy is converted to thermal energy.

The dynamic behavior of a boiler heavily depends on many different operating conditions, as explained below:

- The efficiency of the fuel feeder decreases in time,
- drying of heating surfaces, burners, feeders etc. cause changes in the system dynamics,
- changes in reference variables and load represent changes in the operating point,
- changes of the outlet temperature of the gas turbine in a combinational power station block due to climatic changes may strongly influence the boiler dynamics.

The dynamic and static properties of the system must be well known to design an efficient controller. On the other hand, it is complicated to handle such a complex system with several inputs and outputs. Therefore the most important input and output variables will be used for model buildings. For the investigated power plant, two inputs (Air flow and Fuel feed) and one output (Power) variables are sufficient to describe the desired process behavior as shown in Fig.IV.1.

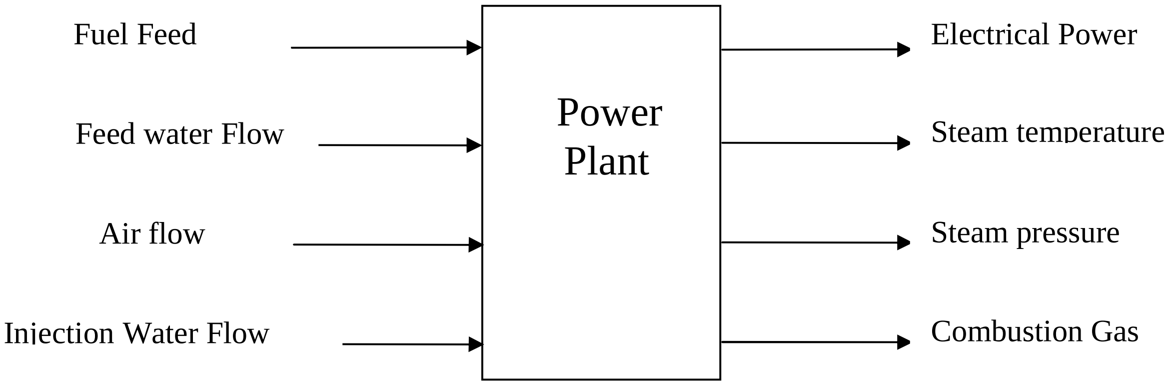

Figure IV.1 Power plants as multivariable dynamic system.

The fuel feed and air flow is chosen as input variables. The output variable is electrical power. The speed of power change depends on only the steam generator. That means, by this operation, the steam generation immediately influences on the generated electrical power, which is important for the user.[14] [15].

Control diagram of the power plant model is shown in Fig.IV.2.

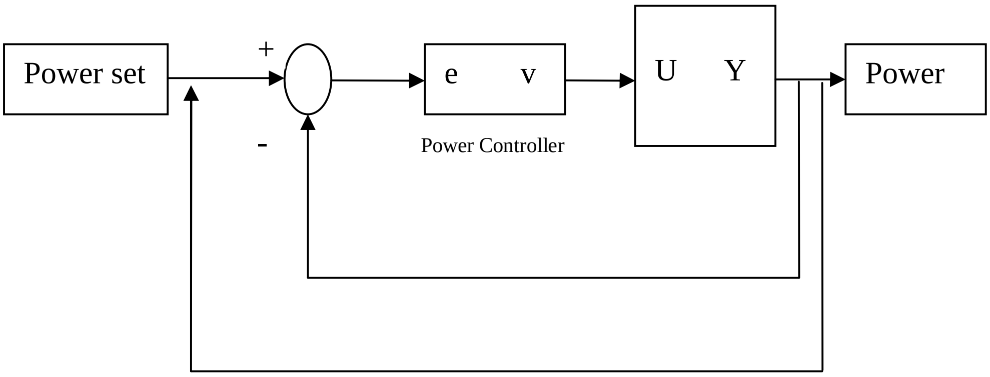

Figure IV.2 Power plant model.

In the Fig.IV.2, three controllers having different structures are used to control the outputs. These controllers were applied to the system one by one. For this reason, first a

PID and following a FL controller and finally a FGPI controller were applied to the power system as power controller. The process model is shown in Fig IV.3
Simulation have been done using Powerful software MATLAB, Parameters that have been used for simulation have been taken from steam Turbine generator (SIEMENS-KWU-SGP) of 176 MW manufactured by consortium of Austria-germane.

The syste model is shown in Fig IV.4, [16] [17].,it is widely used for Thermal power plant having approximatively the same characteristic(Input/output) as Cabdjenet pow plant.

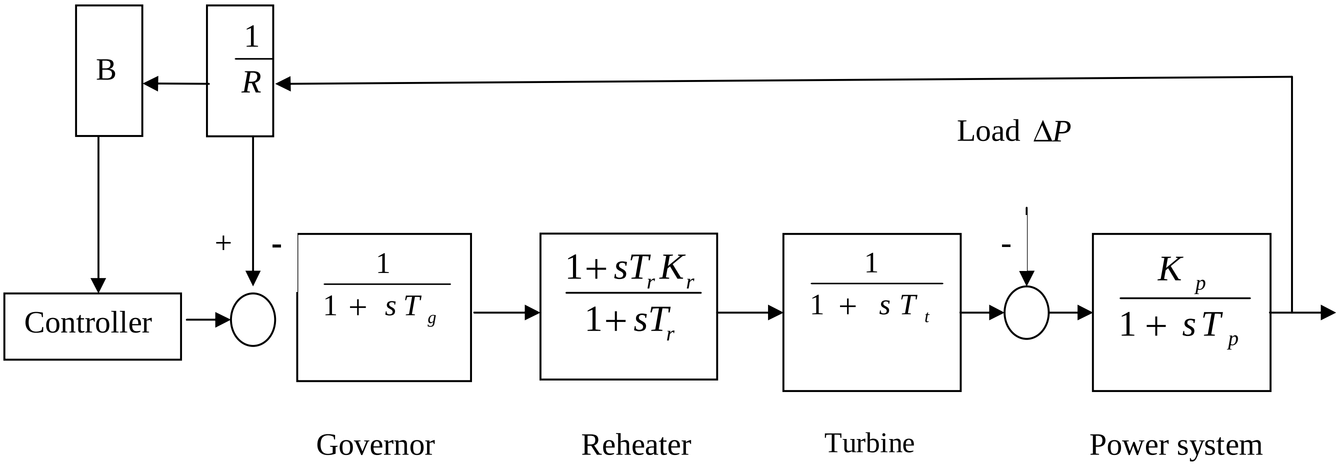

Figure IV.3. The structure of power plan Model.

The correspondent constant values are the following:

Governor time-constant	$T_g = 0.08s$
Turbine time-constant	$T_t = 0.3s$
Reheater time-constant	$T_r = 10s$
Power system time-constant	$T_p = 20s$
Power system gain	$K_p = 120hz\,/\text{p.u.}MW$
Speed regulation due to governor action	$R = 2.4hz\,/\,\text{p.u.}MW$
Reheat coefficient	$K_r = 0.5$

Frequency bias setting $B = 0.425$
From the closed-loop characteristic equation, the stability conditions for the system with t using proportional-integral control are found as :

$$\frac{(T_g + T_t + T_p)(1/T_g + 1/T_t + 1/T_p) - (1 + K_p / R)}{K_p B} \langle k_p \langle \frac{1 + K_p / R}{K_p B} \qquad \text{(IV.1)}$$

And

$$-a.\frac{(1 + K_p / R + K_p B k_p)}{K_p B.(T_g T_t + T_t T_p + T_p T_g)} \langle k_i \langle 0 \qquad \text{(IV.2)}$$

Where

$$a = \frac{(T_g + T_t + T_p).(1/T_g + 1/T_t + 1/T_p) - (1 + K_p / R + K_p B k_p)}{(1/T_g + 1/T_t + 1/T_p)} \qquad \text{(IV.3)}$$

With the specifications given in above, we have:

$$1 < k_p < 5.3471 \qquad \text{(IV.4)}$$

$$0 < k_i < 2.252 \qquad \text{(IV.5)}$$

IV.2. PID CONTROLLER

In steady state operation, a PID controller regulates the value of the output so as to drive the error (e) to zero. A measure of the error is given by the difference between the set point (SP) (the desired operating point) and the process variable (PV) (the actual operating point). The principle of PID control is based upon the following equation that expresses the

output, M(t), as a function of a proportional term, an integral term, and a differential term:

Output = Proportional term + integral term + Differential term

$$M(t) = K_p * e + K_p K_i \int_0^t e.dt + M_{initial} + K_p K_d * de/dt \qquad \text{(IV.6)}$$

$M(t)$: The loop output as a function of time

K_p : The loop gain

K_i : The proportional constant of the integral term

K_d : The proportional constant of the differential term

e : The loop error (difference between set point and process variable)

$M_{initial}$: Initial value of loop output.

In order to implement this control function in a digital computer, the continuous function must be quantized into periodic samples of the error value with subsequent calculation of the output.

The corresponding equation that is the basis for the computer solution is:

Output = Proportional term + integral term + Differential term

$$M(t) = K_p * e + K_p K_i \sum e_x + M_{initial} + K_p K_d * de/dt \qquad \text{(IV.7)}$$

M_n : The calculated value of the loop output at sample time n

K_p : The loop gain

e_n : The value of the loop error at sample time n

e_{n-1} : The value of the loop error at sample time n-1

e_x : The value of the loop error at sample time x

K_i : Proportional constant of integral term

$M_{initial}$: Initial value of the lop output

Kd : Proportional constant of the differential term

From this equation, the integral term is shown to be a function of all the error terms from the first sample to the current sample. The differential term is a function of the current sample and the previous sample, while the proportional term is only a function of the current sample. In a digital computer, it is not practical to store all samples of the error term, and it is not necessary. Since the digital computer must calculate the output value each time the error is sampled beginning with the first sample, it is only necessary to store the previous value of the error and the previous value of the integral term. As a result of the repetitive nature of the digital computer solution, a simplification in the equation that must be solved at any sample time can be made. The simplified equation is:

Output = Propotionel term + integral term + Differential term

$$M(t) = K_p * e + K_p K_i * e_n + MX + K_p K_d * (e_n - e_{n-1}) \qquad \text{(IV.8)}$$

MX : The previous value of the integral term (at sample time n-1)

IV.2.1.The Proportional Term of the PID Equation

The proportional term MP is the product of the gain (KC), which controls the sensitivity of the output calculation, and the error (e), which is the difference between the set point (SP) and the process variable (PV) at a given sample time.

The equation for the proportional term is

$$K_p * e = +K_p (SP_N - PV_N) \qquad \text{(IV.9)}$$

K_p : The loop gain

SP_N : The value of set point at sample time n

PV_N : The value of process variable at sample time n

IV.2.2- The Integral Term of the PID Equation

The integral term MI is proportional to the sum of the error over time. The equation for the integral term is:

$$K_pK_i * e_n + MX = K_p * Ts / Ti * (SP_N - PV_N) + MX \quad \text{(IV.10)}$$

K_c : The loop gain

Ts : The loop sample time

Ti : The integration period of the loop (integration time)

IV.2.3.The Differential Term of the PID Equation

The differential term MD is proportional to the change in the error. the equation for the differential term is:

$$K_pK_d * (e_n - e_{n-1}) = K_p * Td / Ti * \{ \ (SP_N - PV_N) - (SP_{n-1} - PV_{n-1}) \ \} \quad \text{(IV.11)}$$

$SP_n = SP_{n-1}$

To avoid step changes or bumps in the output due to derivative action on set point changes, this equation is modified to assume that the set point is a constant $SP_n = SP_{n-1}$. This results in the calculation of the change in the process variable instead of the change in the error as shown:

$$K_pK_d * (e_n - e_{n-1}) = K_p * Td / Ti * (PV_{n-1} - PV_n) \ \} \quad \text{(IV.12)}$$

Td : The differential period of the loop (derivative time)

IV.3. Control Strategies

IV.3.1 Existing Control Strategy

The most modern thermal generation plants use a control scheme that is usually named an integrated or coordinated control system. This type of controller simultaneously adjusts firing rate, pumping rate, and turbine throttling in order to follow changes in load demand. Such a coordinated control mode is shown in Fig.IV.3 In this type of control, both pressure and generated output are fed back for the control of both boiler and turbine. In this manner, it is possible to achieve the stable and smooth load changes of the turbine-following mode and still enjoy the prompt response of the boiler-following mode. This is accomplished by making maximum use of the available thermal storage in the boiler. Both pumping and firing rates are made proportional to the generation error so that these efforts are stabilized as the load approaches the required value. Pressure deviation is controlled as a function of the thermal storage and the generation error.

The turbine controls the frequency and power that is supplied to the electric network. To control these parameters, the turbine uses three conventional

controllers for speed, power, and pressure. More over, the selector makes decision which of these controllers takes control. The selected controller acts on the inlet of the turbine (inlet of HP and MP cores); by acting on the position setter that acts on the valves of the turbine inlets.

Nowadays, the control strategies for the thermal plant are organized using different hierarchical levels. In the supervisor levels, the control strategies are coordinated and the process set-points are determined.

However, in the regulations level, the control loops of the dynamic parameters of the power plant have been implemented.

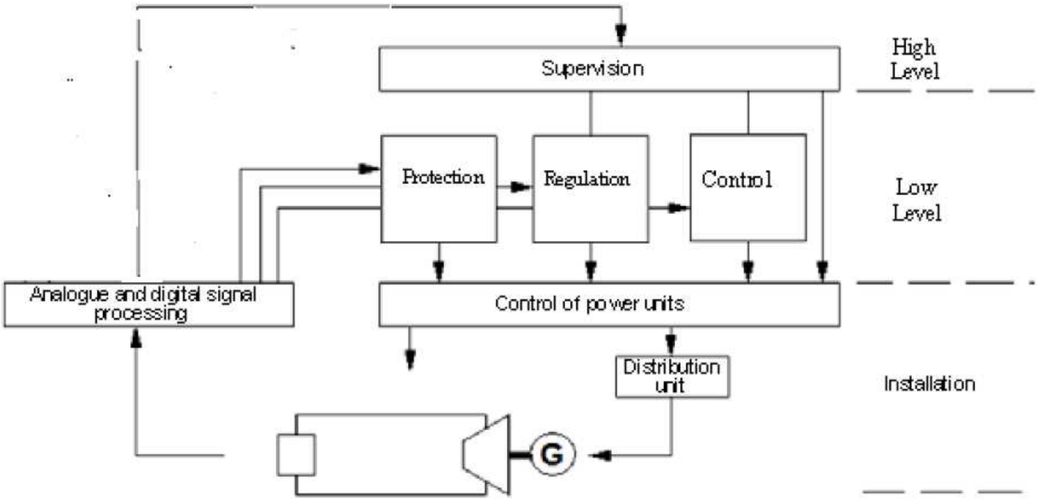

Fig.IV.4 Block diagram of DCS controlling system in power plant.

IV.3.2 A Proposed Control Strategy

The proposed controller is based on supervisor level that is required to determine automatically the optimal process set points of regulations level using an economic optimizer and considering the process environmental and operational constraints. After that the supervisor level makes correction continuously through the use of Fuzzy logic to the existing conventional regulations. In order to implement such control strategy, a distributed control system (DCS) is required as shown in Fig. IV.4. The DCS controlling system is based on computer associated with PLC's. The computer is supervisor level that is required to determine automatically the optimal process set points of regulations level. After that the set points values are sent to PLC's that act as the existing conventional regulations. This distributed control system employs PLCs as direct controllers. In our design, four PLC's of Siemens S-200 CPUs are used, wherein control loops algorithms are implemented to act in response with the supervisory controller; three of them are used to control boiler turbine and generator dynamics separately and the fourth one is dedicated to safety measures. [18] [19]

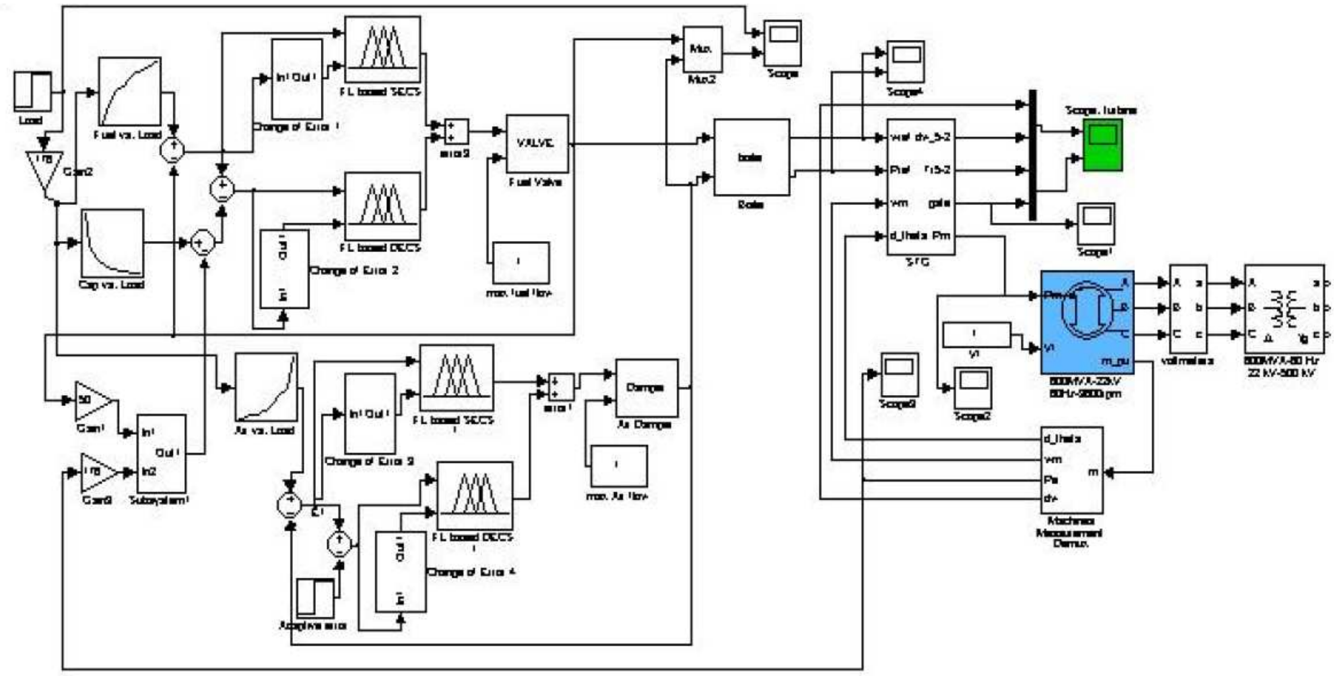

Fig.IV.5 Power Plant Model using Simulink.

IV.3.3 Power Plant Model using Simulink /Matlab

Simulator has been developed for steam turbine generator using the powerful software program Matlab/Simulink. It includes boiler, steam turbine and generator as shown in Fig.IV.4. Parameters that have been used for testing this simulator have been taken from steam turbine generator (SIEMENS-KWU-SGP) of 176 MW located in Cap-Djinet.

The used conventional controllers which are simples in structure are not suitable for non-linear, higher order, time delayed and complex systems that have no precise mathematical models. Besides, these controllers need frequent tuning that is not easy task and is also time consuming.

Several methods have recently been developed, most of them are based on controllers with fuzzy system without incorporating any on line adaptive structure and its applications particularly for combustion control of boiler.

Fuzzy systems, as an artificial intelligence approach, emerge in power plant as a complement to mathematical approaches. For a comprehensive survey of fuzzy set theory in power plants, the reader is referred to chapter III.

Fuzzy-logic controllers (FLC) can be classified as knowledge based systems (KBS). There are principally two classes of KBSs; namely: supervisory expert control systems (SECS) and direct expert control system (DECS) [20],[21]. SECS's use FL to tune the controller in the main loop.

IV.3.4 Adaptive Error Factor

For simulation, The error resulting from actual Power and requested one were used, another option to improve the performance, can be the adaptive variable error set point. When there is dynamic change due to load demand change the adaptive error calculation is proposed by taking into consideration the difference between the actual specific heat consumption and the required one. An adaptive error, which is equivalent to the required (adaptive) at particular load, is calculated as follows:

$$e_a = C_{sp} - (k_c \frac{Q_f}{P_g}) \qquad (IV.13)$$

where, k_c is constant (in this case 9.6), P_g generated power, and C_{sp} specific heat consumption set-point determined from the characteristic of the power plant.

IV.4.TURBINE CONTROLLER

The turbine is another important unit in the power plant. It controls the frequency and power that is supplied to the electric network. To control these parameters, the turbine uses three PID controllers: speed, power, and pressure controller; in our studies we will be interested to the power only as main parameter, the selected controller acts on the inlet of the turbine (inlet of HP and MP cores); by acting on the position setter that plays on the valves of the turbine inlets.

When starting the turbine, the speed is controlled until the generated power frequency reaches the desired one; during this time the generator is not connected to the electric network. When the desired frequency is reached
(50 Hz), the generator is synchronized with the electric network by mean of the synchronizer, and coupled to the electric network.

At this time, the power controller controls the turbine to generate the required power to the network. The power controller acts also on the valves of the turbine's inlet, but this time the position of the valves is controlled to increase or decrease the torque exerted by the turbine, to make it equivalent to the power needed by the load connected to the network**.**

When $\tau_{turbine} = \tau_{load} \Rightarrow$ The speed/frequency is constant in the network.

The power controller ensures the control of power after the alternator synchronization with the network. It consists of set point selector and PI regulator (see Fig. IV.5)

At the power controller, the power set point is selected at the set point selector depending on the operating mode (auto/manual). Before this set point enters the PI regulator, it is combined with the signal that is generated proportional to the influence of the network frequency. The combined signal is limited by the power limit. The difference between the limited power set point and the measured power enters the PI controller and the output passes to the selector (select speed, pressure or power controller).

IV.4.1 Selector:

It is a logic circuit that selects the maximum signal between the signal of speed controller and power controller. The selected signal is compared with the signal of the pressure controller. The minimum signal between the last two signals takes control of the turbine. In case there is an increase of speed over the nominal value, the speed controller is selected. The power controller reacts when the alternator is synchronized with the network.

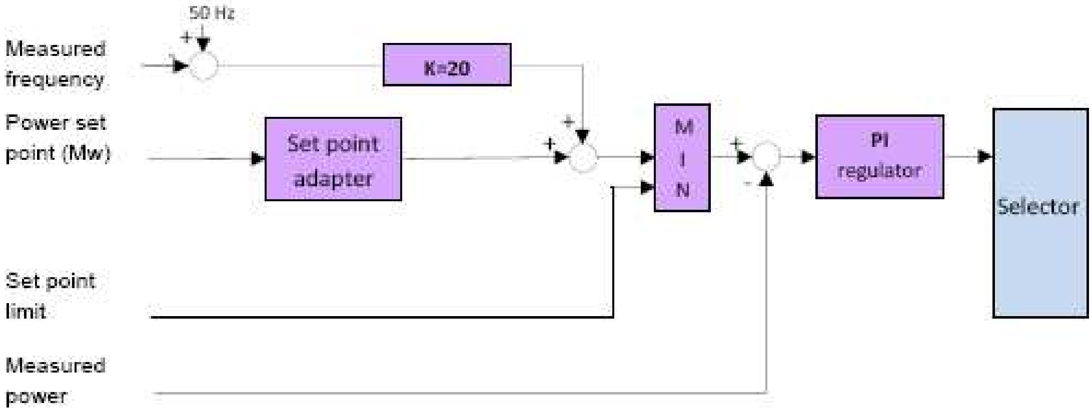

Fig. IV.6 Power set controller

The parameters of the power PI controller are:

$$f(s) = \frac{h(s)}{e(s)} = k_p . (1 + \frac{1}{T_i S}) \qquad \text{(IV.14)}$$

$h(s)$: The output of the PI regulator (desired power)

$e(s)$: input error (power error)

k_p =0.1

T_i =15sec

Chapter V

Simulation Results

V.1 Fuel and Air Controller in the Boiler Using FLC

The proposed fuzzy control for fuel and air control system is shown in Fig.IV.4. The characteristics of thermal power plant (SIEMENS-KWU-SGP) have been used as given table V.1 and shown in two response graphs, one gives fuel as function power demand (Fig.V.1) and the other airflow versus power demand (Fig.V.2).

The fuel and the airflow set points can be derived from the graphs in our simulator from these characteristics (FigsV.1 and V.2).

The difference between the set point and the actual air or gas flow is computed as error signal. The proposed DECS implemented for combustion process using fuzzy logic control has two inputs and one output for fuel and airflow respectively. The inputs are error signal and change in error signal. The universe of discourse of the controller variables are e, Δe and U respectively. The following are the range of database considered. Error (e) =-50% to +50%, Δe = -25% to +25%, control valve position (U) =10% to 100%. The number of linguistic terms for each linguistic variable is 5. (e) for fuel = {MN, N, Z, P, MP}, (Δe) for fuel = {VS,S,M,L,VL}, (U) for fuel ={VS, S,M,L,VL}, (e) for air = {MN, N,Z,P,MP}, (Δe) for air = {VS,S,M,L,VL}, (U) for air = {VS,S,M,L,VL}.

The triangular membership functions are used to represent the linguistic terms. (VS=very small, S=small, M=medium, L=large, VL=very large, MN=medium negative, N=negative, Z=zero, P=positive, MP=medium positive).

The processed signal from the fuzzy controller is defuzzyfied and applied to the respective adder circuit. In the proposed FLC based SECS, the difference between feed-forward error and the adaptive error. The error and the change of the error are taken as inputs of the proposed SECS controller. The processed signal is defuzzyfied and applied to the respective adder circuit.

Table V.1. Cap-Djinet Unit's Fuel and Air Consumption and Power demand.

POWER (MW)	110	120	130	140	150	160	176
Fuel (m^3/h)	25325	27459	29980	31725	33875	35990	40060
Air (m^3/h)	256250	281250	293750	318750	337500	362500	412500

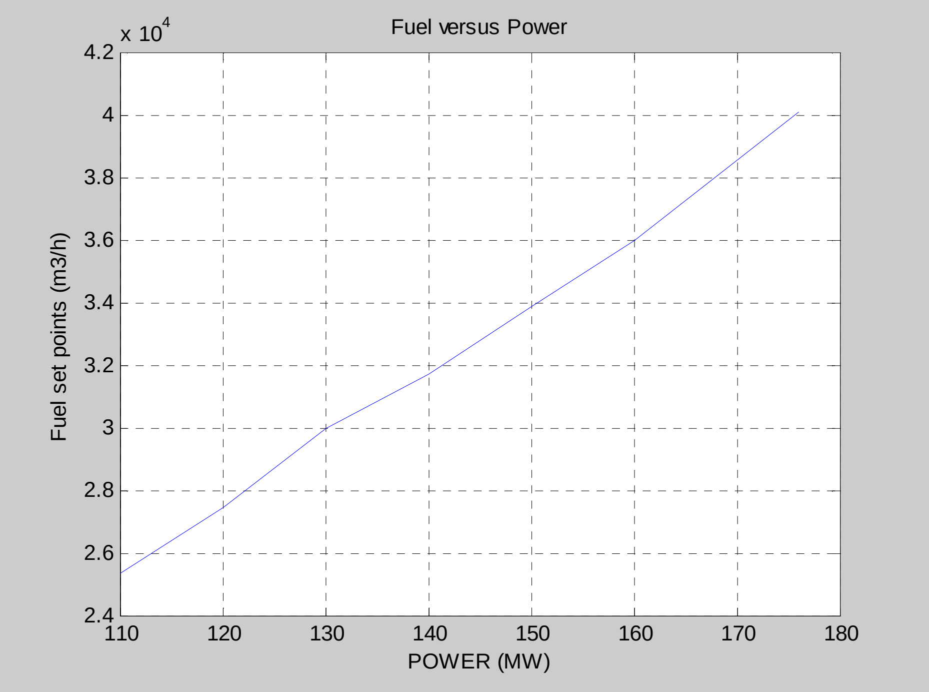

Figure V.1 Fuel consumption set point as function of generated power.

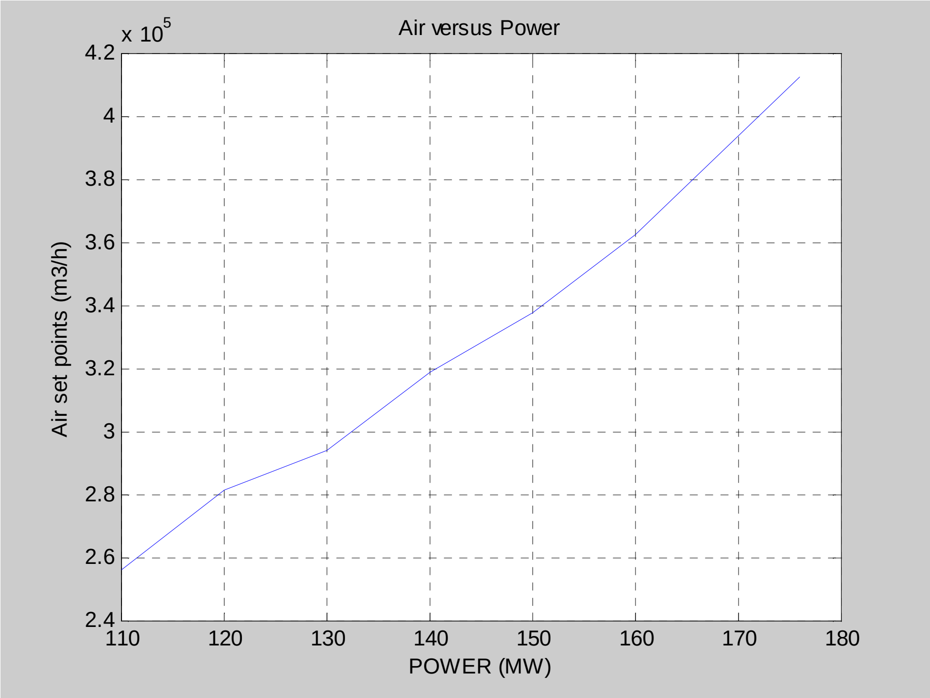

Figure V.2 Air consumption set point versus power output.

The sum of the DECS and SECS output signal is supplied to the fuel control valve as well as the air damper.

V.1.2 Simulation Results and Discussion

The simulator based on the previous equations plus others none described here [22] has been implemented as shown in Fig.IV.4. The simulation results that have been carried out on the combustion control of the boiler have been shown in Fig.V.3 and IV.4. The control objective is to regulate fuel and air flow in proper ratio by including optimization and environmental criteria. The performance of SECS controller is demonstrated for positive changes in the load demand. The closed loop response of the proposed SECS controlling scheme (Fig.V.3 and V.4) shows satisfactory offset in the steady state output for optimizing the fuel consumption when compared to conventional controller without optimizer. Moreover, there is less oscillation in controllers outputs.

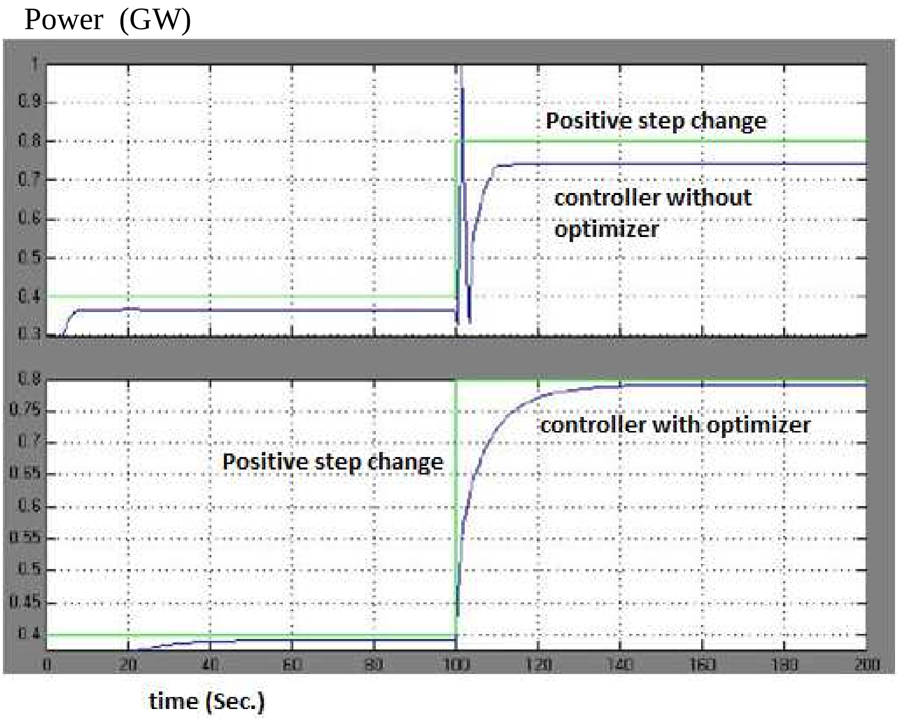

Fig.V.3 Fuel flow Controller response for positive step change in Load, (a) Upper without optimizer, (b) Lower with Optimizer.

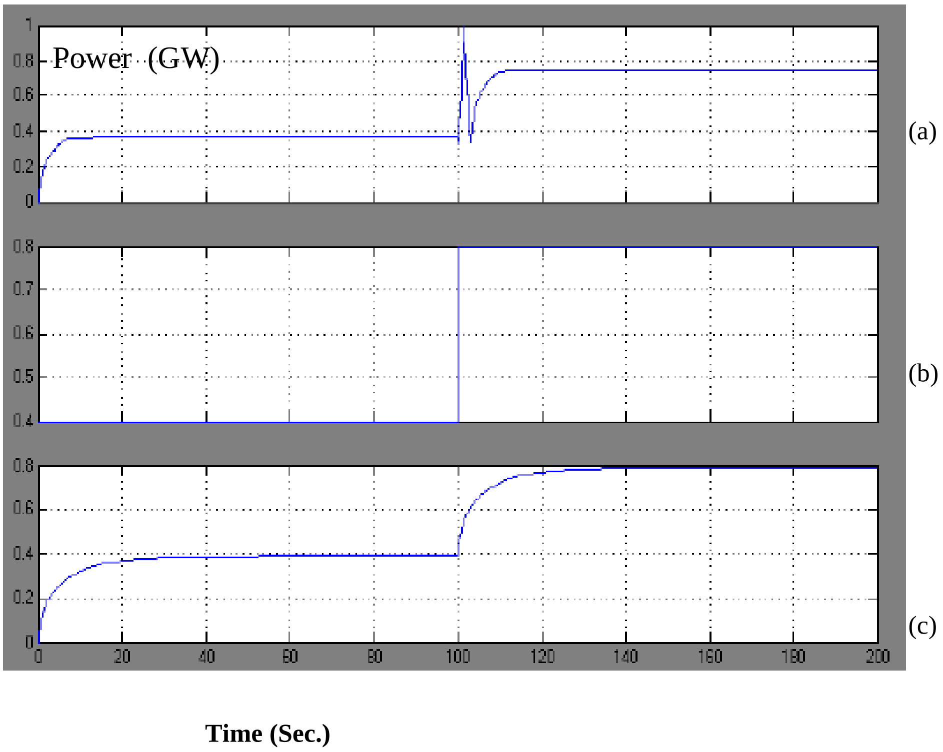

Fig V.4 Air flow Controller response for positive step change in Load, (a) Upper without optimizer, (b) medium air flow set point, (c) Lower with Optimizer.

V.2 TURBINE CONTROLLER

The selector takes the control by selecting the appropriate controller. Since a speed of 50Hz is reached, the selector selects the power controller that controls the generated power according to the network need (depending on the load). The pressure controller is selected in case of pressure drop that is not recovered by the boiler in a desirable time.

Figure (V.5) shows the simulation Result of generated power using PID controller in the power plant.

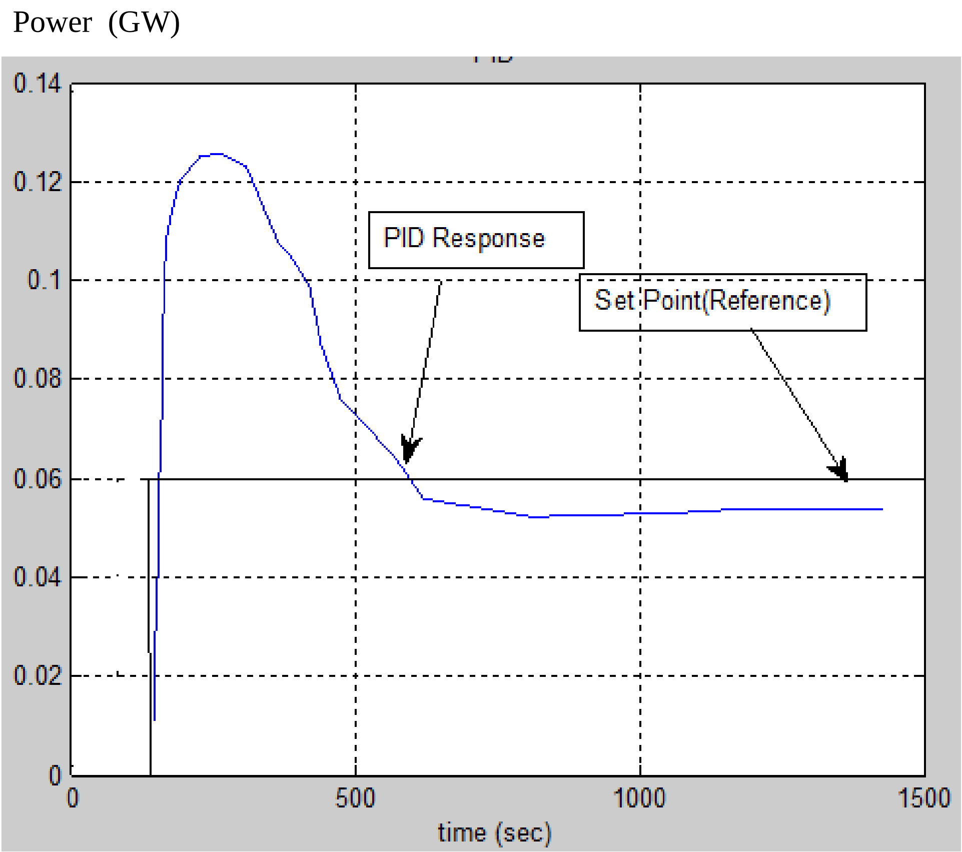

Fig. V.5. Generated power of power plant using PID controller.

V.2.1 Turbine Controller Using FLC

In the proposed power plant, fuzzy logic controller is used for power output. Inference mechanisms of the fuzzy logic controller are realized by seven rules. In addition, defuzzification has been performed by the center of gravity method in the studies. The rules which are belong to the membership function are formed based on the error (*e*) and its time derivative (*de*).

-If the *e* is highly bigger than the set value and *de* is increased rapidly then the output of the controller *V* is also has to be big. Therefore, *u* is increased and output of the system is goes to the set value. In this work, the appropriate rules are given in Table V.2[23] [24] .

Table V.3. Fuzzy logic rules for power output

e \ de	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NB	NM	NM
NM	NM	NM	NM	NM	NM	NS	NS
NS	NS	NS	NS	NS	NS	Z	Z
Z	Z	Z	Z	Z	Z	PS	PS
PS	PS	PS	PS	PS	PS	PM	PM
PM	PM	PM	PM	PM	PM	PM	PB
PB	PB	PB	PB	PB	PB	PB	PB

Names of the abbreviation in Table V.2 are NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium), PB (Positive Big) respectively. Fuzzy logic shows experience and preference through membership functions. These functions have different shapes depending on system experts' experience [25][26].

The membership function sets for error (*ei*), derivative errors (*dei*) and decoupling unit inputs (*Vi*) are shown in Figure V.6, V.7 and Figure V.8.

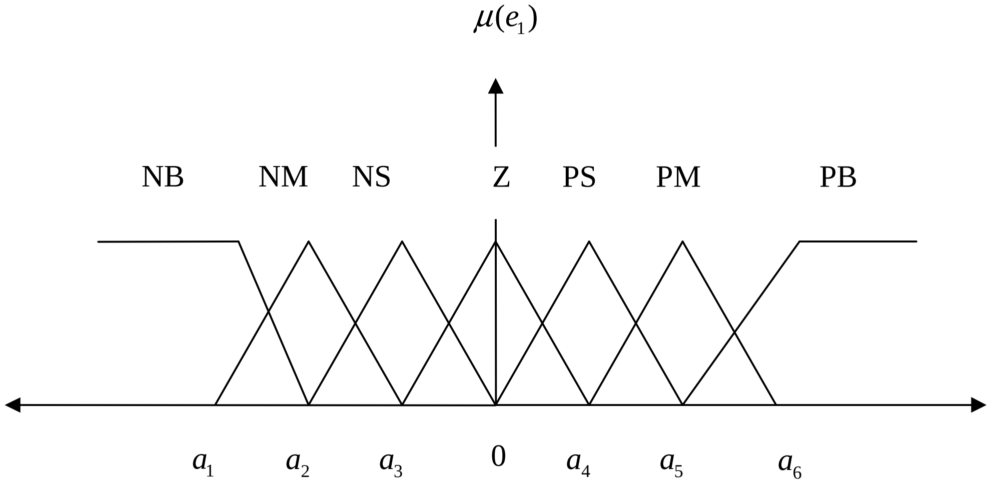

Figure V.6 The membership function sets for error (ei)

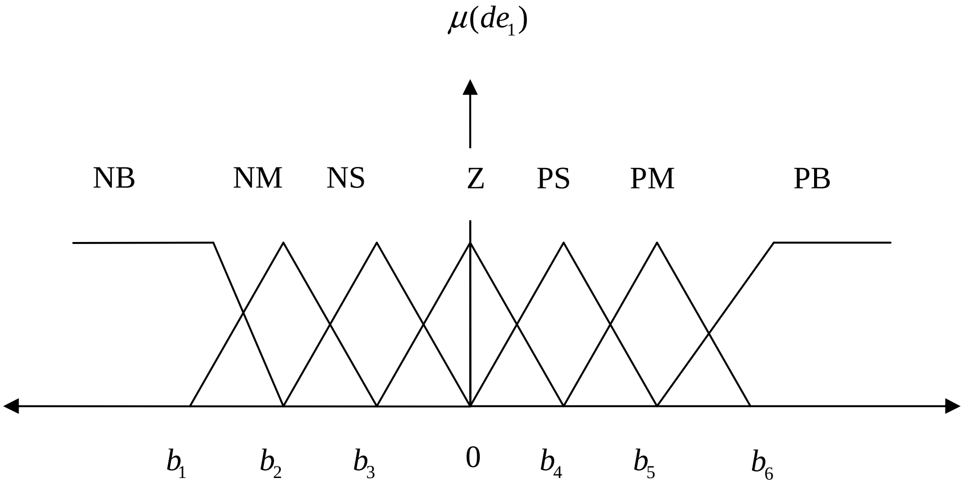

Figure V.7.The membership function sets for error (dei)

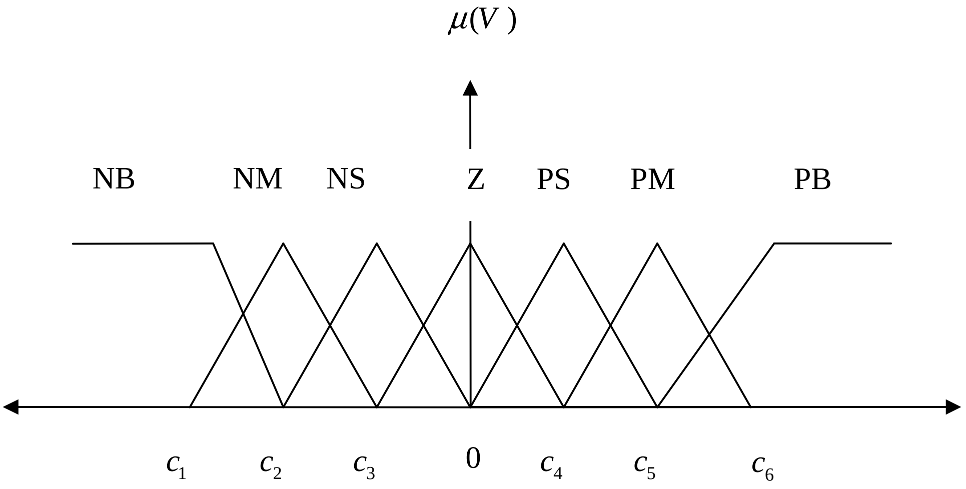

Figure V.8.The membership function sets for the command V

Using Fuzzy logic controller, the following result has been obtained, a further comparison with the first PID controller has been shown in Fig.V.9.

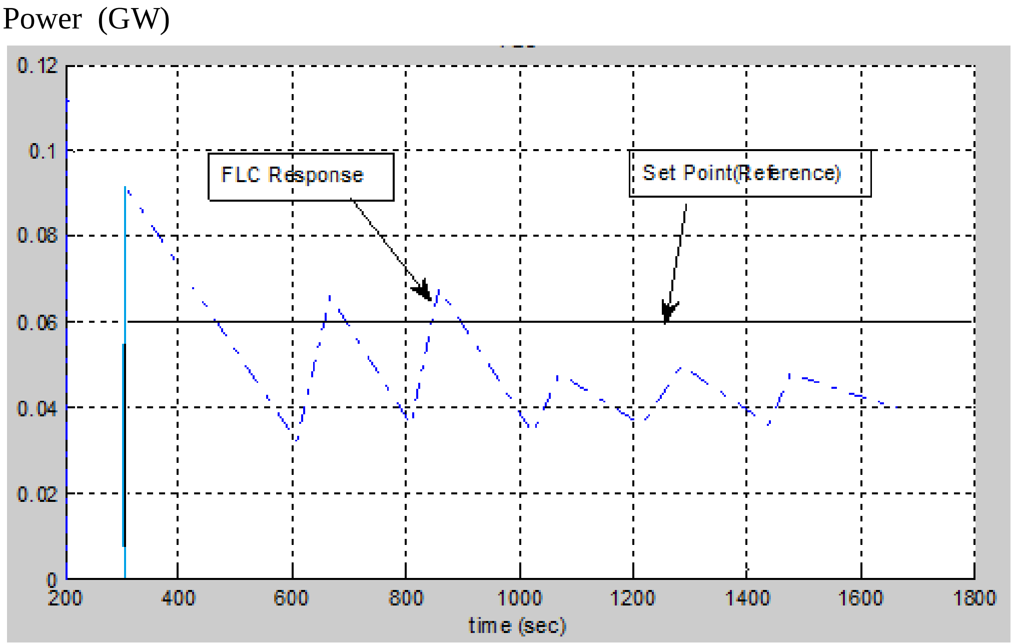

Figure V.9 Turbine Controller using FLC.

V.2.2 Turbine Controller Using FGPI

In this study, a fuzzy gain scheduling proportional and integral (FGPI), controller is proposed to regulate output of power since it is a suitable technique for non-linear and time-variant systems. This technique is used to adjust the gains of the PI controller according to disturbances in the system outputs. Two different FGPI controllers have been applied for power output. The inference mechanism for both controllers has seven rules and membership functions. Th appropriate rules for Ki and Kp are given in *Tables V.4 and V.5,* All rules in the tables are prepared as in FLC. The membership functions of this controller are given in Figure V.10 , V.11 and figure V.12.

Table V.4 Rules of KI parameters for power output

e \ de	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NB	NM	NM
NM	NM	NM	NM	NM	NM	NS	NS
NS	NS	NS	NS	NS	NS	Z	Z
Z	Z	Z	Z	Z	Z	PS	PS
PS	PS	PS	PS	PS	PS	PM	PM
PM	PM	PM	PM	PM	PM	PM	PB
PB	PB	PB	PB	PB	PB	PB	PB

Table V.5. Rules of Kp parameters for power output.

e \ de	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	PB	PB	PB	PB	PB	PM	PM
NM	PM	PM	PM	PM	PM	PS	PS
NS	PS	PS	PS	PS	PS	Z	Z
Z	Z	Z	Z	Z	Z	NS	NS
PS	NS	NS	NS	NS	NS	NM	NM
PM	NM	NM	NM	NM	NM	NM	NB

PB	NB	NB	NB	NB	NB	NB	NB

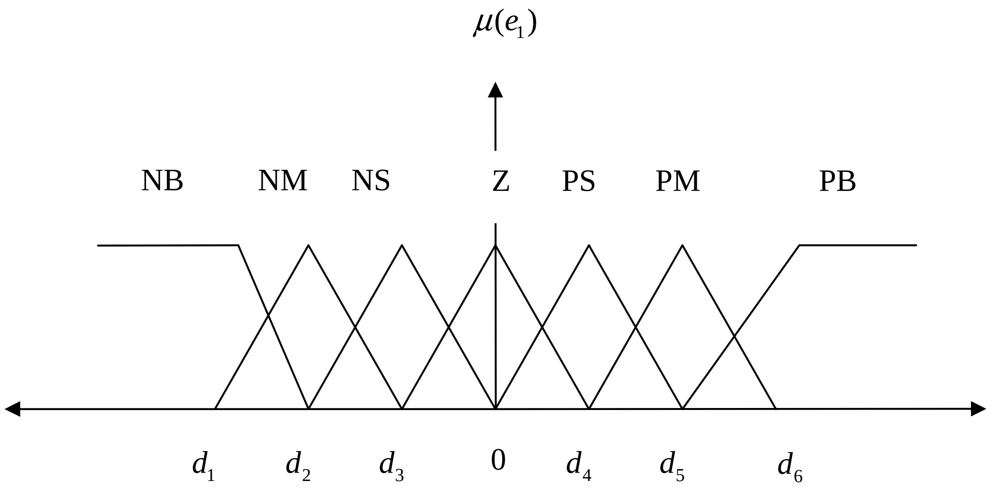

Figure V.10.The membership function sets for error (ei).

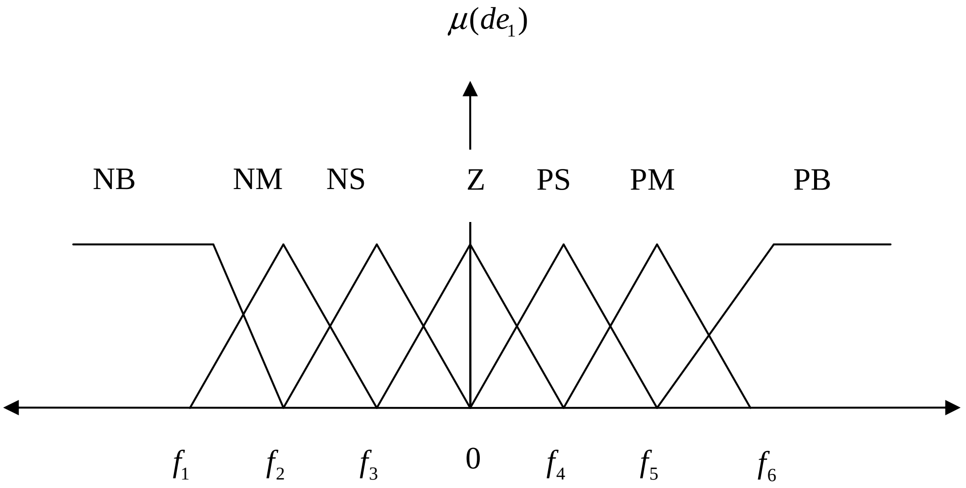

Figure V.11.The membership function sets for error (dei).

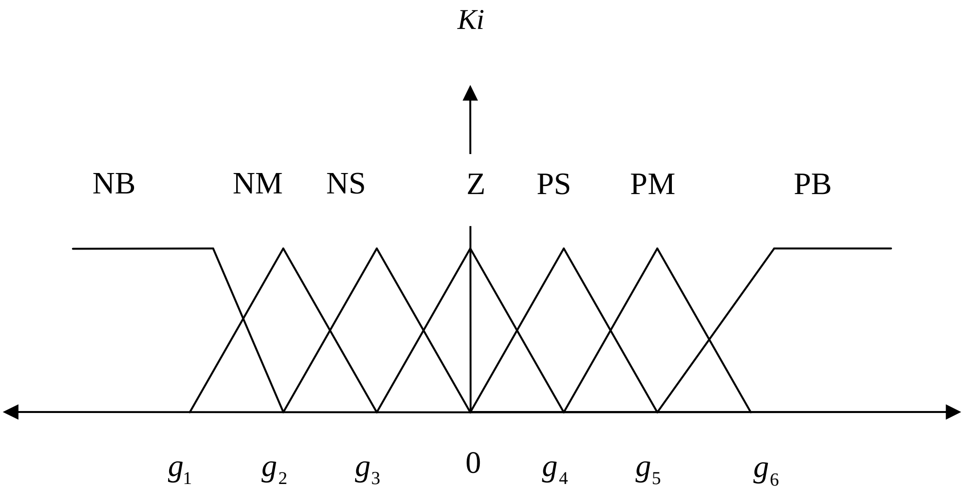

Figure V.12. The membership function sets for the Ki

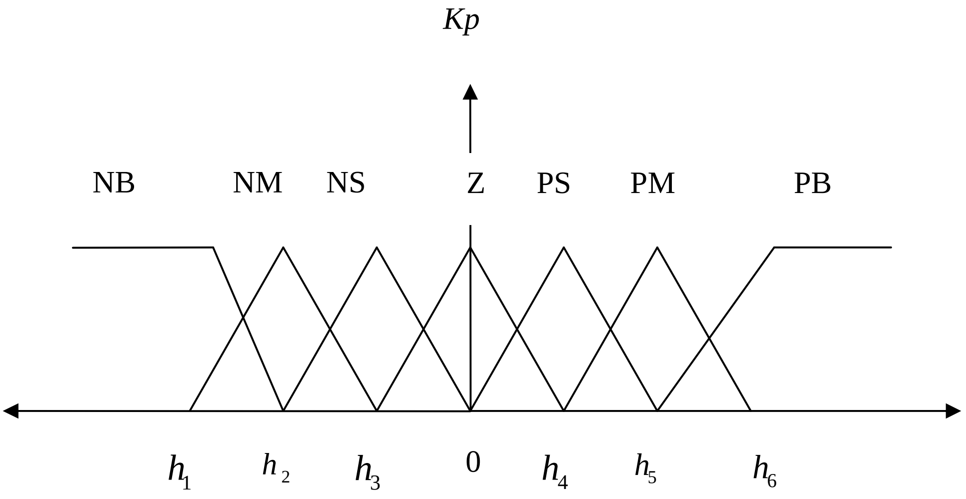

Figure V.13. The membership function sets for Kp

The FGPI simulation result shows better response in time and convergence to the reference or power set point as shown in Figure *V.13.*

Power (GW)

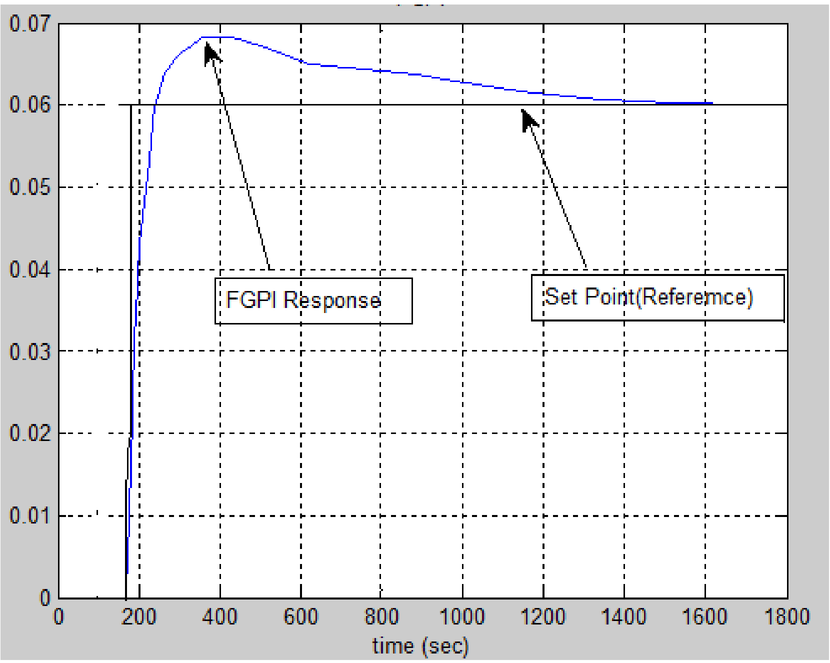

Figure V.13. Turbine controller using FGPI.

Power (GW)

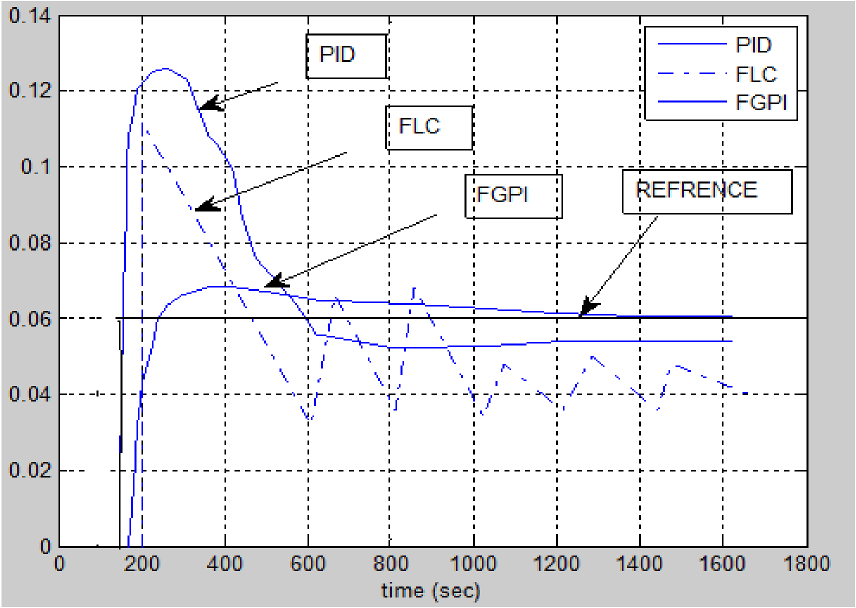

Figure V.14. Turbine Controller using PID, FLC and FGPI controllers.

V.2.3 Simulation Results and Discussion

Simulation results of power plant power output using different controllers such as PID , FL and FGPI are shown in Figure V.14. It can be noticed that the proposed FGPI controller has better performance. Generally, , FLC controller performance is better than the PID controller. However, in this situation the FLC controller has many oscillation, the proposed FGPI controller has better performance for the settling times and the overshoots of the system output again.

The parameters used for Fuzzy logic simulation are :

$(a_1, a_2, a_3, a_4, a_5, a_6) =$ (-0.21 , -0.147 , -0.085 , 0.084 , 0.1467 , 0.21)
$(b_1, b_2, b_3, b_4, b_5, b_6) =$ (-0.3 , -0.2068 , -0.119 , 0.119, 0.2068 , 0.3)
$(c_1, c_2, c_3, c_4, c_5, c_6) =$ (-5.14 , -3.598 , -2.056 , , 2.056 , 3.598 , 5.14)
$(d_1, d_2, d_3, d_4, d_5, d_6) =$ (-0.16 , -01124 , -0.0639 , 0.16 , 01124 , 0.0639)
$(f_1, f_2, f_3, f_4, f_5, f_6) =$ (-0.02 , -0.0124 , -0.0007 , 0.088 , 0.0148 , 0.02)
$(g_1, g_2, g_3, g_4, g_5, g_6) =$ (0.0158 , 0.0188 , 0.0218 , 0.0298 , 0.0328 , 0.0358)
$(h_1, h_2, h_3, h_4, h_5, h_6) =$ (13.16 , 13.52 ,13.86 ,14.46 ,14.80 ,15.16)

this work focuses on comparing the characteristics of the conventional PID controller and the FLC. For this purpose, we suggest an (FGPI) control methos based on tuning the PID controller. Parameters to obtain an optimal gain P and I during processes.

Chapter VI

CONCLUSION

The controller is of a variable structure type in the sense that its parameters can be adaptively adjusted according to only information of the control error.
Thus, it avoids the cumbersome aspect in estimating all the inaccessible system state variables when realising other control strategies such as linear feedback optimal or sliding mode control. Fuzzy logic has been proven to be a prospective tool for dealing with uncertainties in dynamic systems, including power systems.
Generally, the power system state variables and load demand are not always accessible for feedback, optimal control, or conventional variable structure control. Observers can be used for estimating the inaccessible state variables and load. However, telemetering the estimation data over long distances involves additional cost. The adaptive control strategies usually require the satisfaction of the perfect model following conditions or an explicit parameter identification. In view of these inconveniences considerable effort has been made to design controllers that use only the available information of the plant output. The proposed model in *Figure IV.3* is widely used for thermal power plants having the same carecteristic as Cab-Djenat one.

Combustion Control in utility boiler as well as turbine controllers are the most important control loops in power plant. Conventional PI controller used is simple in structure, reliable for operation and robust to certain extent in performance; however, it’s not generally suitable for non-linear, higher order, time delayed and complex systems. The Fuzzy logic technique shows better performance for such complex systems, the step response applied to 176 MW power plant using conventional PID, FLC and FGPI controllers has been investigated separately. As discussed above, the proposed FGPI controller has better performance for the settling times and the overshoots of the system output. Therefore, the FGPI controller is recommended for controlling outputs of such power plant.

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