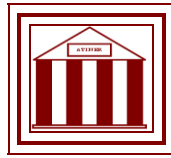


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COM2016-2072**

**Deduction of a Comprehensive Model of the  
Bhutan Power System for Network Stability  
Investigations**

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## **Deduction of a Comprehensive Model of the Bhutan Power System for Network Stability Investigations**

**Axel Holst**

**Pravakar Pradhan**

**Cheku Dorji**

### **Abstract**

This paper describes a comprehensive modelling and simulation method of a complete electrical power system in Bhutan. The modeled system incorporates the Hydropower Plant (HPP) Tala and Chhukha (with high pressure Pelton turbines and a complex control structure) integrated into the transmission and distribution system of Bhutan. The complete nonlinear model of HPPs are developed in Matlab/Simulink software and validated with the measured data. For validation of network elements parameters, the model is developed in the network simulation software DIgSILENT PowerFactory and tested to match the actual system output to the simulated output. To conduct the necessary investigation concerning the dynamic behavior in different operational scenarios (e.g. island mode operation and the transition process), validated HPP models are added to the validated network model in DIgSILENT PowerFactory.

**Keywords:** Hydropower, Modeling, Network restoration, Power system measurements, Simulation, Stability.

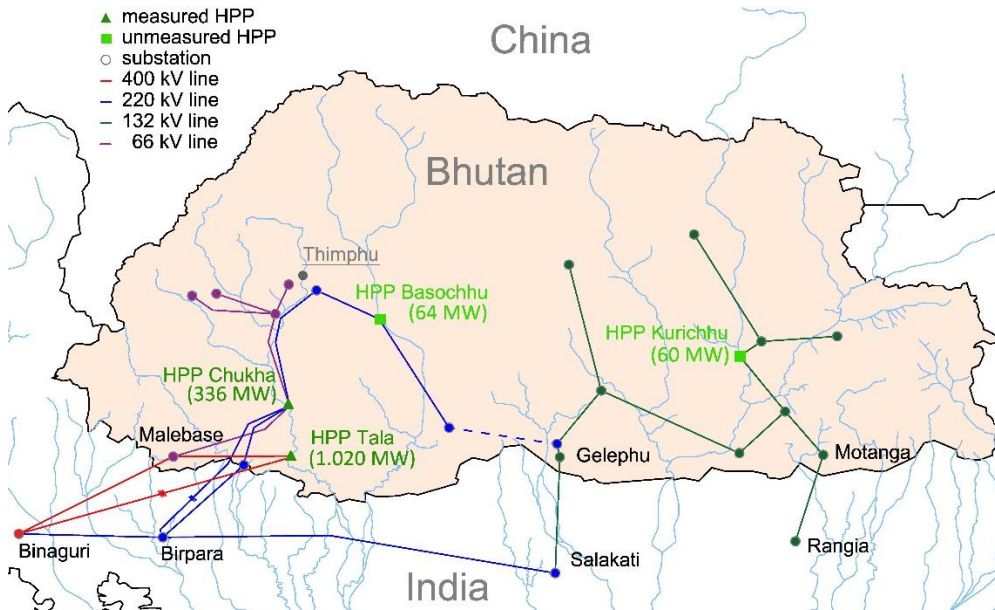
**Acknowledgments:** A research team consisting of experts from the Royal University of Bhutan, the University of Rostock (UR), DGPC and BPC was founded. This work is part of the project ‘Analysis and Modelling of Bhutan’s Hydropower Plants for Investigations by Dynamic Simulation’, supported by the German Academic Exchange Service (DAAD) with financial resources from the German ‘Federal Ministry for Economic Cooperation and Development’ (BMZ). And partly funded by the Annual University Research Grand 2014-15, Royal University of Bhutan.

## Introduction

The existing hydropower plants (HPP) of Bhutan are being managed by Druk Green Power Corporation (DGPC). Bhutan Power Corporation Limited (BPCL) is the power system operator of the Bhutan, which is controlled via an interconnection from the Indian grid. With the rapidly growing power demand within the country and the increase in demand from the interconnection from the Indian grid, there is a need to ensure that all of the generating facilities are prepared to operate in the fast changing network scenario. BPC also needs to enhance its current state of expertise on the dynamic and static studies of the transmission network of Bhutan towards operating the system optimally at present, and in the future with the expected network expansion as per the National Transmission Grid Master Plan (NTGMP).

For this, there is a need to have a comprehensive model of all power plants of Bhutan integrated with the network model. Among the four major power plants in Bhutan, a realistic model of two major power plants (namely HPP Chukha and Tala) and its network are completed. HPP Chukha and HPP Tala are the two biggest generating stations located on the Wangchu river basin in the Western Bhutan with an installed capacity of 336MW and 1020 MW respectively. Table 1, shows the salient features of the four major HPPs of Bhutan. And Figure 1 shows the geographical location of the HPPs.

**Figure 1.** *Geographical Location of HPP's of Bhutan with Interconnection with India*



**Table 1.** *Salient Features of Generating Units*

| <b>Salient features</b>       | <b>Generating Unit</b>       |                    |                     |                 |
|-------------------------------|------------------------------|--------------------|---------------------|-----------------|
|                               | <i>Basochhu HPP</i>          | <i>Chhukha HPP</i> | <i>Kurichhu HPP</i> | <i>Tala HPP</i> |
| <i>Net Head</i>               | 356m - Upper 459m - Lower    | 435 m              | 32 m                | 819 m           |
| <i>Installed Capacity</i>     | 24MW - Upper 40MW - Lower    | 336 MW             | 60 MW               | 1,020 MW        |
| <i>Number of Units</i>        | 2x12MW - Upper 2x20MW -Lower | 4x84 MW            | 4x15 MW             | 6x170 MW        |
| <i>Mean Annual Generation</i> | 291 GWh                      | 1,800 GWh          | 400 GWh             | 3,962 GWh       |
| <i>Turbine Type</i>           | Pelton                       | Pelton             | Kaplan              | Pelton          |

The paper shows the validation process of the HPPs, by comparing the measured signals in Matlab/Simulink with simulated results. Similarly it also shows the validation process of the network model in DIgSILENT PowerFactory. Later the HPP model is migrated to the DIgSILENT PowerFactory and the whole power system is used to simulate/describes initial findings; firstly, for various contingencies (static and dynamic responses) of the system and secondly, for optimal and efficient operation as well as for planning the Bhutan power system of the future which is interconnected to one of the largest electrical Grids: India.

### Measurements and Data Handling

For successful modeling of a plant, well prepared measurements and reliable recordings is vital. It is also vital to know the set-points for active and reactive power, speed and limiter settings to be able to identify the dynamic behavior.

As it is not practical to operate the power plant in islanded mode and take the measurements, usually the power plants are subjected to several suitable dynamic movements to get an idea of the transient behavior of the plant. For this reason, tests in different operational scenarios can be logged as follows (Holst and Golubovic, 2007):

- Dry operation: change of opening positions (measurement signal calibration),
- Interconnected mode: change of set-points (power, voltage, speed, limiters, reactive power) to evaluate performance of all existing controller paths,
- Special sequences (startup, synchronization and load shedding),
- Excitation of oscillation modes (sinusoidal frequency input),
- Transition: interconnected mode to islanded mode with different load steps

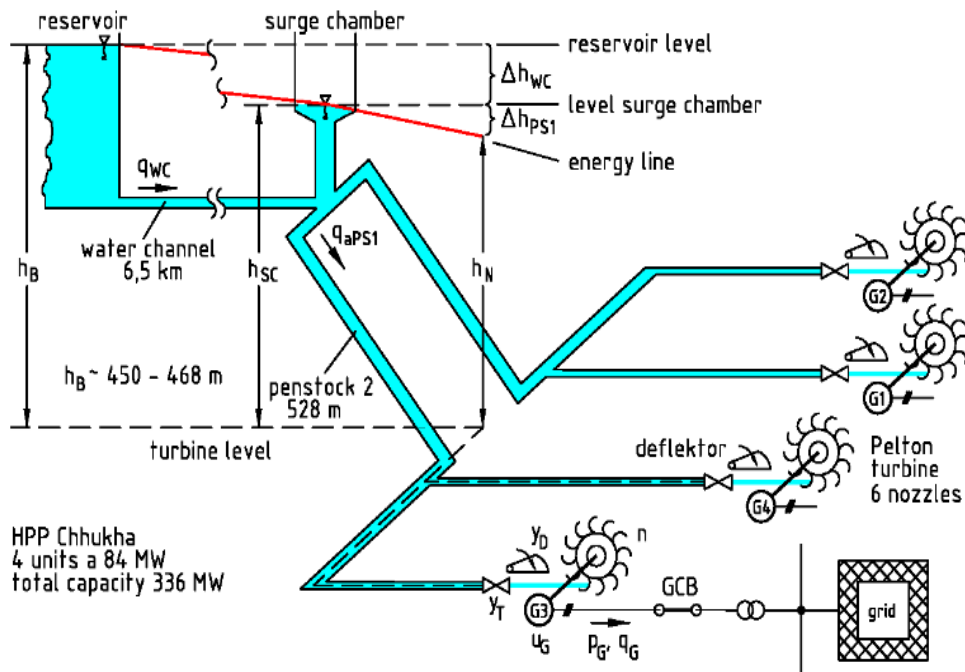
In both HPPs, measurements were conducted by engineers from CST and UR under assistance of the DGPC's engineers and staff. For HPP Tala,

tests in the aforementioned first three operational scenarios were only possible. The measurements were carried out from the 25th till the 26th of March 2014 at Unit 2. During the tests, Unit 1 was run with constant power and all other units were under temporary shut-down. As for the HPP Chhukha, a fifth scenario was also possible in addition to the first three. The measurements were taken from the 30th of March till the 1st April, 2015 at Unit 3. During the tests, Unit 1 and Unit 2 were under temporary shut-down.

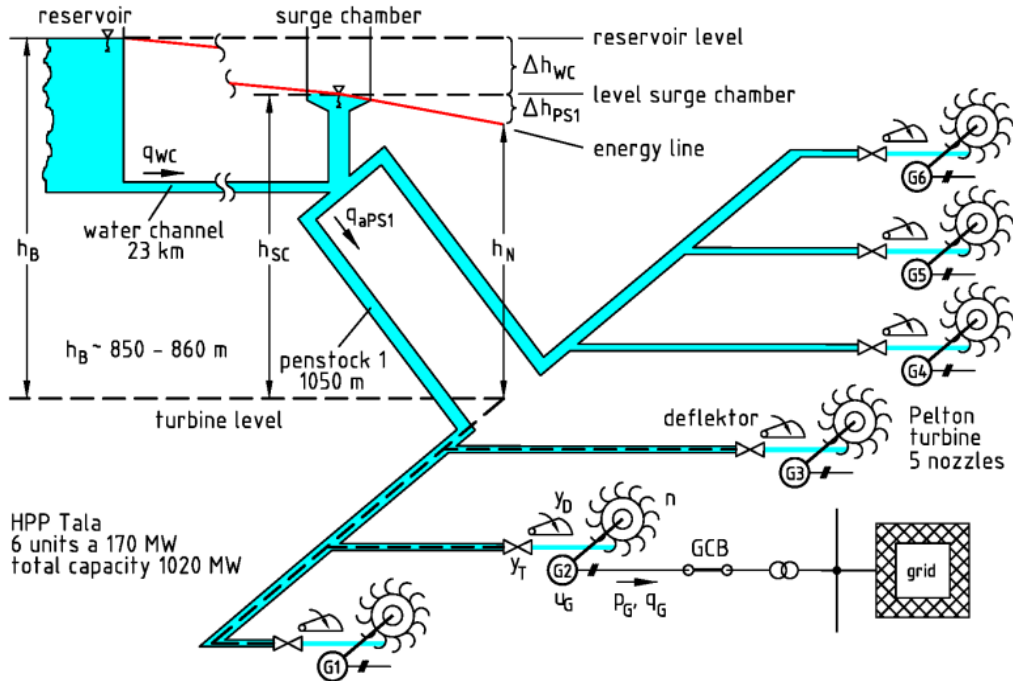
The measurements were conducted only on one unit in both power plants and the other units are – accept the known settings - considered to be identical. The schematic scheme of the HPP Chhukha and HPP Tala are shown in Figure 2 and Figure 3, respectively.

To record the data during the test, LabVIEW™ programmable software installed in a laptop with DAQ card with 12 bit resolution with signal conditioning hardware were used.

**Figure 2.** Schematic Scheme of HPP Chhukha



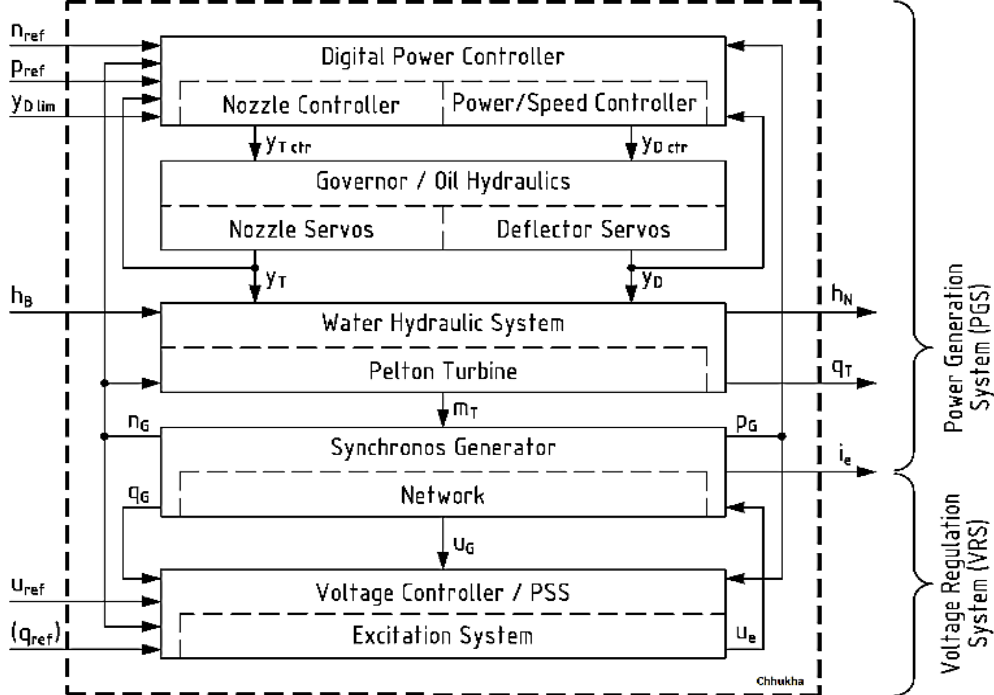
**Figure 3. Schematic Scheme of HPP Tala**



### Model of Hydropower Plant Chhukha

The basic model and main parts of any HPP is the same. Figure 4, shows the structural overview of a HPP with Pelton runners. Using the large compilation of the power plant documentation provided by DGPC and test data of the non-linear models, the subsystems are developed using Matlab/ Simulink software.

**Figure 4. Structural Overview of HPP with Representation of Sub-models**

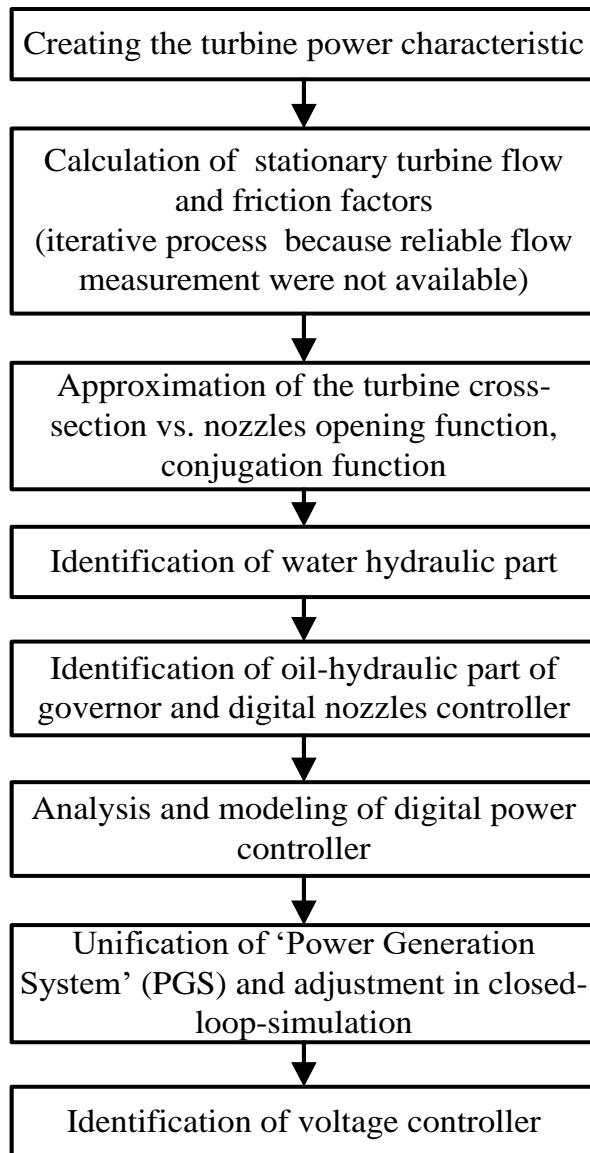


The generator is not modeled in Matlab/Simulink as it is more convenient to be modeled in the network simulation software DIgSILENT PowerFactory.

Firstly, for all modelling aspects, per unit system is used as it simplifies the interconnection of sub-models with respect to the signal handling and linking. Secondly, the Nelder Mead Simplex Algorithm with the mean square method, as a quality criterion is used for identification of more than one parameter simultaneously.

The modelling of HPP Tala was conducted in the previous year and was presented as per reference (Holst et al., 2015). Similarly, the parameter identification and modelling of HPP Chhukha is presented here. The modeling work was executed in the following chronological steps (Figure 5).

**Figure 5.** Chronological Steps for Parameter Identification (Modelling)





### Hydraulic Part and Turbine Model

As per (Weber, 1990), water hydraulic systems which are a fluid mechanical system can be represented with an equivalent  $\pi$ -model of an electrical system where the traveling waves can be slurred to their fundamental wave.

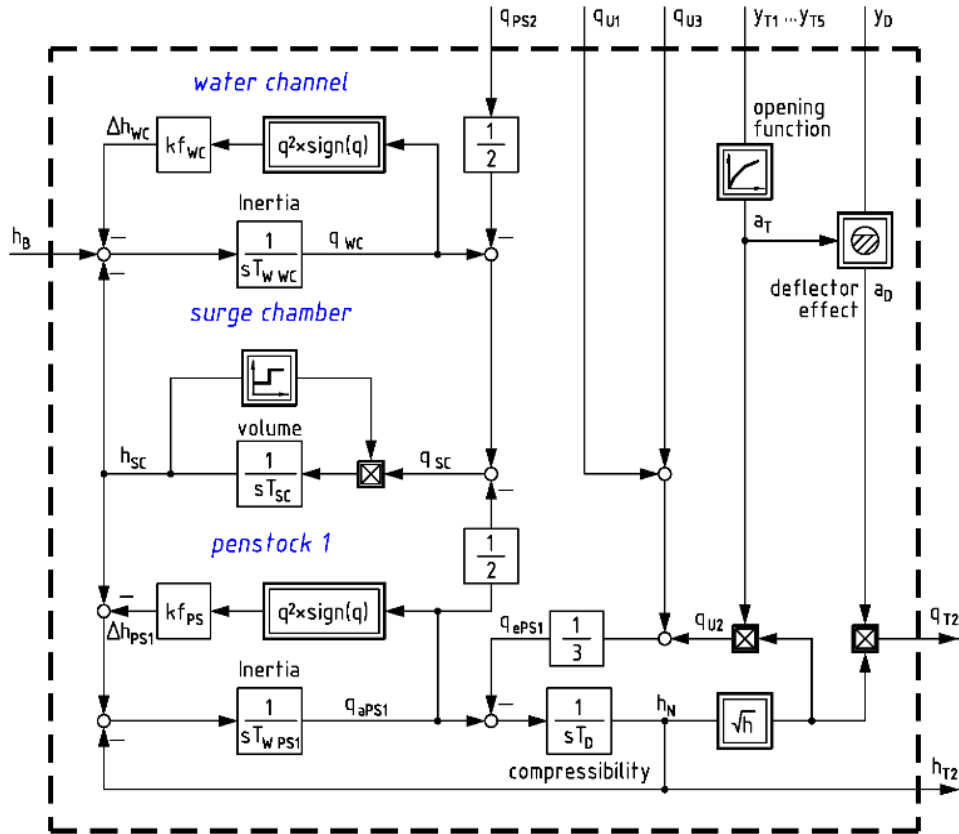
Figure 6, shows the main parts of the hydraulic system for simulations focused on unit 3 of HPP Chhukha. Physical construction dimensions were used to calculate the time constants and later on refined by identification (Table 2).

The discharge the  $q_T$  for each unit is calculated by the Torricelli equation:

$$q_T = a_T \cdot \sqrt{h_N} \quad [\text{p.u.}], \quad (1)$$

where  $a_T$  is the opening cross section of the nozzle assembly which in transient processes is influenced by deflector position and can be replaced by  $a_D$ .  $h_N$  represents the net head.

**Figure 6.** Simplified Sub-model of Water Hydraulic Part of HPP Chhukha

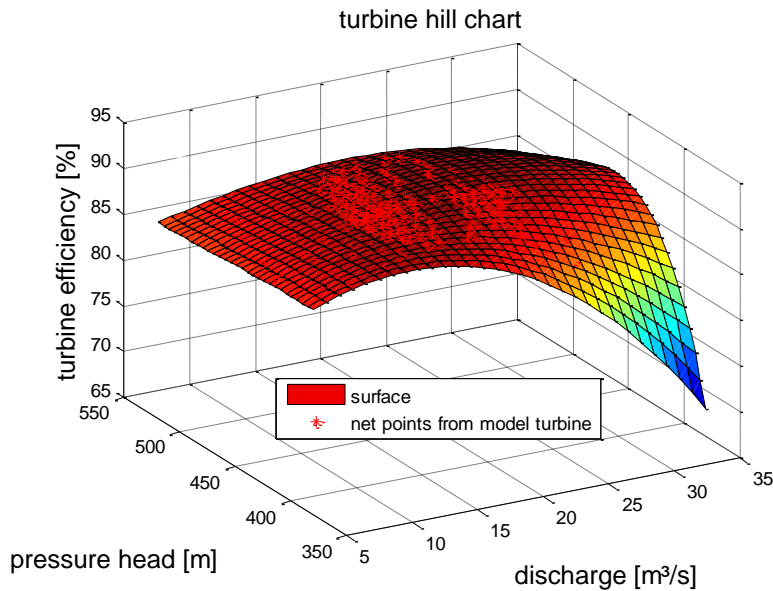
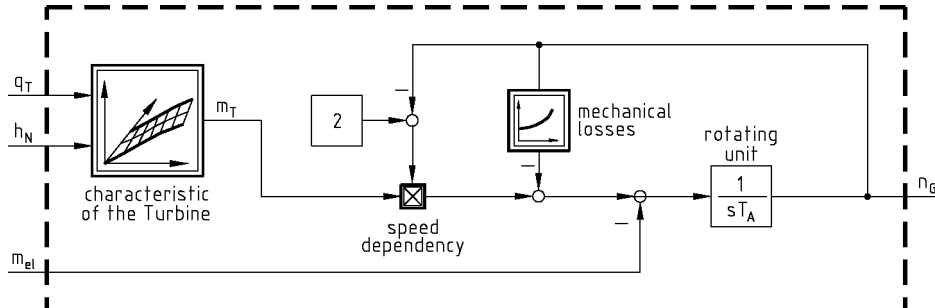


**Table 2. Identified Parameters of Hydraulic Part**

| Parameter        | $T_{W_{wc}}$ | $T_{sc}$ | $T_{W_{ps1/2}}$ | $T_{L_{ps1/2}}$ | $k_{f_{wc}}$ | $k_{f_{ps}}$ |
|------------------|--------------|----------|-----------------|-----------------|--------------|--------------|
| Identified Value | 6.7 s        | 538 s    | 0.75 s          | 0.16 s          | 3.0 %        | 2.0 %        |

Figure 7, shows the 3-dimentional function of the turbine. These functions are derived from the hill chart of the turbine provided by the manufacturer. Instead of modelling the turbine, aforementioned 3-dimentional function of the turbine is used in the HPP model.

Figure 8, shows the sub-model of turbine and generator mechanical model. Here the speed dependency of the turbine is incorporated with respect to the run-away speed and the standstill torque. Mechanical losses were added to the model, as the mechanical (Giesecke and Mosonyi, 2009, p.527). A starting time constant of 10 seconds is used. This includes the starting time constant of the rotational unit which consists of the Pelton runner, the shaft and the generator rotor.

**Figure 7. Turbine Power Characteristic (Subpart of Figure 5)**

**Figure 8. Sub-model of Turbine and Generator Mechanical Model**


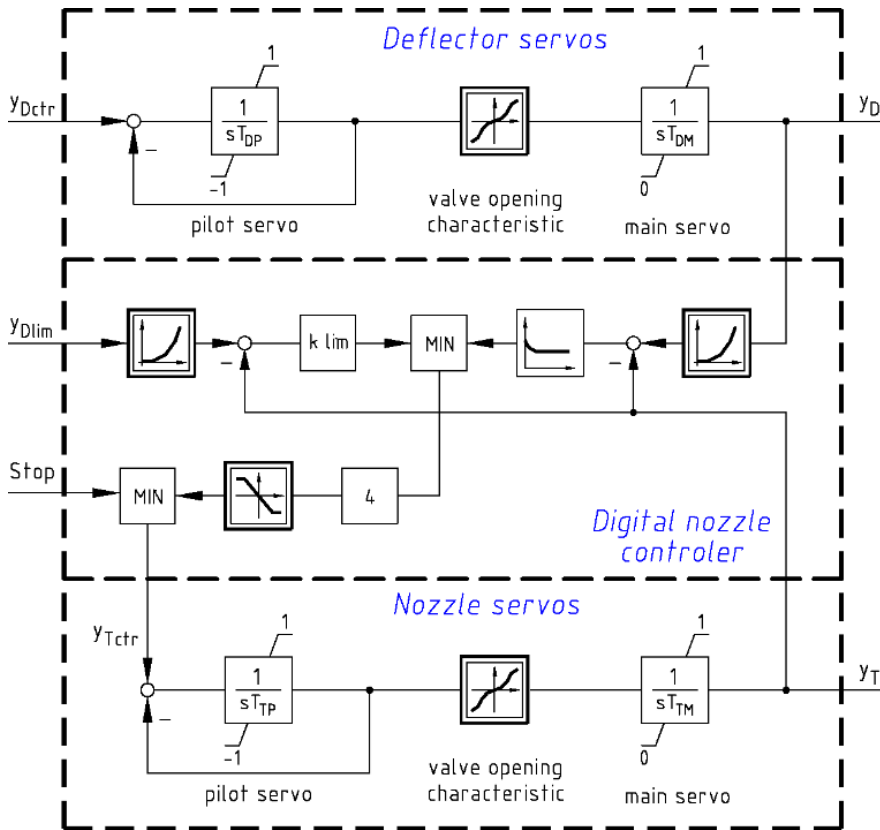
### Governing System

Figure 9, shows the sub-model of oil-hydraulic part of governor as well as the digital nozzle controller. It consists of a digital controller unit with control paths for power or speed control, nozzle control and the oil-hydraulic system. There are 6 nozzles which follow the position feedback of the deflector.

Whenever there is a change in the operation point of the HPP, the deflector moves very fast while the nozzles follow slowly accordingly to their new stationary position, determined by power/speed controller. The relation between the deflector and the nozzle is also determined and is termed as ‘deflector-nozzle conjugation table’.

Table 3, shows the identified values, which are not generally known and can only be determined by conducting tests/measurements. The time taken by the deflector for the full range of movement from practical minimum opening and closing time were measured equal to 10.4s and 1.6s respectively.

**Figure 9.** Sub-model of Oil-hydraulic Part of Governor as well as Digital Nozzle Controller



**Table 3.** Identified Parameters of Oil-hydraulic Part

| Parameter        | $T_{DP} / T_{TP}$ | $T_{DM}$ | $T_{TM 1...5}$ | $y_{PD \max} / y_{PD \min}$ | $y_{PT \max} (1...6)$ | $y_{PT \min} (1...6)$ |
|------------------|-------------------|----------|----------------|-----------------------------|-----------------------|-----------------------|
| Identified Value | 1.0 s             | 1.55 s   | 3.4 s to 6.3 s | 0.11/-0.32                  | 0.1 to 0.17           | -0.18 to -0.43        |

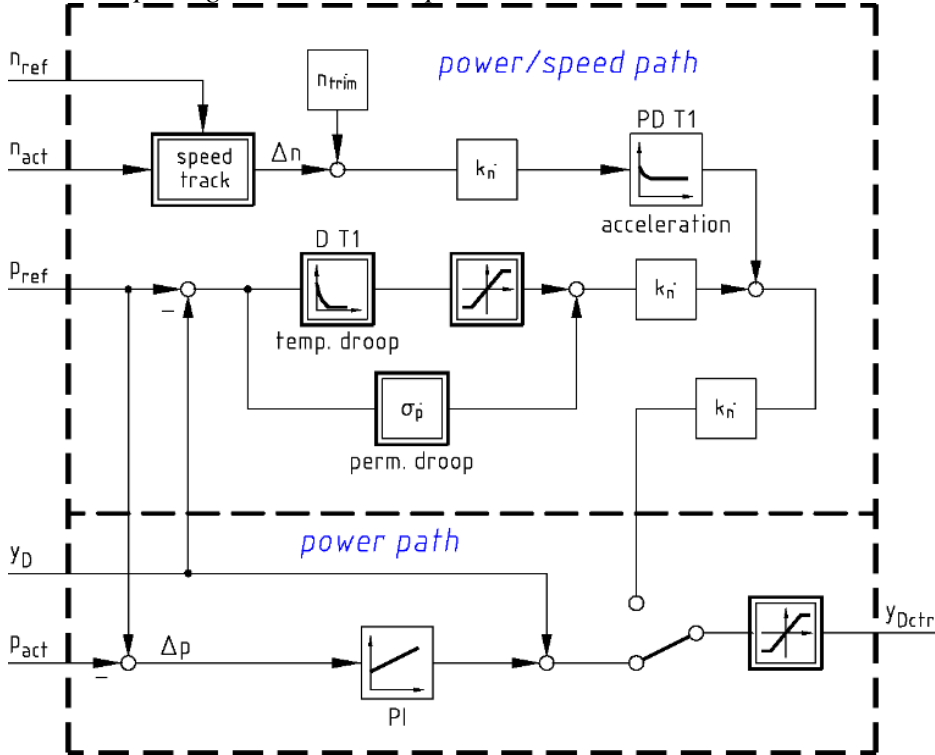
### Power/Speed Controller

As shown in figure 10, there are two different control paths which are active, under a different operational condition with respect to power/speed controller. They are:

- Combined speed and power controller (NPC). This path consists of a P-type controller with both permanent and transient droop with acceleration of a  $\Delta n$  signal.
- Power controller (PC). This path consists of I characteristics. This mode is always active in interconnected mode of operation when the speed is within the predefined speed band from 47.5 to 52 Hz with a hysteresis of 1%.

It is interesting to note that the NPC is always active before synchronization. When the generator circuit breaker (GCB) is closed and if the speed is within the defined speed band, then PC mode is active. Otherwise NPC mode is active.

**Figure 10.** Sub-model of the Digital Power/speed Controller, Simplified without Opening Limiter, Start up Functions and Disabled Controller Paths



The change in the active power output is controlled with the help of a nozzle and deflector. The nozzle movement is comparatively slower than that of the deflector. Therefore the deflector movement  $y_D$  is used for stability as given by the following equation:

$$(n_{ref} - n_G) + n_{trim} + \sigma_p \cdot (p_{ref} - y_D) = 0 \quad (2)$$

It was found that the relation between  $pG$  and  $yD$  was not proportional during the simulation. A new factor  $n_{trim}$  is introduced to make the speed arrive at nominal speed in synchronization mode. In the model, a correction factor of about 3% is used to arrive at the synchronization speed, as the no-load deflector opening operation is 0.3 p.u. and the permanent droop  $\sigma_p$  is adjusted at 10 %.

The value of the  $\sigma_p$  is changed to 6 % after the interconnection of the generator with the network. Speed track block adapts the reference speed according to the actual speed.

When the generator is islanded, the speed control can be in either of the mode depending on the speed of the generator. When the GCB is suddenly closed, the PC control is not able to stabilize the speed and when the speed reaches the band limit, the control path switches to NPC mode. But whenever the speed comes back within the speed band, PC mode is active. This switching between the two modes can cause instability under certain conditions.

#### *Voltage Controller / Generator*

In both HPPs, the digital voltage controller is used which corresponds to the IEEE standard controller ST1A connected to a potential source rectifier exciter system. In this research, the only power generation part is modelled in the Simulink, therefore the voltage controller is not discussed. Moreover the same voltage controller is inherently modelled in the DigSILENT PowerFactory software. The modelled voltage controller is added to the migrated power plant model of the HPP from Simulink into DigSILENT PowerFactory.

### **Model of Power System Network**

The present and expected transmission system of Bhutan along with the Indian Grid interconnection is to be modelled for analysis of static and dynamic scenarios. A complete power system model incorporating the generation system integrated with the transmission system of Bhutan is required which can be used for simulating optimal and efficient operations as well as for planning the Bhutan Power system of the future.

Bhutan is a mountainous country geographically located on the Himalayas. The transmission line parameters provided by the manufacturers cannot be used as it does not include the effect of the uneven terrain. This leads to different line parameters depending on its geographic location. Therefore, the line parameters are calculated using a  $\pi$ -model analysis.

The relationship between the reactive power consumption and the current flowing through the transmission line is purely quadratic in nature. This relation is used to determine the capacitance of the transmission line. From the set of measured data, a quadratic curve fitting is done. To eliminate the linear part, the curve is mirrored vertically as shown in Figure. 11.

The true value of the capacitance is identified by varying the value of capacitance till the constant term of the quadratic equation tends to zero. The numerical technique is used to determine the exact value of the capacitance. Here, an exact line parameter is calculated using Nelder-Mead simplex (direct search) method. Here the quadratic relation is given by,

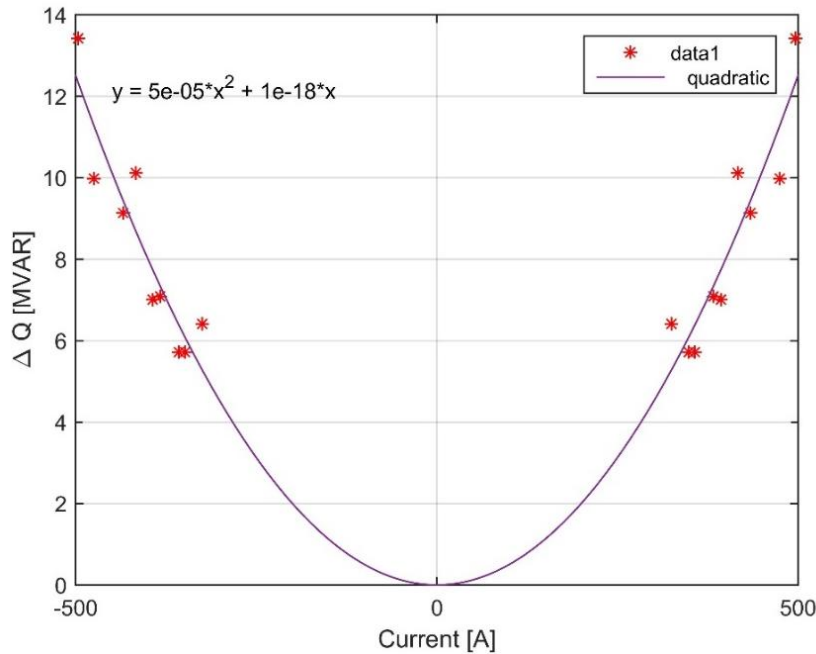
$$Q = (5 * 10^{-5} * I^2) + Const \quad (3)$$

Where Q is the reactive power in MVAR and I is the current in amperes.

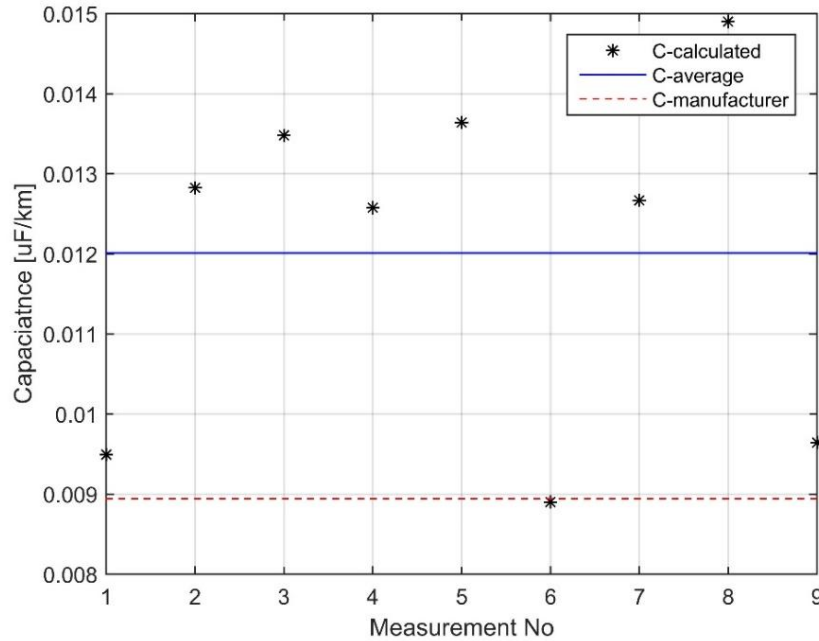
Figure 12, shows the calculated line parameter of one transmission line from the measured values of sending end and receiving end nodes. Multiple measurements are considered to include the influence of different loading conditions of lines.

In the same way the parameter of all the transmission lines of the network can be identified. The final network model is tested to match the actual system output to the simulated output for making the model as close to reality as possible through appropriate adjustment to the system parameters.

**Figure 11.** Relationship between the Reactive Power Consumed and the Current Flowing in Transmission Line from the Measured Data (Shown for 220kV Chhukha – Malbase Transmission Line)



**Figure 12.** *Distribution of the Identified/Calculated Capacitance of the Transmission Line from the Measured Data (Shown for 220kV Chhukha – Malbase Transmission Line)*

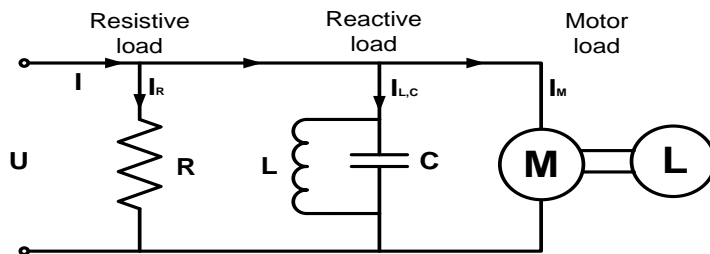


### Model of Loads

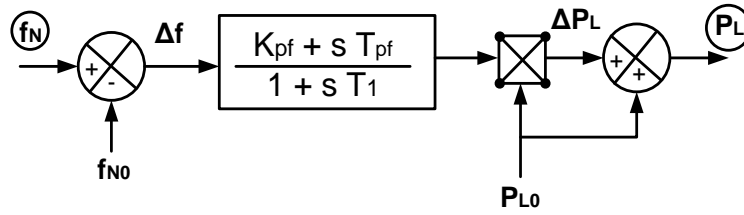
In electrical power systems, electrical load consists of various different types of electrical devices, ranging from incandescent lamps and heaters to large arc furnaces and motors.

For the dynamic analyses of the electrical power system, the general load model is not sufficient. Especially for modelling industrial loads with a large portion of induction motors the general load model might not be adequate. These types of loads are usually frequency and voltage dependent. During the islanded/restoration phase it is adequate to model the load as a combination of resistive, reactive and motor load as shown in Figure 13.

**Figure 13.** *Equivalent Circuit Representation of Electrical Load*



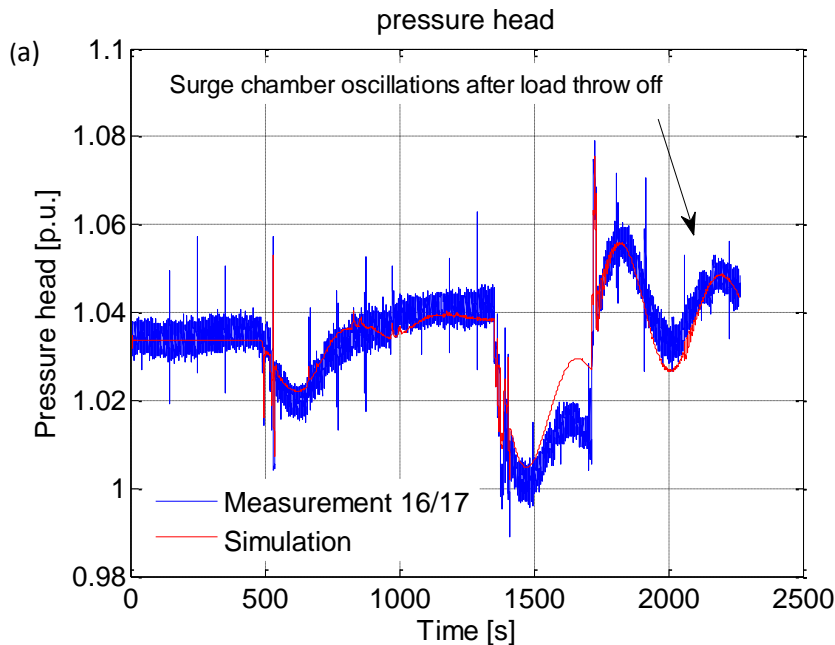
For this paper, the frequency dependence factor is identified from the test conducted in the islanded operation. Figure 14, shows the block diagram showing the frequency depended load modelling, where circled parameter are measured during the test.

**Figure 14.** Block Diagram Representation of Frequency Dependent Load


### Model Validation/Simulations

All sub-models as depicted in Figure 2 were built and tested separately. After the validation of sub-models, the last step was the unification of the sub-models, which enables the simulation of the processes in a closed loop.

For the proof of accuracy of the model, one measurement is compared with the simulation during the load throw off test is shown in Figure15 (a) and (b). A sequence of two tests in a time range of more than one hour is presented in the graph. It is important to compare the results for such a long time period to validate the surge shaft oscillations with a very high period length. This comparison shows that the oscillations are reproduced very close to the measurement signals.

**Figure 15.** Comparison of Measurement and Simulation for Test 16/17: Load Throw off at 1750 Seconds; (a) Pressure Head v/s Time, (b) Active Power v/s Time




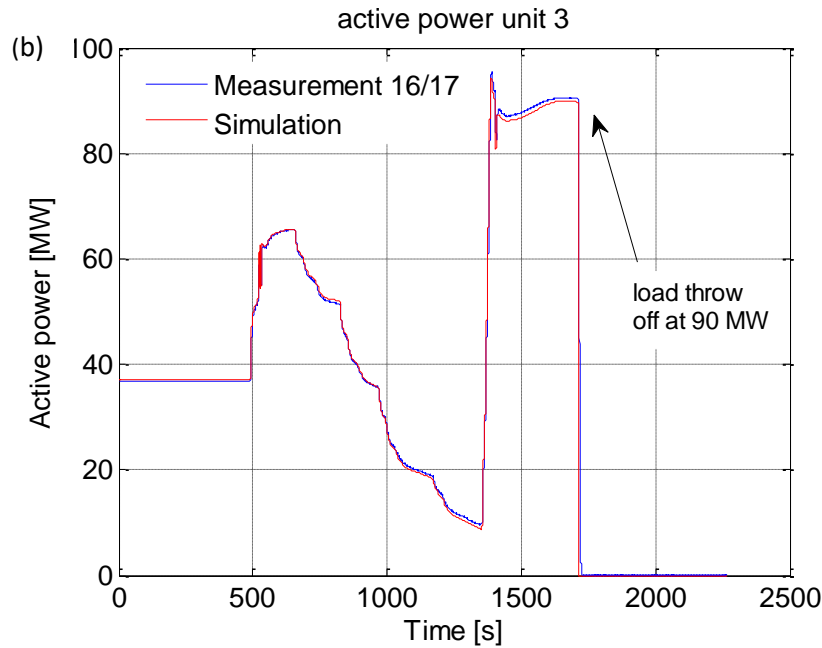
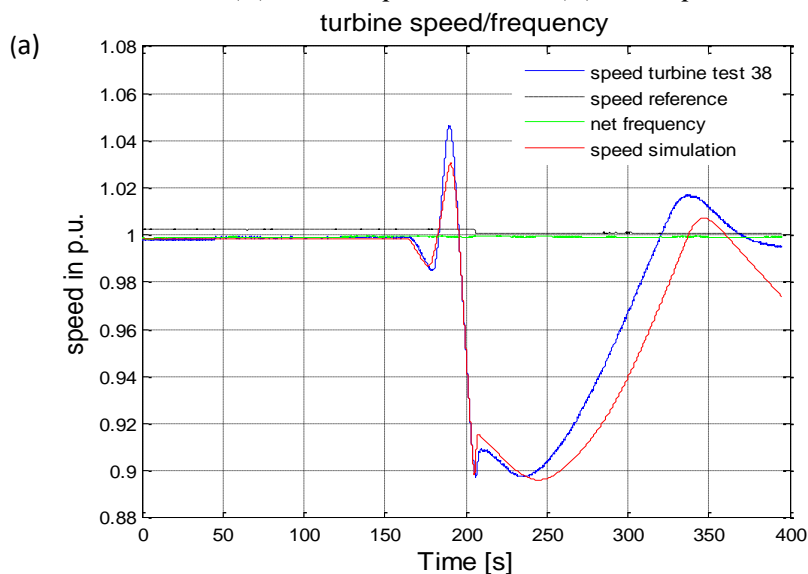


Figure 16 (a) and (b), further shows the validity of the model in islanded operation (test 38). The system was islanded at 165 seconds at a system load of 10 MW. At a time of 205.25 seconds the GCB opened due to the under frequency protection system tripping the unit under test.

The simulations in islanded operation are very difficult to simulate exactly. Lots of nonlinearities and dead times had to be implemented to fit the measurements approximately. A dead time in yD (deflector feedback signal) and speed feedback signal had to be implemented. Especially the Electro-Mechanical Cabinet (EMC) has a lot of inaccuracies which lead to the unstable behavior. The opening characteristics of the main deflector valve and the mechanical-hydraulic system are misarranged and show a bad dynamic behavior.

**Figure 16.** Comparison of measurement and simulation for test 38: Islanding at 165 seconds; (a) turbine speed v/s time, (b) active power v/s time.



(b)

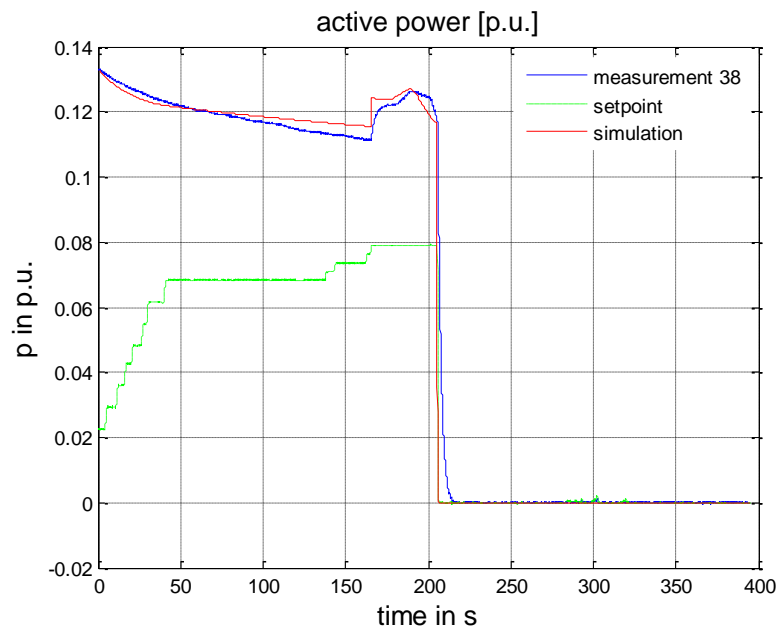
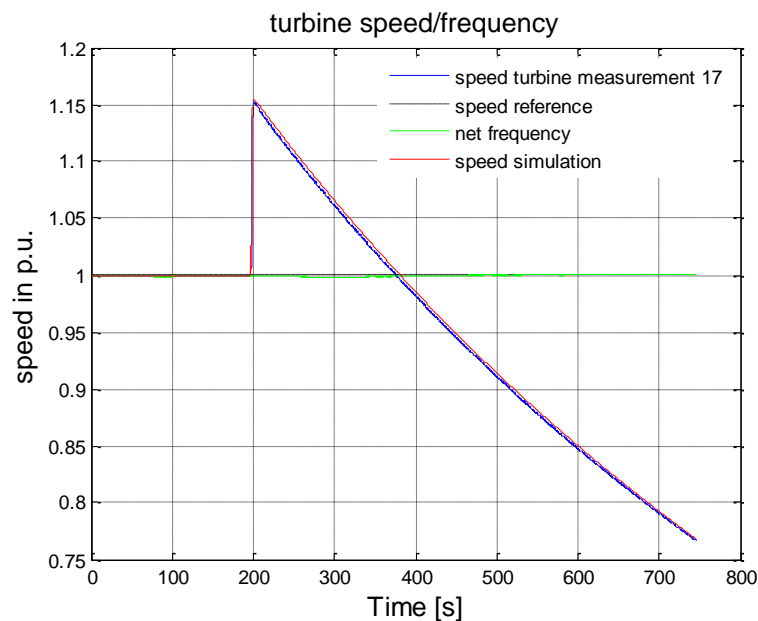


Figure 17 (test 17) shows the speed response of an emergency shutdown at a load of 90 MW (full load). The simulation shows a good fit of ramp rates for speeding up and slowing down of the rotating unit. This happens mainly because of the inertia of the rotating system with the identified time constant of 10 seconds. The no load losses which are mainly mechanical losses is identified to be 4.2 MW at nominal speed.

**Figure 16.** Speed Response of an Emergency Shut down at a Load of 90 MW (Full Load)



Form the simulations, it can be seen clearly, that the model fits the real behavior of the HPP with a high accuracy. The overall results show that both slow as well as fast changes of HPP along with different controller paths can be modeled with a high accuracy.

## **Outlook**

With the complete validated model of HPP Chhukha, a realistic model of two major power hydropower plants of Bhutan is complete. There are two more hydropower plants as shown in Figure 1, namely; HPP Bashochhu and HPP Kurichhu in central and eastern region respectively. There are plans to model these power plants in near future.

Since HPP Chhukha is located in the central region and directly connected to major load centers, strategically it becomes the vital power plant for islanded operation or during restoration by bottom up approach. Therefore HPP Chhukha will be in frequency control mode during the restoration process and other power plants can operate in power control mode during the initial phase.

To conduct the necessary investigation concerning the behavior in island mode operation and the transition process, HPP model will be added to the existing network model.

There are plans to investigate the interconnected model; firstly, for various contingencies (static and dynamic responses) of the system and secondly, for optimal and efficient operation as well as for planning the Bhutan Power system of future which is very strongly interconnected to one of the largest electrical Grids: India. There are also plans to evaluate the static and dynamic performance of its HPPs to ensure a safe and stable performance in interconnected as well as islanded operation in case of faults.

At present the Eastern and Western Transmission Network of Bhutan is interconnected only through India. There is a plan to interconnect the network through a 220 kV line between Jigmeling and Tsirang. Case studies on voltage stability of the entire system under various operating conditions are envisioned.

## **Conclusions**

This paper presents the state of an ongoing work concerning investigations of the dynamic behavior of Bhutan's power system (HPPs and the network model). The goal is to develop a dynamic model of the entire power system of Bhutan with power plants, networks and consumers for large dynamic investigations.

Realistic simulation model is developed for two major Hydropower plants of Bhutan, namely; HPP Tala and HPP Chhukha. The validity of the model is demonstrated for different operation scenarios. The results show a high quality modeling work of HPP of Bhutan. This model can be used to

carry out extensive investigations including the islanded operation of the Bhutan's power network.

These investigations show that the performance of the hydropower plants is not optimized for operation under islanded conditions. There is a need to conduct more studies on the adaption of parameter settings or even the overall control logic has to be re-structured/augmented.

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