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INVESTIGAREA FUNCȚIONĂRII HIDROAGREGATELOR ÎN REGIMURI TRANZITORII

INVESTIGATION ON THE OPERATION OF HYDRAULIC TURBINES IN TRANSIENT REGIMES

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SUMMARY

In the current context, the composition and characteristics of energy systems have significantly changed due to the integration of energy electricity produced from non-dispatchable renewable sources (wind and solar) which are fluctuating and unpredictable in nature. For this reason, the production of electricity from hydroelectric power plants must provide regulation/compensating for production from renewable sources uncontrollable, by flexible operation over a wide range of powers and frequent operation in transient regimes for frequency regulation and power assurance for balancing purposes. Transient hydraulic regimes associated with flexible operation induce overpressures that reduce the lifespan of a hydraulic components and turbines and can even cause catastrophic structural failures.

The thesis objective consists in identifying and analyzing the factors influencing hydrodynamic phenomena in transient regimes, particularly water hammer production, in order to estimate the impact on the operational safety of hydraulic turbine components and the durability of hydraulic circuits. The objective defined above is achieved by developing a methodology for collection and analysis of recorded data, followed by the evaluation and classification of the impact of each operating scenario based on the experimental results obtained in situ. The methodology considers the study of the impact of different types of manoeuvre laws used in closing the governing device on the turbine passages for radial-axial hydraulic turbines (Francis) and axial (propeller, Kaplan, and saxo). The approach to the problem includes three stages: **(1)** establishing the in situ measurement equipment installation configuration, the acquisition procedure and analysis of experimental recorded; **(2)** analysis of the consequences of the closing law on operational safety; **(3)** estimation of the impact of operating scenarios on the lifespan of hydraulic turbines.

In **Chapter 1** the research topic is introduced: study transient phenomena associated with flexible operation of hydropower units and the impact that this mode of operation has on the operational safety of hydraulic turbines. The selection of this research topic was made from the perspective of the current issue of

hydropower unit overloads for grid balancing.

Chapter 2 presents a critical analysis of the specialized literature in the field of operation of hydraulic turbines in transient regimes, from which it resulted that the closing law of the wicket gates has a decisive influence on the operational safety of hydraulic turbines. The analyses in the literature are largely specific, the results of the studies often remain at a theoretical level, and the objectives are not focused on developing maintenance strategies that guide interventions related to safe operation. The measures proposed by the authors are singular and do not aim for direct and widespread applicability of the recommendations in the industrial environment.

Chapter 3 presents the research methodology used for investigating overpressures in the passages of hydraulic turbines, the impact of overpressures on operational safety and the durability of the spiral casing. The main elements of the methodology included in the following chapters are: (i) an experimental study and an analysis of the data obtained (Chapters 4 and 5); (ii) an analysis of the consequences of the closing law on operational safety (Chapter 6); (iii) an estimation of the impact of hydro unit operating scenarios on lifespan (Chapter 7); (iv) a strategy for transferring the results and conclusions of experimental studies to the industry (Chapter 8).

In a first stage, in **Chapter 4**, the in situ evolution of overpressures produced by the closing of the wicket gates during load rejections of the hydraulic turbine is investigated. The tests were predominantly carried out for the emergency closing of the wicket gates, in the case of progressive load rejections. The investigations consist of studying the control laws of the wicket gates depending on the type of hydraulic turbine (Francis, propeller, Kaplan, and saxo) and the impact on the operational safety of the turbine components and the associated hydraulic passage. The experimental data collection program included the use of different closing gradients of the wicket gates, and the overpressure trends are grouped and compared according to the configurations of the hydraulic turbines considered. The overpressures obtained in transient regimes were recorded, in the hydraulic passage section upstream and downstream of the turbine runner. Special attention is paid to the overpressures obtained in the spiral case of the hydraulic turbine. The

analysis and interpretation of the experimental data are performed for 24 hydraulic turbines with powers ranging from 4 MW to 360 MW and their associated passages which equip operating hydroelectric power plants, some of them designed over a century ago. Conclusions are synthesized within group trends based on the type and characteristics of the turbine hydraulic and of the associated passage. Also, the influence of the governor law parameters on the hydropower units overspeed, as well as the simultaneous impact on the overpressure/ overspeed binomial is analyzed. Experimental results showed that the wicket gates closing law parameters have a decisive impact on operational safety, and the consequences differ from one configuration to another. For example, using a closing ramp 3 times slower for a Kaplan turbine than for a Francis turbine (30 sec/100% WG compared to 10 sec/100% WG) causes however overpressure increases above the reference pressure of up to 5 times higher (25% compared to 5%). This type of behavior requires a detailed approach through particular case studies for Francis and Kaplan turbines, which are carried out in Chapter 5.

Through a case study considered for a Francis hydraulic turbine, in **Chapter 5**, the temporal interaction between the factors that produce water hammer in the spiral chamber is analyzed. Using a theoretical model based on the existing configuration of a hydropower unit equipped with a Francis turbine, an analytical calculation of overpressure, and the evolution of pressure over time in the spiral chamber based on numerical simulation is performed. The comparison of the maximum pressure values obtained analytically and numerically with the experimental data led to the validation of the methods used and the identification of their limits. It was found that an analytical calculation can underestimate experimental data by approximately 7%, while numerical results overestimate experimental data within 2%. In conclusion, the use of analytical calculation in design is likely to introduce a degree of risk to the operational safety of a hydraulic turbines due to the fact that it is very sensitive to the simplifying assumptions used. Therefore, it is recommended to use the analytical method only for real-time estimation of the order of magnitude of surges (during tests), while for design (transient studies) the simulation method is recommended.

Next, the impact of the governor law on overpressure induced by the water

hammer phenomenon in the hydraulic passages, for hydropower units equipped with double-regulated axial turbines is explored. For a Kaplan turbine case study, investigations were carried out to determine the maximum pressure when a closing law of the wicket gates with a fast ramp over the entire stroke is selected, compared to the maximum pressure produced by a closing law with two ramps, a fast one followed by a slow closing. The comparative study highlights the fact that a double-slope closing law of the wicket gates can ensure a limitation of overpressures in axial hydraulic turbines with double regulation in order not to compromise the structural integrity of the hydraulic passage. It is also shown that by appropriately selecting the closing gradients of the wicket gates, a balance can be ensured between overpressure and overspeed resulting during load rejections. Analysis of experimental data for a Kaplan turbine highlights the amplification of overpressures resulting from the absence of a slow ramp (by 11% to 78%) and the increase in stresses produced by the absence of the second ramp of the closing law of the wicket gates. In the case of double-regulated hydraulic "saxo" type turbines, the limitations imposed by the use of a single rapid slope over the entire stroke of the wicket gates are analyzed, as well as the impact of the single closing gradient on the overpressure/ overspeed. The study has highlighted the need to use a double-slope closing law for the wicket gates to ensure operational safety of a double-regulated axial turbine. If a single rapid manoeuvre law with a single ramp is used, there is a real risk of exceeding the allowable pressure. In the case study addressed, the maximum extrapolated pressure of 212% far exceeds the allowable pressure of 125% and even the pipe rupture pressure of 200%. This aspect is analyzed in detail in the following chapter dedicated to the impact of the closing law on the operational safety of hydraulic turbines.

In the second stage, in **Chapter 6**, the impact of the closing law on the operational safety of hydraulic turbines caused by overpressures generated by water hammer in the hydraulic passage is analyzed. Case studies for Francis and Kaplan turbines highlight that respecting the allowable pressure of the hydraulic passage is an absolute necessity to avoid catastrophic destruction of the lining. To limit overpressures, a methodology for adjusting the closing law of the wicket gates has been developed based on a series of progressive load rejection tests. Firstly,

the methodology for establishing closing gradients in relation to overpressures generated by water hammer in the spiral chamber is described, and then, in relation to the maximum overspeed of the unit. This methodology is useful for hydraulic turbine operators, especially during the commissioning stage of hydraulic turbines.

Also, the specific case of the catastrophic accident that occurred in 2009 at the Sayano-Shushenskaya HPP in Russia is analyzed, which occurred against the backdrop of non-compliance with the design criteria of the hydraulic turbine (closing of the wicket gates at o a very high speed: 4.1 sec/100%WG, compared to approximately 11.0 sec/100%WG encountered normally for this type of turbine) and the operating mode (intensive use of the hydropower unit in network regulation with frequent operation in transient zones). The triggering element of the accident identified in my research, was the overpressure generated by the water hammer, which exceeded the allowable pressure. Analysis of the data available for this accident outlined recommendations for the safe operation of hydraulic turbines. Based on the investigations carried out, the triggering event of the accident was the overpressure generated by the water hammer, which exceeded the admitted pressure. In conclusion, the overpressures generated by closing gradients higher than the values that guarantee compliance with the allowable pressure can have a catastrophic effect on the safety of operation of hydraulic turbines. Therefore, the impact of the operating mode of the hydraulic turbine on the durability of its components and the respective hydraulic circuit, and on the safety in operation is addressed in the following chapter.

In the third stage, the results of the experimental data analysis are used to establish concrete strategies for transferring mitigation measures for stress effects to turbine operators hydraulic. In **Chapter 7**, the impact of cyclic stresses induced in the hydraulic passage during transient operation is evaluated. Using the S-N curve methodology, a conceptual relationship with the lifespan of a welded spiral case is established for each of the considered stresses. To estimate the impact of the ensemble of stresses on the durability of the spiral case, the results are transposed for various operating scenarios of the hydraulic turbines used in practice. Using analytical estimates, it is determined that the greatest impact on

the durability of the spiral case is caused by the crossing of transient zones, followed by start-up/shut-down sequences. Also, intensive operation of hydraulic turbines for grid regulation can lead to a reduction in lifespan by up to 54%. The study showed that premature aging of hydraulic passages is due to cyclic stresses generated by the operating sequences of the hydropower unit. In conclusion, the operating mode of the hydraulic turbine has a determining impact on safety in operation. Therefore, the choice and implementation of an inspection and maintenance program/system to ensure safety in operation of the hydraulic turbine ș of its components is crucial. Problems related to the inspection/system program and maintenance of hydraulic turbine/passage components are addressed in the following chapter.

The conclusions on cyclic loading impact are used in **Chapter 8** to develop strategies for transferring results to the industry. To obtain a centralized overview of intervention actions, a methodology based on combining a risk matrix with a load effect mitigation matrix is proposed. Classification of hydraulic turbines and associated passages into intervention categories allows for decision-making and selection of measures, depending on the loads generated by different operating modes. The approach considers all stages of a project's life: design, commissioning, operation, maintenance and refurbishment of a hydraulic turbine. The presented methodology allows for simultaneous consideration of the impact of overpressures on the safe operation of the hydraulic passage, by categorizing the assembly hydraulic turbine/hydraulic passage into a maintenance program category. As a materialization of the conclusions and experimental results, a series of specific measures are proposed to ensure the safe operation of hydraulic turbines and general methods for improving maintenance. In particular, for maintenance interventions, it is proposed to transition from the classic, periodic, and corrective procedure to preventive maintenance, based on relative functional indicators resulting from the monitoring of operating parameters. The methodology for a completing the maintenance program with a risk study allows for simultaneous consideration, of both specific measures for safe operation and solutions for increasing the lifespan of the hydraulic turbine and passage. Furthermore, by combining the conclusions of the experimental analyses from the previous chapters

with a structuring of intervention programs according to needs and degradation status, a pragmatic approach from the perspective of plant operating personnel results.

The main achievement of the thesis consists in the systematic approach of the hydraulic turbines operating in transient regimes and estimating the impact on operational safety based on the experience gained in over 15 years as a designer of hydraulic turbines at Alstom/GE Hydro, Canada, and 11 years on operating/testing of hydraulic turbines at Hydro-Quebec, Canada.

The investigations are based on the analysis of and interpretation of experimental data for over 1000 individual load rejections performed on 24 configurations of Francis, propeller, Kaplan and saxo hydraulic turbines with powers ranging between 4 MW and 360 MW and their passages.

The methodology used a led to the centralization of the evolution of measured overpressures and the creation of a synoptic diagram of the studied hydraulic turbines, specifying the parameters of the wicket gates closing law together with the evaluation of the factors that generate the water hammer. Case studies and comparative analyses allowed the establishment of correlations between various types of closing laws for the guide vane and operational safety. Through analytical calculations, the relationships between the parameters of the closing law and their impact on operational safety were theorized.

The conclusions regarding durability and operational safety were integrated into a strategy for transferring the results of experimental studies to industry, simultaneously considering risk factors and maintenance activities based on the operational parameters considered for the hydraulic turbine.

The results of the experimental investigations and theoretical analyses presented in the thesis foreshadow a series of perspectives for continuing research in the direction of overpressures, namely : (i) the selection of the wicket gates closing parameters (number of slopes, gradient, position of slope connection points) depending on the turbine type and the specific constraints of each hydropower unit; (ii) solutions for limiting the overspeed of the hydraulic turbine rotating part (maximum value, time of occurrence, duration of the "overspeed plateau") to increase operational safety.