DYNAMIC SIMULATION OF A 110-KV-NETWORK DURING GRID RESTORATION AND IN ISLANDED OPERATION

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ABSTRACT
This paper presents decisive factors for a stable islanded grid restoration and operation. To get a detailed replication of the electrical conditions during grid restoration network, operators are dependent on dynamic simulations. Therefore, the 110-kV-grid of the Austrian network operator KELAG Netz GmbH (KNG) and the generation units of the Austrian power plant operator KELAG are modeled in a simulation program. By evaluating the simulation model with measured time courses of frequency and active power a realistic simulation model of the real system is obtained. Hence, the grid restoration plan of the KNG is verified and its possibilities of optimization are shown. Completing the restoration plan with a new built generator is determined as well. Finally, an optimized grid restoration plan for islanded grid restoration is provided.

INTRODUCTION
The situation of the liberalized electricity market in Europe combined with the additional power line loading caused by power trading along with the continuous increasing power consumption can lead to load situations of the integrated European network near the capacity limit. Recent examples with considerable impact on whole Europe (e.g. September 2003, November 2006) show the need of an established and detailed grid restoration plan. The difficulty for the network operator is to test the grid restoration plan under realistic conditions, especially with feasible load characteristics, without endangering public power supply.

In 2005 the KNG and the power plant operator KELAG performed islanded operation tests without negative effects on consumers. During these tests a part of the 110-kV-transmission network was separated from the rest. Loads were substituted by pump loads and the critical steps of the grid restoration plan were processed. For offline evaluation active and reactive power, voltage, frequency as well as hydraulic pressure at the turbine inlet were recorded in 1 sec interval.

To optimize the restoration plan, a dedicated software simulation model based on the test results was developed. Validation of the model was done by comparison of simulated and recorded time courses.

DEVELOPMENT OF THE DYNAMIC SIMULATION MODEL
For simulation the software package NEPLAN with the embedded dynamic simulation module SIMPOW is used. The main dynamic components of the modeled grid-frame, such as generators, hydro governors with penstock and the voltage regulators, are transformed in modified IEEE-standard models.

All the modeled power plants are hydro power plants with Pelton or Francis turbines.

Generators
The electrodynamic parameters of the generators are quite completely documented by the power plant operator. Missing parameters are chosen from typical range of values derived from literature [1]. Saturation effects are also considered by implementing the no-load characteristic of each generator. On the mechanical side the inertia constant H of the machines respectively the rotating energy W plays an important role in the oscillatory behavior of the considered system. The inertia constant of a generator is defined as [1]:

\[ H = \frac{J \cdot \omega_{0,m}^2}{2 \cdot \frac{V}{A_{base}}} \]  (1)

where J is the moment of inertia of the generator and the turbine wheel in terms of kgm², \( \omega_{0,m} \) is the rated angular velocity in mechanical radians per second and W is the stored energy at rated speed. Since data from the moments of inertia of the turbine wheels are not documented it can be estimated by [2]

\[ J_{nrb} = J_{gen} \cdot (0.05...0.15) \]  (2)

Figure 1 Coherence between the moment of inertia and the stored energy at rated speed [3]
Figure 1 shows the moment of inertia and the stored energy at rated speed of the involved generators. It can be seen that even if the moment of inertia of the generators M4.1 and M4.2 is a multiple of the other generators their stored energy at rated speed is comparatively low. As a fact the stored energy at rated speed is an important parameter for the system stability especially in islanded grid restoration and operation.

**Hydro turbine and penstock**

For the hydro turbines occurring in the modeled grid section the predefined library model, based on the PSS/E HYGOV model (Figure 2), is used. A determinant factor for this model is the water starting time $T_W$. It describes the time that is needed to accelerate a water column to a certain velocity after a step change in gate opening and is defined as [1]:

$$T_W = \frac{L \cdot Q}{A \cdot h \cdot g}$$

where $L$ is the length of conduit, $Q$ is the water-flow rate, $A$ is the pipe area, $h$ is the hydraulic head and $g$ is the acceleration due to gravity. The parameter $AT$ in Figure 2 describes the relation between the ideal and the real gate opening. A drawback of this model is the restriction to simple hydraulic systems. Coupled systems with several turbines sharing the same penstock cannot be simulated.

**Hydro governor**

The hydro governor and its actuators are the determinant devices for transient stability in isolated operations. Their response is very slow from the viewpoint of transient stability. For digital hydro governors the predefined SIMPOW model in Figure 3 was used. The transfer function of the controller unit is

$$R(s) = \frac{K \cdot (1 + s \cdot T_s)}{(1 + s \cdot T_1)}.$$  \hspace{1cm} (4)

Figure 3 Model describing the hydro governors [4]

Compared to the transfer function provided by the manufacturer

$$G(s) = \frac{\frac{1}{b_p} \cdot (1 + T_s \cdot s)}{1 + T_s \cdot s \cdot \left(1 + \frac{1}{K_p \cdot b_p}\right)}$$

it can be seen that

$$K = \frac{1}{b_p} \cdot T_s = T_N \cdot T_1 = T_N \cdot \left(1 + \frac{1}{K_p \cdot b_p}\right).$$  \hspace{1cm} (6)

Some of the older analog governors had been exchanged after the grid restoration test to modern digital devices. Actually it was not possible to reconstruct the detailed parameter settings of the old devices. It was decided to use the parameters of the digital governors, which of cause complicates the comparison of field test and simulation. For islanded operation hydro governors typically use a special parameterization which needs to be considered for the development of the simulation model. The parameters $K_p$, $b_p$ and $T_N$ are given by the islanded operation mode of the digital device. For the simulation model the parameters $K$, $T_2$ and $T_1$ are given by the equations (6). The gate velocities are taken from the data sheets of each governor.

**Excitation systems**

The involved excitation systems are equipped with excitation units with rotating commutators or static rectifier devices. Simulation was done with predefined SIMPOW models related to the IEEE models DC1 (rotating commutator) and ST1 (static rectifier devices) and the predefined standard parameter set. Figure 4 shows the comparison of the two implemented types of excitation systems.

Varieties can be seen in the design of the actuators, whereas the governor is the same for both types. Comparing the time constants of active power control and reactive power control it can be seen that predominantly dynamic active power stability is decisive for stable islanded grid restoration.
Loads
The consumer loads used in the model are approximated by a resistive fraction of 60% and an inductive rotating fraction of 40% of the respective maximal load. The latter is modeled as an induction motor load.

EVALUATION OF THE DYNAMIC SIMULATION MODELL
To evaluate the dynamic simulation model, selected measured frequency, voltage, active and reactive power time series plots of the field tests are compared with the simulated results. The purpose of the evaluation is to ensure the performance of the simulation model. Figure 5 shows an exemplary comparison of a measured and a simulated frequency time course.

Assuming five generators taking over a ramp shaped pump load characteristic of 21 MW, the frequency course in Figure 5 is obtained. The minimum value, determinant for the stable islanded grid restoration, is 48.8 Hz in the measured course and 48.95 Hz in the simulated course. The time duration obtaining the frequency minimum values, representing the major time constants, are widely coincident. Considering the average values it can be seen that the simulated time course approaches the measured time course. In fact, the oscillation frequency differs clearly from the field test. This is due to the constraints in the modeling of the penstock (fluctuations of hydraulic pressure) and the use of the new digital governor systems. Nevertheless, the shown result and other comparisons of time courses in terms of active power and frequency prove a sufficient accuracy of the modeled system behavior.

IDENTIFYING THE MAIN STABILITY PARAMETERS
As transmission grids cannot store any energy, the sum of the generated power and the sum of the consumed power must be balanced. In case of an unbalance the rotating masses of the machines in the grid are either accelerated (generation surplus) or slowed down (generation deficit). Reconnecting load to an island operated network after a blackout can be seen as a very critical procedure, since the spinning reserve is rather low compared to interconnected operation. Handling the frequency gradient in island operated networks poses a special challenge to the devices, especially to the hydro governors and their actuators.

Stored energy at rated speed, frequency gradient
Disconnected from the superior network, the stored energy at rated speed in island operated networks is only a fraction of the normal operation. This implicates a considerably higher frequency gradient in the moment of load connection compared to the normal operation mode (assuming the same load characteristic). Furthermore, this comprises special demands for the primary control devices since the primary control power needs to be provided in a shorter time than in normal operation.

The frequency gradient in the moment of load connection as shown in Figure 6 is mainly determined by the stored energy at rated speed and the amount of the connected load.

Recapitulatory it can be said that the stored energy at rated speed and the power of the connected load are a decisive parameter for transient stability in an islanded operation network.

Control rate of primary control devices
Without any intervention of the primary control devices, the frequency respectively the speed of the machines in Figure 6 would decrease to zero. Though, the prime control devices are balancing the power deficit and intercept the frequency drop. This operation must pass of within the tolerable frequency boundaries for the islanded operation.

Depending on the individual turbines and governing systems the activation time for primary control lies between 5 s and 10 s. Hence, not every machine being capable of performing primary control in normal operation is usable.
for primary control in islanded grid operation. In the present grid several machines are equipped with special modes for islanded grid operation due parameter sets for the hydro governors and the possibility of controlling the flow by deflectors instead of the valve pin, thus gaining gate velocities faster than machines for normal operation mode. Depending on the time constants of the hydro governors and their actuators the frequency drop can be intercepted. Decisive for timely allocation of primary control power are sufficient control rates of the primary controllers and the use of actuators of a sufficient gate velocity.

**OPTIMIZING THE GRID RESTORATION PLAN**

The evaluated simulation model is used to optimize the grid operator’s original restoration plan. Frequency deviations shall be within the tolerable frequency band of 49 Hz and 51 Hz in order to avoid any unintentional tripping of protection devices. The simulated time courses in terms of frequency of the original restoration plan are shown in Figure 7. Connecting load 2 (18 MW) to the actual machine configuration at this point of the restoration plan leads to an intolerable frequency drop below 46 Hz. After synchronizing another machine the following frequency drops stay within the permitted frequency boundaries although the connected load is 24 MW.

![Figure 7 Simulated frequency time course of the original grid restoration plan](image)

Splitting load 2 in several single loads and optimizing the machine configuration leads to the time course in Figure 8. The frequency can be kept within the limits during the overall grid restoration plan.

![Figure 8 Optimized frequency time course](image)

Additional scenarios, such as unavailability of machines due to maintenance, were analyzed as well. Adding a new built machine to the grid restoration plan increases transient stability by adding stored energy at rated speed and adds some additional degree of freedom to the grid operator. A main result was the determination of the maximum load, allowed to switch on at once, which depends on the available machines and governors, being adapted to primary control in islanded grids with sufficient control speed. In the analyzed configurations it is allowed to connect 11 % of the MW rating of mentioned machines being in operation.

**CONCLUSION**

The developed software model is a useful tool, representing the real situation of a possible grid restoration with sufficient accuracy and respect to frequency deviations during islanded grid operation. The stored energy at rated speed, maximum load, control rate and declared primary control machines are identified as determinant stability parameters for grid restoration and islanded operation. The evaluated software model is used to verify an existing grid restoration plan. Simulations show the possibility of optimizations and leads to an adapted grid restoration plan. Splitting loads and using an optimized machine configuration leads to a simulated frequency time course. Frequency minima and maxima are kept within the permitted frequency boundaries. Additional stored energy at rated speed, allocated from a recently new built machine, contributes to transient stability during islanded grid restoration.

**REFERENCES**