

# Analysis and Modeling of HPP Tala/Bhutan for Network Restoration Studies

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**Abstract** – This paper describes the modeling and simulation method and corresponding results of the Hydropower Plant (HPP) Tala, which is the largest existing plant in Bhutan with 6 units of 170 MW high pressure Pelton turbines and a complex control structure. The goal of the associated overall project is to create a complete dynamic model of the Bhutan power system for investigations concerning stability, island operation, network restoration and system optimization. To test the dynamic behavior, measurements of transient processes in different operation modes of the HPP Tala for one exemplary unit have been conducted. Based on the analysis of the measurements and the plant documentation, a detailed practice-oriented high quality nonlinear model was developed and validated step by step, using the Matlab/Simulink software. Relying on the model, some initial investigations of the dynamic behavior of the plant with the focus on islanded operation were conducted.

**Index Terms** - Hydroelectric power, Islanding, Power control, Power system dynamics, Power system measurements, Power system restoration, Power system simulation, Power system stability, Renewable Energy, Voltage control

## I. INTRODUCTION

Bhutan, a small Himalayan country, located in south-east Asia, is endowed with huge hydropower potential. Of the total 24 GW technical potential, only about 1.5 GW stands harnessed till date. However, rapid developments of numerous new hydropower projects are currently in progress. 10 GW additional generations is slated to be added by the year 2020.

The existing hydropower plants (HPP) are being managed by Druk Green Power Corporation Limited (DGPC); while the Bhutan Power Corporation Limited (BPC) is the power system operator of the Bhutan power network, which works in interconnection with the Indian grid. So far Bhutan doesn't participate in frequency or inter-area control of the much larger Indian grid. Pushed by the rapid growth of the power network and the associated increase in interconnection with the Indian grid, Druk Green feels the urgent need to ensure that its generating facilities are prepared to operate in the fast changing network scenario. Therefore, Druk Green must evaluate the static and dynamic performance of its generating units to ensure a safe and stable performance in interconnected as well as islanded operation in case of faults.

Basis of the investigations are realistic models of power

plants and the power system. The reliability aspects with regard to the operation & control of the generating units and associated power system networks immensely depend on the competencies to study, understand and analyze the overall system. Therefore, a research team, consisting of experts from the College of Science and Technology (CST) of the Royal University of Bhutan, the University of Rostock (UR), DGPC and BPC was constituted, supported by the German Academic Exchange Service (DAAD) within the University-Business-Partnership Programme.

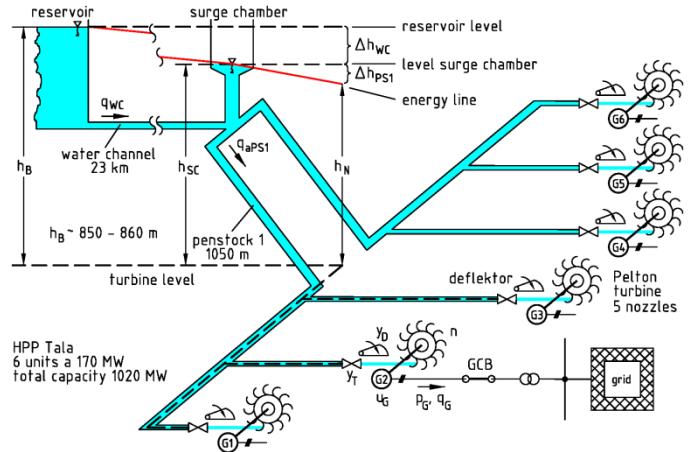


Fig. 1. Plant scheme of HPP Tala

Tala Hydropower plant (THP) is Bhutan's biggest generating station located on the Wangchu river basin in Western Bhutan with a catchment area of 4028 km<sup>2</sup>. It has an installed capacity of 1020 MW, consisting of 6 units with 170 MW each (see Fig. 1). The high pressure plant with a net head of 820 m is equipped with two penstocks having five jets impinging the bucket of a vertical Pelton turbine. Unit transformers finally steps up the voltage to 400 kV before the majority of power is evacuated to Indian grid through four overhead feeder lines. With an average mean annual energy generation of about 4.9 TWh, THP is the main source of Bhutan's country economy (almost 13 %). The plant was constructed between 1997 and 2007, built by an Indian contractor under the finance of Indian Government.

The paper covers the modeling aspects and the methodology relevant to hydropower plant set up considering THP as a case. A detailed non-linear high-quality simulation model was developed and validated through various simulation results compared with the real time measurements.

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).

## II. MEASUREMENTS AND DATA HANDLING

The basis for a successful modeling of a plant are well prepared measurements and reliable recordings. As many signals as possible should be measured, particularly at the interconnections of the subparts (refer Fig. 2). To be able to identify the dynamic behavior, beside of all usual electrical and mechanical values and positions the set-points for voltage/reactive power, active power, speed and limiter settings should be known.

As island operation physically tests are hardly to conduct, usually the plant must be subjected to several suitable dynamic movements to get an idea of the maximal traversing speed of the governor elements. Furthermore, the identification of various non-linear characteristics requires measuring of a lot of operational points that should be tracked during the measurements. For this reason, tests in different operational scenarios can be logged as follows:

- Change of opening positions in dry operation (measurement signal calibration),
- Change of set-points in interconnected mode (power, voltage, speed, limiters, reactive power) to evaluate performance of all existing controller paths,
- Special sequences (startup, run out, synchronization, load shedding),
- Excitation of oscillation modes (sinusoidal frequency input),
- Transition from interconnection to islanded operation with different load steps (if possible) or
- Tests in virtual islanded mode (test equipment temporarily in preparation).

For HPP Tala, tests in the aforementioned first 3 operational scenarios were possible. The measurements were taken from 25<sup>th</sup> till 26<sup>th</sup> of March 2014, at Unit 2 by engineers from CST und UR, under assistance of DGPC's engineers and staff. During the tests, Unit 1 was running with constant power and all the other units were under temporary shut-down.

The test sequences were recorded by measurement equipment from UR, consisting of a Laptop with DAQ card (12 bit resolution) and signal conditioning hardware (isolation amplifier, current shunts), controlled by *LabVIEW*<sup>TM</sup> programmable software. 28 channels were measured simultaneously with a sampling rate of 50 ms, which is sufficient to record the fastest signal changes of the voltage controller with a good resolution.

Additionally, a large compilation of power plant documentation was provided by DGPC, where of particular importance were the plant's digital controller design and the controller parameter settings.

To be able to use the measured sequences for simulations, the signals had to be rescaled from voltages into their actual values, partly corrected and transferred into per unit dimensions. For this, a consistent set of nominal values is necessary, which has to be defined firstly, derived from the documentation. A table of stationary states was extracted as a basis for investigations of internal stationary characteristics.

## III. MODEL OF HPP TALA

Studying the plant structure gives an idea of the signal flow in the plant. Every power plant is unique, but the main parts are essentially the same.

Fig. 2 shows the structural overview, which is typical for hydroelectric plants with Pelton runners. Special for HPP Tala is the number of 5 nozzles and the very long head race tunnel (water channel).

The idea of this kind of high quality modeling is to identify the subparts, subsequently, step by step, supported through the comparison of interface signals and simulation results. The quality of modeling can be improved by increasing the number of measured signals.

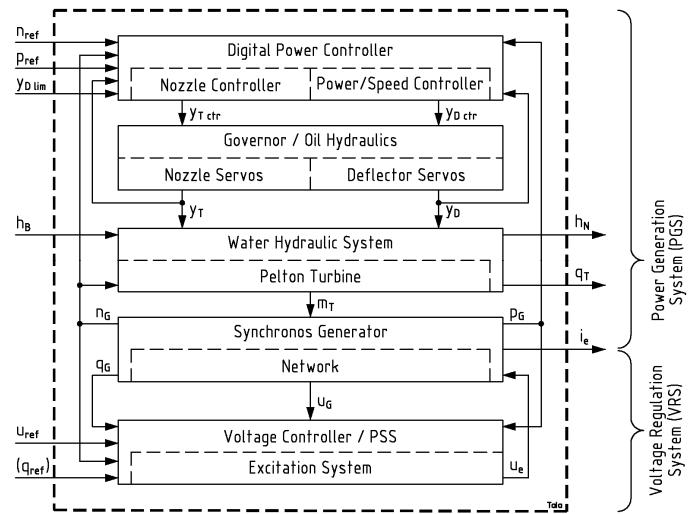


Fig. 2. Structural overview of HPP Tala with representation of sub-models

### A. Sequences and procedures

The basic modeling work has been done in *Matlab/Simulink*. This software package is simple to handle and flexible in programming.

The first steps are to justify the stationary behavior and to define the practical nonlinear characteristics. It is an iterative process, as not all stationary parameters are known from the beginning. For the work, the per-unit-system is constantly used; it simplifies the handling and signal linking enormously.

The modeling work was executed in the following order:

- Creating the turbine power characteristic (Fig. 4),
- Calculation of stationary turbine flow and friction factors (iterative process  $\circlearrowleft$  because reliable flow measurement were not available),
- Approximation of the turbine cross-section vs. nozzles opening function, conjugation function,
- Identification of water hydraulic part,
- Identification of oil-hydraulic part of governor and digital nozzles controller,
- Analysis and modeling of digital power controller,
- Unification of 'Power Generation System' (PGS) and adjustment in closed-loop-simulation,
- Identification of voltage controller.

Because the THP model is going to be implemented in the network simulation software *DIGSILENT PowerFactory* as a subpart of the complete Bhutan system, the generator model was not added and unified to the ‘Voltage Regulation system’. For the PGS, a simplified mechanical model was used (see section III.E).

Whenever automatic parameter identification for one or more parameter simultaneously was necessary, the *Matlab* application of the Nelder Mead Simplex Algorithm with the mean square method as quality criterion was used.

### B. Hydraulic part and turbine model

The model of the water hydraulic system represents the fluid mechanical system comparable to an equivalent Pi-model of a power line. The traveling waves are slurred this way to their fundamental wave. Scientific investigations verify that this level of detail measures up the requirements of power system simulations [1]. Fig. 3 shows an overview of the main parts of the hydraulic system for simulations focused on THP unit 2, reduced to a nonlinear water channel – surge chamber – single penstock simplification with water elasticity. The time constants were calculated considering the physical construction dimensions and later on refined by identification (Table I).

The discharge  $q_T$  for each unit is assigned 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 can be modified to a deflector effected  $a_D$ .  $h_N$  represents the net head, while the gross head  $h_B$  in stationary state is reduced by the pipe friction pursuant to:

$$h_N = h_B - \Delta h = h_B - k_f \cdot q \cdot |q| \quad [\text{p.u.}] \quad (2)$$

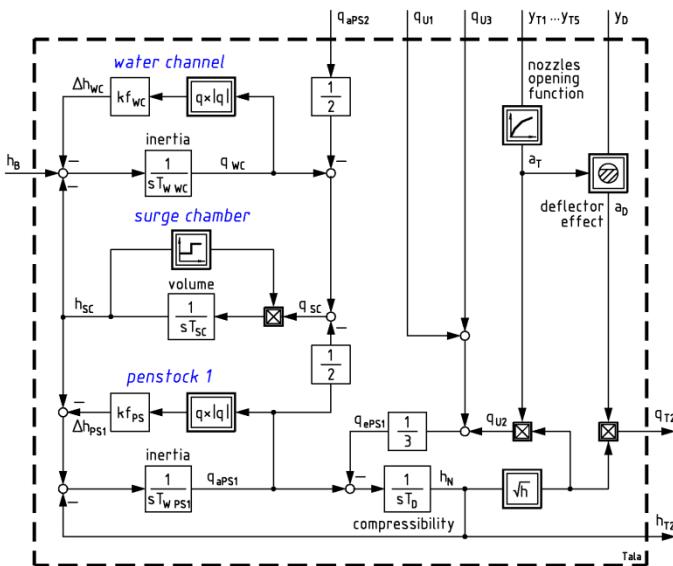


Fig. 3. Simplified sub-model of water hydraulic part of HPP Tala, particularly for unit 2

The deflector of HPP Tala is of the diverting type in contrast to the divider type (cut-in-deflector). The effect of this type of deflector is highly nonlinear. It is represented by an interference factor which expresses the loss of torque dependent from the penetration depth of the jet radius. The factor inside of the ‘deflector effect block’ was identified from measurements of load shedding tests.

TABLE I  
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 | 11.0 s      | 1040 s   | 1.13 s / 1.07 s | 0.3 s / 0.3 s  | 3.8 %       | 4.5 %       |

The turbine model is derived from the manufacturer’s hill chart for the model (prototype) turbine, where power and efficiency are visualized as a function of flow and net head. The grid points were taken from the hill chart, inter- and extrapolated and transformed into a 3-dimensional lookup table. Fig. 4 shows the graph of the 3-dimensional function.

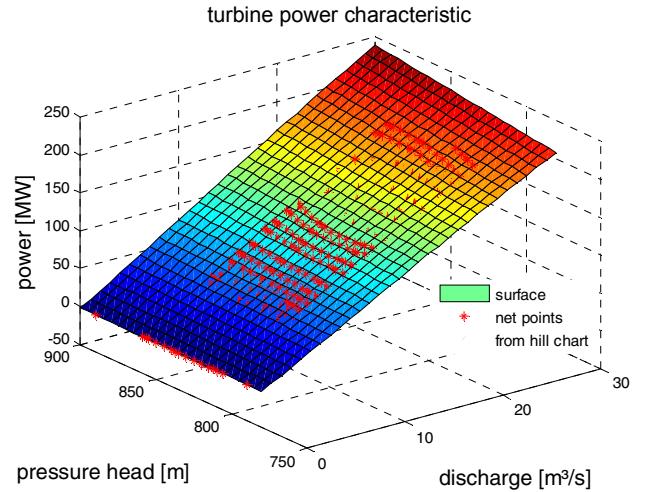


Fig. 4. Turbine power characteristic (subpart of Fig. 5)

As the mechanical torque output of the turbine is also dependent on the turbine speed, the speed dependency under compliance with the run-away speed and the standstill torque as well as the mechanical losses were added to the model as shown in Fig. 5 [2]. Recapitulating the power output of the turbine model is now 4-dimensional with  $p_T = f(q_T, h_N, n_T)$ . The starting time constant of the rotational unit, consisting of the Pelton runner, the shaft and the generator rotor amounts to about 10 s.

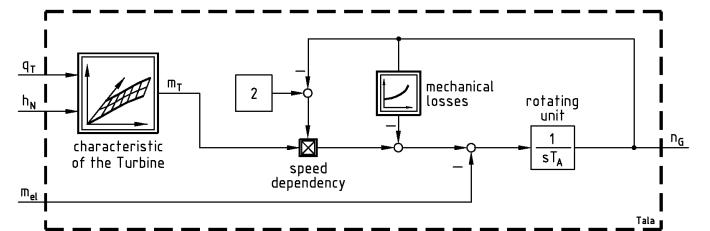


Fig. 5. Sub-model of turbine and generator mechanical model

### C. Governing system

The governing system consists of a digital controller unit with control paths for power/speed control (explained in section III.D) and nozzle control as well as the oil-hydraulic system (two most upper blocks in Fig. 2). The electro-hydraulic transducer (EHT), acting as the interface between both systems, transforms the electrical control signal into a mechanical movement. The movement is amplified via a pilot servomotor to be able to control the main valves of servomotors for deflector and the five nozzles (Fig. 6). The pilot and main servomotor of a single nozzle is shown in Fig. 6 below. Physically, there are 5 nozzles following the position feedback of the deflector.

According to the position of the nozzle  $y_T$ , the water jet gets a cylindrical form with variable cross section  $a_T$  (Fig. 7, a-c). The stationary characteristics between  $y_T$  and  $a_T$  was already integrated into the water hydraulic subpart (Fig. 3).

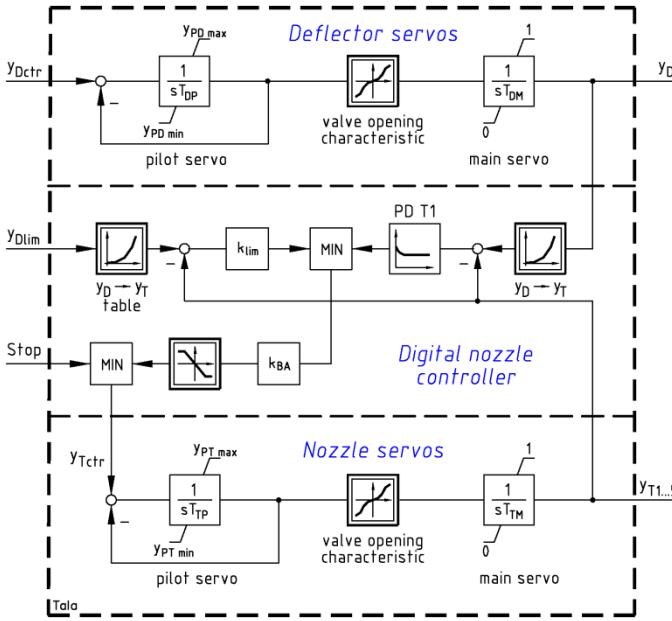


Fig. 6. Sub-model of oil-hydraulic part of governor as well as digital nozzle controller, exemplary for one nozzle

The power/speed controller forces the deflector to move very fast to a certain position. The nozzles follow slowly accordingly to their new stationary position, determined by a ‘deflector-nozzle conjugation table’, which fixes the relation between deflector and nozzle position. The conjugation table causes the deflector edge standing constantly at a small distance above the jet radius under stationary conditions. As the speed of the deflector is much faster than the speed of the nozzles, the deflector affects the water jet during fast closing processes (load rejection) to prevent the turbine from overspeeding under islanded conditions (Fig. 7, d).

Besides the controller function, the traversing velocity of deflector and nozzles are determinant for the performance of the plant in transient processes. The maximal moving velocity of the main servomotors are dependent on their respective time constants and the adjustment of the maximal opening positons of the main valves. Table II shows the identified

values, which are not generally known and can only be found by tests. The practical minimum opening/closing time of deflector for their full range of movement were measured equal to 10.4 s / 1.6 s, whereas for the nozzles 2, 4 and 5 as 34 to 39 s / 18.6 to 20.3 s and for the nozzles 1 and 3 as 37 to 39 s / 14.5 to 14.9 s.

TABLE II  
IDENTIFIED PARAMETERS OF OIL-HYDRAULIC SYSTEM

| Parameter        | $T_{DP} / T_{TP}$ | $T_{DM}$ | $T_{TM \text{ 1...5}}$ | $Y_{PD \text{ max}} / Y_{PD \text{ min}}$ | $Y_{PT \text{ max}} / Y_{PT \text{ min}}$ | $(1...5)$      |
|------------------|-------------------|----------|------------------------|---|---|----------------|
| 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 |

From the introduced values, it can be seen that the nozzles 1 and 3 show a bit different behavior with slightly faster closing speed. The reason are different operational modes for different power stages. At a power output lower than 40 MW only the nozzles 1 and 3 are active, thus they are known as lead jets. The nozzles 2, 4 and 5 are disabled by the stop signal shown in Fig. 6 at the digital nozzle controller part. For generator active power values higher than 40 MW, the plant changes to the 5-nozzle operation mode. The changing process between the operation modes is accompanied by transition processes and a non-stable power output.

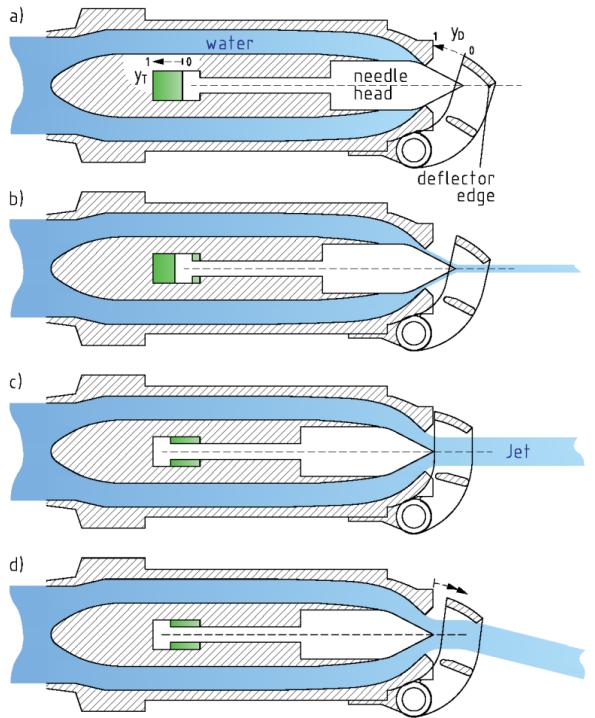


Fig. 7. Working principle of nozzles and deflector; a) closed position, b) slightly opened position, c) fully opened position, d) interference of the deflector during a closing transition process

### D. Power/Speed controller

The digital power/speed controllers of HPP Tala consist of different control paths, which are active under different operational condition.

On one hand, there is the combined speed and power controller (NPC) with power statics. It is a P-type controller,

equipped with permanent and transient droop and acceleration of the  $\Delta n$  signal. On the other hand, there is a pure power controller (PC) with I-characteristic, which is always active in interconnected operation when the speed is inside of the defined speed band from 47.5 to 52 Hz (hysteresis of 1 %) (see Fig. 8). There are further limiter and run-up functions which are not shown in the simplified picture, but included in the model.

The NPC contrastingly is active before synchronization, when the generator circuit breaker (GCB) is switched off or when the generator speed gets outside of the defined speed band in grid interconnected condition.

The usually used control equation for stationary state of a combined speed/power controller is:

$$\Delta n + \sigma_p \cdot \Delta p = 0 \quad . \quad (3)$$

Due to the very slow change of active power, connected with the slow nozzle speed, the much faster feedback of the deflector position  $y_D$  is used for stability reasons as follows:

$$(n_{ref} - n_G) + n_{trim} + \sigma_p \cdot (p_{ref} - p_G) = 0 \quad . \quad (4)$$

Because  $p_G$  and  $y_D$  does not have a proportional relation, the factor  $n_{trim}$  had to be introduced to get the nominal speed in synchronization mode. The deflector opening position in no-load operation is about 0.3 p.u., the permanent droop  $\sigma_p$  is adjusted at 10 %, the speed reference is 1 p.u.. Therefore, a correction factor  $n_{trim}$  of about 3 % is necessary to reach the synchronization speed.

After grid interconnection,  $\sigma_p$  is switched to 6 % and the speed reference is adapted by the ‘speed track’ block according to the actual speed.

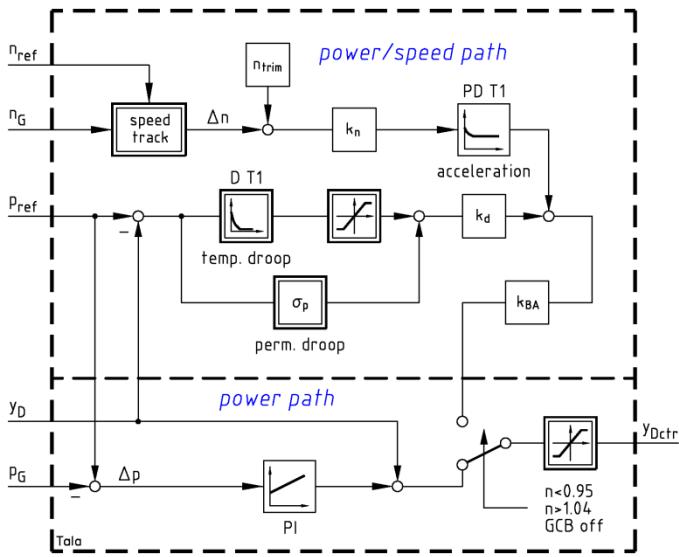


Fig. 8. Sub-model of the digital power/speed controller, simplified without opening limiter, start up functions and disabled controller paths

In case of islanding the generator with closed GCB, the PC path is not able to stabilize the frequency. The speed will reach the band limit and the controller switches over to the NPC path. The speed reference will now be kept at the

boundary of the speed band, managed by the ‘speed track’ block. When the speed gets back inside of the speed band (under the hysteresis limit), the controller switches back to the PC path. This switching logic can cause instabilities under certain conditions (compare chapter V).

#### E. Voltage controller / Generator

The digital voltage controller corresponds to the IEEE standard controller ST1A connected to a potential-source controlled rectifier exciter system [3]. It is a simple P-type controller consisting of an amplification gain with transient gain reduction, reactive current compensation and influence of a dual input Power System Stabilizer (type IEEE PSS2A, frequency input disabled) for damping of power swings. As only the power generation path of the plant was modeled in Matlab/Simulink, the voltage controller is not a part of the Simulink model yet. It will be added during migration of the model into DIgSILENT PowerFactory Software. A separately done revision showed that the voltage model is able to fit the measurements of the controller output signal.

Due to the above mentioned reasons, the generator model was reduced to its mechanical equivalent connected to the strong Indian grid. The easiest analogue of this system is a two-mass-model, representing the Tala rotating unit as a small and the Indian system as an almost infinite big mass. The elastic coupling between the masses generates the electrical synchronous torque according to the rotor load angle relation:

$$m_{el\ syn} = \frac{u \cdot u_p}{n \cdot x_d} \sin \vartheta \quad [\text{p.u.}] \quad (5)$$

While the synchronous torque is proportional to  $\sin \vartheta$  and dependent on the excitation, there is also a reluctance torque in salient pole generators, which is independent of excitation and proportional to  $\sin 2\vartheta$ . In the two-mass-model the torque can then be further expressed as:

$$m_{el} = \frac{1}{n} (k_{syn} \sin \delta + k_{reluc} \sin 2\delta) \quad [\text{p.u.}] \quad (6)$$

Another possibility is to model the generator according to [4] as nonlinear model of fifth order. In this case, also the network has to be calculated in RMS values, to provide the complex generator voltage. As this method is much more wasteful, the easier way was chosen for this investigation. Anyway, to a later stage of this project, the model will be implemented inclusive of voltage controller to the DIgSILENT PowerFactory Software, where the complex generator voltage is already built in. The influence of the generator-voltage controller system for stability investigations will be considered then. For this first stability checks those effects are secondary.

#### IV. MODEL VALIDATION / SIMULATIONS

The sub-models according to Fig. 2 were built and separately tested. The last step was the unification of the sub-models to a complete model, which enables the simulation of the processes in closed loop.

Measurement delays had to be implemented owing to real time scenarios, where the signals and feedbacks have to be

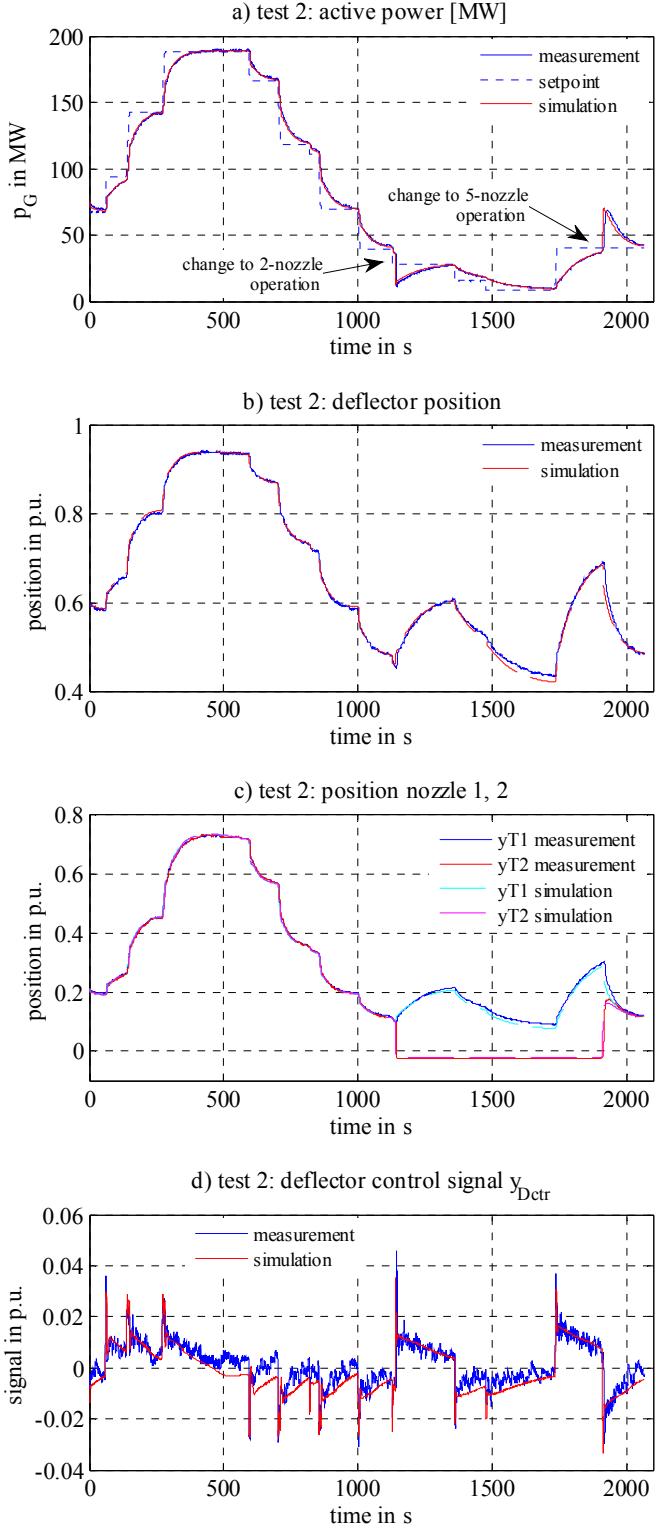


Fig. 9. Comparison of measurement and simulation for test 2: change of power set-points within the whole power range

inevitably transformed into the controllers' signal format, where small delays are unavoidable. For the proof of accuracy of the model, one comparison of measurement and simulation in interconnected operation mode (test 2) and one load shedding process (test 25) are shown as valid examples. (Fig. 9 and 10)

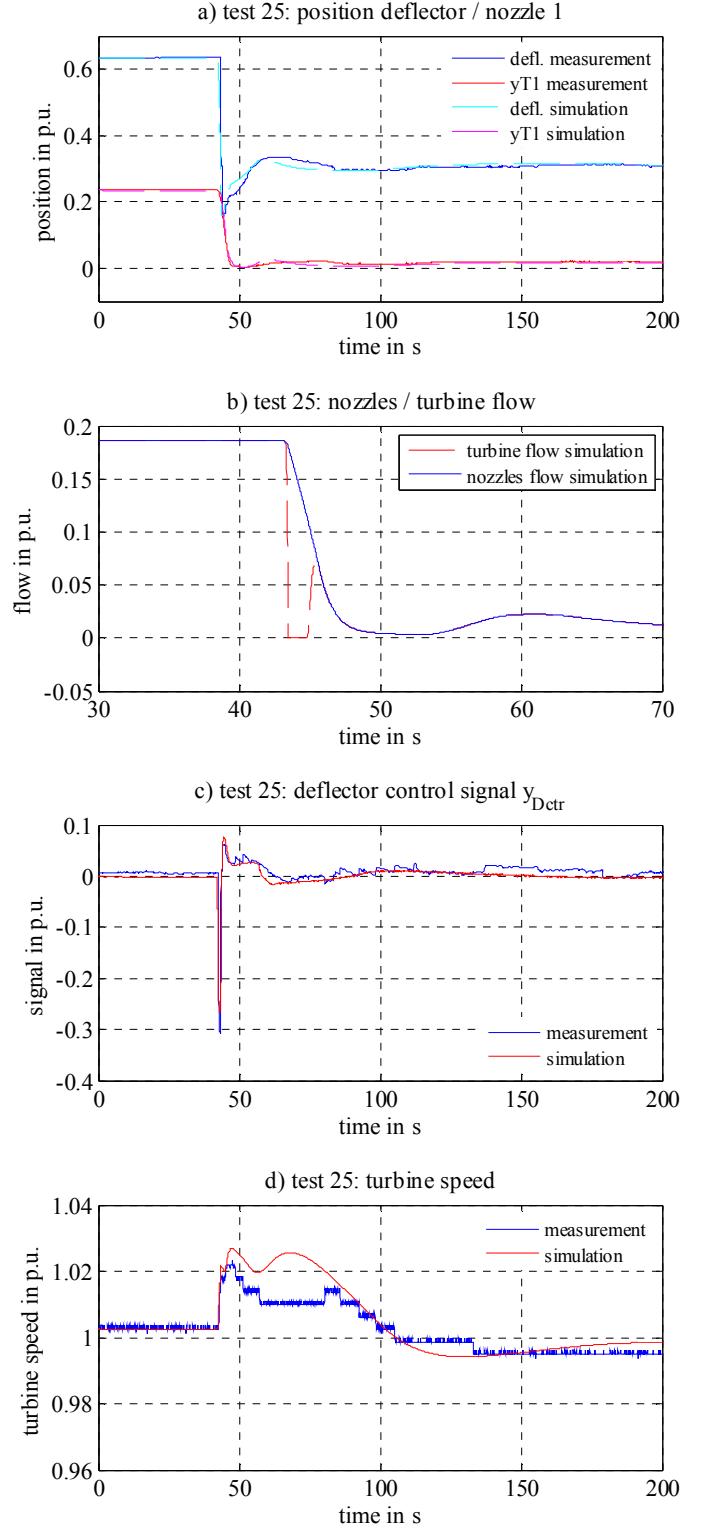


Fig. 10. Comparison of measurement and simulation for test 25: load shedding of 30 MW in 2-nozzle operation

Of course for all of these simulations the model works with the same structure and set of parameters. The state of the plant is detected by the control structure and the model acts like the real plant under the boundary conditions of test ambience.

Fig. 9 shows the results of a change of power set-points within the whole operational range. Even the transitions from 5-nozzles-operation to 2-nozzles-operation and back are

included. In test 25 (Fig. 10) a load of about 30 MW was shed by opening the generator main circuit-breaker (GCB). Also the simulated flow of water through the nozzle assembly and the diverting effect of the deflector are shown in Fig. 10 b. For both simulations, it can clearly be seen, that the model is able to fit the real behavior with a high accuracy. Slow as well as fast changes and different controller paths can be modeled with a comparable high quality.

Fig. 11 and 12 illustrate the validity of the model for further test measurements. In Fig. 11 a sequence of 3 tests in a time range of more than one hour is presented. This wide range is needed to get a proof of the surge shaft oscillations with a very high period length, which occur after a fast shut down in test no. 8. In the zoomed-in picture below, the fast slightly damped penstock traveling waves can be recognized. The different oscillations of very different time ranges are reproduced very close to the measurement signal. From this comparison, it can be derived that the fundamental wave model of water hydraulics is sufficient for these purposes.

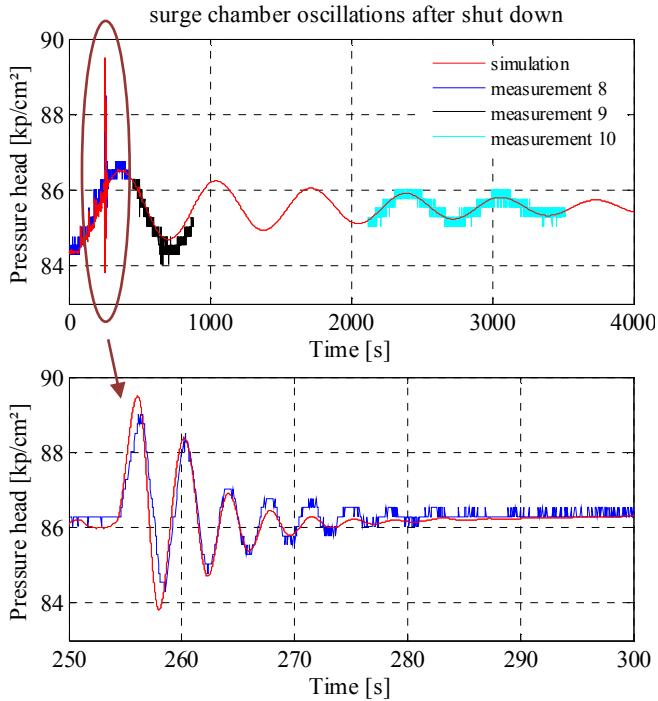


Fig. 11. Proof of validity in the water hydraulic part: oscillations in different time ranges, surge shaft oscillations and penstock traveling waves

The speed simulation in Fig. 12 according to test 23 shows a good fit of ramp rates for speeding up and slowing down of the rotating unit after a load shedding of full load (170 MW). Responsible are the inertia of the rotating system with an identified time constant of 10 s and the no load losses (mainly mechanical losses) of about 2.3 MW at nominal speed. During this test, the unit tripped because of an unknown reason. Anyway, the reaction of the system under cooperation of the deflector can accurately be simulated.

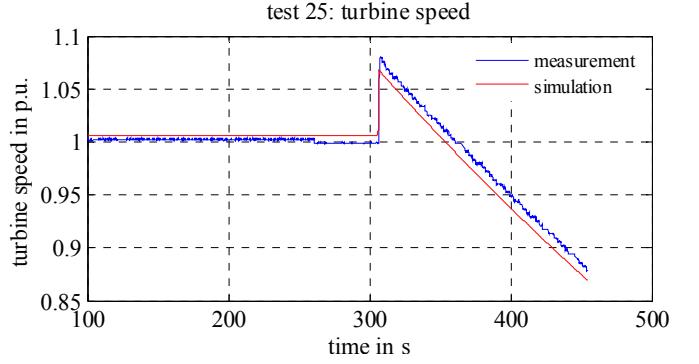


Fig. 12. Speed simulation of a load shedding test of full load (170 MW)

## V. INVESTIGATION OF ISLANDING PERFORMANCE

Based on the introduced model, some initial simulations of islanding performance of the existing constellation can be conducted. It is assumed, that one unit is running in separate operation and suddenly an arbitrary islanded load, after a network disconnection, has to be taken over. A usual load frequency dependency factor of 2 p.u. is considered.

Fig. 13 shows some examples of stable and unstable transition. For the transient process the limit of electrical over speed detection at 55 Hz (1.1 p.u.) as well as the plant disconnection limit of 47 Hz (0.94 p.u.) has to be taken into account (marked with red lines in Fig. 13). The speed band limit exit in power control mode is marked with solid green lines; the smaller speed band entry because of the hysteresis is marked with dashed green lines.

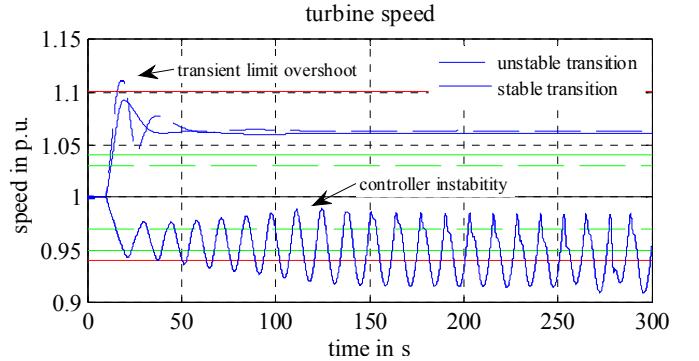


Fig. 13. Speed simulation of transitions from interconnected to islanded operation, initial load 70 MW, islanded load 40, 50, 50 (stable) and 80 MW

For cases when equation (4) gives a speed settlement between  $1.04 \leq n \leq 1.1$ , a stable transition can be achieved, when the transient overshoot doesn't cross the limiting lines. In the example shown in picture 13 this is the case only for the transition from 70 MW to 50 MW. For the transition from 70 MW to 80 MW, controller instability can be expected, where the controller continuously switches between NPC and PC mode and fomentes sustained oscillations.

Fig. 14 shows a generalization of the transition combinations in a grid of 10 MW steps with the above mentioned boundary conditions. There is a wide band of steady stable working points, but due to the transient overshoot only a small band of dynamically stable transitions exist. A maximal load step of only 30 MW can be balanced.

Also the change of operation mode, particularly from 2-nozzle to 5-nozzle operation is problematic because of associated turbulences.

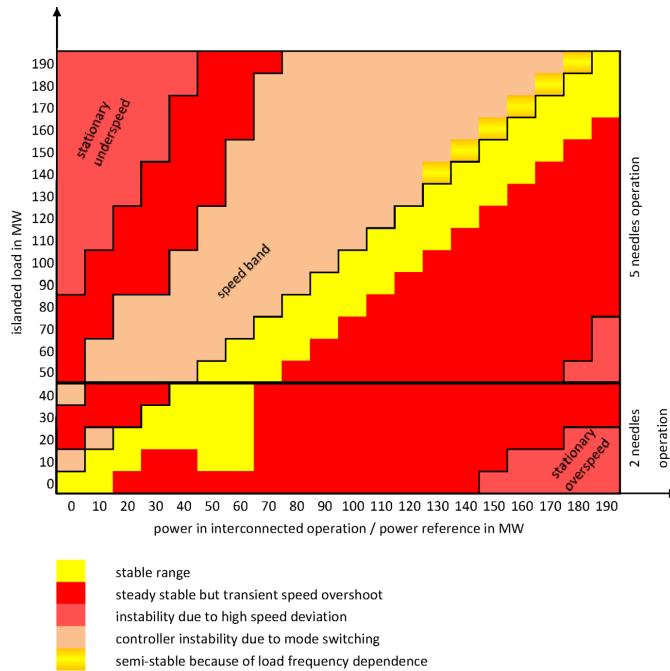


Fig. 14. Generalization of stability aspects for transition combinations from interconnected to islanded operation in a grid of 10 MW steps of THP

A broad spectrum of investigation in this field as well as investigations of measures to improve the island mode performance are in the focus of the future activities in this project.

## VI. CONCLUSION

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

The first Hydropower plant HPP Tala was measured and a practical oriented simulation model was developed. The validity of the model was demonstrated for different operation scenarios. The results show a high quality modeling work, which will be the basis of extensive investigations with the focus on isolated operation of the Bhutan's power network. First investigations with the Tala model show, that the performance of the plant is still not optimized for operation under islanded conditions. The adaption of parameter settings or even the overall control structure can further improve the performance of THP.

The migration of the model into the network simulation software *DIGSILENT PowerFactory* enables extensive investigations, concerning the behavior of the complete system in island mode operation and the transition process, which is hardly possible to test in practice. The development of an islanding concept and a network restoration plan as well as the optimization of control structures can be considered as

further goals on a dynamic model basis.

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## VIII. BIOGRAPHIES



**Karchung** was born in Tashiyangtse, Bhutan, on March 5, 1990. He is studying the final year BE in Electrical Engineering at College of Science and Technology (CST), under Royal University of Bhutan, Bhutan. His special field of interest includes Renewable energy and Hydropower.

Karchung was a scholarship supported member of the Bhutan's students exchange group at the University of Rostock, Germany, for Modeling and Simulation of Bhutan's Hydropower plant, Tala.



**Axel Holst** was born in Rostock, Germany, in May 1970. After his professional training as electrician he studied at the University of Rostock.

He has professional experience in planning and design of electrical networks and in the field of wind turbines. Since 2001 he works as a scientific assistant and PhD student at the Institute for Electrical Power Engineering at the University of Rostock. His special field of interest are calculations and simulations in electrical power systems as well as power quality. He is the coordinator of the DAAD funded project "Analysis and Modelling of Bhutan's Hydropower Plants".



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