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Effect of start and stop cycles on hydropower plants: modelling the deterioration of the equipment to evaluate the cycling cost

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Abstract. With the high energy demand, renewable energies emerged and the deregulation of the energy market appeared in the late '90. These types of energies are intermittent and can produce high fluctuations in the power grid because they are connected only in certain weather conditions (for example: solar energy can be produced only by day and wind energy only when it is windy). Hydropower energy is recognized for its flexibility in responding to the demands of the network in order to maintain a constant level of energy and to guarantee the security of the electrical network. Nowadays, the hydropower plants are the main provider of energy adjustments thanks to a high number of start and stop cycles (which can sometimes be around 6 per day), the fast variations in load and the use of PSH (pumped-storage hydropower). But these rapid changes in the production conditions of hydroelectric power plants lead to high stresses on the components and consequently to faster degradation (mechanical, electrical, thermal, hydraulic, etc.). This work focuses on the design of a methodology that relies on auditable methods to estimate the cost of start and stop cycles and presents three complementary, representative (by equipment), reproducible (can be applied by different operators) methods based on explicit assumptions and validated by experts and in function of the available data in order to estimate the degradation of the main components of the hydropower plant (shut-off valve, runner, generator, transformer and circuit-breaker). These methods are based on the main degradation phenomena. The first method uses on-site measurements to study the fatigue on runners, the second method uses a reliability law to estimate the lifetime of generators and a predictive model using online temperature measurements and the last method uses expert judgement due to the lack of measurements on the equipment.

1. Introduction

The shift towards green and sustainable energy systems, which has accelerated over the past 30 years, is reflected in the policy decisions of governments worldwide [1]. Nowadays, with the emergence of new energies such as solar or wind, which can produce energy according to climatic conditions (wind



and sun), energy fluctuations in the electrical network are fast and high. Solutions were implemented to respond to the intermittent nature of these renewable energies in order to guarantee the security of the electrical network: the energy gaps are filled by hydropower energy. An important role is played by the storage of energy in water dams and the use of PSH (pumped-storage hydropower) to generate electricity when necessary. We can observe the production of energy on the load curve that is the graphical representation of the load (in MW) in chronological order (in hours) by type of energy. The curve is useful for choosing the economic sizes of different generation units and allows for estimating the cost of production [2]. It determines the operating modes of the power plants (system services) and the priority or order in which the different generation units should operate [3]. In figure 1. is represented the load curve for a day in France. At the top of the figure, there is the amount in MW that has been produced, on the right of the image, the percentage of production by type of energy and in the graph, we can see at what time of the day a certain type of energy is produced. It can be seen that in case of need (morning or evening), hydroelectric energy is used to balance the network.

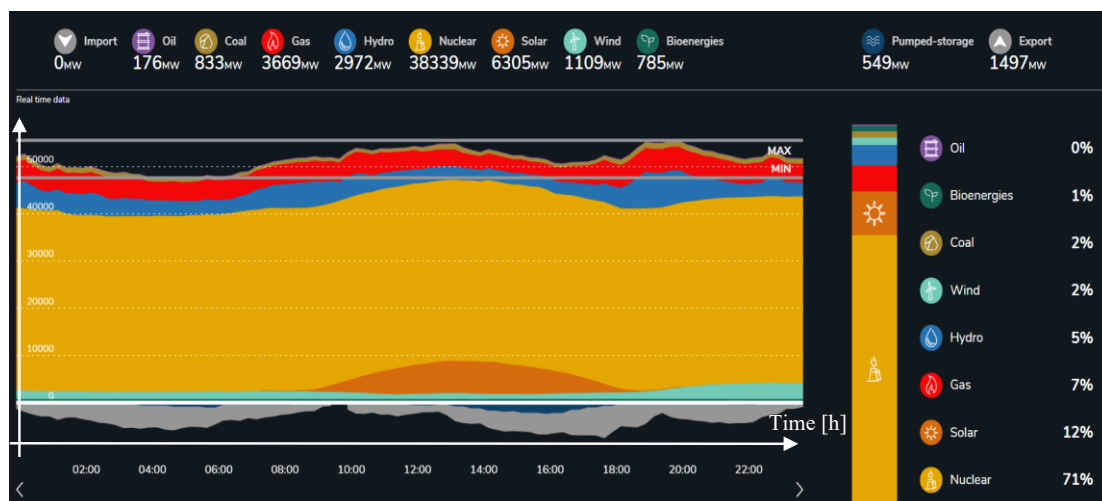


Figure 1. Electricity production by type of energy over one day (23/10/2021) – the load curve (Source: RTE France website).

The high demand of energy and these new modes of functioning (high and partial load operations, rough zone operation, spinning reserve, synchronous condenser) comes with a cost. This increase in the number of cycles has proven effects in terms of degradation and failures of the materials involved, on operational practices and maintenance, and consequently on the overall costs of the installation [4]. Therefore, a more detailed knowledge needs to be acquired for the complete costs generated by these new operating modes with more and more start and stop cycles in order to be able to offer its services at the right cost and to support the economic decisions of equipment operation and maintenance.

This work aims at developing an original approach to evaluate the cost associated with hydroelectric start and stop cycles focusing on the material cost. The details of this work are presented in the articles [5,6,7] and in the thesis written in French [8] and in this paper we summarize and discuss the methodology used. Three methods are proposed to estimate the deterioration of the hydro power equipment taking into consideration the main phenomena of degradation and the available data.

2. The methodologies used in the literature to estimate the start and stop costs

The issue of increasing costs related to start and stop cycles appeared in Europe after the deregulation of the energy market in the late '90 [9]. The need for a short/long term operating strategy for hydropower plants (in terms of operation but especially in terms of cost), has led to the emergence of *top-down* and *bottom-up* models in the hydropower industry to estimate the cost of start and stop cycles [10]. A review

of existing work on assessing and modelling costs are described in [5] and shows two types of approaches that have been considered: *economic* and *technical-economic*. In these two categories, six methods are identified (figure 2).

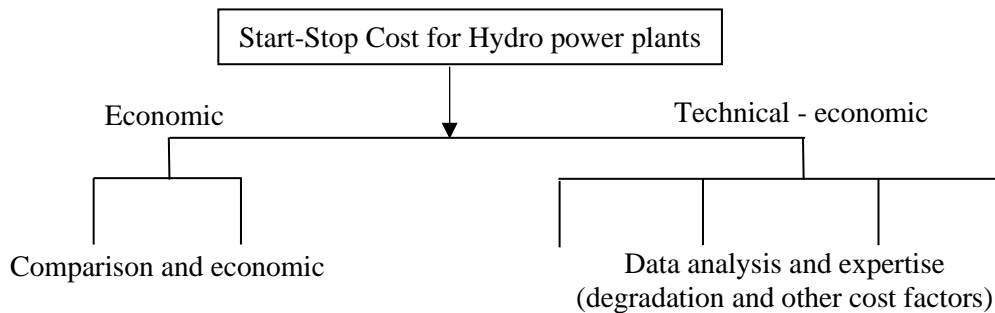


Figure 2. Start and stop cost methodologies [5].

The price range goes from 200\$ up to 900\$ depending on the equipment, type of turbine and year of estimation. On the one hand, the top-down approach is usually an economic approach, where the overall cost of operating and maintaining of two units are compared: one with high and one with low number of start and stop cycles and assumes that the difference in cost is due to increased start and stop cycles. On the other hand, the bottom-up approach is usually a technical-economic approach and attempts to identify the potential cost factors associated with an individual production unit and to model their relationship with respect to changes in operating conditions. The reliability of hydroelectric plants and the effects of degradation have been discussed and assumptions vary considerably in these models. The cost can be *equipment related* (increasing cost as more frequent and costly maintenance) or *non-equipment related* (reducing revenues as loss opportunity or reduce availability) As observed in [5], these methods do not rely on explicit modelling of deterioration and lifetime consumption due to start and stop cycles. Furthermore, there is no consensus on the influencing factors to be considered or on the methodology for calculating costs.

3. The strategy proposed for estimating the cost of a start and stop cycle

The main research objectives are to develop a methodology that relies on auditable methods for estimating the degradation of hydro power plant equipment and to propose a strategy for estimating the start and stop costs [5,8]. Thus, the methodology is focusing on equipment related costs. These methods are specific, representative (by material) and reproducible (can be applied by different operators) and are based on explicit assumptions validated by EDF (Electricité de France) experts. Priority has been given to the technical-economic (bottom-up) strategy where the main affected equipment and degradation phenomena have been identified. Then, physical and reliability models were proposed with the data available at EDF in order to quantify the impact of transient phases (starts and stops) and to estimate the associated costs. This approach mobilizes skills of analysis, processing and exploitation of data and skills on the engineering of the considered equipment:

- it requires access to a large amount of data on defaults, equipment condition, operating and maintenance costs where the quality of the quantitative results depends on the availability and quality of the existing data;
- this method also requires technical expertise on the materials and on the degradation phenomena involved.

3.1. Data required and used for the study

We systematically search for the impacted equipment and the degradation phenomena involved, as well as their consequences, in terms of malfunction, failures and loss of efficiency. Thus, in-depth research on two axes was carried out: the first one concerns the knowledge of the degradation and the associated

phenomena of the equipment of the hydropower plants and the second one synthesizes the information obtained by the interview of the experts, the return of experience and the analysis of the EDF data bases [8]. The interest is to link the approaches based on physics, data and feedback for a cross analysis of the available information. The process is summarized in figure 3.

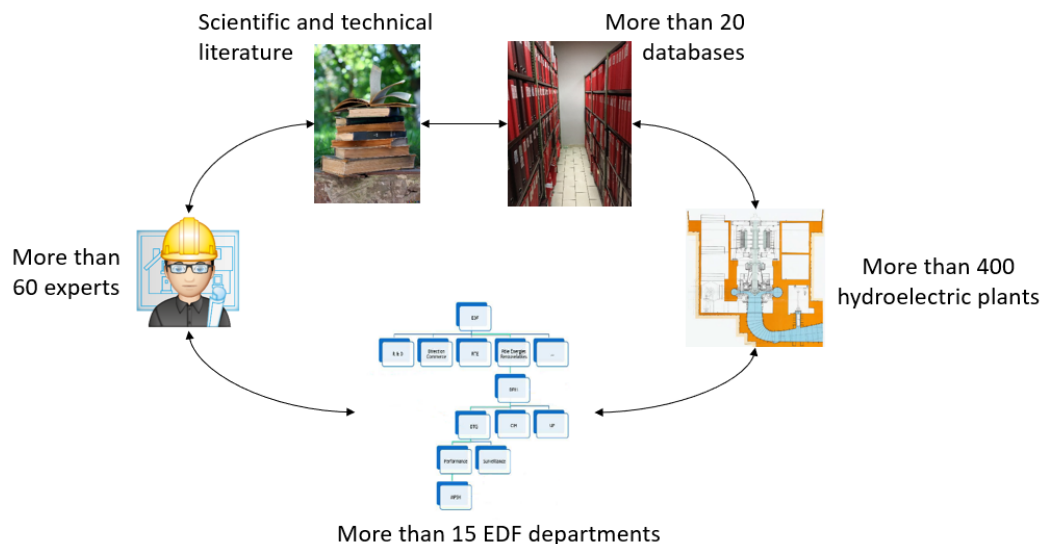


Figure 3. Diagram of the data sources used [8].

3.2. Identification of the impacted equipment and the main phenomena of degradation

In the literature, the generator is one of the most studied equipment. Diagnostic measurements for the remaining lifetime or aging models based on available data associated with the production units on the stator showed that the effect of thermal cycling and mechanical stress (centrifugal force) are the main causes of degradation [11,12]. The turbine was also studied and measurements in the technical literature showed the impacted of fatigue on Pelton and Kaplan turbines [13], [14]. For the circuit breaker, the main causes of failure [15] and methods for estimating remaining life are reviewed [16], but the effect of degradation due to start and stop cycling is not listed. In a methodology where expert judgement is used to validate technical [10], the cost attributable to start and stop cycles is 50% of total replacement cost. In an internal EDF report [17], a correlation between the number of cycles, defaults, and the size of the crack that appeared on the trunnions reveals the impact of start and stop cycles on spherical valves. In the methodologies used to estimate the start and stop costs [5], the authors from the papers reviewed consider that transformers are not significantly affected by cycling.

Furthermore, the specialized EDF employees (experts, equipment referents, engineers, technicians, maintenance managers and operators) in the field of engineering and reliability were interviewed in several areas (mechanical - turbine, guard valve, electrical - generator, transformer, circuit breaker, etc.) in order to identify the degradation mechanisms of the equipment of a hydroelectric plant. An internal EDF report [18] presents the feedback and a list, as exhaustively as possible, the disorders and pathologies affecting the equipment, the damages and defaults encountered that are possibly related to start and stop cycles. Following the research in the literature and these interviews, the degradation phenomena of materials that are impacted by cycling have been identified.

The system, which in our case is the hydroelectric power plant, was decomposed into sub-components (equipment) and the sequences of start and stop were analyzed in details to identify the main degradation phenomena. In figure 4 is represented a start-up phase in respect with time and the equipment that is impacted [8]. On the vertical axis, one can observe the power in [MW], the pressure of the penstock in [bar] and on the horizontal the speed (which is the rotational speed of frequency) in [Hz] and the opening of the shut-off valve in [mm]. The degradation phenomena are briefly described

according to their operating mechanisms. Repeated opening of the shut-off valve to let water through the turbine causes fatigue and subsequently accelerated degradation. The runner is affected by fatigue caused by the mechanical forces of water impact. The torque is transmitted to the generator where start and stop cycles produce heating and cooling due to the electrical energy flowing through the stator and rotor, which then produces thermal cycling that can be damaging. The electrical energy is transmitted to the transformer which is affected by the same thermal cycling degradation forces as the generator, that heats up and cools down during start and stop cycles. Finally, in order to transmit electricity to the grid, the circuit breaker is stressed by mechanical operations which cause accelerated wear to coupling and decoupling the unit from the grid.

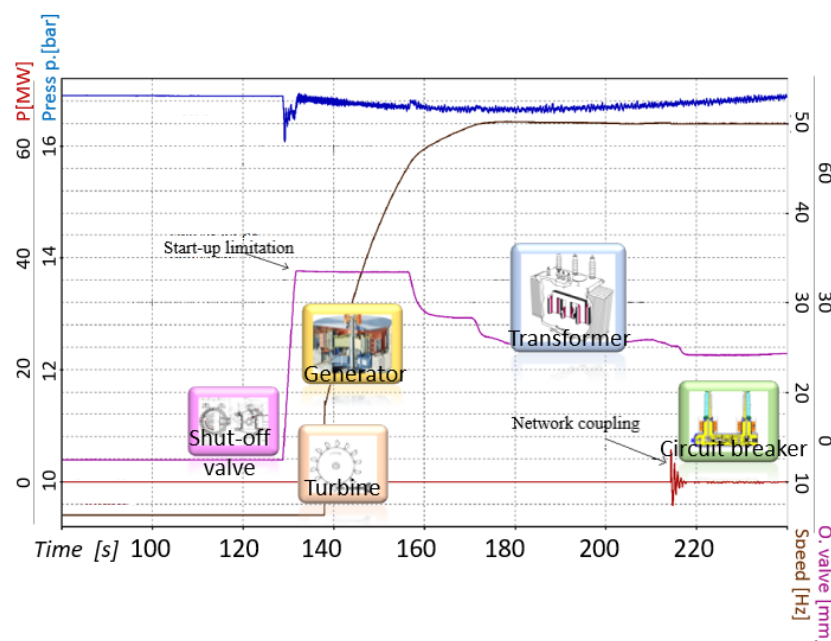


Figure 4. Recordings of a start-up phase of a Francis turbine [8].

The state-of-the-art shows that there are five main materials impacted by start and stop cycles. In table 1 we summarize the main materials and their degradation mechanisms:

Table 1. Equipment impacted by start and stop cycles [8].

Equipment	Sub-component	Mechanism (phenomena) of degradation
Shut-off valve	Spherical and butterfly valves	Mechanical fatigue, wear of sealing parts
Turbine	Runner	Mechanical fatigue
Generator	Stator insulation	Thermal cycling
Transformer	Insulation	Thermal cycling for the transformers with fast power-up
Circuit breaker	Mechanical system	Mechanical fatigue and electrical arc

Once the most impacted equipment has been identified (shut-off valve, runner, generator, transformer and circuit breaker) and their predominant degradation or aging phenomena have been analyzed, physical or stochastic models have been created from the available data and feedbacks from EDF. Thus, the degradation or the decrease in lifetime is estimated from the main degradation phenomenon or the primary end-of-life failure mode. Finally, the lifetime operating cost can be estimated from the purchase and maintenance prices and then divided by the number of cycles.

4. The methods used to estimate the degradation of the equipment

The methods used to estimate the degradation of the equipment are detailed in the articles [6,7] and in the thesis written in French [8]. Three complementary methods are used in function of the available data: comparative damage on runners for fatigue study described in [6], empirical study and lifetime model for thermal cycling on generators described in [7] and estimation of degradation using expert feedback. In the following sub-sections, we describe how the cost was estimated from the estimation of the degradation.

4.1. Comparative damage for runners under high cycle fatigue

The method is presented in details in [6] and uses strain measurements on the runner as a part of a fatigue study. It estimates the degradation of the transient phases (start and stop) and compare them with the normal operation phase to determine a number of normal operating hours for these transient phases. Rain flow analysis [19] is used to extract the numbers and magnitudes of stress cycles from these three sequences.

The study was conducted on regulatory and probabilistic Wöhler curves or S-N curves (cyclic stress “S” against the cycles to failure “N”). In the end, the Palmgren-Miner rule [20] allowed the estimation of the damage rates for each sequence. This method is used when fatigue is the main degradation phenomena, in that case, for Francis and Pelton runners.

Authors obtained results from 6 hours of normal operation (*HNO*) for a start and stop cycle up to several hundred hours depending on the S-N curve used. It should be taken into account that for different materials, the S-N curves can also be different. As an application, an advantage of this method is that it can be used on other materials for which fatigue is the main degradation phenomenon, as for example in the case of a hydroelectric power plant, for guide vanes, servomotors, penstocks, etc.

Once the number of normal operating hours for the start and stop phases (*HNO*) was estimated, it is then multiplied with the number of start and stop cycles of the runner done since commissioning and the results is added to the normal of operating hours (*H_i*) that the turbine done it in his lifetime. The sum represents the total equivalent hours (*HEOt*) over the lifetime. We can estimate the cost of an operating hour (*C_h*) by dividing the purchase price and maintenance by the total equivalent hours estimated. Finally, the cost of an operating hour (*C_h*) is multiplied by the number of normal operating hours estimated and the cost of one runner start and stop (*C_R*) is obtained.

4.2. Empirical study and lifetime model for thermal cycling on generators

Authors in [7] proposed two methods that can be used together or separately. The main degradation phenomenon of generators was considered the thermal cycling of the stator. In the first method, it was highlighted the effect of cycling on the lifetime of generators by estimating the lifetime for two categories of generators that have experienced different cycling during their lifetime (cycled, with 2 or more cycles per day and non-cycled, with less than 1 cycle per day) using a Weibull reliability law [21] on historical rewind year data. The estimated lifetime for cycled plants (46 years) is lower than the estimated lifetime for less cycled plants (55 years).

The second method consists in estimating an acceleration factor using Coffin-Manson law [22] by integrating the temperature profile characteristics due to cycling into the lifetime law. The advantage of this method is that it allows the use of monitoring measurements over a period of days to years. Another advantage of this method is that it can be used on other materials where the thermal cycling participates in the degradation, as for example in the case of a hydroelectric plant, for *transformers*.

Two scenarios have been tested from the simulated cycles in pump mode for PSH. In both cases, the increase in the number of start and stop cycles leads to a reduction of the lifetime. The method can be tested on different generators and the turbine mode should be added. Finally, the cost of a generator start and stop cycle can be approximated from the difference between cycled and non-cycled plants. The purchase and maintenance price are divided by the total number of cycles performed by a generator over the estimated lifetimes (cycled and non-cycled).

4.3. Expert feedback on the degradation of shut-off valves and circuit breakers

The last method consists in estimating the degradation of shut-off valves and circuit breakers by feedback and expert judgement. For some equipment, such as circuit breakers, experts say that the lifetime and maintenance depend on the number of mechanical operations, which coincide with the number of start and stop cycles. In this case, the number of start and stop cycles can be directly considered as an indicator of degradation and the cost of a circuit breaker start and stop cycle can be estimated based on the number of mechanical operations. For the shut-off valve, the link between the number of start and stop cycles and degradation was not as obvious. For this reason, the authors investigated if there was a correlation between a significant default, the trunnion cracking, and the number of cycles. Indeed, a correlation was found in an internal report [17]. The fact that the valves are mainly used during their opening and closing and that most of the defaults are related to these operations, allowed the experts to attribute 75% of the degradation to the start and stop cycles and the rest to the degradation due to ageing. The start and stop cost for shut-off valves can be approximated by dividing the purchase price and maintenance by the estimated number of cycles over the lifetime and taking into account the degradation assigned.

5. Conclusions

Due to the diversity of the equipment present in a hydroelectric power plant (mechanical and electrical equipment), the realization of the thesis called upon a multidisciplinary approach that combines several fields, each one working in an autonomous frame of reference with specific documentary needs and methods (mechanical and electrical engineering, hydraulics, data processing, reliability, safety and maintenance, etc.) to study the effects of degradation of various natures (hydraulic, mechanical, electrical and thermal). The particularity is represented by the diversity of the methods (probabilistic models, ageing models, degradation models, expert feedback) which are adapted according to each material and which are applied in the field of hydropower (section 4). The multiplicity of degradation phenomena, causes of failure and mobilized competences makes complex the realization of a unique model for all the components of a hydraulic production group.

The start and stop cost (C_{SS}) is the sum of all the costs of the materials studied (equation 1). The details of this study are presented in the confidential EDF report [23].

$$C_{SS} = C_R + C_G + C_T + C_{CB} + C_{SV} \quad (1)$$

where C_R is the cost for the runner, C_G is the cost for the generator, C_T is the cost for the transformer, C_{CB} is the cost for the circuit breaker and C_{SV} is the cost for the shut-off valve.

It is important to mention that the cost is estimated only from the degradation of the equipment point of view and does not include other costs like unavailability costs or commodity costs.

Finally, the role of hydropower electricity in the network is very important as presented in introduction. While the run-of-rivers plants assures the production of a constant level of energy, more and more hydropower plants, such as PSH and impoundment power plants are solicited by an increased number of start and stop. This paper also emphasizes the role of constant monitoring and informatics in hydropower due to the usage of sensors where the output is used to estimate the degradation of the equipment.

6. Results and discussion

This paper resumes three methods based on real and available data (fatigue tests for runners, on-line monitoring for generators and transformers) in order to estimate the degradation of the hydropower equipment to estimate the start and stop cost. It can also represent a *decision-making tool* to operate the power plants and optimize the operation of the machines according to different scenarios (e.g. optimized start-ups for runners or adjustment of the generators' operating time). It needs to be mentioned that due to the fact that every hydropower plant is unique, the methodology needs to be tested on every plant in function of the site configuration for relevant results. For example, if the methodology is carried out on a 50 MW Francis hydropower plant, making the hypothesis that all five equipment are impacted, the

start and stop cost range between 200\$-250\$. This represents only the wear and tear cost, while the other costs are not included (e.g., lost opportunity cost, efficiency losses, etc – costs that depends on the geographical region, grid and on the electrical network in general). For this study, more than 400 equipment were studied for all types of hydropower plants (PSH, impoundment and run-of-rivers) and the average uncertainty for the total cost is $\pm 33\%$ [8].

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