Review of Hydropower Plant Models

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ABSTRACT
This paper consists of an extensive review on the modeling of hydropower plant. First a background was provided on all components needed to develop a full and comprehensive model on hydropower plant including penstock, governor, turbine and generator. The review of existing models was started with simple analytical models that were followed by system modelling. The complexity of modeling the dynamic aspect of water flowing through the penstock as well as the opening and closing of wicket gate have led to the development of complex control systems to model hydropower plant. Those complex models were rather represented as systems instead of been analytical. They are mostly equipped with numerous feedback as well as modern control systems such as fuzzy logic and PID control logic that improves their performances. However, these models are most often constructed and simulated with software of which Matlab is a fundamental one. In line with this, the paper investigated a simulation of hydropower plant including a model of hydraulic turbine, governor and synchronous machine, all simulated under Matlab software. A three phase to ground fault was introduced in the model at t=0.2s and remove after t=0.4s and this shows that the generated voltage quickly regained its stability due to the high excitation voltage that was maintained by the PID control system incorporated in the hydraulic turbine model. The speed of the motor also regained stability but this case was slower than the voltage one. In all, simulation results showed a perfect generation of energy from hydropower plant that was robust enough to resist faults.

General Terms
Hydropower plant, Control, Modeling and Simulation

Keywords
Hydraulic turbine, penstock, governor, synchronous generator, system simulation.

1. INTRODUCTION
According to Karady & al. (2005), [1], hydropower plants convert the potential energy of water head to mechanical energy by using a hydraulic turbine. The hydro-turbines are in turn connected to a generator that converts the mechanical energy to electric energy. Naghizadeh & al. (2012), [2] later describe the main components of a hydropower plant as illustrated in figure 1.

The hydropower plant is basically made of a generator, a turbine, a penstock and wicket gates. Generally, two types of turbines are used: impulse turbine for instance Pelton Wheel turbine and reaction turbine like Francis and Kaplan turbine. The generator and turbine are mostly connected directly by a vertical shaft. The existence of high head produces fast-flowing water that flows through the penstock and arrives to the turbine. The flow of water into the turbine is controlled by the wicket gates. Wicket gates can be adjusted together with the opening of pivot around the periphery of the turbine to control the quantity of water that flows into the turbine. Servo-actuators, controlled by the governor, help to adjust these gates.

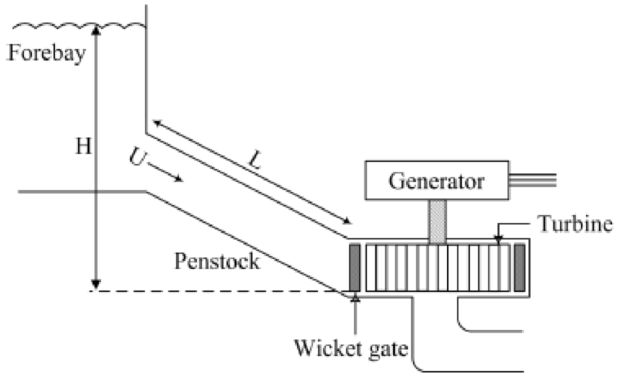

Fig 1: Components of a Hydropower plant

The water drives the turbine-generator set and the rotating generator produces electricity. At the initial stage, the stored water with clear hydraulic head, possesses potential energy. As it flows through the penstock it gradually loses potential energy and gain kinetic energy before reaching the turbine. A critical look at the process of energy generation by hydropower plant shows that hydropower plant models are highly influenced by the penstock-turbine system, the electric generator and numerous control systems.

2. LITERATURE REVIEW
Several models of hydropower generation were investigated by scientists. The existing models depend upon the requirement involved in the study. Some of these models were simply analytical while others were constructed from robust system models showing the dynamic characteristics. IEEE working group/committee [3, 4] have shown various models of hydro plant and techniques used to control the generation of power. [5] describes an approximation of hydro-turbine transfer function to a second order for multi-machine stability studies.

Similarly, Qijuan et al. [6] introduced a novel model of hydro turbine generating set which uses recursive least square estimation algorithm. This model is dynamic.

In reality, the performance of hydro-turbine is mainly determined by the parameters of the water been supplied to the turbine. According to Singh & al. (2011), [7], some of these parameters include the effects of water inertia, water compressibility, pipe wall elasticity in penstock.

The effect of water inertia is to ensure that changes in turbine flow do normally lag behind changes in turbine gate opening for a smooth operation. On the other hand, the effect of elasticity introduces some element of pressure and flow in the pipe, a phenomenon known as "water hammer", [7]. Other parameters of the flowing water also affect the flow of water and indirectly affect the turbine speed which is directly connected to the generator. In order to have constant power generation it is therefore necessary to implement strong control measures to overcome the variability of the initial flowing water.

Moreover, there are existing models of linear and nonlinear hydro-turbine set with non-elastic and elastic water column effects. Non-elastic water column have been largely handled by previous works including Malik et al. [8], Ramey et al. [9], Bhaskar [10] and Luqing et al. [11].

However, the most general model of hydropower plants start with the determination of hydraulic power. Hydraulic power is exhibited whenever a volume of water falls from a higher level to a lower level. The general formula for the determination of hydraulic power is shown by [12]-[14] as follow:

$$P_h = \rho g Q H \tag{1}$$

Where: P_h is the mechanical power produced at the turbine shaft (Watts), ρ is the density of water (1000 kg/m3), g is the acceleration due to gravity (9.81 m/s2), Q is the water flow rate passing through the turbine (m3/s), H is the effective pressure head of water across the turbine (m).

The hydraulic power is later transformed into mechanical power by the turbine. Many attempt have been made in the past to come out with an analytical model of hydraulic turbine. This has always been a difficult task due to the nature of hydropower generation systems that exhibit a high level of dynamism and nonlinear behavior [2].

Based on [2], the mechanical power available at the output of the turbine is determined as follow:

$$P_m = \eta_t \cdot P_h \tag{2}$$

Where η_t is the efficiency of the turbine.

The determination of the hydraulic turbine efficiency is very challenging and for this matter robust mathematical models are used to numerically compute it. Some of these models were reviewed by Martez & al. (2010), [15] and Singh & al. (2010), [7]. According to one of the method developed in [7], the efficiency is determined as follow:

$$\eta_t(\lambda, Q) = \left[\frac{1}{2}\left(\frac{90}{\lambda_i} + Q + 0.78\right) \cdot \exp\left(\frac{-50}{\lambda_i}\right)\right](3.33Q) \tag{3}$$

Where

$$\lambda_i = \left[\frac{1}{(\lambda + 0.089)} - 0.0035\right]^{-1} \text{ and } \lambda = \frac{RA\omega}{Q} \tag{4}$$

Q is the flow rate of water, ω is the angular speed of turbine rotor, R is the radius of the hydraulic turbine blades (m) and A is the area swept by the rotor blades (m^2).

This is pure analytical model that can be programmed and simulated with Matlab to show the power exhibited by a hydropower plant with variation of parameters related to water flow models.

In general, linear models are used for small signal performance of turbine whereas non-linear models are more appropriate for large domain signal-time simulations.

On the other hand several models were not made analytical but consisted of simulated systems under various software. For instance, the model presented by Nassar (2009), [16] was built in Simulink and consisted of the following dynamic sub-models: controller, hydraulic and mechanical system, turbine regulator. Figure 2 presents the block system of the entire model with its sub-systems.

The type of turbine is Francis with a rated power of 300 (MW), a rated flow of 218.5m3/s and a rated head of 151.2m. Power generation and speed control model have been further modeled analytically and simulated. Such system is more adapted to increasing power generation than the analytical model because it is built on feedback that are solution to high level differential equations that best describe the dynamic nature of the flowing water. The controller includes artificial intelligence such as PID control.

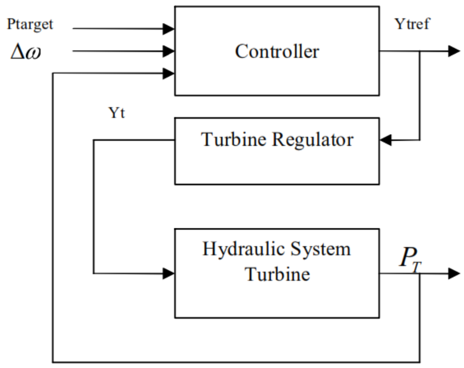

Fig 2: general representation of sub-models by Nassar (2009)

Where

- P_{target}: Power set-point
- Δ_W: Deviation of Energy
- Y_{tref}: Set-point position governor guide vane
- Y_t: Position governor guide vane
- P_T: Power of the turbine

A similar study was carried out by Gagan Singh (2011), [17] who investigated a simulation and modeling of hydropower plant to time response during different gate states. In fact, gate state of hydraulic turbine does affect the asynchronous condition of Hydropower plant which depends upon the speed variation in turbine-generator set. [17] represents a hydropower plant by integrating a linear time invariant model of gate, penstock, turbine and generator in order to find out the dynamic response to gate input. The simulation results show that the steady state speed of turbine depends on gate position and head. This is possible due to the fact that the gate position and head determine flow and volume of water that rotate the turbine which in term determine the speed of the shaft coupled to the generator. The stability of the water parameters will determine the permanency of the steady state speed. However transient regime can be managed by control systems applied to the input of the turbine. The control system will act on the rate of closing/opening of the gate to ensure that the speed on the shaft do not suffer the high variability of the incoming water. Governors are used in hydropower plants as speed regulating device for frequency control. In all, [17] model, describes a complete power plant including all necessary aspects at the contrary of previous models which focus on only one aspect.

Moreover, Munoz-Hernandez (2004), [18] used Simulink to develop a Model Predictive Control for hydroelectric power-plant. His work made some comparisons between the response of the plant and the one of a PID controller. Results show improvement in the control. Furthermore, [18] developed another robust model of hydroelectric power station in which two reputed control methods were compared. These methods include the traditional Integral controller (PI) and the Model Predictive Control. It was found that the Model Predictive Control yield better results in terms of robustness as it was able to maintain its performance both in SISO and MIMO cases.

Other researches also dealt with hydropower modeling but were more of case studies rather than generic models. Fred Prillwitz (2007), [19], designs a simulation model of the hydro-power plant SHKOPETI. Zagona (2013), [20] on the other hand works on modeling hydropower in RiverWare which is a river basin modeling tool that provides flexibility to model a range of timestep events with multiple solvers including simulation and optimization. The RiverWare provides four basic ways to model hydropower namely: simple power method, peak base power method, plant power method and finally unit generator power method.

The Simple Power method, [20], models power, P, according to the relationship

$$P = \alpha(O_H, Q_T) \cdot Q_T \cdot O_H \qquad (5)$$

where α is an empirical coefficient which captures the properties of water and the plant efficiency, Q_T is turbine flow, and O_H is operating head, given by headwater elevation minus tail-water elevation. The Peak Base Power method determines the power and energy generated by the entire plant based on the fractions of each timestep operated at peak flow and base flow. The other two methods also determined the maximum operating point of the hydropower plant by considering algorithm based on the best choice of Q_T and O_H at given conditions.

Furthermore, [7] also works on the modeling and control of an isolated micro-hydro power plant with battery storage system.

3. MODEL OF HYDROPOWER PLANT

An extensive review of the modeling of hydropower plant is handled at this level with the help of a model of hydraulic turbine designed by IEEE working group (1992), [21] under Matlab simulation software and available on the Mathworks website, [22]. The model is first described and further modified and simulated. The Hydraulic Turbine and Governor block implements a nonlinear hydraulic turbine model, a PID governor system, and a servomotor as described in figure 3.

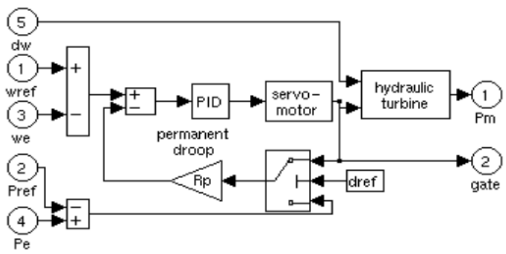

Fig 3: Typical model of hydropower plant

The hydraulic turbine is modeled by the nonlinear system illustrated in figure 4

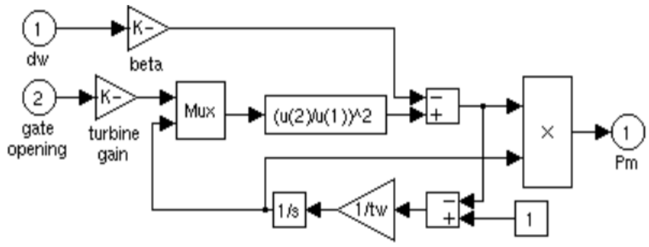

Fig 4: Nonlinear model of hydraulic turbine

The gate servomotor is modeled by a second-order system shown in figure 5.

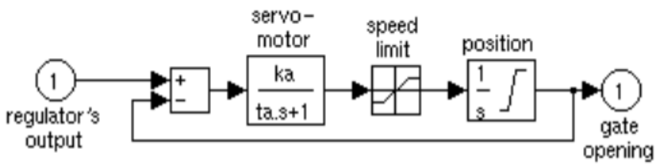

Fig 5: Model of Gate Servomotor

The summary of inputs/output to the hydraulic model is illustrated in figure 6.

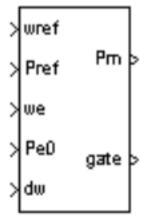

Fig 6: Summarized model of hydraulic turbine under Matlab/Simulink

- **ωref**: Reference speed, in pu.
- **Pref**: Reference mechanical power in pu.
- **ωe**: Current Speed of Machine in pu.
- **Pe0**: Electrical power of the machine in pu. This input can be left unconnected if the gate position is used as input to the feedback loop instead of the power deviation.
- **dw**: Speed deviation, in pu
- **Pm**: Mechanical power Pm for the Synchronous Machine block, in pu.
- **Gate**: Gate opening, in pu.

With consideration to all the components described previously in figures 3, 4 and 5, the final model of figure 7 is built and simulated under Matlab/Simulink. The model consists of a synchronous machine associated with the Hydraulic Turbine and Governor (HTG) and Excitation System blocks. This model is extracted from Matlab 2012 examples, [22] and modified to serve as an extensive review on the hydropower plant. The model is made of a 250 MVA, 14 kV three-phase generator with a nominal speed of 112.5 rpm that is connected to a 161 kV network through a Delta-Y transformer rated 300 MVA

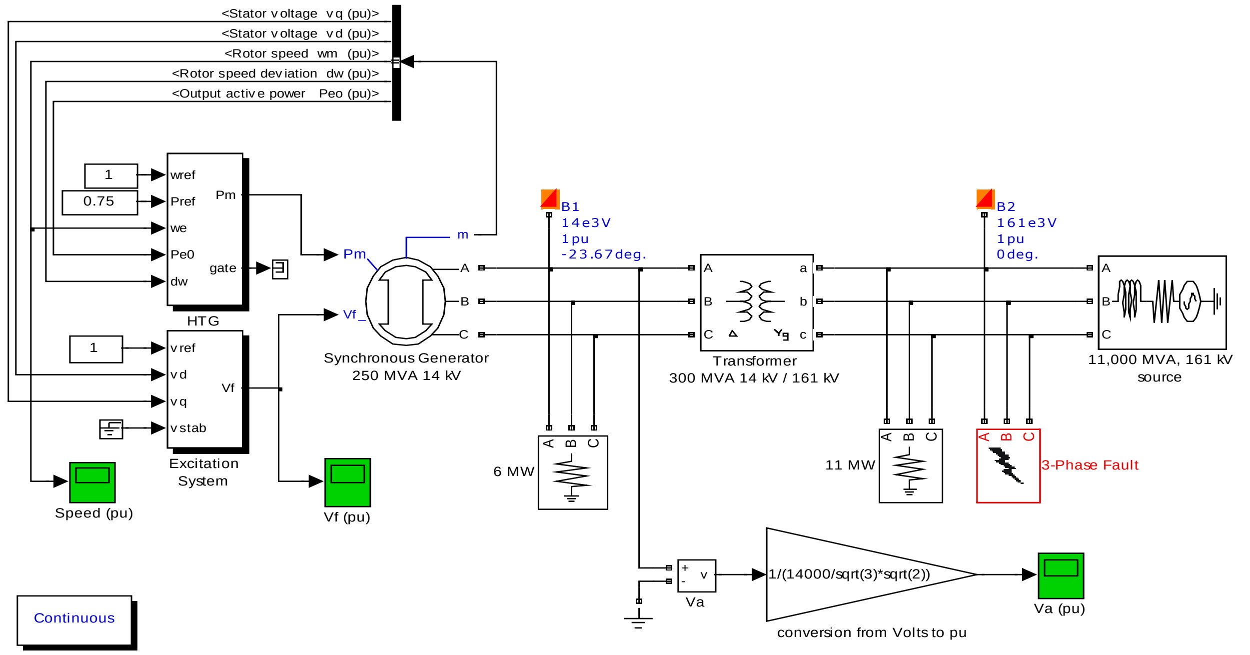

Fig 7: General model of Hydropower plant under Matlab software

The hydraulic turbine block described above is used in figure 7 to generate the mechanical power that drives the synchronous generator. In addition, an excitation system block is used to generate the excitation voltage that supplies the synchronous generator. Feedback systems are used through PID controllers to regulate both the generated excitation voltage as well as the mechanical power produced by the turbine. The output of the generator which is initially 14 kV is fed to a step-up power transformer that feeds 161 kV on the transmission line. Also an 11 MW load is added at the end with a fault stimulating block. The following settings were adopted for the simulation purpose:

- Machine Initialization: The type of machine selected is 'Bus type' and it is initialized as 'PV generator', which indicates that the initialization is performed with the machine controlling the active power and its terminal voltage. The desired terminal voltage parameter is set to 14000 and the active Power to 160^6

- The phasors of AB and BC machine voltages as well as the currents flowing out of phases A and B are updated.

- The machine reactive power, mechanical power and field voltage requested to supply the electrical power were also configured as follow: Q = 3.5 Mvar; Pmec = 160 MW ; field voltage Ef = 1.3 pu.

- Hydraulic turbine: the initial mechanical power was set to 0.8 pu (160 MW).

- For the excitation System block, the initial terminal voltage and field voltage have been set respectively to 1.0 and 1.3 pu.

After all these settings, the system was simulated and the obtained results are presented in the next paragraph

4. RESULT AND DISCUSSION

To analyze the simulation results, three graphs have been plotted: the speed characteristic, the output characteristic and the excitation voltage with respect to time. The reliability of the hydropower plant can only be tested by the plant’s capacity of overcome fault quickly and effectively. For this matter we introduced a short-circuit fault into the system in order to analyze its response and conclude on the reliability. The fault, also known as three phase to ground fault [22] was introduced at a time t=0.2s. A close look at the graphs provided in figure 8, 9 and 10 respectively show that before the introduction of the fault, the system was in steady state with nominal speed of 1 pu, an output voltage of amplitude 1 pu and an excitation voltage of about 1.5 pu. The fault lasted for about 0.2s, that is from 0.2s to 0.4s and during the fault there was a significant drop in the output voltage which became 0.4 pu in amplitude. In addition the excitation voltage increased highly to an average of 11.5 pu and the speed also increased slightly to 1.01 pu. The increase in the excitation voltage is a very positive response of the system vis-a-vis the fault because it leads to an increase in the flux value which further relates to the induced voltage by the famous equation (6).

$$E = KØN \tag{6}$$

K is a constant related to the machine, Ø is the flux per pole and N is the speed.

From equation 6, it can be seen that the induced voltage is proportional to the flux and therefore an increase in flux will have the effect of bringing the voltage back to its previous value as it was highly reduced by the fault.

For more increase in the induced voltage the speed can also be increased and this is controlled by the governor from the opening and closing of wicket gates. However, the increase in speed did not yield a big change as it can be observed that the increase was only about 0.01 pu due to the fact that it is dependent on the availability of the flowing water.

Furthermore, after the fault was removed at t=0.4s, the system quickly regain stability with an output voltage of 1pu which is equivalent to the previous steady state value. Automatically the excitation voltage drops and continues with oscillations in order to maintain the output voltage constant. It can also be realized that the speed also oscillate around and average value of 1 pu. The oscillations of the speed took longer time to stabilize as compared to the ones of the voltage and this may be due to the rate of valve opening/closing in the governor system.

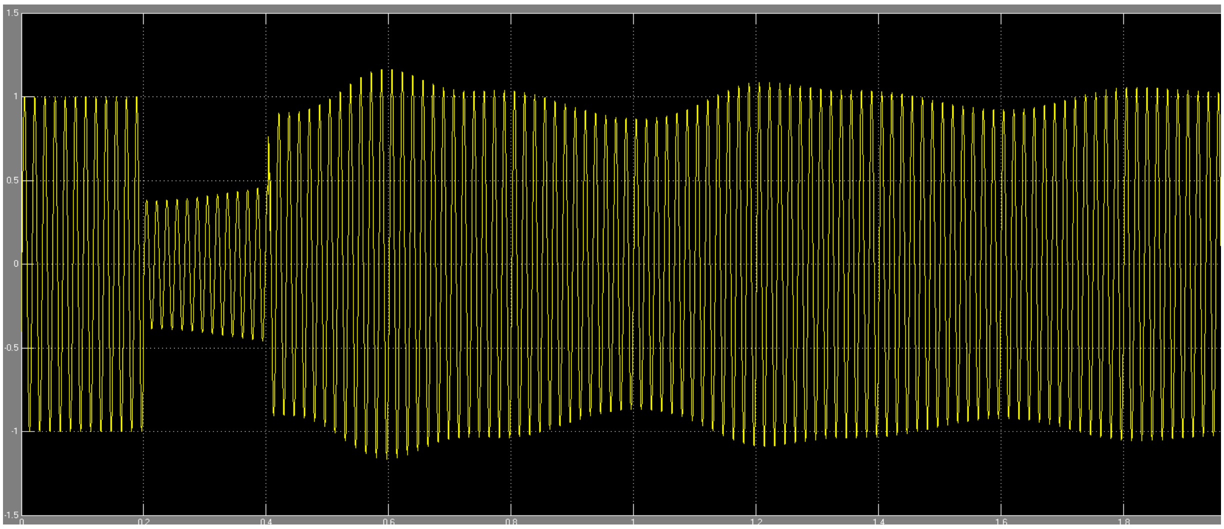

Fig 8: Output Voltage (Generated voltage Va) of the Synchronous Generator

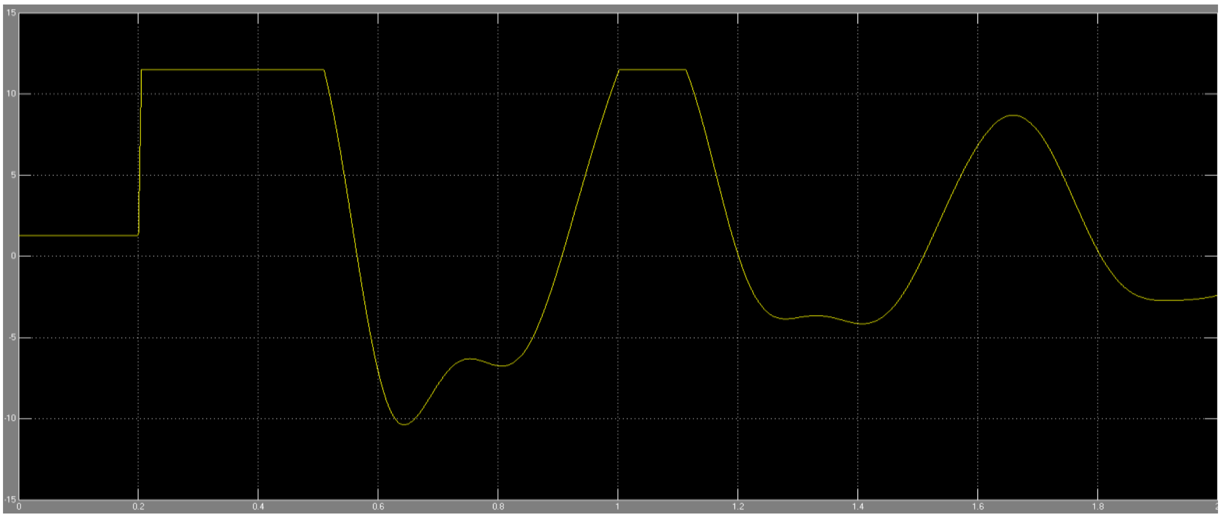

Fig 9: Excitation voltage (Vf)

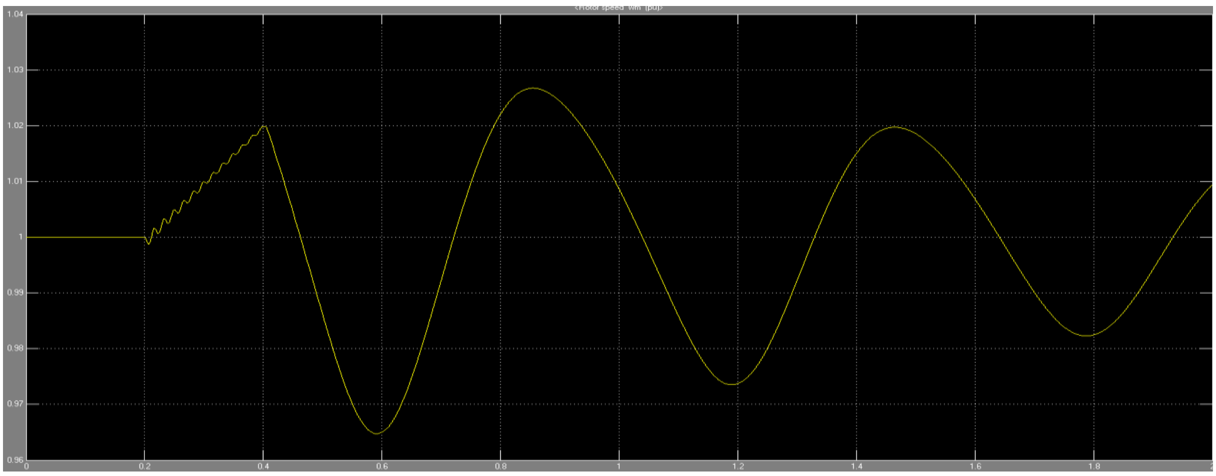

Fig 10: Speed characteristics vs time

5. CONCLUSION

In summary, analytical models of hydropower generation were first reviewed. These models were revealed inadequate for the proper modelling of the dynamic aspect of flowing water, gate controlling and others. System simulation was further reviewed and a common objective of this latter type of modeling was to look at the speed variation, the generated power and its stability and dependency on input parameters such as opening and closing of gate (which relate to the speed and amount of water flowing to the turbine), penstock, turbine and generator modeling. The review showed that modern systems modeling adopt software simulation approach among which MATLAB/SIMULINK software and Riverware can be cited. The last stage of the review therefore adopted an existing model of hydropower plant in Matlab software, modified it and simulated it. Prominent result were obtained in terms of speed and output voltage stability vis-à-vis network faults. A three phase to ground fault was introduced at 0.2s, the system output voltage quickly became stable after the removal of the fault at t=0.4s owing to the excitation voltage that was maintained high because of the PID control systems.

However, in reality, the rise in excitation voltage is also limited to the capacity of the existing source of supply. In case of this simulation, the rise in excitation voltage was about 10 pu which is actually very difficult to attain in real conditions. An additional rise in speed can help to improve upon the problem but the control system established in the simulation showed that the rise in speed were negligible. It is henceforth recommended that the governor control systems should be improved upon with modern control techniques such as fuzzy logic and this should be embedded in future models of hydropower plants.

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