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Sudan University of Science and Technology

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Modeling and Simulation For Kaplan Turbine in Roseires Power Plant

نمذجة ومحاكاة توربينة كابلان فى محطة توليد كهرباء الروصيرص

A thesis Submitted in Partial Fulfillment for the

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Mechanical Engineering

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اهداء

الى من مهدا لى طريق العلم بعد الله...

الى من ذللا لى الصعاب بدعواتهما الصالحة...

الى من وقفا بجانبى وكان لهما الفضل بعد الله فيما وصلت الية...

الى والديَ امد الله فى عمرهما ورزقنى برهما ورضاهما...

من صبرت وعايشت مشوارى ...زوجتى

الى من مدوا يد العون لى...اخوانى واخواتى

الى اساتذتى الكرام

الى الزملاء والعاملين بمحطة كهرباء الروصيرص

الى طلاب الدراسات العليا...

اليهم جمعيا اهدى هذا الجهد المتواضع

الشكر والعرفان

الحمدلله وحده والصلاة والسلام على من لا نبى بعده

اشكر الله عز وجل أن وفقنى لاكمال هذا البحث العلمى فله الحمد على جزيل فضله وإنعامه ، ثم الشكر موصول لأهل الفضل اعترافا بفضلهم وتقديرا لجهدهم وسعيهم .

كما يشرفنى أن اتقدم بجزيل الشكر والعرفان الى من كان له الفضل بعد الله فى اخراج هذا البحث العلمى بصورته الحالية ، الاستاذ الدكتور الهادى بدوى عميد كلية الهندسة بجامعة الامام الهادى ، والمشرف على هذه الرسالة ، والذى وجدت فيه استاذا فاضلا معطاء سخيا فى علمه وخلقه بذل الجهد وقدم التوجيه السليم والراى السديد ، فجزاه الله خير الجزاء

كما اتقدم بالشكر لاعضاء هئية التدريس بجامعة السودان كلية الدراسات العليا فلهم خالص الشكر والعرفان

كما اتقدم بالشكر والعرفان للاخوة والزملاء بالشركة السودانية للتوليد المائى وبالاخص محطة توليد كهرباء الروصيرص فلهم خالص الشكر والتقدير .

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ABSTRACT

The aim of this thesis is to develop a model to study the performance of Kaplan turbine of unit number four in rosiers hydro power station .To achieve this aim , a model was develop using simulation soft ware matlab/simulink based on the dynamic equations of Kaplan turbine , then the simulation results were compared with the results of the real system in case of loading and idling mode .The simulation results showed very good agreement with the results of the real system , with small deviations in the results of guide vanes opening and runner blade opening and this due to the change in the pressure of turbine outlet and downstream level.

المستخلص

يهدف هذا البحث الى تطوير نموذج حاسوبى لدراسة اداء توربينة كابلان للوحدة رقم (4) بمحطة توليد كهرباء الروصيرص . لانجاز هذه الدراسة تم عمل نموذج حاسوبى باستخدام برنامج المحاكاة ماتلاب Simulink اعتمادا على المعادلات الدنياميكية لتوربينة كابلان ومن ثم تمت مقارنة النتائج المتحصل عليها من المحاكاة مع النظام الحقيقى للوحدة رقم (4) فى حالتى الحمل واللاحمل . أظهرت النتائج المتحصل عليها من المحاكاة توافقا جيدا مع النظام الحقيقى مع وجود بعض الانحرافات الصغيرة فى نتائج فتحة الابواب المتحركة وفتحة الريشة وذلك نتيجة الى تغير الضغط فى مخرج التوربينة ومستوى المنسوب الخلفى للبحيرة .

Table of Contents

LIST OF FIGURES

LIST OF ABBREVIATIONS

H_{Gr} : Gross Head

P_1: Static Pressure in Spiral

P : Static Pressure at Tail

ρ: Density of Water

g: Gravity Acceleration

Z_1: Elevation at Spiral inlet

Z_2: Elevation at Tail Water

H_n: Net Head

A: Area

Q: Turbine Discharge

η: Efficiency of Turbine

η_{hy}: Hydraulic Efficiency

η_{mec}: Mechanical Efficiency

η_o: Overall Efficiency

H: Head

$\boldsymbol{W}$**:** Angular Velocity

$\boldsymbol{S.P}$: Power available at the Shaft

$\boldsymbol{R.P}$: Power Developed by the Runner

$\boldsymbol{m_{dam}}$**:** Incoming Mass Flow Rate

$\boldsymbol{P_{atm}}$**:** Atmospheric Pressure

$\boldsymbol{P_{out\ dam}}$**:** Pressure Outlet of Dam

$\boldsymbol{\dot{m}_{out\ dam}}$ **:** Outgoing Mass Flow Rate

$\boldsymbol{H}$: Head

$\boldsymbol{C_p}$ **:** Friction Coefficient

$\boldsymbol{P_f}$ **:** Pressure Drop

$\boldsymbol{L}$ **:** Length

$\Delta\ \boldsymbol{P}$ **:** Pressure drop between P_{in} and P_{out}

$\boldsymbol{R}$ **:** Hydraulic Average Depth

$\boldsymbol{\Delta H_f}$ **:** Head loss

$\boldsymbol{M_{gen}}$ **:** Kinetic Rotational Momentum

$\boldsymbol{M_f}$ **:** Mechanical Friction Momentum

$\boldsymbol{P_m}$ **:** Pressure Drop, which Contributes to the Turbine's Torque

$\boldsymbol{K_m}$ **:** Mechanical Friction Coefficient

F : Force

$\boldsymbol{\delta}$**:** The Angle of the Guide Vanes

$\boldsymbol{M}$**:** Material Coefficient

$\boldsymbol{h_f}$ **:** Friction Height loss

$\boldsymbol{v}$ **:** Water's Velocity

APPENDEX

CHAPTER ONE

Introduction

1.1 Preview:

In1999 the hydropower represented 19% of the world electricity production and the development of hydroelectric power will be increased in the near future since there is an increased interest in renewable energy sources. The basic process of the hydropower plant is to convert the hydraulic energy to mechanical energy by using the water turbine and then transfer the mechanical energy to electrical energy by using a generator. . There are two types of water turbines impulse turbines (pelton) and reaction turbines (Kaplan & Francis).Roseires Hydroelectric Power Plant harnesses the water of the Blue Nile River and is located some 550 km south of Khartoum near the city of El-Damazin. The dam was constructed between 1964 and 1966, initially for irrigation purposes. From 1971 onwards, a total of seven (7) Kaplan turbines each unit produce 40MW.

The Kaplan turbine is an inward flow reaction turbine, which means that the working fluid changes pressure as it moves through the turbine and gives up its energy. The design combines radial and axial features. The inlet is a scroll-shaped tube that wraps around the turbine’s wicket gate. Water is directed tangentially through the wicket gate and spirals onto a Kaplan shaped runner, causing it to spin. The outlet is a specially shaped draft tube that helps decelerate the water and recover kinetic energy.

The turbine does not need to be at the lowest point of water flow, as long as the draft tube remains full of water. A higher turbine location, however, increases the suction that is imparted on the turbine blades by the draft tube that may lead to cavitations due to the pressure drop. Typically, the efficiencies achieved for Kaplan turbine are over 90%, mainly due to the variable geometry of wicket gate and turbine blades. This efficiency however maybe lower for very low head applications. Since the Kaplan blades are rotated by high-pressure hydraulic oil, a critical design element of Kaplan turbine is to maintain a positive seal to prevent leakage of oil into the waterway. Kaplan turbines are widely used throughout the world for electrical power production. They are especially suited for the low head hydro and high flow conditions – mostly in canal based hydropower sites. Inexpensive micro turbines can be manufactured for specific site conditions (e.g. for head a slow as one meter). Large Kaplan turbines are individually designed for each site to operate a t the highest possible efficiency, typically over 90%. They are very expensive to design, manufacture and install, but operate for decades. Usually the head ranges for Kaplan turbines are between 6 meters to 60 meters [2].

1.2 Research Importance:

The importance of this research is to model all the needed parameters of the hydraulic part (dam, penstock, guide vane, runner blade) of Kaplan turbine.

1.3 Statement of the Problem:

The problem of this research lies on the study of all parameters of the Kaplan turbine mathematically by using Matlab/Simulink software.

Since 1971 Roseires hydro power station with no model to explain and illustrates how the generation process acts, and this research would investigate how the turbines work.

1.4 Objectives:

- To model mathematically the Kaplan turbine.
- To simulate the run of the model for the Kaplan turbine using Matlab Simulink
- Compare between the mathematical model and the real life run of the turbine in terms of performance (runner blade opening, guide vane opening).

1.5 Methodology Approach:

- Model formulation of Kaplan turbine by preparing all the required the equations for Kaplan turbine.
- Drafting a computer program using MATLAB programming language to solve equations of the model.
- Taking the final values obtained from the program after making sure to check the accuracy in these values, these values are plotted charts in order to facilitate analysis.

1.6 Thesis Outlines:

- Chapter one: The Introduction.
- Chapter Two: The Kaplan turbines- general theory.
- Chapter Three: The modeling and simulation for Roseires's hydropower plant.
- Chapter Four: The simulation Results.
- Chapter Five: The Conclusions and recommendations.

CHAPTER TWO

THE COMPONENTS OF KAPLAN TURBINE

2.1 Background:

This section will give a brief presentation of the main components of a Kaplan Turbine hydropower plant. From the water inlet to resulting generation of power, the plant is divided into the subsystems; penstock, turbine and generator. An overview of the system is depicted in Figure (2.1). The theory presented for each of the subsystems constitutes the base of the simulation model and the purpose is to give a basic understanding of each part's properties and functions.

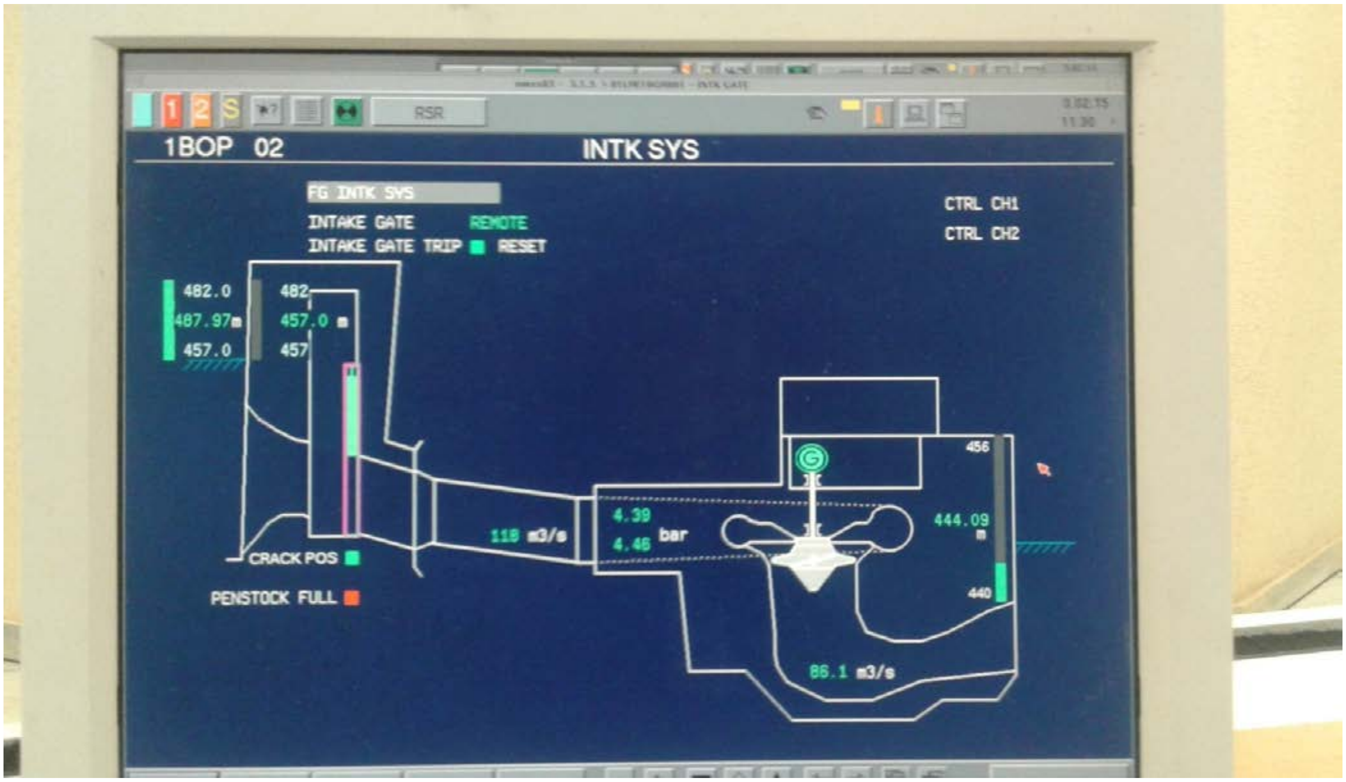


Figure (2.1) Kaplan Hydropower Plant

2.2 The Dam:

The purposes of dams include water supply, and creating a reservoir of [water to supply generating hydroelectric power]. Most hydropower plants rely on dam that holds back water, creating a large reservoir. For Kaplan turbine hydropower plant the hydroelectric power comes from the potential energy of the water in the dam, which drives the turbine and generator the figure (2.2) show the dam [3].

Figure (2.2) The Dam

2.3 The Penstock:

Penstocks are pressurized conduits that transport water from the reservoir to a turbine. Penstocks can be either exposed or built integral with the dam structure. There are many different materials of penstocks such as wood, concrete and steel. Usually the length of a penstock is varying. In a dynamic process of a hydropower plant the water inertia is proportional to the length of the penstock which can increase the dynamic height loss the penstock given in Figure (2.3).

Figure (2.3) The Penstock

2.4 The Spiral Case:

The function of the spiral case is to supply water from the intake to the stay vanes, directly to the upstream portion of the turbine, and through a unique shape of continual cross sectional area reduction to the downstream portion of the turbine; maintaining a near uniform velocity of water around the stay vanes (fixed gates) and wicket gates, the spiral case given in Figure (2.4) [1].

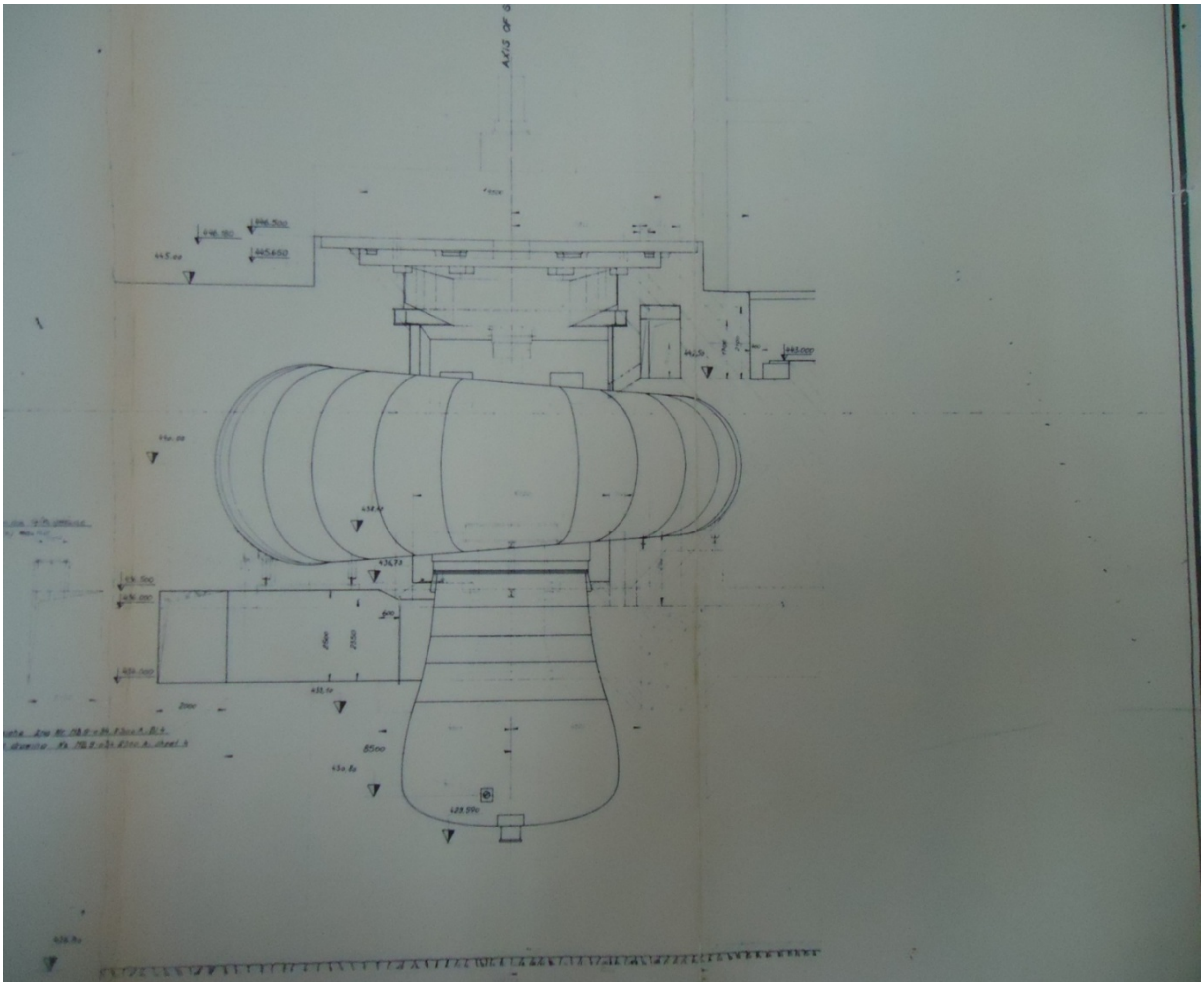


Figure (2.4) The Spiral Case

2.5 The Guide Vanes:

Guide vanes are the special constructions of Kaplan turbines. A unit of guide vanes consists of many small gates, which are divided by numbers of guide vanes. The guide vanes are manufactured of steel plate material. The vanes design is purposely to obtain optimal hydraulic flow conditions, and they are given a smooth surface. Guide vanes are warped around by a scroll-shaped tube inlet. The primary function of wicket gates, or guide vanes, is to control and direct the flow of water to the turbine runner. Guide vanes are generally supported in two or three bearings or bushings. Usually, Francis and vertical Kaplan turbines are three-bearing arrangements show Figure (2.5) [1].

Figure (2.5) The Guide Vanes

2.6 The Discharge Ring:

The discharge ring's function is to transmit pressure containment loads and portions of the powerhouse loads above it to the foundations that support the unit.

The discharge ring or the bottom ring when not integral with the discharge ring supports the lower guide vanes stem bushings, forms a portion of the water passage adjacent to the wicket gates, and forms a tight clearance with the ends of the guide vanes. For Francis-type machines, it also contains the stationary portion of the lower wearing ring that provides a close running clearance with the rotating runner. For axial flow machines, the discharge ring forms the primary water passage adjacent to the periphery of the runner blades Sufficient stiffness must be provided to ensure that the discharge ring will not undergo unacceptable distortions in these critical areas during anchorage pre-load, embedment in concrete, grouting operations, and transient operating conditions to provide protection against cavitations pitting, consideration should be given to specifying stainless steel material for portions of the discharge rings adjacent to the runner in axial flow machines given in Figure (2.6) [1] .

Figure (2.6) The Discharge Ring

2.7 The Runner Blades:

The runner in a Kaplan turbine is a very challenging part to design. The Kaplan shaped runner is mounted vertically with several blades. The length and number of blades can determine the turbine's rotational torque, which can indirectly influence the hydraulic effect. Usually runners consisting of 4 blades can be used up to heads of 25-30 meters while 6 blades could be used for heads 60 meters given in Figure (2.7) [3] .

Figure (2.7) The Runner Blades

2.8 The Generator:

Turbines are coupled to generators in a hydropower scheme in order to transform the mechanical energy produced by the turbine in to electrical energy. There are two main types of generator, synchronous or induction, which is used depending on what, is required in terms of network characteristics. Both types of generator are being constantly improved and the newest generators have efficiencies of almost 100%given in Figure (2.8).

Figure (2.8) The Generator

2.9 The Draft Tube:

The outlet of a Kaplan turbine is a specially shaped draft tube. The function of draft tubes is to decelerate the water at the outlet of a turbine. Since the power extracted from a turbine is a directly function of the drop in pressure across it, the reduction of water velocity will reduce the pressure on the outlet side, which can increase the difference in water pressure between inlet and outlet side. Usually the draft tubes are conical shaped which are similar to an inverted ice cream cone given in Figure (2.9)[3].

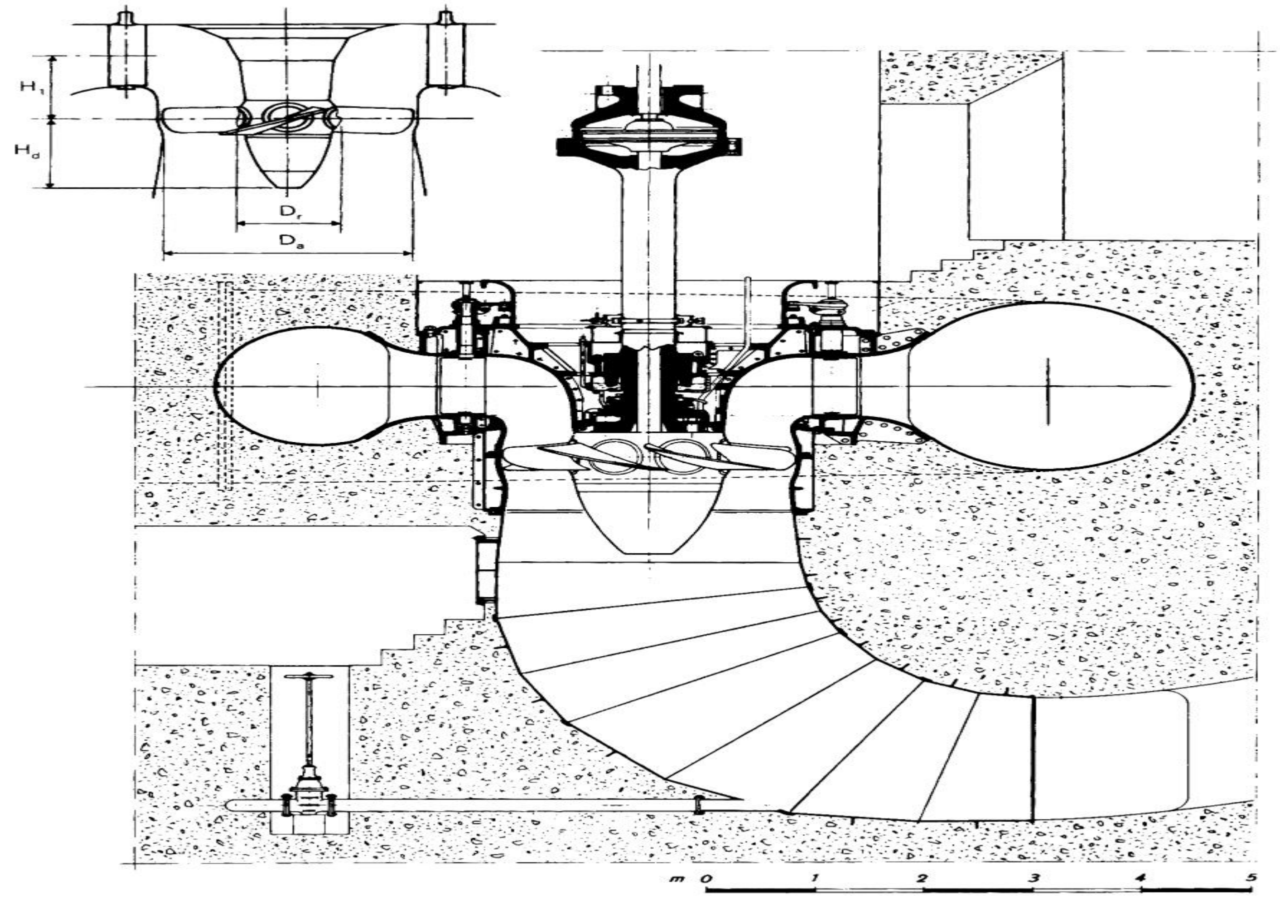


Figure (2.9) The Draft Tube

2.10 The Bearings:

The bearing system for hydraulic turbine-generator units typically consists of two or three guide bearings and a thrust bearing. The guide bearings are arranged to meet the requirements of the shafting system's mechanical design. The number of guide bearings and their spacing are important factors in determining the critical speed of the shafting system.

The type of guide bearing that offers adjustability, good combined (oil and structural) stiffness, and the closest load support to the runner is the adjustable shoe or segment bearing given in Figure (2.10) [1] .

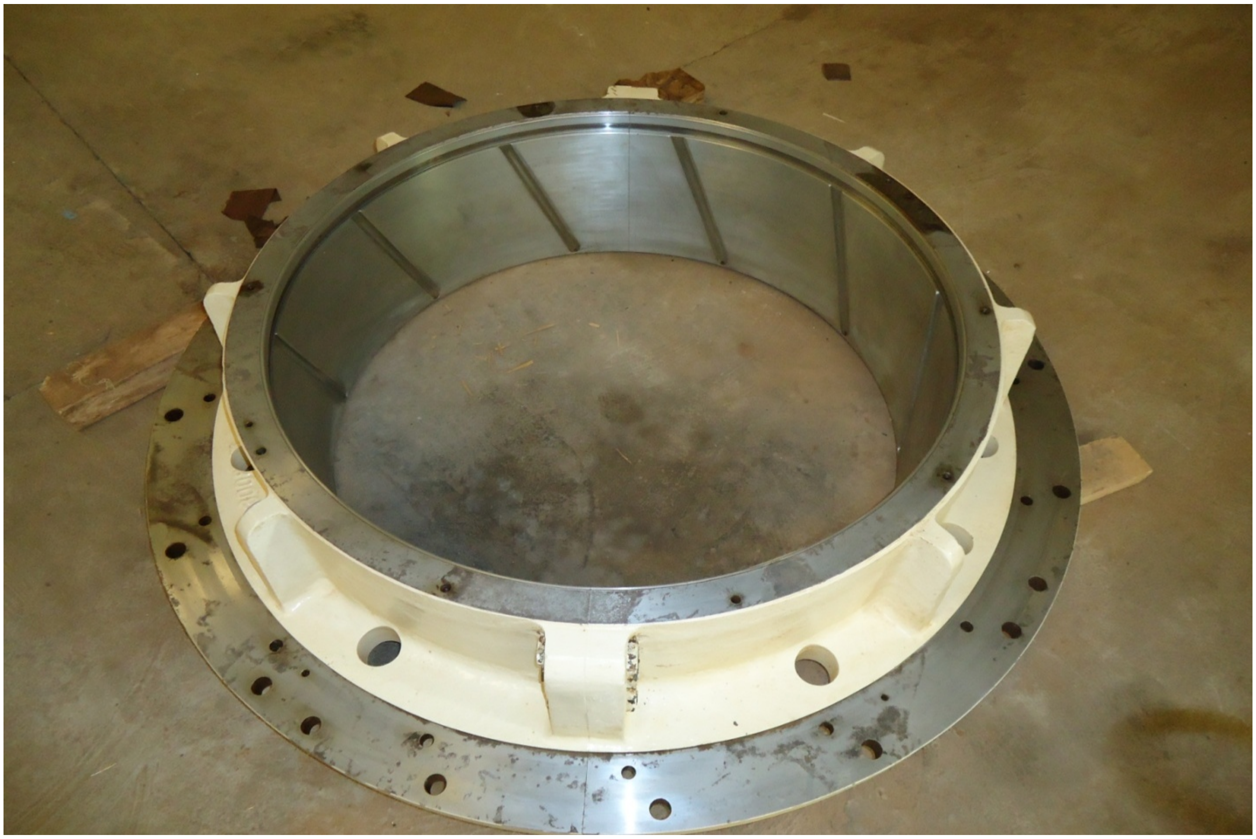


Figure (2.10) Turbine Guide Bearing

A thrust bearing supports the weight of the rotating elements in the turbine generator and hydraulic thrust loads. Normally, thrust bearings are designed so that the rotating element builds a supporting oil film against a series of thrust shoes that are rigidly or elastically supported. The thrust bearing components are housed in an oil basin and flooded with oil for lubrication. Oil coolers in the oil basin or an external lubrication system equipped with heat exchangers, controls, and pumps removes the heat. Many thrust bearings use a hydrostatic lift system to pump oil into the bearing surface for starting and stopping to minimize wear at low speed operation. The high-pressure lift system is used often during maintenance to reduce bearing friction during manual rotation of the turbine-generator given in Figure (2.11) [1].

Figure (2.11) Turbine Guide Bearing

2.11 Basic Definition:

2.11.1 The Head:

A water turbine uses the potential energy from the difference in the elevation an upstream water reservoir and the turbine exit water level (the tailrace) to convert this so-called head. There are some different types of head, which are normally used in turbine [1].

2.11.2The Gross Head:

Gross head is the difference between hydraulic heads in the upstream and downstream reservoirs

$$H_{Gr} = \frac{\mathrm{P}_1}{\rho * g} + Z_1 - \left(\frac{\mathrm{P}_2}{\rho * g} + Z_2\right) = \frac{\mathrm{P}_1 - \mathrm{P}_2}{\rho * g} + Z_1 - Z_2 \quad (2.1)$$

2.11.3 The Net head:

Net head is lower than gross head due to energy losses in the penstock

$$H_n = H_{Gr} + \frac{{V_1}^2 - {V_2}^2}{2 * g} = H_{Gr} + \frac{{Q_T}^2}{2 * g} * \left(\frac{1}{{A_1}^2} - \frac{1}{{A_2}^2}\right) \qquad (2.2)$$

UNIT1 REMOTE
U.S 481.1
D.S 445.4
N.H 33.15
P.B.T 3.41
P.B.T 3.46

UNIT2 REMOTE
U.S 481.1
D.S 445.4
N.H 32.86
P.B.T 3.43
P.B.T 3.39

UNIT3 REMOTE
U.S 481.1
D.S 445.4
N.H 36.28
P.B.T 3.77
P.B.T 3.73

UNIT4 REMOTE
U.S 490.8
D.S 445.4
N.H 33.0
P.B.T 3.4
P.B.T 3.5

UNIT5 REMOTE
U.S 481.1
D.S 445.4
N.H 33.18
P.B.T 3.55
P.B.T 3.48

UNIT 6 LOCAL
U.S 481.1
D.S 445.4
N.H -0.9
P.B.T 0.1
P.B.T 0.0

UNIT7 REMOTE
U.S 481.1
D.S 445.4
N.H 34.45
P.B.T 3.54
P.B.T 3.60

	MW actual	MW setpoint	Freq.
U1	35.0	35.0	50.0
U2	36.5	36.5	50.0
U3	24.9	25.0	50.0
U4	39.3	39.0	50.0
U5	34.8	36.0	50.0
U6	-0.0	0.4	43.1
U7	39.0	39.0	50.0

Figure (2.12) Net Heads

2.12 Efficiency:

Efficiency is a dimensionless number, with a value between zero to one, which is defined as the ratio between the power developed by the available water power. [4]

$$\eta = \frac{P_1}{P_{available}} \qquad (2.3)$$

P1: Static pressure in spiral case

$P_{available}$: Water power

2.12.1Hydraulic Efficiency:

The hydraulic efficiency of turbine is defined as the ratio of mechanical output power of runner and hydraulic input power

$$\eta_{hy} = \frac{\mathrm{P}_{hy}}{W*Q*H} \qquad (2.4)$$

P_{hy} : Hydraulic power

$W*Q*H$: Mmechanical output power of runner

2.12.1 Mechanical Efficiency*:*

It is the ratio of the power available at the shaft to the power developed by the runner of a turbine.

$$\eta_{mec} = \frac{S.P}{R.P} \qquad (2.5)$$

$S.P$: Shaft power

$R.P$:Power developed by the runner blade

2.12.3 Overall Efficiency*:*

Is a product of the hydraulic efficiency time's mechanical efficiency.

$$\eta_{o} = \eta_{hy} \mathrm{x} \eta_{mec} \qquad (2.6)$$

CHAPTER THREE

MODELIND AND SIMULATION

3.1 Dam Modeling:

The parameters and variables that are utilized to this model are shown in Figure (3.1).

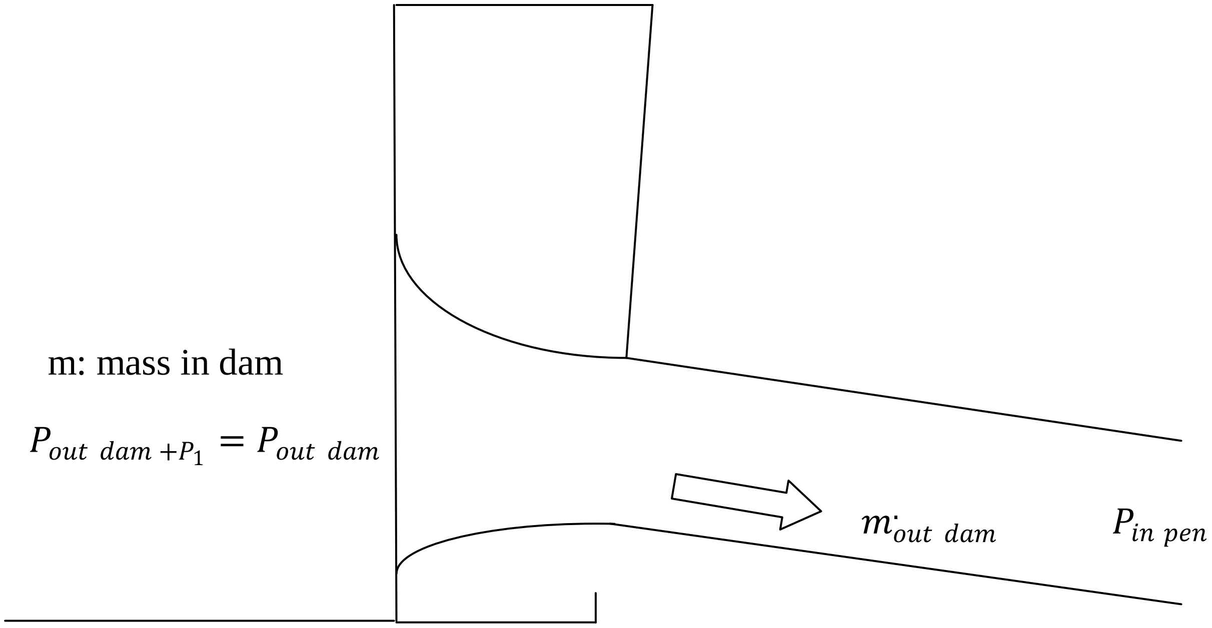


Figure (3.1) the Dam

Parameters:

g =Gravity acceleration

ρ =The density of the fluid

P_{atm} =Atmospheric pressure

Variables:

m:The mass of the water [kg]

h:The height of water in the dam [m]

V:The volume of water in the dam [m^2]

$P1$:Pressure [Pa]

$P_{out\ dam}$:The pressure at the outlet of the dam [Pa]

m_{dam} :Incoming mass flow rate [$\frac{kg}{s}$]

$\dot{m}_{out}$:Outgoing mass flow rate [$\frac{kg}{s}$]

Q:Volume flow rate [m^3]

Equations:

$$P_{atm} + P_1 = P_{out\ dam} \tag{3.1}$$

$$m = m_{dam} - \dot{m}_{out\ dam} \tag{3.2}$$

Equation 3.1 describes the pressure balance of a dam.

$$p1 = \rho * g * h \tag{3.3}$$

Equation 3.2 represents the mass flow rate balance of the dam.

3.2 Penstock Modeling:

A penstock is a large pipe which connects the dam's outlet to the wicket gate's inlet. The variables and parameters that are utilized to this model are shown in Figure (3.2).

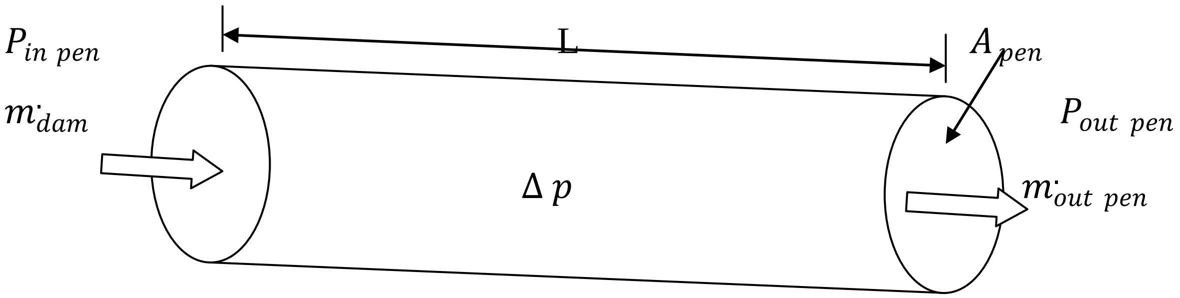


Figure (3.2) The Penstock

Parameters:

A_{pen} :the cross section area of penstock $[m^2]$

L:The length of the penstock [m]

ρ: Water density $[\frac{kg}{s^3}]$

g: A cceleration due to gravity $[\frac{m}{s^2}]$

C_p: The friction coefficient $[\frac{pas^2}{m^6}]$

m : The mass of the water $[\frac{kg}{s}]$

a : Acceleration $[\frac{m}{s^2}]$

Variables:

$P_{in\ pen}$: The pressure at the penstock's inlet $[Pa]$

$P_{out\ pen}$:The pressure at the penstock's outlet $[Pa]$

Pf_{pen} :The pressure drop due to the friction $[Pa]$

Pi_{pen} The pressure drop due to the water inertia $[Pa]$

$m_{in\ pen}$:Incoming mass flow rate $[\frac{kg}{s}]$

$m_{out\ pen}$: Outgoing mass flow rate $[\frac{kg}{s}]$

Q :Volume flow rate $[\frac{m^3}{s}]$

Equations:

$$P_{in\ pen} - \Delta P_{pen} - P_{out\ pen} = 0 \qquad (3.4)$$

$$m_{in\ pen} - m_{out\ pen} = 0 \qquad (3.5)$$

Equation 3.5 describes the mass flow rate balance of the penstock.

Equation 3.4 describes the pressure balance of penstock.

ΔP_{pen} Is the pressure drop between pin_pen and $pout\_pen$ and in this case it is considered by two different types of the pressure drop

$$\Delta p = Pf_{pen} + Pi_{pen} \qquad (3.6)$$

Pf_{pen} Is the pressure drop due to the turbulent flow friction

Pi_{pen} Is the pressure drop due to the inertia of the water.

Δp Is the pressure drop between P_{pen} and $P_{out\ pen}$ and in this case it is considered by two different types of the pressure drop.

According to the Bernoulli equation [3] a turbulent flow friction in enclosed Tube could be modeled as

$$Pf_{pen} = Cf_{pen} * Q^2 \qquad (3.8)$$

Cf_{pen} =Friction coefficient.

3.3 Guide Vanes Modeling:

The guide vanes are located between the outlet of the penstock and the inlet of the Kaplan turbine. The variables and parameters of the equation-based modeling are given by Figure 3.3. Figure 3.3 is an illustration of the guide vane's angle σ. σ is the angle between the guide vanes relative to the stay vane.

(Fixed gates)

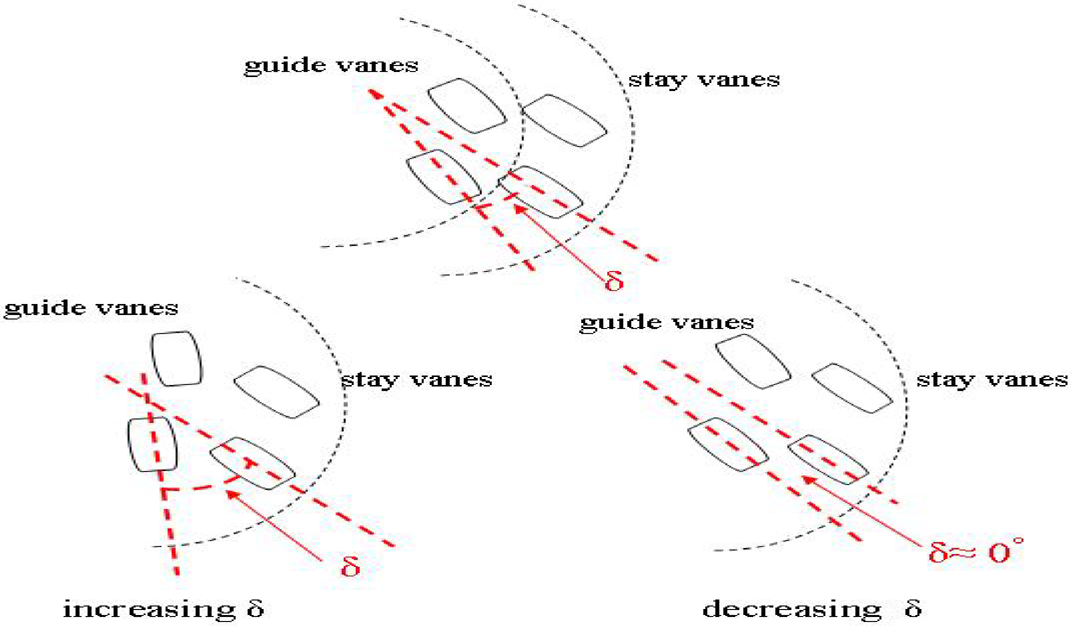


Figure (3.3) The Guide vanes

Parameters:

ρ:The water density $[\frac{kg}{m^3}]$

σ:The angle of the guide vane $[rad]$

Cf_{gate} :Friction coefficient $[\frac{pas^2}{m^6}]$

Variables:

$P_{in\ gate}$:The pressure at the wicket gate's inlet [Pa]

$P_{out\ gate}$:The pressure at the wicket gate's outlet [Pa]

Pf_{gate} : The pressure drop due to turbulent friction [Pa]

$m_{in\ gate}$:Incoming mass flow rate [$\frac{kg}{s}$]

$m_{out\ gate}$:Outgoing mass flow rate [$\frac{kg}{s}$]

Equations:

$$P_{in\ gate} - Pf_{gate} = P_{out\ gate} \qquad (3.9)$$

$$m_{in\ gate} - m_{out\ gate} = 0 \qquad (3.10)$$

Equation 3.10 describes the mass flow rate balance of the wicket gate, the incoming mass flow rate is equal to the outgoing mass flow rate in the wicket gate

Equation 3.9 describes the pressure balance of the guide vane. P_{ingate} is the Inflow pressure of the guide vane and $P_{outgate}$ is the out flow pressure of the wicket gate. Pf_{gate} is the pressure drop when the water flows through the gate The pressure drop is created by a turbulent fluid flow through the gate vanes The turbulence occurs on the vane surface and increases with the fluid flow rate.
This flow can be modeled by utilizing Bernoulli's equation of turbulent flow
Friction in an enclosed tube. This will in this case be described as

$$Pf_{gate} = Cf_{gate}\, \mathrm{X} \qquad (3.11)$$

Here Cf_{gate} is a constant parameter. In this case, equation 3.10 could be modeled As equation 3.12 which represents the pressure drop is determined by δ in equation 3.12 δ 0 is the optimal angle, 25. When δ is equal to $\delta 0$ then the pressure drop is at its minimum and results in the maximum$P_{out\ gate}$.

$$P_{in\ gate} - Cf_{gate}\, X\, (2 - cos(\delta - \delta 0)) * Q^2 = P_{out\ gate} \qquad (3.12)$$

3.4 Kaplan Turbine Modeling:

The Kaplan turbine model has adjustable runner blades. The variables and parameters of the equation-based modeling are followed by an illustrated Figure3.4.

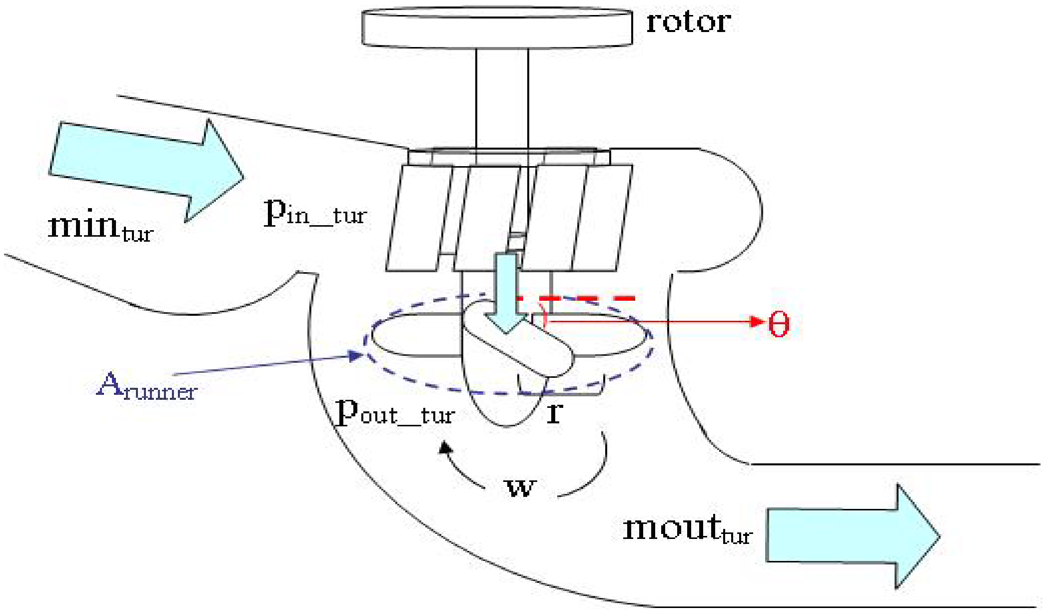


Figure (3.4) The A schematic of the turbine

Parameters:

r: The average radius of the turbine propeller [m]

A: runner: the cross sectional area of the turbine propeller [m^2]

ρ:Density [$\frac{kg}{m^3}$]

g:Acceleration due to gravity[$\frac{m}{s^2}$]

Cf_{tur} :Hydraulic friction coefficient [$\frac{kg}{m^8}$]

Km_{tur} :Mechanical friction coefficient [$\frac{kg}{m^8}$]

Variables:

F :Force [$\frac{kgm}{s^2}$]

Pf_{tur} : The friction pressure drop [Pa]

Q :Volume flow rate [$\frac{m^3}{s}$]

W : Angular velocity [$\frac{rad}{s}$]

θ: The angle between the runner blades to the horizontal plan [rad]

Equations:

$m_{in\ tur}$ - $m_{out\ \ gate}$ = 0 (3.13)

$P_{in\ tur} - \Delta P_{tur} = P_{out\ \ tur}$ (3.14)

Equation 3.13 describes the mass flow rate balance of the turbine. Equation 3.14 describes the pressure balance of the turbine. $P_{in\ tur}$ is the inflow pressure of the turbine and $P_{out\ tur}$ is the outflow pressure of the turbine. ΔP_{tur} is the pressure drop when the water flows through the turbine .

$$\Delta P_{tur} = Pf_{tur} + Pm \qquad (3.15)$$

Pf_{tur} is the turbulent flow friction and could be modeled as below as the same Way as in Equation 3.11. Pm is the pressure drop due to the interaction of the flowing water with the runner blades transforming the hydraulic energy to the mechanical energy.

$$Pf_{tur} = Cf_{tur} XQ^2 \qquad (3.16)$$

Cf_{tur} Is a friction coefficient

3.5 Equations of Penstock:

$$H_f = \frac{L*V^2}{M^2*R_{\frac{4}{3}}} \qquad (3.17)$$

$$L = 53\ m$$

$$V = 5.58 \frac{m}{s}$$

$$M = 140$$

$$R = \frac{A_{pen}}{2*\pi*2.9} = 1.449 \qquad (3.18)$$

$$H_f = \frac{53*5.58^2}{140^2*10449^{\frac{4}{3}}}$$

$$H_f = 0.0514$$

$$Pf_{pen} = \rho * g * hf \qquad (3.19)$$

$$999.8394 * 9.81 * 0.0514 = 504.234\, pa$$

$Cf_{pen} = \frac{Pf_{pen}}{Q^2}$ (3.20)

$$\frac{504.234}{147.5^2} = 0.023pa$$

3.5 Equations of Guide Vanes:

ΔHf =β∗sinα $*(\frac{d}{a})* 1.25 \ * \frac{V^2}{2} * g$ (3.21)

$2.42 * \ sin43 *(\frac{15}{20})* 1.25 \ * 5.58^2 * 9.81$

=1.827m

$Pf_{gate} = \rho \ * g * \Delta Hf$ (3.22)

$999.8394 * 9.81 * 1.827$=$17924.44pa$

$Cf_{gate} = \frac{Pf_{gate}}{Q^2}$ (3.23)

$\frac{17924.44}{147.5^2}$ = 0.82

3.6 Equations of Turbine:

$P_{out\ dam} = \rho \ * g * h$+$P_{atm}$ (3.24)

$9.81 * 999.8394 * 50$= $490422.25\, pa$

$P_{in\ tur} \ = \ P_{out\ dam} - Pf_{pen} - \ Pf_{gate}$ (3.25)

$490422.25 \ - 17924.44 - 504.234 = \ 471993.0pa$

$\Delta\, P_{tur} \ = \ P_{in\ tur} - \ P_{out\ tur}$ (3.26)

$\Delta\, P_{in\ tur} \ = Pf_{tur} \ + \ P\, m$ (3.27)

$471993.0 - P_{out\ tur} \ = \ \Delta\, P_{tur}$

Assume

$$P\ m * Q\ = Min * W \qquad (3.28)$$

$$M_{in}\ = M_f\ + M_j\ + M_{in} \qquad (3.29)$$

When W is constant and M_j is zero

$$M_{gen}\ \ = \frac{p}{w}$$

$$\frac{40 * 1000000}{14.28}$$
$$= 2801120.45 pa$$

$$M_f\ \ = K_f\ * w \qquad (3.30)$$

$$1 * 14.28$$
$$= 14.28$$

$$M_{in}\ = M_f\ +\ \ +M_{gen}$$

$$2801120.45 + 14.28 = 2801134.728$$

$$Pm\ =\ M_{in}\ *\ \frac{Q}{w} \qquad (3.31)$$

$$Pm = 2801134.728 * \frac{147.5}{14.28} = 271187 pa$$

$$Pf_{tur}\ \ =\ P_{in\ tur}\ -\ P_{out\ \ tur}\ -\ Pm \qquad (3.32)$$

Assume $P\ out\ tur = 200000 pa$

$$471993.0 - 200000 - 271187 = 805.2 pa$$

$$Cf_{tur}\ \ = \frac{Pf_{tur}}{Q^2} \qquad (3.33)$$

$$\frac{805.2}{147.5 * 14 =} = 0.3726$$

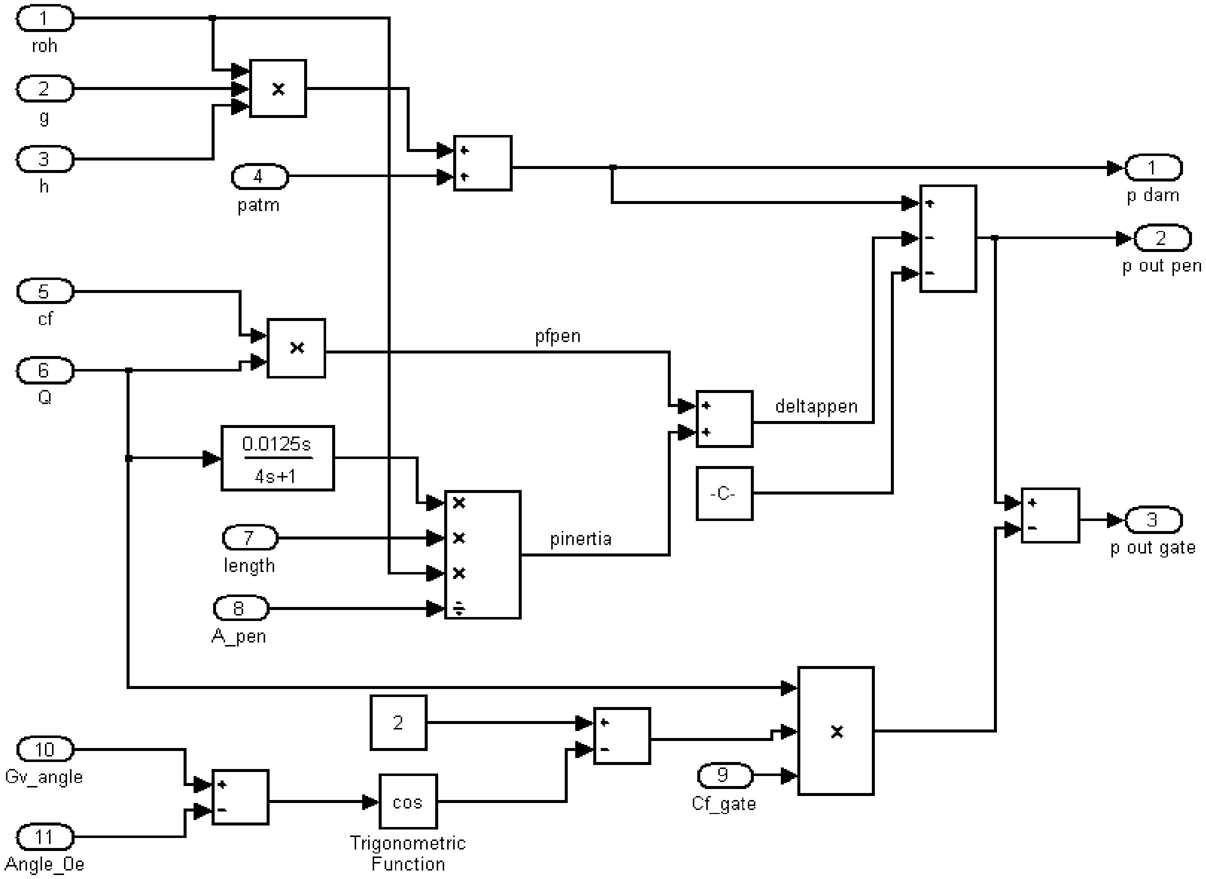


Figure (3.5) Dam-Penstock-Guide Vanes

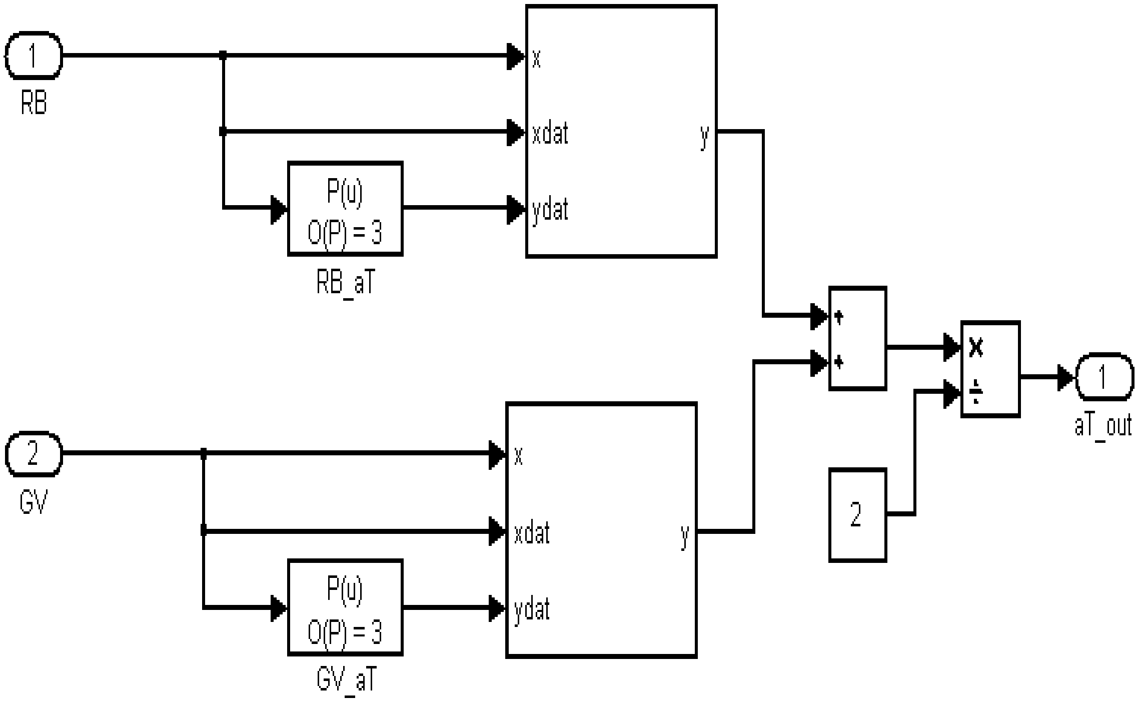


Figure (3.6) Gv and_Rb_Cross-section-Relation

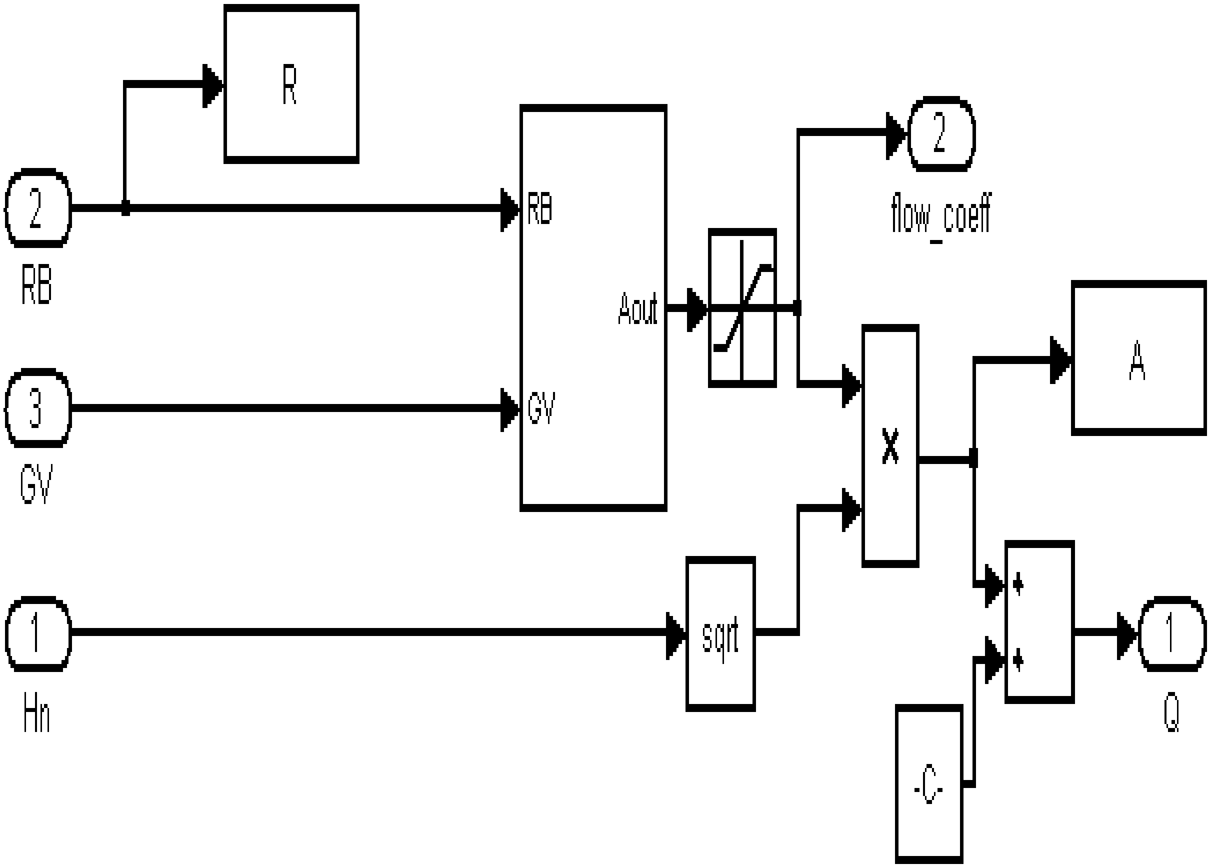


Figure (3.7) Turbine-Flow

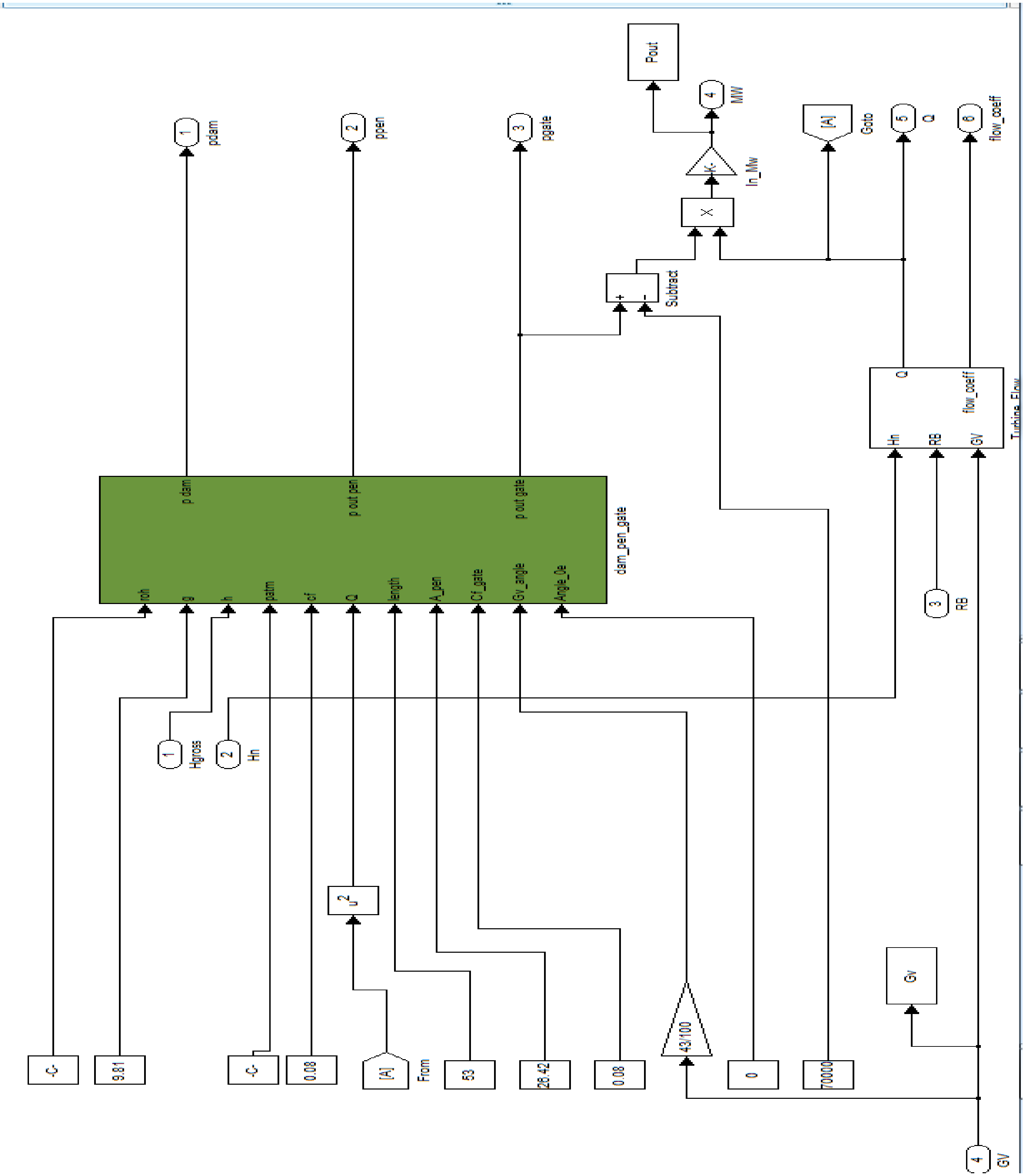


Figure (3.8) Turbine Model

CHAPTER FOUR

SIMULATION RESULTS

4.1 Start up:

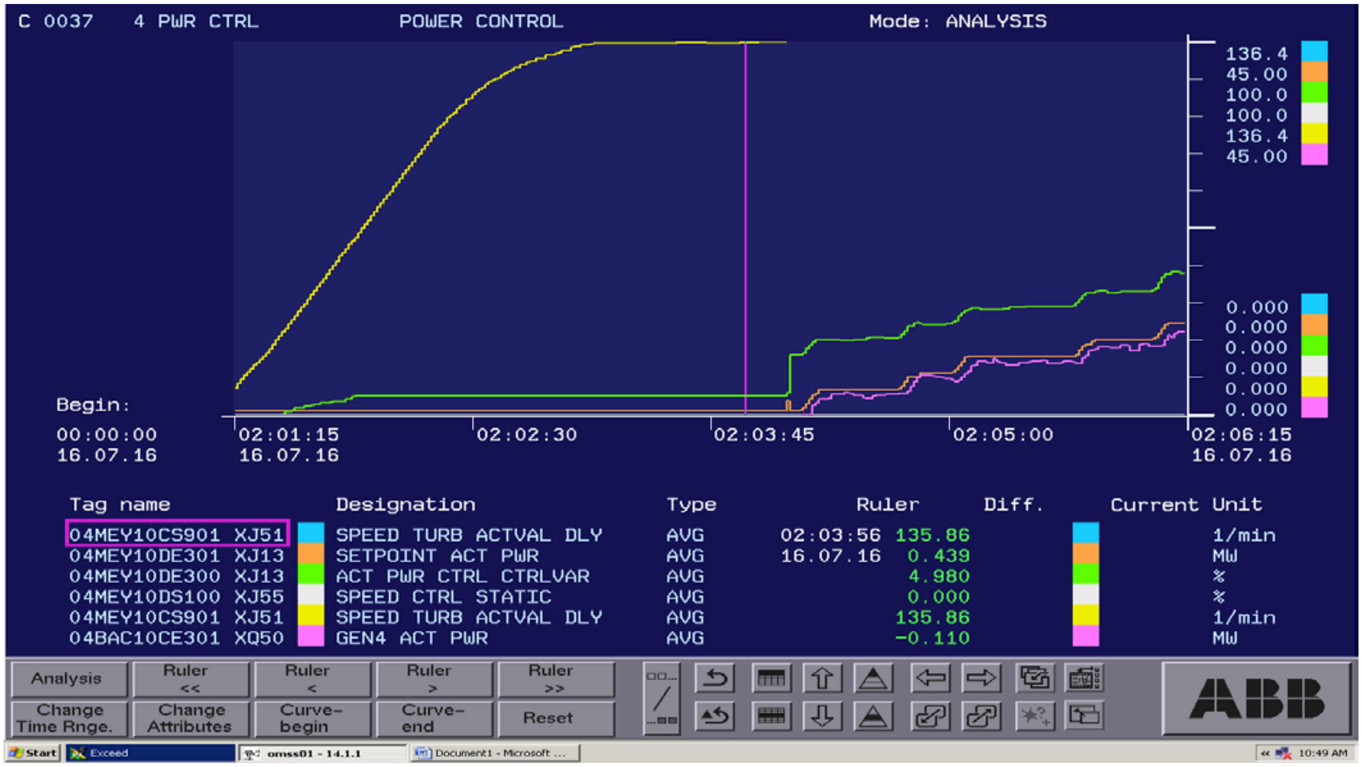
The response of the model at start up compared with the illustrated in Figures[4:1 and Figures 4.2] unit number four response .the guide vane opening of the model is(14.38%) as in Figure (4:3) which is approximately equal to the plant response(15.7%). The deviation which is (1.32%) due to variation of downstream level.

4.2 Loading Condition:

Step set-point of (3MW) applied to the model and the response time was found to be (4sec).While the real life to unit four was found to be (5 sec) given in Figure (4.4), (4.5) respectively

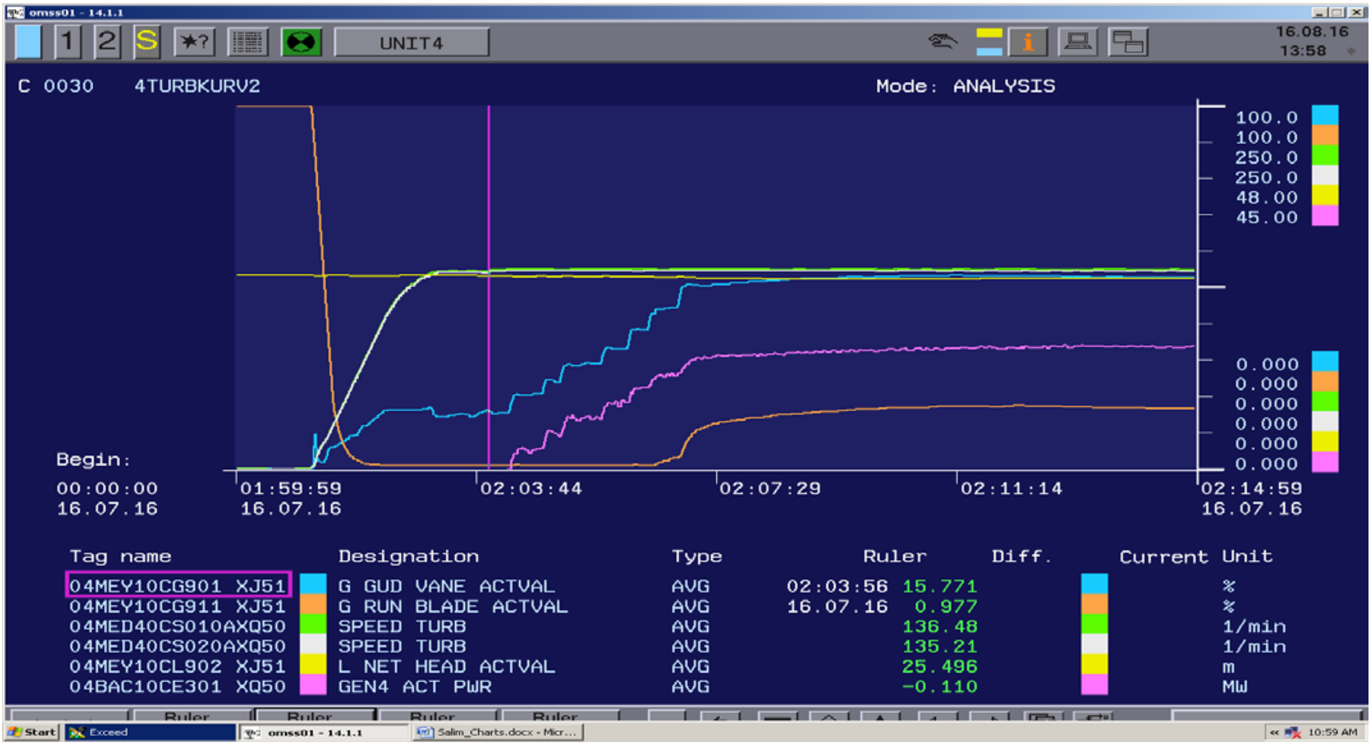
4.3 Hill Chart:

Head of 35m and using the model the efficiency was found to be 89.98%. While using the mathematically equation it was found the efficiency 89.29%. The hill chart as in Figure (6.4) to explain that.



Tag name	Designation	Type	Ruler	Diff.	Current	Unit
04MEY10CS901 XJ51	SPEED TURB ACTVAL DLY	AVG	02:03:56 135.86		🟦	1/min
04MEY10DE301 XJ13	SETPOINT ACT PWR	AVG	16.07.16 0.439		🟧	MW
04MEY10DE300 XJ13	ACT PWR CTRL CTRLVAR	AVG	4.980		🟩	%
04MEY10DS100 XJ55	SPEED CTRL STATIC	AVG	0.000		⬜	%
04MEY10CS901 XJ51	SPEED TURB ACTVAL DLY	AVG	135.86		🟨	1/min
04BAC10CE301 XQ50	GEN4 ACT PWR	AVG	-0.110		🟪	MW

Figure (4.1) Start up set-point



Tag name	Designation	Type	Ruler	Diff.	Current	Unit
04MEY10CG901 XJ51	G GUD VANE ACTVAL	AVG	02:03:56 15.771		🟦	%
04MEY10CG911 XJ51	G RUN BLADE ACTVAL	AVG	16.07.16 0.977		🟧	%
04MED40CS010AXQ50	SPEED TURB	AVG	136.48		🟩	1/min
04MED40CS020AXQ50	SPEED TURB	AVG	135.21		⬜	1/min
04MEY10CL902 XJ51	L NET HEAD ACTVAL	AVG	25.496		🟨	m
04BAC10CE301 XQ50	GEN4 ACT PWR	AVG	-0.110		🟪	MW

Figure (4.2) Gv and_RB opening to reach synchronous speed

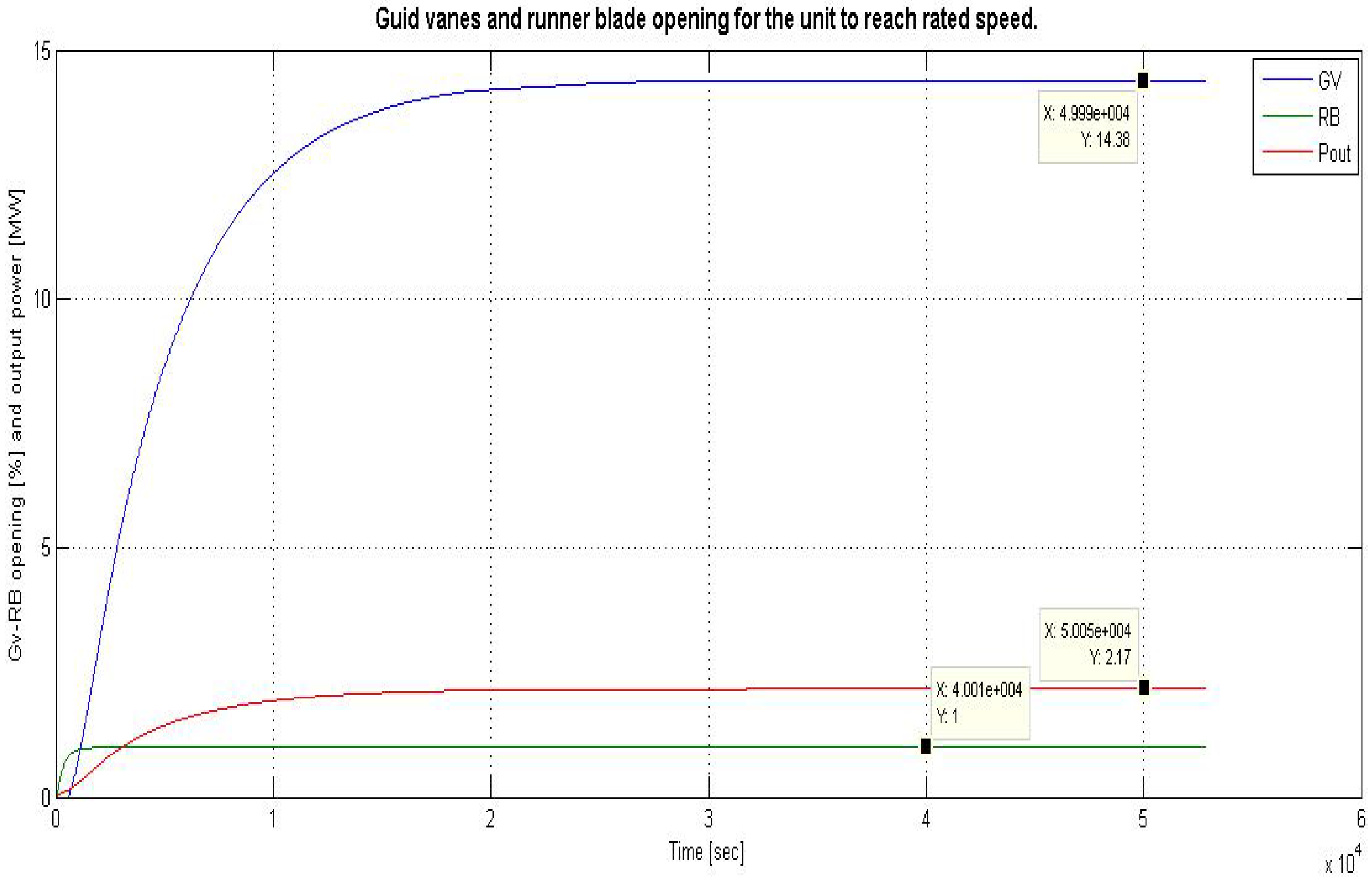
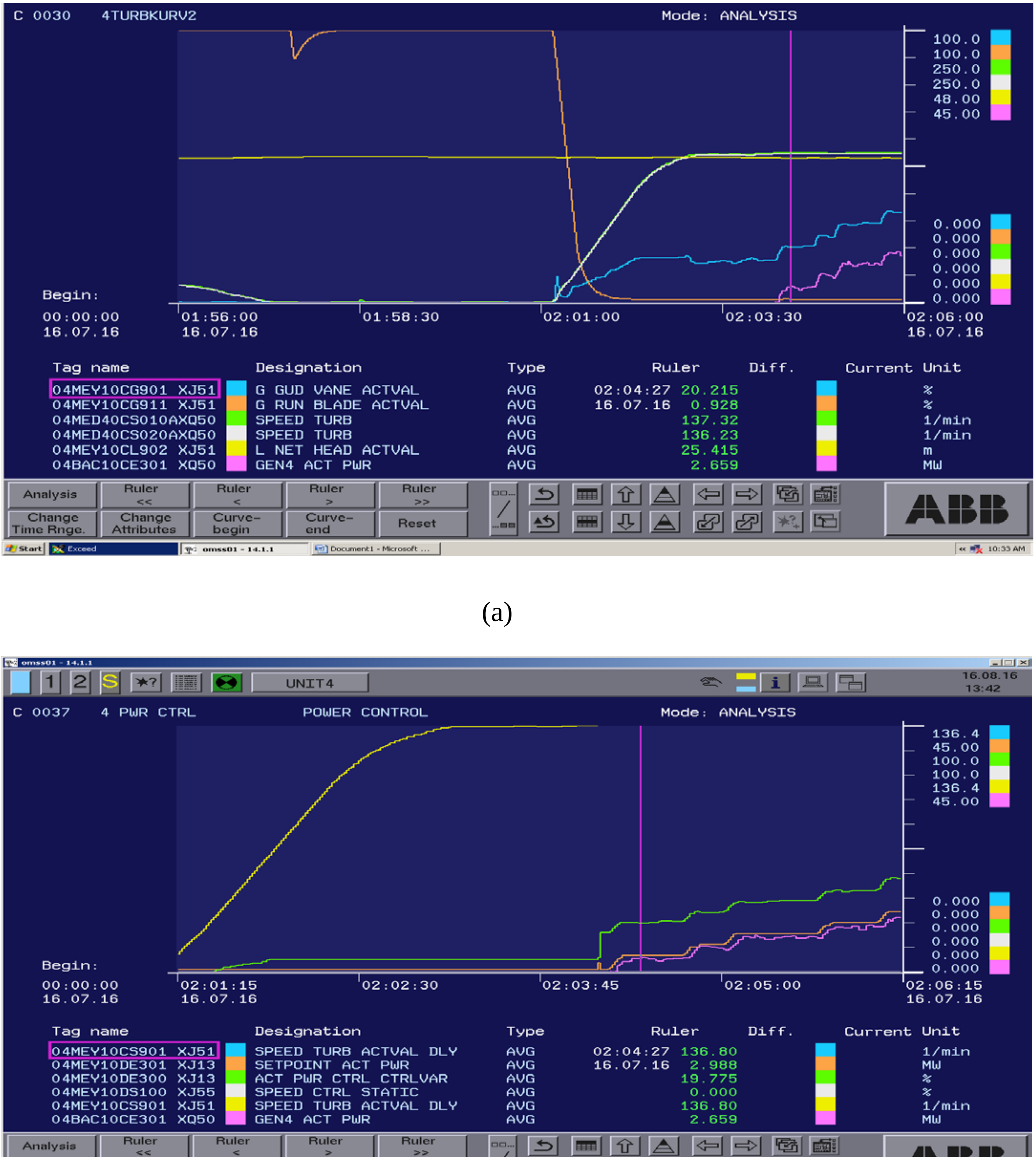


Figure (4.3) Comparison of Startup Opening



Tag name		Designation	Type		Ruler	Diff.	Current	Unit
04MEY10CG901 XJ51	🟦	G GUD VANE ACTVAL	AVG	02:04:27	20.215		🟦	%
04MEY10CG911 XJ51	🟧	G RUN BLADE ACTVAL	AVG	16.07.16	0.928		🟧	%
04MED40CS010AXQ50	🟩	SPEED TURB	AVG		137.32		🟩	1/min
04MED40CS020AXQ50	⬜	SPEED TURB	AVG		136.23		⬜	1/min
04MEY10CL902 XJ51	🟨	L NET HEAD ACTVAL	AVG		25.415		🟨	m
04BAC10CE301 XQ50	🟪	GEN4 ACT PWR	AVG		2.659		🟪	MW

(a)

Tag name		Designation	Type		Ruler	Diff.	Current	Unit
04MEY10CS901 XJ51	🟦	SPEED TURB ACTVAL DLY	AVG	02:04:27	136.80		🟦	1/min
04MEY10DE301 XJ13	🟧	SETPOINT ACT PWR	AVG	16.07.16	2.988		🟧	MW
04MEY10DE300 XJ13	🟩	ACT PWR CTRL CTRLVAR	AVG		19.775		🟩	%
04MEY10DS100 XJ55	⬜	SPEED CTRL STATIC	AVG		0.000		⬜	%
04MEY10CS901 XJ51	🟨	SPEED TURB ACTVAL DLY	AVG		136.80		🟨	1/min
04BAC10CE301 XQ50	🟪	GEN4 ACT PWR	AVG		2.659		🟪	MW

(b)

Figure (4.4) Response to 3 MW Step Change. (a) GV AND,RB Open, (b) Set point

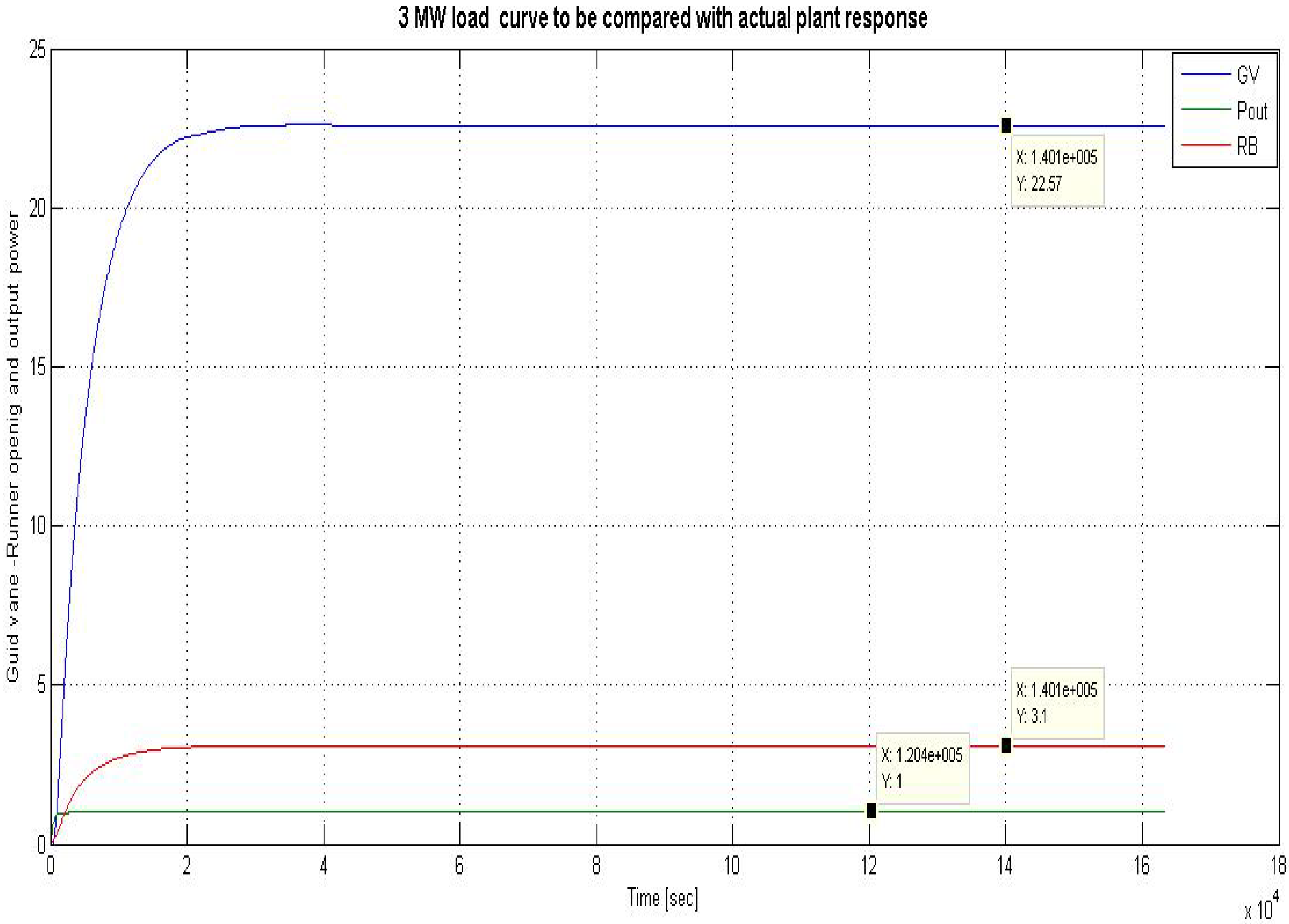


Figure (4.5) Response to 3 MW Set-point

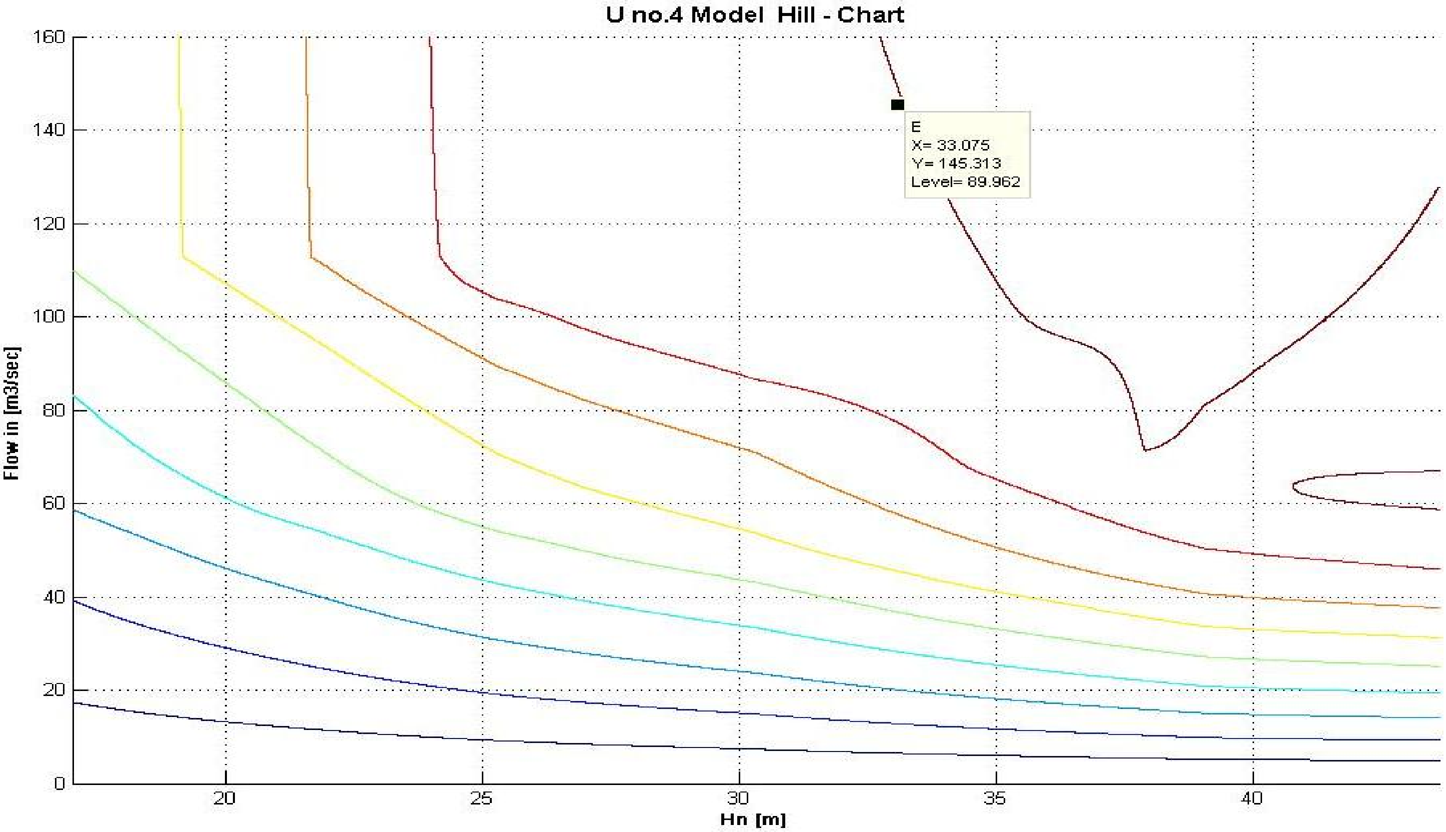


Figure (4.6) Model Hill-Chart Generated using Matlab/Simulink.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 **Conclusions**:

The conclusion on the research was as follows:-

●Kaplan turbine unit number four has been mathematically, modeled.

●Using Matlab Simulink in unit number four the simulation was done.

●To make the performance of the model as identical as the turbine, losses account have been in every part of the turbine unit and included in the model equation.

●The model were compared to the performance of the unit number four Roseires hydropower plant, and compared the reading of the guide vane and runner blade in loading and no loading conditions ,the guide vane opening in simulated (14.38%) while the real life in unit number four is (15.7%). The deviation which is (1.32%) due to variation of downstream level .the efficiency in the simulated was found to be 89.98% while the real life is 89.295%. The deviation due to pressure in draft tube is not constant. The performance of the model almost identical to the turbine.

5.2 **RECOMMENDATIONS**:

After the study was completed, the following recommendations are suggested:-

●To carry study taking into accounts the variation in the pressure in the draft tube.

●To study the losses in the intake control gates and bearings.

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[10] http: www.//en.wikipedia.org/wiki/ Drag equation

APPENDICES

Constant parameters

Table 3.1 constant parameters used in the Modeling and simulation for Roseires's hydropower plant,

Parameter	**Description**	Units
g	gravity acceleration	9.801 [m^2]
ρ	water density	999.8394 [$\frac{kg}{m^2}$]
P	atmosphere pressure	100000 [Pa]

Table (A. 1) Constant parameters of the Matlab program Test

Variables	**Description**	**Unit**
Q	water flow rate	147.5 [$\frac{m^3}{s}$]
P	Power	45 [MW]
w	turbines angular velocity	14.28 [$\frac{m}{s}$]
h	water height in the dam	50 [m]
Parameters	**Description**	**Unit**
K	th**e mechanical friction**	1[$\frac{Nm}{rad}$]
L	the length of the penstock	53 [m]
A	the area of the penstock	26.42 [m^2]
A	the area of the dam	6000 [m^2]
r	the average radius of the propeller	2.25 [m]
A	the cross section area of the propellers	12.6 [m^2]

Table (A.2) assumption variables and parameters of the Modeling for Roseires's hydropower plant, used in Matlab program test

Figure (B.1) Location of Roseires HEPP at the Blue Nile River

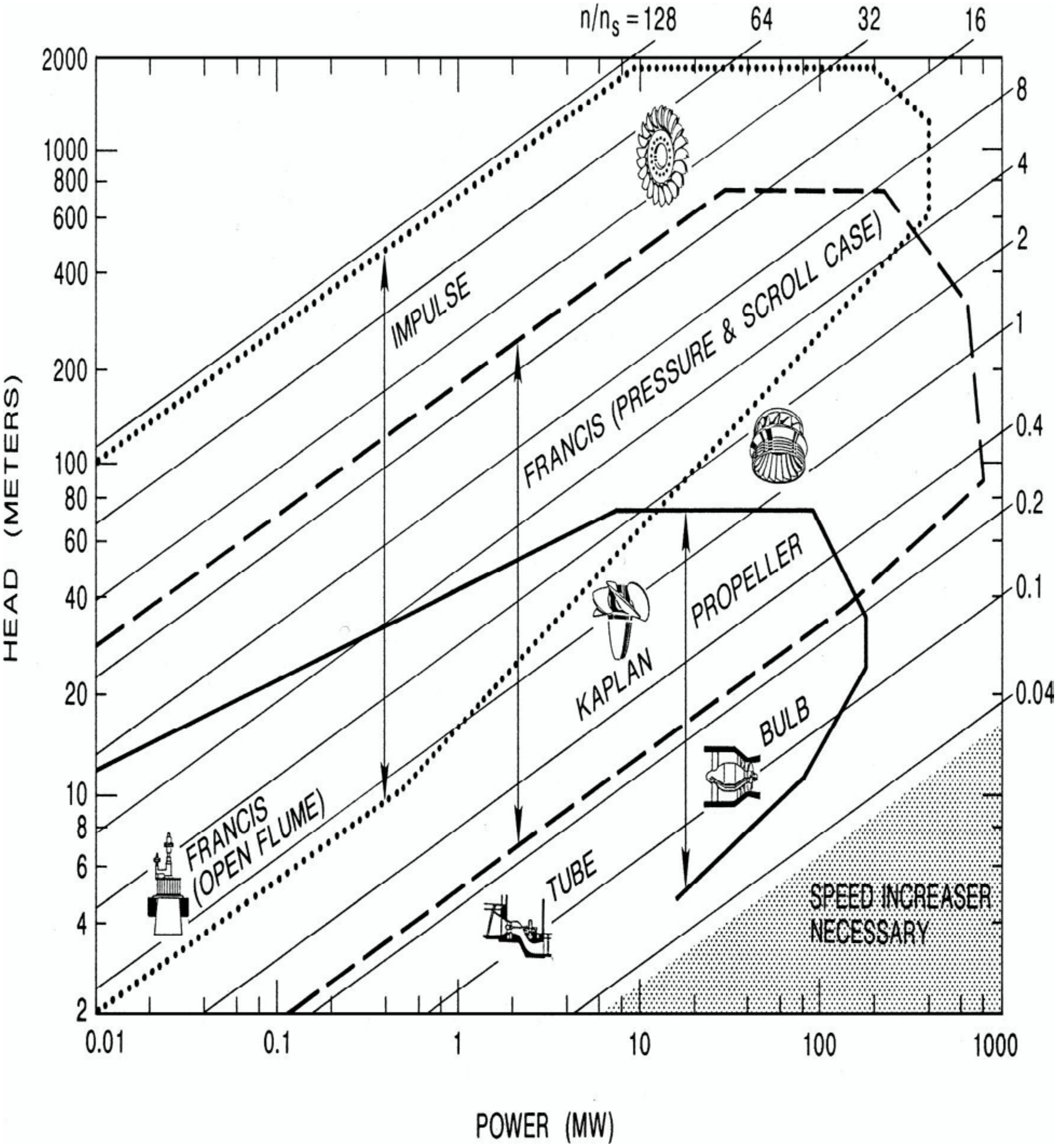

Figure (B.2) Application Ranges of the Main Turbine Types

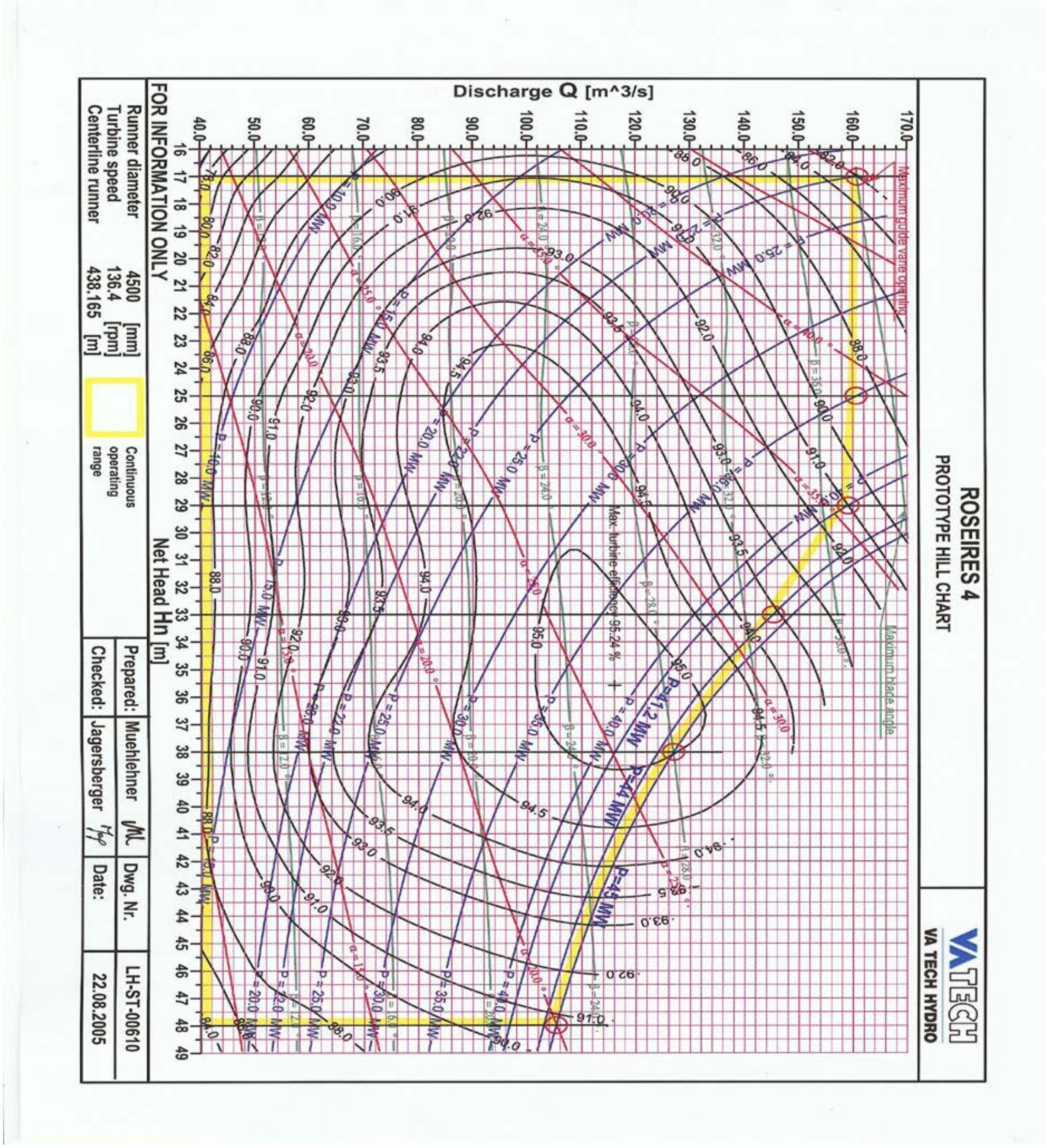

Figure (B.3) Hill Chart Unit Number Four