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Original Paper (Invited)

Improved prediction of Pump Turbine Dynamic Behavior using a Thoma number dependent Hill Chart and Site Measurements

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Abstract

Water hammer phenomena are important issues for the design and the operation of hydro power plants. Especially, if several reversible pump-turbines are coupled hydraulically there may be strong unit interactions. The precise prediction of all relevant transients is challenging. Regarding a recent pump-storage project, dynamic measurements motivate an improved turbine modeling approach making use of a Thoma number dependency. The proposed method is validated for several transient scenarios and turns out to improve correlation between measurement and simulation results significantly. Starting from simple scenarios, this allows better prediction of more complex transients. By applying a fully automated simulation procedure broad operating ranges of the highly nonlinear system can be covered providing a consistent insight into the plant dynamics. This finally allows the optimization of the closing strategy and hence the overall power plant performance.

Keywords: pump turbine, hydraulic transients, turbine modelling, draft tube pressure, Thoma number, automated simulation.

1. Introduction and motivation

Water hammer phenomena and furthermore the possible risk of water column separation are important issues for high head hydro power plants. Quantities such as maximal penstock and spiral case pressure, minimal draft tube pressure and maximal transient overspeed have to be determined in an early design stage since they are acting as inputs to the further design process. Besides that, final tuning of the operational procedures during commissioning again requires the application of transient simulation models. Since the hydraulic machine is evidently an integral part of the waterway, its interaction with the overall dynamical system has to be considered comprehensively in this modeling and simulation process.

In general, the overall precision of the applied simulation models is of great importance due to many reasons. First, if the plant layout is still to be defined in an early project stage, detailed simulations allow cost saving and efficient designs of global parameters such as waterways, surge tanks, penstock dimensions, turbine setting, and so on. Also single components such as spiral case, draft tube, rotating parts and others can be optimized on the basis of reliable transient simulations. On the other hand, many of these key plant parameters are often either fixed in early design stages or simply given as predefined constraints, e.g. for power plant rehabilitations. If this is the case, only operational procedures such as mode change sequences or opening and closing times can be adapted in order to fulfil all requirements and to optimize the power plant performance. Thus, the more reliable the power plant dynamic behaviour can be computed, the more efficient the power plant can be designed and operated.

In this work, a recent pump storage project has been investigated. For simple plant configurations, peak values of interest can be found with limited effort, since powerful simulation tools are available and standard load cases are well known. However, things become more sophisticated for complex surge shaft arrangements, for low-specific-speed pump-turbines with their typical S-shaped hillchart, and for multiple unit configurations, as the degrees of freedom and the corresponding modelling uncertainties rise rapidly [2]. For the actual project, which is shown in Fig.1, the waterway layout has been fixed at an early stage. Hence, adequate operational procedures such as closing laws had to be defined to fulfil all requirements. During numerical transient investigations, it turned out that especially draft tube pressure drop is a critical issue for scenarios with low tailwater level. The forming of a cavity caused by low transient pressure has to be avoided in any case, as reverse waterhammer (water column separation) during subsequent implosion of the cavity can lead to fatal damage of the hydraulic unit [1]. To overcome these risks a combination of three different measures has been selected [10]. First, an asynchronous wicket gate closing (AWG) has been chosen which is known to reduce water hammer phenomena

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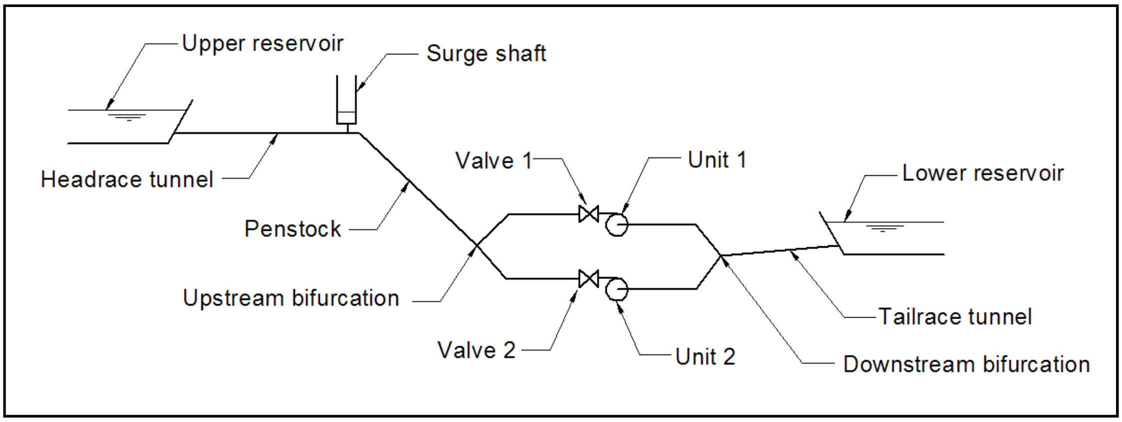

Fig. 1 Two-unit configuration with upstream surge shaft and common waterway components

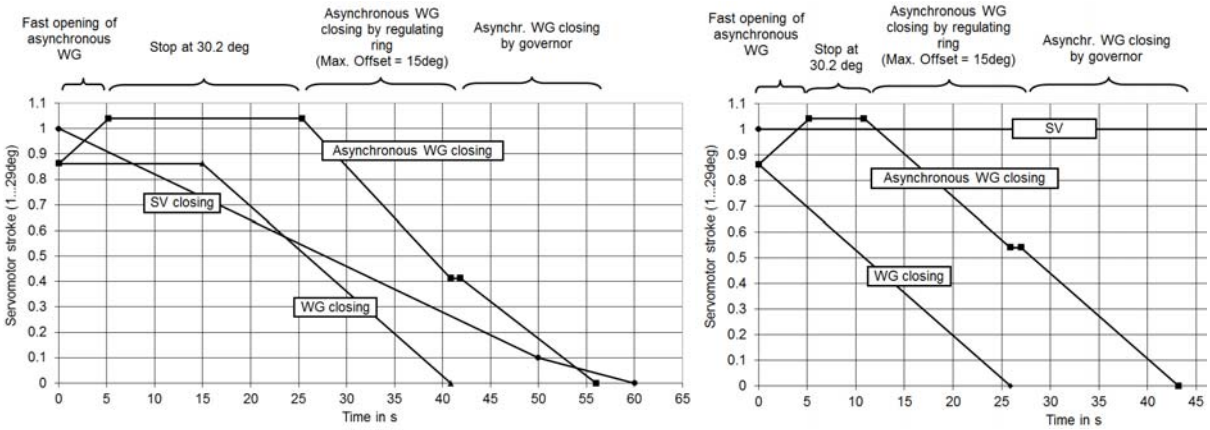

Fig. 2 Originally proposed (left) and finally implemented closing law (right)

induced by the S-shaped hillchart. AWG means, that during wicket gate closing, a pair (or two pairs) of gates initially open and finally follow the others with a certain angular delay. As a second measure against water hammer, the overall wicket gate closing has been delayed by 15 seconds whereas an immediate main inlet valve (MIV) closing has been initiated. The MIV throttling is known to contribute to the overall system damping. This reduces the S-shape induced instability, as well as the water hammer and reverse pumping tendency of the overall power unit. The corresponding initially chosen closing strategy is shown subsequently on the left hand side of Fig. 2. In contrast, a rather standard procedure including AWG closing is shown on the right hand side of Fig.2.

To confirm the simulation results and check the desired improvement of the draft tube pressure level, a test program was launched for the case example including single and double unit prototype measurements under various transient conditions [12]. Some test program results and their contribution to optimize the simulation model are described in this paper. Step by step the test procedure was navigated to the lowest draft tube pressure values. It soon became clear that the prediction of pressure values could be significantly improved by the adaption of certain model properties. This was successfully done based on the results of the first tests. Furthermore there was room for optimization of the closing strategy as described later.

2. State-of-the-art simulation and measurement experiences

For determining critical values for pressure head as well as for overspeed, the power plant layout from Fig.1 has been converted into a numerical simulation model which is shown in Fig.3. The underlying software tool is the latest version of SIMSEN, which is developed at EPFL (http://simsen.epfl.ch) [3]. All subsequent time domain simulations have been carried out using this software environment. The pump-turbines are modelled using the well-known quasi-stationary hillchart which is obtained by model tests in the hydraulic lab. The key load cases which will be shown subsequently are either single-unit or simultaneous multi-unit load rejections including closing of the wicket gates. These scenarios are denoted as emergency shutdown (ESD). A special focus has been on draft tube (DT) pressure drops since these turned out to be crucial for safe and secure plant operation. Further measurements have been taken at the spiral case (SC) as well as at the spherical valve (SV).
It is well-known that system dynamics and transients of pumped storage power plants are especially complex, if several units which are connected to the same waterways are operated simultaneously. The reasons are the strong interactions between the hydraulic machines. Thus, in a first purely simulative example such a simultaneous emergency shutdown scenario will be illustrated. In case of load rejections of two or more units from different operating conditions or with time delay, the prediction of the dynamic behaviour is especially challenging due to some high frequency components and thus high pressure and speed fluctuations which can be observed in the time signals. These oscillations are often in temporal coincidence with their overall extremal values. Hence, they are of great importance for further design and optimization.

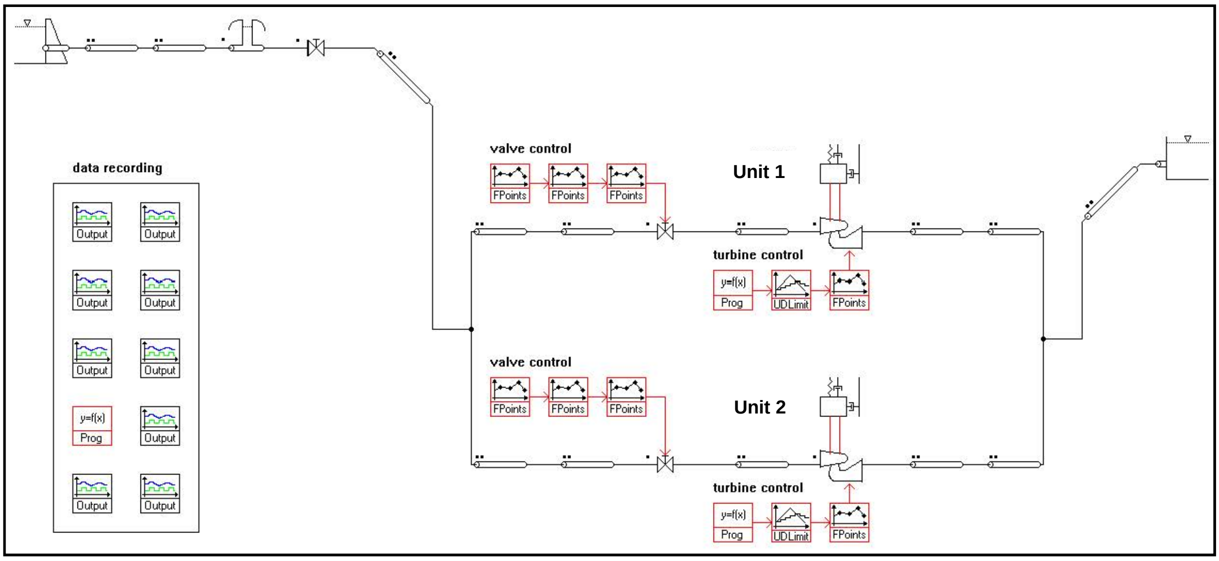

Fig. 3 SIMSEN model layout - Pump storage layout with two units connected to the same waterway system

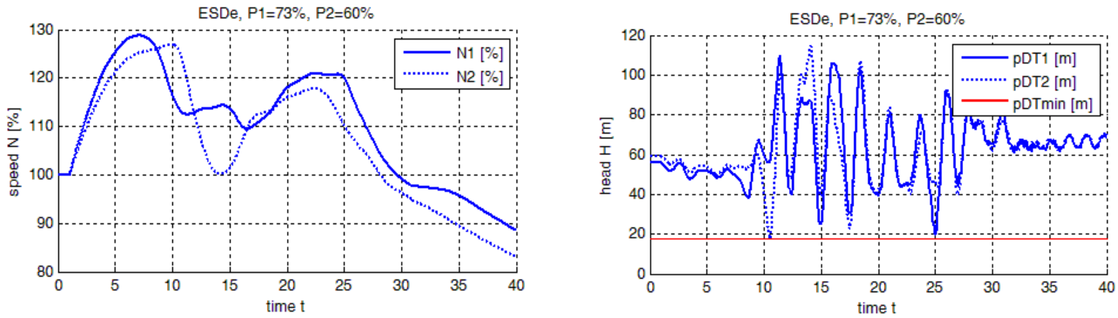

Fig. 4 Speed (N) and draft tube (DT) head (**simulation**) for **two-unit load rejection** using the standard pump turbine modeling approach

The simulation results of the above mentioned simultaneous load rejection of two units are shown in Fig.4. Since both units were tripped at different loads (73%/60%) the initial slope of unit speed is different as well. After some time unit 1 reaches its maximum speed and subsequently – while decelerating – starts to block the discharge due to the unstable S-shaped hillchart characteristic. An indication is given by the draft tube pressure drop of unit 1. This induces a water hammer also for unit 2 which leads to a temporal additional acceleration of the latter. Consequently, between t=10s and t=25s both units are oscillating inversely phased in terms of speed. Due to comparably short waterway connections and hence low hydraulic inertia between both units this finally results in strong discharge and pressure fluctuations as observable at the draft tube. Depending on the turbine setting and the actual tailwater level (TWL) this may have safety related implications. It is important to note, that the AWG closing procedure has some significant impact on the turbine behaviour. Based on model measurements, the effect of AWG had already been considered in the simulation model. Comparisons with measurement results for two-unit operation will follow in subsequent sections.

To compare simulations with measurement results we will first focus on a one-unit load rejection. The corresponding measurements from site were taken with an appropriate data acquisition system at a sampling rate of 4.8 kHz including an anti-alias Bessel filter with 2 kHz cut-off frequency. Due to the high sampling rate high frequency components which are caused by local pressure oscillations in cross-section plane and in addition some measurement noise could be observed. Since the in-plane oscillations can neither be captured by common transient 1D-approches nor interact with travelling waves along the waterway system, measurement signals have been further filtered to improve comparability with respect to simulation results. This has been achieved using a 4Hz cut-off frequency which turned out to show best comparability without losing relevant 1-D spectral components. In parallel, the original signal was still checked for high frequency travelling waves by comparing signals along the waterway (SV and SV pressure signals of both units), to avoid suppressing relevant signal components.

Using the classical quasi stationary turbine hill chart representation, Fig.5 shows the comparison between simulation and measurement results for the one-unit load rejection. All elementary model parameters such as unit inertia, hydraulic inertia, and wave speed have been adapted to obtain a best possible match between simulations and measurement. In this scenario the WG closing has been carried out with 15s time delay from the tripping as initially proposed (see Fig. 2). Note that, there are still some significant (peak) pressure deviations observable. Regarding the spiral case and spherical valve pressures the first and second simulated peaks show a pressure rise overestimation in the order of 4-5bar (40-50mwc). Also note, that some intermediate dynamics at t=11s are also not captured by the simulation model. Similar observations can be made regarding the draft tube surges. Minimal values differ by about 1bar (10mwc). Even though the predicted pressure magnitudes are higher than the measured water hammer and the simulation outcome

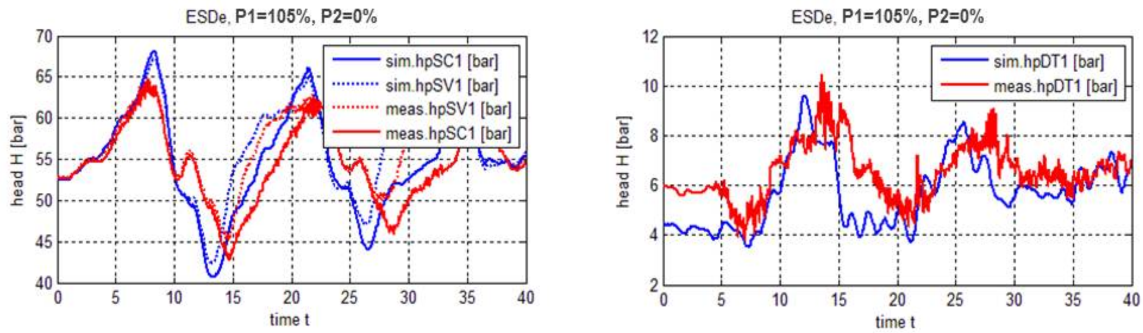

Fig. 5 Spiral case (SC), spherical valve (SV), draft tube (DT) head (**simulation and measurement**) for **one-unit load rejection** using the standard pump turbine modeling approach

is hence conservative, there is obviously some room for improvement. To obtain a best possible matching between simulation and measurement, all typical parameters such as water wave speed, rotating inertia and so on have been optimized. This leads to the indication that the turbine behaviour (hillchart) itself seems to have some significant influence on simulation results and thus has to be subject of further investigations.

3. Development of an adapted hillchart model

From the previous comparisons, it can be deduced that the pressure rise is slightly overestimated for the investigated pump-turbine scheme if the quasi-stationary hillchart modeling technique is applied. The motivation for the usage of a Thoma number dependent hillchart will be explained in the following.

For low or medium specific speed pump-turbines, the S-shape-characteristic of the pump-turbine becomes one main driving factor for transient situations. This behavior is still subject of ongoing research work, although known and being investigated for a long time [2], [4]. Different shapes of the characteristics cause different dynamic behavior as described in [5]. Passing through this region causes high dynamic load on the power plant. The existence of positive unit speed-torque and unit speed-discharge characteristics can lead to problems during synchronization, load rejections, model testing and other transient events ([6], [7], [8]). In contrast to low head Francis turbines, the S-shaped characteristic of high head machines and pump turbines may result in instabilities. These instabilities appear for example in terms of speed and pressure oscillations in runaway conditions [9].

From model measurements it is also known, that the hillchart may look differently if different turbine settings or, in other words, different Thoma numbers are investigated. Depending on σ, especially the slope of the opening lines in the S-shaped region as well as the reverse pumping quadrant may change significantly. Qualitatively, this is described by Fig.6. The definition of unit speed n11 and unit discharge Q11 (axes description) is given by $n_{11} \coloneqq nD/\sqrt{H}$ and $Q_{11} \coloneqq Q/(D^2\sqrt{H})$, where n is the rotational speed, D is the pump-turbine reference diameter, Q is the discharge and H is the net head of the respective unit. The Thoma number σ is defined as

$$\sigma \coloneqq \frac{NPSH}{H} = \frac{h_b - h_v - h_s}{H} \tag{1}$$

where h_b, h_v, h_s refer to barometric head, water vapor head, and suction head, respectively. For higher Thoma numbers the slope of the opening lines in the S-shaped region decreases (stronger S-shape) which is typically a measure for the instability in that operating region. Detailed hillcharts including transient machine trajectories during load rejection can be found in [10]. A motivation for the subsequently described approach is finally given by Fig. 7. It is evident that the largest values for the turbine

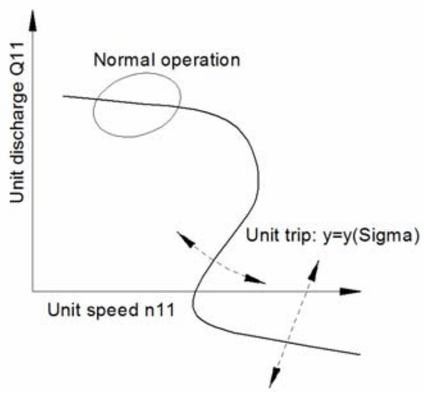

Fig. 6 σ-dependent hillchart

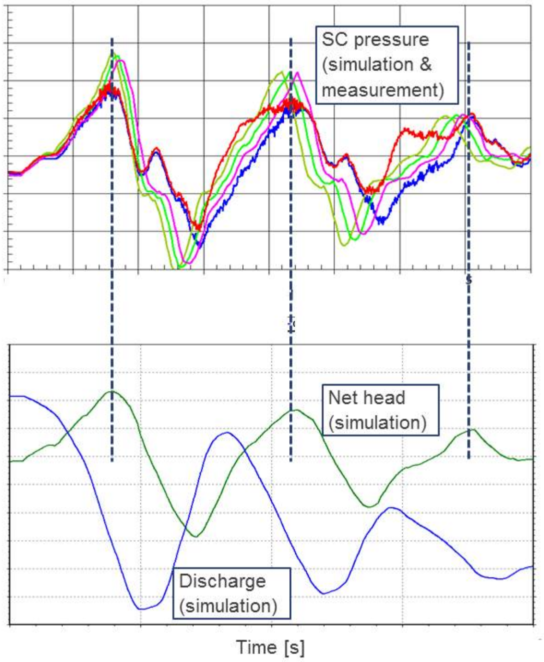

Fig. 7 Qualitative Comparison of max. SC pressure (measurement and simulation) and max net head

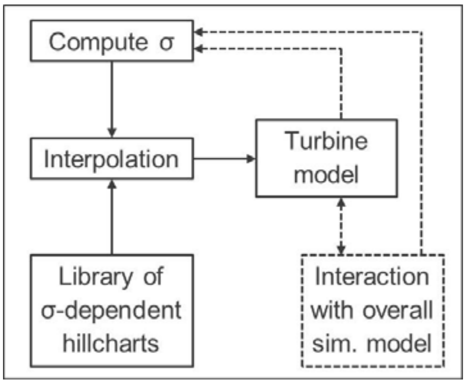

Fig. 8 Online model adaptation procedure to consider explicit hillchart Thoma number dependency

net head and thus the lowest Thoma numbers are occurring when the spiral case pressure and thus the modeling error are at their maximal values. Thus, temporarily using a different hillchart for lower Thoma numbers gives rise to possible model improvements. It was furthermore checked that changing of elementary model parameters such as inertia of the machines did not lead to a significant model matching improvement (see set of curves in Fig.7).

In the following, a new SIMSEN pump-turbine model has been set up, which consists of two different individual hill charts. Since some hillchart measurements for low Thoma numbers were available and could be extrapolated to some extent, this hillchart could be used for low Thoma numbers. Additionally, for higher Thoma numbers the standard hillchart which is typically measured on the model test rig and which is usually taken for standard transient simulations could be used as in the standard transient simulation. In the intermediate range (medium Thoma numbers), a linear interpolation between these two hillcharts has been

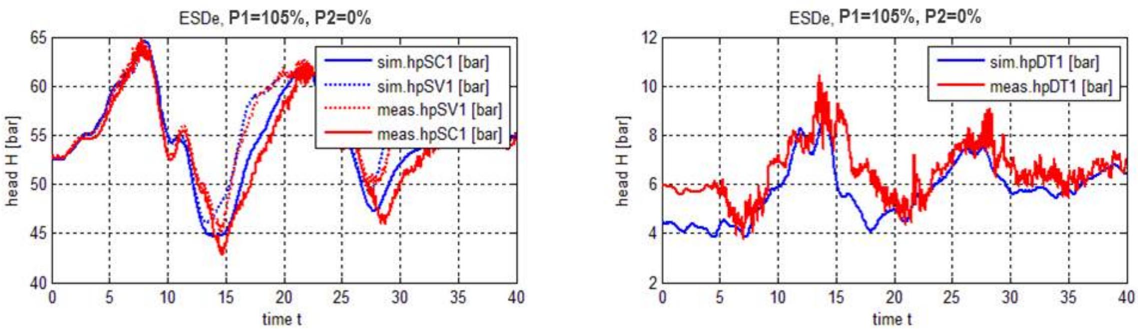

Fig. 9 Spiral case (SC), spherical valve (SV) and draft tube (DT) head (simulation and measurement) for Thoma number dependent pump turbine modeling

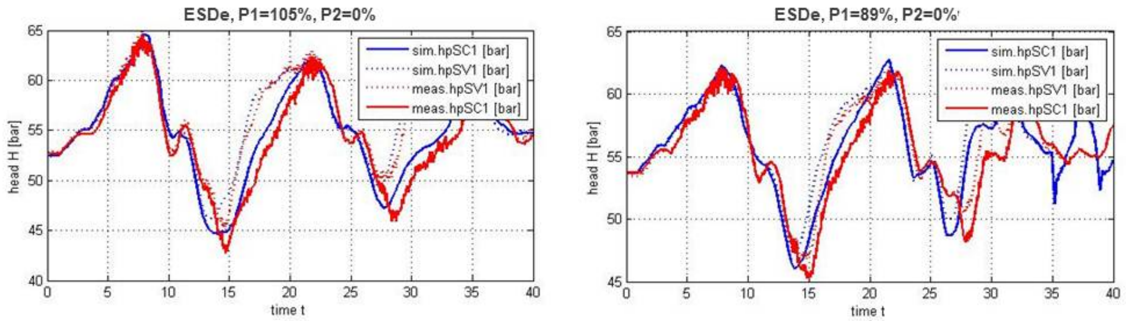

Fig. 10 Single unit load rejection from 272MW (matching case/left) and 230MW (validation case/right)

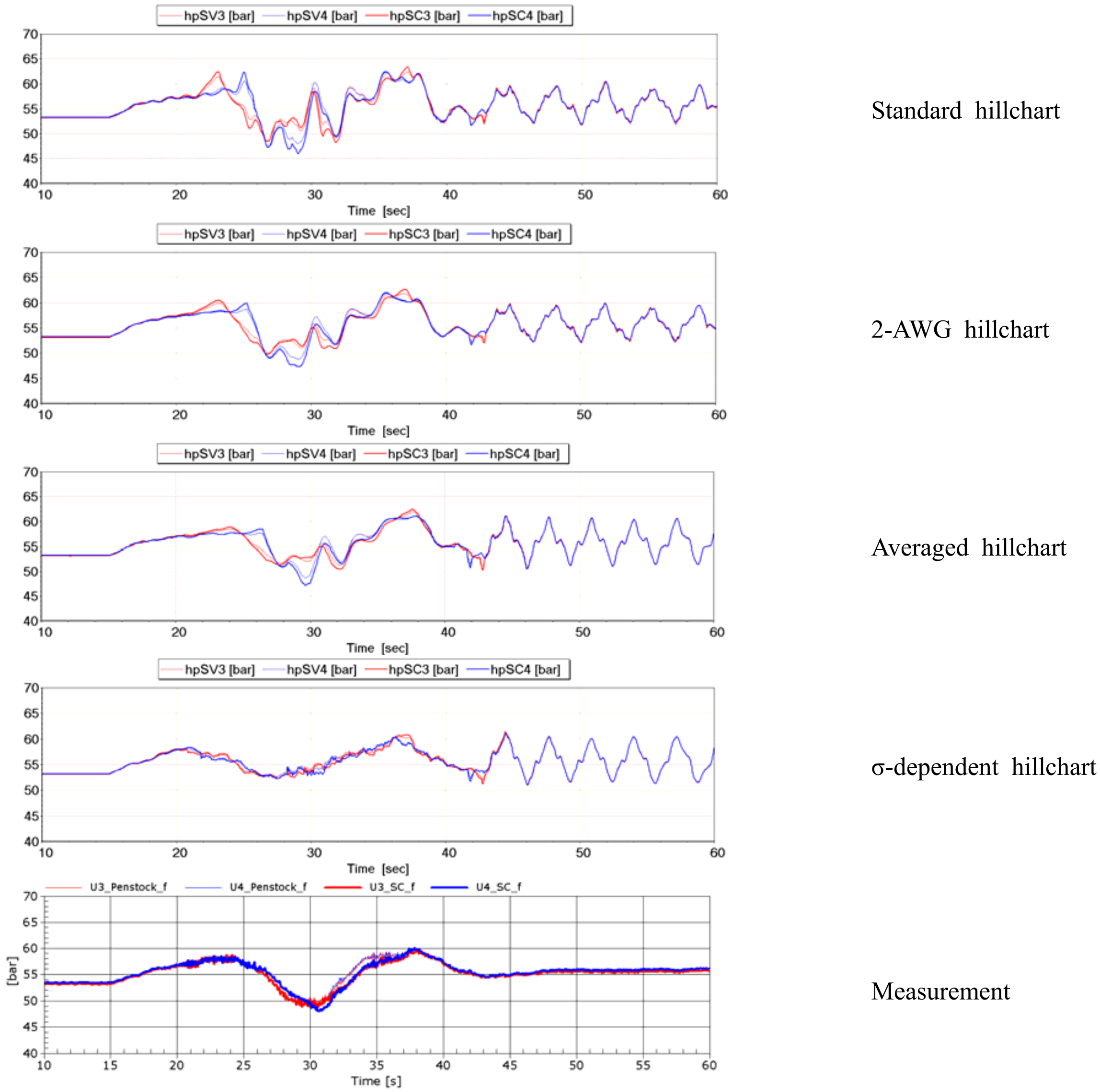

Fig. 11 Parallel 2-unit load rejection using different simulation models: SC and SV pressure

carried out, depending on the actual Thoma number which was computed in parallel. This procedure is applied online during each simulation time step. A sketch of the computational procedure is given by Fig.8.

After some brief model adaptations, the trajectories of Fig.9 are finally obtained for single unit operation whereas load case of Fig.4 was serving for comparison. Obviously, the consistencies of pressure trajectories in SC and SV as well as in DT have been improved significantly compared to the common modeling approach. This applies not only to minimal and maximal values, but also to minor intermediate dynamics which are matching quite well, if the σ-dependency is applied.

Deviations in the DT pressure between simulation and prototype can be explained by the non-uniform discharge and thus an inhomogeneous pressure distribution over the DT diameter [10]. Differences turn out to be especially high for high draft tube

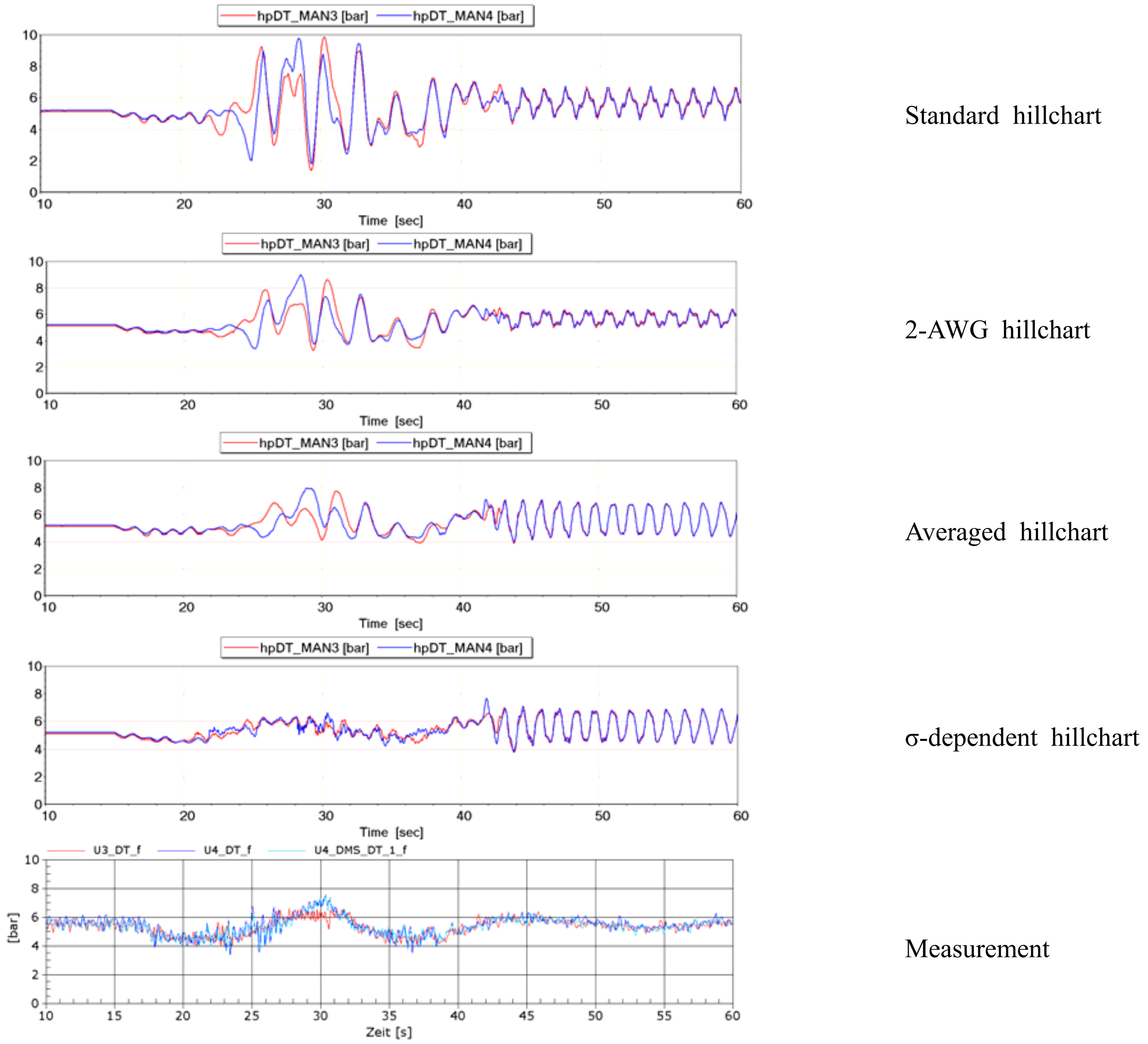

Fig. 12 Parallel 2-unit load rejection using different simulation models: DT pressure

discharges. However, this has no influence on the minimum draft tube pressure values since they occur at discharge close to zero. As a validation case for the new approach, a single machine load rejection from a different initial load has been investigated. Both, model matching and validation cases are shown in Fig.10. They turn out to be in good accordance with the corresponding measurements.

After consolidation of measurements and simulation results the overall closing strategy could be changed to the standard instantaneous wicket gate closing procedure. The final closing law is shown on the right hand side of Fig.2. Major advantage is a significant shortening of resynchronization procedure after load rejection. The AWG closing was maintained since it additionally reduces the draft tube pressure drop. Simulation results and measurements for the final (classical) closing law are depicted in Fig.11/12 where another more complex load case is shown – the two unit synchronous load rejection. Even though the consensus between simulation and measurement is quite satisfying regarding the Thoma number dependent hillchart model, it turns out that the corresponding simulation is rather time consuming. Besides that, the authors were looking for a model which preserves some conservatism to ensure that pressure minima and maxima are still slightly overestimated. Thus, an additional intermediate but not explicitly Thoma number dependent hillchart model has been developed which is close to an arithmetic mean between the two hillcharts. This will be referred to as ‘Averaged hillchart’ in the following.

As illustrated by Fig. 11/12, also for the 2-unit operating scenario the Thoma number dependent hillchart approach produces simulation results which match the measurements quite well. Furthermore, the pragmatic approach using the averaged hillchart comes clearly closer to measurement results than the standard approach, but indeed preserves some conservatism.

4. Automated simulation and evaluation

The behaviour of pump turbines is highly nonlinear in general. Thus, extrapolating results from single operating conditions and load cases to other nearby operating conditions is rather difficult and should be done carefully. Especially, if two or more units are operated in parallel, results might strongly depend on interaction and specific initial conditions. Consequently, several operating conditions have to be investigated. To overcome time consuming manual simulation and optimization procedures, an automated procedure has been developed. This will be used in the following for further investigations of simultaneous load rejections.

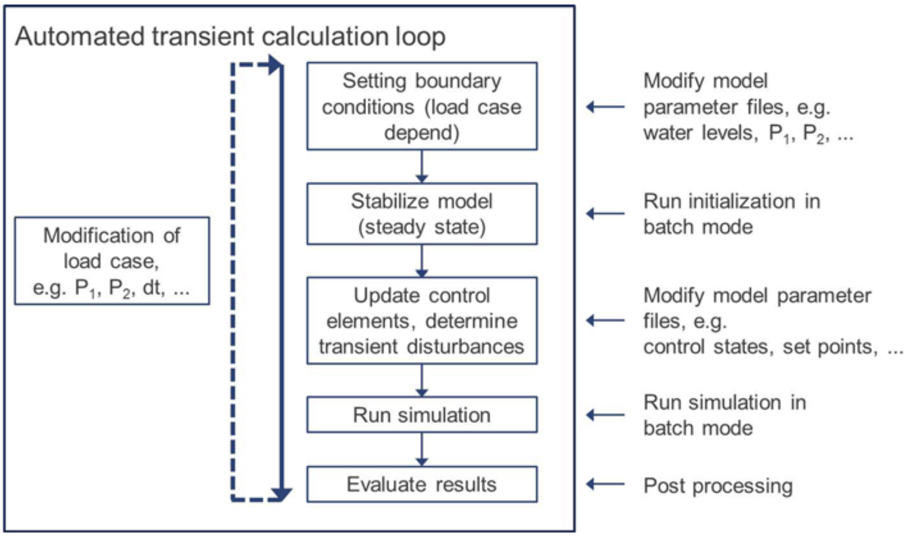

Fig. 13 Automated simulation procedure – flow chart

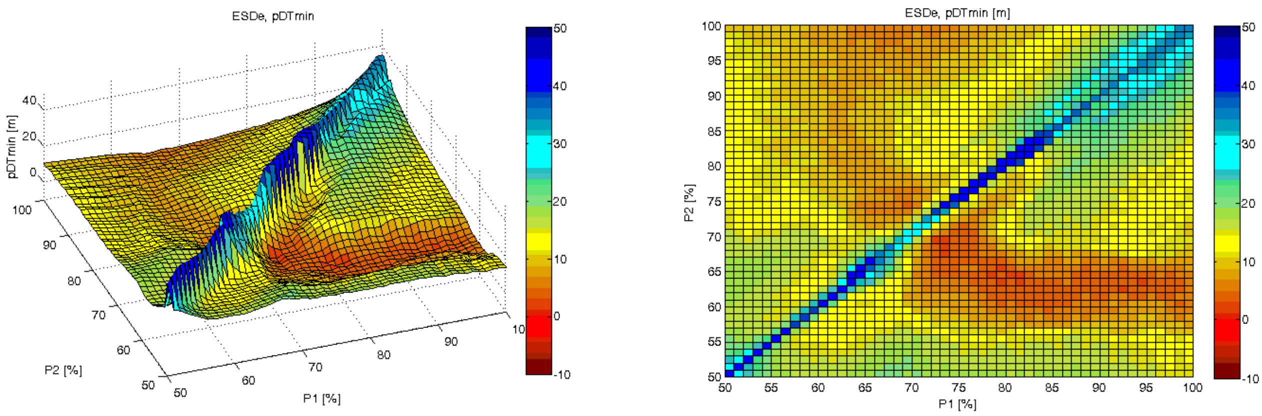

Fig. 14 Minimal DT pressure for all **2-unit simultaneous emergency shutdown** operating conditions using **standard hillchart** model

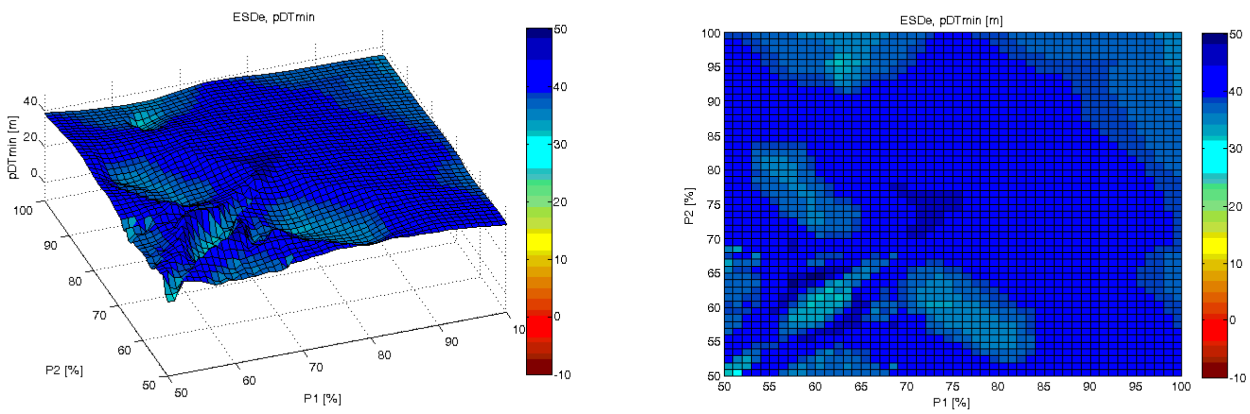

Fig. 15 Minimal DT pressure for all **2-unit simultaneous emergency shutdown** operating conditions using **σ-dependent hillchart** model

A sketch of the automated procedure is shown in Fig.13. The SIMSEN simulation environment is driven in batch mode using an external script. In an outer loop, operating points and load cases are defined and updated. The computed operating conditions are used in order to modify all relevant SIMSEN data files in a first step. Afterwards, an initialization run can be carried out in batch mode in order to find the full steady state conditions for the overall model. Additionally, some functional and control related blocks such as governor states and set points have to be updated since these cannot be covered automatically by the SIMSEN initialization methods. If all parameter files and the tripping of the desired events are set appropriately, the time domain simulation is launched in batch mode. Finally, result files are read and data post processing is done by the external script to obtain the desired values.

This general procedure can be adapted to most scenarios and parameters of interest. Since draft tube pressure turned out to be the key issue in a recent project, its minimal value has been investigated for simultaneous load rejections (time curves are such as in Fig.4). To cover all possible scenarios both initial power output levels have been varied from 50% to 100%. For the original hillchart model, the simulation results are graphically represented in Fig.14 from different angles of view. The map gives a good impression of operating zones which are more or less critical. Additionally, it can be observed that there is a minor non-symmetric design of the waterways. The same investigation has been carried out using the newly developed σ-dependent hillchart model. Results are shown in Fig.15. Due to higher modeling quality, prediction is more accurate and shows a significant reduction of draft tube pressure sunk.

The obtained maps are quite helpful also for commissioning issues since emergency shutdown scenarios can be tested and compared starting from rather uncritical load combinations. Similar investigations have also been carried out for time delayed load rejections since these can have similar implications for minimal draft tube pressures. Step by step, the most critical load cases have been approached. All tests have been successfully carried out and good correlation between the measured and the simulated minimum draft tube pressure was found.

5. Summary and conclusions for future developments

In this work, on the basis of an actual pump storage project, a refined transient simulation model has been derived using a Thoma number-dependent hill chart representation. The presented approach has been used to improve operational procedures of a pumped storage power plant. This was achieved by more accurate computations of draft tube pressure time curves. Simulation results have been compared in a step-by-step procedure with measurement results during commissioning and showed good correspondence. Thus, the predictability of prototype behavior has been improved significantly which turns out to be very helpful for power plant commissioning.

Concerning the investigated case study, the overall closing strategy could be chosen less conservative by these means. This allows a wider operating range and faster resynchronization after load rejections due to electrical grid faults. Risks because of time delayed load rejection could be systematically excluded. Furthermore, the automated simulation procedure gives an improved and systematic inside into the overall system dynamics. The proposed procedure is furthermore helpful to detect potential risks for certain power plant operating conditions.

The approach was motivated by model test measurements for different Thoma numbers which appears to have significant influence on the turbine hill chart shape. Consequently a Thoma number-dependent hill chart implementation has been developed and subsequently used in an overall transient simulation model. It turns out that this additional degree of freedom of the numerical turbine model has a noticeable effect on the simulation results and leads to significant improvement of the correlation between simulation results and site measurements. Thus, the proposed method allows a more precise prediction of critical pressure and speed values for transient simulations.

Making use of the proposed hillchart modeling technique, a fully automated computation procedure has been developed in order to investigate both load rejection scenarios from asymmetric operating conditions as well as time delayed load rejections. Graphical illustrations provide a reliable insight into possibly safe or unsafe operating regions and thus help to find an appropriate commissioning and operating strategies of the power plant.

Summarizing, the proposed method has proven to be successful and the modeling process seems to be a rather general approach. Hence, it can easily be extended to other transient problems and quantities. Besides that, after site measurements of such a power plant, a large fund of prototype measurement records is now available. The presented procedure has offered some promising potential for future VOITH hydro power projects.

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