EVALUATION OF ISLANDED GRID OPERATION TESTS AND DYNAMIC MODELLING

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ABSTRACT

To investigate the electrical conditions during grid restoration after a blackout network operators are dependent on accurate and reliable simulation models. This paper describes the setup of a dynamic simulation model including nonlinearities of the mechanical governor systems based on high resolution measurements of islanded grid operation tests. The model is used to detect a root cause for low frequency oscillations which occurred during tests. Further a minimal generator configuration is developed to provide a stable grid restoration. The effect of integrating recently built power plants in the grid restoration plan is also investigated.

INTRODUCTION

The liberalized energy market and the increasing number of actors in the energy supply system have led to an increasing volatility of national and international load flow. As a consequence the risk of blackouts in the ENTSO-E grid has increased over the last years due to possible security violations [1]. Thus, network operators have the responsibility to investigate and, if possible, implement an established grid restoration plan.

To meet this demand, KELAG Netz GmbH and KELAG power plant operator have provided and evaluated islanded grid operation tests in cooperation with Graz University of Technology in the years 2005 [2], 2009 and 2010. The first critical steps of the grid restoration plan have been practically exercised by switching pump loads to a designated generator configuration in a separated part of the 110-kV-network. High resolution measurements of active- and reactive power, frequency, governor output, deflector position and needle position of involved hydro power plants with Pelton turbines are used as a reference for the adjustment of a comprehensive dynamic simulation model. This model is further used to simulate critical sequences of the grid restoration plan assuming real consumer characteristics instead of pump loads.

The following tasks have been investigated in this paper:

- During islanded operation tests in 2009 low frequency oscillations occurred at certain machine configurations and operating points. The first task was the identification of a root cause for these measured low frequency oscillations.
- For a stable gird restoration after a blackout the minimum-generator configurations for expected load configurations were determined
- The extension of the machine configuration during grid restoration with recently built generators contributing to the stored kinetic energy is also investigated.

DEVELOPMENT OF THE DYNAMIC SIMULATION MODEL

The development of the dynamic simulation model is done in MATLAB-Simulink. Each grid element is implemented with its required accuracy level. The main focus is on the modelling of the respective governors and their actuators since their behaviour is decisive for frequency control and transient stability.

Generators

In the developed simulation model a subtransient generator model is used. Especially the inertia constant of the machines respectively the rotating energy plays a vital role in the oscillatory behavior of the considered system. The excitation systems are consistently implemented as static excitation systems. The IEEE based type used in these simulations is type ST1 [3].

Hydro governor

The main challenge for a realistic simulation model in islanded operation is the reproduction of the hydro governors and their actuators. The model of each hydro governor can be split up in two parts: the digital controller and the mechanical part, thus the needle and deflector positioning system. The exact nonlinear behavior of the mechanical actuators was implemented into the simulation model by using the measured interrelationship between the regulator output signals and the needles respectively the deflector positioning system. Especially in low power operating points, during the first critical steps of the grid restoration process, these nonlinearities must not be neglected for the reproduction of the control behavior.

The simulation model contains five different hydro governor models. A short description of the most important types is shown below.

Hydro governor M 1 and M 2

The hydro governors of the machines M 1 and M 2 are able to control the frequency very stable at low power operating points. Therefore, these machines are used to control the frequency in the initial stage of the grid restoration. This has been proved in several island grid operation tests. Figure 1 shows the principle block diagram of the hydro governors of the generators M 1 and M 2.

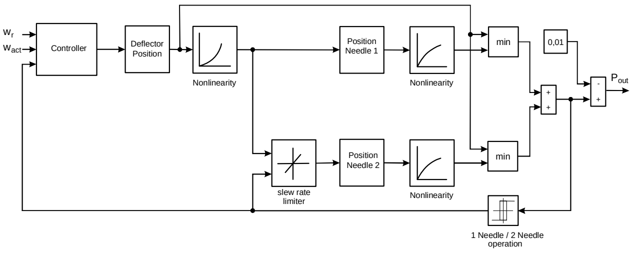


Figure 1 Electrical and mechanical part of the hydro governor of machine M 1 and M 2

The primary actuator for frequency control in islanded operation is the deflector. The position of the needle is following the deflector position via a hydraulic system with some time delay. Several measured time courses provide the nonlinear characteristic of this mechanical part which was implemented in the simulation model. Also the nonlinear interrelationship between the needle position and the mechanical power of the governor was implemented.

To improve the efficiency of the hydro turbine in normal operation it is driven with only one active nozzle in the power range from 0 to 0.5 p.u. Above 0.5 p.u. both nozzles are active. Measurements have shown that the transition between those operation modes causes a temporary active power surplus. Hence, the frequency value in islanded operation rises above the given frequency limits. This behaviour, insignificant during normal operation, can possibly lead to transient instability in islanded operation. This operating mode selection is also implemented in the hydro governor model.

Hydro governor M 3

The hydro governor of generator M 3 is based on an electronic governor and an electrohydraulic actuator system. The used model is shown in Figure 2.

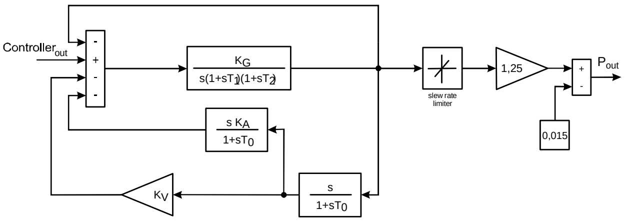


Figure 2 Electrohydraulic system of machine M 3

K_G is the gain of the actuator (servomotor) circuit. For stable control behaviour the feedback of the servomotor speed (boosted with K_V) and the servomotor acceleration (boosted with K_A) are necessary. The transfer function with the time constants T1 and T2 represents the behaviour of the servomotors and the main control valves. The needle position depends on the position of the servomotor. By evaluation of recorded time courses from island grid tests, a constant factor of 1.25 between the needle position and the turbine per unit power was detected.

The speed controller of the turbine is shown in Figure 3.

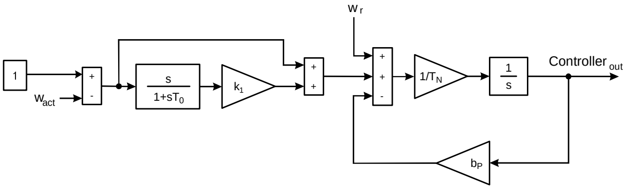


Figure 3: Speed controller M 3

Each parameter can be adjusted with an analog potentiometer. For the exact parameterization of the controller in the model the value of the potentiometer position was converted into a suitable parameter for the model.

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.

During the island grid operation tests a pump load was used to simulate consumer load connections. This pump load, an induction motor with a nominal power of 5.1 MW, is also part of the simulation model.

110-kV-grid and transformers

The components of the electrical grid (lines and transformers) are implemented within a hybrid-matrix. This matrix is used to calculate the input current of the generator model and input voltage of the load model by a given generator voltage and load current.

EVALUATION OF THE DYNAMIC SIMULATION MODEL

The simulation model was evaluated by comparing measured time courses from real islanded grid tests with time courses provided by the simulation model. The aim of the evaluation is to ensure the realistic performance of the simulation model. An exemplary comparison of a measured and a simulated frequency time course is shown in Figure 4.

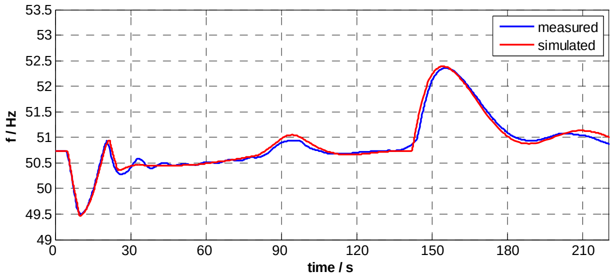


Figure 4: Connection and Disconnection of an asynchronous pump, measured and simulated frequency time course

This frequency time course was measured during one sequence of the island grid operation test in the year 2009, showing the behaviour of five generators during load changes.

At simulation time t=5 a pump load of 5.1MW is connected to the islanded grid. After 140 seconds the pump is disconnected again. The frequency minimum, as a consequence of the power unbalance after the load connection, is 49.5 Hz. The simulation model provides the same value as the measured minimum frequency value. Further, the results for the frequency maximum after the load disconnection at 142 s are almost the same.

The detailed implementation of the hydro governors of machine M 1 and M 2 provide the possibility to compare the measured and simulated needle and deflector position. Figure 5 shows the comparison of the corresponding measured and simulated needle position during the analyzed sequence.

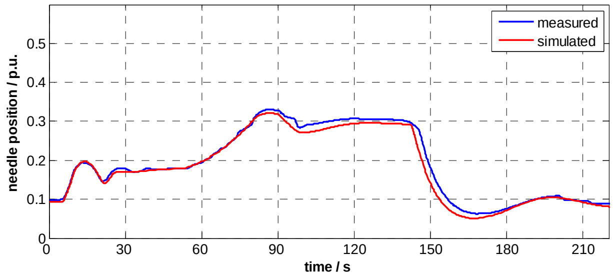


Figure 5: Measured and simulated needle position time course

Based on the shown results a realistic behaviour of the implemented model can be confirmed.

LOW FREQUENCY OSCILLATIONS

During island grid operation tests, several sequences of the restoration plan showed a significant low frequency oscillation with a cycle length of 17 s and peak to peak frequency variation up to 300 mHz, as shown in Figure 6.

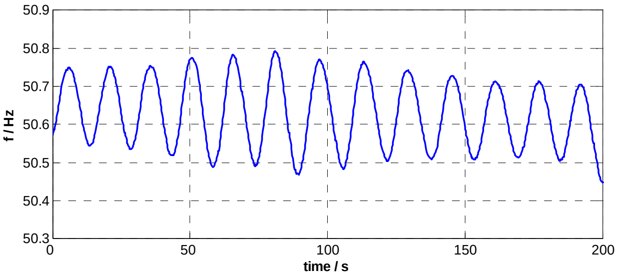


Figure 6: Measured frequency oscillation, islanded operation tests 2009

To avoid these frequency oscillations in case of a real grid restoration after a black out it was very important to find the origin. Especially in the first phase of the grid restoration an excitation of the oscillation, obviously caused by a primary control device, can lead to stability problems.

The analysis of recorded time courses suggested that the hydro governor of machine M 3 interacts with other active generators located in the eastern part of the islanded grid. To gain more information about the control behaviour of the hydro governor of machine M 3 islanded operation tests in 2010 were performed. During these tests, time courses of controller input and output, active and reactive power, frequency as well as needle and deflector positions were recorded.

It was intended to excite the low frequency oscillation by a load connection. However, the typical frequency oscillations already appeared when machine M 3 started to take over active power. After the load connection peak to peak values of the low frequency oscillation up to 1.5 Hz were registered.

With the results of this additional island grid test the simulation model was improved. Hence, it was possible to reproduce frequency oscillations with the same characteristics as the measured ones. Figure 7 shows a comparison of the measured and simulated time course of the islanded grid frequency.

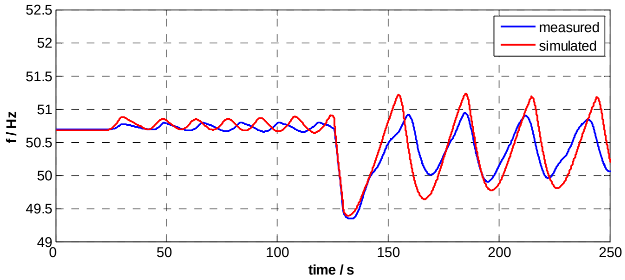


Figure 7: Measured and simulated frequency time course

As a reason for the instability of the hydro governor of machine M 3 nonlinearities of the mechanical system during low power operation points could be determined. The rated power of this machine is 38 MW, during island grid operation tests it was maximum loaded with 7 MW.

In case of a real grid restoration after a blackout this machine should not be used in the frequency control mode. Instead it should contribute to the kinetic energy at rated speed with constant power output.

STORED ROTATING ENERGY AT RATED SPEED

In the moment of load connection the available rotating energy at rated speed is decisive for the frequency gradient. Figure 8 shows a comparison of two simulated frequency time courses during a load connection in islanded grid operation.

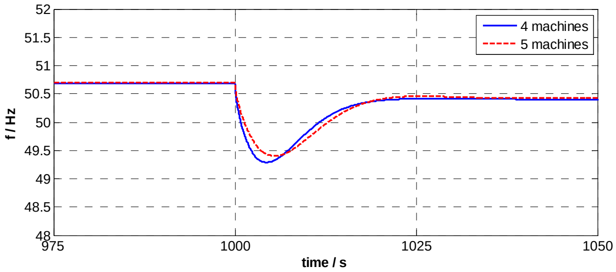


Figure 8: Comparison of a frequency time course during a load connection

The use of four instead of five active generators causes a higher frequency gradient. Hence there is less time to compensate the active power unbalance before the frequency falls below the given limits. With activation of two recently built generators it is therefore possible to increase the stored energy at rated speed. Although their ability for primary control is restricted due to primary control time constants it is recommended to connect them to the grid as soon as their minimal active power limit is covered by reconnected loads.

Besides the additional stabilisation due to the contribution of kinetic energy for the entire restoration procedure the integration of these two generators is essential to meet the given frequency limits especially during the first load connections.

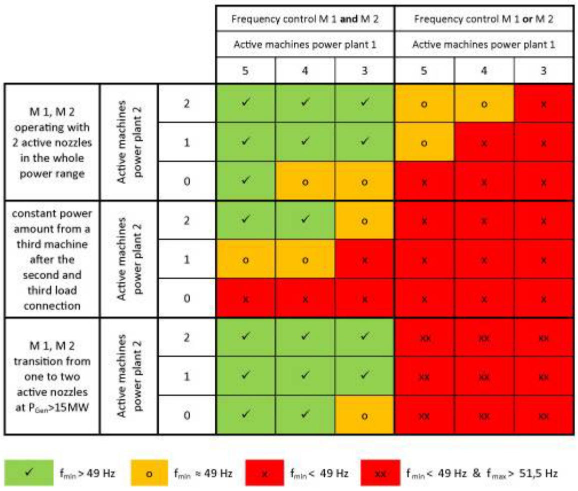
MINIMAL MACHINE CONFIGURATION

Finding a minimal machine configuration for a stable grid restoration is important especially for the first cirtical steps of the grid restoration plan. These results should also be considered in the periodic generator maintenance plan. At any time enough machines should be available to accomplish a stable grid restoration. Frequency limits were defined with the upper limit of 51Hz and the lower limit at 49Hz in order to avoid any unintentional tripping of protection devices.

Using the evaluated model, different machine configurations (number of active machines) with varying machine operating modes (number of active frequency control machines, one or two active nozzles, operating points) of the prime controlling generators are analysed. The number of active nozzles of the hydro governor from machine M 1 and M 2 has a significant influence on the frequency behaviour during the simulated grid restoration. Therefore, the hydro governors of machine M 1 and M 2 should be driven with two needles in the whole power range. Moreover, for a minimal machine configuration, it is necessary to find a mix of hydro governors with fast actuators providing primary control as well as enough rotating energy at rated speed.

A summary of the investigated configurations' characteristics is listed in Table 1. The first vertical section shows the operating mode of the primary control machines. The inner label of the rows and columns contain the number of machines connected to the grid and therefore a parameter for the rotating energy at rated speed. The columns 4, 5 and 6 contain simulated grid restoration configurations with two machines (M 1 and M 2) in frequency control mode. Columns 7 to 9 contain scenarios with one machine (M 1 or M 2) in frequency control mode.

The simulations have shown that it is necessary to have two generators (M 1 and M 2) in primary control mode and both with two active nozzles from the very beginning of the grid restoration plan to keep the frequency within the given limits of 49 Hz and 51 Hz.



			Frequency control M 1 **and** M 2			Frequency control M 1 **or** M 2		
			Active machines power plant 1			Active machines power plant 1		
			5	4	3	5	4	3
M 1, M 2 operating with 2 active nozzles in the whole power range	Active machines power plant 2	2	✓	✓	✓	o	o	x
		1	✓	✓	✓	o	x	x
		0	✓	o	o	x	x	x
constant power amount from a third machine after the second and third load connection	Active machines power plant 2	2	✓	✓	o	x	x	x
		1	o	o	x	x	x	x
		0	x	x	x	x	x	x
M 1, M 2 transition from one to two active nozzles at P_{Gen}>15MW	Active machines power plant 2	2	✓	✓	✓	xx	xx	xx
		1	✓	✓	✓	xx	xx	xx
		0	✓	✓	o	xx	xx	xx

✓ $f_{min} > 49$ Hz
o $f_{min} \approx 49$ Hz
x $f_{min} < 49$ Hz
xx $f_{min} < 49$ Hz & $f_{max} > 51{,}5$ Hz

Table 1: Investigated machine configurations

CONCLUSION

The developed simulation model is a detailed representation of the real conditions during the grid restoration. Based on high resolution measurements it was possible to implement nonlinear interrelationships of the mechanical governor systems in the model. These nonlinearities must not be neglected regarding investigations on transient stability of grid restoration plans, especially during the first critical steps.

Due to the detailed reproduction of the mechanical governor system generator M 3 could be identified as a root cause for real measured low frequency oscillations. This knowledge sustains the suggested constant power control strategy for this machine during grid restoration.

In a further step the possible role of new built generators in the grid restoration plan, regarding the contribution of stored energy at rated speed, was investigated. Moreover, a minimal generator configuration and optimal control strategies for the primary control generators, providing a stable grid restoration, were determined. Especially the use of two active primary control machines and the activation of the two-nozzle-operation for the entire power range contribute considerably to the compliance of the frequency limits.

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