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Evaluation of the maintenance and operational dependability of small hydropower plant

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Abstract- Small hydropower plants located at dams are frequently used for power generation in the Czech Republic, where, the advantage of the availability of both pressure head and environmental outflow are exploited for this purpose. The performance of hydropower plants is significantly influenced by the dependability and service life of installed technical equipment. This study presents the results of dependability analysis based on the analysis of defects and failures affecting two turbines (Francis, crossflowBanki) installed on the bypass of the bottom outlets of the Sance Dam in the Czech Republic. Firstly, the quantifiers of dependability are introduced and shutdowns are defined. Empirical probability distribution curves for time to shutdown and shutdown duration are plotted for both turbine generator units based on available records of incidents and reasons for individual shutdowns from 10 years of operation. The analysis was conducted separately for each turbine generator unit and shows the average periods between shutdowns, and their duration. Period length probabilities for both periods between shutdowns and the durations of shutdowns were also evaluated.

Index Terms- small hydropower plant, dependability analysis, maintenance, probability of failure, hydro-power production

I. Introduction

The effort to increase the proportion of electric power produced using renewable sources is currently a worldwide trend. In the Czech Republic (CR), hydropower plants (HPP) represent one of the most significant means of obtaining power from renewable sources. Unfortunately, the geographic situation of the CR provides only a limited number of locations suitable for new HPP installations capable of the effective utilization of water energy. Therefore, upgrades to existing HPPs that enhance their efficiency have become important for many owners and operators. The motivation is the chance to gain higher purchase prices for the energy produced. The minimum range of upgrades to obtain is given by the requirements of the Energy Regulatory Office of the Czech Republic. Important information for the evaluation of the economic benefits of possible HPP reconstruction can be gained from the dependability assessment of existing installations.

System analysis and dependability management are quite widely-known and well-developed branches in engineering practice [2], and have already been introduced into international standards [6]. Dependability is usually quantified through reliability. As a result, engineering reliability and its application in mechanics has seen considerable development [11] and [16]. Reliability assessment is used for the optimization of maintenance strategies and cost reduction [3], [17]. With regard to renewable energy, reliability assessment has been extensively developed especially for wind energy [9], [13] and [18]. However, wind turbines are usually grouped together into so-called wind farms consisting of large numbers of practically identical machines with the same dimensions, layout, etc. Thus, large data sets are available for incidents and failures involving wind turbines, while this is not the case for hydropower, where installations are usually unique, with different parameters and layout.

Several studies on maintenance, operation and profitability analyses in hydro power production have been made by SINTEF Energy Research in Norway [22] and [23] and USACE [1]. However, these are mainly focused on large HPPs.

Dependability quantifiers are recommended in [12], [16] and [19], these being the reliability or probability of failure for a given time interval, failure rate, mean up time, mean down time, and asymptotic availability. All of these quantifiers were derived from operational data assuming semi-Markov processes [7], [19].

A HPP is defined as a system of components. In principle, the whole system (HPP) can be divided into two main parts, namely the civil engineering structure itself and its technical equipment (also including electrical equipment). Here, the Eurocode [5] recommends a “design working life” of 100 years for civil engineering structures and 10 to 25 years for machines and electrical equipment. Based on experience gained during HPP operation described in [8], the technical lifespan of such structures is estimated to be 80 to 150 years for their structural parts, 25 to 70 years for mechanical parts and 15 to 60 years for electrical parts. Therefore, the service life of an HPP is governed mainly by the condition of its technical components, and so durability analysis has to be focused on that.

The operational dependability of a small HPP is generally considered to be the ability of an HPP to be in a state allowing it to perform a required function under given conditions at a given instant of time or over a given time interval [4], [10]. Within the text below, dependability is characterized by the reliability of the HPP, and especially of its technical parts. Reliability is the ability of an item to perform a required function under given conditions for a given time interval. Here, the said item is the technical equipment of the power plant, i.e. a turbine generator unit.

II. Definitions and methods

For the purposes of the dependability assessment carried out for this study, each turbine generator unit in the HPP was assumed to be an independent serial system of components with non-zero time to restoration. Every HPP owner usually tries hard to operate their turbines as continuously operating items. However, the operation of a turbine is significantly affected by external conditions such as a combination of discharge and pressure head, or the stability of the distribution network, which is out of control of the plant owner or operator. As a result, an HPP is considered to be an intermittently operating item (IOI). During the first step in the analysis, detailed operational data have to be evaluated and failures have to be specified [1], [15].

The following terms are used within the text:

Shutdown for any reason– stoppage of a turbine due to any unexpected maintenance activity (including the exchange, repair, dismounting or mounting of any part of the HPP) necessary to put it back into operation.

Shutdown for a significant reason – stoppage of the turbine due to a defect or the failure of any part of the turbine which calls for the repair and/or exchange of part of its equipment (typically the exchange of a runner, shaft, generator, bearings, coupling, transition part of an intake pipe, etc.).

Up time – the time interval during which the turbine is in an “up state” (a period of operation between two consecutive shutdowns).

Down time – the time interval during which an item is in a “down state” (comprises the necessary time for repair and delays due to administration, the delivery of spare parts, etc.).

The reliability of turbines in an HPP was assessed using the following quantifiers:

- mean up time *MUT*,
- mean down time *MDT*,
- mean failure rate λ,
- asymptotic availability *A*,
- up time $K_{(p)}$ between two adjacent shutdowns, which is expected at a given probability *p*,
- down time $N_{(p)}$, which is expected at a given probability *p*.

The mean up time *MUT* between two adjacent shutdowns may be calculated as [7]:

$$MUT = \frac{1}{n}\sum_{i=1}^{n} UT_i, \qquad (1)$$

whereUTi is the up time period between two adjacent shutdowns and *n* is the number of shutdowns recorded in the monitored time period.

Mean down time *MDT* is determined as follows [7]:

$$MDT = \frac{1}{n}\sum_{i=1}^{n} DT_i, \qquad (2)$$

whereDTi is the down time period after shutdown.

Mean failure rate λ is the inverse of the mean up time [7]:

$$\lambda = \frac{1}{MUT}. \qquad (3)$$

Asymptotic availability *A* holds [7]:

$$A = \frac{MUT}{MUT+MDT}. \qquad (4)$$

The up time *UT* between two adjacent shutdowns with a given probability was expressed as a quantile of a cumulative distribution function representing the probability of failure occurrence after the time of operation UT_i from the last shutdown. Based on operational records, a vector (UT_i, ... ,UT_n) of a random variable where UT_i (i = 1, ... , n) represents times between shutdowns (i.e. up time periods). The empirical cumulative distribution function for up time periods UT_i is defined as [20]:

$$F_n(t) = \frac{1}{n}\sum_{i=1}^{n} 1\{UT_i \leq t\}, \qquad (5)$$

where

$$1\{UT_i \leq t\} = \begin{cases} 1 & \text{for } UT_i \leq t \\ 0 & \end{cases}. \qquad (6)$$

Then, the quantile$K_{(p)}$ (the up time between two adjacent shutdowns which is expected at a given probability *p*) is defined as follows:

$$P\left(UT \leq K_{(p)}\right) = p \text{ , and therefore } F\left(K_{(p)}\right) = p, \qquad (7)$$

or using the inverse function:

$$K_{(p)} = F^{-1}(p). \quad (8)$$

An analogous approach was used to calculate the down time at a given probability $N_{(p)}$ by substituting UT_i by DT_i in equation (6). Empirical cumulative distribution functions for both turbine generator units were fitted with distribution functions using the mean failure rate λ (3).

III. Description of the Sance dam and the hydropower plant

The Sance dam is located in the north-east of the Czech Republic. It was built on the Ostravice River between 1965 and 1969. The dam body is 62 m high and consists of rockfill shoulders and a clayey core. It is equipped with an emergency spillway, two bottom outlets, an outlet tower and a stilling basin. The valve chamber at the downstream edge of the bottom outlets is joined with the powerhouse of the small hydro power plant (figure 1 and figure 2). The layout of the Sance Dam with appurtenant works is shown in figure 1. A close-up view of the entrance to the HPP is shown in figure 2.

Figure 1: Overhead view of the right abutment of the Sance Dam

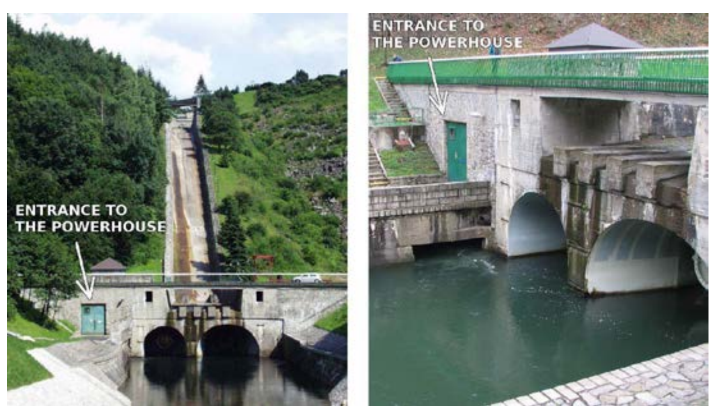

Figure 2: Close-up view of the entrance to the HPP

The bottom outlets are formed by two bypass tunnels drilled through the right abutment. The emergency spillway comprises a side weir, side channel, chute and stilling basin. The chute terminates in a ski jump and stilling basin that also serves the bottom outlets, the sanitary outflow and the outflow from the turbines (figure 2).

The small hydropower plant is equipped with two turbine generator units, HC1 and HC2. The inflow to the turbines is provided by an 800 mm-diameter diversion penstock which is driven from the left bottom outlet. The penstock is equipped with a cross-shaped distribution piece which distributes the flow to both turbines and for the raw water supply (figure 3. and figure 4).

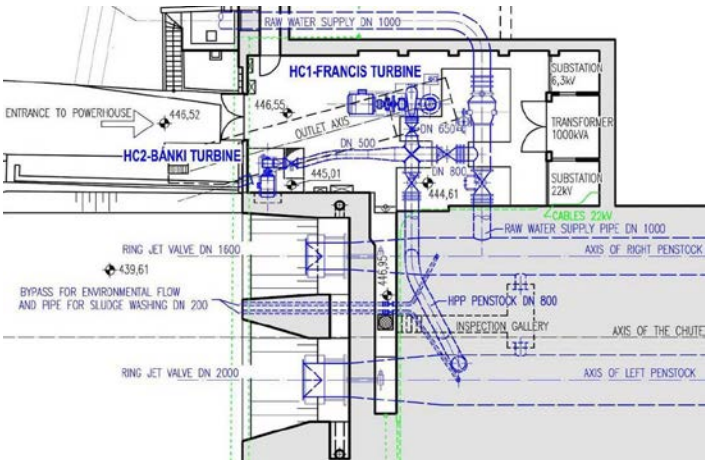

Figure 3: Ground plan of the HPP

Figure 4:View of turbines HC1 Francis (left) and HC2 Banki (right)

Turbine generator unit HC1 was installed in 1974 and is composed of a Francis F25 horizontal turbine with a runner diameter of 525 mm, a capacity of 1.6 m3/s, a gross head of 60 m and a maximum power output of 810 kW. The turbine consists of the following components: runner (stainless steel), turbine shaft, coupling, flywheel, spiral case, draft tube, wicket gate, bearings, regulating mechanism, brake and hydraulic aggregate. An asynchronous generator is connected to the turbine through the coupling. HC1 is equipped with electrical protection devices, electrical distribution boards, an oil transformer and an automatic control system.

Turbine generator unit HC2 was supplementarily installed in 1992 and consists of a Banki turbine (CINK 3.4Bx312) with a runner diameter of 340 mm, an effective width of 288 mm, a discharge capacity of 0.624 m3/s, a gross head of 60 m and a maximum output of 243 kW. The turbine consists of the following components: turbine chamber, runner, shaft, coupling with cover, frame, draft tube, bearings, regulating mechanism and transition inlet part. A horizontal asynchronous generator is connected to the turbine through the coupling. HC2 is also equipped with electrical protection devices, a transformer and an automatic control system. The gross head to the HPP is approx. 60 m.

The view on both turbines is shown in figure 4.

IV. Dependability Analysis of the Sance HPP

The dependability analysis was performed separately for each turbine generator unit (HC1 and HC2) in two steps, namely the assembly of a shutdown database, and reliability quantification.

A. Dependability Analysis of the Sance HPP

The first step of the analysis was the evaluation of operational data and the compilation of the shutdown database. The main sources of data were operation and service logs. Unfortunately, these were not available for the entire time the HPP has been in operation, and information given about shutdowns and repairs in the last decades of the 20th century was not very detailed. As a result, other sources of information were used, such as reports about repairs, invoices and related documents, and for the last ten years also logs from the control system. Based on the analysis of data sources, the operating period of each turbine within the Sance HPP was divided into three main periods related to data availability and depth of information; see table I.

Table I: Availability of operational data from Sance HPP

Description	**HC1 - Francis**	**HC2 - Banki**
No data	1974-1995	1992-1996
Limited data about main maintenance, alterations and failures	1996-2002	1997-2002
Detailed operational data	2003-2013	2003-2013

The most reliable data are available from the period 2003 to 2013, as the shutdown information is taken from several sources and may be checked. It was also possible to discuss contradictory information and several other issues with the staff responsible for the operation and maintenance of the HPP. The current reliability of the HPP was therefore assessed using data from the period 2003 to 2013.

The final shutdown database contains the dates when each shutdown commenced and ended, and the reasons why it occurred. Two data sets were prepared for each turbine generator unit (HC1 and HC2). The first of these is related to shutdowns for any reason, and the second to shutdowns for significant reasons according to the definitions mentioned above. The main reason for the division of shutdowns into two types was the fact that shutdowns for significant reasons usually lead to both a longer period of down time and higher costs, and therefore are of the greatest interest to the HPP owner. Note that shutdowns for significant reasons are a subset of all shutdowns.

Each data set starts at the time of restoration after the first recorded shutdown and ends at the time of restoration after the last recorded shutdown. This ensures that each period is either the up time between shutdowns or the down time (duration of the shutdown), and that the number of up and down time periods within the data set is the same. The basic characteristics of the data in each data set are shown in table II.

Table II: Basic characteristics of the data used for reliability quantification

	Unit	HC1 – Francis		HC2 – Banki	
		Shut-downs	Shut-downs for signifi-cant reasons	Shut-downs	Shut-downs for signifi-cant reasons
Observed period	-	30 Jan 2003 30 Jun 2013	31 May 2003 12 Apr 2013	11 Apr 2003 27 Jan 2013	17 Dec 2003 5 Oct 2012
Total length of observed period	days	3 803.03	3 604.45	3 578.51	3 215.00
Total length of up time	days	3652.10	3496.27	3462.53	3118.01
Total length of down time	days	150.93	108.18	115.98	96.99
Number of records *n*	-	63	14	47	10

B. *Reliability quantification*

Values of reliability quantifiers calculated according to formulas (1) to (8) for each data set are shown in table III.

Table III: Values of reliability quantifiers for turbines HC1 and HC2

Quanti-fier	Unit	HC1 - Francis		HC2 – Banki	
		Shut-downs	Shut-downs for signifi-cant reasons	Shutd-owns	Shutdowns for signifi-cant reasons
Minimum up time	day	0.08	4.94	0.03	2.38
Maximum up time	day	444.99	912.82	436.54	663.00
Minimum down time	day	0.01	0.07	0.01	1.99
Maximum down time	day	35.49	35.49	26.41	26.41
MUT	day	57.97	249.73	73.67	311.80
MDT	day	2.40	7.73	2.47	9.70
λ	1/year	6.30	1.46	4.95	1.17
A	-	0.960	0.970	0.968	0.970
$K_{(0.95)}$	day	155.84	713.81	242.57	650.35
$N_{(0.95)}$	day	11.14	21.12	11.15	24.72

The HC1 turbine generator unit (Francis) has recently become rather obsolete, corresponding to turbine design trends common when it was installed (1974). Continued operation of the turbine is possible thanks to periodic maintenance and servicing. Several significant repairs carried out on this turbine are described within operating records. These mainly consisted of a general repair made to the turbine (1995), the exchange of bearings (2002, 2004), the exchange of the generator, as well as repairs and the exchange of the pumping aggregate for wicked gate control system (1998, 1999), the modernization of the control system, etc.
The HC2 turbine generator unit (Banki) requires quite frequent servicing to keep it in operation. The main reason is the rather high loading of the runner, which is causing cavitation (figure 5). Based on the operating records it can be concluded that on average the complete exchange of the runner is necessary approximately every 12 years, but significant servicing and maintenance (the exchange of some components, welding, balancing, etc.) is necessary approximately every 7 to 8 years. The period between minor repairs is shorter: up to 2.5 years on average.

Figure 5: Cavitation on the HC2 runner (source: the PovodíOdry River Basin Authority)

The period between two consecutive shutdowns for significant reasons lasts on average 0.7 years for HC1 and 0.9 years for HC2 (table III). Such periods can be regarded as unacceptable when considering the performance currently expected from similar machines. The rather short intervals between shutdowns for significant reasons indicate the low durability of both turbine generator units. Turbine producers generally state service lives in the order of decades without significant maintenance. On the other hand, the mean down time of both turbines is quite low, which is also expressed by the availability $A \geq 0.960$. Small turbines and their parts are easy to move without special equipment like heavy cranes, which is probably the main reason why repairs are easy to execute.
Both of the empirical cumulative distribution functions (the up time between two consecutive shutdowns and the down time (duration of the shutdown)) were constructed for both turbine generator units (HC1 Francis and HC2 Banki) using equations (5) and (6). The empirical cumulative distribution functions describing the probability of up time between two consecutive shutdowns are shown in figure 6. The empirical cumulative distribution functions describing the probability of down time (shutdown duration) are shown in figure 7. Values of quantiles

representing up and down time values with the probability p = 0.95 are shown in table III.

Figure 6 shows the good agreement of empirical curves exhibiting exponential distribution with the mean failure rate λ, except for in the case of shutdowns for significant reasons affecting the HC2 Banki turbine (the black line in figure 6 on the right). Here, the application of uniform distribution with the parameter $k = 0.465 \cdot \lambda$ seems to be more appropriate for the approximation of empirical data. Based on the results shown in table III and figure 6 it can be concluded that for a high exceedance probability (0.95), a forced shutdown should be expected after approximately $K_{(0.95)}$ = 160 days (0.4 years) of operation from the last repair for HC1, and about $K_{(0.95)}$ = 250 days (0.7 years) for HC2, while a shutdown for a significant reason (a major defect) should be expected after approximately every $K_{(0.95)}$ = 720 days (2 years) for HC1, and after approximately every $K_{(0.95)}$ = 650 days (1.8 years) for HC2.

Table III and figure 7 only show the good agreement of empirical functions with the exponential distribution function in the case of the duration of shutdowns for significant reasons. Due to the quite frequent short shutdowns for any reason (for example, the rectification of an error in the control system, switch breakers, etc.), the cumulative distribution function is extremely steep. Here, the Weibull distribution with parameters a and$b$ calculated as the maximum estimate of the likelihood of Weibull distribution was found to be suitable [14]. Based on the results shown in figure 7 it is possible to conclude that at a high probability of p = 0.95, the shutdown duration is not expected to extend for a longer period than $N_{(0.95)}$ = 11 days for both turbines, while the duration of a shutdown for significant reasons is not expected to last longer than $N_{(0.95)}$ = 21 days for HC1 and $N_{(0.95)}$ = 22 days for HC2.

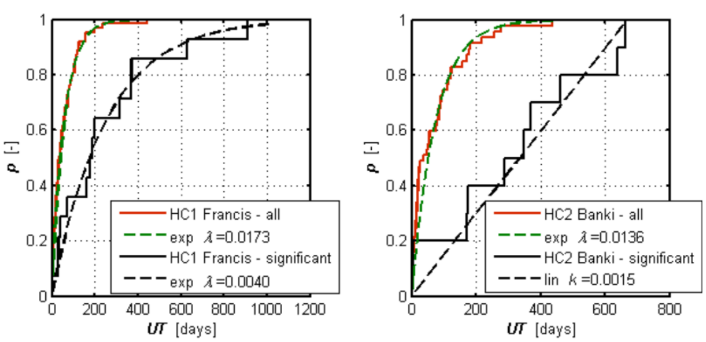

Figure 6: Distribution functions describing the probability of up time between two consecutive shutdowns

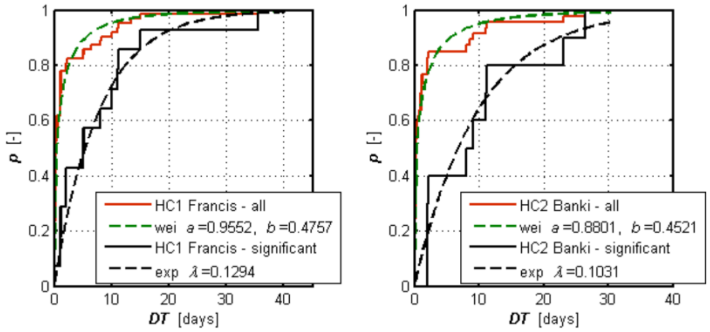

Figure 7: Distribution functions describing the probability of down time (shutdown duration)

V. Conclusions

In this paper a dependability analysis was carried out for two turbine generator units located at the Sance HPP using operating records and other reliable resources. Unfortunately, practically no records exist for the Francis turbine generator unit (HC1) during its first 19 years of operation. The following decade also provides only poor information about the performance of both turbine generator units. The analysis therefore provides relevant results only for the period of the last 10 years of operation. However, the contribution of the presented method is that it can act as a guide in the durability analysis of any HPP. The obtaining of relevant and high quality records about shutdowns is a key factor in the analysis.

The results of the analysis show quite short periods between forced shutdowns, which in general is not favourable for the HPP owner. Shutdowns for significant reasons that call for the exchange of parts may occur on average practically every year (table III). Probability analysis indicates that common forced shutdowns can be expected with a relatively high probability (70 - 80%) within about 100 days of a previous repair, though one may happen much earlier. The short intervals between shutdowns for significant reasons indicate the low reliability of both turbine generator units. Although the standard periodic maintenance activities have been performed, the current technical state of the Sance HPP only enables further operation if quite frequent repairs are performed on the technical equipment. On the other hand, the shutdown duration (i.e. down time), which in most cases may be assumed as time to restoration, is quite short. Both turbine generator units (Francis and Banki) have recently become rather obsolete. HC1 (Francis) corresponds to turbine design trends common for the period when it was installed (1974). The installation of the Banki turbine generator unit (HC2) for a head of close to 60 m causes significant detrition of the machine.

A further step in the analysis should be the assessment of the economic efficiency of possible variants for future remedial works at the Sance HPP. The presented results can be used for comparison with the reliability of other HPPs.

Appendix

Nomenclature used in this article is as follows:

UTi [day] up time period between two adjacent shutdowns

DTi [day] down time period after shutdown

n	[-]	number of shutdowns recorded in monitored time period
MUT	[day]	mean up time
MDT	[day]	mean down time
A	[-]	asymptotic availability
t	[day]	time
$K_{(p)}$	[day]	p-percent quantile of up time
$N_{(p)}$	[day]	p-percent quantile of down time
p	[-]	probability
λ	[1/day]	mean failure rate
k	[1/day]	parameter of uniform probability distribution
a, b		parameters of Weibull probability distribution

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