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Investigation of the dynamic behaviour of hydro power plants for restoration scenarios

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Abstract

With the deregulation of the European Interconnected Network, a reduction of the system stability and reliability has to be expected. Therefore, the realization possibilities of existing network restoration plans have to be investigated more in detail. The most important elements in a real restoration procedure are the power plants, and especially the hydro power plants if existing and reliable. Therefore, in this contribution, the development of a reality oriented simulation model of the hydro power plant 'Airolo' in the Swiss Alps for power system restoration studies is presented in detail. The francis type power plant belongs to the ATEL Company and is located in the canton Tessin. Islanding tests were performed to record the measurement of the transients. Then with parameter identification, a comprehensive model was developed. Comparisons of the measurements and the simulation results show the high quality of the developed power plant model for all time scales necessary for restoration studies.

Keywords: Power system restoration; Hydro power plants; Reality oriented simulation models; Comparison of measurements and simulations

1. Introduction

In a deregulated electricity market, e.g. in Germany or—as expected—in near future also in Switzerland, several system services are to be provided by the transmission system operator (TSO). One of these services is 'restoration after black-out'. For that, the TSO must rely on certain generation units in its area of responsibility. In a document called 'GridCode' [1], it is described in detail which key requirements of a power plant must be fulfilled to be involved in restoration strategies. It is also described how the owner of a power plant is paid for providing this service. The major key requirements are:

- black-start capability
- capability of islanded operation
- stability after a fast increase or decrease of the load (islanded and connected operation).

It is obvious that these requirements have to be checked or even proved by measurements. On the other hand, there is nearly no practical experience of the state of the transmission grid and how to operate the grid and the generation units during the restoration process due to the fact that black-outs are (fortunately!) quite rare. Up to now, restoration scenarios have often been made plausible only by carrying out load flow studies. These steady-state calculations do not consider the dynamical character of the system during the restoration process. Even in stability studies today, often very simple and restricted models of power plants loads and equipment are used for control purposes. The parameters of these models are often estimated only roughly. Nevertheless, this kind of model is sufficient for investigations concerning the so called global behaviour of interconnected networks (oscillations, primary and secondary frequency control), because the related dynamic transients only influence the usually very well modelled major control loops of these models [2]. But for computer simulations of restoration scenarios, much more detailed models of power plants and power systems are needed, because in these investigations, especially for a particular power plant, all control loops and protection equipment have to be modelled exactly. In this case, all possible transients are important for the whole working range of the plant, from zero to full operation. Especially, protection equipment with different triggering values, non-linearities, and characteristics play a very important role in the dynamics of the restoration process.

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Here, as an example, the modelling prerequisites of the Swiss hydro power plant 'Airolo' equipped with pelton turbines and its electrical and (hydro-) mechanical components for dynamical simulation of a restoration study is described not only to increase the significance of the model, but also to check practically the above mentioned key requirements. The model parameters have been identified based on measurements, made during the transition from connected to islanded operation. The measurements and the simulation calculations have been carried out within the framework of the study project 'DynaSim' of the Swiss TSO's. Within this project also, seven other hydro power plants have been measured and identified [3]. This project will finally be completed by a computer simulation of several restoration scenarios, which will be published later.

2. The power plant

The power plant 'Airolo' with two 30 MV A units (Fig. 1) is part of the cascade system 'Lucendro' (Fig. 2) situated in canton Tessin in Switzerland. Usually it is operated in the programme mode and if necessary, for secondary frequency control purposes.

3. Measurements

The dynamic behaviour of a power plant can best be derived from measurements during the transition from interconnected to islanded operation. Although the maximum power decrease is reached by the transition to zero operation, those measurements cannot show the interactions of the power plant components, because all control signals then are set to be zero. Fig. 3 shows the basic scheme of the facility and the available signals (marked by a circle) which could have been measured. The signals are

- active power (p_G)
- reactive power (q_G)
- speed (n_G)
- generator voltage (u_G)
- excitation voltage and current
- turbine gate position (y_T)
- water flow to the turbine (q_T)
- water pressure (h_{eDR}) in terms of the height difference between turbine (ground line) and lake Lucendro (h_{OW})
- position of the deflector (y_D).

Fig. 1. Swiss map, location of hydro power plant Airolo.

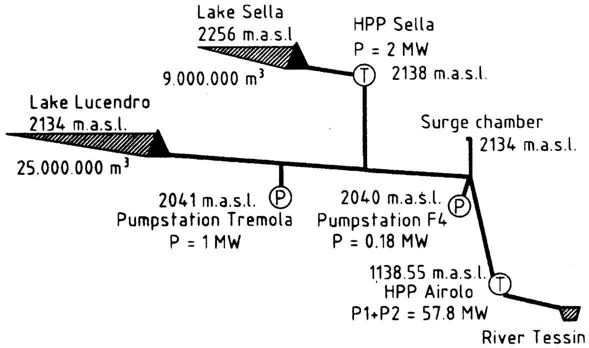

Fig. 2. Hydro power system 'Lucendro' with power plant 'Airolo'.

It is sufficient that only one unit is investigated. The other unit may remain in its planned programme operation, because it is expected to be identical in its dynamic behaviour. The influence of the other unit to the hydraulic system is considered in the model.

The measurements which have been performed consist of three steps:

1. Starting from connected operation, a switch (cf Fig. 3, switch 'S') is opened to disconnect the unit and the load from the transmission grid.
2. Active power and reactive power are changing from the initial values to values according to the supplied load (cf Fig. 3, 'consumer' with $P_L \approx 1.9$ MW, Hospiz 'Gotthard'). This leads to another working point.
3. When the transition processes have worn off, the unit can be re-synchronized and prepared for further measurements or programme operation.

In this case, seven experiments have been performed, starting from several values of generator active and reactive power, which were partly larger partly smaller than the expected load in islanded operation. The maximum ΔP_G was about 7 MW. The measurement equipment consists of a Laptop computer with PCMCIA-DAQ (16 bit, 16 channels) using the Labview measuring software [4], see Fig. 4.

4. Modelling and identification

Using all available information about the power plant like commissioning and test data a general block scheme,

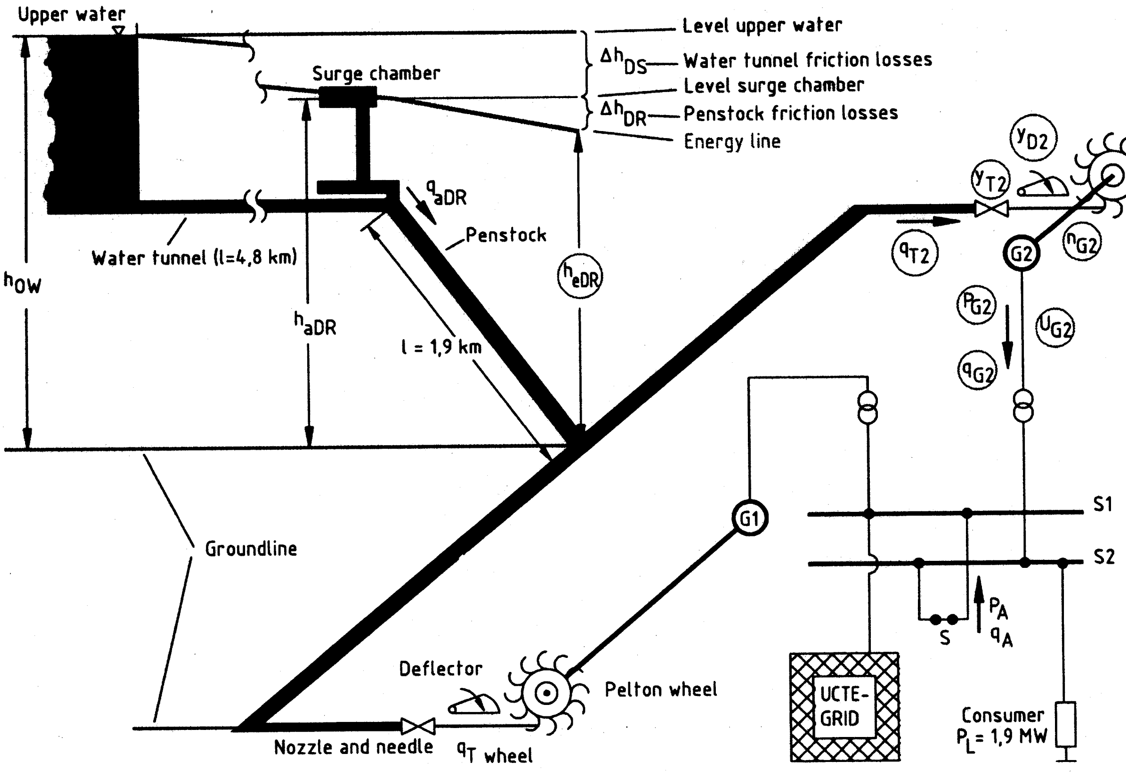

Fig. 3. HPP Airolo, scheme of power plant and grid situation during tests.

'Hydro Power Plant' could been generated (Fig. 5). This general scheme is also the base for the preparation of the measurements. The input signals for the identification algorithm are the measured generator active and reactive power, respectively (cf Fig. 5, p_G and q_G). The parameters of the components, excitation system, generator (electrical part), generator/turbine (mechanical part), hydraulic system and deflector have to be determined in such a way that the simulated and measured output signals (marked by a circle in Fig. 5) fit best in a least square fit algorithm. Fig. 6 shows the excellent agreement of measured and simulated values

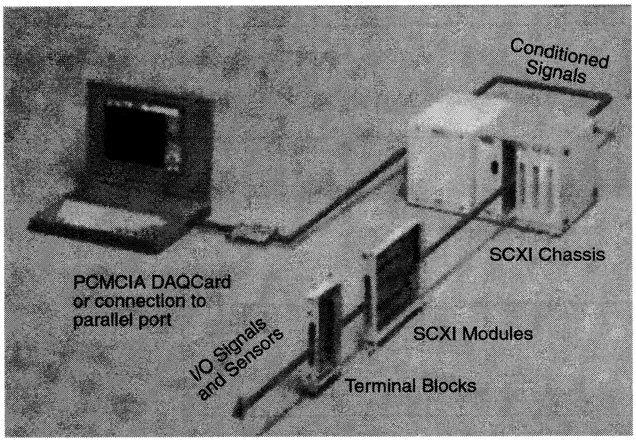

Fig. 4. Measurement equipment in power plant 'Airolo'.

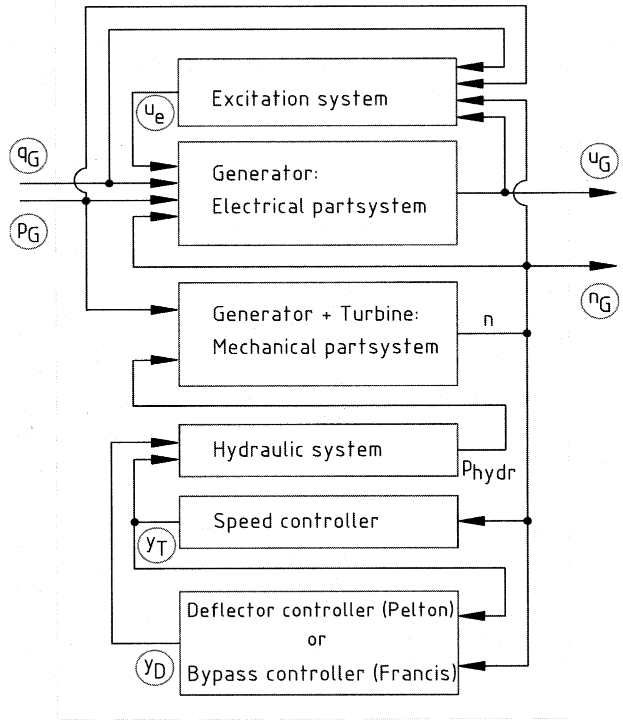

Fig. 5. General block diagram for hydro power plants. Except for the deflector or bypass controller part, it is the same for hydro power plants with turbines of pelton or francis type.

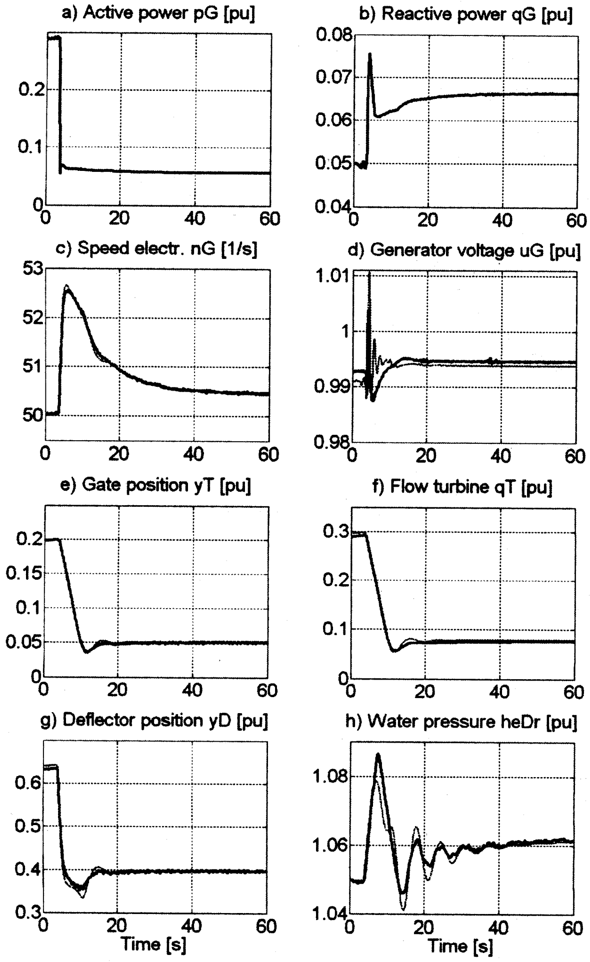

Fig. 6. Comparison between measurement (blue) obtained during the transition from connected to islanded operation and simulation (red).

of input and output signals. The data shown in Fig. 6 have been obtained from an experiment with $\Delta P_G \approx 6.5$ MW.

In Fig. 6a, starting from $P_G \approx 8.4$ MW, the active power decreases to about 1.9 MW in islanded operation according to the consumption of the supplied load (cf Fig. 3). The fast increase of the speed (Fig. 6c) is rapidly limited by the deflector (Fig. 6g) followed by the slower closing motion of the needle (Fig. 6e). Simultaneously, the water flow to the turbine wheel is reduced (Fig. 6f) due to the closing motion of the needle. Because of the steep decrease of the water flow pressure, peaks are induced and because of its large time constant (about 10 s.) the excited oscillations of the water column wear off slowly (Fig. 6h).

5. The turbine controller

As an example, for the detailed modelling, the turbine controller of 'Airolo' is shown (Fig. 7). It is a Sulzer–Escher Wyss controller. A special feature of this type is that the frequency/power characteristics can be changed from the 'Opening Control' mode (OPC) to 'Speed Control' mode (SPC) (cf left part of Fig. 7). This can either be done by the operator maintaining an external switch or an internal signal will be sent out to change the position of the switch if the frequency or the speed, respectively, of the turbine is outside the range between 0.97 and 1.02 pu ($f_0 = 50$ Hz $\Leftrightarrow$ $n_0 = 1$ pu). It is obvious for that type of a turbine controller that the SPC mode is necessary for a stable islanded operation where the generator active power is only determined by the consumed active power of the supplied load. In SPC mode, the frequency is determined only by the speed set point ($\Delta n_I + n_0$) for islanded operation and the static droop σ_P (cf left part of Fig. 7). The selection of the value of Δn_I is according to the expected consumption of

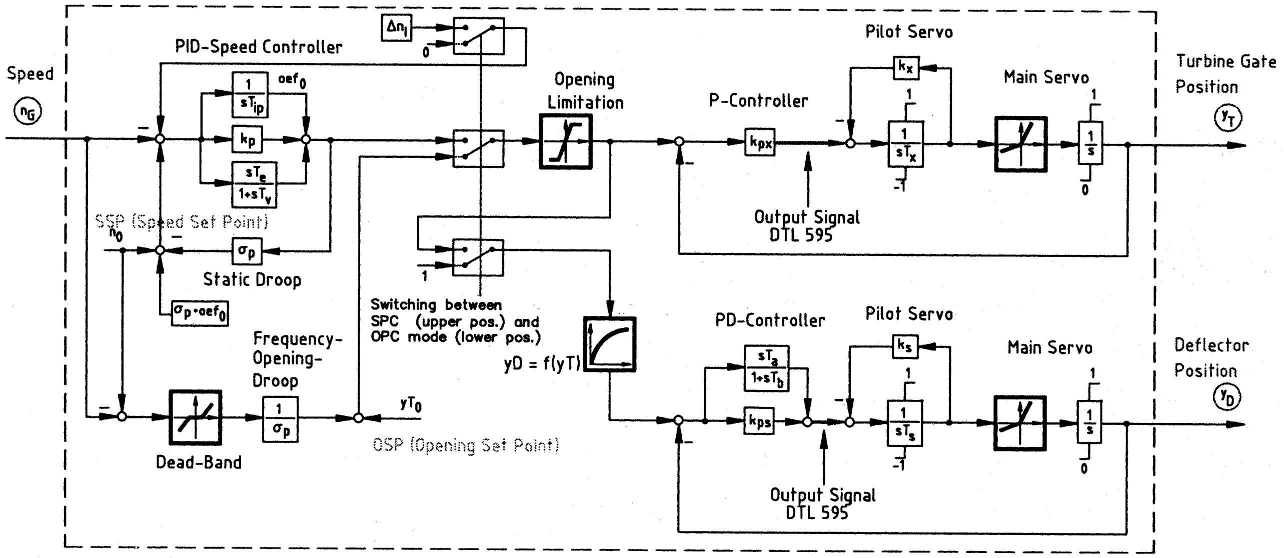

Fig. 7. Turbine controller Sulzer–Escher Wyss of 'Airolo'.

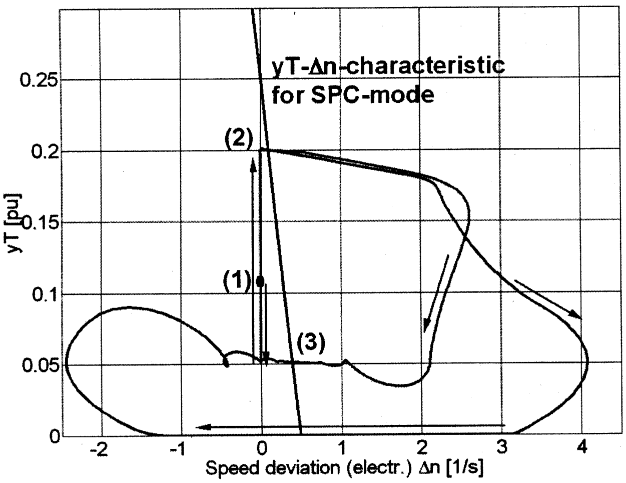

Fig. 8. Static $yT^*(\Delta n)$ characteristic for SPC mode (black line), measured values $yT(t)-\Delta n(t)$ (red), simulated values $yT(t)-\Delta n(t)$ (blue), controller values: $\sigma_P = 3.91\%$, $\Delta n_I = 0.0098$ pu. (1) Switching from OPC to SPC, (2) switching the circuit breaker, (3) stationary point at the $yT-\Delta n$ characteristic.

the load, which has to be supplied in islanded operation. Fig. 8 shows the $yT^*(\Delta n)$ characteristic for SPC mode (black line). Also shown in Fig. 8 are the measured values $(yT(t), \Delta n(t))$ during the transition from interconnected to islanded operation (red). Point (1) marks the start-working point in interconnected operation and manual switching from OPC to SPC mode. At point (2), the circuit breaker is opened for islanding power unit with consumer (loadstep). Point (3) marks the end-working point in SPC mode. During the measurements in point (1), the controller mode was switched from OPC to SPC. Notice that this was done before the loadstep. Then, the unit changed the working point slowly with $\Delta n = 0$ to reach the SPC mode characteristic. But in point (2), the loadstep took place and so the unit reached point (3) in pure SPC mode. The blue curve (blue) in Fig. 8 shows the simulated behaviour of the unit for the case, that point (2) is still the working point in interconnected operation (OPC mode) and the loadstep also takes place in point (2). As shown in Fig. 8, the behaviour is more dynamical (overspeed $54.02\ \mathrm{s}^{-1}$, minimum speed $47.56\ \mathrm{s}^{-1}$) because the controller has to switch in point (2) from OPC to SPC mode internally. Static speed deviation at point (3) is $\Delta n = 0.41\ \mathrm{s}^{-1}$.

6. Simulation

As an example for a computer simulation,the power plant will be tested according to the GridCode requirements 'Stability in islanded operation' and 'changing active power of the supplied load'. The simulation has been performed using DIgSILENT Power Factory simulation software, which allows to define a so called event stack where a user defined sequence of simulation events is listed (Table 1).

Table 1
Event stack for a dynamic simulation

Time step (s)	Event
0	Beginning of the simulation, connected operation
10	Open switch S (Fig. 3): transition from connected to islanded operation
100	Active power of load decreases 50% from its initial value of 25 MW

The load is modelled with a static and a dynamic part (each 50%) according to

$$P = \frac{1}{2}P_0 + \frac{1}{2}P_0(U/U_0)^{k_pU}[1 + k_{pf}(f/f_0 - 1)] \tag{1}$$

$$Q = \frac{1}{2}Q_0 + \frac{1}{2}Q_0(U/U_0)^{k_qU}[1 + k_{qf}(f/f_0 - 1)] \tag{2}$$

where P_0 and Q_0 are active and reactive power of the load at $U_0 = 50$ kV and $f_0 = 50$ Hz and with $k_pU = 1.9$, $k_qU = 1.8$, and $k_{pf} = k_{qf} = 0.1$ [5].

The results of the simulation are shown in Fig. 9 where the lapse of selected values is depicted:

(a) active power of generator
(b) radius of the jet and position of deflector edge (deflector radius < jet radius means deflector is touching the jet)
(c) generator speed
(d) needle and deflector position.

Phase 1 (connected operation) from $t = 0$ to 10 s. All signals are constant due to the steady-state situation. The value of the active power of the generator is according to a preselected value, e.g. according to the energy programme. For that example, the active power of the load is lower than the generator active power.

Phase 2 from $t = 10$ to 100 s. At $t = 10$ s switch S (cf Fig. 3) is opened. Immediately after the disconnection, the active power of the generator is decreasing to the value of the supplied load (≈20 MW) and the speed is increasing. Simultaneously, an internal control signal changes the turbine controller from OPC to SPC operation mode leading to the action of the needle and the deflector according to the SPC characteristics. It is remarkable that the deflector is much faster ($\Delta y_D/\Delta t = -0.55$ pu/s) than the needle ($\Delta y_T/\Delta t = -0.02$ pu/s), hence the steep decrease of the speed is induced by the deflector as long as the deflector is 'destroying' the jet (radius deflector < radius jet), here about 3.25 s. On the other hand, the steep decrease of the speed induces a re-reaction of the turbine controller a few seconds later resulting in a slow increase of the speed, which is determined by the opening speed of the needle. From this moment, the deflector is no longer touching the jet, but—in contrast to the OPC mode (phase 1)—still very close to jet.

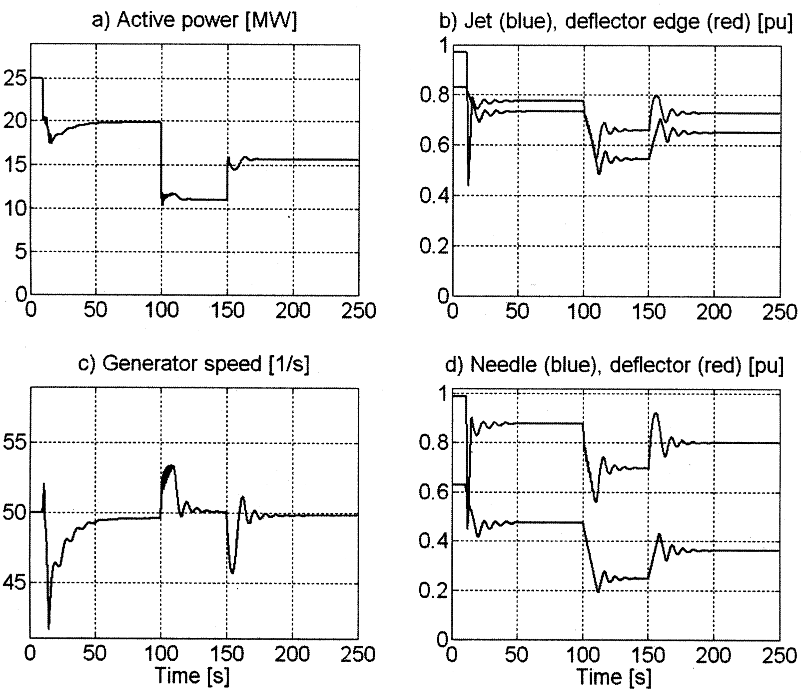

Fig. 9. Upper left: generator active power. Upper right: radius of the water jet (blue) outside of nozzle and position of deflector edge (red) in units of jet radius. Deflector edge < jet radius means deflector is touching the jet. Lower left: speed of unit. Lower right: position of needle (blue) and deflector (red). Phase 1, $t = 0-10$ s: connected operation. Phase 2, $t = 10-100$ s: at $t = 10$ s switch S (cf Fig. 3) is opened. Phase 3, $t = 100-150$ s: $\Delta P_{\mathrm{Load}} = -50\%$. Phase 4, $t = 150-250$ s: $\Delta P_{\mathrm{Load}} = +10\%$.

Phase 3 from $t = 100$ to 150 s. Simulation phase 3 was started at $t = 100$ s after the oscillations of the signals in phase 2 weared off. At $t = 100$ s, it is assumed that the load is reduced to 50% of its initial value. The behaviour of the needle is similar to phase 2 as the needle is closing in contrast to the deflector. It does not destroy the jet as in phase 2, but it scratches the jet, which leads to not only small but also fast oscillations of the speed and also the active power (cf the period between 100 and 108 s in Fig. 9).

Phase 4 from $t = 150$ to 250 s *(end of the simulation).* At $t = 150$ s, it is assumed that the load is increasing +10%. This is followed by a steep decrease of the speed and active power, because the opening of the needle is relatively slow, $\Delta y_{\mathrm{T}}/\Delta t = +0.02$ pu/s, same as the closing speed. But after a few seconds, the power lack can be compensated and the whole system (power plant and load) is in a stable steady-state situation. Remark, the deflector is not touching the jet. The final speed is $n = 0.996$ pu, which is equivalent to $f = 49.8$ Hz, according to the SPC characteristics.

Because of the measurements and the results of the simulation, it can be expected that the power plant 'Airolo' fulfills the key requirements for restoration of the network. However, the overall behaviour of 'Airolo' reflects the difference of power plants equipped with pelton turbines compared to those equipped with francis turbines. The reaction of the needle is quite slow and the reaction of the deflector is very fast but also very steep leading to a large decrease of the speed. In Switzerland, many other power plants are equipped with pelton turbines. It must be examined for the special situation whether these power plants are also fulfilling the requirements for network restoration [6].

7. Conclusion

With the ongoing liberalization of electricity markets, restoration strategies after severe disturbances have to be examined in advance. For these examinations, correctly developed dynamic models of the power plants and power systems are necessary. It is obvious that the power plant models are the most complicated elements of a power system model. The power plant model dealing with restoration scenarios has to be valid for the whole working range from zero to full operation. On the other hand, the model order should be low, because there could be several dozen power plants working together in one power system model. As an example, for the capabilities of the model, a simulation dealing with islanding the power plant was performed.

This paper shows the possibilities of high quality modeling for a hydro power plant in the Swiss Alps, considering the problem of limiting the complexity of the model for better handling.

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