Improved pump turbine transient behaviour prediction using a Thoma number-dependent hillchart model

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Abstract. Water hammer phenomena are important issues for high head hydro power plants. Especially, if several reversible pump-turbines are connected to the same waterways there may be strong interactions between the hydraulic machines. The prediction and coverage of all relevant load cases is challenging and difficult using classical simulation models. On the basis of a recent pump-storage project, dynamic measurements motivate an improved modeling approach making use of the Thoma number dependency of the actual turbine behaviour. The proposed approach is validated for several transient scenarios and turns out to increase correlation between measurement and simulation results significantly. By applying a fully automated simulation procedure broad operating ranges can be covered which provides a consistent insight into critical load case scenarios. This finally allows the optimization of the closing strategy and hence the overall power plant performance.

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 pressures, minimal draft tube pressures and maximal transient overspeeds 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 once 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.

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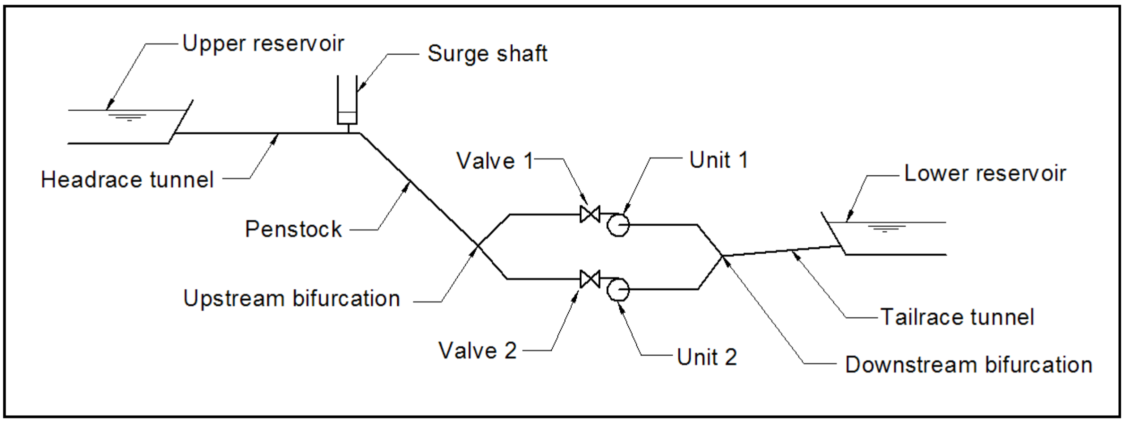


Figure 1. Two-unit configuration with upstream surge shaft and common waterway components

In the following, a recent pump storage project will be investigated in a case study. 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 one or more surge shafts being part of the waterway, for low-specific-speed pump-turbines with their typical S-shaped hillchart and for multiple unit configurations, as the degrees of freedom 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 considered to fulfil all requirements. During 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 must be avoided in any case, as reverse waterhammer 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 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 derating effect of MIV closing is known to reduce the net head of the actual hydraulic machine and thus water hammer phenomena induced by the hydraulic machine itself. 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.

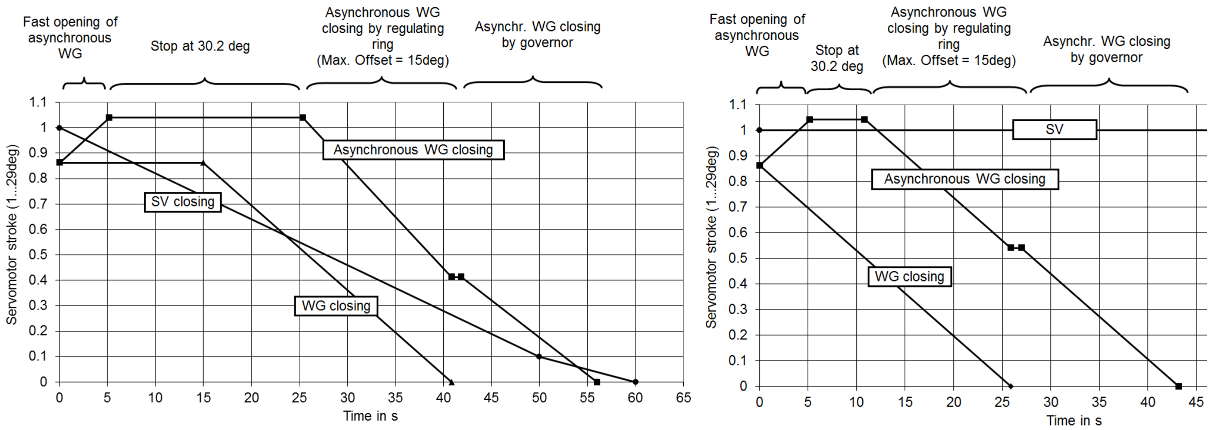


Figure 2. Originally proposed (left) and finally implemented closing law (right)

During commissioning however, it turned out that penstock pressure rise as well as draft tube pressure drop are significantly lower than predicted by standard transient modeling approaches (see Fig.4). Since delayed wicket gate closing and MIV closing are rather time consuming procedures (e.g. resynchronization would be delayed significantly!), the question appeared if these measures and also the corresponding restrictions on the operating range can be omitted by improved transient modeling techniques. A new method will be provided in the following.

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

For determining critical values for pressure heads as well as for overspeeds, 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 was developed at EPFL (http://simsen.epfl.ch) [3]. All subsequent time domain simulations have been carried out using SIMSEN. The pump-turbines are modelled using the well-known quasi-stationary hillcharts which are obtained by model tests in the hydraulic lab. The key load cases which will be shown subsequently are single unit or synchronous load rejections including closing of the wicket gates. A special focus will be 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).

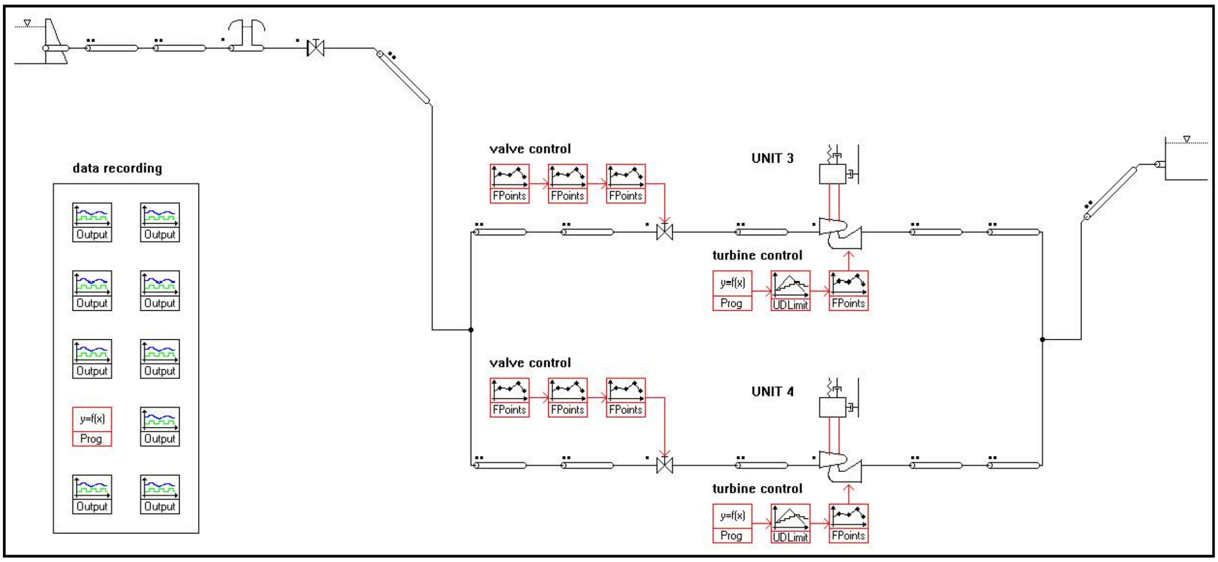


Figure 3. SIMSEN model layout - Pump storage layout with two units connected to the same waterway system

Measurement technique: The corresponding measurements from site were taken with a sampling rate of 4.8 kHz including and 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 oscillation in cross-section plane 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 filtering of relevant signal components.

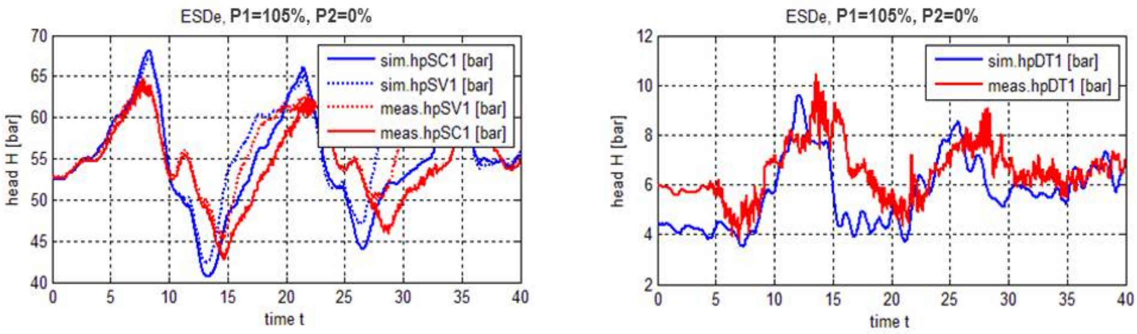


Figure 4. Spiral case (SC), spherical valve (SV) and draft tube (DT) head (simulation and measurement) for standard pump turbine modeling

Fig.4 shows the comparison between simulation and measurement results for one unit operation where a standard quasi stationary turbine hill chart representation has been used (delayed WG closing as initially proposed). Note that, there are 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 about 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 is hence conservative, there is obviously some room for improvement.
Modeling uncertainties are certainly growing, if several units are connected to the same waterways since there may be strong interactions between the hydraulic machines. 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 could 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.

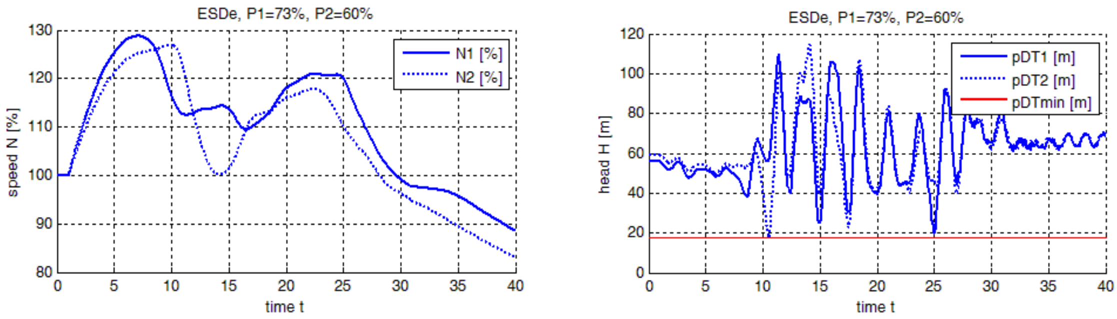


Figure 5. Simultaneous load rejection (simulation) for standard pump turbine modeling

A simulative example of a synchronous load rejection of two units is shown in Fig.5. Since both units where 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 which can be observed by the initial draft tube pressure drop of unit 1. This induces a water hammer also for unit 2 which leads to a temporal 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. Comparisons with measurement results for two-unit operation will follow in subsequent sections.

3. Development of an adapted hillchart model.

From the previous investigations, it can be deduced that the pressure rise is slightly overestimated for pump-turbine schemes using the quasi-stationary hillchart modeling technique. The motivation for the usage of 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 slopes can lead to problems during synchronization and measurement during model testing ([6], [7], [8]). When analyzing single unit trips with subsequent closing procedures of the distributor and/or the main inlet valve, periodical speed and pressure fluctuations can be observed during transient operation until the flow in the waterway is cut. Same results arise on a perfectly parallel operated multiple unit plant but with higher amplitudes of the values of interest [9].

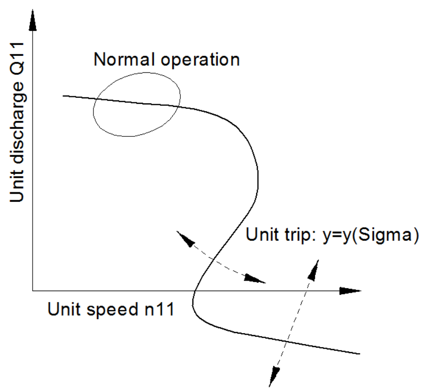


Figure 6. σ-dependent hillchart: dashed opening lines = σ high; solid opening lines = σ low

From model measurements it is also known, that the hillchart may look differently – especially in the S-shaped region – if different turbine settings or in other words different Thoma numbers are investigated. Qualitatively, an example is shown in Fig.6. The definition of $n11$ and $Q11$ is given by $n_{11} = nD/\sqrt{H}$ and $Q_{11} = Q/(D^2\sqrt{H})$, 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 $\sigma := \frac{NPSH}{H} = \frac{h_b - h_{va} - h_s}{H}$ where h_b, h_{va}, 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 further modeling approach is finally given by Fig. 7. It is evident that largest values for the turbine net head and thus the lowest Thoma numbers are just occurring when the spiral case pressure and thus modeling error were reaching their maximal values. Thus, temporarily using a different hillchart for lower Thoma numbers gives rise to possible model improvements. It was furthermore identified that changing of elementary model parameters such as inertia of the machines could not lead to a significant model improvement (see set of curves in Fig.7).

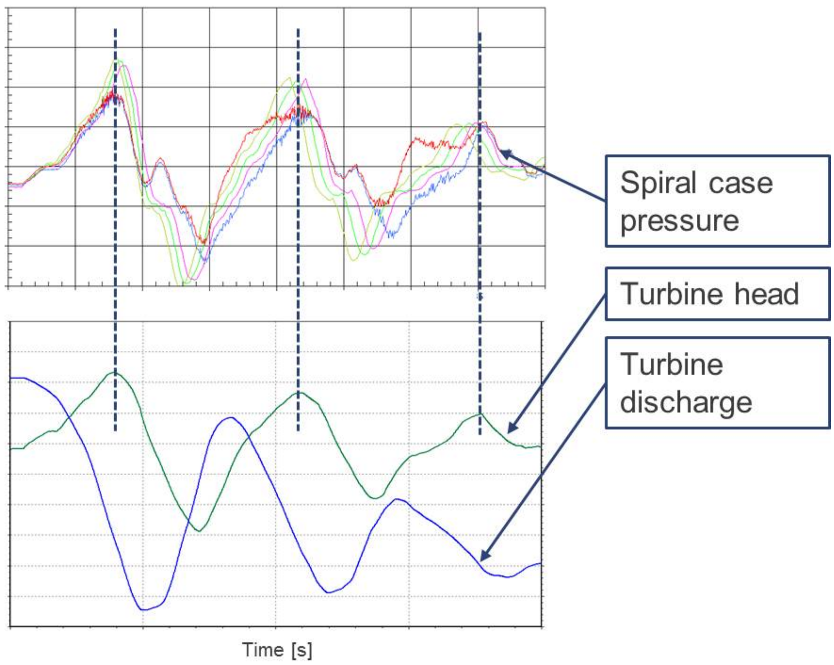


Figure 7. Qualitative Comparison of max. SC pressure (measurement and simulation) and max net head

In the following, a new SIMSEN pump-turbine model has been set up, which consists of two different individual hillcharts. Since some hillchart measurements for low Thoma numbers where 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 carried out, depending on the actual Thoma number which was computed in parallel. After some brief model adaptations, the trajectories of Fig.8 are finally obtained for single unit operation whereas load case of Fig.4 was serving for comparison. It can be seen that the fitting of pressure trajectories in SC and SV as well as in DT are significantly improved 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.

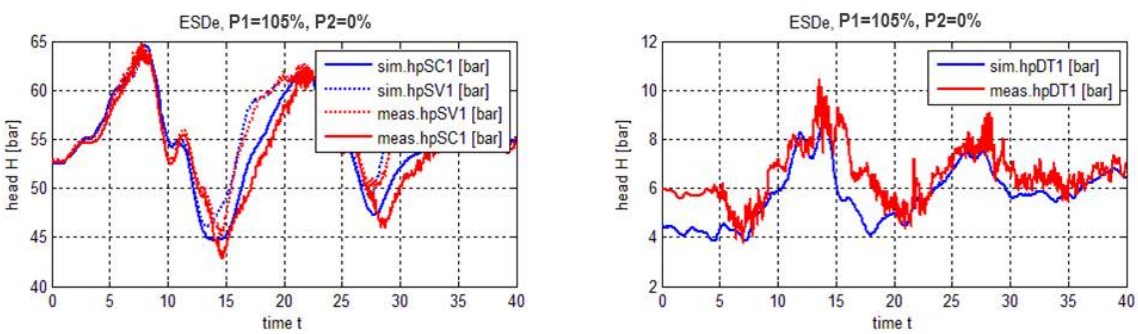


Figure 8. Spiral case (SC), spherical valve (SV) and draft tube (DT) head (simulation and measurement) for Thoma number-dependent pump turbine modeling

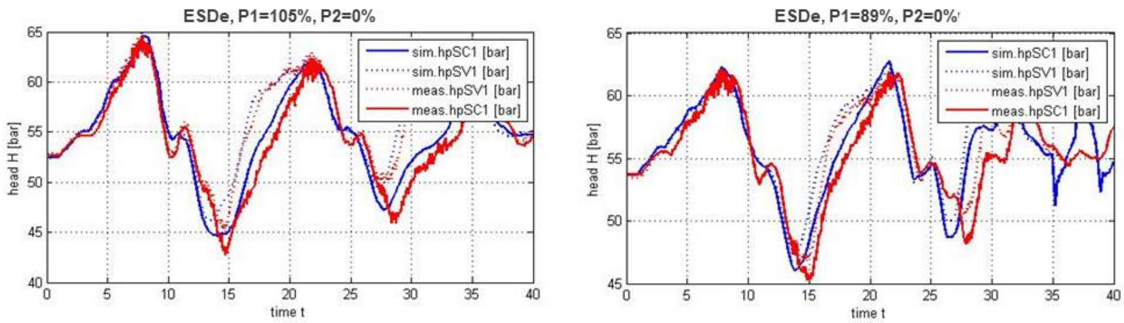
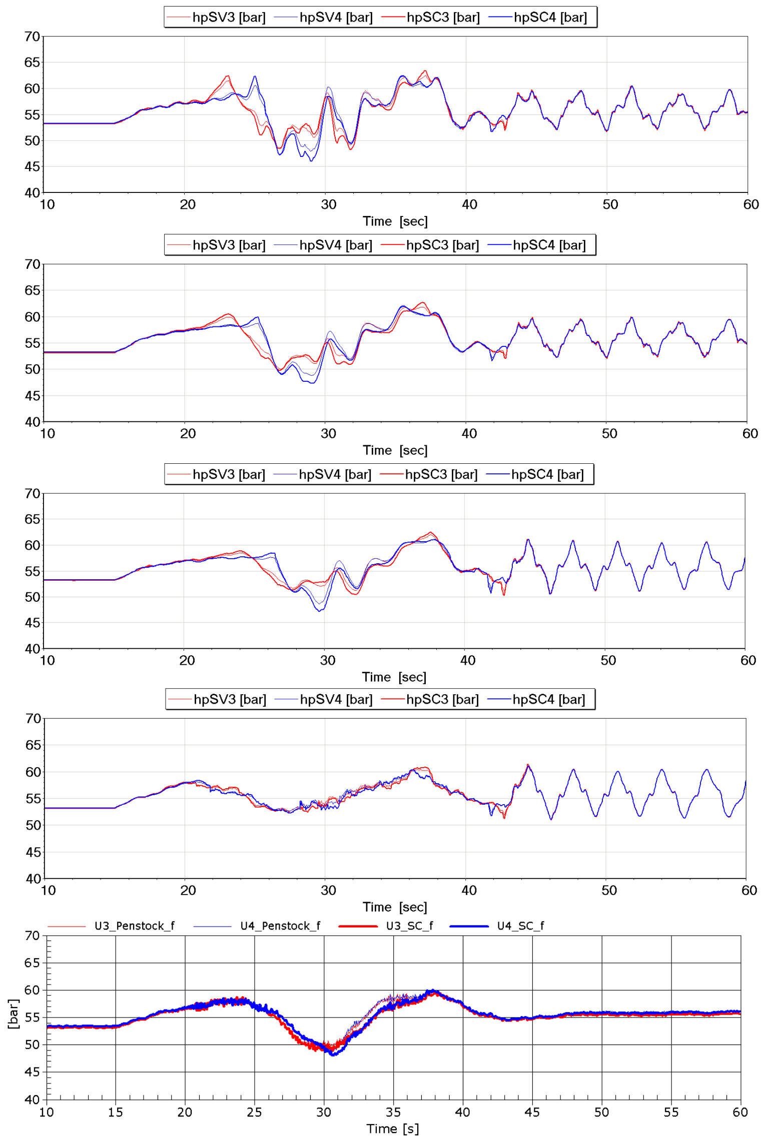


Figure 9. Single unit load rejection from 272MW (matching case/left) and 230MW (validation case/right)



Standard hillchart

2-AWG hillchart

Averaged hillchart

σ-dependent hillchart

Measurement

Figure 10. Parallel load rejection using different simulation models: SC and SV pressure

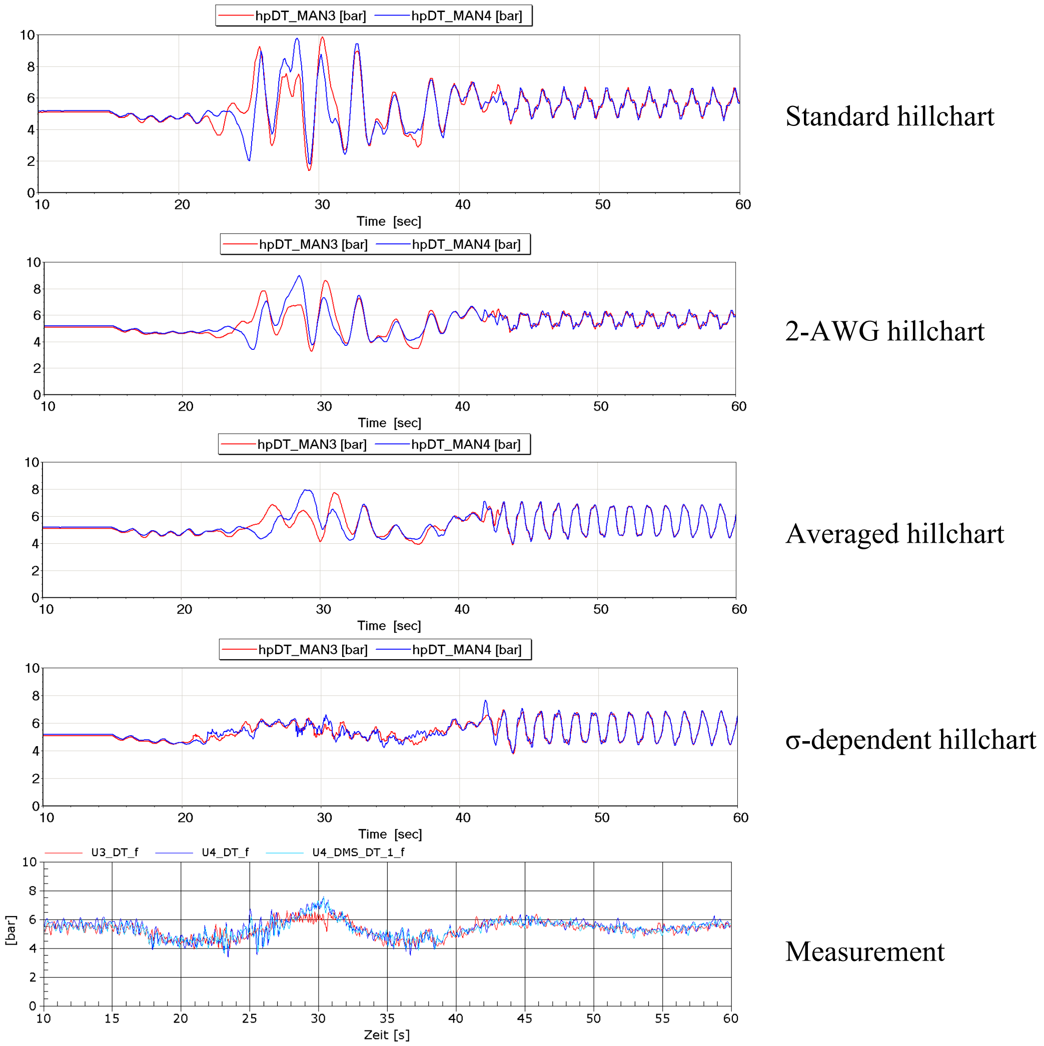


Figure 11. Parallel load rejection using different simulation models: DT pressure

Differences in the DT pressure between simulation and prototype can be explained by the non-uniform discharge and thus pressure profile over the DT diameter [10]. Deviations turn out to be especially high for high draft tube discharges. As a validation case, a single machine load rejection from a different initial load has been investigated. Both, model matching and validation cases which are shown in Fig.9 turn out to be in good accordance with the corresponding measurements.

After final consolidation between measurements and simulation results the overall closing strategy could be changed to the standard instantaneous wicket gate closing procedure. The 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 draft tube pressure drop. Simulation results and measurements for the new (classical) closing law are depicted in Fig.10/11 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 actual 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 can be seen, also in the 2-unit operating scenario the Thoma number dependent hillchart approach produces simulation results which match the measurements very 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.

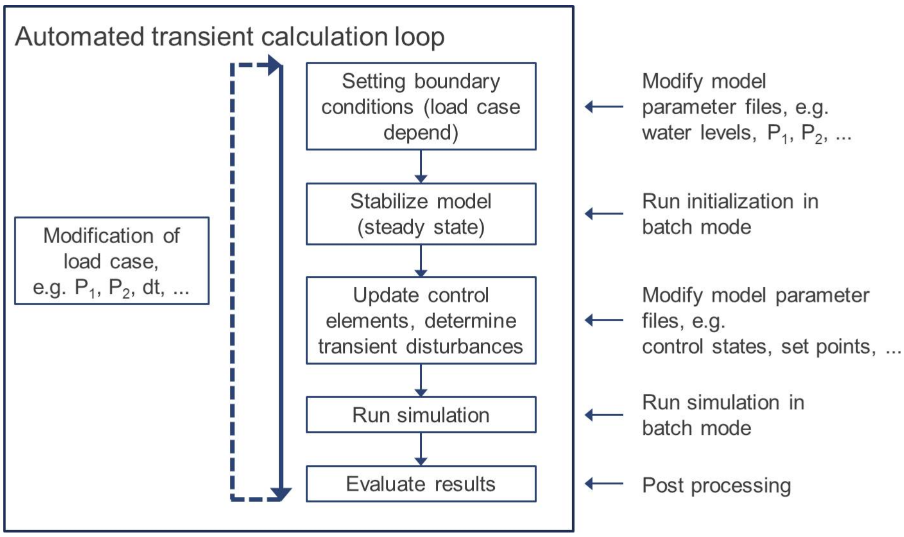


Figure 12. Howto description – flow chart

A sketch of the automated procedure is shown in Fig.12. The SIMSEN simulation environment is driven batch mode using some 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 50-100%. The simulation results are graphically represented in Fig.13 for the original hillchart model and different angles of view. The map gives a good impression of operating zones which are more or less critical. Note that, there is a minor non-symmetric design of the waterways which can be observed in these plots. However, the same investigation has been carried out using the newly developed σ-dependent hillchart model. Results are shown in Fig.14. Due to higher modeling quality, prediction is more accurate and shows a significant reduction of draft tube pressure sunk.

Note that, these maps are quite helpful also for commissioning issues since emergency shutdown scenarios can be tested and compared starting from rather uncritical to critical 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. This procedure has been carried out for the actual project of interest. Step by step, the most critical load case has been approached, which is an offset unit trip from different power levels. All tests have been successfully carried out and good correlation between the measured and the simulated minimum draft tube pressure was found.

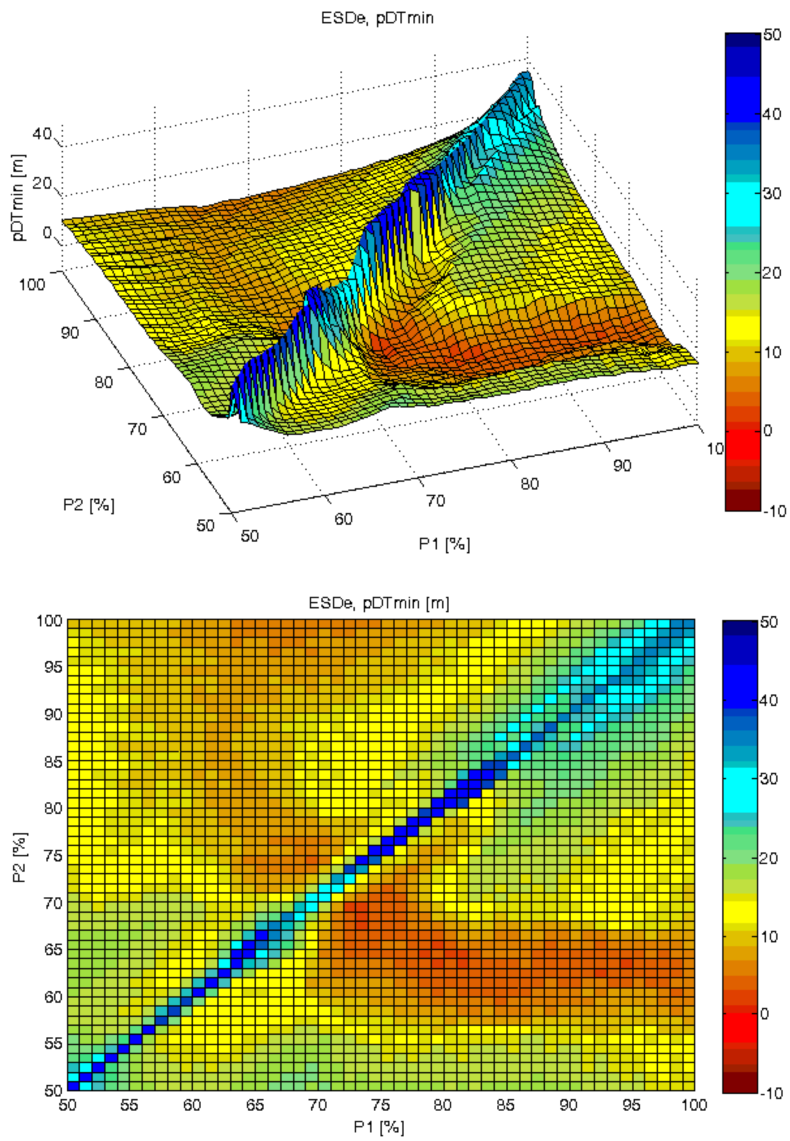


Figure 13. Minimal DT pressure for all operating conditions using standard hillchart model

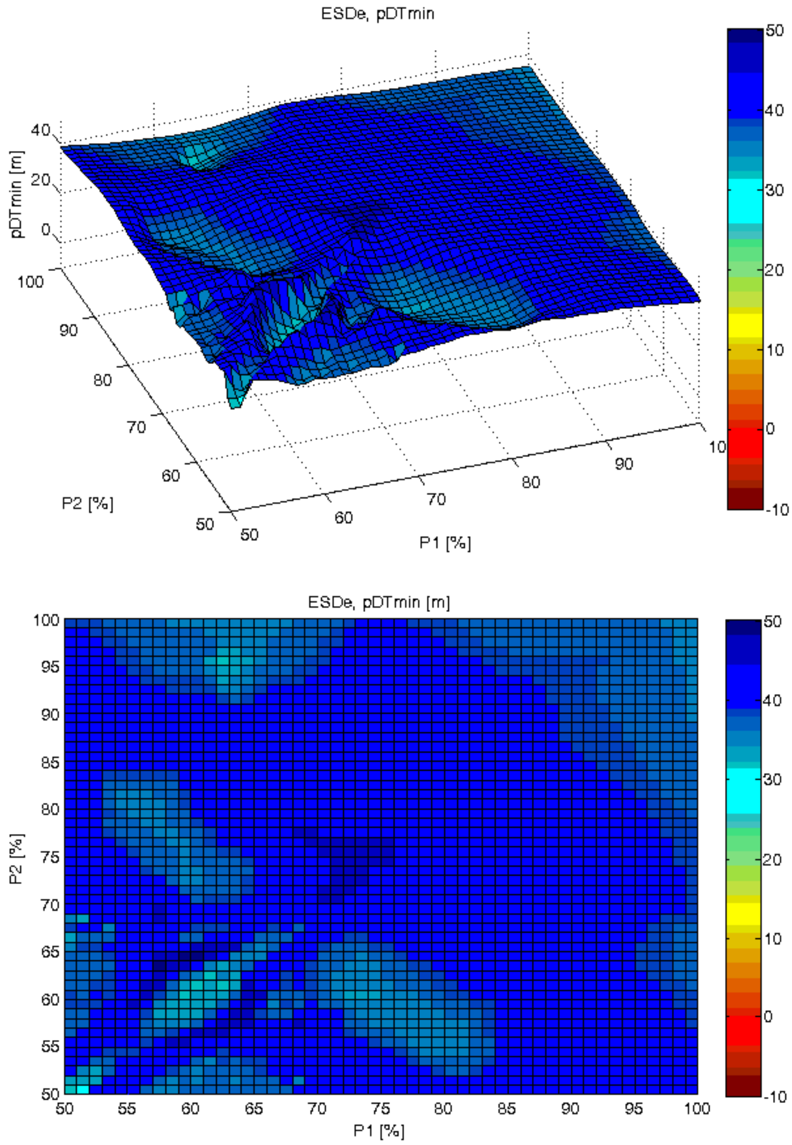


Figure 14. Minimal DT pressure for all operating conditions using σ-dependent hillchart model

5. Summary and outlook for future developments.

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

By these means, the overall closing strategy could be chosen less conservative. This allows a wider operating range and faster resynchronization after possible load rejections due to electrical grid failures. Risks because of time delayed load rejection could be systematically excluded. Furthermore, the automated simulation procedure gives a better inside into system dynamics and is helpful to detect potential risks for certain power plant operating conditions.

The approach was motivated by model test measurements for different Thoma numbers which appear 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. Therefore, the presented procedure has offered some promising potential for future projects.

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