NUMERICAL INVESTIGATION OF PROTECTION MEASURES AGAINST WATER HAMMER IN THE YESILVADI HYDROPOWER PLANT

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ABSTRACT

NUMERICAL INVESTIGATION OF PROTECTION MEASURES AGAINST WATER HAMMER IN THE YESILVADI HYDROPOWER PLANT

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The purpose of this thesis is to analyze protection measures against water hammer numerically and compare the results with measured field data of Yesilvadi HEPP project. Pressure relief valves are used as protective measure against water hammer in Yesilvadi HEPP project formulation. The hydropower system is investigated numerically with software, Bentley HAMMER, which uses method of characteristics for solving nonlinear equations of transient flow. Yesilvadi HEPP project is analyzed for load rejection, instant load rejection, load acceptance and load variation scenarios for three different cases which are system without a protection measure, the existing system including pressure relief valves, and system as if including a surge tank instead of pressure relief valves against water hammer. The pressure variations at the inlets of turbines, maximum and minimum hydraulic grade lines of the water transmission line and rotational speed of turbines are computed and compared with measured data for these three different cases. Eventually, the effectiveness of protection measures are compared and some suggestions are made for appropriate operation of existing pressure relief valves to either diminish or decrease the effects of water hammer in Yesilvadi HEPP project.

Keywords: Water Hammer, Pressure Relief Valve, Protection Measures, HAMMER

ÖZ

YEŞİLVADİ HES PROJESİNDEKİ SU DARBESİNE KARŞI ALINAN KORUYUCU ÖNLEMLERİN SAYISAL OLARAK ANALİZ EDİLMESİ

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Bu tez çalışmasının amacı su darbesine karşı alınan koruyucu önlemlerin sayısal olarak analiz edilmesi ve elde edilen sonuçların Yeşilvadi HES projesine ait saha sonuçlarıyla karşılaştırılmasıdır. Yeşilvadi HES proje formülasyonunda oluşabilecek su darbesine karşı koruyucu önlem olarak basınç düşürücü vanalar kullanılmıştır. Proje sistemi, doğrusal olmayan diferansiyel denklemlerin çözümünde karakteristikler metodunu kullanan Bentley HAMMER adlı bilgisayar programı ile sayısal olarak incelenmiştir. Yeşilvadi HES projesi, koruyucu önlem alınmayan, mevcut durumdaki basınç düşürücü vana ile ve koruyucu önlem olarak sanki bu vanalar yerine denge bacası kullanılmış gibi üç farklı durum için yük atma, ani yük atma, yük alma ve yük değişimi senaryolarında incelenmiştir. Bu üç durum için türbinlerin girişlerindeki basınç değişmeleri, iletim sisteminde oluşan minimum ve maksimum hidrolik eğim çizgileri ile türbinlerin dönme hızları hesap edilmiş ve sahadaki sonuçlar ile karşılaştırılmıştır. Nihayetinde, koruyucu önlemlerin verimliliği karşılaştırılmış ve Yeşilvadi HES projesindeki su darbesi etkilerinin yok edilmesi veya azaltılabilmesi için sistemdeki basınç düşürücü vanaların yönetimi hakkında tavsiyelerde bulunulmuştur.

Anahtar Kelimeler: Su Darbesi, Basınç Düşürücü Vana, Koruyucu Önlemler, HAMMER

To My Family

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A	The cross-sectional area of the pipe (m^2)
a	Pressure wave speed throughout the fluid in pipe (m/s)
CS	Control surface
CV	Control Volume
D	Pipe diameter (m)
E	Young's Modulus (Modulus of Elasticity) (N/m^2)
e	Thickness of pipes (m)
f	Darcy friction factor
g	Gravitational acceleration
H	Pressure head in the pipe (m)
HEPP	Hydroelectric Power Plant
HGL	Hydraulic Grade Line
FRP	Fiber Reinforced Pipe
PRV	Pressure Relief Valve
H_0	Initial pressure head during steady-state flow (m)
K	Bulk modulus (N/m^2)
L	Length of the pipe (m)
MOC	Method of Characteristics
P	Pressure (N/m^2)
rpm	Revolution per minute
Q	Discharge in the pipe (m^3/s)
t	Time (s)
V	Velocity (m/s)
V_0	Initial velocity (m/s)
V_f	Final Velocity (m/s)
γ	Unit Weight (N/m^3)
ΔA	Change in cross-sectional area of the pipe (m^2)
ΔH	Change in pressure head of the fluid in the pipe (m)
ΔS	Stretching of the pipe in length (m)
ΔV	Change in velocity of fluid in the pipe (m/s)
$\Delta\rho$	Change in density of the fluid (kg/m^3)
μ	Poisson's ratio
ρ	Density of fluid (kg/m^3)
σ_f	Allowable tensile stress (N/m^2)
τ_w	Shear stress (N/m^2)

CHAPTER 1

INTRODUCTION

1.1 Introduction

Energy consumption is one of the indicators which reflect development of a country. The amount of energy generation is identified as power and technological development for countries. Growing population and increase in energy consumption per capita make energy generation one of the most important issues for Turkey. Providing uninterrupted, high quality and sustainable energy requirement is increasing day by day. As from 1990, yearly energy demand has increased 4.6 %, and it is estimated that increase in yearly energy demand will be 6.7 % (low scenario) or 7.5 % (high scenario) up to 2020 for Turkey (Turkyilmaz,2012). Unbalance between supply and demand has caused the country to import electricity from other countries for many years. To prevent that unbalanced situation and dependence on energy import, some governmental precautions have been taken since 2001. Turkey decided to encourage the private sector especially about renewable energy sources to meet that rapid increase in demand. Hydropower sources have been promoted by several laws and regulations. In March 2001, Electricity Market Law No. 4628, and later in March 2003, Water Usage Right Agreement were published. These laws have given chance to investors to build and operate hydropower plants with a license given by the Electricity Market Regulation Authority (EMRA). After that, Energy Law No. 5346 was published in May 2005. That law contains governmental guarantee for buying electricity generated by investors' hydroelectric power plants for the duration of 10 years. Besides these laws, procedures for getting license for hydropower plants has been made easier by some regulations.

That governmental promotion attempt has reached its objective immediately. According to the records of EMRA, there have been totally 1975 hydro electrical license applications till December 2013. 347 of them are now in operation and their total electrical power capacities are 9679 MW. 273 of these license applications are approved by EMRA and some of them are in construction, and some of them are at design stage now. There are 96 records for hydro electrical license applications that are in approval process. The rest of the applications are expired or cancelled (EMRA, 2013).

There are many variables which affect operation stage, and the amount of energy generation, determined by project license, in a hydropower system. Some of these variables may be diminished during design stage, some of them during construction period. The rest of them are about operational variables.

In hydraulic point of view, a power plant may operate mainly in two different states. First one is steady state which means there is no variation in hydraulic parameters such as discharge and pressure head at a point with time. Steady state condition is safe, because; hydraulic parameters are obvious. Hence, in this state only concerns are about hydrostatic and hydrodynamic forces which can be easily computed. Second one is unsteady state. Steady state condition is a special case of unsteady state which the unsteady flow equations must satisfy. When the flow conditions are changed from one steady state condition to another steady state, the intermediate stage flow case which is called transient state flow or transient flow occurs.

There are many possible causes for rapid or sudden changes in the hydropower plant system. Some of them are power failures, pipe breaks, a rapid valve opening or closure, equipment malfunctions, and operator errors. Because, there are many unpredictable variables during transient state, calculations about transients are more complicated than steady state. Every change in discharge or in other hydraulic parameters cause pressure change in pressurized pipeline system, which are penstocks commonly for small hydropower plants. The pressure fluctuations in pressurized pipeline system are named as water hammer. Water hammer may cause extremely high or low pressures in the pressurized pipeline system. Extremely high and low pressures may end up with burst or collapse of pipe. Also, turbines, valves and some other attached equipments of the system may be damaged. Moreover; it is possible that pressure head in the pipeline system may drop below the vapor pressure of the liquid during water hammer, and that may cause collapse of pipeline.

Water hammer is a very hazardous problem for hydroelectric power plants. It may cause fatalities, serious injuries, and costly damage to facilities and equipment. In the recent past, there are many events due to water hammer. The well known one is Sayano-Shushenskaya hydroelectric power plant accident. The hydroelectric power station is located on the Yenisei River in Russia. Before the accident, it was the largest power plant in Russia and the sixth-largest hydroelectric power plant in the world. At the accident day (17 August 2009), the station suffered a catastrophic pressure surge in turbine 2. The sudden water pressure surge, which is caused by water hammer, resulted in the ejection of turbine 2 with all equipment, a total weight some 900 tones, from its seat. The other turbines also suffered from severe damage. Turbine room roof fell, and water immediately flooded the engine and turbine rooms and caused a transformer explosion. On 23 August 2009, authorities said 69 people were found dead while 6 people are still listed as missing (Cruz et al, 2009).

Many studies have been made on hydraulic transients in closed conduits, and different types of protection systems have been developed to prevent similar events caused by transient flow and water hammer. Surge tanks, air chambers, valves are some control devices against undesirable transients.

1.2 Literature Survey

The study of fluid transients has a great historical background. The following paragraphs which are based on Chaudhry (1987) and a report of Tijsseling and Anderson (2006), give the most of the materials presented in transient history chronologically.

The propagation of sound waves in air, the propagation of waves in shallow water, and the flow of blood in arteries were the first subjects that attracted attention to the study of transients. Both Newton and Lagrange studied on these subjects in 17th and

18th century, however; they could not find a correct expression about these subjects. Euler derived partial differential equation and developed a general solution of wave propagation. Other subject studied by Euler was the flow of blood through arteries, but he failed to find a solution. A correct expression for the celerity of waves in a canal was derived by Lagrange. The well known term “Method of Characteristics” was entered the literature by Monge in 1789. Laplace studied on the theoretical expressions derived by Newton and Lagrange, and measured values of the velocity of sound in air. Following that study, about 1808, Laplace pointed out that, theoretical and experimental results were not matching, because theoretical expressions were based on Boyle’s Law which was valid for fixed pressure condition. The pressure wave speed for incompressible liquids contained in elastic pipes was firstly investigated by Young in 1808. Weber and Marey tried to determine the velocity of pressure waves in an elastic pipe. Marey conducted many series of tests. He gathered that the wave velocity was independent of the amplitude of the pressure waves; it was proportional to the elasticity of the tube. As distinct from earlier researchers, Korteweg was the first one who used the elasticity of both the pipe wall and the fluid to determine the wave velocity. Protection devices, which were air chambers and valves, were designed and used to deal with the problem of water hammer by Michaud in 1878. Frizell was consulting engineer of the Ogden hydroelectric development in Utah. He studied the water hammer problem of that hydroelectric plant. During his studies, he derived expressions for the velocity of water hammer waves and for the pressure rise due to change of flow. The effects of branch lines, and wave reflections were the other subjects which were studied by Frizell. In 1897, Joukowsky published a report about his experiments in Moscow on water hammer analysis in pipes. As Korweteg, he considered both elasticity of water and pipe material to develop the wave speed expression. He investigated the relationship between the flow velocity and the resulting pressure when flow pattern changed. By the help of these studies, he concluded that maximum pressure rise would occur for the closing times, $\mathrm{Tc} \leq 2\mathrm{L}/a$ where “Tc” is time of closure of the valve, “L” is the pipe length, and “a” is the wave speed. This fundamental equation in water hammer theory is commonly known as "Joukowsky Equation" in literature. Because, Frizell(1898) and Allievi(1902,1913) also found that well known equation unaware of the Joukowsky, it is sometimes named as "Joukowsky-Frizell" or "Allievi" equation. Joukowsky also studied on protective devices to eliminate water hammer problem. In 1926, Strowger and Kerr were the first ones who investigated the hydraulic turbine under changing load conditions. They analyzed the turbine speed variation and turbine efficiency during water hammer in the system. They also studied the effects of uniform and non-uniform gate movements on water hammer problem.

As time went by, increase in population and energy consumption necessitated renewable sources to produce energy. Hydropower was the first thing come to mind as a source. To use that source properly, many researchers have extended the literature on hydraulic transients by the help of previous studies mentioned above.

L.M. Hovey (1962) studied on the optimum settings of governors to ensure stability of Monitoba Hydro in Winnipeg River. For that purpose, he tried to find the values of compensation and dashpot time of governors. Then, he achieved to establish a general approach to measure and adjust the temporary drop with some assumptions.

H.Yokota et al. (1979) also studied on the stability of hydraulic turbines. They expanded the works done by Hovey and Chaudhry. They used P.I.D. (proportional-integral-derivative) governor to analyze the stability boundaries of a hydraulic turbine. Main criteria of their studies were the effect of derivative gain and other governor parameters on the stability boundaries of a hydraulic turbine. Finally, they provided a general guide for the optimum adjustment of the proportional, integral, and derivative gains.

P.H. Azoury et al (1986) used the computerized method of characteristics to analyze the effect of valve closure schedule on water hammer under turbulent friction conditions.

Jimenez and Chaudhry (1987) studied the elasticity of the pipe walls and the compressibility of the water column effects on plant stability. They managed to derive an analytical criterion for the stability of a single hydropower station unit. A computer simulation was utilized to verify the validity of that criterion. In the end, they introduced that hydro system under consideration is adversely affected by the elasticity of the pipe material, and that effect becomes critical for values of the Allievi parameter (r) less than one.

Hu Peicheng et al. (1989) tried to use an impulse relief valve and safety membranes instead of surge tank to reduce water hammer effect in small hydropower project systems. Field tests were conducted at Linzhenqu Water Power Station. After the tests, it was concluded that impulse relief valve and safety membranes could replace surge tank in small hydropower systems. Also, these devices were very simple and convenient in manufacture, operation and maintenance.

O.H. Souza et al. (1999) developed an analog/digital simulation method of nonlinear analog discrete models to analyze hydraulic transients in hydropower plants. They were able to determine flow, pressure head, and pressure oscillations in some point of the system by using the discrete hydraulic model of penstock. Also, they proposed a hydraulic turbine model by using characteristic curves and coefficients of test model. Finally, to verify the validity of the simulation, they solved transient equations of the test model analytically by using characteristics method. That comparison proved the accuracy of these analog/digital simulation methods.

Selek et al. (2004) used the method of characteristics to analyze the effects of the valve closure mechanism at the end of the penstock of Catalan Power Plant in Turkey. They used different computational schemes which were simple fixed-grid system, fixed-grid system with space-line interpolation, and variable grid system to solve numerically the governing equations of water hammer. Catalan hydropower plant have three Francis turbines and the data of those turbines during load rejection, emergency shut down, and quick stop conditions were collected by them. Then, they compared the theoretical and experimental results. That comparison showed that results agreed reasonably well for general pattern. For the maximum transient pressure, the variable-grid method of characteristics gave the nearest results to the field records.

Thi C. Vu et al. (2006) analyzed the partial discharge condition for Francis turbines. They said that helical vortex (so-called vortex rope) is formed in the draft tube cone during partial discharge condition through the system. A method was introduced to reduce that vortex rope. By that method, they offered to use water jet which is supplied with high-pressure water from spiral case inlet, through the tubular shaft.

Hongqing Fang et al. (2008) developed a simulation system in MATLAB/Simulink-based software of a typical hydroelectric power plant. They analyzed and simulated the nonlinear characteristics of hydraulic turbine and the inelastic water hammer effect. Also, they used that simulation to observe the influences of other parameters such as hydraulic turbine speed governor PID gains, and surge tanks. That simulation was applied for an actual hydroelectric power plant in China, and the results showed that MATLAB/Simulink-based software is accurate and effective enough.

Calamak (2012) studied on the protective measures against transient flow conditions in Erfelek hydropower plant. Three different kinds of measurements were tested by a computer program which uses method of characteristics to solve nonlinear partial differential equations of transient flow. Also, system was simulated as built (without a protective device). Then, results of the system with the protective devices were compared with the results of as built condition (without a protective device). He concluded that, using flywheels as protective measure would be effective for protecting mechanical equipment, because it decreased the turbine rotational speed during water hammer. Then he used pressure relief valves against transient flow condition and demonstrated that pressure relief valves are very effective in reducing water hammer pressures. Also he analyzed the effects of safety membranes against water hammer condition. Results proved that safety membranes could be used as standalone protective measure in hydro power plants.

1.3 The Motivation and Scope of the Study

Energy demand is increasing day by day all over the world. To supply that demand in Turkey, governmental precautions were taken to encourage the private sector especially about renewable energy sources. Hydropower systems are one of the most important parts of that pie.

After encouraging laws and regulations, investment on hydropower has been in rising trend and, projects have been widespread all over Turkey. There are 347 hydropower projects in operation, and 273 projects that some of them are in construction stage, and some of them are in design stage (EMRA,2013).

Safety of these hydropower systems is very crucial. Accidents in a system can cause deaths of people and loss of money by damaging the equipment. Hence, systems should be designed and constructed carefully.

The most critical issue in small hydropower plant is transient flow or water hammer. Any change in flow or pressure can cause transient flow in the system. Transient flow may cause burst or collapse of the penstocks.

Many of the small hydropower projects are run off river plant type. These systems generate energy in peak times generally. Hence, system does not always connect to grid. The connection or disconnection to the grid may cause transient conditions in the system. Also, there are many possible causes for rapid or sudden changes in a pipeline system such as power failures, pipe breaks, rapid valve opening or closing patterns, and operational errors. Therefore, precautions against transient events should be always taken.

The aim of the study is to analyze transient events in Yesilvadi HEPP (hydroelectric power plant) Project which is constructed in Hatay. Yesilvadi Diversion HEPP Project is a small hydropower project which has two horizontal Francis turbines. Installed electrical power capacity of each turbine is 4.99 MW. All the water transmission line is pressurized and consists of 4443 m long fiber reinforced pipe (FRP) and 315 m long penstock. In that system, pressure relief valves were preferred as protective measure against water hammer problem instead of surge tank, because topographical conditions are not appropriate for economical design.

In the present study, a computer program which solves the nonlinear partial differential equations of transient flow is used. By using that program, the field conditions (system with pressure relief valves) will be simulated. Also surge tank will be modeled as a protective device and the results will be analyzed. Finally, system without a protective measure will be simulated. These results will be compared to each other and advantages and drawbacks of the protective measures will be discussed. Then, the measured field data will be collected by the help of investor of the project. The response of the system against water hammer will be analyzed, and the proportionality of the program results and field test results will be discussed.

1.4 Organization of the Study

Next chapter is dedicated to the transient flow concepts. Due to the transient flow, water hammer occurs in the system. The water hammer concept and the causes of water hammer are explained. Then, the equations used in the study are derived.

In Chapter 3 general information about small hydropower plants (SHPs) is presented and the situation of SHPs in the world is discussed. After that, how SHPs were developed through the history and the types of SHPs are explained. Finally, the effects of water hammer in SHPs are discussed.

Bentley Hammer which is a computer software used in this study is presented in Chapter 4.

In Chapter 5, the detailed information about Yesilvadi HEPP is given. Then, three different case studies are performed for Yesilvadi HEPP. The pressure variations, changes in turbine rotational speeds due to water hammer effects with and without a protective device are determined.

In Chapter 6, results of the computer software are compared with measure field data, and some conclusions and suggestions are given according to that comparison.

CHAPTER 2

TRANSIENT FLOW

This chapter reviews the fundamental concepts and principles of transient flow. Firstly, definition of transient flow is given. Then, the fundamentals of water hammer are developed on the basis of basic conventional relationships of physics or fluid mechanics. Wave speed, continuity and momentum equations are derived. Then, details of method of characteristics (MOC), which is used for transforming nonlinear, hyperbolic partial differential equations into ordinary differential equations, are given. Next, those equations are integrated to obtain some algebraic equations to be solved in an x-t solution domain using relevant boundary conditions.

2.1 Definition of Transient Flow

In steady flow there is no change in flow conditions such as pressure, discharge and velocity at any location in the pipeline system with time. If flow conditions at a point are changing with time, flow is called unsteady flow. Steady flow is a special case of unsteady flow. In other words, unsteady flow equations are valid for steady flow conditions, too. Transient flow definition is used to describe unsteady flow of fluids in pipeline. Transient flow is an intermediate-stage flow, i.e., it is observed when the flow conditions are changing between two successive steady state conditions. Transient flow develops in pipeline system when there are changes in the hydraulic systems or the surrounding environment which affects the flow.

In general, transient flow can be divided in two types. The first type of transient is called as *quasi-steady flow*. The main characteristic of that type of transient flow is the gradual variation of discharges and pressure with time. Hence, the flow appears as steady over short time interval. Drawdown in the large reservoirs or in large tanks is a gradual process, so these situations are typical example of quasi-steady flow. The other type of transient flow is called as *true transient flow*. The main factors that affect the development of true transient flow are the fluid inertia and/or the elasticity of the fluid and pipe. If pipe and fluid elasticity effects are negligible while the inertial effects of pipeline system are significant, true transient flow is referred as *rigid-column flow*. On the other hand, if elasticity effects of pipe and fluid are under consideration in addition to the inertial effects, true transient flow is referred as *water hammer* (Larock et al, 2000).

2.2 Water Hammer

2.2.1 General

Water hammer term describes unsteady flow of water in pressurized pipeline system and, means hydraulic shock in basic. Changes of direction or velocity of the water in the system cause sudden increase in pressure. Those changes in pressure result in shock waves which move back and forth along the pipeline system. When shock waves encounter with a solid obstacle, a hammering sound is heard. That is the reason for the expression, water hammer in fluid transients.

Generally, because many factors are affecting flow and pressure in a pressurized pipeline system, flow cannot be always maintained at steady state condition. Pump or turbine stop and start, demand fluctuations, reservoir or tank level changes, equipment malfunctions, operation errors and many unforeseen events may cause hydraulic transients in the system. Typically the causes of water hammer may be categorized in four common events as follows (Bentley HAMMER, 2010):

- Pump startup may cause the rapid collapse of void spaces, and that result in high pressure generation in the pipeline system.
- Pump power failure may cause a rapid change in flow. On the pump side (discharge side) hydraulic grade line may fall down the pipeline elevation. That causes the pressure to reach the vapor pressure of the fluid in the pipeline and results in vapor column separation.
- Opening and closing time of valves in the pipeline system may cause pressure waves in the system. If the closing time of a valve is shorter than the elapsing time

during the travel of pressure surge between valve and reservoir and back to valve, it is called as sudden valve closure. Sudden valve closure cause rapid velocity changes which result in pressure rise in the system.

- Using improper protective devices or improper operation of protective devices may cause more harm than benefit.

A transient event may be defined as disturbance in the pipeline system. Transient events cause imbalance in the steady state flow condition. That imbalance in energy causes compression of fluid, pipe extension and expansion. However, water is not easily compressed, much of the kinetic energy generated by that imbalance caused by transient events cause significant pressure forces through the system. Pressure forces propagate to the whole pipeline system quickly and change the flow and pressure characteristics through the system. That propagation of pressure may cause fractures or weaken the pipeline or its supports.

2.2.2 Derivation of Transient Flow Equations

Momentum and mass conservation equations are generally used to model transient flow in closed conduits. Firstly, the unsteady momentum equation is applied to a control volume containing a section of pipeline system. Then, the continuity equation is developed for the fluid in the pipeline.

Figure 2.1(a) describes a hydraulic system containing a reservoir and pipeline system which has a valve at the end.

Suddenly, the valve at the downstream side of a pipeline system is closed; the velocity of the fluid layer immediately adjacent to the valve is brought from V_0 to rest by the effect of high pressure force developed at the valve face. After the velocity of the first layer is brought to rest, the same procedure is applied for consecutive layers through the whole pipeline. A pressure wave travelling at some sonic wave speed a from valve to upstream end of the pipeline system is visualized as the consecutive layer velocities are brought to rest. For a section of pipeline system shown in Figure 2.1(a), the application of momentum equation to a control volume is described in Figure 2.1(b). Absolute pressure wave speed which is caused by the small change in valve setting, and moving to the left is a-V_0. The head increase ΔH at the valve is directly related with the velocity change of flow ΔV. The momentum equation for the x axis shows that the resultant force on the control volume for x component is just equal to the time rate of increase of x momentum within the control volume plus the net efflux of x momentum from the control volume (Wylie et al., 1993).

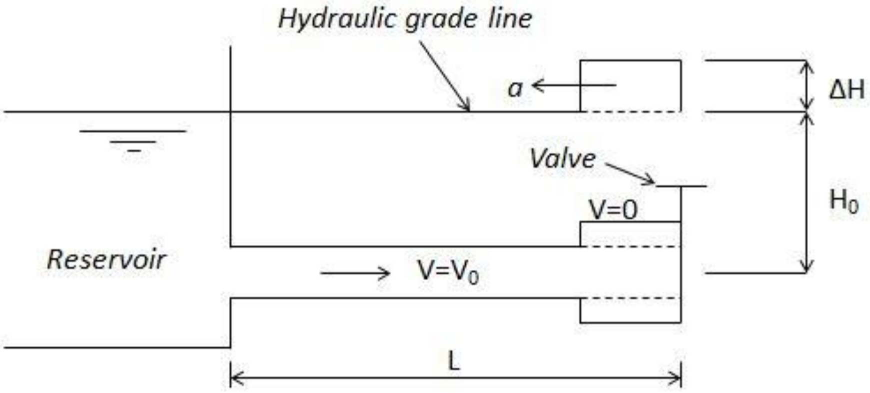


Figure 2.1(a) Pressure Rise in a Pipeline due to Instant Valve Closure

The momentum equation states

$$-\gamma \Delta H A = \rho A (a - V_0)\Delta V + \rho A (V_0 + \Delta V)^2 - \rho A {V_0}^2 \qquad (2.1)$$

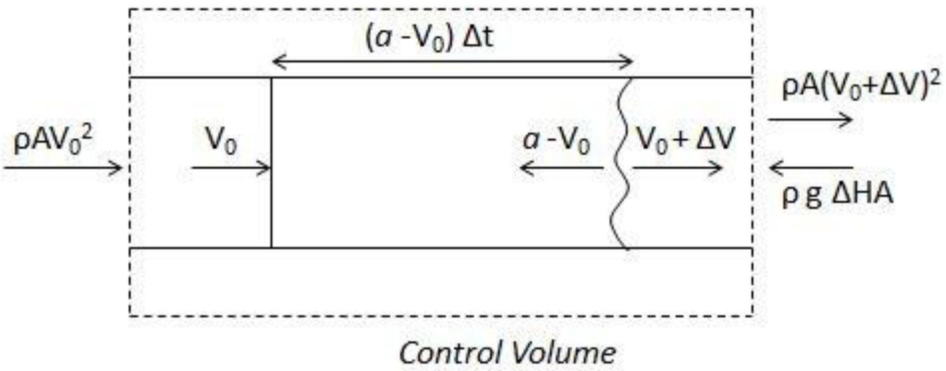


Figure 2.1(b) Momentum Equation Applied to Control Volume

where,

γ	:	specific weight of fluid (N/m^3)
ρ	:	mass density of fluid (γ/g) (kg/m^3)
g	:	acceleration of gravity (m/s^2)
A	:	cross-sectional area of pipe (m^2)
V_0	:	initial velocity (m/s)
ΔV	:	increment of flow velocity (m/s)
a	:	unknown wave speed (m/s)
ΔH	:	increment of head change (m)

The velocity change of the mass of fluid $\rho A(a - V_0)$ in one second is ΔV which is equal to $(V_f - V_0)$. V_f is the velocity of the fluid after valve operation and V_0 is the initial flow velocity before valve operation. ΔV^2 quantity is small and negligible. By eliminating that term equation reduces to

$$\Delta H = -\frac{a\Delta V}{g}\left(1+\frac{V_0}{a}\right) \approx -\frac{a\Delta V}{g} \tag{2.2}$$

Wave speed *a* value is generally very high when it is compared with initial velocity of the flow V_0. Hence, V_0/a value is very small compared with 1 for liquids in many pipe types. If the valve closed completely, final velocity of the flow is 0.

$$\Delta V = V_f - V_0 \tag{2.3}$$

Then, $\Delta V = 0 - V_0 = -V_0$, and when that value is put into Eq. 2.2 ΔH is found as aV_0/g. If the valve at the end of the pipeline has an incremental closure pattern, Eq. 2.2 can be redefined as

$$\sum \Delta H = -\frac{a}{g}\sum \Delta V \tag{2.4}$$

and valid for any movements of the valve until the pressure wave has not reached the upstream end of the pipeline system and returned as a reflected wave. In other words, that equation is valid for $t<2L/a$, where L is the pipe length.

By the application of continuity equation and using Eq. 2.2 the magnitude of wave speed a can be calculated. With reference to Figure 2.2, sudden closure of the valve at the end of the pipe causes pressure rise in the system. That pressure increase may cause the pipe to stretch in length ΔS, depending on how the pipe is supported. It is assumed that stretching of pipe occurs in L/a seconds, or velocity is $\Delta Sa/L$. Hence, ΔV is equal to $\Delta Sa/L\text{-}V_0$. During the elapsed time L/a, mass of fluid entering the pipe is $\rho AV_0L/a$. That mass is balanced with increase in cross sectional area ΔA and extension of the pipe ΔS. Also, compressing of liquid causes higher mass density of the liquid $\Delta\rho$. Application of continuity principle gives the following equation (see Eq. 2.5).

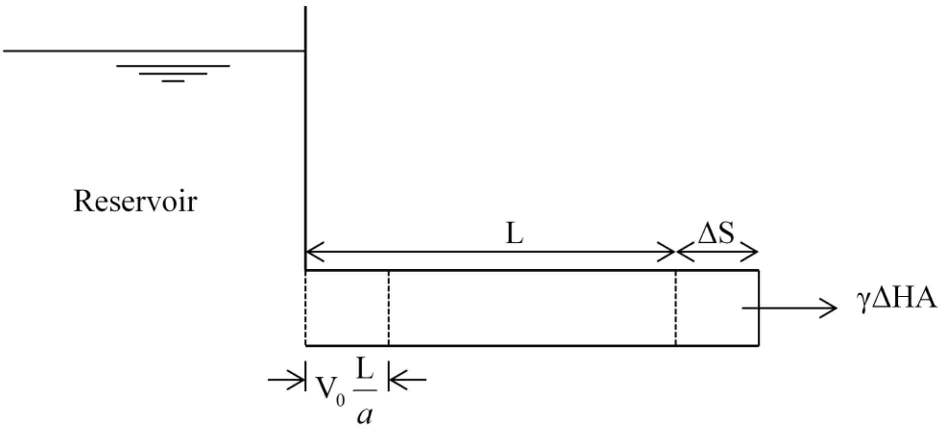


Figure 2.2 Continuity Relations in Pipeline

$$\rho AV_0\frac{L}{a}=\rho L\Delta A+\rho A\Delta S+LA\Delta\rho \tag{2.5}$$

To simplify Eq. 2.5, $\Delta V = \Delta Sa/L - V_0$ equality may be used to eliminate V_0 and equation is

$$-\frac{\Delta V}{a} = \frac{\Delta A}{A} + \frac{\Delta \rho}{\rho} \tag{2.6}$$

After that, to eliminate ΔV, Eq. 2.3 may be used and equation is

$$a^2 = \frac{g\Delta H}{\dfrac{\Delta A}{A} + \dfrac{\Delta \rho}{\rho}} \tag{2.7}$$

If the pipe extension is prevented by the help of pipe supports, $\Delta S = 0$ and the same equation for wave speed is obtained (see Eq.2.7), with or without expansion joints. Eq.2.7 may be redefined with *the bulk modulus of elasticity K* of the fluid. *The bulk modulus of elasticity K* is defined as

$$K = \frac{\Delta \rho}{\dfrac{\Delta \rho}{\rho}} = -\frac{\Delta \rho}{\dfrac{\Delta \forall}{\forall}} \tag{2.8}$$

where $\Delta\forall/\forall$ is the fractional volume change. Then, Eq. 2.7 can be rearranged as

$$a^2 = \frac{\dfrac{K}{\rho}}{1 + \dfrac{K}{A} + \dfrac{\Delta A}{\Delta \rho}} \tag{2.9}$$

If the pipe used in the system has thick wall, pressure rise due to valve closure may not cause a significant increase in cross sectional area. Hence, pressure rise mostly accommodated with liquid compression which causes rise in density of the fluid. Consequently, $\Delta A/\Delta \rho$ is very small and, $a \approx \sqrt{K/\rho}$ the acoustic speed of a small disturbance in an infinite fluid. On the other hand, for very flexible pipes, pressure rise caused by transients is mostly accommodated with the increasing cross sectional area of the pipe. Hence, the 1 is small and negligible when compared to the other terms in the denominator.

Then, acoustic wave speed for very flexible pipes is

$$a \approx \sqrt{\frac{A}{\rho}\frac{\Delta\rho}{\Delta A}} \tag{2.10}$$

Finally, acoustic wave speed for thin walled pipes is

$$a = \frac{\sqrt{\frac{K}{\rho}}}{\sqrt{1 + \left[\left(\frac{K}{E}\right)\left(\frac{D}{e}\right)\right] C_1}} \tag{2.11}$$

where C_1 is a constant that shows the effect of pipe constraint conditions.

If a pipe is anchored at its upstream end only $C_1 = 1 - \mu/2$, if the pipe anchored throughout against axial movement $C_1 = 1 - \mu^2$, and if the pipe anchored with expansion joints throughout $C_1 = 1$, in which μ is Poisson's ratio.

2.2.3 Continuity and Momentum Equations

Water hammer analysis is done to obtain the velocity, *V* or discharge, *Q* and pressure, *P* or piezometric head, *H* at any point at any time during transient event. To obtain these variables continuity and momentum equations are used. To derive the continuity equation, law of conservation of mass is applied. According to Newton's second law of motion, the time rate of change of momentum of system is equal to the sum of the forces exerted on the system by its surroundings. Figure 2.3 describes the parameters for continuity and momentum equations. It is considered that flow is compressible and walls are elastic. Also, it is considered that the control volume may shorten or elongate due to pressure changes. With reference to Figure 2.3 flow is one dimensional and pressure is uniform at the end sections of the control volume.

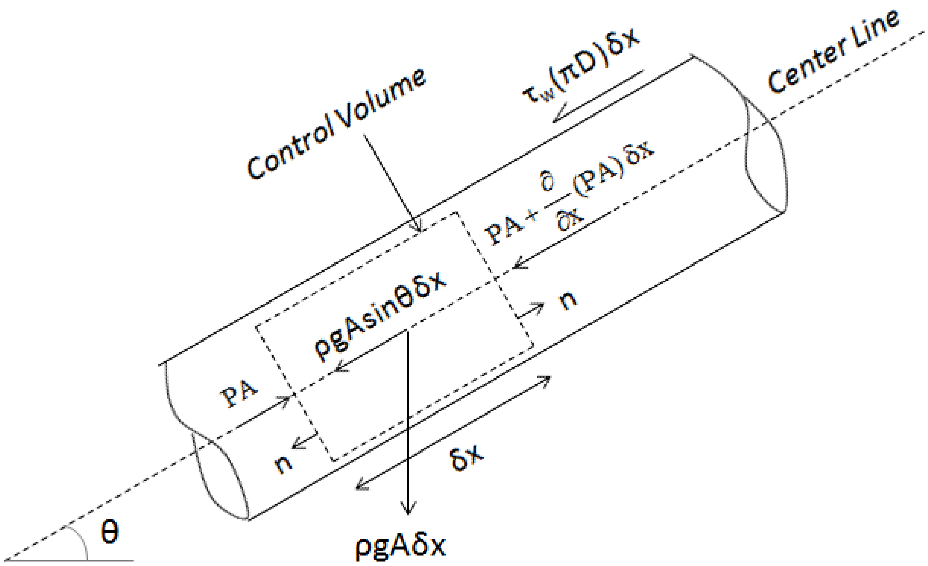


Figure 2.3 Continuity Relations in Pipeline

The following equations are derived for continuity and momentum conservation in the system.

Continuity Equation:
$$\frac{\partial P}{\partial t} + V\frac{\partial P}{\partial x} + \rho a^2 \frac{\partial V}{\partial x} = 0 \quad (2.12)$$

Momentum Equation:
$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + \frac{1}{\rho}\frac{\partial P}{\partial x} + g\sin\theta + \frac{4\tau_w}{\rho D} = 0 \quad (2.13)$$

where,

ρ	:	mass density of fluid (m^3/s)
P	:	Pressure (N/m^2)
V	:	Velocity of the fluid (m/s)
a	:	Acoustic wave speed (m/s)
τ_w	:	Wall shear stress (N/m^2)
D	:	Diameter of the pipe (m)
g	:	Gravitational acceleration (m/s^2)

A closed-form solution of these equations is not available. Hence, some solution methods such as *method of characteristics, finite element method, finite-difference methods, boundary integral method* and, *spectral method* should be applied to solve these kinds of equations. For this study, a computer program Bentley HAMMER is used to analyze water hammer. That software uses *method of characteristics (MOC)* to solve these equations.

2.2.4 Solution of Basic Differential Equations for Transient Flow with Method of Characteristics

For hydraulic transient problems which are one dimensional, *method of characteristics* is quite better than the other methods in several aspects, such as correct simulation of steep wave fronts, illustration of wave propagation, ease of programming, and efficiency of computations (Chaudhry, 1987).

The continuity and momentum equations are given in Eq 2.12 and Eq 2.13, respectively. These equations contain two dependent variables, velocity and hydraulic grade line elevation, and two independent variables which are distance along the pipe and time. By using method of characteristics, these equations are transformed into four ordinary differential equations (Wylie et al., 1993).

To simplify the transformation steps, momentum equation is identified as L_2 and continuity equation is identified as L_1. Also, $\frac{4\tau_\omega}{\rho D}$ $+g sin\theta$ term in Eq 2.13 is defined as F. Then, these equations are combined linearly using an unknown multiplier λ.

$$L_1 + \lambda L_2 = 0 \tag{2.14}$$

$$\frac{\partial P}{\partial t} + V\frac{\partial P}{\partial x} + \rho a^2 \frac{\partial V}{\partial x} + \lambda\left(\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + \frac{1}{\rho}\frac{\partial P}{\partial x} + F\right) = 0 \tag{2.15}$$

By rearranging the Eq 2.15,

$$\left[\frac{\partial P}{\partial t}+\left(V+\frac{\lambda}{\rho}\right)\frac{\partial P}{\partial x}\right]+\lambda\left[\frac{\partial V}{\partial t}+\left(V+\frac{\rho a^2}{\lambda}\right)\frac{\partial V}{\partial x}\right]+\lambda F=0 \tag{2.16}$$

From calculus it is known that if θ(x,t),

$$\frac{d\theta}{dt}=\frac{\partial\theta}{\partial t}+\frac{\partial\theta}{\partial x}\frac{dx}{dt} \tag{2.17}$$

Therefore, first term in Eq 2.16 is $\frac{dP}{dt}$ if $V+\frac{\lambda}{\rho}=\frac{dx}{dt}$, and similarly the second term is equal to $\frac{dV}{dt}$ if $V+\frac{\rho a^2}{\lambda}=\frac{dx}{dt}$. Consequently, Eq. 2.14 becomes

$$\frac{dP}{dt}+\lambda\frac{dV}{dt}+\lambda F=0 \tag{2.18}$$

Recalling,

$$\frac{dx}{dt}=\left(V+\frac{\lambda}{\rho}\right)=\left(V+\frac{\rho a^2}{\lambda}\right) \tag{2.19}$$

When Eq 2.19 is solved, λ value is determined as

$$\lambda=\pm\rho a \tag{2.20}$$

When λ value is put into Eq. 2.19,

$$\frac{dx}{dt}=V\pm a \tag{2.21}$$

Because, wave speed is much larger than flow velocity in general, *V* term in Eq. 2.21 may be neglected. When the value of λ obtained in Eq. 2.20 is put into Eq. 2.18, two pairs of equations which are grouped and identified as C^+ and C^- equations are derived.

$$C^{+}: \begin{cases} \dfrac{1}{\rho}\dfrac{dP}{dt} + a\dfrac{dV}{dt} + aF = 0 & (2.22) \\ \dfrac{dx}{dt} = +a & (2.23) \end{cases}$$

$$C^{-}: \begin{cases} \dfrac{1}{\rho}\dfrac{dP}{dt} - a\dfrac{dV}{dt} - aF = 0 & (2.24) \\ \dfrac{dx}{dt} = -a & (2.25) \end{cases}$$

Hence, two partial differential equations are converted into four ordinary differential equations by using two real values of λ. Acoustic wave speed *a* magnitude is dependent on the properties of the conduit and the fluid. Hence, it remains constant until the conduit or fluid properties change. Consequently, characteristic equations which are given in Eq. 2.23 and Eq. 2.25 plot straight lines with slopes "*+1/ a*" and "*-1/ a*" on the *xt* plane which is independent variable plane (Fig 2.4). These lines are named as "*characteristic*" lines and compatibility equations given in Eq. 2.22 and Eq.2.24 are valid only on the appropriate characteristic line.

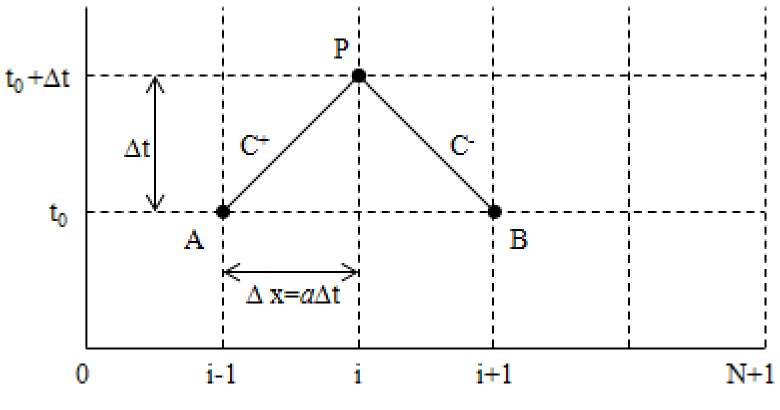


Figure 2.4 Characteristic Lines

With reference Figure 2.4, a pipe is divided *N* equal reaches. In the *x axis* of the xt plane, it is seen that the length of the each reaches is Δ*x*. Δ*t* is in the *y axis*.

According to the Courant condition time step size Δt should be equal or smaller than $\Delta x/a$. At each time step, characteristic equations must be solved for *N+1* nodes. The line between points *A* and *P* represents Eq. 2.23, and the characteristic line between points P and B represents Eq. 2.25. It is assumed that the dependent variables *V* and *H* are known at point *A.* Then compatibility equation at point *P* can be written in terms of dependent variables by integrating Eq. 2.22 which is valid on the C^+ line, between the limits *A* and *P*. In the same manner, Eq. 2.24 is valid on the C^- line, and by integration compatibility equation along the *BP* characteristic line a second equation in terms of the same two unknowns at point *P* is gathered. Simultaneous solution of these equations gives the unknowns at point *P* at the particular time.

To simplify the integration of compatibility equations, shear stress defined by Darcy-Weisbach can be applied in transient flow.

$$\tau_w = \frac{\rho f V|V|}{8} \tag{2.26}$$

Therefore,

$$F = g\sin\theta + f\,\frac{V|V|}{2D} \tag{2.27}$$

Then, by multiplying C^+ compatibility equation by $a\frac{dt}{g} = \frac{dx}{g}$, and by introducing the pipeline area to write the equation in terms of discharge ,where it is equal to velocity multiplied by cross sectional area, in place of velocity, the equation may be placed in a form suitable for integration along the C^+ characteristic line.

$$\int_{H_A}^{H_P} dH + \frac{a}{gA}\int_{Q_A}^{Q_P} dQ + \frac{f}{2gDA^2}\int_{X_A}^{X_P} Q|Q|dx = 0 \tag{2.28}$$

After similar procedures along the C^- line, following equations in terms of *H* and *Q* are derived.

$$C^{+}: H_{P} = H_{A} - B(Q_{P} - Q_{A}) - RQ_{A}|Q_{A}| \qquad (2.29)$$

$$C^{-}: H_{P} = H_{B} + B(Q_{P} - Q_{B}) - RQ_{B}|Q_{B}| \qquad (2.30)$$

where $B = \dfrac{a}{gA}$ and $R = \dfrac{f\Delta x}{2gDA^{2}}$

In general form

$$C^{+}: H_{Pi} = C_{P} - BQ_{Pi} \qquad (2.31)$$

where

$$C_{P}: H_{i-1} + BQ_{i-1} - RQ_{i-1}|Q_{i-1}| \qquad (2.32)$$

and

$$C^{-}: H_{Pi} = C_{M} + BQ_{Pi} \qquad (2.33)$$

where

$$C_{M}: H_{i+1} - BQ_{i+1} + RQ_{i+1}|Q_{i+1}| \qquad (2.34)$$

CHAPTER 3

SMALL HYDROPOWER PLANTS

3.1 Introduction

The main process of a typical hydropower system may be defined in the following way. Water is diverted by a diversion weir to the intake structure from a stream. Then, the water of the stream is carried downhill by a hydraulic conveyance line. After that, water is transferred into penstock and it passes through the turbine by generating electricity. The water is pressurized in the penstock and that pressurized flow creates force that drives the turbine. Basically, more flow and head produce more power.

As mentioned above, the source of the hydropower is the natural potential of usable water, and hydropower compensates about one quarter of the world's power requirement at present. Although, hydropower is a renewable source of the energy, detail planning, which includes economy, environmental concerns, and state water laws, is necessary for a successful result. In the planning stage, the precise data must be gathered especially for head, and flow which are the main components determining the amount of power generation. Because, process of hydropower includes the conversion of water energy first to mechanical energy and then to electrical energy, efficiency of the plant to convert mechanical energy to electrical energy is the other key factor that must be taken into consideration to determine the amount of power that can be obtained.

3.2 Power Supply and Demand

Demand is a variable which change from hour to hour during the day, from day to day, and from year to year. Demand can be defined as the total load needed by the consumer at any instant. At any instant time, system should compensate the demand to provide uninterrupted, high quality, and sustainable energy. A typical demand curve is given in Figure 3.1.

Supply is the instant generated energy in a system. A basic condition of system operation is that electricity cannot be stored. This means that electricity must be consumed immediately, while it is being generated. Hence, to have a balanced between supply and demand supplied energy must always be equal to consumed energy in real time (Sevaioglu, 2007).

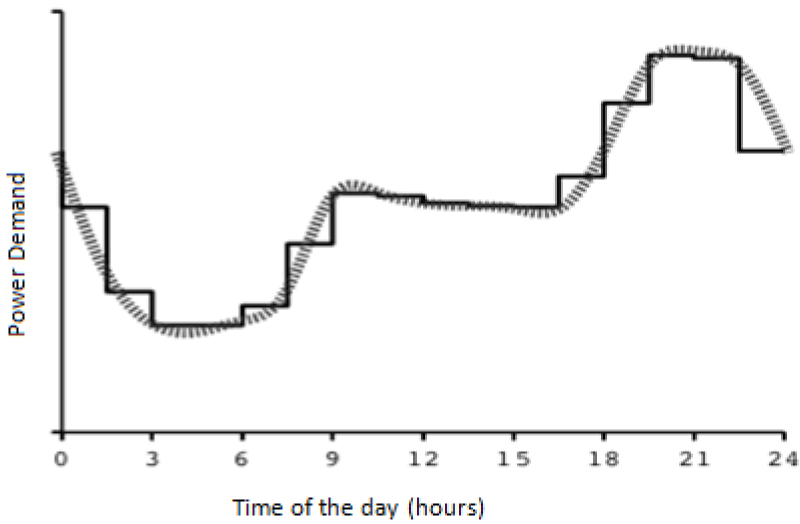


Figure 3.1 Typical Power Demand Curve During a Day

3.3 Some Fundamental Definitions of a Small Hydropower System

The gross head (H_g) is defined as the vertical difference in water level between the reservoir behind the dam and the water level in the tail water. *The effective or net head (H_n)* is the available head for energy generation. Net head is determined by deducting the minor and friction losses in the system from gross head. The hydraulic power of a hydropower system is calculated with the following formula.

$$P = \eta \rho g Q H_n / 1000 \text{ (kW)} \tag{3.1}$$

where

η	:	turbine efficiency
Q	:	flow rate (m3/s)
H_n	:	net head (m)
ρ	:	density of water (kg/m^3)
g	:	acceleration of gravity (m/s^2)

The hydraulic efficiency of the plant is defined as the ratio of net head to gross head (H_n/H_g). *Installed capacity* of a system means the maximum power that can be produced by the hydraulic turbines at normal head with full flow. Because, Eq 3.1 contains only turbine efficiency, it defines mechanical installed capacity. To gather electrical installed capacity, generator efficiency should also be added to Eq. 3.1. The unit of the electrical installed capacity is kilowatt (kW). To obtain the electrical energy generation, that power must be multiplied with the time of generation, so the unit of the electric energy is kilowatt-hour (kWh).

After gathering the stream flow data of a river that hydropower project is located on, flow-duration curve is derived. That curve helps to determine *design discharge* which is the maximum flow rate that all the system designed for, and flow rate determining installed capacity of the system. Also, flow-duration curve helps to determine firm and secondary power of the system. *Firm power* is the power which is always available for the system. It corresponds to the flow rate that is always available in the stream. *Secondary power* is the remaining part of the installed capacity, and its corresponding flow rate is not always available in the stream.

A general view of a hydropower system is given in Figure 3.2.

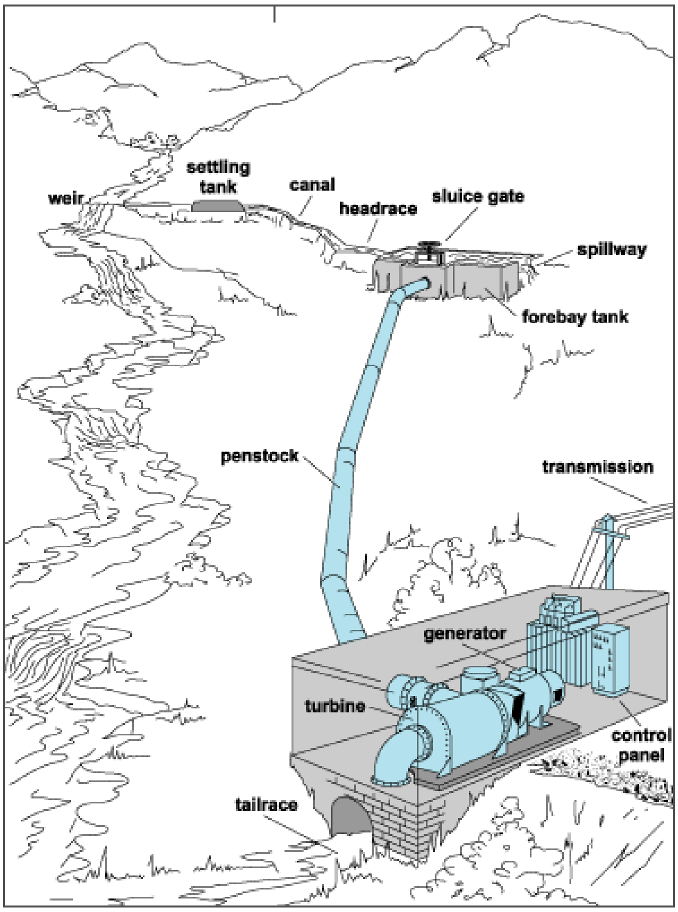


Figure 3.2 General View of a Hydropower System

3.4 Types of Hydropower Plants

3.4.1 Run-Of-River Plant

That kind of plants contains a small weir or barrage across the river. In run-of-river plant system, power station is generally an integral part of the dam structure. Because, it has limited storage capacity, electricity is generated only when water is available in the stream. Because the water in the stream is changing through the year, its firm capacity is low, but it can serve as a base load plant.

3.4.2 Diversion Canal Plant

Planning and construction of a hydropower plant contain many variables. Sometimes topographic, geological and hydrological conditions and, economic and environmental considerations may favor diversion-type power development schemes (P.Novak et al., 2004). Also, that kind of plants may be used when the natural bed slope of the stream is steeper than the diversion canal, to gain some head. Water is diverted with the help of diversion weir into a power canal where power station is located on. Then, the water rejoins the river further downstream. A general layout of diversion canal plan is given in Figure 3.3.

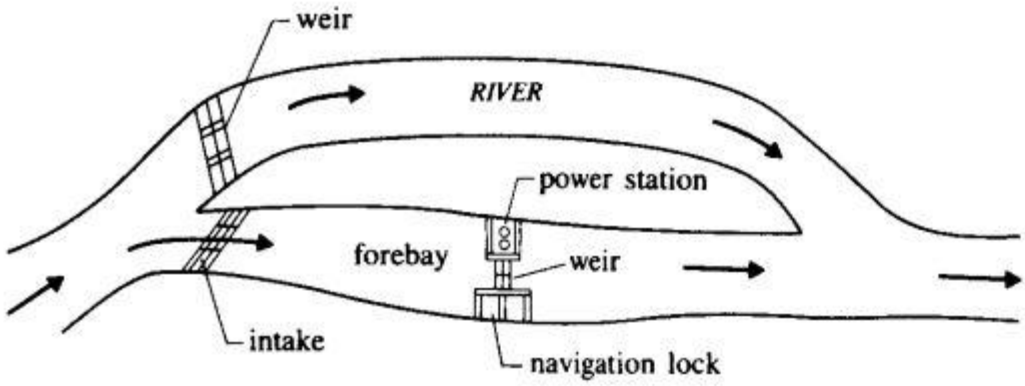


Figure 3.3 Typical Layout of a Diversion Canal Plant (P. Novak et al, 2004)

3.4.3 Storage Plant

That kind of plants has large reservoir capacities and creates head to produce hydropower. Power plant is separated from intake structure. Water is conveyed with tunnel, pipeline or some other kinds of hydraulic conduits between water intake structure and power plant. By the help of storage capacity, that kind of plants may be used as a base load or peak-load installation. Figure 3.4 shows a typical layout of storage plant system.

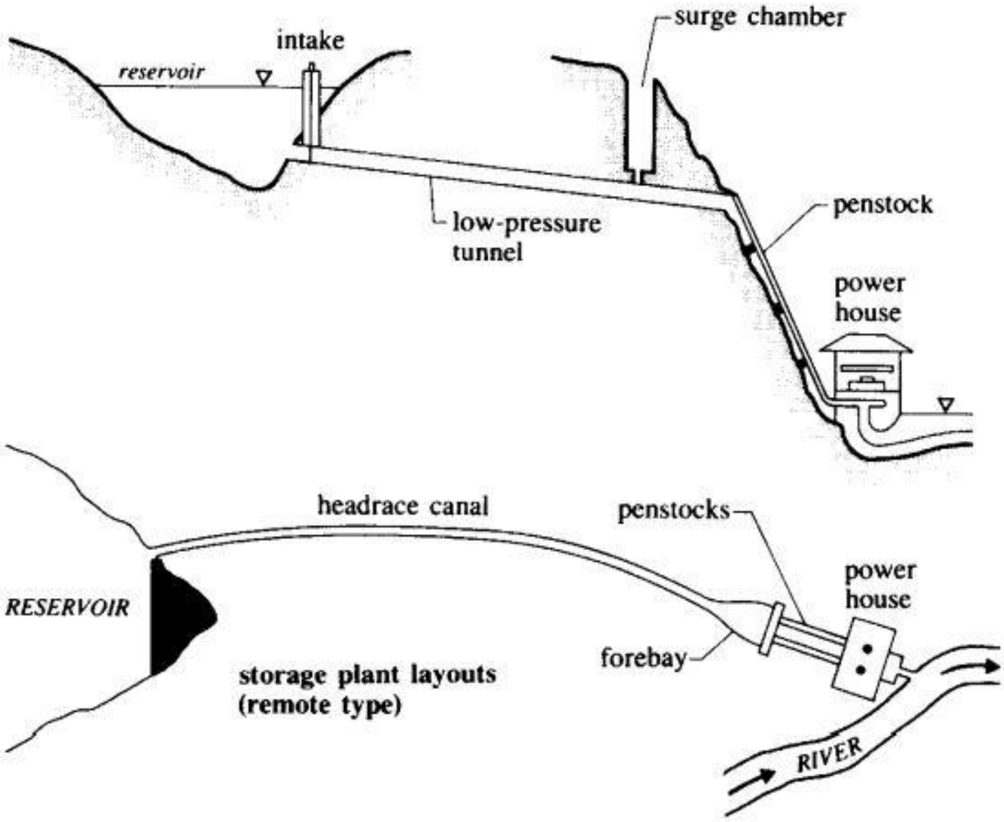


Figure 3.4 Typical Layout of a Storage Plant (P. Novak et al, 2004)

3.4.4 Pump Storage Plant

Because, electricity cannot be stored, storing energy as potential energy of water is the best way to supply demand in peak times. If the topographic conditions let to have two different reservoirs at the head and tail water locations, pump storage plant is a convenient plant design. Careful economic analysis is needed at the planning stage for that kind of plants. Water is pumped to upper reservoir when the demand and consequently price of electricity is low. Then, by using the stored water, electricity is generated at peak demand hours. Figure 3.5 shows a typical layout of pump storage plant.

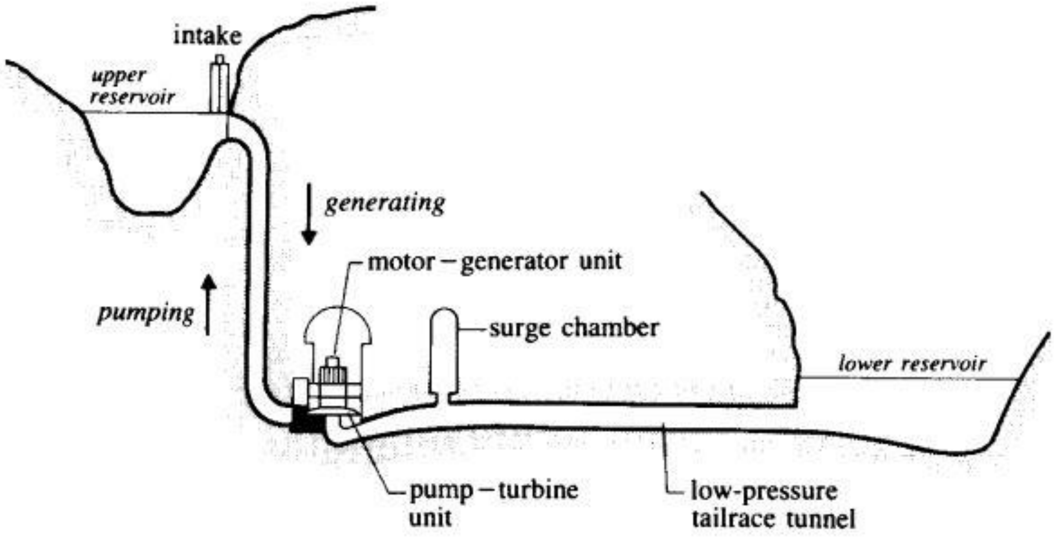


Figure 3.5 Typical Layout of a Pump Storage Plant (P. Novak et al, 2004)

3.5 Classification of Hydropower Plants

3.5.1 According to Head

Hydropower plants are classified in three categories according to head they have (Yildiz, 1992). These are,

- *Low Head Plants (H<15 m):* In general, that kind of plants is located on the streams having great amount water, and natural mild bed slope. Kaplan turbine is generally preferred for that kind of plants.
- *Medium Head Plants (H=15-50 m):* That kind of plants may be located on the streams having various flow schemes. Kaplan or Francis turbines may be preferred.
- *High Head Plants (H>50 m):* That kind of plants are generally needed at rough countries such as mountainous regions, or they are located on dams. Generally, they have long hydraulic conveyance lines and penstocks. Francis and Pelton turbines may be preferred.

3.5.2 According to Energy Generation Characteristics

There are two categories for that classification (Yildiz, 1992). Plant factor is an important term for that classification. Plant factor is defined as the net capacity factor of a power plant. In other words, plant factor is the rate of the amount of energy generated during a period of a time, and the amount of energy that the plant would have produced at full capacity during that time period. Categories are,

- *Base Load Plants:* That kind of plants always generates energy with plant factor greater than 30%.
- *Peak Load Plants:* That kind of plants generates energy at peak times. Hence, plant factor may be lower than 30%.

3.5.3 According to Installed Capacity

- *Small Capacity Plants:* P<99 kW
- *Low Capacity Plants:* 100<P<999 kW
- *Medium Capacity Plants:* 1000<P<9999 kW
- *High Capacity Plants:* 10000<P

3.6 Major Components of a Small Hydropower System

A hydropower system is a series of interconnected components. The main components:

- Diversion weir and intake structure,
- Hydraulic conveyance systems such as conveyance canal, tunnel, penstock,
- Forebay, in other words, headpond,
- Powerhouse

3.6.1 Diversion Weir and Intake Structures

The main purposes of the diversion weir structures are to raise the water level behind it, and to divert water to intake structure. Also, a diversion weir contains sluiceway structure to remove dirt, sediment and debris. Spillway is another important part of a diversion weir. In Turkey, diversion weirs are designed to withstand a flood discharge having a return period of 100 years, Q_{100}.

Water used for power generation is taken into hydropower system via intake structure. An intake structure contains settling basin to prevent sediment entry into conduit flow. Diverted water velocity decreases rapidly when it gets into settling basin. Hence, suspended particles have enough time to deposits. That accumulated sediment is washed time to time with flushing galleries at the end of the settling basin.

An intake structure should carry out the following requirements.

- assures required water supply,
- reduces sediment entry to minimum,
- checks trash and debris entry along with water entering in,
- prevents entry of ice,
- secures entry of water with minimum disturbance so that head loss is minimum.

A general layout of a diversion weir and water intake structure is given in Figure 3.6 (Yanmaz, 2006).

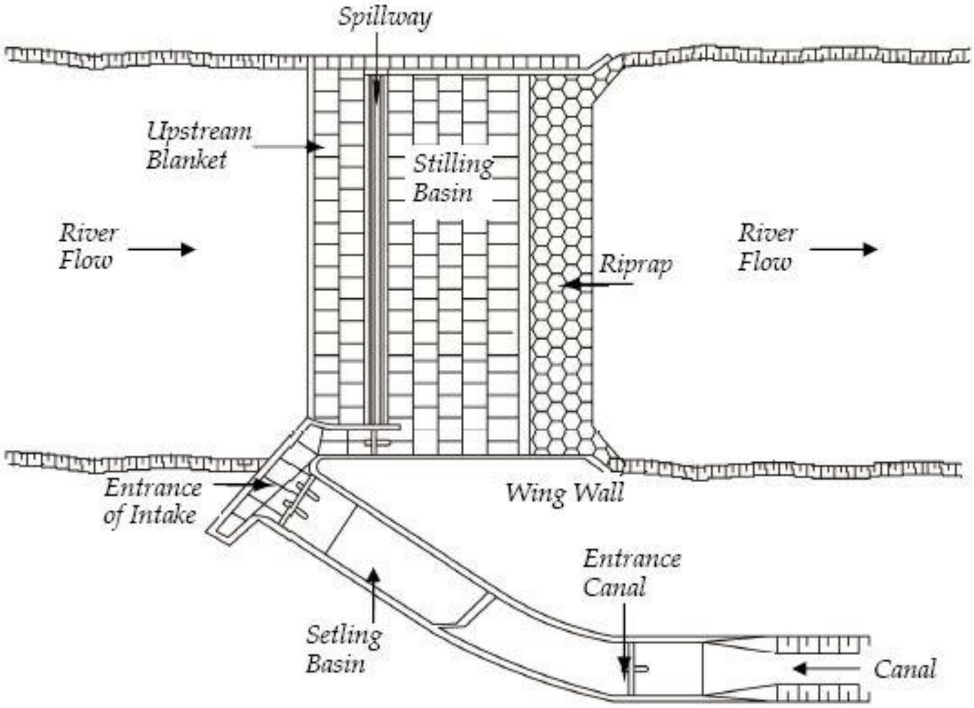


Figure 3.6 General Layouts of an Overflow Spillway and a Lateral Intake

3.6.2 Conveying Structures

After diverted water is purified at the settling basin, it is conveyed to headpond. Because, the topographical and geological conditions are different for every project, the conveyance system may change form one system to another. Canals, tunnels, pipelines and conduits may be used as conveying system in a SHP. Generally, slope of the conveyance system is mild to gather the maximum possible gross head in a SHP system. The flow from settling basin to headpond is open channel flow. To keep the water purified, conveyance system should be a closed section. Also, closed systems are beneficial to prevent water freeze. Manning-Stricler formula, which is given in Eq. 3.2, is used for hydraulic calculation in conveyance line.

$$Q = \frac{A}{n} R^{\frac{2}{3}} \sqrt{S_0} \tag{3.2}$$

Where,

Q	:	discharge (m^3/s)
A	:	cross-sectional area of flow (m^2)
R	:	hydraulic radius (m)
S_0	:	slope of the conveying structure
n	:	Manning's roughness coefficient

Sometimes, conveyance systems may be very long because of topographical conditions. Also, there may be some geological, environmental, economical or some other problems that make canal construction unfeasible. Tunnel is the best for neglecting these problems. Hydraulic and structural calculations are very important for tunnel maintenance.

3.6.3 Forebay or Headpond

Headpond is a connection structure between open channel flow in conveyance system and pressurized flow in penstock. The diverted water is conveyed with a conveyance system having mild slope to headpond. Generally, headpond is located on a high point to gather possible maximum gross head, and to shorten the penstock. Its volume capacity is important for load acceptance and load rejection conditions of turbines. Aims of a headpond are

- Distributing the water into penstocks,
- Regulating water flow from open channel to pressurized flow,
- Preventing sediment entrance to penstock, so protecting turbine blades,
- Supplying water demand to preventing air entrainment into penstock in load acceptance condition of the turbines,
- Damping upsurge, so protecting the system during load rejection condition of the turbines.

A typical cross section of a headpond is given in Figure 3.7.

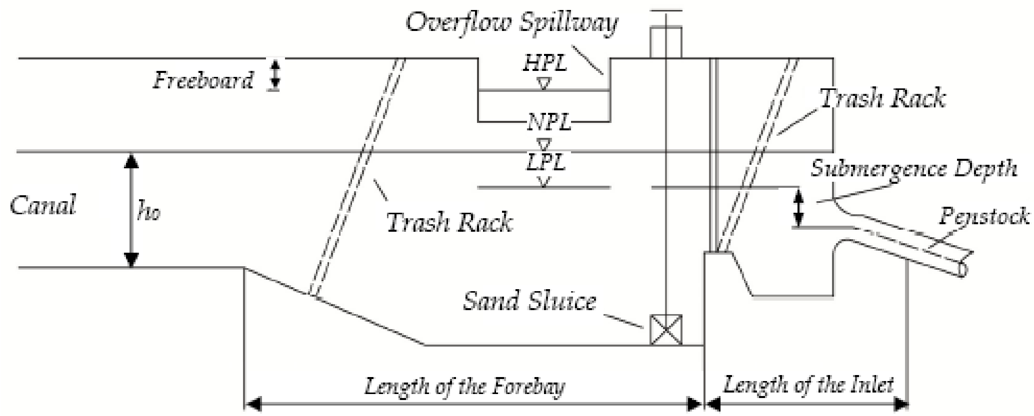


Figure 3.7 A Typical Cross Section of a Headpond (Jiandong et al, 1997)

3.6.4 Penstock

The penstock is pressurized pipeline system that transfers the water from headpond to turbines in the powerhouse. An optimum penstock means short, straight, steep as practical and, having a continuous downward slope. These characteristics reduce construction costs and friction loss.

During the design stage of penstock, location and direction should be selected carefully by thinking accessibility to construction area, geological condition of the area, existence of natural or man-made obstructions, and installation type of it.

Generally, penstock material is steel. On the other hand, PVC (polyvinyl chloride), polyethylene, and FRP (fiber reinforced pipe) may be used as penstock material. Cost, availability, physical properties and joining methods and installation limitations are some factors for selecting penstock material type.

Penstock diameter size is usually governed by project economics. For a specific discharge value, as the diameter of the penstock decreases, the velocity of the water flowing in it increases. Hence, the friction loss through the penstock increases. On the other hand, as pipe diameter increases, water velocity and correspondingly friction loss decreases. However, larger pipe diameter means high cost. Therefore, optimization study should be made to select penstock diameter. There are mainly three factors should be considered for a satisfactory design.

- Friction losses through the penstock,
- Pressure limitations of the pipe,
- Cost and installation of the pipe.

There are some empirical equations to determine economic penstock diameter (Yildiz, 1992). These are,

Sarkaria Equation : $$D = 0.634\left(\frac{P^{0.5}}{H^{\frac{3}{4}}}\right)^{0.86} \quad \text{(m)} \tag{3.3}$$

Bier Equation : $$D = 0.438\left(\frac{P^{0.5}}{H^{\frac{3}{4}}}\right) \quad \text{(m)} \tag{3.4}$$

Davis Equation: $$D = 0.175\left(\frac{P}{H}\right)^{0.466} \quad \text{(m)} \tag{3.5}$$

Warnick et al. Equation: $$D = CQ^{0.5} \quad \text{(m)} \tag{3.6}$$

Where,

D	:	penstock diameter (m)
P	:	rated capacity of the plant (hp)
H	:	rated net head (m)
Q	:	rated design discharge (m^3/s)
C	:	coefficient (C=0.72 for metric units)

Penstocks should withstand the pressure forces. There are two types of pressure to be considered. These are static pressure and pressure waves. Static pressure depends on the head between the free surface of the forebay and the interested point on the penstock. Pressure waves are caused by transient events due to sudden opening and closing of a valve at the end of the penstock. To determine the minimum thickness of the penstock, based on the need for stiffness, corrosion protection, and handling requirements, the following formula can be used (U.S. Bureau of Reclamation, 1967; Warnick et al., 1984).

$$t_{\min} = \frac{D + \mathrm{K}}{400} \tag{3.7}$$

Where,

t_{min} : the minimum thickness of the penstock (mm)

D : inside penstock diameter (mm)

K : constant (if stiffeners are used K=500, if not K=800 for metric units)

3.6.5 Powerhouse

The powerhouse is a building that contains turbine, governor and generator. In a powerhouse, potential energy of the water is converted into rotational mechanical energy by the help of hydraulic turbines. Then, that mechanical energy is converted into electrical energy via generators. Proper design is very critical for the efficiency of the hydropower system.

3.6.5.1 Hydraulic Turbines

A hydraulic turbine is usually designed for a particular net head and discharge. Turbines are classified into two categories according to energy conversion principles. First one is called as impulse turbines. Impulse turbines convert the hydraulic potential energy to velocity energy. These turbines contain nozzles to produce high velocity jets. Runner operates in nearly atmospheric pressure. Water jets leaving from one or more nozzles hit tangentially into the buckets or paddles of a wheel-shaped runner turning in air and hydraulic energy converts into rotational mechanical energy. The most commonly used type is Pelton turbine for this category. Second turbine type is called as reaction turbines. Reaction turbines are completely submerged in water and enclosed in a pressure casing, and driven by two different actions. First one is impulse action caused by the change of velocity direction from the runner inlet to the outlet. Second action is reaction which is caused by the difference in water pressure between the pressure side and the discharge side of the runner blade. Francis, Kaplan and Bulb turbine are the most commonly used types for this category. A Pelton turbine and a Francis turbine are given in Figure 3.8, and Figure 3.9, respectively. Turbine shafts may be in vertical or horizontal orientation.

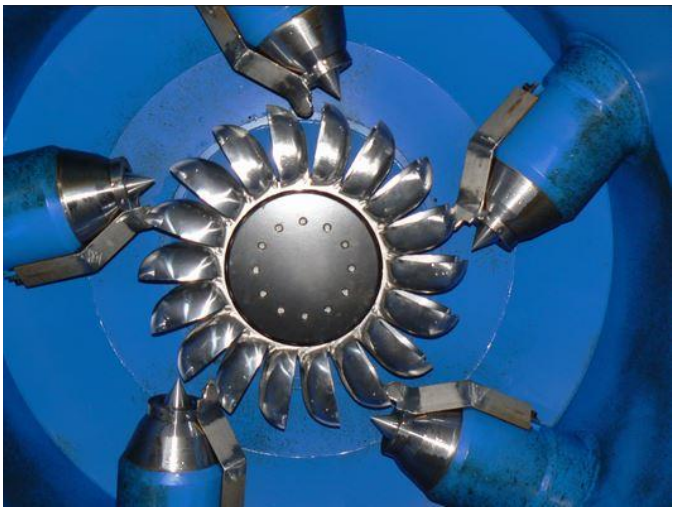


Figure 3.8 Pelton Turbine

Figure 3.9 Francis Turbine

Powerhouse configuration primarily depends on the type and size of the hydraulic turbine used. During turbine type selection, it is important that turbine should have the ability of producing required power at maximum efficiency and at the highest possible speed. The higher speed of turbine runner means smaller size of hydraulic equipment and generator. Hence, an optimization between the size, efficiency, and speed is necessary. Efficiency diagram of turbine types is given in Figure 3.10.

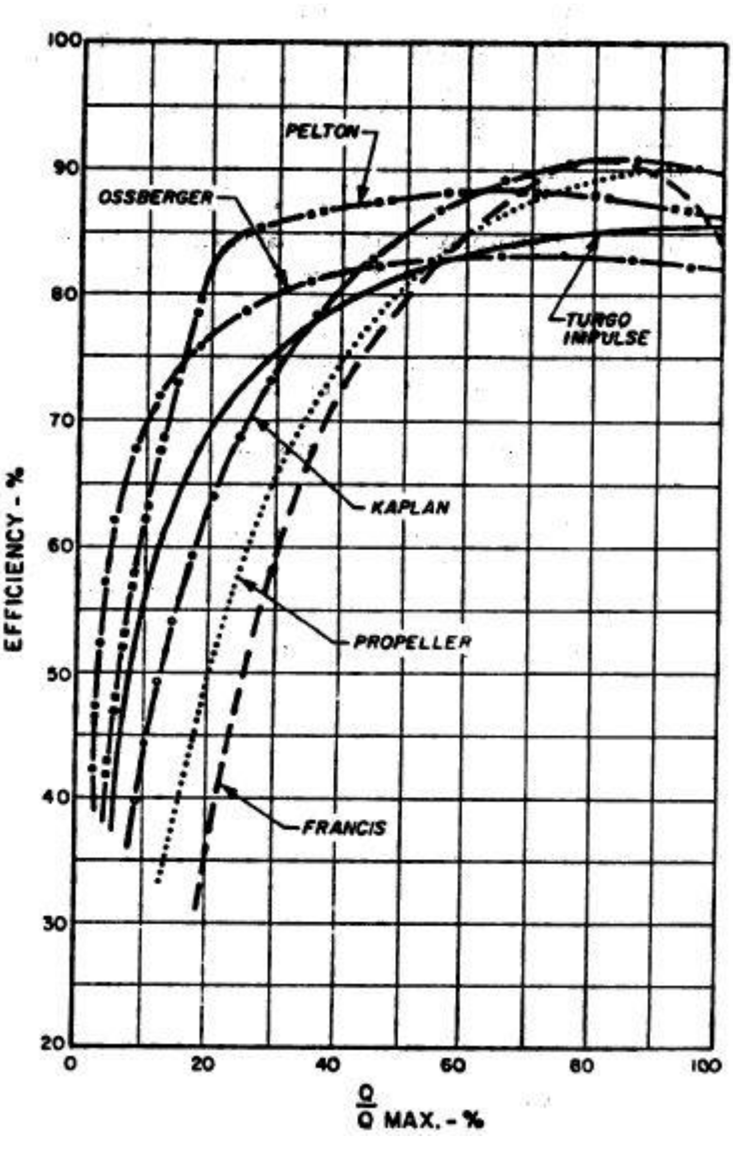


Figure 3.10 Turbine Efficiency Diagram (ASCE/EPRI Guides, 1983)

Turbine type is mainly based on the following characteristics of the SHP system.

- net design head (H_n),
- design discharge (Q),
- installed capacity (P),
- number of units.

After determining these characteristic, turbine type may be specified by using application chart (Figure 3.11).

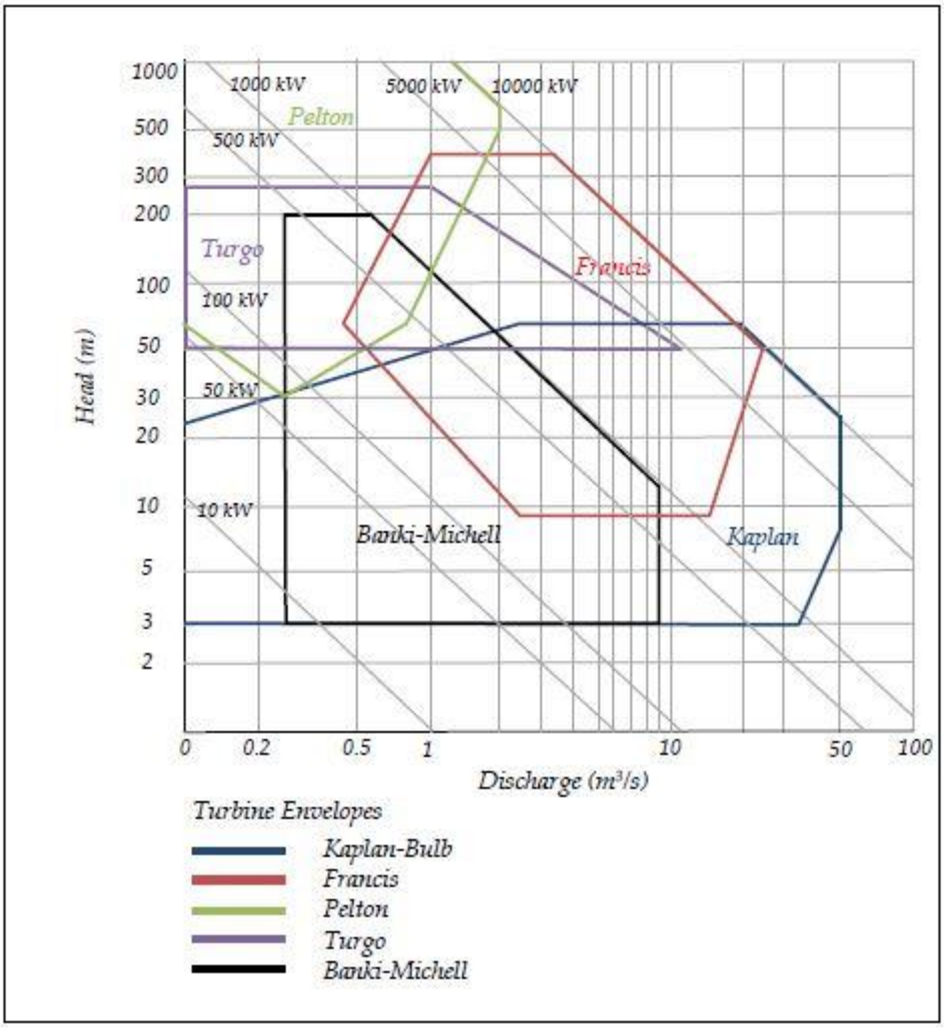


Figure 3.11 Turbine Type Selection Chart

3.6.5.2 Governor

The turbine- generator is designed for a particular net head and design discharge. Hence, any variation in these parameters must be compensated to maintain constant power out, constant speed, and constant flow. Hence, turbine governor is basically used for maintaining turbine speed constant or nearly constant, maintaining generator output constant or nearly constant, and minimizing the speed variations. Governor adjusts the guide vane or Pelton needle opening according to speed or frequency of the turbine runner.

3.6.5.3 Generator

Rotational mechanical energy of the turbine is converted into electrical energy by the help of generators. For hydropower plants, only 3- phase generators are used. There two types of generators which are synchronous and induction generators. Also, a generator has two main parts. These are rotor and stator. Rotor is the rotating part which is driven by the turbine and stator is the stationary part.

3.6.5.4 Main Turbine Valves

Hydropower systems include a main valve in front of the turbine(s) which is the part of the normal starting/stopping system. Main valves are used for emergency closing at large flows in case of penstock rupture or similar serious events. Some types of the main valves are spherical valves, butterfly valves, gate valves and ring and needle valves.

3.6.5.5 Draft Tube and Tailrace

The water energy is absorbed by vanes and runner of reaction turbines. Hence, its pressure reduces through the turbine and finally without draft tubes, the pressure could drop below atmospheric pressure in absence of water. That causes the entire turbine to fail to work and power could be lost. The major function of the draft tube is to increase pressure to a higher level than atmospheric pressure to propel turbine to produce enough energy. Tail race may be defined as the minimum water level of a SHP system. The draft tube is a connection between tail race and the turbine. Hence, water is discharged to tail race by draft tube and required water to ensure pressure higher than atmospheric pressure is supplied from tail race.

3.7 Water Hammer in Small Hydropower Plants

Water hammer is defined as pressure surge or wave results from an abrupt change in pressure or velocity of fluid in the pipeline system. In a SHP, water hammer may be observed as pressure fluctuations in pipeline system, as rotational speed variations (overspeed, reverse rotation) in hydraulic machines or as water level oscillations in reservoirs or surge tanks.

There are many variables that cause water hammer in a hydropower system. Because, SHP projects are commonly located on the mountainous regions, and their installed capacity is low, length of penstocks are high, and the inertia of turbines and runners is low in general. These conditions of SHP make transient events more serious. Hence, a SHP system should be designed in detail for transients caused by those variables. Every parameters of a system should be identified carefully. Maximum and minimum pressures caused by water hammer should be determined approximately to control whether the system limits are appropriate or not. If system is not designed properly, pressure surges may reach magnitudes sufficient to burst or collapse the penstock of the system.

In design stage of a SHP, system parameters and layout should be determined firstly. Then, transient events should be analyzed for various possible operating conditions and the system reaction should be viewed whether transient effects in acceptable limits or not. If the system comeback is not in acceptable limits, the system parameters or system layout should be changed. Also, various control devices may be an alternative to have satisfying design.

3.8 Protective and Control Devices for Water Hammer in Small Hydropower Plants

During the lifetime of a SHP project, transient events may occur many times. Improper design conditions may cause significant damage to hydropower system, and also it may result in loss of life. Hence, safety of the system should be ensured by eliminating or reducing undesirable transients, such as excessive pressures, column separation, and pump or turbine overspeed. Many transient control strategies have been developed, including changes within the conveyance system, wave speed reduction, optimal operational measures, and installation of protective devices.

When the fundamental equation ($\Delta H = -a\Delta Q \ / \ gA$) in water hammer theory is considered, it can be inferred that undesirable transients may be reduced by increasing pipe cross-sectional area or reducing wave speed for a particular project. It is well known that wave speed depends on fluid type, pipe material type, pipe diameter and thickness of the pipe. Hence, those characteristics may be arranged to reduce wave speed and correspondingly water hammer in small hydropower plant system. On the other hand, selection of large pipeline diameter or very thick pipeline wall may not be economical. In such cases, water hammer effects may be controlled by some protective devices. Surge tanks, air chambers, and valves are some of the protective devices. Proper protective device choice must contain not only a study of its effectiveness and reliability, but also an assessment of relative initial costs and the character and frequency of maintenance necessities over a complete period.

3.8.1 Surge Tanks

Surge tank is a standpipe or pressure vessel like storage reservoir connected to pipeline system. Surge tank is used to neutralize pressure rises and falls to eliminate or decrease the water hammer effects in hydropower system. Surge tank absorbs sudden rises of pressure by increasing the water level in it, and also quickly provides extra water until the pressure is equalized again to avoid water column separation throughout a brief drop in pressure. Besides, pipeline length which is affected by water hammer is shortened by surge tank installation, and correspondingly pressure rise or drop is less than if the surge tank were not provided. Location and size of a surge tank depend on the hydraulic transient analysis, because each system will have its own characteristics. There are different types of surge tanks depending upon its arrangement such as *simple, orifice, differential, one-way,* or *closed.* Some of the surge tank types are shown in Figure 3.12.

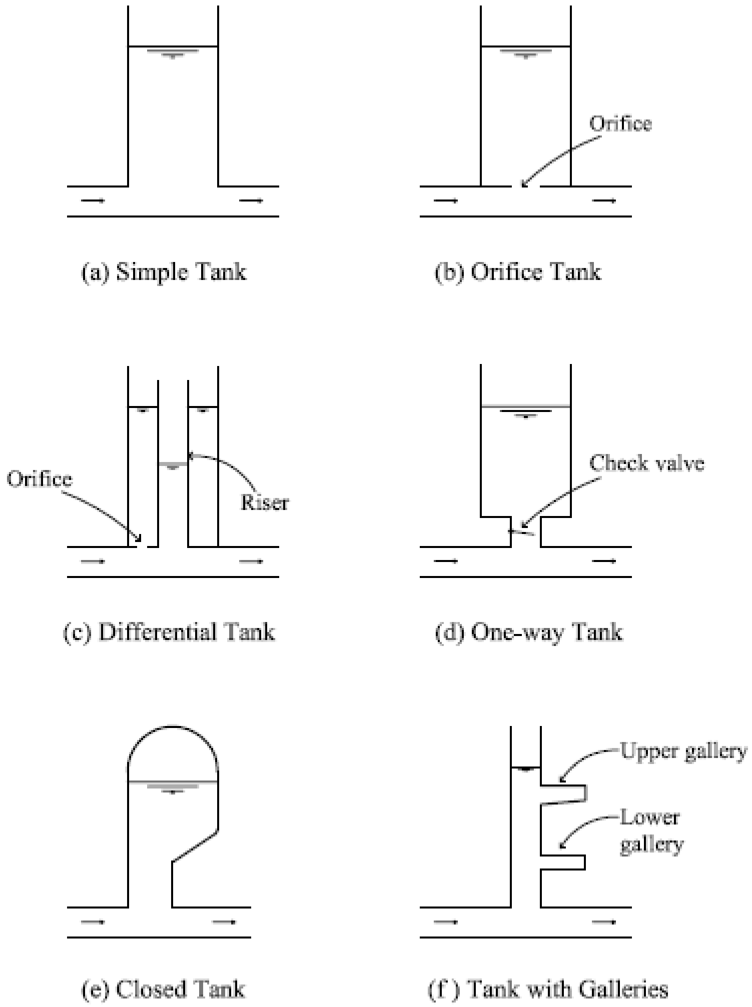


Figure 3.12 Some Surge Tank Types

3.8.2 Gas Vessel or Air Chambers

Air chambers working principles are similar to surge tank. It absorbs the excessive energy due to upsurge pressure and supplies extra water needed to prevent negative pressure caused by negative upsurge in the pipeline system. However, energy storing system is different than surge tank. An air chamber is a closed protective device that it is filled with water and compressed air. As the pressure in the system is rising, water filling the air chamber compresses the air in it. Hence, compressibility of the air is important to meet the maximum pressure rise in the pipeline system and to determine the air chamber size. On the other hand, during pressure decrease, compressed air forces the water out of chamber into cavity. Air chamber generally is more efficient system than other forms of water hammer protection devices to prevent negative pressures. Surge tanks are open to atmospheric pressure, so normal water level in a surge tank is equal to the normal water level of upstream reservoir minus hydraulic loses through the conveyance system between upstream reservoir and the surge tank. Therefore, needed surge tank height is very long, and consequently it is uneconomical and impossible to construct in structural point of view in high head plant systems. In such cases, installing an air chamber is preferable.

During the initial filling of an air chamber, sufficient air volume should be determined carefully. The volume of air at standard atmospheric pressure may not be adequate to supply the necessary volume under pressure. Hence, air chamber size may be selected larger than necessary or it can be topped up with the compressor. Also, air in the air chamber dissolves into the water in time, especially when the system is under the effect of overpressure. Therefore, the air needs to be recharged periodically (Stephenson,2002). A typical figure of an air chamber is shown in Figure 3.13.

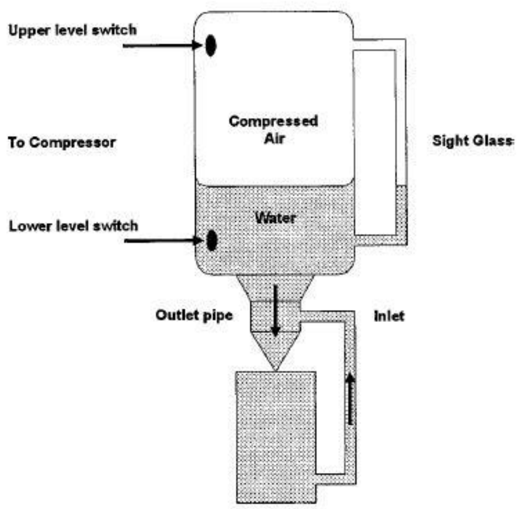


Figure 3.13 Air Chamber

3.8.3 Valves

There are different kinds of valves to control transient events in a hydropower system. Depending on the type, a valve is used to control transient conditions by valve operations such as proper opening and closing schemes to regulate flow velocity change, discharging the water from pipeline system when the pressure exceeds a set limit, and admitting air into the pipeline to prevent vapor pressure formation. Some of the valves commonly used as protective devices are *safety valves, pressure-relief valves, pressure-regulating valves, air-inlet valves,* and *check valves.*

Pressure-relief valves are the most commonly used type of valves as a protective device in a hydropower project. A pressure set point is determined for a PRV, and when the pressure in the pipeline near the valve exceeds that preset pressure limit, it is opened to allow outflow. That outflow causes a pressure drop and consequently reduces the maximum pressure for the remaining part of pressurized pipeline system. Continuous inflow supplies required water volume to prevent low pressure even cavitation. A PRV must have a low physical inertia so that it can react quickly to sensated pressure and open before the set point is greatly exceeded (see Figure 3.14). After pressure in the pipeline system drops under the set pressure limit, and pipeline is full again, PRV closes (Chaudhry, 1987).

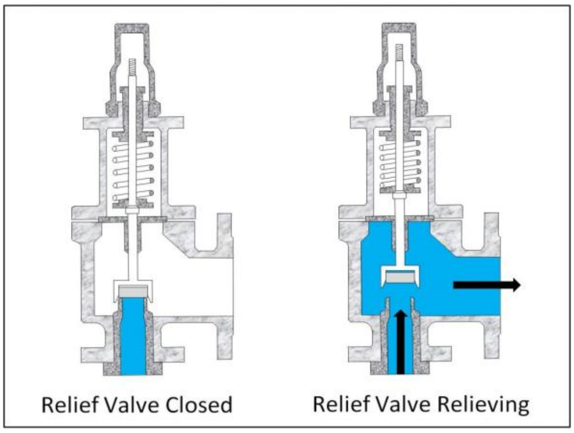


Figure 3.14 Relief Valve

Air inlet valves may be preferred to protect a pipeline system from collapsing due to low pressure. These devices generally positioned at high elevations of the pipeline. When the pressure in the pipeline drops below the atmospheric pressure around the system, air is admitted into the pipeline by air inlet valve. By this way, pressure difference between inside and outside of the pipeline, and consequently the risk of collapse of the pipeline is reduced. When the inside pressure increases to above outside atmospheric pressure, air inlet valve allows air leakage, usually at a much lower rate. On the other hand, water leakage is not allowed. Another function of that kind of valves is to reduce generation of high pressure during rejoining of liquid columns following column separation by providing an air cushion in the pipeline (Chaudhry, 1987).

Safety valves discharges water from pipeline to reduce pressure, when the inside pressure exceeds the preset pressure limit of the valve. A safety valve is characterized by rapid opening and closing action. It is either fully closed or fully open. It is a spring or weight-loaded valve (see Figure. 3.15).

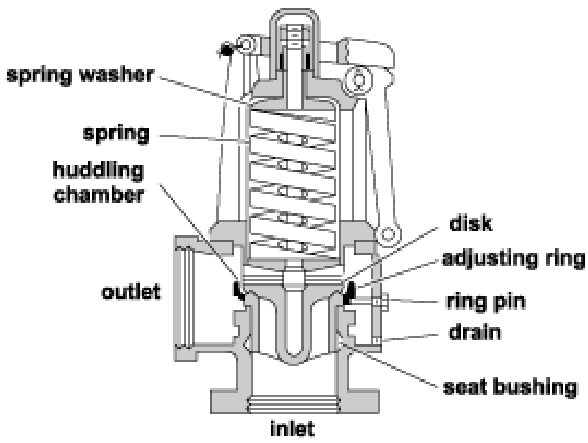


Figure 3.15 Safety Valve

CHAPTER 4

COMPUTER SOFTWARE

4.1 Overview and Necessity of Computer Software

Small hydropower plants have an important role for compensating electricity demand of unstable electricity market. Generally, small hydropower plants do not operate all day. They adapt the energy production to the demand of energy by storing water. Hence, startup and shutdown sequences of turbines are experienced almost every day for a small hydropower plant. Also, there are many other possibilities that may change flow conditions or pressure and cause hydraulic transients in pipeline system. Pipe breaks, power failures, inconvenient valve operations, some other operational errors and equipment malfunctions are some causes of transient flow in small hydropower plant systems. A safe and reliable design of the HEPP is only possible by making accurate definition of the transient phenomena with all boundary conditions for different operation cases. Reservoirs, headponds, valves, turbines and protective devices, branches, transitions in pipe diameters are the types of boundaries in a typical HEPP.

Transient flow in closed conduits is described by the continuity and momentum equations which are quasi-linear, hyperbolic, partial differential equations. Some numerical methods have been developed to solve these equations, but solving these equations manually is only possible for very simple pipeline systems. Also, it is time consuming, tedious and requires complex calculations which may lead to computational errors. Therefore, using computer software is indispensible for large systems or systems having more complex boundary conditions. There are many computer codes using method of characteristics to solve differential equations.

Also, there are some computer programs that simulate a complete HEPP system with its all boundary conditions.

Bentley HAMMER is one of the software that is able to simulate a complete system by using method of characteristics to solve differential equations of transient flow. Bentley HAMMER is a powerful yet easy-to-use program that has the capability of analyzing of very complex systems. It may be used for pumping systems, piping networks, hydropower system, etc. There are many advantages to use Bentley HAMMER. Some of them are listed below (Bentley HAMMER V8i Edition User's Guide, n.d.).

- By viewing the results, necessary precautions can be taken. Hence, the risk of transient-related damage to system can be reduced. That will ensure less service interruptions to customers.
- The effects of the transient phenomena on each element can be observed. Weak parts of the system can be strengthened, so the useful life of the system may be maximized.
- A hydropower plant can be modeled completely to simulate load rejection, acceptance and variation cases.
- There are many protective devices that can be modeled with Bentley HAMMER. Therefore, it is possible to compare the results and determine the most cost-effective surge control strategy.

Due to the advantages of HAMMER, it is used in the thesis studies by Middle East Technical University. The list of these thesis studies are given below.

- "Investigation of Water Hammer Problems in the Penstocks of Pumped-Storage Power Plants" is studied by Ali Ersin Dincer and completed in January 2013.
- "Investigation of Water Hammer Problems in Çamlıdere Dam-İvedik Water Treatment Pipeline at Various Hydraulic Conditions" is studied by Emre Sakabas and completed in February, 2012.

- "Investigation of Water Hammer Problems in the Penstocks of Small Hydropower Plants" is studied by Melih Calamak and completed in September, 2010.
- “Use of Air Chamber against Water Hammer in Penstocks” is studied by Birand Adal and completed in August, 2011.

4.2 Creating model with Bentley HAMMER

4.2.1. The Interface and the Toolbars of the Bentley HAMMER

Bentley HAMMER is user friendly software. Default workspace contains toolbars and their shortcuts, properties of the selected element, element symbology pane, user notification pane and the drawing pane. According to user preference, placement of the toolbars’ shortcuts may be changed and some shortcuts may be added or removed. Figure 4.1 shows default interface of the Bentley HAMMER.

Bentley HAMMER includes 8 toolbars. The name of these toolbars and their functions are listed below.

- File toolbar contains opening, closing, saving, and printing functions.
- Edit toolbar is used for deleting, finding, undoing, and redoing actions.
- Analysis toolbar contains scenarios, alternatives, and calculation options. This toolbar contains analyzing functions.
- View toolbar has functions to manage the appearance of the main window. Also, graphs, profiles, and flextables can be viewed by using this toolbar.
- Tools toolbar contains some useful tools such as wave speed calculator.
- Report toolbar has functions to report the results of the analysis.
- Help toolbar includes User’s Guide for Bentley HAMMER computer software.

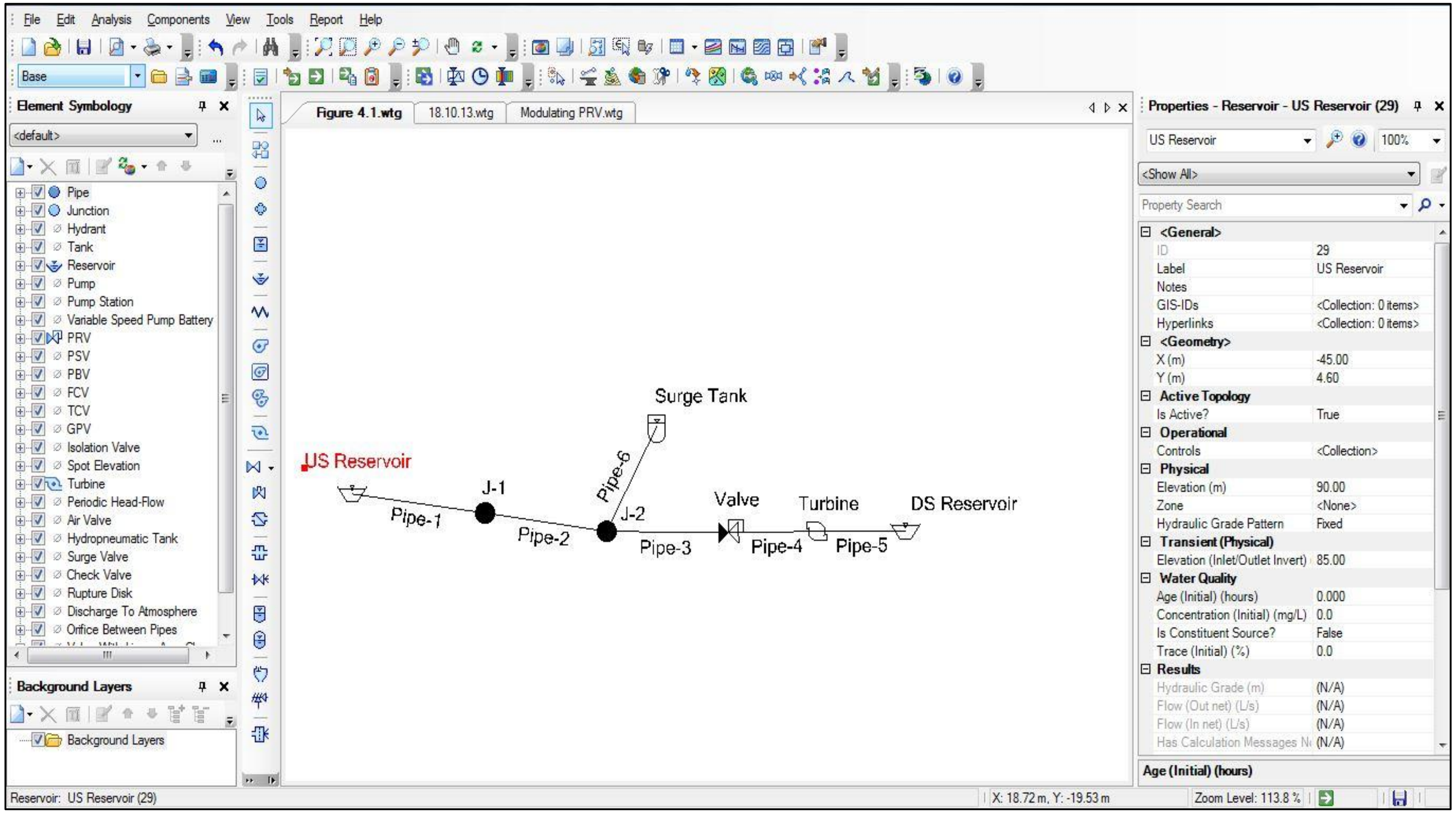


Figure 4.1 Default Workspace of Bentley HAMMER

4.2.2. Creating Model Layout

Creating a model layout is a very easy process by using Bentley HAMMER. This software has large database for modeling network systems, pumping systems, and hydropower systems. Default workspace of the software includes layout toolbar shown in Figure 4.2. By clicking the required element, model layout can be created schematically or scaled. Properties and usage of some significant elements included in layout toolbar are listed below.

Figure 4.2 Layout Toolbar of Bentley HAMMER

-  *Pipe:* In a hydraulic system, pipe is one of the main elements. All elements included in a system must be connected to another element by pipe element. Properties of the pipe material should be defined completely for a successful model. The required properties of a pipe element are its diameter, material type, length, friction factor, minor loss coefficient, and wave speed which can be calculated by using *wave speed calculator* toolbar. Material type of the pipe element can be chosen from existing engineering library. If a new material type is required, the properties can be defined and add to the material library to assign the pipe.
-  *Junction:* This element is used for connecting two or more pipes having different physical or transient properties in a hydraulic system. Furthermore, *Demands* can be assigned to junctions to satisfy user demands especially for network systems. For a successful hydropower system, the only required parameter of a junction is its elevation.
-  *Reservoir:* This element refers a storage node and used for defining free water surface in a hydraulic system. Diversion weirs, dams, forebays, and tailwaters can be defined by using reservoir element. Water surface elevation can

be defined as fixed or variable. However, water surface elevation does not change with pressure surge during transient simulation. Its water surface and inlet/outlet elevations are required for model simulation.

-  *Valves:* Valves are the control elements that open, throttle, or close to satisfy and maintain specified turbine conditions in a hydropower system. There are many types of valves defined by Bentley HAMMER. These are PRV (pressure reducing valve), PSV (pressure sustaining valve), PBV (pressure breaker valve), FCV (flow control valve), TCV (throttle control valve), and GPV (general purpose valve). The type of the valve is selected according to purpose of usage. Also, Bentley HAMMER has not a defined element to model an impulse turbine such as Pelton Turbine. A valve may be used for modeling impulse turbine during transient analysis. Properties window is shown in Figure 4.3 (a) for a PRV valve.
-  *Surge Tank:* Bentley HAMMER has many types of equipment as protective measures against water hammer phenomena. For a hydropower system, the most commonly used equipment is surge tank. Its normal water level is equal to the hydraulic grade line elevation at its located position. During load rejection case, it absorbs pressure waves, and during load acceptance case, it feeds the system. Bentley HAMMER includes two different kinds of surge tanks which are simple surge tank, and differential surge tank. Surge tank type, its section type and size of the section, initial, minimum and maximum water surface elevations are required for modeling.
-  *Turbine:* The turbine element in HAMMER is used for model reaction turbines. Impulse turbine can be modeled approximately by using a *Throttle Control Valve* (TCV) or *Discharge to Atmosphere* element. The elevation, efficiency, moment of inertia, rotational speed, rated head and flow, turbine curve, electrical torque curve are the required parameters for defining a turbine element. Figure 4.3(b) shows the properties window of a turbine element.

<Geometry>	
X (m)	144.88
Y (m)	14.00
Active Topology	
Is Active?	True
Initial Settings	
Status (Initial)	Active
Setting Type	Pressure
Pressure Setting (Initial) (kPa)	199.2
Operational	
Controls	<Collection>
Physical	
Elevation (m)	28.46
Installation Year	0
Zone	<None>
Diameter (Valve) (mm)	152.4
Valve Coefficient Type	Minor Loss
Specify Local Minor Loss?	True
Minor Loss Coefficient (Local)	0.500
Pattern (Valve Settings)	Fixed
Valve Type	Globe
Transient (Operational)	
Modulate Valve During Transient?	True
Opening Rate Coefficient (Transient	0.328
Closure Rate Coefficient (Transient)	0.328
Water Quality	
Age (Initial) (hours)	0.000
Concentration (Initial) (mg/L)	0.0
Trace (Initial) (%)	0.0

(a)

<Geometry>	
X (m)	81.00
Y (m)	10.00
Active Topology	
Is Active?	True
Initial Settings	
Status (Initial)	Open
Physical	
Elevation (m)	126.74
Installation Year	0
Zone	<None>
Transient (Operational)	
Time (Delay until Valve Operates) (:	0.0
Time For Valve To Operate (sec)	0.0
Pattern (Gate Opening)	Load Rejection
Operating Case	Load Rejection
Transient (Physical)	
Diameter (Spherical Valve) (mm)	657.0
Efficiency	0.92
Moment of Inertia (kg·m²)	2,111.200
Speed (Rotational) (rpm)	1,000
Specific Speed	SI=115, US=30
Turbine Curve	<Collection: 4 items>
Electrical Torque Curve	<Collection: 3 items>
Transient (Reporting)	
Report Period (Transient)	3
Water Quality	
Age (Initial) (hours)	0.000
Concentration (Initial) (mg/L)	0.0

(b)

Figure 4.3 Properties windows for (a) PRV, (b) Turbine

4.2.3. Calculation Options

Bentley HAMMER has two calculation steps. Firstly, steady state model should be created or imported. The input parameters to create a steady state model are listed below. Also, initial calculation summary is shown in Figure 4.4.

- Each system element such as reservoir, pipe, turbine, protective devices must be placed and connected to each other.
- Nodes must be placed where characteristics of the pipeline system change.
- Elevations of each elements and nodes must be entered manually.
- Pipe lengths and diameters, material types and properties such as young's modulus, roughness height, manning's coefficient, must be entered.
- Fluid conditions must be entered to calculate wave speed and to determine vapor pressure.
- Minor loss coefficient should be entered.
- Turbine characteristics such as diameter, moment of inertia, efficiency, rotational speed must be entered.
- Turbine curve must be entered.

Second calculation option of the Bentley HAMMER is transient solver. After all system characteristics entered and the steady state analysis completed, necessary data required for transient state must be entered. Bentley HAMMER has 4 different operating case alternatives which are load rejection, instant load rejection, load acceptance and load variation. The main steps are listed below. A typical transient calculation summary for load rejection case is shown in Figure 4.5.

- A profile must be created to view transient results.
- Operating case must be selected.
- Gate opening pattern data must be entered according to the operating case.
- For load rejection operating case, electrical-torque curve data must be entered.
- For load acceptance operating case, rated flow and rated head data must be entered.

- Run duration time must be entered.

4.2.4. Creating Scenarios and Alternatives

Bentley HAMMER is very powerful software to analyze many different operation conditions without editing or copying data. Some advantages of scenario management are listed below.

- Many alternatives may be generated with a single project file.
- Results of different alternatives may be compared directly.
- New scenarios may be created without having to re-declare any data.

Especially for large projects having hundreds or thousands of network elements, the advantages listed above becomes clearer.

4.2.5. Viewing Results

Initial calculation summary gives some useful information such as success or failure of the calculation, status messages for elements and the system flow results (Bentley HAMMER V8i Edition User's Guide, 2010.).

Transient results viewer has two alternatives. First one gives the option of viewing initial, minimum, and maximum values of hydraulic grade, pressure, velocity, air/vapor volume along the selected path (see Figure 4.6). Second alternative gives the option of viewing transient time history at any selected point along the path (see Figure 4.7). Also, transient time history of the selected point may be animated.

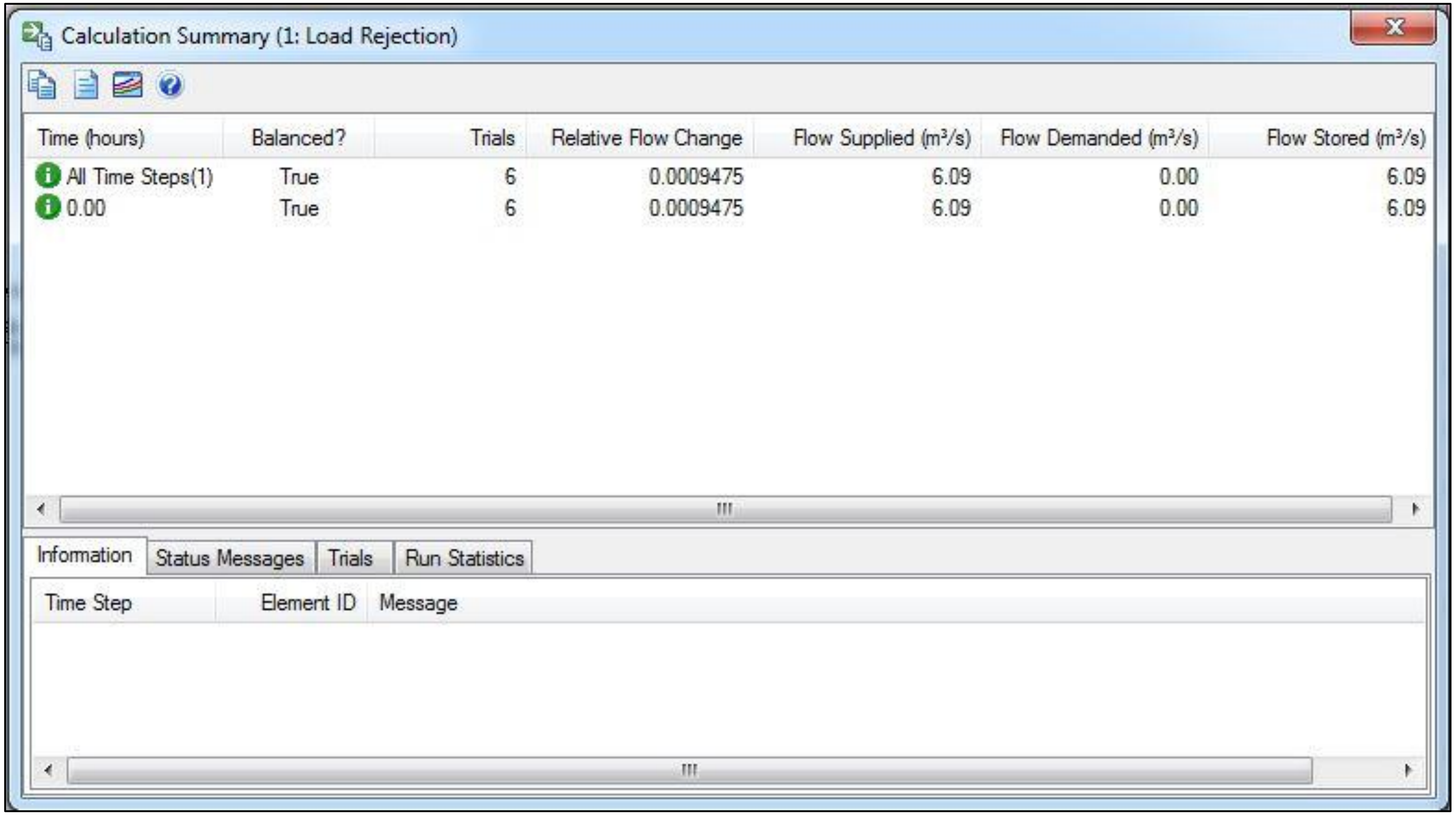
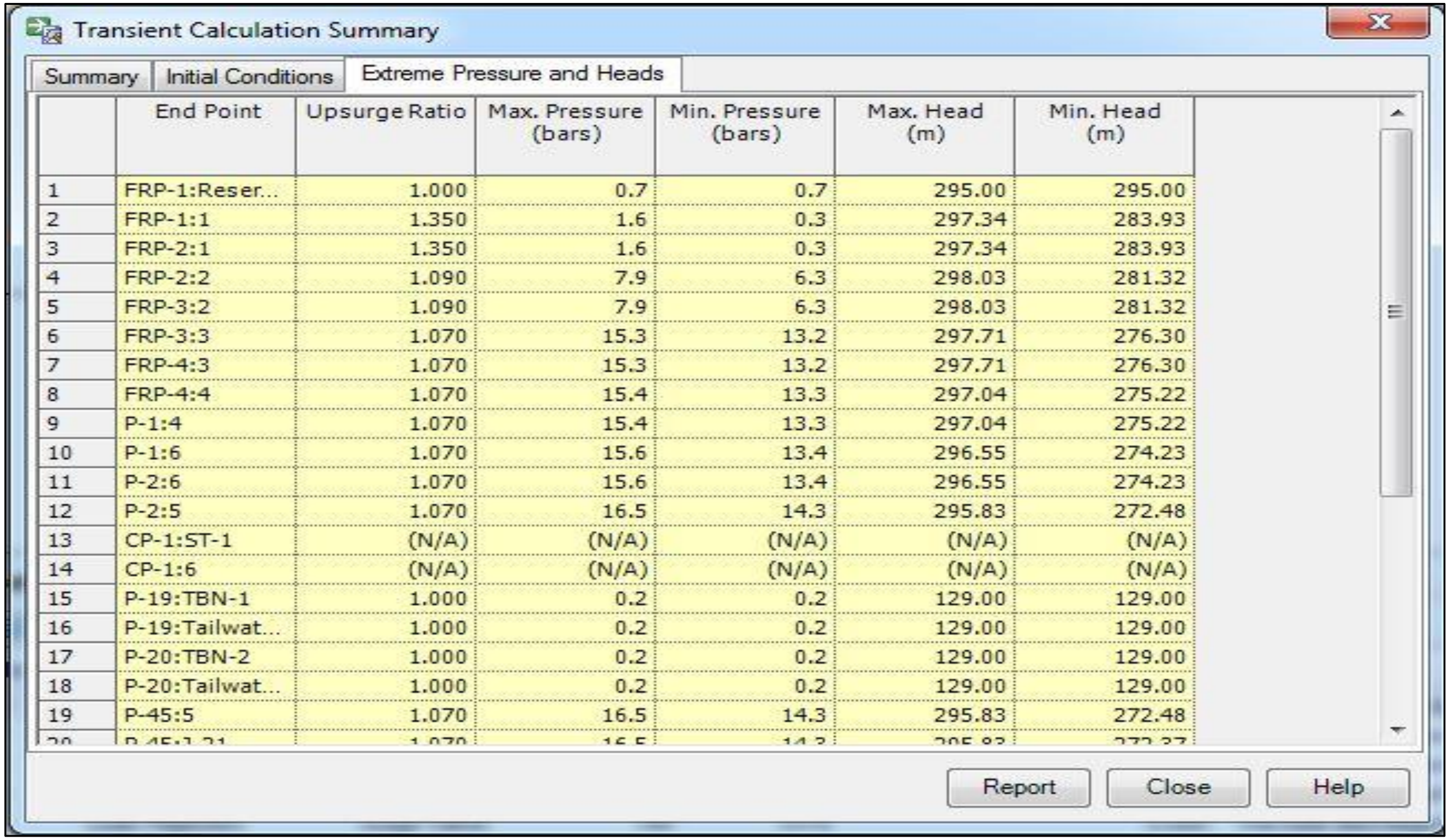


Figure 4.4 Initial Conditions Calculation Summary



	End Point	Upsurge Ratio	Max. Pressure (bars)	Min. Pressure (bars)	Max. Head (m)	Min. Head (m)
1	FRP-1:Reser...	1.000	0.7	0.7	295.00	295.00
2	FRP-1:1	1.350	1.6	0.3	297.34	283.93
3	FRP-2:1	1.350	1.6	0.3	297.34	283.93
4	FRP-2:2	1.090	7.9	6.3	298.03	281.32
5	FRP-3:2	1.090	7.9	6.3	298.03	281.32
6	FRP-3:3	1.070	15.3	13.2	297.71	276.30
7	FRP-4:3	1.070	15.3	13.2	297.71	276.30
8	FRP-4:4	1.070	15.4	13.3	297.04	275.22
9	P-1:4	1.070	15.4	13.3	297.04	275.22
10	P-1:6	1.070	15.6	13.4	296.55	274.23
11	P-2:6	1.070	15.6	13.4	296.55	274.23
12	P-2:5	1.070	16.5	14.3	295.83	272.48
13	CP-1:ST-1	(N/A)	(N/A)	(N/A)	(N/A)	(N/A)
14	CP-1:6	(N/A)	(N/A)	(N/A)	(N/A)	(N/A)
15	P-19:TBN-1	1.000	0.2	0.2	129.00	129.00
16	P-19:Tailwat...	1.000	0.2	0.2	129.00	129.00
17	P-20:TBN-2	1.000	0.2	0.2	129.00	129.00
18	P-20:Tailwat...	1.000	0.2	0.2	129.00	129.00
19	P-45:5	1.070	16.5	14.3	295.83	272.48

Figure 4.5 Transient Calculation Summary

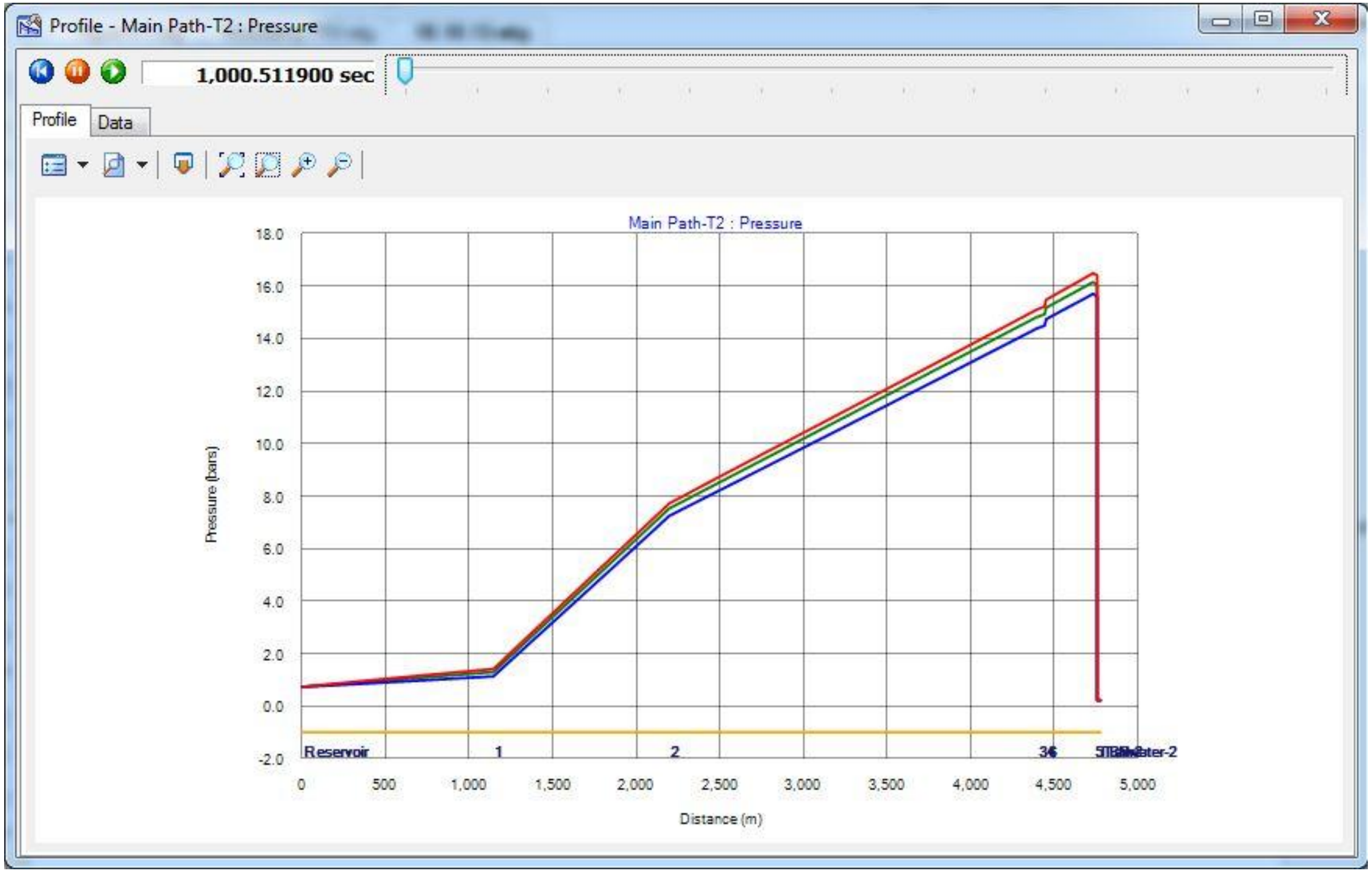


Figure 4.6 Initial, Minimum, and Maximum Pressure Graph along Selected Path

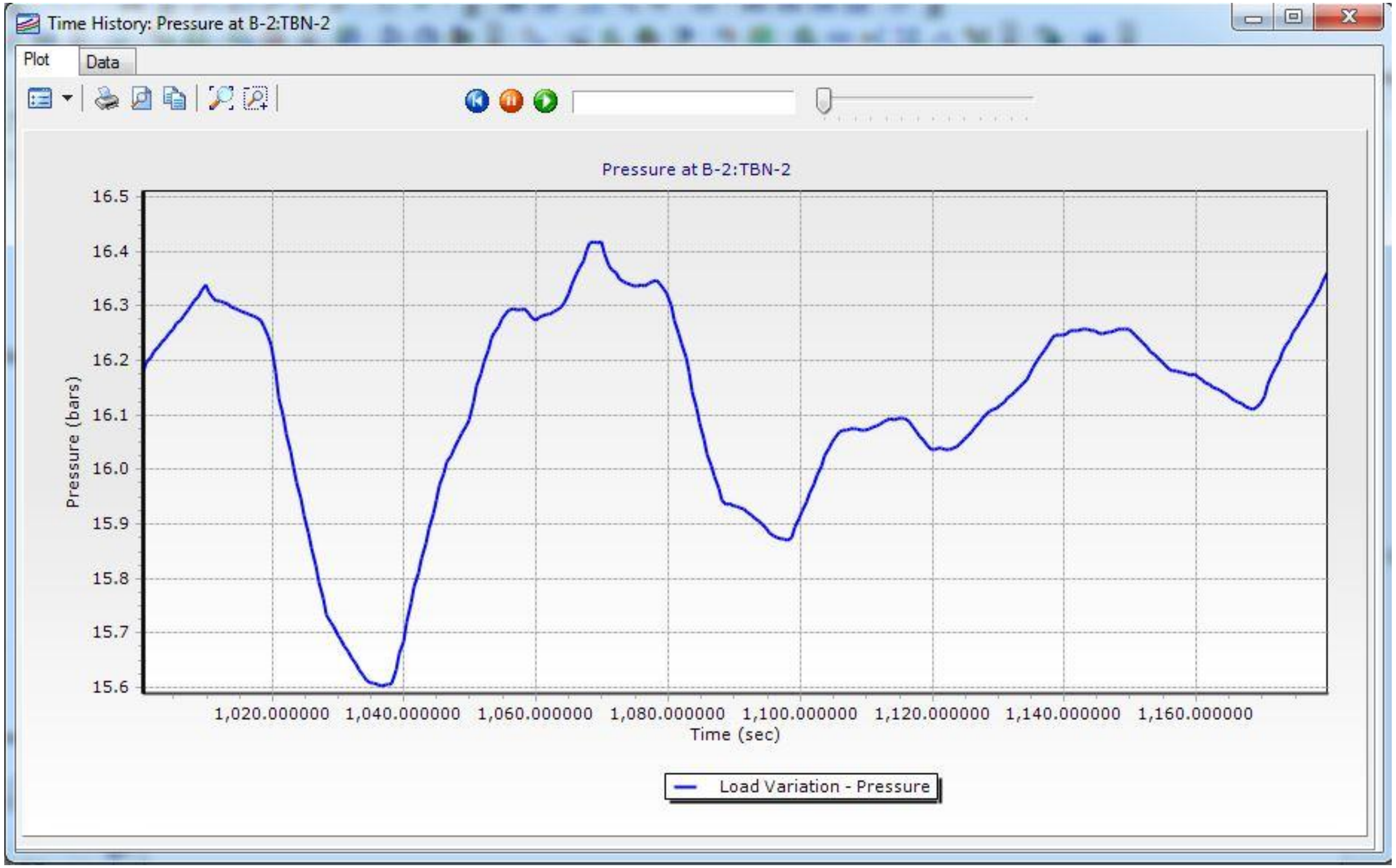


Figure 4.7 Transient Time History of Pressure at Turbine

CHAPTER 5

CASE STUDY AND COMPARISON OF THE MEASURED AND CALCULATED RESULTS

This chapter includes the studies of transients in Yesilvadi Diversion Weir and HEPP project. The measured field data is collected and a computer model of the system is simulated with Bentley HAMMER software. Then, the measured data and calculated results are compared to analyze the effects of the pressure relief valves (PRV) used in the system.

5.1 Brief Information about Yesilvadi Diversion Weir and HEPP Project

Yesilvadi Diversion Weir and HEPP project is located at Dortyol District of Hatay City in Turkey. The diversion weir is located on Delicay Stream. The project system includes a diversion weir consisting of spillway, water intake, settling basin, forebay, and energy stilling basin, pressurized conveyance line, valve chamber, penstock and powerhouse structure.

The purpose of the system is transforming the potential energy between normal water level, which is 295.00 m, and tail water level, which is 129.00 m, into mechanical energy by the help of turbines. Then mechanical energy is converted into the electrical energy by using the generators. There are two identical horizontal axis Francis turbines at powerhouse. Each of the turbines has 4.99 MW installed capacity.

Water of Delicay Stream is diverted by the diversion weir structure to the water intake. Then, diverted water is cleared of suspended sediment along settling basin. There is a forebay adjacent to the settling basin. At the end of the forebay, fiberglass reinforced plastic pipe (FRP) is installed to convey diverted water with pressure. During the design stage of the project, necessary vortex head was calculated to supply pressurized flow without air intrusion into the conveyance system.

Total length of the FRP pipeline is 4443.00 m. FRP pipeline system connects to penstock which is 290.00 m in length. Penstock pipe is divided into two branches which are 25.00 m in length. Each of these branches is connected to the horizontal axis Francis turbines at the powerhouse.

In Yesilvadi HEPP, PRV (pressure relief valve) is used as protective measure against water hammer effect. There are 5 sets of PRV's. 2 sets are located on the first branch and 2 sets are on the second branch. The last one is located on the connection between FRP pipe and penstock.

The general layout of Yesilvadi powerhouse and model layout of project are shown in Figure 5.1 and Figure 5.2, respectively. Figure 5.3 shows the summary of all cases, scenarios and conditions analyzed in this present study. The elevations of elements in the computer model are given in Table 5.1. The properties of water transmission line are given in Table 5.2. Also, properties of turbines are given in Table 5.3.

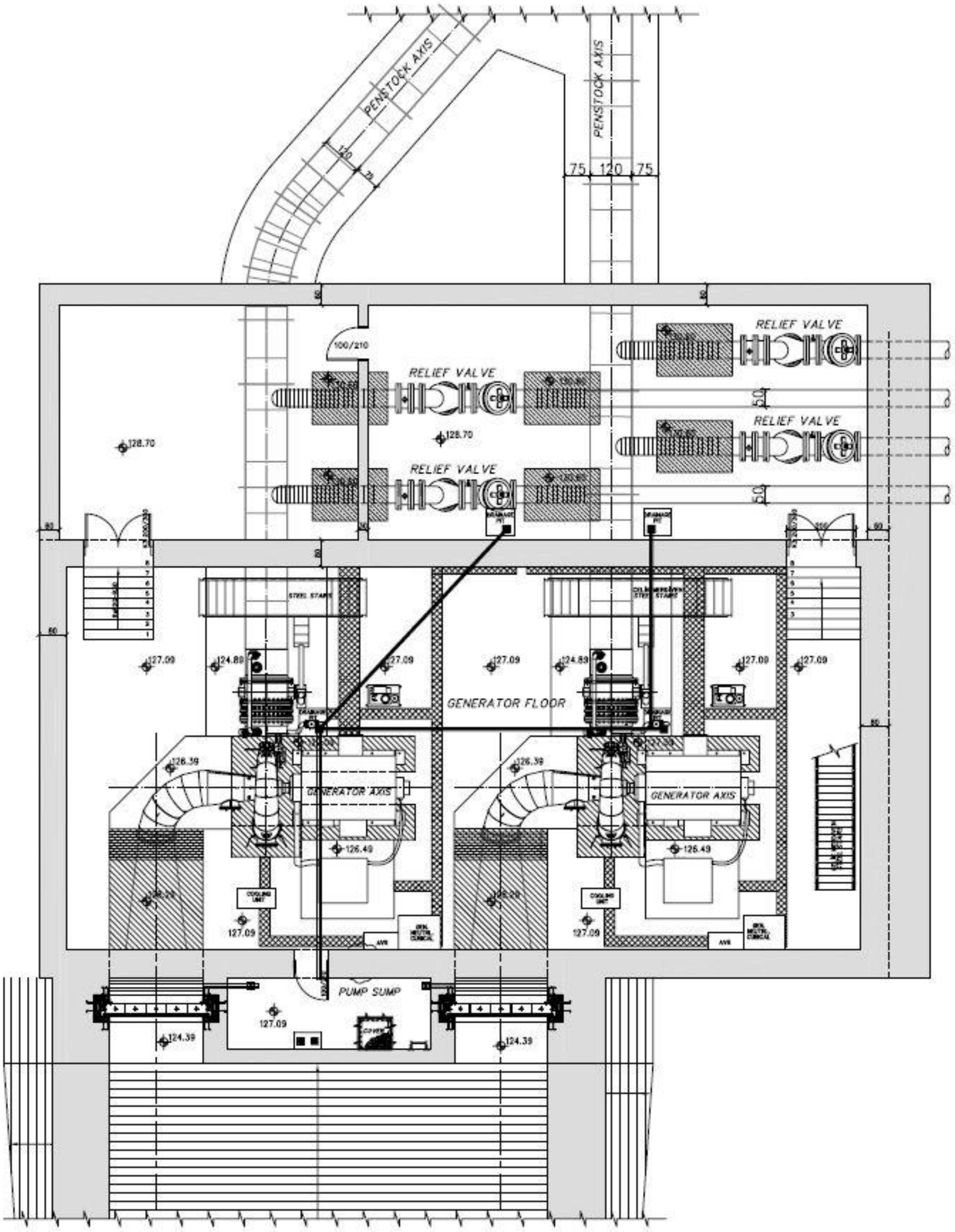


Figure 5.1 The General Layout of Yesilvadi Powerhouse

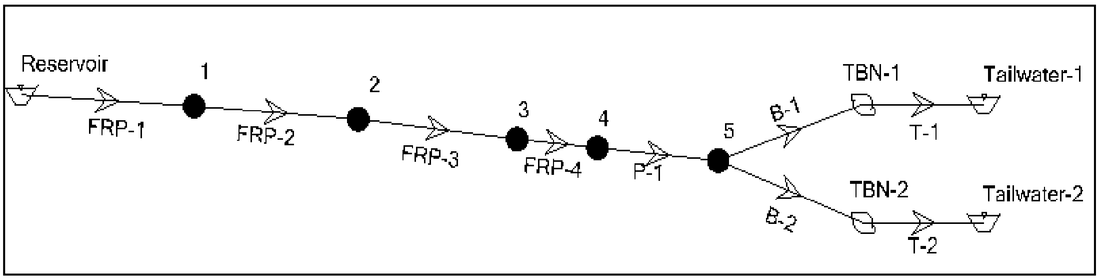


Figure 5.2 The Computer Model Layout of Yesilvadi HEPP Project

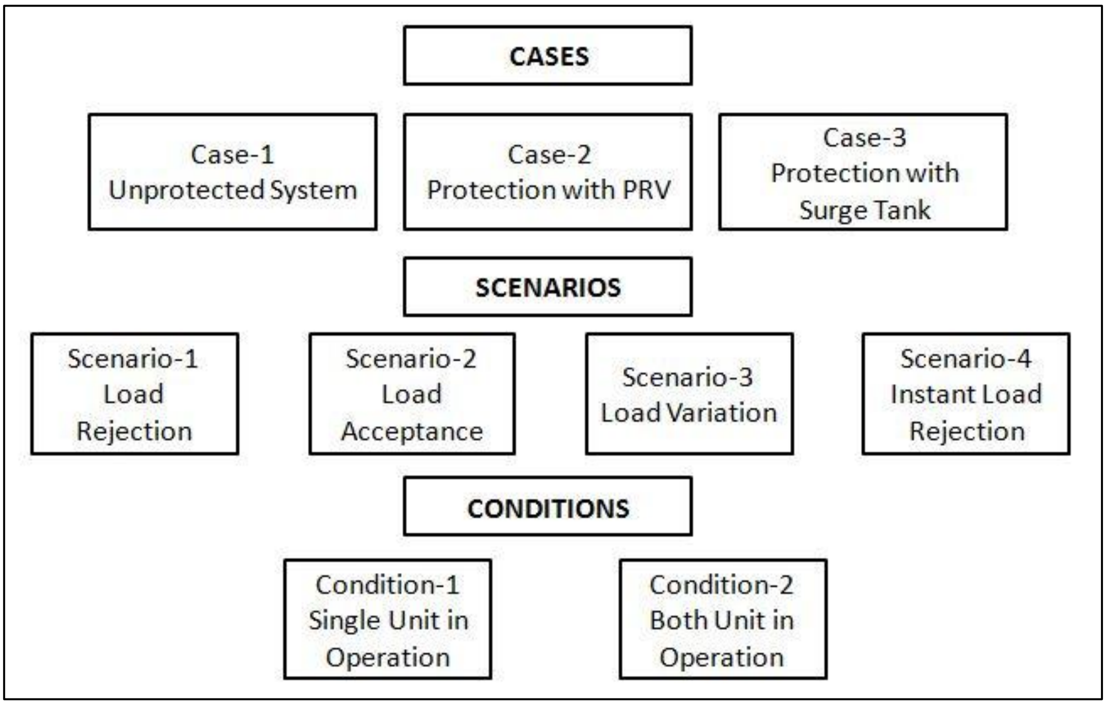


Figure 5.3 Summary of the Present Thesis Study

Table 5.1 Elevations of the Elements in Computer Software Model

Node	Elevation (m)
Reservoir	295.00
1	281.18
2	216.90
3	141.14
4	139.82
5	126.74
TBN-1&2	126.74
Tailwater-1&2	129.00

Table 5.2 Properties of Water Transmission Line in Computer Software Model

Pipe Type	Pipe Name	Pipe Length (m)	Pipe Diameter (m)	Pipe Wall Thickness (mm)	Wave Speed (m/s)
FRP	FRP-1	1145.00	1.90	22.96	504.77
	FRP-2	1053.50	1.90	26.87	540.74
	FRP-3	2199.00	1.80	23.92	526.29
	FRP-4	45.50	1.70	25.47	554.38
Penstock	P-1	290.00	1.70	12.00	936.95
Branch	B-1	25.00	1.20	14.00	1072.51
	B-2	25.00	1.20	14.00	1072.51

Table 5.3 Properties of Turbines

Type	Horizontal Axis Francis Turbine
No of identical turbine units	2
Turbine output(kW_m)	2 x 5150
Rated Speed(rpm)	1000
Rated Discharge(m^3/s)	2 x 3.75
Nominal Gross Head(m)	166.00
Nominal Net Head(m)	155.19
Moment of Inertia($kg.m^2$)	2111.20
Runner Diameter(mm)	657.00

5.2 Comparisons of Measured Data and Computer Model Results of Yesilvadi HEPP Project

The turbine operations are controlled and the data is collected by a supervisory control and data acquisition software (SCADA) provided by the turbine manufacturer company of Yesilvadi HEPP project. The electric power that must be generated for a specific time is determined by Turkish Energy Market Regulatory Authority (TEMRA) for each hydropower plant. Hence, generated power must be adjusted to the pre-determined electricity power. For this adjustment procedure, the required power value is entered into the SCADA software by hand. Then, software makes calibration between head and flow to generate required power by arranging wicket gate openings of the turbines. The SCADA software gives pressure, wicket gates opening, turbine speed, and generated power data of the turbines which are in operation.

This study includes analyses of load rejection, instant load rejection, load acceptance, and load variation scenarios. These scenarios were studied under 3 different cases.

In Case-1, a computer model was created for the unprotected system to compare the results with related measured field data. This study helps determining the accuracy of the model study. Also, it gives some critical information about the water hammer effects in unprotected system.

For Case-2, the measured data which includes PRV (pressure relief valve) opening and closing movement during transient state in the system were collected. To introduce the effects of PRV valve operations during transient state in the system, unprotected system models were created by using same hydraulic and operational variables. The required parameters such as turbine gate opening pattern, initial pressure head at turbine inlet for unprotected models were taken from related measured data.

Finally, a surge tank is added into the models instead of PRV valves to compare the effects of the PRV and surge tank against water hammer.

Table5.4 Description of the Cases

Name	Definition
Case-1	Unprotected System
Case-2	Protection with PRV
Case-3	Protection with Surge Tank

5.2.1 Case-1: Unprotected System

Case-1 is actually not applicable for the Yesilvadi project since there are 5 sets of PRV already installed on the system to control the pressure, and head increase in the water transmission line and the rotational speed of the turbines. However, analyzing the unprotected system response against transients is important to observe the vulnerable parts of the system, and to justify the use of PRV valves. Therefore, results of such an analysis are crucial for selecting appropriate protective measures.

Many conditions were tested before the commissioning of Yesilvadi HEPP. Some of these tests were done while PRV valves were kept closed. These tests represent the unprotected case studies. During computer model creation process, the measured data is used to determine turbines' wicket gate opening ratios, initial pressure heads on the turbines' inlets, and discharge in the water transmission line system.

In this case, the following scenarios are analyzed with computer model studies and the results are compared with related measured field data.

- Load rejection
- Load acceptance
- Load variation

There is no recorded field data for *instant load rejection scenario* for this case. To be able to analyze this scenario, rapid closure time of the turbine is calculated and an imaginary gate opening pattern is formed. Then, the results of this simulation are compared with *load rejection scenario* results.

5.2.1.1 Case-1-Load Rejection Scenario

Two different conditions are analyzed for *Case-1 Load Rejection Scenario*. The first condition contains the analysis carried out when single unit is in operation and the second condition contains the analysis carried out when both units are in operation.

5.2.1.1.1 Case-1-Load Rejection during Single Unit in Operation Condition

In this condition, only one of the turbines, Turbine-2, is in operation and the generated power is 4900 kW. Figure 5.4 shows power change against elapsed time. The closure time of the turbine is obtained from measured test data. In real case, valve opening is %52.34 when generated power is 4900 kW. It starts closing after 6.5 seconds and the generated power is 0 at 55th second when gate opening is approximately 5%. After that point, because of leakage, opening of the gate oscillates between 2.5% and 0. To reflect that leakage in model study, it is assumed that opening of the wicket gate is 0 % at 1000th second.

During computer modeling process, initial opening percent of the wicket gate, which is %52.34, is accepted as 100%. Then, the gate opening percent of the following data is calculated by taking ratio according to initial opening. The gate closing pattern is given in Table 5.5 during regular stop procedure. Also, gate closing pattern is given graphically in Figure 5.5.

After gathering the required data for computer model study from measured data, pressure change over Turbine-2, and minimum, maximum and initial hydraulic grade lines along water transmission line are obtained.

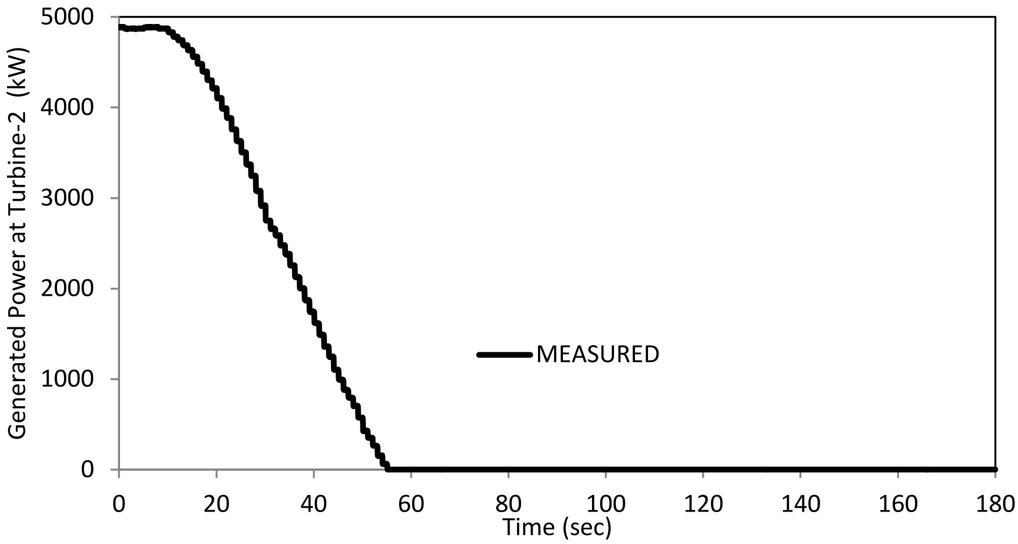


Figure 5.4 Power Change against Elapsed Time for Case-1-Load Rejection during Single Unit in Operation Condition

Table 5.5 Gate Opening for Case-1-Load Rejection during Single Unit in Operation Condition

Time (sec)	Gate Opening (%)	Time (sec)	Gate Opening (%)	Time (sec)	Gate Opening (%)
0	100	26	60	52	10
6.5	100	32	50	54	5
12	90	37.5	40	180	2.5
17	80	42.5	30	1000	0
21.5	70	47.5	20		

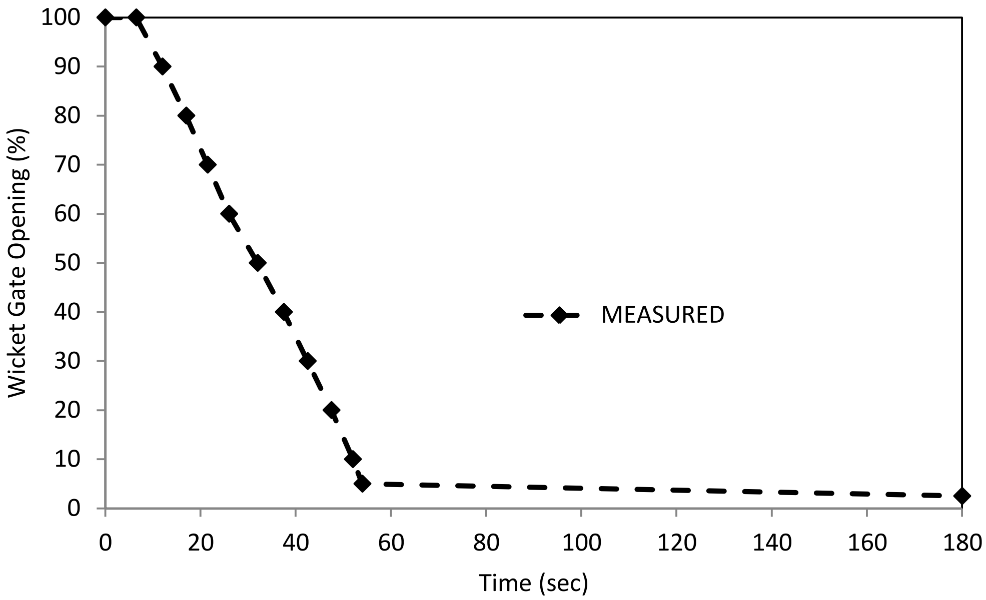


Figure 5.5 Wicket Gate Opening Pattern for Case-1-Load Rejection during Single Unit in Operation Condition

Figure 5.6 shows that, computer model study calculation results are very close to the measured data. The amplitude, and the period of oscillations show great similarity. To observe the effects of water hammer through whole water transmission line because of load rejection, calculated HGL (hydraulic grade line) for maximum and minimum values should be analyzed. Figure 5.7 shows HGL for load rejection scenario.

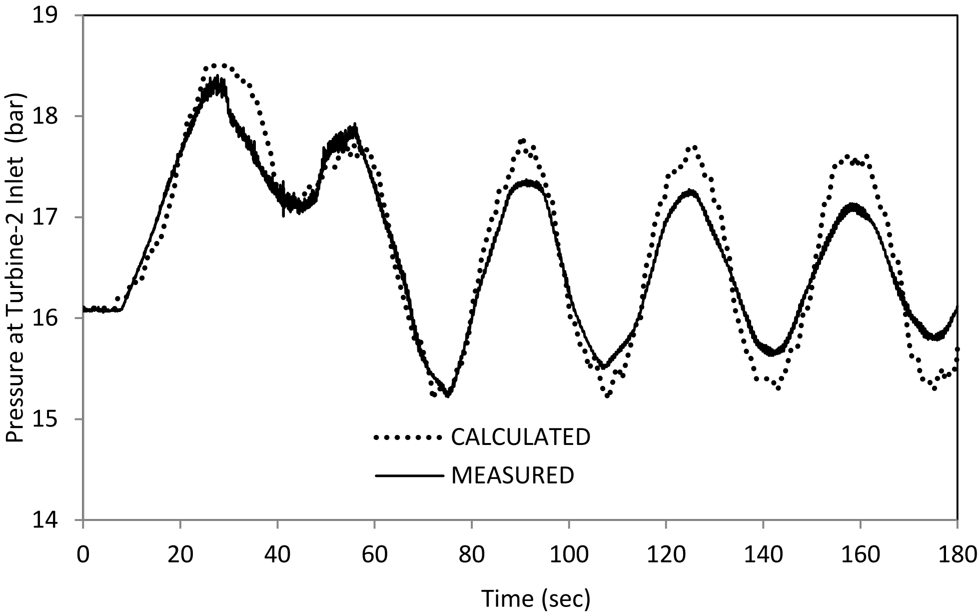


Figure 5.6 Computed and Measured Pressures at Turbine-2 Inlet for Case-1-Load Rejection during Single Unit in Operation Condition

Before the closure of wicket gate of Turbine-2, the piezometric head at turbine inlet is 291.20 m. Because of load rejection, head increases at turbine inlet and it reaches maximum value of 315.80 m. Also, it is seen from Figure 5.7 that piezometric head does not drop below the centerline of the pipeline anywhere. Hence, there will be no sub-atmospheric pressure occurrence through the water transmission line. The head increase percentages at turbine inlet based on tail water elevation are given in Table 5.6. The tail water elevation of the turbine is 129 m.

Table 5.6 Head Increase at Turbine Inlet for Single Unit in Operation Condition

	Initial Head (m)	Maximum Head (m)	% Increase Compared to the Initial Head
Net Head	162.2	186.8	15.2
Gross Head	166.0	186.8	12.5

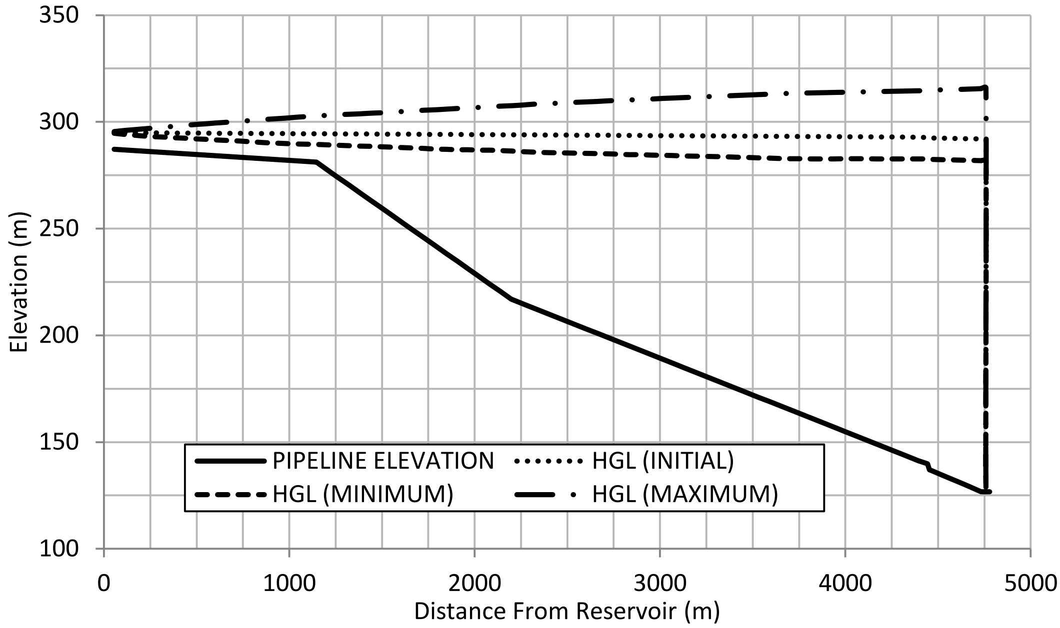


Figure 5.7 Initial, Maximum, and Minimum Hydraulic Grade Lines for Case-1-Load Rejection during Single Unit in Operation Condition

5.2.1.1.2 Case-1-Load Rejection during Both Units in Operation Condition

For load rejection during both units are in operation, there is no measured data. However, Figure 5.6 shows the consistency of the measured and calculated data when there is single unit in operation. Hence, it is possible to estimate effects of water hammer for this condition by using the software. The results of this condition are compared with model results of the previous condition, which is *load rejection during single unit in operation condition*. In this model study, discharge value for each turbine unit is set equal to the previous condition for consistency. In other words, the discharge value for each turbine is 3.07 m^3/s.

In Figure 5.8, it is seen that initial pressure values at Turbine-2 inlet are different from each other. The reason why the initial pressure values are not the same is that total discharge in the system is twice as much when both units are in operation than there is single unit in operation. Therefore, there is more head loss when both units are in operation. Other than that, the general behavior of these two conditions is very compatible. Figure 5.9 shows HGL over water transmission line for load rejection scenario when both of the turbine units are in operation.

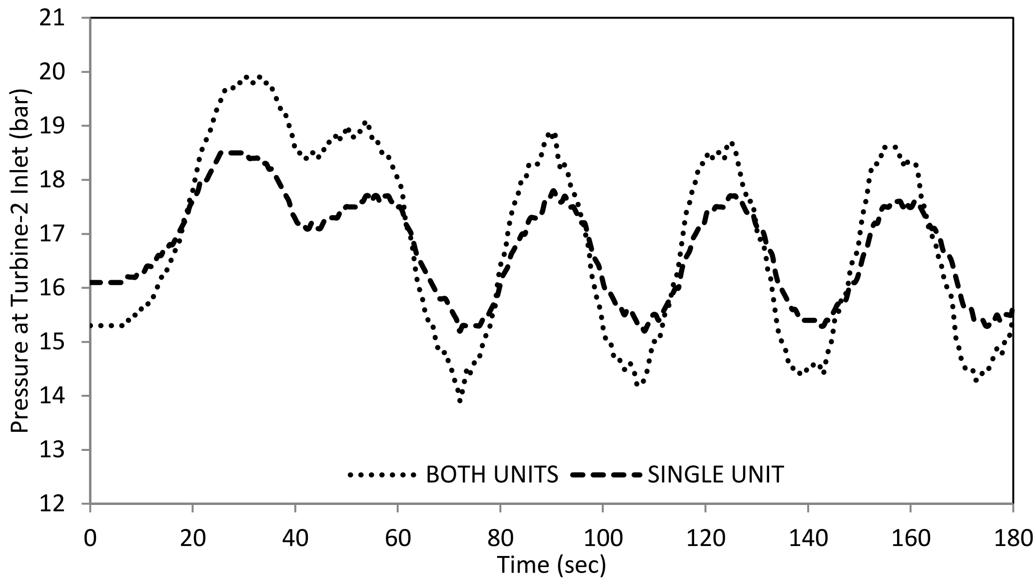


Figure 5.8 Model Results of Pressure Variations at Turbine-2 Inlet for Case-1 Load Rejection Scenarios of Single Unit in Operation and Both Units in Operation

Piezometric head increases to its maximum value 330.00 m at each turbine inlet. The head increase percentages at turbine inlet based on the tail water elevation are given in Table 5.7. Also, it is seen from Figure 5.9 that piezometric head does not drop below the water transmission line elevation anywhere. Hence, there will be no sub-atmospheric pressure occurrence through the water transmission line.

Table 5.7 Head Increase at Turbine Inlet for Both Units in Operation Condition

	Initial Head (m)	Maximum Head (m)	% Increase Compared to the Initial Head
Net Head	154.2	201.0	15.2
Gross Head	166.0	201.0	12.5

The reason why the head increase is higher when both of the units are in operation is that discharge and consequently velocity in the water transmission line in that condition is more than the operation of single unit condition. As basic equation of water hammer (see Equation 2.4) states, greater velocity change (ΔV) causes greater head increase (ΔH).

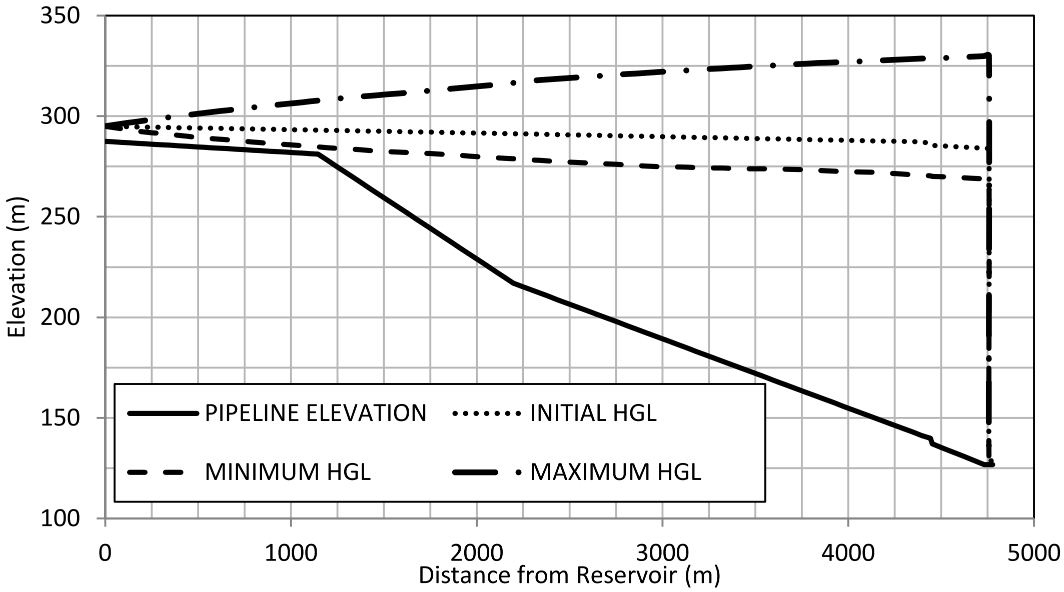


Figure 5.9 Initial, Maximum, and Minimum Hydraulic Grade Lines for Case-1-Load Rejection during Both Units in Operation Condition

5.2.1.2 Case-1-Load Acceptance Scenario

Two different conditions are analyzed for *Case-1 Load Acceptance Scenario*. The first condition contains the analysis carried out when single unit is in operation and the second condition contains the analysis carried out when both units are in operation.

5.2.1.2.1 Case-1-Load Acceptance during Single Unit in Operation Condition

In this study, measured data which was recorded during generated power increase from 0 kW to 4500 kW is used. The power change against elapsed time is shown in

Figure 5.10. This data was recorded when there is single unit in operation. The other unit, Turbine-1, was not in operation during that power increase process. The wicket gate opening pattern is obtained from measured data. In real case, the maximum gate opening percent is 52.90. To model that condition correctly, this maximum opening percent is accepted as 100. The other opening percent of the measured data is rated according to this maximum opening percent. After that adjustment, the gate opening pattern, which is given in Table 5.8, is obtained and entered in the computer model. Also, gate opening pattern is given graphically in Figure 5.11.

There are 4 different transient operating cases defined in the computer software for turbine element. These are *Load Rejection*, *Instant Load Rejection*, *Load Acceptance*, and *Load Variation*. Firstly, the transient operating case is selected as load acceptance. However, after running the computer software for initial computations, there is an error warning. Error states that for load acceptance operating case, wicket gate closure percent must start from 0% and it must be in increasing order up to 100%. As can be seen from Table 5.8 or Figure 5.11, the gate opening percent of this condition is not in increasing order.

Also, the computer software assumes the turbine governors are either disconnected or 'perfect'. In other words, software is not capable of modeling turbine and governor workings explicitly. Hence, it assumes that the power produced by the turbine always equals the electrical load. Consequently, under the load acceptance and load variation operating cases the turbine will always operate at its rated (or synchronous) speed. To create a correct computer model of this condition study under these requirements, the operating case is selected as load variation. Measured data shows that Turbine-2 starts generating power when the gate opening percent reaches 30% of its full opening. At that opening percent, turbine speed reaches its rated speed. Hence, measured data is arranged as if its starting time is 0 at 30% gate opening. After that there is one more problem to solve. It is that wicket gate opening percent must be 100 at starting time for load variation operating case. Hence, the computer model analysis is started 1000 seconds before the starting time of power generation at 100% gate opening. This time period is long enough to prevent closure effect of the wicket gate.

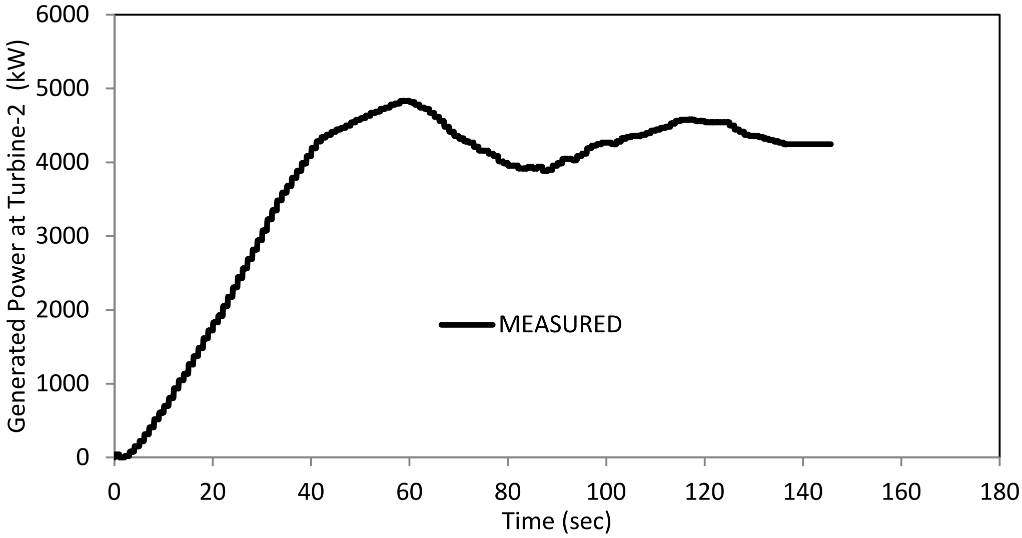


Figure 5.10 Power Change against Elapsed Time for Case-1 Load Acceptance during Single Unit in Operation Condition

Table 5.8 Gate Opening Pattern for Case-1 Load Acceptance during Single Unit in Operation Condition

Time (sec)	Wicket Gate Opening (%)	Time (sec)	Wicket Gate Opening (%)	Time (sec)	Wicket Gate Opening (%)	Time (sec)	Wicket Gate Opening (%)
0	30	40	92	75	81	110	95
10	45	45	94	80	80	115	94
15	52	50	92	85	85	120	91
20	57	55	90	90	87	125	88
25	65	60	89	95	91	130	85
30	73	65	86	100	94	135	84
35	83	70	83	105	95	140	83

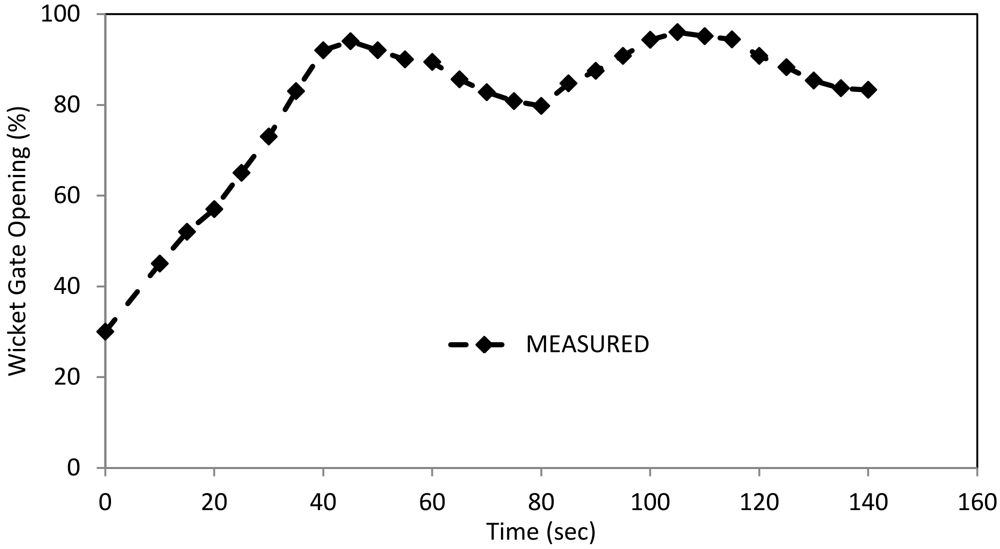


Figure 5.11 Gate Opening Pattern for Case-1 Load Acceptance during Single Unit in Operation Condition

Figure 5.12 shows the pressure variation at turbine inlet. The behavior of the software model shows parallelism with field tests. Turbine-2 reaches nearly its full capacity in this case study. Maximum pressure at Turbine-2 inlet is approximately 17 bars. This study confirms that load acceptance scenario cause less severe results than full load rejection scenario. The reason why there are small differences between calculated and field data is using the lower data frequency of wicket gate opening pattern in model.

Load acceptance does not disturb system safety against occurrence of sub-atmospheric pressure. There is no point that minimum piezometric head falls below water transmission line elevation. Figure 5.13 shows maximum, minimum and initial hydraulic grade line elevations over whole transmission line. Also, the elevation of all the project profile can be seen from Figure 5.13.

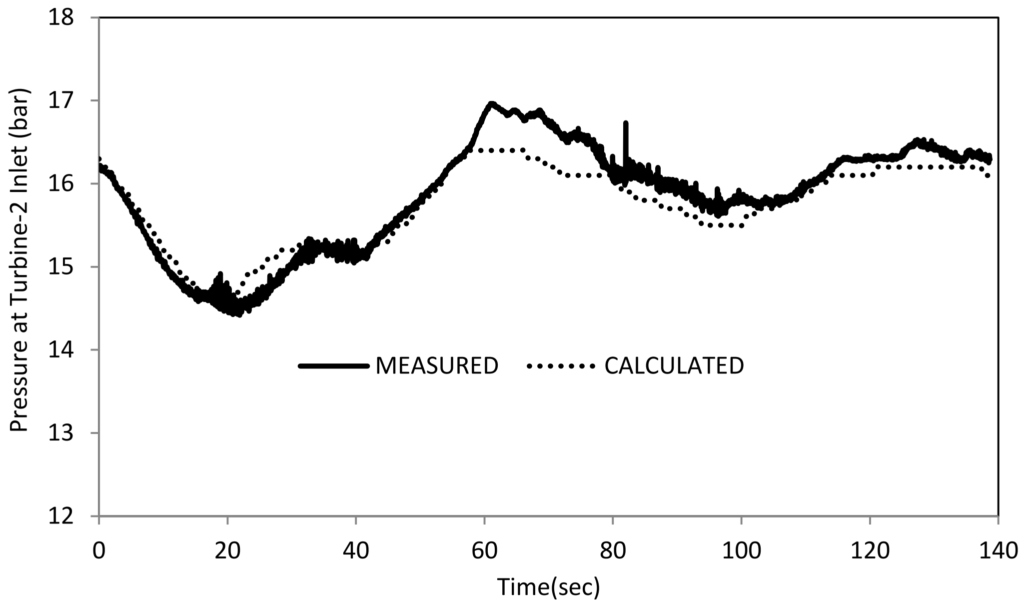


Figure 5.12 Computed and Measured Pressures at Turbine-2 Inlet for Case-1-Load Acceptance during Single Unit in Operation Condition

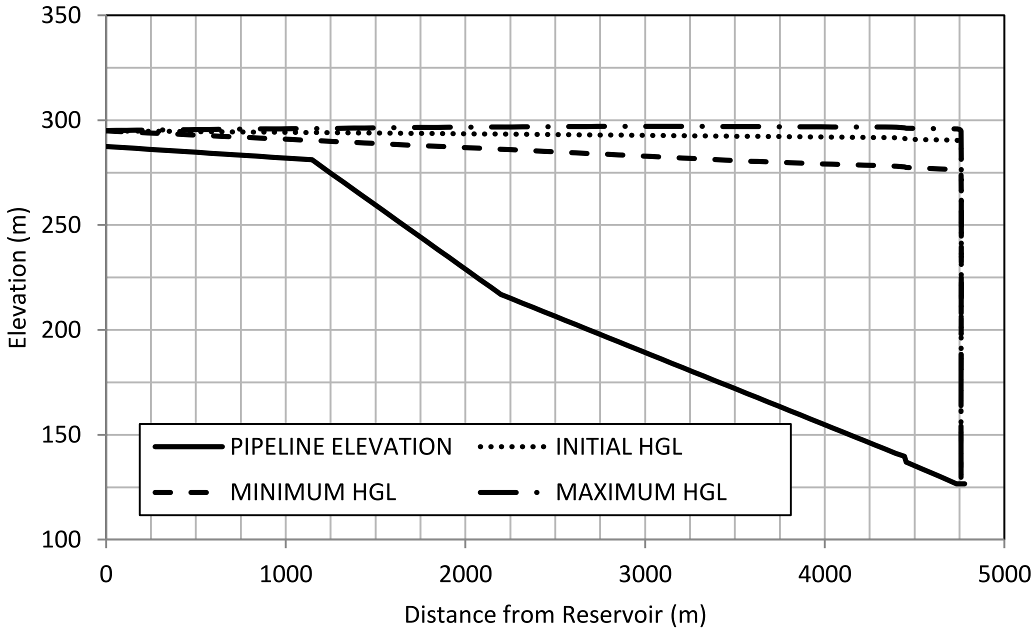


Figure 5.13 Initial, Maximum, and Minimum Hydraulic Grade Lines for Case-1-Load Acceptance during Single Unit in Operation Condition

5.2.1.2.2 Case-1-Load Acceptance during Both Units in Operation Condition

For this condition, there is no recorded field data. Hence, an imaginary condition is modeled with computer model. Initially, both of the units are closed, in other words, they are not in operation. Then, the wicket gates of turbines start opening with gate opening pattern given in Table 5.9. It is assumed that, gate opening is linearly increasing and gates are fully open at 50th second. The reason why gate opening time is selected as 50 seconds is that the measured data for gate closing time of normal load rejection scenario is approximately 50 seconds. In fact, the opening time will be longer, but to analyze most critical condition, opening time selected as 50 seconds. The generated power at that instant is 4990 kW for each turbine. Discharge and head values are equal to design values which are 3.75 m^3/s and 155.19 m, relatively.

Table 5.9 Gate Opening Pattern for Case-1-Load Acceptance during Both Units in Operation Condition

Time (sec)	**Wicket gate opening (%)**
0	0
10	20
20	40
30	60
40	80
50	100

Figure 5.14 shows the pressure variation at turbine inlets. It is seen from Figure 5.15 that system is still safe for the most critical load acceptance case. The hydraulic grade line never drops below the water transmission line elevation even if there is no protection device against water hammer.

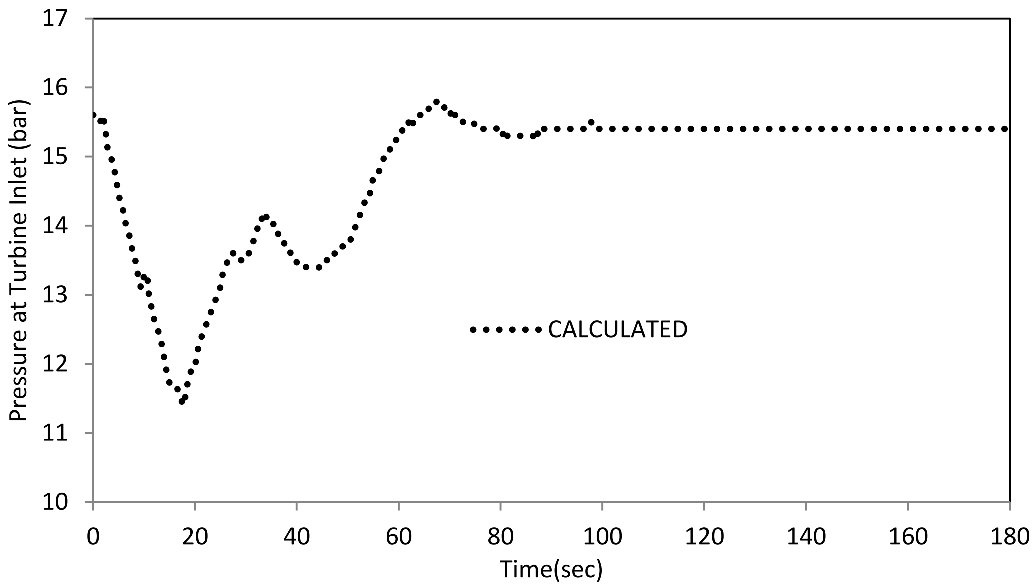


Figure 5.14 Computed Pressures at Turbine Inlet for Case-1-Load Acceptance during Both Units in Operation Condition

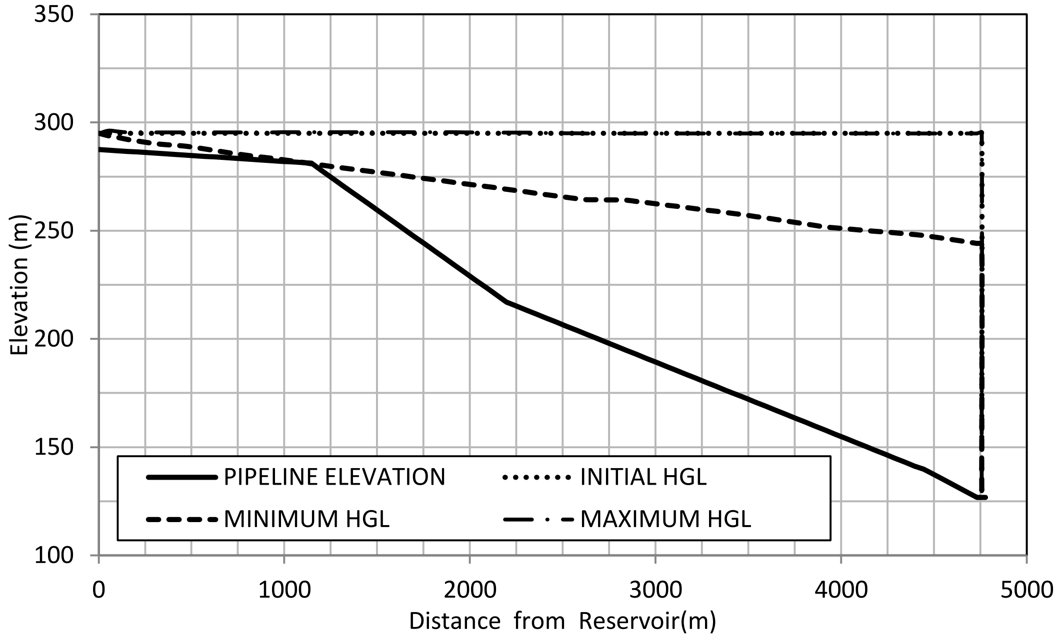


Figure 5.15 Initial, Maximum, and Minimum Hydraulic Grade Lines for Case-1-Load Acceptance during Both Units in Operation Condition

5.2.1.3 Case-1- Load Variation Scenario

In this study, the field test data that was recorded during load variation of Turbine-2 from 3500 kW to 4000 kW is used to analyze load variation scenario. The power variation against elapsed time is shown in Figure 5.16. Turbine-1 was not in operation during that record process. The gate opening pattern is defined by using measured data and given in Table 5.10. Also, wicket gate opening curve is given in Figure 5.17.

As mentioned in load acceptance scenario, wicket gate opening percentage must be 100 at starting time for load variation operating case. Hence, the software analysis is started 1000 seconds before the starting time of measured data at 100% gate opening. As stated before this time period is long enough to prevent closure effect of the wicket gate.

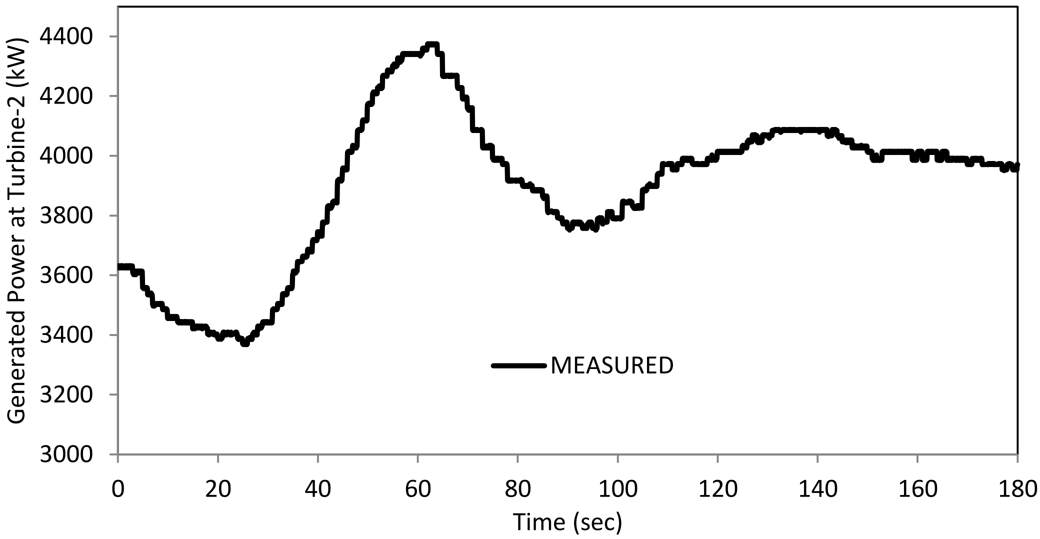


Figure 5.16 Power Change against Elapsed Time for Case-1 Load Variation Scenario

Table 5.10 Gate Opening Pattern for Case-1 Load Variation Scenario

Time (sec)	Wicket Gate Opening (%)	Time (sec)	Wicket Gate Opening (%)
0	80	100	89
10	76	110	93
20	77	120	95
30	86	130	93
40	94	140	90
50	98	150	87
60	94	160	86
70	85	170	86
80	83	180	80
90	87		

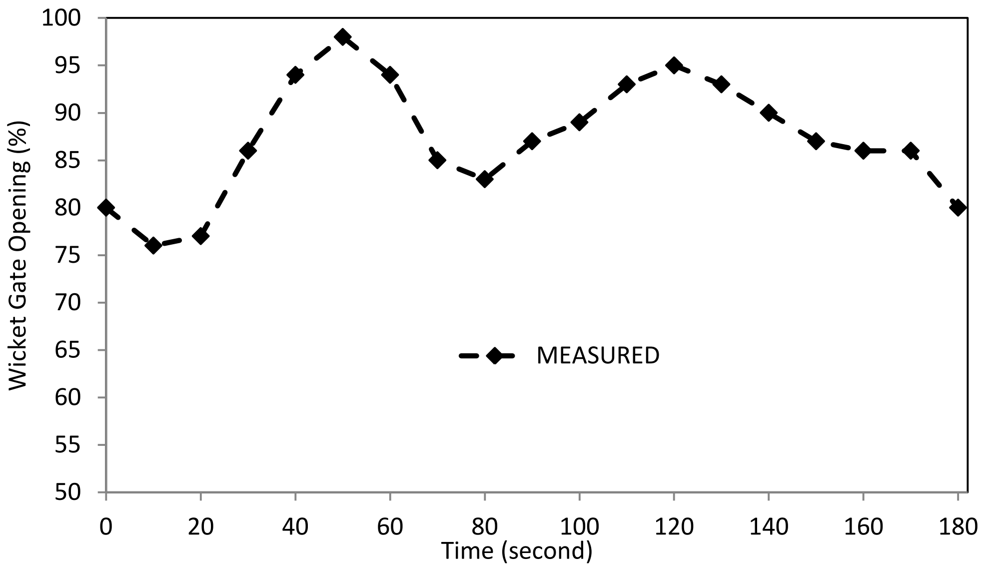


Figure 5.17 Gate Opening Pattern for Case-1 Load Variation Scenario

The calculated and measured transient-state pressures at Turbine-2 are shown in Figure 5.18. Calculated computer model results and measured field test data are compared. As can be seen from related figure, the behavior of the pressure variation is very similar for calculated and measured data. The small differences in pressures values are caused by wicket gate definition for the software. Field data was recorded for every 0.01 sec. It is not possible to define such a detailed gate opening pattern for the model study. To reflect general behavior, 10 seconds time interval is selected for the model study.

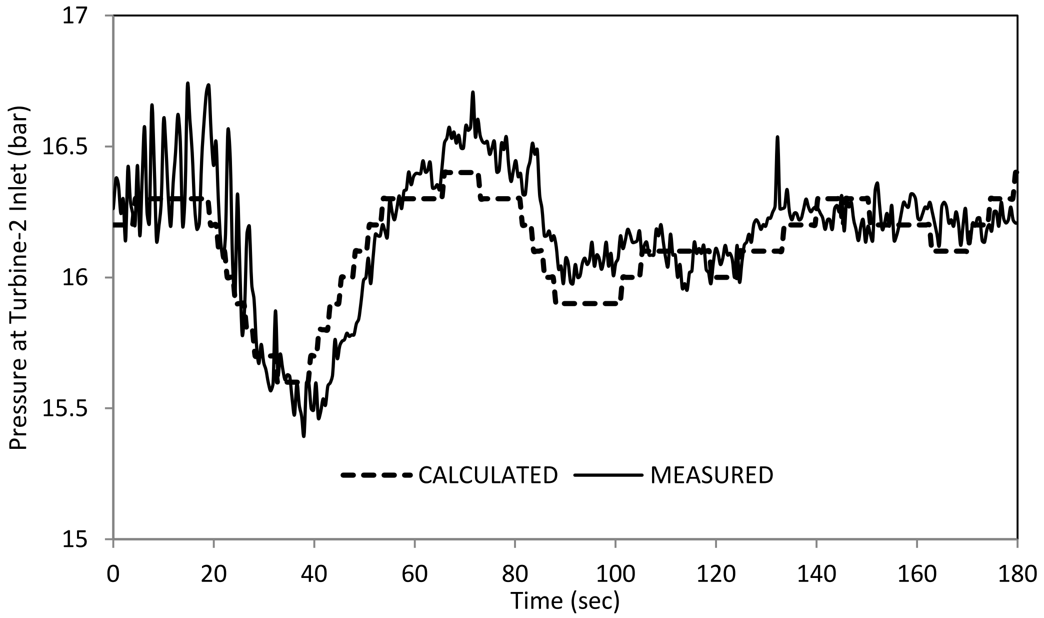


Figure 5.18 Measured and Computed Pressures at Turbine Inlet for Case-1-Load Variation Scenario

Hydraulic grade lines in Figure 5.19 show that, there is no problem during that load variation scenario through whole water transmission line system. Because of the fact that power varies in small range, wicket gate opening percents, and the discharge in the system do not change significantly. Hence, head variations over the water transmission line are small. This can be seen from Figure 5.19.

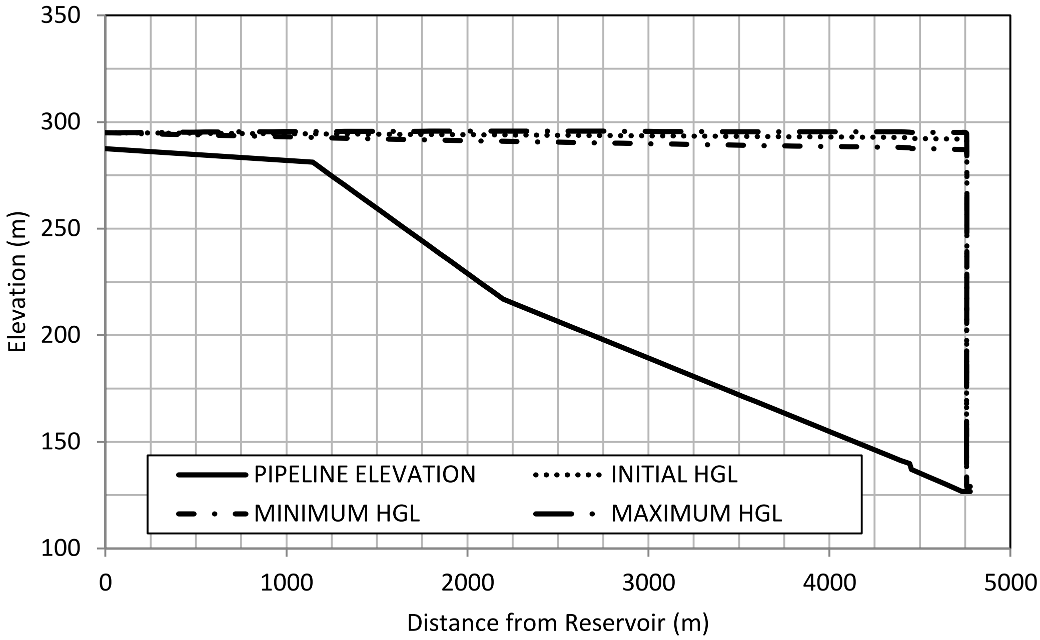


Figure 5.19 Initial, Maximum, and Minimum Hydraulic Grade Lines for Case-1-Load Variation Scenario

5.2.1.4 Case-1- Instant Load Rejection Scenario

Instant load rejection scenario takes place when the wicket gate of the turbine is closed rapidly. There is no measured data for this scenario. To analyze that scenario with a model study, firstly instant closure time of the system is determined. $\sum \mathrm{L}/a$ is equal to 8.81 seconds and instant closure time $(2\mathrm{L}/a)$ is equal to 17.62 seconds. Hence, the closing time of wicket gate is selected as 15 seconds for that scenario and an imaginary linear gate closure pattern given in Table 5.11 is applied. To observe the most critical results, both of the units are considered in operation at full load capacity at the beginning. Then, given wicket gate closure pattern is applied for both of the units.

Table 5.11 Gate Opening Pattern for Case-1 Instant Load Rejection Scenario

Time (sec)	Wicket Gate Opening (%)
0	100
5	66
10	33
15	0

Figure 5.20 shows that closure time of wicket gate is very critical for safety of the system. Pressure reaches at its maximum value 45.1 bars and its minimum value -1 bar. These pressure values may cause pipe to burst and collapse.

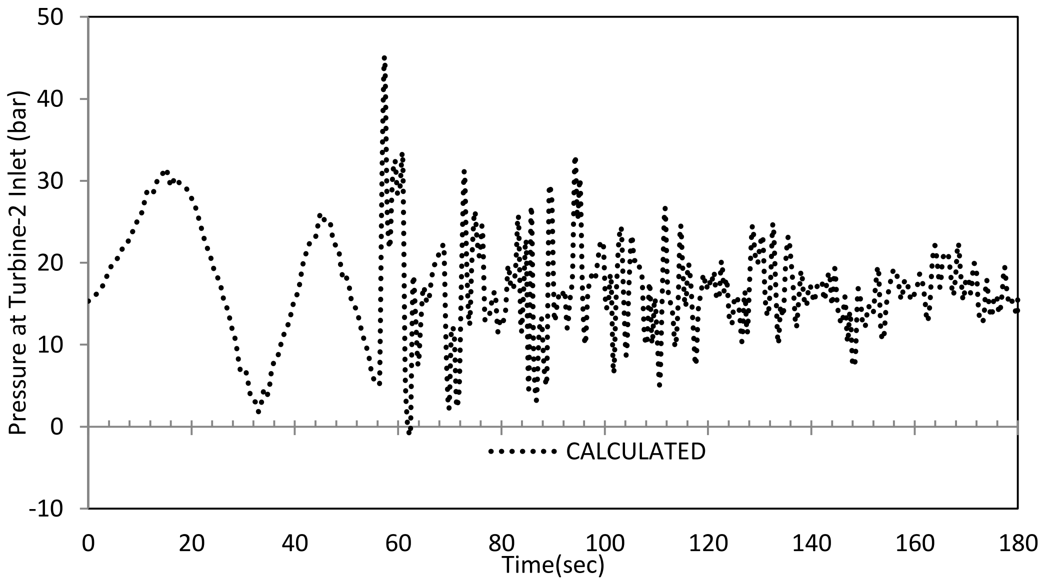


Figure 5.20 Computed Pressures at Turbine-2 Inlet for Case-1-Instant Load Rejection Scenario

Figure 5.21 shows that hydraulic grade line drops below water transmission line elevation. This means that pressure at these points may drop below vapor pressure. Hence, there may be sub-atmospheric pressure occurrence, and consequently vapor cavity may be formed in the transmission line. This vapor cavity acts as a vacuum and cause water column separation. The collision of these two liquid columns may cause a large and instantaneous pressure rise in the system. That high pressure travels along the transmission line and cause severe problems for turbines, pipes, and supporting structures. This cavity may cause pipe to collapse.

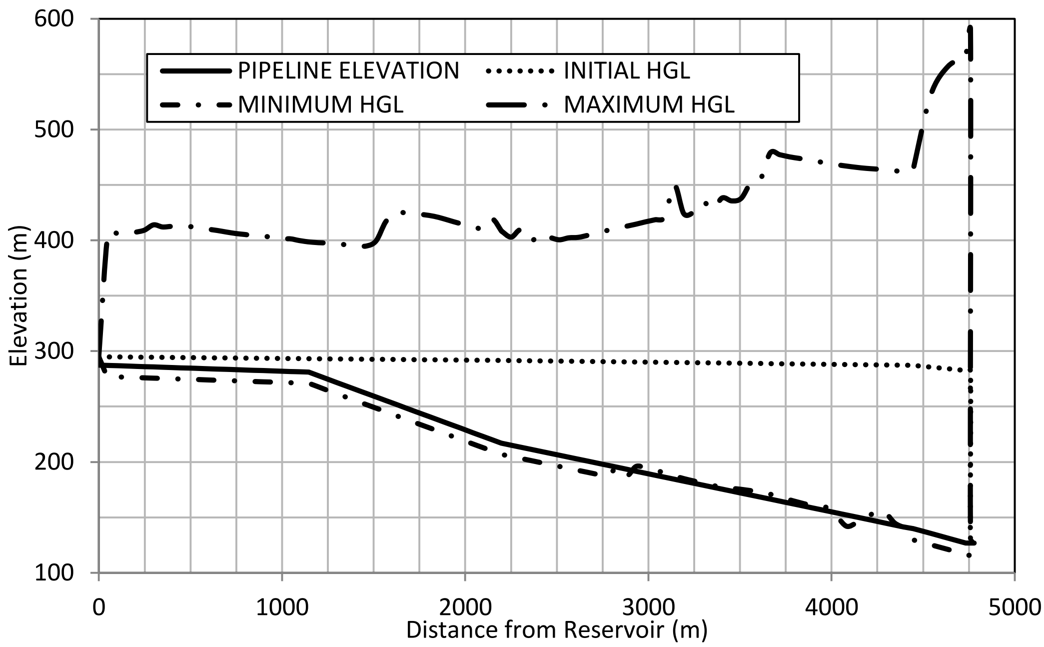
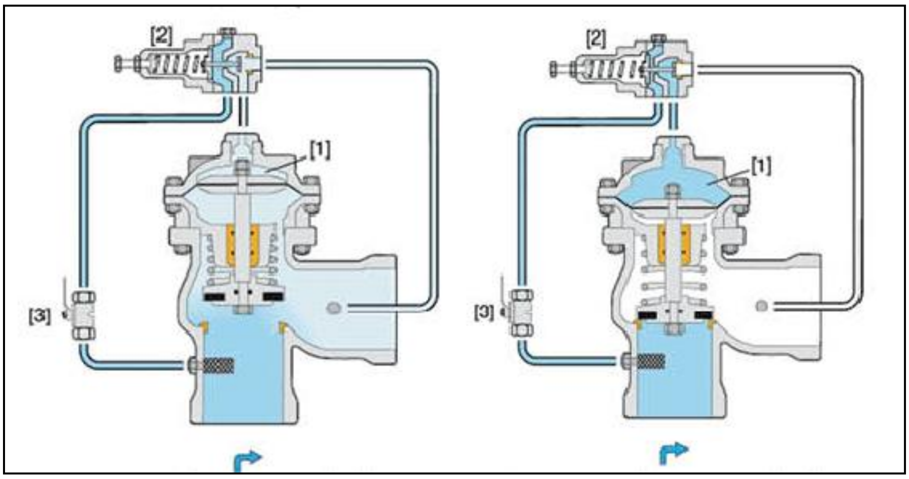


Figure 5.21 Initial, Maximum, and Minimum Hydraulic Grade Lines for Instant Load Rejection Case

5.2.2 Case-2: Protection with PRV Case

This is the valid case for Yesilvadi HEPP project in normal conditions. There are 5 sets of pressure relief valves on the water transmission line. 2 sets of them are located on the first branch just before the Turbine-1 inlet. The other two sets are located on the second branch just before Turbine-2 inlet. The last one is located between the beginning of main penstock and end of the FRP pipe. The diameters of these PRV valves are 500 mm. Their set pressure value is not known exactly. During the installation of these valves, the pressure value at valve locations was approximately 15.6 bars. After installation of the valves, set pressure was set a higher pressure value by analogously. It is estimated that set pressure is most probably between 16 and 17 bars range.

The PRV valves in Yesilvadi HEPP project can be controlled by automatically or it can be controlled by mechanically. The mechanical working principle is summarized in Figure 5.22(a) and Figure 5.22(b) schematically.



(a) (b)

Figure 5.22 Working Principle of PRV Valve during (a) Opening (b) Closing

The part which is shown by [1] in Figure 5.22 is the upper reservoir in the PRV. [2] represents the pilot. Pilot is the part where the set pressure value is arranged. This part controls the pressure value in the branch. [3] represents needle valve which controls water flow between upper reservoir and branch. If the pressure in the branch is higher than the set pressure of pilot, pilot empties the water in the upper reservoir. Hence, the pressure in the upper side is less than the pressure in the branch. Consequently PRV comes to open position and water in the branch flows through it. Pilot keeps the PRV open till the pressure value inside the branch drops below the set pressure. After the pressure value in the branch drops below the set pressure, needle valve let water flow to the upper reservoir. Pilot always controls the pressure value inside the branch and it equalizes the upper reservoir pressure to the branch pressure. By this way, the total force exerted on the PRV plate comes to zero. This ensures a non-leaky closure.

Bentley Hammer software includes various types of valves which are frequently used in steady or Extended Period hydraulic models. It is very important to understand valve behavior in model study. The controlling effects of valve types defined in software are only applied to the initial conditions calculation. In other words, during a transient simulation process and the system conditions vary, valves do not have the ability of automatically reaction like they do during the initial conditions. One way to operate PRV valve during transient simulation is defining the open and closure times of these valves manually by using *Operating Rule* tool existing under valve properties. However, the exact operation times, opening and closing times, of PRV valves are not clear. Also, the required times of PRV valves to come open position from closed position and vice versa are not known. Hence, creating a model with PRV is very complicated and it is hard to compute compatible results with measured data. For this reason, unprotected models were created by using measured data. The required hydraulic and operational parameters were taken from measured data. The results of the model study are compared with the measured data to observe the effects of PRV valve.

In this case study, the following scenarios are analyzed with model studies and the results are compared with related measured data.

- Load rejection
- Load variation
- Instant load rejection

5.2.2.1 Case-2-Load Rejection Scenario

Two different conditions are analyzed for *Case-2 Load Rejection Scenario*. The first condition contains the analysis carried out when single unit is in operation and the second condition contains the analysis carried out when both units are in operation.

5.2.2.1.1 Case-2-Load Rejection during Single Unit in Operation Condition

In this condition, the measured data recorded during closing of Turbine-2 is used. Before the closure, the power generated by Turbine-2 was 4900 kW. At that power generation, wicket gate opening is 52.72%. The remaining gate opening percents are rated according to this value and gate opening pattern of Turbine-2 during load rejection is obtained as given in Table 5.12. Figure 5.23 shows the generated power curve. That sudden decrease behavior of the generated power called as circuit break.

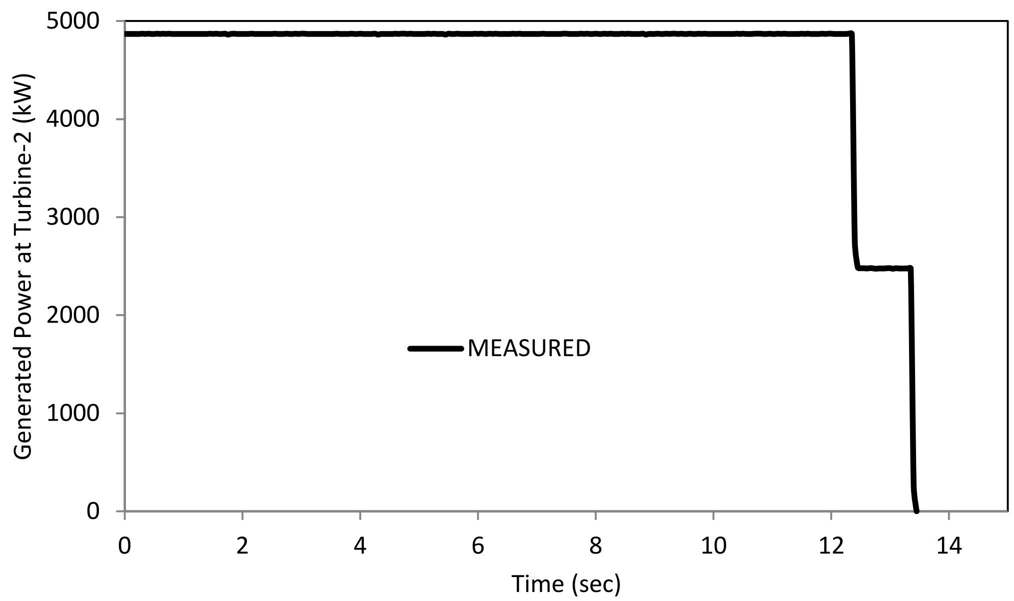


Figure 5.23 Power Change against Elapsed Time for Case-2 Load Rejection during Single Unit in Operation Condition

Table 5.12 Gate Opening Pattern for Case-2 Load Rejection during Single Unit in Operation Condition

Time (sec)	Wicket Gate Opening (%)	Time (sec)	Wicket Gate Opening (%)	Time (sec)	Wicket Gate Opening (%)
12.2	100	23.45	65	35.7	30
13.05	95	25.35	60	37.5	25
14.65	90	27.25	55	39.35	20
16.45	85	28.80	50	41.15	15
18.15	80	30.75	45	43.00	10
19.85	75	32.40	40	44.75	5
21.65	70	34.15	35	46.05	0

Figure 5.24 shows pressure changes at Turbine-2. The pressure gage at Turbine-2 is located on the penstock side of the wicket gate. In other words, this gage reads pressure values of water in penstock branch. The software gives the results in the same manner.

Firstly, the measured data shows that system is in equilibrium at the beginning. The pressure inside the penstock is steady and it is approximately 16.1 bars. However, starting of wicket gate closure increases the pressure inside the penstock. That increased pressure gets a higher pressure value than the PRV set pressure. At that point, pilot discharges the water in the upper reservoir of the PRV. Consequently, PRV is opened, and the pressure decreases rapidly. As can be seen from Figure 5.24, the reaction time and opening time of the PRV valve are very short. After that rapid decrease in pressure, pilot fills the upper reservoir of the PRV by the help of needle valve. This charging and discharging cycle of PRV continues till the system pressure inside the penstock is re-stabilized.

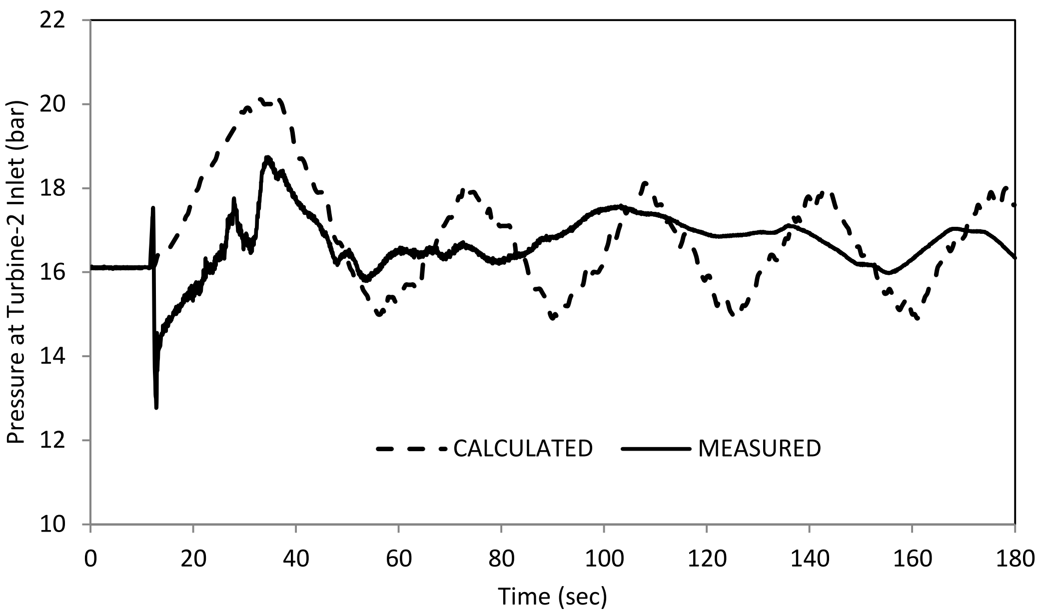


Figure 5.24 Measured and Computed Pressures at Turbine-2 Inlet for Case-2-Load Rejection during Single Unit in Operation Condition

5.2.2.1.2 Case-2-Load Rejection during Both Units in Operation Condition

In this condition, the measured data recorded during the successive closures of Turbine-2 and Turbine-1 is used. Before the closure of wicket gates, the generated power of each turbine unit is 4900 kW. The SCADA software is started to measure Turbine-2 data at 15:48:55. The record starts at 15:50:09 for Turbine-1. The time difference between these two measurements is 74 seconds. This is a critical point during modeling process. Wicket gate of Turbine-2 starts closing at approximately 4^{th} second. The closure of Turbine-1 starts at its 7.6^{th} second of recorded data. To gather all the data in an order, the time difference between measurements is added to the data of Turbine-1 and the gate opening pattern given in Table 5.14 is obtained. The gate opening pattern of Turbine-2 is given in Table 5.13. The generated power curves of Turbine-2 and Turbine-1 are given in Figure 5.25 and Figure 5.26, respectively.

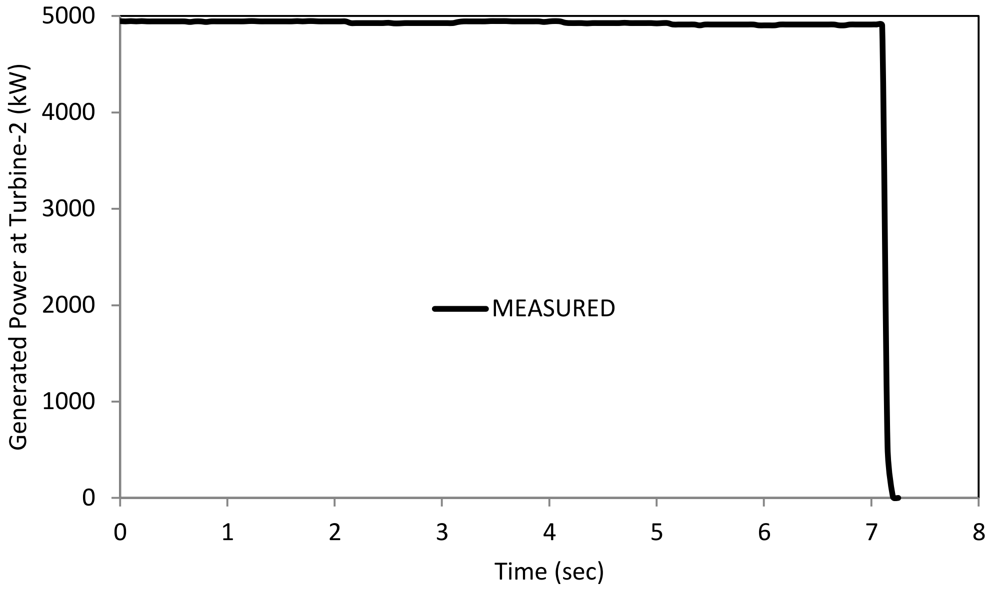


Figure 5.25 Power Change of Turbine-2 against Elapsed Time for Case-2 Load Rejection during Both Units in Operation Condition

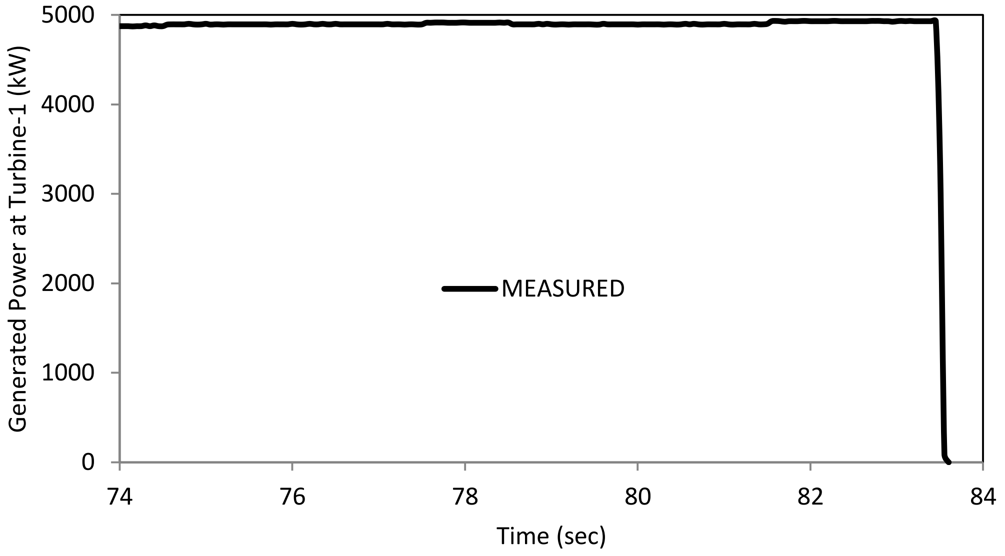


Figure 5.26 Power Change of Turbine-1 against Elapsed Time for Case-2 Load Rejection during Both Units in Operation Condition

Table 5.13 Gate Opening Pattern of Turbine-2 for Case-2 Load Rejection during Both Units in Operation Condition

Time (sec)	Wicket Gate Opening (%)	Time (sec)	Wicket Gate Opening (%)	Time (sec)	Wicket Gate Opening (%)	Time (sec)	Wicket Gate Opening (%)
4.2	100	14.8	70	25.6	40	36.6	10
5.8	95	16.6	65	27.5	35	38.6	5
7.7	90	18.4	60	29.3	30	40.6	0
9.3	85	20.3	55	31.1	25		
11.2	80	22.1	50	33	20		
13	75	23.8	45	34.8	15		

Table 5.14 Gate Opening Pattern of Turbine-1 for Case-2 Load Rejection during Both Units in Operation Condition

Time (sec)	Wicket Gate Opening (%)	Time (sec)	Wicket Gate Opening (%)	Time (sec)	Wicket Gate Opening (%)	Time (sec)	Wicket Gate Opening (%)
81.6	100	92.2	70	103.3	40	114.3	10
83.1	95	94.1	65	105.2	35	115.9	5
84.8	90	95.9	60	107	30	117.7	0
86.7	85	97.8	55	108.8	25		
88.6	80	99.6	50	110.7	20		
90.3	75	101.3	45	112.3	15		

The pressure gage of Turbine-1 is located on the turbine side of the wicket gate. For Turbine-2, the pressure gage is located on the penstock side of the wicket gate. This is the reason why the measured pressure of Turbine-1 decreases to 0 after the closing time of its wicket gate. Figure 5.27 and Figure 5.28 shows the pressure variation of Turbine-2 and Turbine-1, respectively. In this condition, all of the PRV valves operate time to time.

As can be seen from Figure 5.27 and Figure 5.28 the maximum pressure value of measured data is higher than the calculated data. The reason of this higher pressure is mainly the closing time of PRV after its operation. When the pressure value in the branch drops below the set pressure of PRV valves located on it, the pilots in PRV valves fill the upper reservoir rapidly and that rapid closure causes a secondary water hammer effect. Also, the second reason is that the discharging capacities of the valves are more than requirement. After the opening of PRV valves, system water demand increases. Total volume of water that is entering the turbine and discharging from PRV valves is more than the initial steady state. Higher volume of water causes higher flow velocity. These conditions cause higher maximum pressure. After that point, the pressure oscillations are in smaller scale, because the pressure value in the penstock is close to set pressures of PRV valves and that prevents high variations in system demand.

During the closure time of Turbine-1 wicket gate, the results of unprotected system show that the pressure values over Turbine-1 and at Turbine-2 inlets increase to high values. PRV valves prevent that pressure increase.

As stated before, the pressure gage of Turbine-1 is located on the turbine side of wicket gate. Therefore, after complete closure of its wicket gate, its pressure value reaches 0.

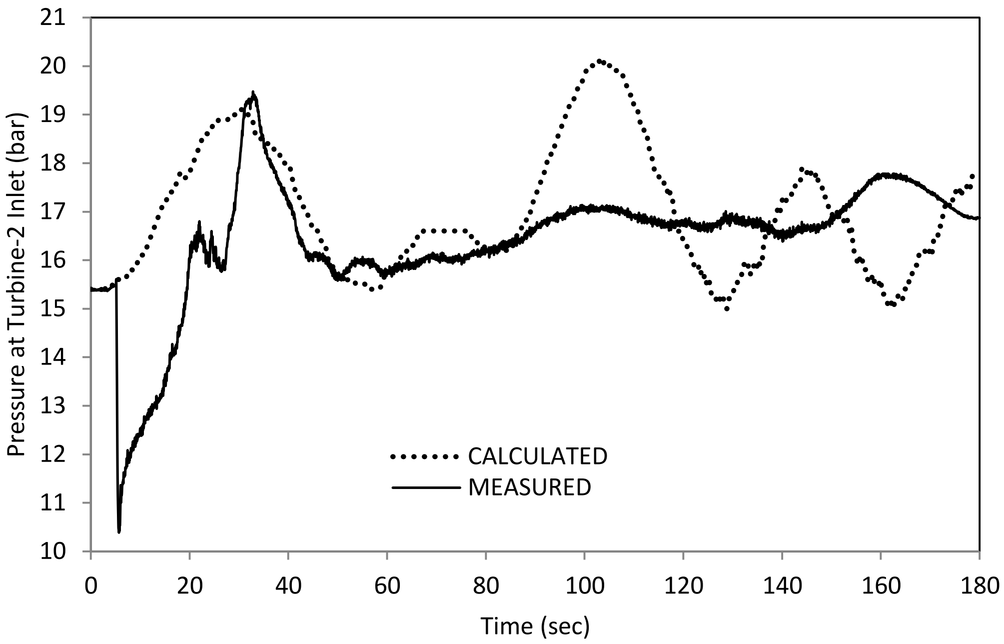


Figure 5.27 Measured and Computed Pressures at Turbine-2 Inlet for Case-2-Load Rejection during Both Units in Operation Condition

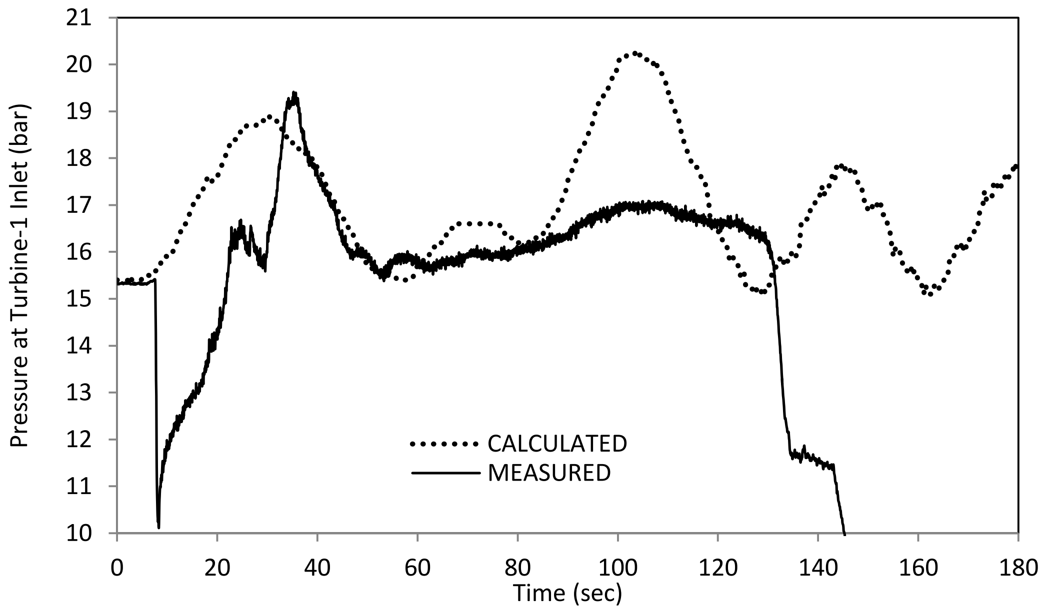


Figure 5.28 Measured and Computed Pressures at Turbine-1 Inlet for Case-2-Load Rejection during Both Units in Operation Condition

5.2.2.2 Case-2-Load Variation Scenario

In this study, the measured data recorded during the load variation of Turbine-2 between 4000 kW and 4500 kW is used. Turbine-1 was closed during this record period. The gate opening pattern and initial pressure head at Turbine-2 inlet are taken from measured data for model study. Also, discharge value is calculated approximately by using measured data. Figure 5.29 shows the generated power variation. The gate opening pattern is given in Table 5.15 for this scenario.

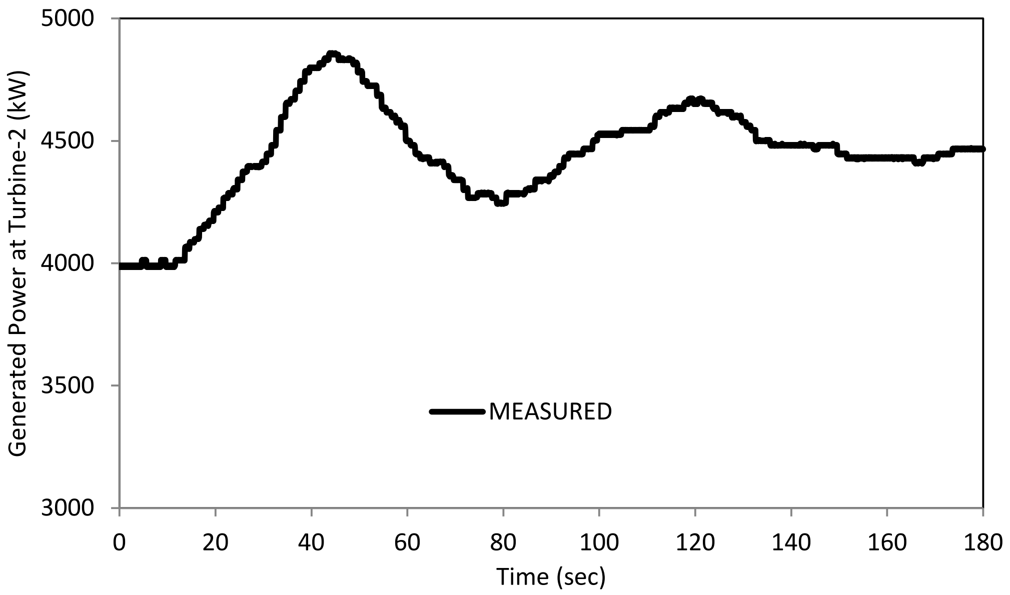


Figure 5.29 Power Change of Turbine-2 against Elapsed Time for Case-2 Load Variation Scenario

Table 5.15 Gate Opening Pattern of Turbine-2 for Case-2 Load Variation Scenario

Time (sec)	Wicket Gate Opening (%)	Time (sec)	Wicket Gate Opening (%)	Time (sec)	Wicket Gate Opening (%)
0	0.83	70	0.84	140	0.87
10	0.84	80	0.9	150	0.87
20	0.93	90	0.92	160	0.88
30	0.97	100	0.96	170	0.91
40	0.98	110	0.96	180	0.94
50	0.89	120	0.92		
60	0.85	130	0.88		

The power varies in small scale. Hence, pressure variations are also in small scale for this scenario. Figure 5.30 shows that pressure variations are less for measured data than calculated data. PRV valves stabilize pressure in the system in shorter time interval.

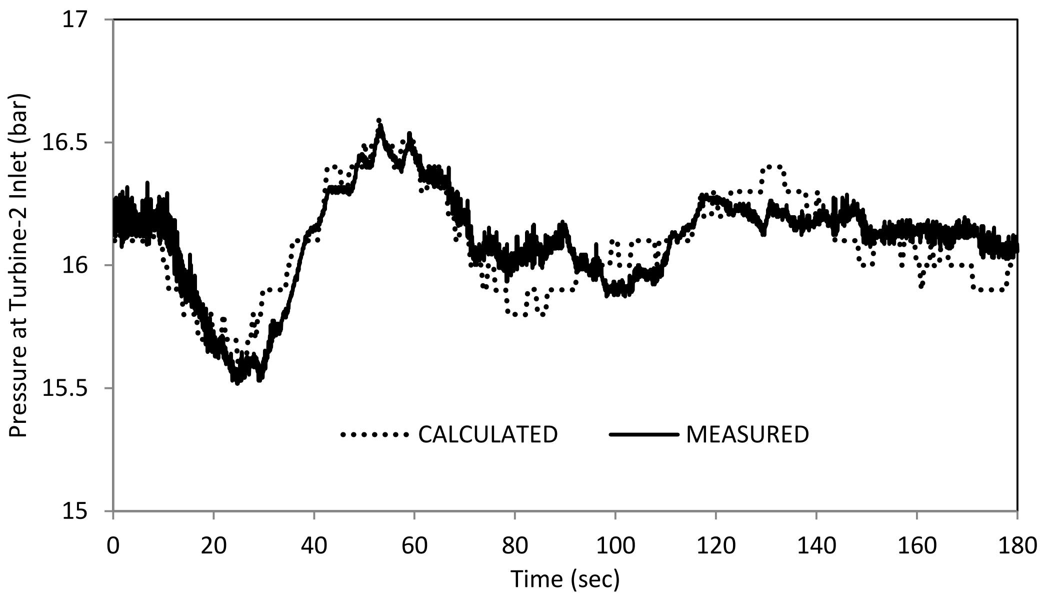


Figure 5.30 Measured and Computed Pressures at Turbine-2 Inlet for Case-2-Load Variation Scenario

5.2.2.3 Case-2-Instant Load Rejection Scenario

In this study, 3 different measured data is used to analyze PRV valve effects. Turbine-1 was closed instantly for 3 times. Each of these closures is applied when the generated power of Turbine-1 is 1700 kW. Turbine-2 was kept closed all along that test process. At the first closure, PRV valves located on the branch which is connected to Turbine-1 are kept closed and instant closure is applied. At the second measurement, one of the PRV valves is kept closed, and the other one is free to operate. Finally, both of the PRV valves on the branch are free to operate under high or low pressure occurrences. The power curves of these 3 conditions are given in Figure 5.31. Wicket gate opening patterns are given graphically in Figure 5.32.

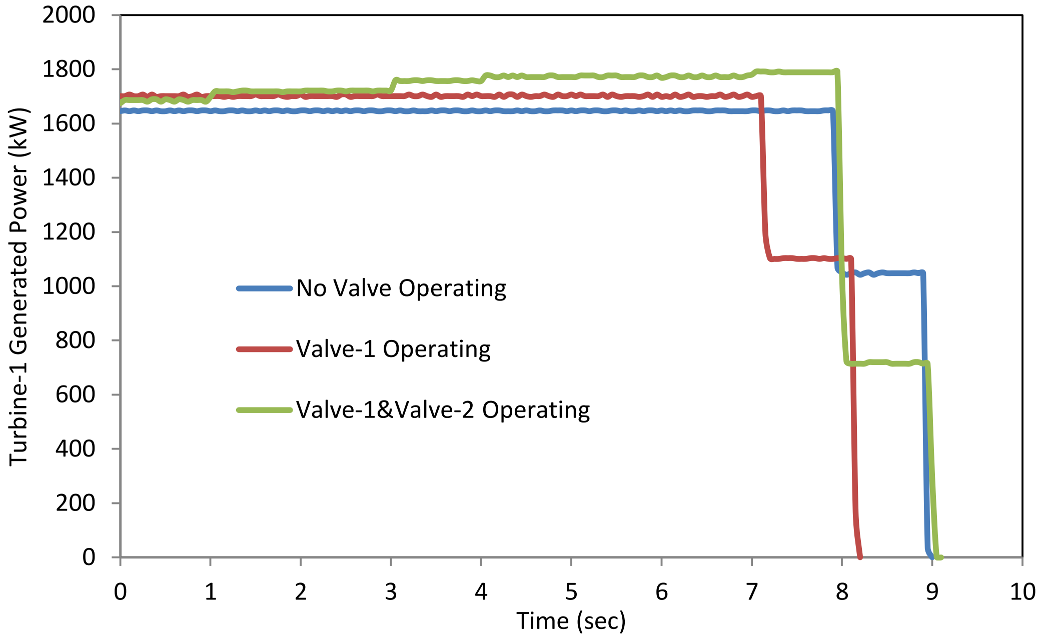


Figure 5.31 Power Change of Turbine-1 against Elapsed Time for Case-2 Instant Load Rejection Scenario

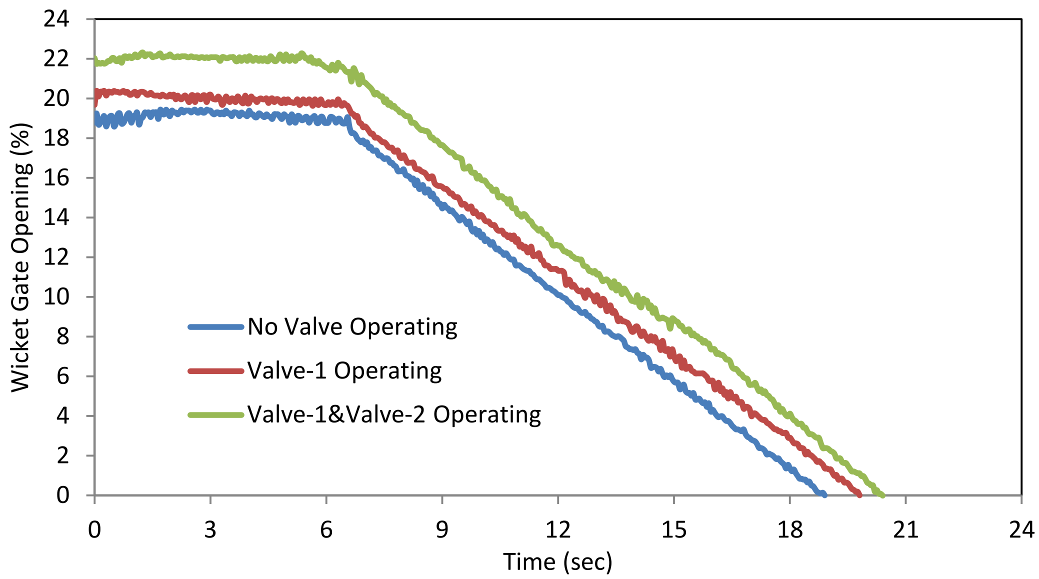


Figure 5.32 Gate Opening Patterns of Turbine-1 for Case-2 Instant Load Rejection Scenario

Figure 5.33 shows the pressure variations of 3 conditions. System pressure is stable at first for three conditions. Then, an increase in pressure causes PRV to open. The amount of water discharged during single valve condition is lower than operation of both of the valves condition. Hence, the pressure value in the penstock reaches a lower value at 8.45^{th} second when both of the valves free to operate. However, the amount of water demand increases parallel to discharged water. More water volume in pipeline system results in higher velocities. Also, the rapid closure pattern of valves causes an extra pressure surge in the pipeline system. These are the reasons why maximum pressure values at approximately 40^{th} second are higher for PRV operating conditions. Also, the reasons of the pressure difference between the peaks of one valve operation and two valve operations at approximately 40^{th} second are again the rate of increased system demand and consequently the rate of increased velocity in the penstock. After that point, the pressure difference between PRV set pressure and pressure in the penstock is less. Hence, system demand variation is less and consequently pressure is more stable than unprotected case.

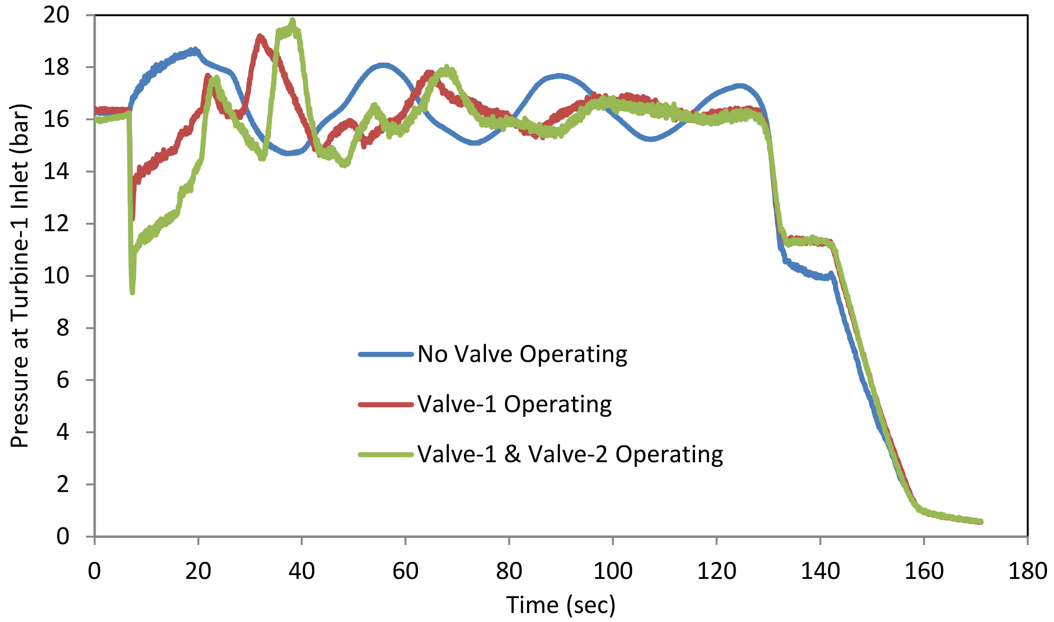


Figure 5.33 Measured Pressures at Turbine-1 Inlet for Case-2-Instant Load Rejection Scenario

Figure 5.34 shows the rotational speed of Turbine-1 for 3 conditions. It is clear that PRV valves decrease the rotational speed effectively during transient events. The reason of this is that PRV operation postpones the peak pressure occurrence by discharging water. Hence, the water volume entering the turbine is less for conditions containing PRV valves. The wicket gate continues to closing during that postponed time interval. Therefore, the amount of water entering the turbine keeps less than the unprotected case. It can be seen from Figure 5.34 that the peak pressure occurrence time of the two valves operating condition is later than the one valve operating condition. Also, the discharge capacity of two valves operation is more than single valve operation. These are the reason why turbine rotational speed is less for two valve operation condition than one valve operation condition.

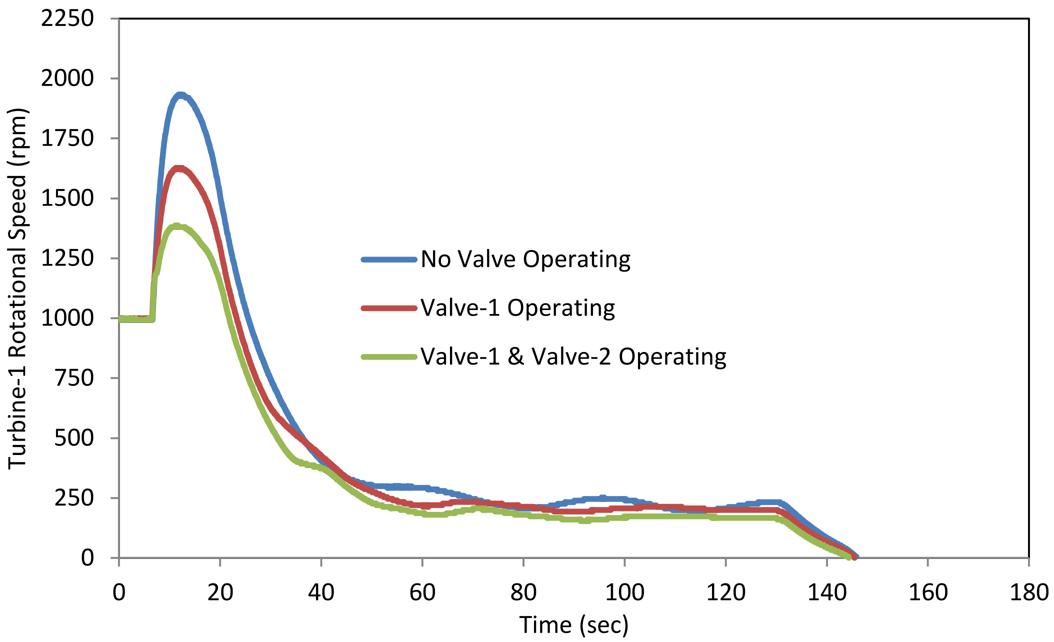


Figure 5.34 Measured Rotational Speeds of Turbine-1 for Case-2-Instant Load Rejection Scenario

5.2.3 Case-3: Protection with Surge Tank Case

In this case, the same scenarios and conditions analyzed for Case-2 are studied with surge tank instead of PRV valves. The results are compared with measured data and computer model results of unprotected system.

Topographical and economical conditions make impossible to construct a surge tank for Yesilvadi HEPP project. However, to show the effects of surge tank against water hammer and to compare the results with unprotected system and system including PRV as protection measure, a surge tank is modeled by using the computer model. Surge tank is located at the beginning of penstock. Its type is simple surge tank.

In this case study, the following scenarios are analyzed with computer model studies and the results are compared with results of Case-2.

- Load rejection
- Load variation
- Instant load rejection

5.2.3.1 Case-3-Load Rejection Scenario

Two different conditions are analyzed for *Case-3 Load Rejection Scenario*. The first condition contains the analysis carried out when single unit is in operation and the second condition contains the analysis carried out when both units are in operation.

5.2.3.1.1 Case-3-Load Rejection during Single Unit in Operation Condition

In this study, the computer model used for the same condition of Case-2 is re-modeled with a surge tank instead of PRV valves. The gate opening pattern of the Turbine-2 is given in Table 5.12.

In Figure 5.35, pressure variations at Turbine-2 inlet are shown for 3 different conditions. The results show that protective measures are effective in stabilizing excess pressure in the system. However, the effect of surge tank on the first pressure wave is not significant. The maximum pressure is nearly the same with that of unprotected system.

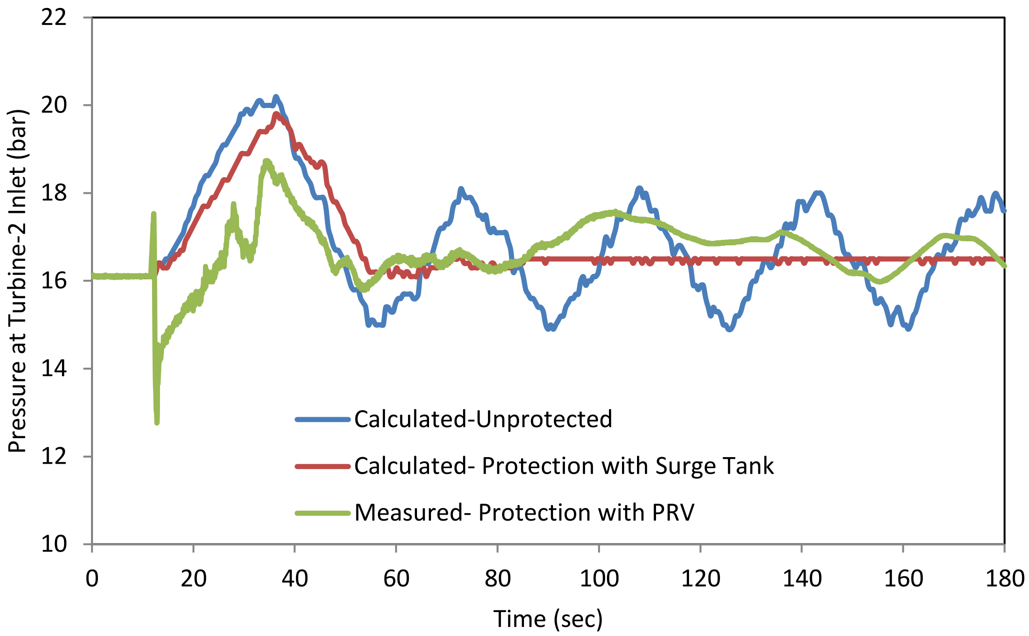


Figure 5.35 Comparisons of Measured and Computed Pressures at Turbine-2 Inlet for Case-3 Load Rejection during Single Unit in Operation Condition

5.2.3.1.2 Case-3-Load Rejection during Both Units in Operation Condition

In this study, the computer model used for the same condition of Case-2 is re-modeled with a surge tank instead of PRV valves. Gate opening pattern of Turbine-2 is given in Table 5.13 and gate opening pattern of Turbine-1 is given in Table 5.14.

Figure 5.36 and Figure 5.37 show the pressure variations at Turbine-1 and Turbine-2 inlets, respectively. As stated in the previous condition, surge tank is not effective to decrease first pressure wave. Therefore, after the closure of Turbine-2 and Turbine-1, pressure value in the pipeline system is nearly the same with that of unprotected system. However, the pressure in the system is stabilized effectively by surge tank after first surge wave reaches to it.

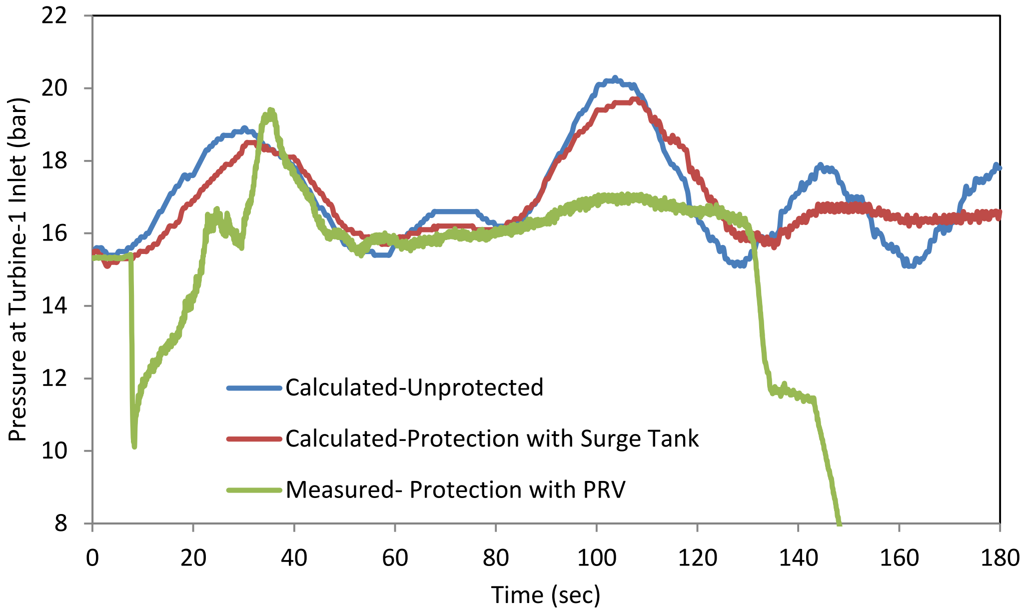


Figure 5.36 Comparisons of Measured and Computed Pressures at Turbine-1 Inlet for Case-3 Load Rejection during Both Units in Operation Condition

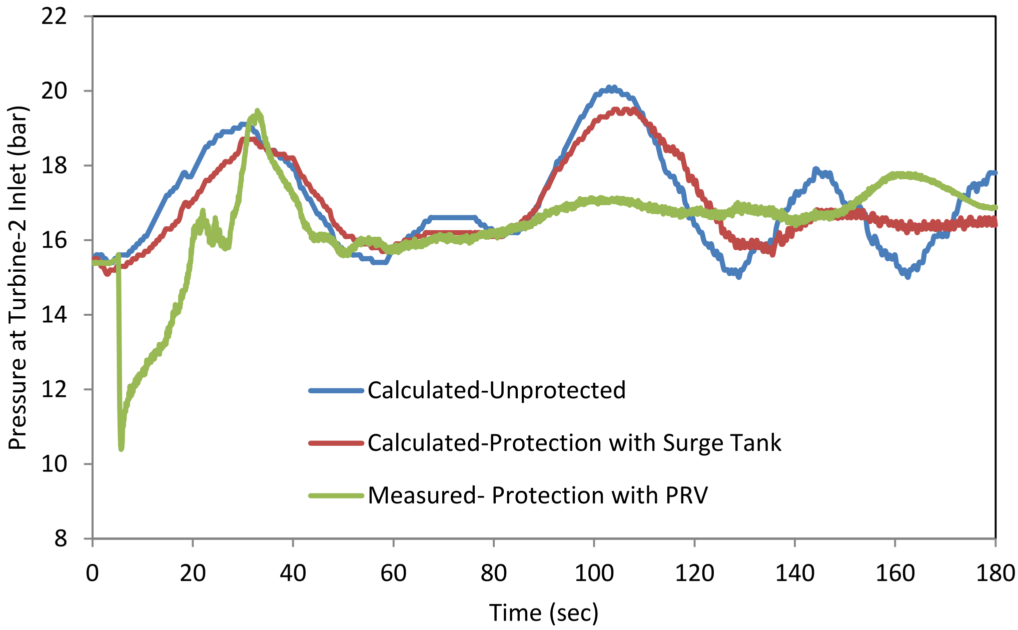


Figure 5.37 Comparisons of Measured and Computed Pressures at Turbine-2 Inlet for Case-3 Load Rejection during Both Units in Operation Condition

5.2.3.2 Case-3-Load Variation Scenario

In this study, the model used for the same scenario of Case-2 is re-modeled with a surge tank instead of PRV valves. Gate opening pattern of Turbine-2 is given in Table 5.15.

Figure 5.38 shows the pressure variations at Turbine-2 inlet. Because the variation in generated power is small, the discharge value in the system is not changing significantly during that scenario. Hence, variations in pressure are in small amount. This is the reason why surge tank effect is not apparent.

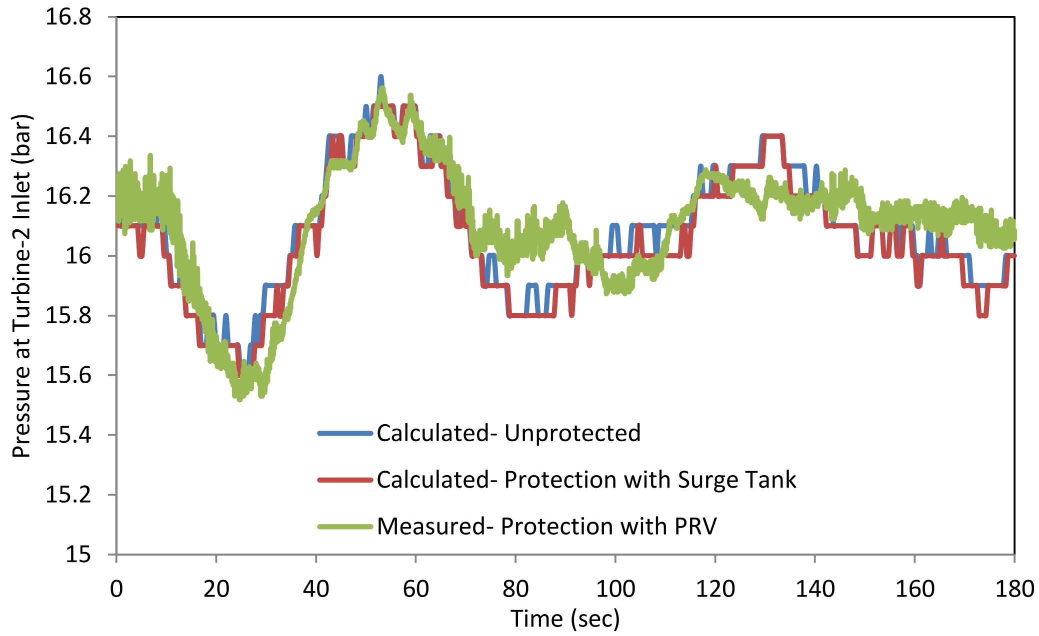


Figure 5.38 Comparisons of Measured and Computed Pressures at Turbine-2 Inlet for Case-3 Load Variation Condition

5.2.3.3 Case-3-Instant Load Rejection Scenario

In this study, the model used for the same scenario of Case-2 is re-modeled with a surge tank instead of PRV valves. The pressure variations at Turbine-1 inlet are compared for 4 different cases. Because the pressure gage of Turbine-1 is located on the turbine side of the wicket gate, the measured pressure value decreases by the closure of turbine gate and finally reaches 0 after full closure. However, calculated data represents the pressure values at the penstock side of the wicket gate. Hence, the result that can be inferred from this study is the effectiveness of surge tank in stabilizing the excess pressure in the pipeline after first pressure wave reaches to it.

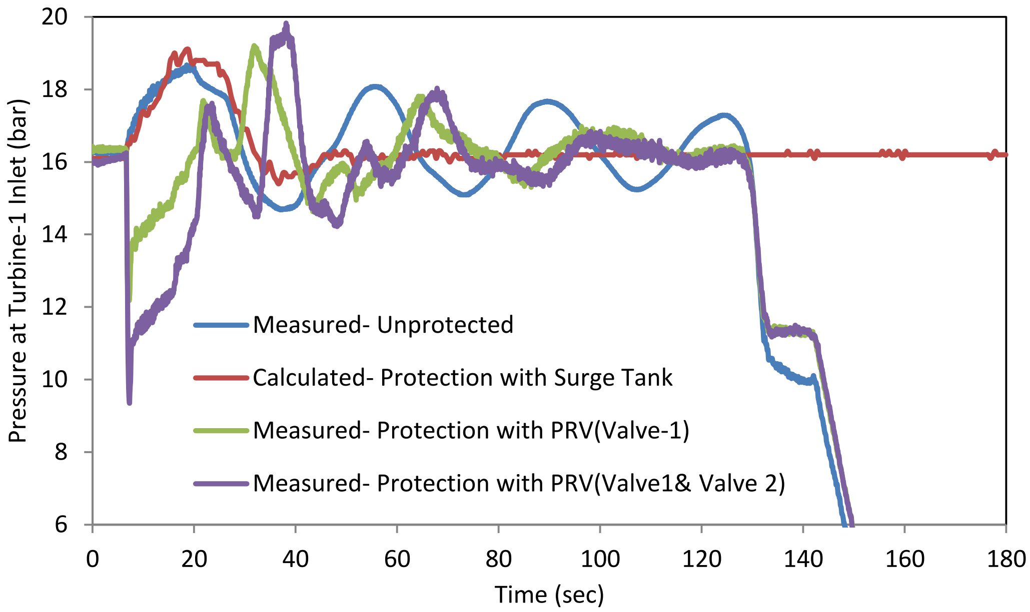


Figure 5.39 Comparisons of Measured and Computed Pressures at Turbine-1 Inlet for Case-3 Instant Load Rejection Scenario

5.3 Discussion of the Results

In this chapter, various transient scenarios and conditions are produced numerically by the help of computer software and the results are compared with measured data of Yesilvadi HEPP project. The pressure variations at turbines' inlet, the hydraulic grade line over the water transmission line, and rotational speeds of turbines are analyzed with numerically and experimentally.

The validation of the numerical modeling of scenarios is performed by comparison with measured data in Case-1 study which represents the unprotected system results.

The numerical results of this study show that computer model is capable of predicting the system transient response accurately. There are many parameters affecting transient behavior in a pipeline system such as the pipe material type, wall thickness of the pipes, temperature of water in the system, wicket gate opening and closing patterns, turbine characteristics. Hence, it is not possible to model an existing system precisely. Small differences between the calculated and measured data in the transient behavior may be the consequence of inadequate defining of those parameters in the software.

In the second case study, the measured data that contains PRV valve operations are represented. To protect the system against water hammer effects, PRV valves were installed as protective measure in Yesilvadi HEPP. A computer model study having the same hydraulic and operational parameters except the PRV valves is tried to be simulated to analyze the effects of PRV valve. Then, the calculated results of unprotected system and measured data are compared. The results show that the opening and closing time of the PRV valves are very short. That rapid opening of PRV valves cause pressure to drop significantly. Pressure drop in the penstock as a consequence of discharging of water from PRV valves increases the system demand. More water volume in the system results in velocity increase. That increased velocity and rapid closure of the PRV valves cause secondary water hammer effect in the system. This is the reason why maximum pressure value is more when PRV valves operate. After the first surge wave of secondary water hammer increases the system pressure to maximum value, PRV valve stabilizes the system to set point efficiently. Also, measured data shows that PRV valve operations are very effective in decreasing rotational speed of turbine. As the number of PRV valves increase, the maximum rotational speed of turbines decreases.

In the third case, an imaginary surge tank is modeled instead of PRV valves to analyze the system response against water hammer. The results show that surge tank implementation is not effective for decreasing the maximum pressure. The maximum pressure of unprotected system and the maximum pressure of the system with surge tank are nearly the same. However, after the arrival of the first pressure wave to surge tank, the reflections in the system caused by water hammer are submerged by it and system pressure is stabilized immediately.

The gate opening patterns given for scenarios show that wicket gate closing time is generally between 35 seconds and 40 seconds. For Yesilvadi HEPP project, rapid closure time of the wicket gates is 17.62 seconds. This shows that system mostly experience a gradual closure. The measured data shows that Yesilvadi HEPP project is safe against water hammer effects except instant load rejection scenario even if there is no protection measure. However, the frequency of the gate operation may cause serious problems in time. Hence, existence of PRV valves is important in the long term.

CHAPTER 6

CONCLUSIONS

Growing population and increase in energy consumption per capita make uninterrupted and reliable energy generation one of the most important issues for Turkey. To meet the ever increasing demand, private sector has been promoted by governmental incentives especially for small hydro electrical power projects.

For a hydro electrical power project, the accurate analysis of transient behavior is very important. Negligence of some issues at the design stage may cause serious economical problems and also lead to loss of human lives in some situations. Yesilvadi HEPP project is one of the small hydro electrical power plant projects whose transient analysis has been performed in the present study and the following conclusions are drawn:

- Numerical analysis of hydropower systems is very beneficial to foresee the weak points of the system. Computer software serves as an accurate and rapid problem solver. Hence, it should be used in design stage of hydro electrical power plants.
- For Yesilvadi HEPP project, the theoretical rapid closure time of the wicket gates is approximately $2L/a$ = 17.6 seconds. Measured data show that actual closing time of the wicket gates is mostly between 35 and 40 seconds. Hence, the system technically experiences gradual closure and consequently acceptable pressure variations mostly.
- Yesilvadi HEPP project was tested for unprotected scenarios during commissioning (Case-1). It has been found to be safe against water hammer

- phenomenon, but it was decided that installing a protective measure would be necessary in the long term.

- To protect the system against potential water hammer effects, PRV valves were installed as protective measure in Yesilvadi HEPP. The reaction time of these valves is impressive. They react to the pressure increment in the system within 1 second and open to discharge water to prevent excess pressure occurrence, and rotational speed increase of turbine.

- The computer software used in the study, despite its worldwide use and popularity, is not entirely capable of simulating the PRV valves during transient state. Hence, it is not possible to analyze effects of PRV valves without measured data.

- The results show that maximum transient pressure value is higher for two sets of PRV valve in operation than single set of PRV valve in operation for the same scenario (Case-2). The number and discharge capacity of the PRV valves determine the system demand of extra water volume while in operation. During a transient event, as the water volume flowing in the system increases, also the velocity of flow increases. Increased velocity of flow causes higher pressure values in the system. This, in turn, results in secondary water hammer effects. This is one of the good outcomes of the study since the shortcomings of the PRV valves installed in Yesilvadi HEPP emerged clearly. As stated above, in the operation of PRV valves, the rapid opening and closing patterns of the valves cause secondary water hammer effects in the system. To reduce the maximum pressure value caused by secondary water hammer effect, the opening and closing time of PRV valves should be extended. This will be recommended to the plant owners.

- The results show that pressure variations in the system are nearly same for two sets of PRV operation and one set of PRV operation after the generation of maximum pressure (Case-2). Hence, the second sets of pressure relief valves on the branches are not needed. They may be used as spare PRV.

- PRV valves are very effective in reducing the rotational speed of turbines. This feature is very important to keep the turbines from adverse conditions. Maximum allowable speed rise for turbines should be obtained from the manufacturer company. If the maximum turbine speed value exceeds the allowable limit during the single valve operation, the discharge capacity of single PRV valve should be increased.

- It is obvious that PRV valves may be used as standalone protective measure in a hydropower project if they are operated appropriately. Maximum transient pressure values experienced by the system and the maximum speed rise of the turbine due to water hammer effects may be reduced by using PRV valves provided that they are operated appropriately.

- The results of the system analysis with surge tank show that it is not efficient for reducing the maximum transient pressure values occurring near the turbines. However, surge tank is very effective in stabilizing the system pressure immediately after arrival of the first surge wave. In light of these considerations, a surge tank which is an expensive structure as a protective device is not suggested for the Yesilvadi HEPP project.

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