ISSN No:-2456-2165

Designing of Load Response Generation Synchronized 15MW Hydropower Station and Simulation Based Electromechanical and Structural Analysis

H.D.Milan Ravinath Perera
MSc, BEng (Hons), C&G(A.Dip), Member of IET, Member of IEEE
Independent Research
362/G, 9th Lane, Mahara, Kadawath, Sri Lanka

Abstract:- Hydropower station development is mainly based on the reservoir type and its available head. Therefore, this paper was written on basis of how to design a 15MW Hydropower Station considering environmental factors, civil concerns and electromechanical integrations. This paper discuss the most important design arguments under construction of the specific 15MW small hydropower station structure and its mathematical modellings. It was used MatLab/Simulink, SolidWorks, and ANSYS software tools to observe its simulation results. The hydropower system will be changing its generation as the load requirement deviates and the author contributed the load response power generating system design in this paper.

Keywords:- *Hydropower, Civil Structure, Electromechanical, PID Governor control, Excitation.*

I. INTRODUCTION

Renewable energy is the cleanest energy generation source that can be used to cater the demand of the consumer's electricity. Therefore, optimizing the natural resources and obtaining the most reliable energy generation is one of the key factors that sustainable energy engineers should be concern about. As in perspective of hydropower, it discussed the complete design strategies of a 15MW hydropower station in both electromechanical and hydraulic structures using MatLab/Simulink, SolidWorks and ANSYS software interfaces. Hydropower generation uses flowing water to produce electricity utilizing the phenomenon of water cycle. The effect of gravity contains the potential energy on water which then convert it to kinetic energy with the help of turbine blades. The turbine will couple with the generator using a shaft and the rotation of turbine will rotate the generator and produce electricity. The first commercial hydropower station was developed in 1882 in Wisconsin, and at the 21st century, hydropower cater the 20% of worldwide electricity demand with a consumption of 12900 TWh per year [1]. As per the data, 1.21 TW of hydropower have been installed around the world as at 2016 update. The five main hydropower penetrated countries are China, Brazil, Canada, United States of America and Russia [2].

Hydropower generation classifications can be breakdown into 3 main sections. Such as,

A. Classification from Viewpoint of power supply capability

There are three of the classifications according to the view point of power supply,

1. Run-of-river type

The water from water flow is directly taken to generate electricity from hydro turbines. In this design, it is required to build a weir across the river as the intake to the powerhouse to divert the water. The water taken from intake will follow through channel, fore bay and then connect to penstock line which then take the water flow towards the turbine [3].

2. Pond type

This is also a run-of-river type architecture, but it includes a pond which used as a water storage. Therefore, it can regulate the run-of-river for several days and mainly it can vary the power generation in parallel to the changes of demand. Hence, these power stations can be used as a base load power stations or peak load power stations because of its reliability due to pond storage system[4].

3. Reservoir type

Many large and medium hydro power stations are in this category. This architecture requires a dam and store water to use in a controlled manner. This water store can be used throughout the year even in dry season. Similar with pond type, this method will be also taken as base load or peak load power stations since it's more reliable in power generation. The construction of dam plays an important role in designing these reservoir type hydropower stations and the selected site should have a high precipitation value compared to other locations[4][5].

B. Classification according to the head

The hydropower stations will be developed as per the head determined at site, since the head water level will determine the potential of energy extractable from the water flow. The value of head can be obtained with specification point of the intake weir and at the outlet of the turbine. The measurement of head is one of the important survey process that the hydropower stations undergo, and it uses Hand-level, an altimeter and GPS tuner as measurement tools [4]. Therefore, there are three main head levels in hydropower,

1. High head

If the difference between the height of intake and the turbine out is equal or greater than 100 meters, will be taken as high head hydropower stations. These power stations with high heads, need long length of penstock line since the distance between the intake and powerhouse is large. The high elevation will be effect on water volume by negative coefficient, as the higher the elevation the system needs a smaller volume of water to produce an equivalent amount of energy. Most of the large hydroelectric power stations use high or medium head water levels.

2. Medium head

If the difference between the height of intake and the turbine out is minimum 10m or not more than 100m, it is taken as medium head systems. These systems do need penstock line to flow water, but the distance is not long compared to high head hydro systems.

3. Low head

The head difference around 10m or less is considered as low head hydropower systems. Most of the small and mini/micro hydro systems with run-of-river concept use this method for power generation. The penstock line will not be too long, thus it designed to flow heavy water flow rate to the turbine to produce the power generation [6].

C. Classification according to the installed capacity

According to the generation capacity of hydropower stations, these will be sectioned into 5 main categories. Those are, Micro hydro, Mini hydro, Small hydro, Medium hydro and Large hydro. Depending on the country's electricity generation profile, these categories will be varied. Such as, if a country has hydro power station maximum capacity of 100MW it will be its large hydro station, meanwhile, another country has hydro power station maximum capacity of 30MW and it will be the large hydro power station for that specific country[1]. With refer to all the classifications of hydropower systems, the below chart can be developed in summery.

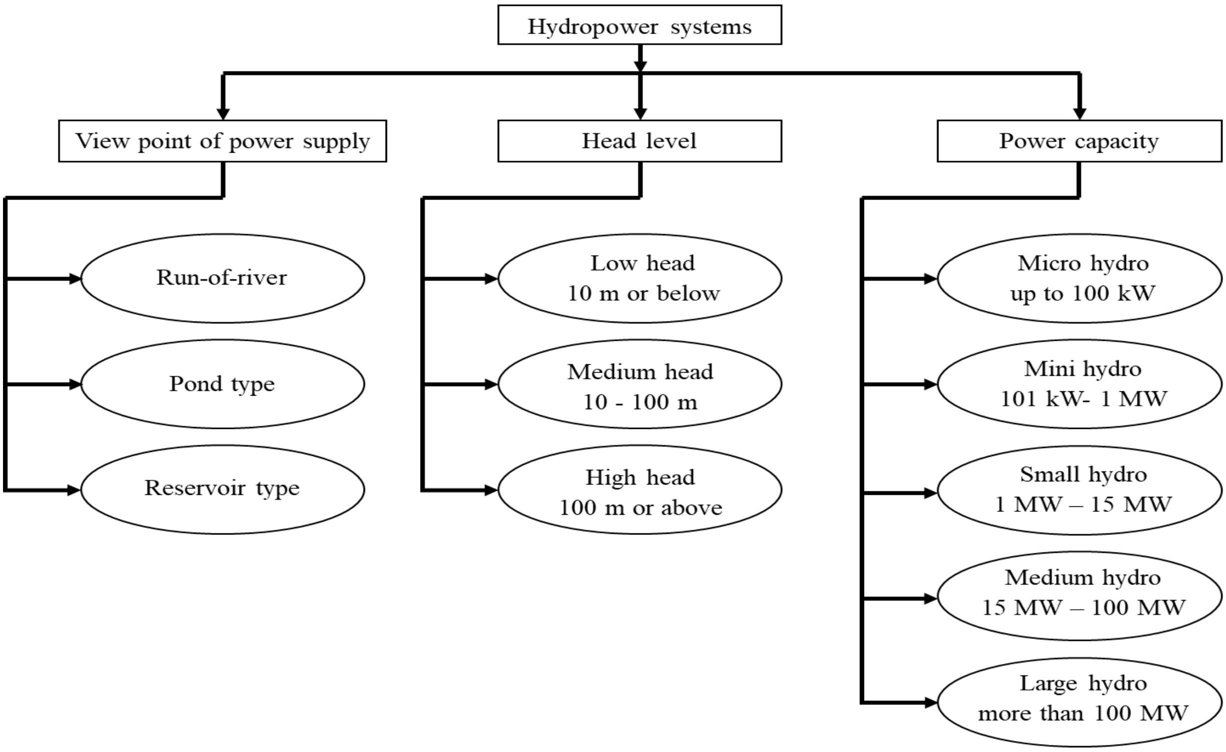


Fig. 1:- Complete classifications of hydropower systems.

Compared to other power supply techniques, such as thermal power generation, hydropower plants (HPP's) are unique because it requires custom design as per the site specifications. Also, HPP's require substantial initial investment in the development of project, thus the operating cost with regard to its life cycle is comparatively less. Typical small hydro will have an agreed life span of 25 year and large or medium hydropower stations will have an agreed life span of more than 40-50 years. Therefore, building a HPP's is challenging and it required several phases during the development process [7]. These HPP stations requires both civil and electromechanical components to extract power from flow of water and produce electricity generation. Therefore, with regards to the location, geographical condition and material, the civil structures which is also known as hydraulic structures can be subdivided into following areas of a standard HPP [3].

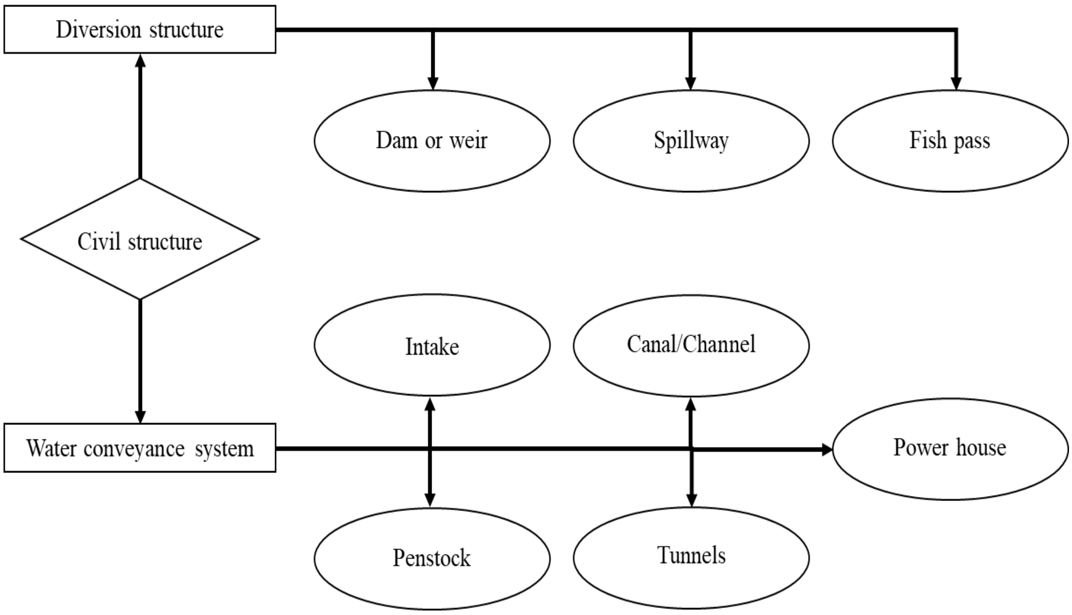


Fig. 2:- Hydraulic structures in HPP.

A. Dam/weir and settling basin

The dam in a hydropower station will store the water in a reservoir by blocking the flow towards downstream. The water will flow using spillways and penstock lines. Thus, weir is different from dam since it does not completely block water as dam, thus water comes from upstream runs over the top of weir while allowing for water to pool behind the weir [8]. The weir height should be planned by following the below equations,

$$D_1 = d_1 + h_i \tag{1}$$

Where D_1 is the weir height, d_1 is the height of the bed of the scour gate to the bed of the inlet (Usually 0.5-1.0m), h_i is the water depth of the inlet (Usually determined to make the inflow velocity approximately 0.5-1.0m/s). To remove sediments of specified size and quantity, the settling basins are used on irrigation or reservoir hydropower channels. These settling basins are designed in compartments more commonly and used to protect mechanical equipment from sediments [9]. The length of the settling basin can be designed by using the following equation,

$$\mathrm{L} \geq \left(\frac{\mathrm{V}}{\nu}\right) * \mathrm{h_s} \tag{2}$$
$$\mathrm{L_s} = 2 * \mathrm{L}$$

Where, L - minimum length of the settling basin (m), L_s - length of the settling basin, h_s - water depth of the settling basin (m), ν - marginal settling speed for sediments to be settled (m/s), V - mean flow velocity in the settling basin (m/s). Thus, V can be calculated by,

$$\mathrm{V} = \frac{\mathrm{Q_d}}{(\mathrm{b} * \mathrm{h_s})} \tag{3}$$

Where, Q_d - design discharge rate of water (m3/s) and b - width of the settling basin (m)[3]. The discharge water flow rate (Q_d) of the reservoir will depend on the Cross-sectional area of natural water course (Ar) and average water flow speed (V). Thus, the below relationships can be developed,

$$\mathrm{Ar} = \frac{(\mathrm{a}+\mathrm{b})}{2} * \frac{\mathrm{h1}+\mathrm{h2}+\mathrm{h3}+\cdots+\mathrm{hk}}{\mathrm{k}} \tag{4}$$

$$\mathrm{V} = \mathrm{Ki} * \mathrm{Vrs} \tag{5}$$

$$\mathrm{Q_d} = \mathrm{Ar} * \mathrm{V} \tag{6}$$

Where, a - width of top river, b - width of bottom river and $\frac{h1+h2+h3+\cdots+hk}{k}$ is the average height of water in the reservoir. Ki - Correction factor (vary between 0.6~0.85), Vrs - surface speed of water[10].

B. Fish passage and spillway

Designing a dam or weir will also prevent fish to pass towards the downstream which will be an issue towards the ecosystem. Therefore, it is created a fish passage that helps the fish to pass towards downstream without harm. The fish ladder, fish lifts and juvenile bypass systems are used as fish passages in hydro power stations[11]. These dams and weirs are designed to hold water levels up to a certain value, thus to prevent from damage caused by floodwater levels in a hydropower station, the spillway is built, which helps the floodwater to pass downstream with a safe path. There are 5 ways of spillway designs, Ogee spillway, Chute spillway, Side channel spillway, Bell-mouth spillway and Siphon spillway[12].

C. Head race channel

The water taken from the intake should be taken towards fore-bay or turbines using the headrace channel. The head race channel is designed with a slope and bends considering the water to flow in a controlled velocity that it will not spill along. When designing an open channel foundation two requirements should be satisfied, the stability of structure with rigid and do not permit deformation, channel does not support thrust or up lift pressure[10]. The flow capacity calculation is shown below for the purpose of head race channel designing.

$$Q = A * R^{\frac{2}{3}} * S_L^{0.5} / n \quad (7)$$

Where, Q - design discharge of head race (m^3/s), A - area of the cross section (b*h), b - width of the channel, h - depth of the channel, R=A/P, P - wetted perimeter (b+2h), SL - longitudinal slope of the head race, n - coefficient of roughness [13].

D. Fore-bay

The Fore-bay is also known as the head tank in a hydropower application. This will help to control the water discharge in a penstock and also remove trash in the dirt water so it is preventing entering trash to the penstock line and damage the turbines and equipment. This can be defined by the terms of water depth from hc to ho with the length L, and thus the below equation can be developed,

$$V_{sc} = A_s \times d_{sc} = B \times L \times d_{sc} \quad (8)$$

Where, V_{sc} - head tank capacity, d_{sc} - water depth form uniform flow of a head race under maximum discharge ho and critical depth of head tank hc, B- width of the head tank, L - length of head tank.

E. Penstock

Penstock is a conduit or tunnel that creates a water flowing path from reservoir/fore-bay to hydro turbine. The penstock is designed to withstand high pressure of water under static and dynamic conditions. Most widely used penstock materials are mild steel, glass reinforced plastic (GRP), reinforced cement concrete (RCC), wood stave, Cast iron and high density polyethylene (HDPE)[14]. The penstock diameter (D) for a given power station can be calculated with the below equations,

$$A = \frac{Q}{V} \quad (9)$$

Where, A is the internal diameter (m^2), Q - is the discharge rate (m^3/s) and V - penstock flow velocity (m/s). Thus, with the help of circle of the area equation, and justify for the term (D), diameter[3][14],

$$D = 2 * \sqrt{\frac{A}{\pi}} \quad (10)$$

The thickness of the penstock is required to determine since it is necessary to withstand the pressure inbuilt due to water flow. The below equations will be used to calculate the thickness of the penstock pipes require,

$$t_p = P * r / \sigma \quad (11)$$

Where, t_p - penstock thickness, P - total pressure, r - radius of penstock, σ - stress. The total pressure (P) can be defined by below equation,

$$P = P_h + P_s \quad (12)$$

Where, P_h - pressure due to water hammer effect, P_s - static water pressure. Thus, pressure due to water hammer effect (P_h) can be obtained by below equation,

$$P_h = \rho_w * C_p * V \quad (13)$$

Where, ρ_w - water density (1000), C_p - water coefficient under ordinary conditions (1120), and V - penstock flow velocity. The static pressure (P_s) can be obtained by using the below equation,

$$P_s = \rho_w * g * H \quad (14)$$

Where, g - gravitational force (9.81), H - Net head.

Comparatively to the diameter of penstock, the revenue and cost can be varied with the effect of head loss. For smaller diameter penstocks will incurred less cost on the pipe design but under operation it will create more head loss and influence in higher energy loss and revenue loss. When the diameter of penstock increases, the cost of pipeline under construction will be increased, but the head loss is minimum and therefore, the revenue and energy generation will be higher. There are different head losses in penstock line, the intake loss (h_i), gate/valve loss (h_g), bend loss (h_b), bi/trifurcation loss (h_y), inlet valve loss (h_g) and transition piece loss (h_{tr}) can be represented in a single equation as mentioned below[14],

$$h_v = K * \frac{V^2}{2 * g} \quad (15)$$

Where, K - loss coefficient, V - penstock flow velocity and g - gravitational effect (9.81). Apart from these losses the other is the friction loss (hf) which resulting from the flow of water with the effect of friction induce by the material of penstock. Manufactures develop the penstock with minimum friction properties to avoid the losses. The friction losses can be calculated by the following equation,

$$h_f = f * \left(\frac{L_p}{D_p}\right) * (\frac{V^2}{2g}) \quad (16)$$

Where, f - friction factor in Darcy Weisbach and ASCE relation, L_p - length of penstock pipe, D_p - diameter of penstock, V - flow velocity in penstock, and g - gravity effect (9.81). Therefore, the total head loss can be calculated by the below equation [14],

$$T_{hl} = \frac{fL_pV^2}{2gD_p} + K_0 \frac{V^2}{2g} \quad (17)$$

The electromechanical equipment is placed mainly near the intake structure and inside the powerhouse. With refer to a standard hydropower station, the below chart is produced with including all the possible electromechanical equipment.

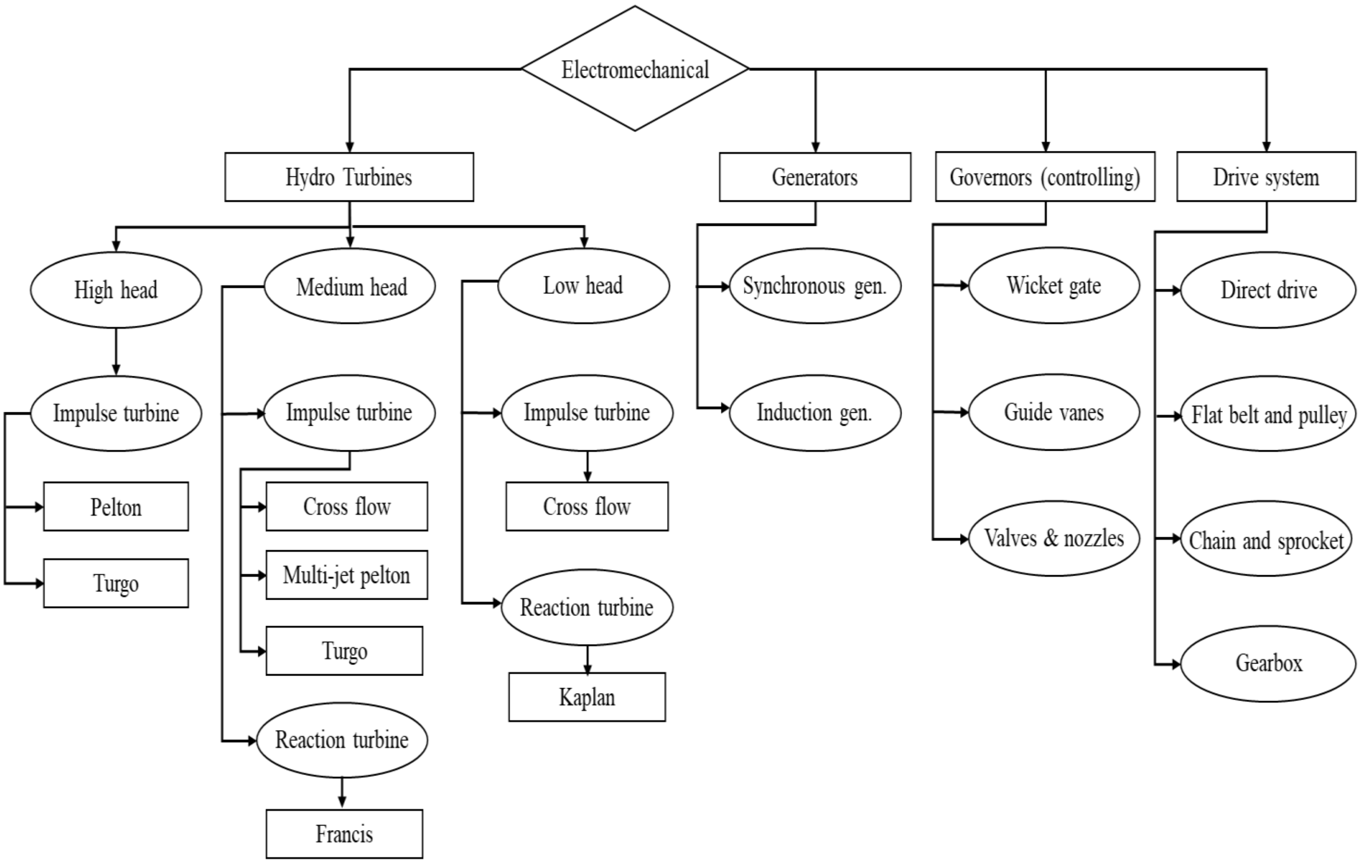


Fig. 3:- Electromechanical equipment of HPP

F. Turbines

Water turbines are one of the main important components in a HPP's, that it extracts the water power and produce a momentum to rotate a generator shaft to generate electricity. With the physical properties of turbine, it can be divided into two main categories such as Impulse turbine and reaction turbines. Impulse turbine is a horizontal or vertical wheel that uses the kinetic energy of water striking its buckets or blades to cause rotation. The wheel is covered by a housing and the buckets or blades are shaped so they turn the flow of water a certain degree inside the housing. After turning the blades or buckets, the water falls to the bottom of the wheel housing and flows out. The Pelton turbine and Crossflow turbine are the two main impulse turbines that widely use in hydropower applications. With compared to other turbines, impulse turbines are relatively higher in efficiency at low flow rates and the design is less complex to fabricate. Reaction turbine is a horizontal or vertical wheel that operates with the wheel completely submerged, a feature which reduces turbulence. This works like a rotating lawn sprinkler where water at a central point is under pressure and escapes from the ends of the blades, causing rotation. The Francis and Kaplan turbines are widely used in industry for hydropower [15]. Selection of these turbines for a specific hydro site will depend on the net head and flow discharge rates observed at site.

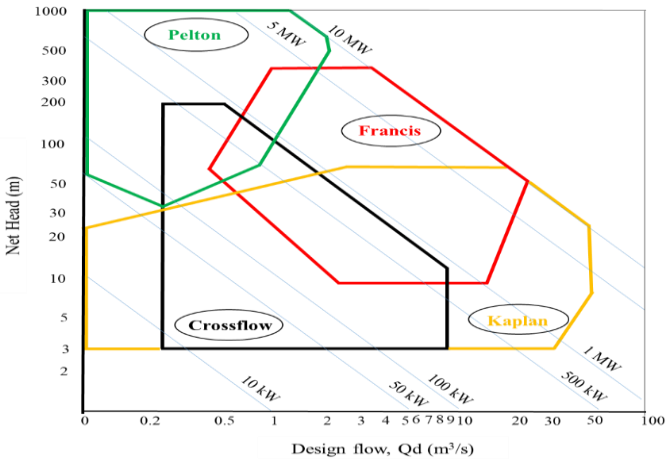


Fig. 4:- Turbine selection chart according to the net head and flow rate

G. Governor system

The variations of load will affect the frequency of the generated power. To avoid these variations in frequency, the hydro turbine governor is used, and it will operate the turbine under constant speed under load variations. In the process of controlling, the governor will adjust the gate opening of the wicket gates, control the servo motor and pilot valve. Under designing of governors, there are two main concepts that will be hydraulic-mechanical governor model and electro-hydraulic PID governors[16]. Compared to both of these techniques, the PID based controlling is widely used in the industry. The below figure shows the block diagram of a hydraulic power plant operation.

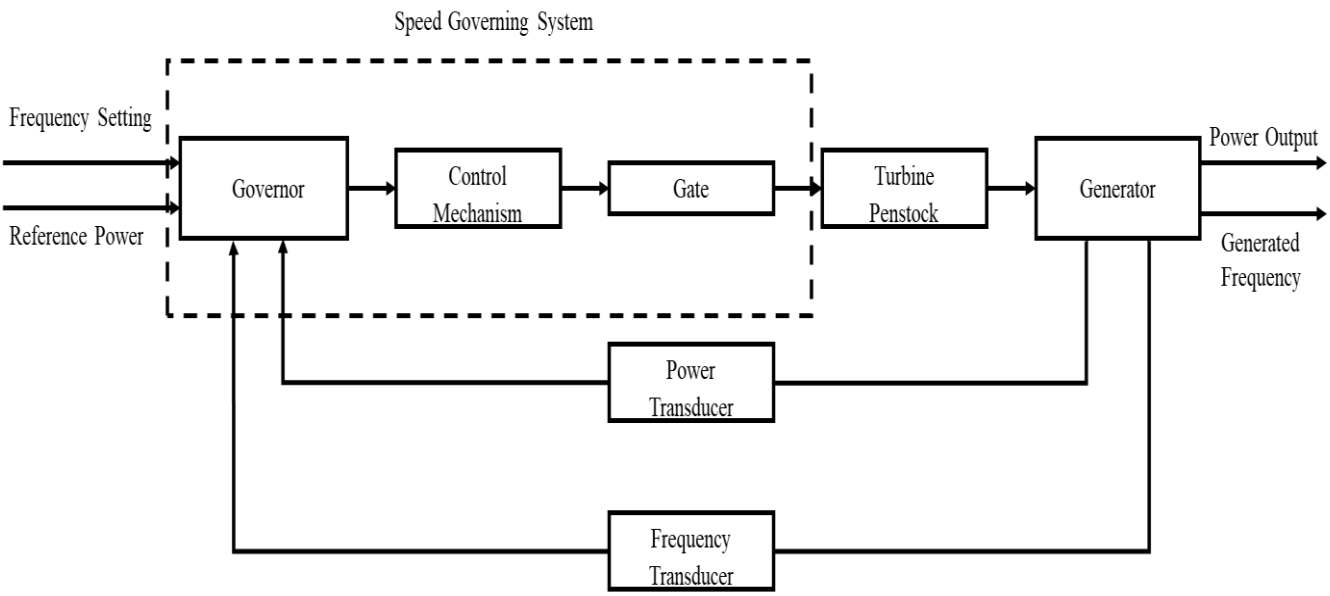


Fig. 5 Block diagram of a Hydro power plant operation

The hydropower systems have been designed to operate under different power conditions with using different methodologies. According to the paper [17], it is used an induction generator to design the variable speed hydropower system with using Inverter system which will be tracked and accelerate the torque to process the required power. This will change its both rpm and power at any load power given and also the gates will be controlled simultaneously. The paper [18] used a fixed blade, propeller type turbine with current reference controlling synchronous rotating 'dq' frame to produce variable power under variable load conditions. The generator output was fed through AC/DC and DC/AC converters to produce the synchronous power to the grid according to the load variations. It was considered constant head at all conditions while assuming the water flow rate was variable entering the turbine. For slight power variations, this system will occur power transients about 6 seconds while high power variations will be not responded and always limited to small variations of power.

Reference	**Method summery**	**Pros**	**Cons**
[19] [20]	Governor speed controlling, frequency controlling, and power controlling/gate position adjusting with the use of power reference.	Power can be varied with load demand variation	Small scale power stations only. Stability problems during higher power variations.
[17][18]	Variable speed design with induction generators and converters to convert AC/DC & DC/AC	Under small power variations the power transients are less. Within 6 seconds power variation can be obtained.	Unstable in large power variations. More power electronic controlling. Less life span of turbine.
[21][22] [23][24]	Used ARIMA, SVM, ANN and Grey model to predict the power demand requirements.	Can identify the requirement of grid upgrade for a government purpose. Help to plot the expected fuel consumptions for long term use.	Need large number of sample data. Inaccuracy of samples will lead for inaccurate results. Error percentage will be minimum 5-10%.
[25][26]	Micro-grid operations with PV, wind, diesel and ESS system	More reliable operation, increase power stability.	Diesel power will emit CO2 during operation. Complete system will cost more and not feasible. Higher complexity.

TABLE 1:- Hydropower control systems with demand response (pros and cons)

II. MEHODOLOGY

A. Hydropower System Modeling

From the methods that it is discussed in the literature review, it is used the PID controlling method for the hydro project design. When the error signal from the speed variations was observed, the PID controller will reduce the difference between the actual speed and the reference speed by changing the controller constants. The PID itself has the P (proportional), I (Integrator) and D (Derivative) controls and these will be depending on present error, past error and prediction of future error accordingly. The PID output signal will be as follows with the error signal, where, $\theta(s)$ is the output of the PID controller position signal.

$$\theta(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \tag{18}$$

Taking Laplace transform on both sides it can be expressed as,

$$\theta(s) = K_p E(s) + K_i \frac{E(s)}{s} + K_d sE(s) \tag{19}$$

Therefore, the transfer function of PID controller can be expressed as follows,

$$C(s) = \frac{Q(s)}{E(s)} = K_p + \frac{K_i}{s} + K_d S \tag{20}$$

The simulation model for the PID is shown in below figure,

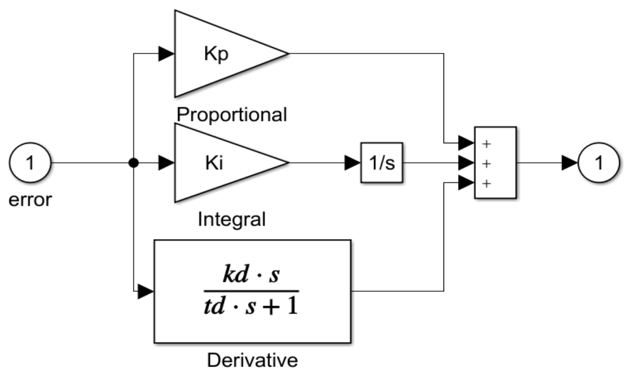


Fig. 6:- PID controller design.

The electro servo system used to control the gate valve operation accordingly with the gate position signal generated by the controller. The torque of the motor is the function of the speed and error signal; thus, it can be expressed as following equation,

$$T_m = f(\theta', e) \tag{21}$$

With the assumption of higher order terms neglect and considering zero initial conditions, the torque equation can be expressed as,

$$T_m = K_e(t) - f\theta'(t) \tag{22}$$

Where, $K = \frac{dTm}{de}$ and $f = -\frac{dTm}{d\theta'}$, thus the mechanical relations of the motor is $T_m = J\theta' + B\theta'$ which J and B are friction coefficient and moment of inertia respectively. Therefore, with the Laplace transformation it can be derived the below equation for servo operation, which controls the wicket gate opening according to the speed variation of the generator shaft and will continue the constant speed and frequency in the operation.

$$\frac{\theta(s)}{E(s)} = \frac{K}{Js^2 + (B+f)s} = \frac{K}{s(Js + B + f)} = \frac{K}{s(t_a s + 1)} \tag{23}$$

Where, $K_a = \frac{K}{B+f}$ is the gain and $t_a = \frac{J}{B+f}$ the time constant respectively. Therefore, the below figure expressed the servo operation modeling for the given application.

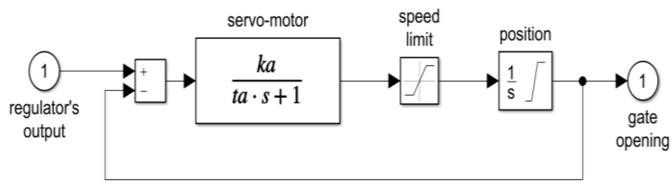


Fig. 7:- Servo gate operation controller design

Under the considerations of the power capacity and the net head at the designed hydropower station, it was selected to use a Francis turbine. In the modeling of turbine operation, it is used equations related to the selected turbine and it features. The developed output power of turbine is proportional to the product of net head and velocity flow which can be expressed as following,

$$Q = G\sqrt{H_{net}} \tag{24}$$

Where, G is the wicket gate opening in radians, H is the net head at site in meters and Q is water flow rate in m^3/s.

Thus, the power developed in the turbine, (Pm) can be written as below mentioned, where, A_t is turbine gain and Q_{nL} is the no load water flow rate.

$$P_m = A_t H(Q - Q_{nL}) \tag{25}$$

The turbine gain A_t can be derived as,

$$A_t = \frac{1}{g_{FL} - g_{NL}} \tag{26}$$

Where, g_{FL} is full load gate opening in per unit and g_{NL} is the no load gate opening in per unit. Therefore, the equation 25 can be changed as per the below mentioned equation, which U is the velocity of the water in penstock and K_U is the proportional constant.

$$U = K_U G\sqrt{H_{net}} \tag{27}$$

Therefore, if it is obtained the parameter of U and flow rate Q, the below equations can be developed,

ISSN No:-2456-2165

$$Q = AU \tag{28}$$

The penstock water will be accelerated during flow, and it can be defined as,

$$\frac{dU}{dt} = -\frac{a_g}{L}(H - H_o) \tag{29}$$

Which a_g is the gravitational acceleration with constant 9.81 ms^{-2} and L is the length of penstock line which will be derived later in the design process. With the above equations, the below relationships can be developed with the water starting time Tws,

$$H = \left(\frac{U}{G}\right)^2 \tag{30}$$

And,

$$\frac{U}{(H - H_O)} = -\frac{1}{T_{ws}} \tag{31}$$

The Tws can be derived by using the below equation,

$$T_{ws} = \frac{LQ_r}{a_g . A . H_r} \tag{32}$$

Therefore, with the help of equation 28, the below equation can be developed to model the turbine,

$$Q = \frac{A_t . (H - H_O)}{T_{ws}} \tag{33}$$

With the combination of the governor controller with PID, servo mechanism for wicket gate position control and droop controlling for speed regulation in HPP, the simulation model is created for the Hydropower station, with the transfer functions as mentioned below.

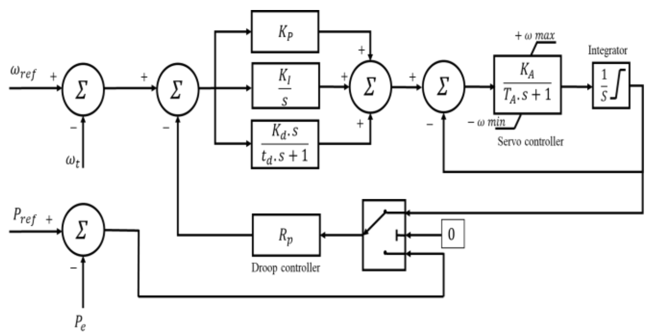


Fig. 8:- Speed regulation controlling schematic diagram.

Therefore, with the above schematic diagram, it can control the speed of the turbine at rated rpm at any power fluctuations or after a faulty condition. In a conventional HPP station, the wicket gates are used to control the water flow rate inlet to the turbine which the gate position should be maintain at 0.7~0.9 pu values to obtain the desired angle of attack at the turbine and to gain the highest efficiency. As it obtained the speed governing system and gate controlling respect to the above design methods, the mechanical power fed into the generator model should be varied, and it is introduced a turbine model as mentioned in the below schematic diagram.

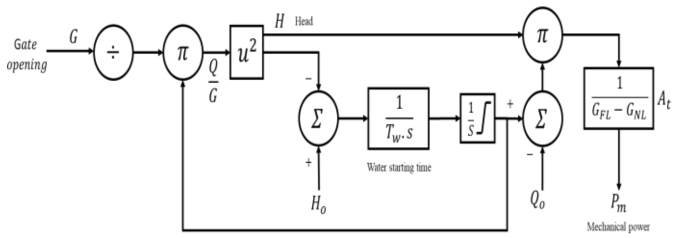


Fig. 9:- Turbine model schematic diagram

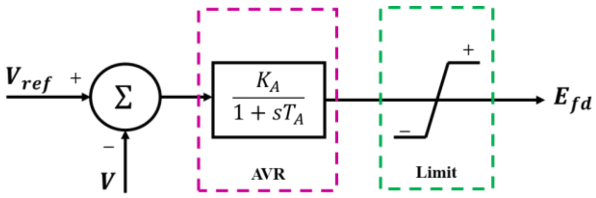
With change of load demand, the generation variation cannot be possible only by changing the water flow rate. If the water flow is only changed, it will change the mechanical torque and will change the rpm of the turbine which will cause of speed variation of generator and thus generator synchronism will be out of synchronization. Therefore, to avoid this scenario, the AVR (Automatic Voltage Regulator) system with excitation control should be implemented in these HPP stations which then control the Efd (Field voltage apply to Vf input of generator) that help the generator to produce required power with constant voltage but change of current at terminal. The simplified AVR system with static excitation can be produced with the below equation and can express in the given block representative,

$$\frac{dx_E}{dt} = \frac{1}{T_A}[-X_E + K_A(V_{ref} - V)] \;\; ; \;\; X_E \neq E_{fd};\, X_E = E_{fd} \} \; VRmin < X_E < VRmax \tag{34}$$

Where,

$V = \sqrt{V_d^2 + V_q^2}$; (park transformed terminal voltages of generator)

$V_{ref} = V + \frac{E_{fd}}{K_A}$; (reference voltage for error signal)



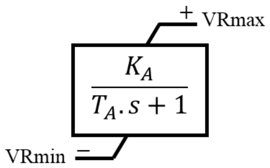
Typically, the voltage Vd and Vq will be usually send through low pass filter which its transfer function can be obtained as,

$$\frac{1}{1+sT} \tag{35}$$

Which derived by the state space of,

$$\frac{dx}{dt} = -\frac{1}{T}x + \frac{1}{T}u$$

The compared Vref and Vdq positive voltage components as an error value will be input to the main regulator block which can be express as the below mentioned transfer function block, thus it will regulate the signal in a limits as VRmax and VRmin as it will not exceed any threshold values in the system.



To generate the voltage regulation, thus to vary the power generation at generator, the excitation system was modified by the author introducing a novel design method with current reference input signal which derived by the help of power reference, power threshold and stability gain constant values as shown in below equation.

$$\sqrt{\frac{V_{stability}}{P_{theshold}} \times \left[\frac{P_{reference}}{e^6}\right]} \qquad (36)$$

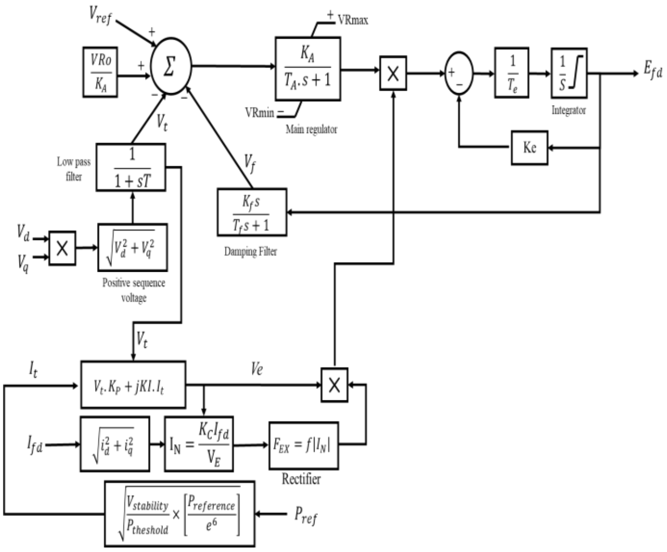


Fig. 10:- Excitation schematic diagram.

The control parameters of the excitation design are mentioned in the below table,

Item	Description	Given value
Tr	Low pass filter time constant (seconds)	20e-3
Ka	Voltage regulation gain	120
Ta	Regulation time constant (seconds)	0.0015
VRmin	Voltage regulation minimum limit (pu)	0
VRmax	Voltage regulation maximum limit (pu)	1.0
Kf	Damping filter gain	0.05
Tf	Damping filter time constant (seconds)	1.0
Ke	Exciter gain	1.0
Te	Exciter gain time constant (seconds)	0.5
KI	Current circuit gain coefficient (pu)	8.0
Kp	Potential circuit gain (pu)	4.88
Xd	Direct axis synchronous machine reactance (pu)	1.56
Kc	Rectifier loading factor (pu)	1.82
Vt(0)	Initial terminal voltage (pu)	1.0
Efd(0)	Initial field voltage (pu)	1.0
It(0)	Initial terminal current (pu)	1.0

Table 2:- Exciation Control Parameters

Thus, the hydropower station development is mentioned below with the simulation schematic diagrams explained before,

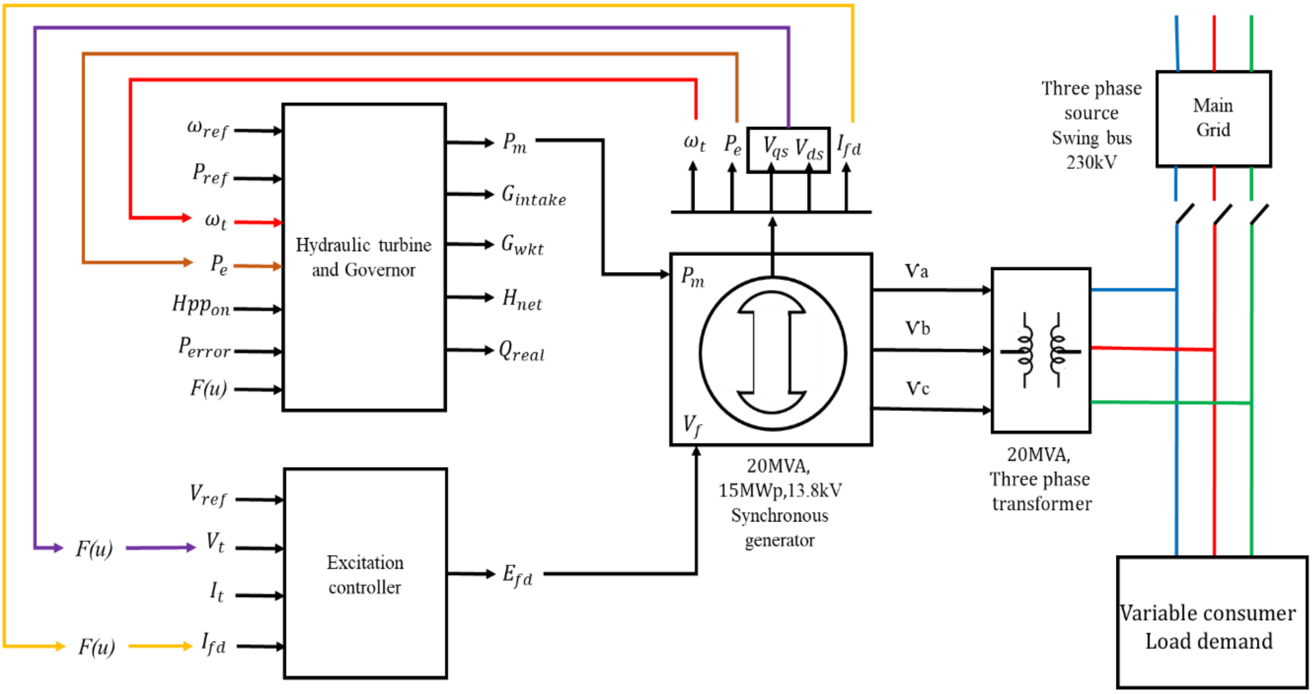


Fig. 11:- Grid connected hydropower station schematic diagram

B. Mathamatical Modelling of Hydropower System

From the literature review Fig.4, it was selected the Francis turbine for the 15MW application. Therefore, the below efficiency parameters were taken from an example real model hydro technical specification.

- Turbine efficiency η_t = 0.94 (Francis turbine)
- Transmission efficiency η_m = 0.98 (Belt driven)
- Generator efficiency(η_G) = 0.97(Synchronous Gen.)

Therefore, the overall efficiency can be given as below,

$$\eta_T = \eta_t \times \eta_m \times \eta_G \quad (37)$$
$$\eta_T = 0.94 \times 0.98 \times 0.97 = 0.89$$

With the gravitational acceleration a_g of 9.81ms^{-2}, overall efficiency η_T of 0.89, net head H of 72.3m, water density P_w of 1000 and the maximum allowable water flow rate Q of 23.75m^3/s, it can be calculated the maximum generated power at site from the below equation,

$$P = g \times Q \times H \times \eta_T \times \rho_w \quad (38)$$
$$P = 9.81\text{ms}^{-2} \times 23.75\text{m}^3\text{s}^{-1} \times 72.3\text{m} \times 0.89 \times 1000$$
$$P = 14.99 \text{ MW} \sim 15 \text{ MW}$$

When designing the weir, it was considered that water from the reservoir will be extracted with the weir as run-of-river method. Thus, the weir height D1 can be calculated by using equation 1 and 6 with the standard flow velocity V of 1m/s, and taken the side intake width b as 5.4m.

$$Q_d = A \times V \quad (39)$$
$$A = \frac{23.75\text{m}^3\text{s}^{-1}}{1\text{ms}^{-1}}$$
$$A = 23.75\text{m}^2$$

Where A is the area of the weir. Thus,

$$A = b \times h_i = 23.75\text{m}^2$$
$$h_i = \frac{23.75\text{m}^2}{5.4\text{m}}$$
$$h_i = 4.398 \text{ m} \sim 4.4\text{m}$$

Therefore, by considering the height of the bed of the scour gate to the bed of the inlet (Usually 0.5-1.0m) as 0.8m,

$$D_1 = d_i + h_i \quad (40)$$
$$D_1 = 0.8 \text{ m} + 4.4 \text{ m}$$
$$D_1 = 5.2 \text{ m}$$

The water taken from the intake will be dispatch through the settling basin architecture and the equation 2 and 3 will be used to determine the required parameters. It is taken V as 0.6m/s inflow velocity that approximately lies between 0.5-1.0m/s.

$$V = \frac{Q_d}{b \times h_s}$$
$$b \times h_s = \frac{23.75 \text{ m}^3\text{s}^{-1}}{0.6 \text{ ms}^{-1}}$$
$$b \times h_s = 39.58 \sim 40 \text{ m}^2$$

It is selected b as 8m and h_s as 5m for the specific application, Therefore,

$$L \geq \left(\frac{V}{v}\right) * h_s$$
$$L \geq \left(\frac{0.6}{0.1}\right) * 5$$
$$Ls \geq 30 \text{ m} * 2$$
$$Ls \geq 60 \text{ m}$$

ISSN No:-2456-2165

The settling basin will be 60 m in length (Ls), 8m in width and 5m in depth to perform optimum in the 15MW hydro power station.

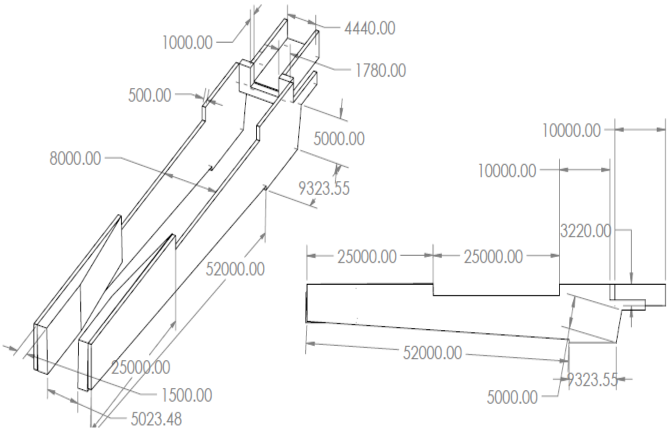


Fig. 12:- Settling basin design

The water that released from the selling basin will be carried out by the Head race open channel and the equation 7 will be used to calculate the dimensions of the required channel. As per the cost of design parameters, the cross section is more economical when,

$$h = \frac{b}{2} \quad \text{and} \quad R = \frac{h}{2} \tag{41}$$

Therefore, using b = 2h,

$$A = b \times h$$
$$A = 2h \times h = 2h^2$$

From substituting the A and R parameters with the equation 7, it can express as follows,

$$Q = A * R^{\frac{2}{3}} * S_L^{0.5}/n$$
$$23.75 = 2h^2 \times \left[\frac{h}{2}\right]^{\frac{2}{3}} \times \frac{\left[\frac{1}{1500}\right]^{0.5}}{0.015}$$
$$h = \sqrt[6/2]{10.9}$$
$$h = 2.22 \text{ m}$$

Thus,

$$b = 2 \times h = 2 \times 2.22 = 4.44 \text{ m}$$

Therefore, the depth (h) and width (b) of the head race open channel will be 2.22m and 4.44m accordingly.

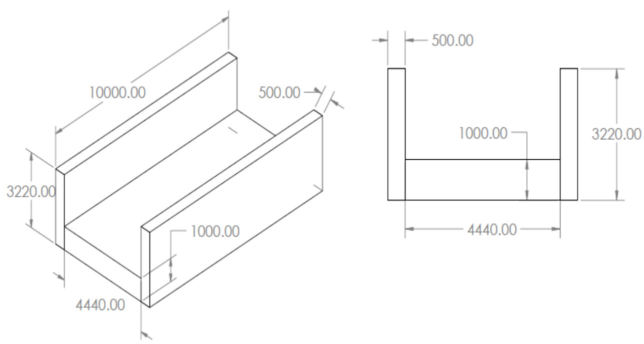


Fig. 13:- Headrace open channel design

The water flow which taken from head race channel will be delivered to the Fore-bay. The design of fore-bay can be obtained by using the equation 8.

$$V_{sc} = 17 \times Q_d$$
$$V_{sc} = 17 \times 23.75 = 404 \frac{m^3}{s}$$

Thus,

$$V_{sc} = B \times L \times d_{sc} = 404 \tag{42}$$
$$B = 2 \times 4.44 = 8.88 \text{ m}$$
$$L \times d_s = \frac{404}{8.88} = 45.49 \text{ m}^2$$
$$d_{sc} = \frac{h_o}{2}$$

h_o is the height of the head race channel - 2.22 m, and therefore,

$$d_{sc} = \frac{2.22}{2} = 1.11 \text{ m}$$

With the substitutions,

$$L = \frac{45.49\text{m}^2}{1.11\text{m}} = 40.98 \text{ m}$$

Therefore, the width of the fore-bay (B) will be 8.88m, head tank capacity (Vsc) will be 404 $\frac{m^3}{s}$, and the length (L) will be 40.98m. It was considered 0.30m of thickness of concrete structure and all the dimension included drawing is mentioned below,

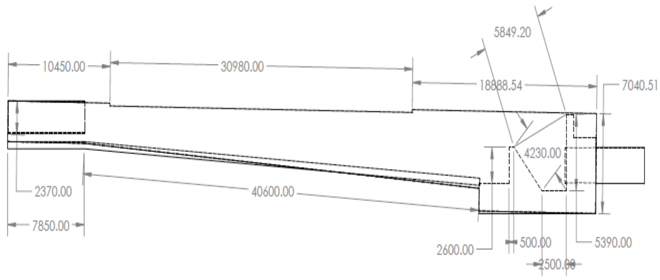


Fig. 14:- Fore-bay design side view.

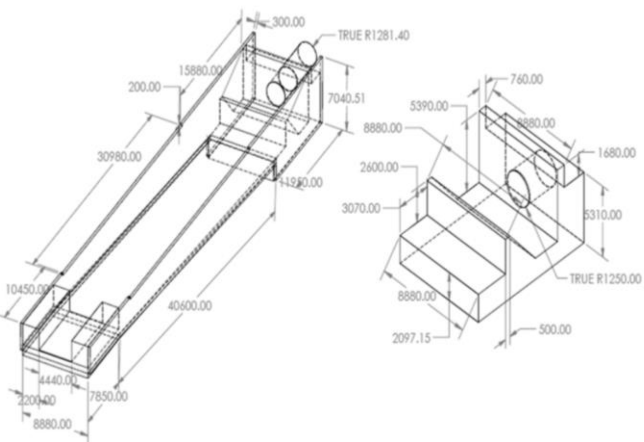


Fig. 15:- Fore-bay design

The water that collected in fore-bay will be delivered to the powerhouse with the help of the penstock. To design the Penstock for the given application, the equation 25, 26, 27, 28, 29 and 30 were used. It was taken the penstock flow velocity as 4.8m/s, discharge flow rate of 23.75 m^3/s and net head of 72.3m Therefore,

$$A = \frac{Q}{V} = \frac{23.75}{4.8} = 4.94\ m^2$$

Thus,

$$D = 2 \times \sqrt{\frac{A}{\pi}} = 2\ \times \sqrt{\frac{4.94}{\pi}} = 2.5\ m$$

To withstand the pressure developed due to water flow in penstock, the pipe should be designed with a thickness (t_p) which can be calculated as per the following sequence,

$$P_h = P_w \times C_p \times V$$
$$P_h = 1000 \times 1120 \times 4.8$$
$$P_h = 5.38\ Mpa$$

P_h - Pressure due to water hammer effect will be 5.38MPa, and also it is necessary to find the P_s - static water pressure,

$$P_s = P_w \times g \times H$$
$$P_s = 1000 \times 9.81 \times 72.3\ \ ;\ \ P_s = 0.71MPa$$

By considering the safety factor n=4 in the current design and considering the stress rate of the penstock material which is $\sigma_{yp} = 970MPa$, it can be found that,

$$P = P_h + P_s$$
$$P = 5.38 + 0.71$$
$$P = 6.09\ MPa$$
$$\sigma_{allowable} = \frac{\sigma_{yp}}{n} = \frac{970MPa}{4} = 242.5MPa$$

Thus,

$$t_p = P * r/\sigma_{allowable}$$
$$t_p = 6.09MPa\ \times \frac{\left[\frac{2.5}{2}\right]}{[242.5\ MPa]}$$
$$t_p = 0.03139m \sim 31.4mm$$

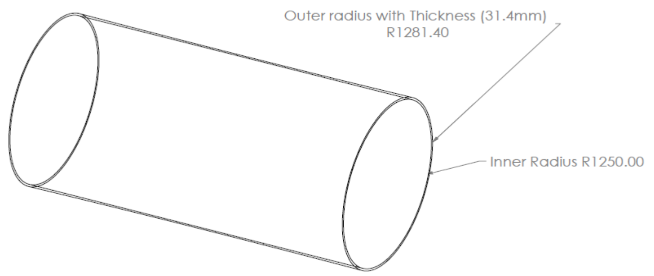


Fig. 16:- Penstock pipe dimensions

During the flow towards the powerhouse, there are several losses that will incurred in the penstock. These losses will be calculated by using the equations 31 and 32.

Head loss due to entry and exit,

$$h_v = K * \frac{V^2}{2 * g}$$

With the k value of 0.2 and substituting the previously proven values to the above equation,

$$h_v = 0.2 * \frac{(4.8)^2}{2 * 9.81}$$
$$h_v = 0.234m$$

Since there are two valves installed at entry and exit which assumed to be identical,

$$h_g = 0.234 * 2 = 0.468m$$

Head loss due to bends will be calculated with an assumption of 45-degree deflection at C=0.09.

$$h_b = C \times \frac{V^2}{2 * g}$$
$$h_b = 0.09\ \times \frac{(4.8)^2}{2 * 9.81} = 0.105m$$

The most common and most influencing loss is considered as friction loss in a typical HPP. Therefore, with the f friction factor of 0.00920, and considering the length of penstock of 400m.

$$h_f = f * \left(\frac{L_p}{D_p}\right) * (\frac{V^2}{2g})$$
$$h_f = 0.00920 * \left(\frac{400}{2.5}\right) * (\frac{4.8^2}{2 * 9.81})$$
$$h_f = 1.73m$$

Thus, the total head loss h_T will be,

$$h_T = 0.234 + 0.486 + 0.105 + 1.73$$
$$h_T = 2.537m$$

Therefore, the gross head will be,

$$H_g = 2.537 + 72.3 = 74.83m$$

To evaluate the safe design criteria, it is used the below equation, which should be below the limits.

$$h_L \leq 0.05 \times H_{gross}$$
$$2.537m \leq 0.05 \times 74.83$$
$$2.537m \leq 3.74m$$

Since the h_L less than the limitation value, the penstock design will be under safety conditions.

With respect to the net head vs flow chart graphical representation of different turbines, it was selected the Francis turbine for the designed system with efficiency of 94%. Under designing the turbine, it is important to obtain the specific speed and the rotational speed from the following equations,

$$N_s = \frac{1.924}{H_n^{0.512}} \tag{43}$$

$$N_s = \frac{1.924}{72.3^{0.512}} = 0.2149$$

Where, N_s is the specific speed, and which the value of 0.2149 is acceptable since the Francis turbine specific speed should be in region of $0.05 \leq N_s \geq 0.33$. The rotational speed, N can be found by the below equation,

$$N = N_s \times \frac{E^{\frac{3}{4}}}{\sqrt{Q}} \tag{44}$$

Where, E is the hydraulic energy, that can be found by the below equation,

$$E = g \times H_n = 9.81 \times 72{,}3 = 709.263 \tag{45}$$

Therefore,

$$N = 0.2149 \times \frac{(709.26)^{0.75}}{\sqrt{23.75}}$$
$$N = 6.06 \frac{t}{s} \text{ (turns per second)}$$
$$N = 363.6 \text{ RPM}$$

Thus, the turbine required a speed of 360 rpm under operation and at any given condition. Therefore, in the simulation process, the turbine should be able to gain the required rpm after any grid faulty condition or any power variation to keep the frequency constant with the grid synchronization. To operate in the given conditions, the turbine should consist the below dimensions,

Outlet diameter (D3),

$$D3 = 84.5 \times [0.31 + (2.488 \times N_s)] \times \frac{\sqrt{H_n}}{(60 \times N)} \tag{46}$$

$$D3 = 1.669 \text{ m}$$

Inlet diameter (D1),

$$D1 = \left[0.4 + \frac{0.095}{N_s}\right] \times D3 \tag{47}$$
$$D1 = 1.405\, m$$

Inlet diameter (D2),

$$D2 = \frac{1.669}{[0.96 + 0.3781 \times N_s]} \tag{48}$$
$$D2 = 1.602\, m$$

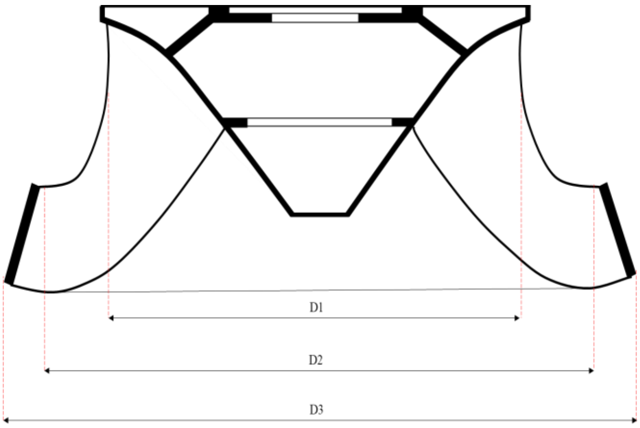


Fig. 17:- Francis turbine dimensions.

Therefore, the parameters for the simulations of hydropower system can be listed as in the following table,

Number	Term	Description	Value	Units
1	Q_{max}	Water flow rate	23.75	m^3/s
2	H_{net}	Net head	72.3	m
3	Hg	Gross head	74.83	m
4	h_T	Total head loss	2.537	m
5	Pw	Maximum power	15.0	MW
6	η_T	Turbine efficiency	89	%
7	ρ_w	Water density	1000	kg/m^3
8	ka	Servo gain	10/3	-
9	Ta	Servo time constant	0.07	sec
10	T_{ws}	Water starting time	2.67	sec
11	g_{FL}	Full load gate opening	0.975	Per unit
12	g_{NL}	No load gate opening	0.01	Per unit
13	Rp	Permanent Droop	0.05	
14	Kp	proportional	1.163	-
15	Ki	Integrator	0.105	-
16	Kd	Derivative	<0.105	-
17	V	Standard flow velocity	1	m/s
18	V	Penstock flow velocity	4.8	m/s
19	ν	Inflow velocity	0.6	m/s

Table 3:- Hydropower Simulation Parameters.

III. SIMULATION AND ANALYSIS

The power generation from HPP will be varied with load requirement. Therefore, the required power generation in the given scenario will be plotted using red line and the actual power generated by the HPP will be plotted using blue line as mentioned in the below Fig.18. It is desined to generate 0.6~0.8MW more than the expected under the different load periods that to overcome sudden variations in loads. When the load is reaching maximum, the generation and the expected will be almost equal since the generation will be close to the saturation point. To analyse the HPP system under faulty conditions and breaker operations, it was considered three-phase-breaker operation during the 15th second and three-phase fault condintion during the 30th second and observed the HPP responses.

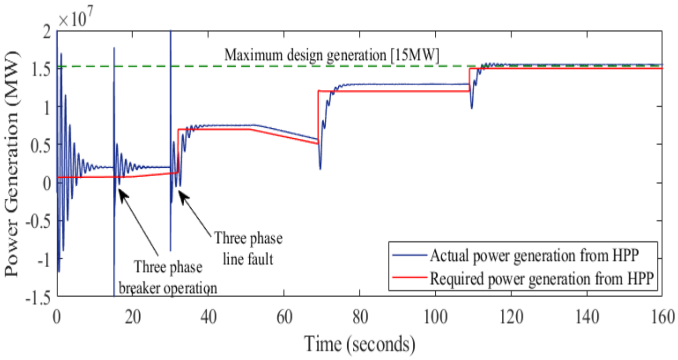


Fig. 18:- HPP actual generation Vs required generation comparison

To obtain the given performance of the generation, the mechanical power should be varied with the load variation and therefore, the Per Unit value of mechanical power variation can be plotted as per the below figure which compared with the HPP power generation, since the power generated will be directly influenced by the mechanical power produced by the turbine, thus the power generation should be following the mechanical power variations.

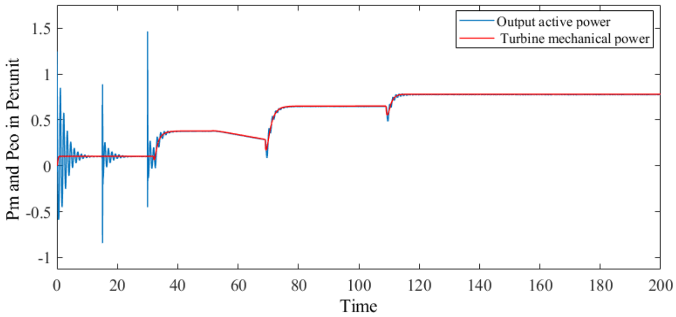


Fig. 19:- Power generation tracking mechanical power variation.

To observe the variation of generated power, the flow rate should be varied as for the variation of required power demand. Thus, the below Fig. 20 express the required flow rate and the actual flow rate in per unit values.

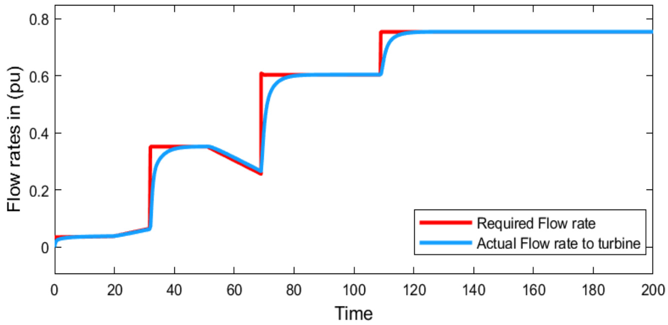


Fig. 20:- Actual flow rate vs required flow rate

With the varied flow rate, the excitation will be varied in the generator to vary the generation output. With regard to the derivation of excitation model in the methodology chapter, the filed current Ifd will be changed according to the required power generation which will be simultaneously function with the flow rate variation and gate position controlling. Therefore, the below figure represents the excitation current variation, power generation, and intake gate controlling for flow rate variations in per unit values.

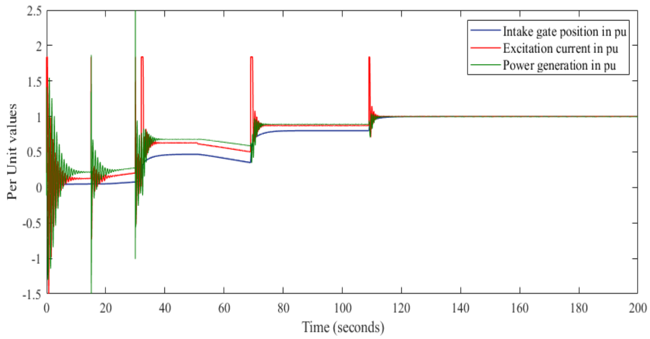


Fig. 21:- Power generation, Excitation current and Intake Gate positions n in Per Unit values

As per the observation, when the excitation increases, the Ifd will be increased creating higher flux of magnetization at the generator in which the generator rpm will be lead to drop down due to higher electrical torque induced by electromagnetic effect. If the rpm at the generator keep falling below the synchronous speed of the generator, the frequency will be imbalance with refer to the grid frequency, and thus the turbine will be de-synchronized, and the breakers will off the circuit. Therefore, to prevent this scenario, the turbine should keep its rpm at the rated speed, and thus the designed intake gates of the HPP station will operate and increased flow rate of water that will create more mechanical torque at the turbine and will produce the required rpm to the generator shaft.

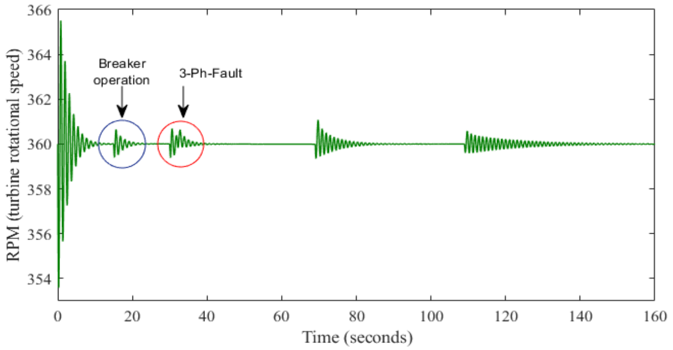


Fig. 22:- RPM response during the HPP operation

Even though the power increase, the voltage at terminal should remain same with the help of AVR, which the Efd field voltage will be controlled.

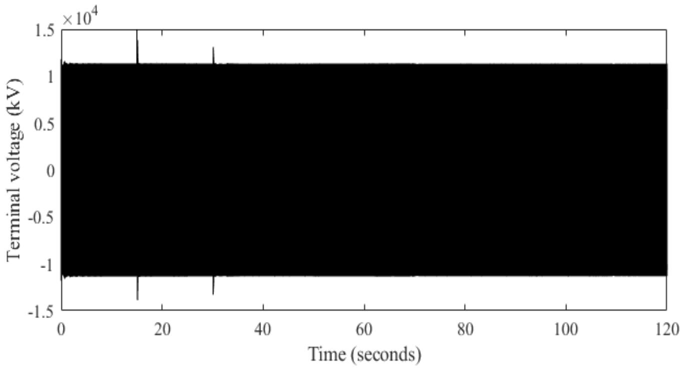


Fig. 23:- Regulated 11kV voltage at terminal with respect to the power generation.

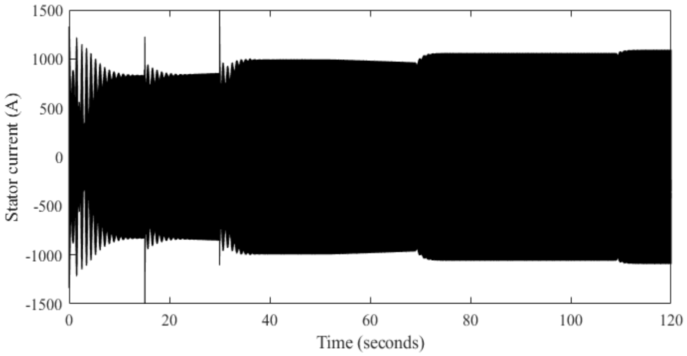


Fig. 24:- Varied current at stator with respect to generation

The hydropower structures designed in the methodology chapter should be withstand the maximum flow rates in the fore-bay and settling basin, and it has simulated the structure strengths and used Computer Fluid Dynamics (CFD) to observe the pressure, velocity and turbulence of kinetic energy in the ANSYS software interface as mentioned below.

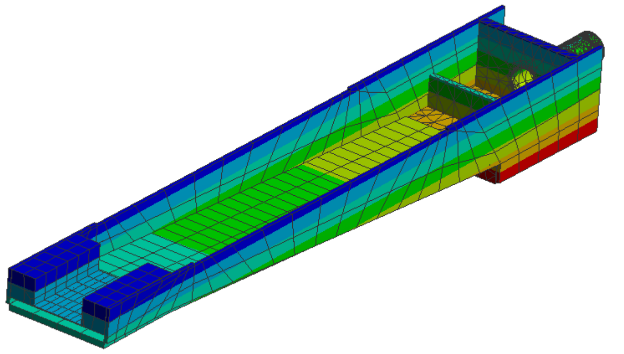


Fig. 25:- Hydropower structure deformation analysis in ANSYS.

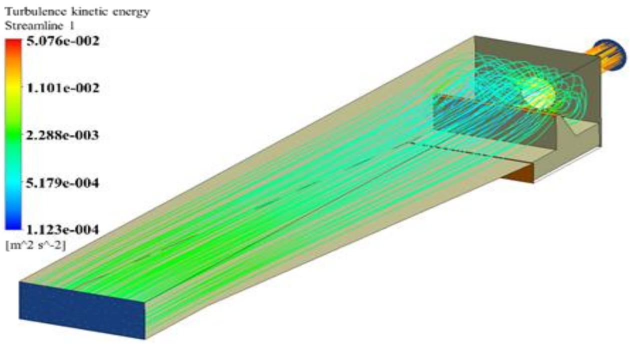


Fig. 26:- Turbulence of kinetic energy in fore-bay (CFD simulation).

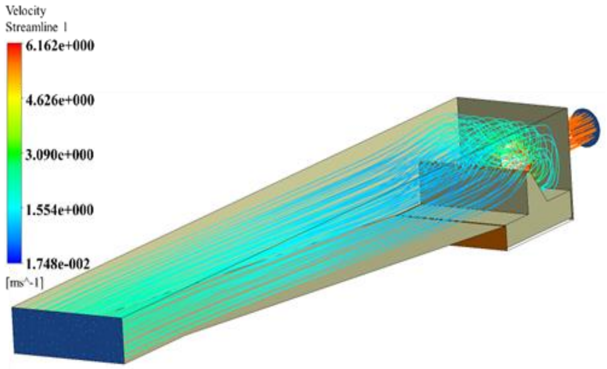


Fig. 27:- Water flow velocity distribution in fore-bay (CFD simulation).

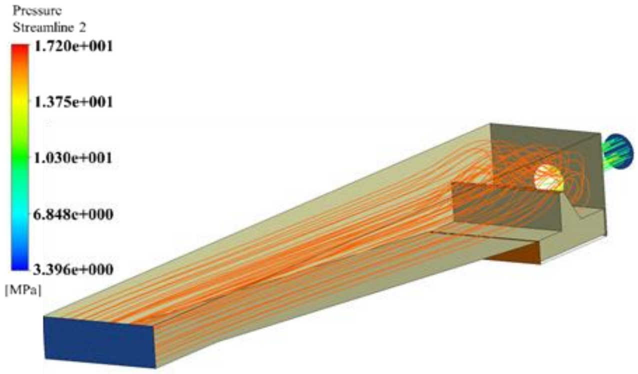


Fig. 28:- Pressure induced in fore-bay (CFD simulation).

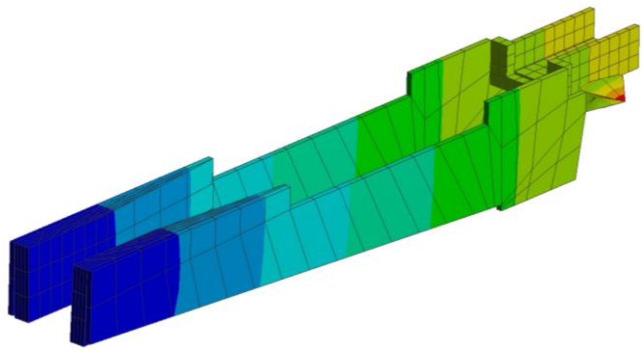


Fig. 29:- Settling Basin structure deformation analysis in ANSYS.

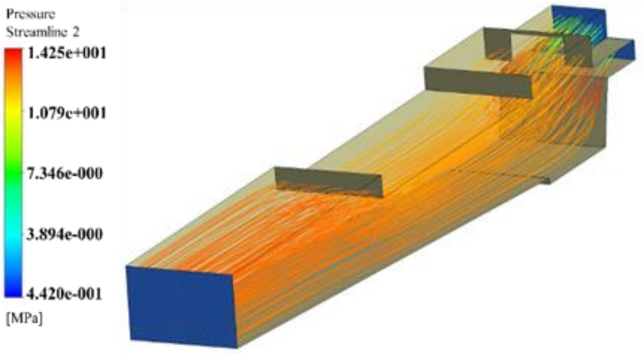


Fig. 30:- Pressure induced in settling basin (CFD simulation).

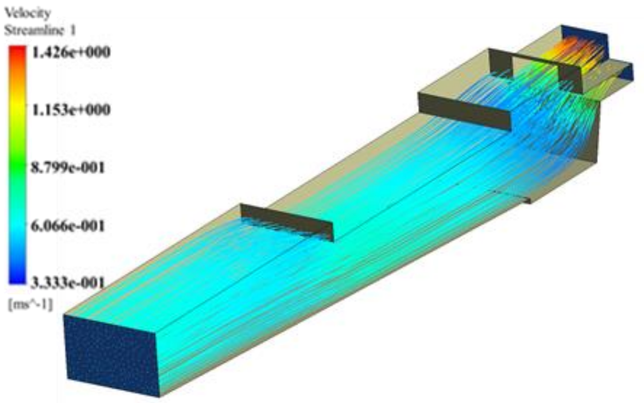


Fig. 31:- Water flow velocity distribution in settling basin (CFD simulation).

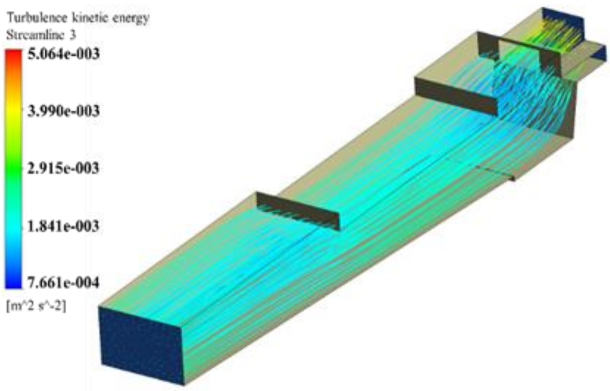


Fig. 32:- Turbulence of kinetic energy in settling basin (CFD simulation).

In the above results, the fore-bay and settling basin structures will not get deformed at the maximum flow rate, and the flow velocities entering the penstock line will achieve 4.4m/s speed which will be increasing from 0.6m/s at fore-bay area inlet. The pressure built before penstock (inlet 17.2MPa) is higher than the pressure inside penstock (outlet 6.8MPa) since the pressure will be reduced when the velocity increases. The turbulence of kinetic energy in fore-bay is much lower than the inside of the penstock, which is true that the turbulence will increase under higher velocity with sudden reduced pressure regions, and also respectively to the change of viscosity of water. Compared to the fore-bay flow velocities, the settling basin flow is much lower (outlet 1.4m/s) and as well with the pressure (outlet 3.89MPa). Therefore, the turbulence kinetic energy is much lower than fore-bay since the less pressure and less flow velocities. Therefore, considering all the above CFD simulations, it can be identified that the mathematical modeling produced, and structure designed are well align with the simulation results, and therefore these structures can be implemented in a real project.

IV. CONCLUSION

The paper discuss the design of 15MW hydro power station in all electromechanical, structural and mathematical modelling. It describes the governor controlling schematic, flow rate variation method, and load variation response generation synchronization process. The flow rate was controlled by the Wicket gate and the turbine was designed to operate in constant RPM at any given point after any disturbances. The voltage at terminals were regulated at 11kV and the current was varied with the different power levels. With respect to the structures, the Fore-bay and Settling Basin were mainly simulated using Computer Fluid Dynamics (CFD) and observed that the designed structures in SolidWorks with the help of Mathematical modelling was well align, and this can be physically implement.

ACKNOWLEDGEMENT

I wish to record my deep sense of gratitude and profound thanks to my parents for their motivation and support given throughout this research, and thank all the researches who involved in renewable energy studies to make this world more greener and better place.

CERTIFICATION STATEMENT

I hereby declare that this thesis is my own original work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, except due acknowledgement has been made in the text.

REFERENCES

[1]. M. H. Power, "Asian and Pacific Centre for Transfer of Technology," no. September, 2009.

[2]. World Energy Council, "World energy resources>Hydropower," 2016. [Online]. Available: https://www.worldenergy.org/data/resources/resource/hydropower/.

[3]. J. Odhach, "Designing a Small Hydro Power Plant Capable Of Producing 10 MW of Electricity at Webuye along River Nzoia," 2015.

[4]. C. Jica Agency, "Guideline and Manual for Hydropower Development Vol . 2 Small Scale Hydropower," vol. 2, no. March, 2011.

[5]. Mechanical Tutorial, "Types Of Hydroelectric Power Plant or Hydroelectric Power Station Price Drop Alert : Dubai Holiday," 2019. [Online]. Available: http://www.mechanicaltutorial.com/classification-of-hydro-electric-power-plant-or-hydro-electric-power-station.

[6]. J.M.K.C. Donev, "Hydraulic head," *Energy Education*, 2018. [Online]. Available: https://energyeducation.ca/encyclopedia/Hydraulic_head. [Accessed: 26-Jun-2019].

[7]. International Finance Corporation (IFS), "Hydroelectric Power: A guide for developers and investors."

[8]. J. M. K. C. Donev, "Weir," *Energy Education* -, 2017. [Online]. Available: https://energyeducation.ca/encyclopedia/Weir. [Accessed: 27-Jun-2019].

[9]. G. Singh and A. Kumar, "A Review of Desilting Basins Used in Small Hydropower Plants," vol. 3, no. 5, pp. 440–444, 2013.

[10]. B. A. Nasir, "Design Considerations Of Micro hydro-electric Powe Plant," *Energy Procedia*, vol. 50, pp. 19–29, 2014.

[11]. P. Dang, L. Goodfellow, and J. Hanania, "Fish passage," *Energy Education*, 2015. [Online]. Available: https://energyeducation.ca/encyclopedia/Fish_passage. [Accessed: 27-Jun-2019].

[12]. J. M. K. C. Donev, "Spillway," *Energy Education*, 2015. [Online]. Available: https://energyeducation.ca/encyclopedia/Spillway. [Accessed: 27-Jun-2019].

[13]. Energy technology expert, "How to Design a Mini-Hydro Power Types of Hydro Power Plants," 2015.

[14]. A. Kumar and M. K. Singhal, "Optimum Design of Penstock for Hydro Projects Optimum Design of Penstock for Hydro Projects 2 . Relations Available vailable for Optimized Design esign of Penstock," no. August, 2015.

[15]. V. Yildiz and J. A. Vrugt, "Environmental Modelling & Software A toolbox for the optimal design of run-of-river hydropower plants," *Environ. Model. Softw.*, vol. 111, no. August 2017, pp. 134–152, 2019.

[16]. S. Tsegaye, "Hydro governor control of synchronous machines: MATLAB/SIMULINK based analysis," no. December, 2018.

[17]. M. Mauri, F. C. Dezza, and G. Marchegiani, "A novel small-scale variable speed hydropower emulator using an inverter-controlled induction motor," *2007 Eur. Conf. Power Electron. Appl. EPE*, no. 1, 2007.

[18]. L. Belhadji, S. Bacha, and D. Roye, "Direct Power Control of variable-speed micro-hydropower plant based on propeller turbine," *Proc. - 2012 20th Int. Conf. Electr. Mach. ICEM 2012*, pp. 2079–2084, 2012.

[19]. W. Yang *et al.*, "A mathematical model and its application for hydro power units under different operating conditions," *Energies*, vol. 8, no. 9, pp. 10260–10275, 2015.

[20]. T. E. Del Carpio Huayllas, D. S. Ramos, and R. L. Vasquez-Arnez, "Microgrid systems: Current status and challenges," *2010 IEEE/PES Transm. Distrib. Conf. Expo. Lat. Am. T D-LA 2010*, no. December 2010, pp. 7–12, 2011.

[21]. I. El Kafazi, R. Bannari, and A. Abouabdellah, "Modeling and forecasting energy demand," *Proc. 2016 Int. Renew. Sustain. Energy Conf. IRSEC 2016*, pp. 746–750, 2016.

[22]. S. Wang, Q. Yong, and Y. Liu, "The model of energy demand forecast based on support vector machine," *Proc. 2013 6th Int. Conf. Inf. Manag. Innov. Manag. Ind. Eng. ICIII 2013*, vol. 3, no. 7, pp. 267–269, 2013.

[23]. N. Ayoub, F. Musharavati, S. Pokharel, and H. A. Gabbar, "ANN Model for Energy Demand and Supply Forecasting in a Hybrid Energy Supply System," *2018 6th IEEE Int. Conf. Smart Energy Grid Eng. SEGE 2018*, pp. 25–30, 2018.

[24]. H. W. Ma, K. P. Ma, and D. Q. Zhang, "Grey prediction on China's energy consumption and production," *Proc. 2007 IEEE Int. Conf. Grey Syst. Intell. Serv. GSIS 2007*, pp. 663–667, 2007.

[25]. M. A. Fouad, M. A. Badr, and M. M. Ibrahim, "Modeling of Micro-grid System Components using Matlab/Simulink," *Glob. Sci. Journals*, vol. 5, no. 5, pp. 163–177, 2017.

[26]. M. W. Gul, M. Ullah, M. A. K. Khalil, and A. Nawaz, "Design and Operation of Microgrid," *Sarhad Univ. Int. …*, no. 2, pp. 4299–4304, 2017.