# Cost model for operation of a hydropower generator

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## ABSTRACT

*Hydropower generators can be operated in modes of higher physical impact in order to optimize revenue. Such modes could include frequent starts and stops, running at off-design point, or deferring maintenance. In order to optimize revenue, the costs associated with the higher-impact operation needs to be considered. This is especially true when operating in a competitive market where dispatch is driven by the price and market opportunity.*

*The costs associated with the higher-impact operations are largely dependent on maintenance strategies. These are reviewed to develop an understanding of their impact on the costs.*

*The costs are then broken down by the type of operation and the source of these costs are identified for each type of operation.*

*The dominant source of costs common to the different operations is the cost associated with increased degradation. A probabilistic model for estimating this cost is discussed.*

## 1. INTRODUCTION

Power generators operate under a range of conditions. Some operating conditions have a higher physical impact on the assets than others. In the present project, the assets owned by Hydro Tasmania have been used as a case study to develop a predictive model of costs associated with higher physical impact. However, the model is applicable to any hydropower generator and the principles can be applied across the power generating industry.

Hydro Tasmania is Tasmania's predominant power generator and provides about 60% of Australia's renewable energy through hydropower generators and wind farms. The vast majority of this energy is generated in its hydro developments, comprising of 27 hydropower stations[1].

Historically, due to Tasmania's isolation from the mainland grid, demand has been met by generation from Hydro Tasmania. However, upon completion of Basslink, the DC power link to the mainland, Hydro Tasmania will begin competing with other national power generators operating in the National Electricity Market (NEM).

### 1.1. THE NATIONAL ELECTRICITY MARKET (NEM)

The NEM is Australia's competitive electricity market. Participating generators place bids on a half hourly basis for their generating capacity. The NEM Management Company (NEMMCO) sorts the bids and dispatches the cheapest generators to meet the demand[2]. The majority of Australia's electricity generation is from coal fired thermal plant. Steam powered thermal stations have a very fast response time, however they cannot sustain this initial response for prolonged periods. Hydroelectric generators utilize the relatively quick and sustainable response of hydropower generators to capture the peak prices. As a result of the ability of Basslink to transfer energy to and from Tasmania, Hydro Tasmania will experience an increase in peak generation and a reduction in off-peak generation. This is expected to change the operating profiles of individual power stations and generating sets.

Operating in the NEM, the dispatch of a generating plant will be determined by the bid prices set for the power station. In determining the bid price, all operating costs should be taken into account, including value of water, cost of consumables, maintenance, risk and reliability and impact on asset life. It may seem financially viable in the short-term to operate in a high-impact fashion (for example increase the number of stop/starts, run at a less efficient operating point, or defer scheduled maintenance), but this could increase the longer-term costs by increasing the required maintenance and decreasing the reliability.

### 1.2. ESTIMATING LONG TERM COSTS

In determining bid prices, the long term cost component of high-impact operation need to be well understood to ensure long-term profits are maintained. A model of long term reliability and maintenance requirements for power station components needs to be applied in conjunction with scheduling software in order to determine the true cost of production.

The longer-term maintenance and reliability costs depend heavily on the type of maintenance strategy that is employed. Before breaking down these extra costs further, typical maintenance strategies employed by Hydro Tasmania will be discussed.

## 2. MAINTENANCE STRATEGIES AND RELIABILITY CENTERED MAINTENANCE (RCM)

Over the years the role of maintenance has evolved[3]. Initially, when machines were relatively simple and downtime was not critical, machines were run to failure. However, as time went on machines became more complicated and downtime became more critical. Investigations were done on component reliability and it was discovered that most components had a definitive life. As shown in the reliability plot (conditional probability of failure) in figure 1, the life of a component is made up of a constant random portion followed by a steep rise in probability of failure toward the end of the component life.

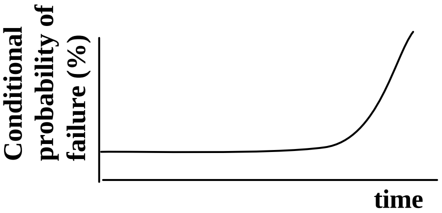

Figure 1: Aged failure reliability plot

### 2.1. PREVENTATIVE MAINTENANCE

This led to the introduction of preventative maintenance (PM) to prevent the majority of failures. PM consists of regular overhauls, which can improve reliability and reduce downtime costs. Another trend that emerged after the introduction of PM was the "infant mortality" effect as shown in figure 2[3, 4].

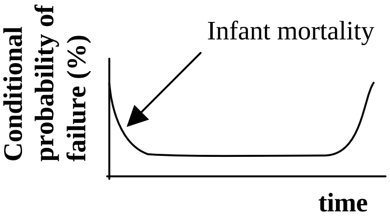

Figure 2: Aged failure with "infant mortality"

The infant mortality was often due to the running in of new components or imperfections introduced during the maintenance activity. This gave a limit to how often the preventative maintenance should be done.

As the machines got more complicated and more reliable, especially with the shift towards electronic components, the failure rates of components would remain constant for the whole life of the component. In particular, the failures became more uniformly distributed over the lifetime of the component as opposed to increasing with age. This meant that the reliability could not be improved by routine PM. Another problem emerging was budget constraints. This was particularly true for the airline industries, which first developed condition based maintenance and reliability centred maintenance.

### 2.2. PREDICTIVE MAINTENCE

Condition based maintenance involves monitoring the condition of a component to detect when it is just about to fail. Most components, even if they randomly fail, give some kind of warning prior to failure. This warning is commonly called the potential failure as shown in figure 3.

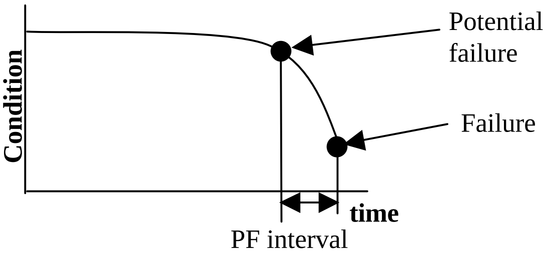

Figure 3: potential failure of a component[3]

The condition monitoring could be on-line or off-line, continuous or at fixed intervals. It could be done using complicated sensors and analysis techniques, or even just a visual inspection. The desire is to have a continuous, online, cheap and accurate condition monitoring system. The interval of the condition monitoring is very important. If it is done too often, money is wasted on the monitoring and the component is kept off-line (if the monitoring is off-line and non-continuous). However, if the interval is too long then there is a risk that the potential failure might be missed and the component completely fails. This is especially true if the potential failure interval is random in length, which can often be the case if the component is subjected to variable stress levels.

### 2.3. RELIABILITY-CENTERED MAINTENACE

Reliability-Centered Maintenance (RCM) is a process of deciding the type and frequency of maintenance required to ensure reliability. It was first introduced into the airline industry as a means of lowering maintenance costs while ensuring reliability. The process starts by breaking a system down into product units and then into maintainable items. Each maintainable item has a defined function(s) and a series of failure modes, which are the ways the maintainable item might fail to function. For each failure mode a preventive Fixed Time Maintenance (FTM) or a predictive Condition Based Maintenance (CBM) task is assigned and the most cost effective one is used. If no task is found then some default action must be chosen such as redesign or Operate Till Failure (OTF), where no maintenance is performed on the maintainable item at all[3].

Hydro Tasmania is currently preforming an RCM analysis of their assets. The study provides optimum task selection and frequency. This list of tasks and optimum frequency will be used to schedule maintenance tasks. However, if the data used in the RCM study, such as the failure rates of the components, changes then the tasks may no longer be preformed at the optimum frequency and the cost of maintenance may increase. The next sections look at why the data may change and how to determine what the effects will be.

## 3. COST MODEL FOR HIGH-IMPACT OPERATION

High-impact operations will be defined as any operation other than running at the design point of the turbine and includes:

- Starts and stops
- Off-design point operation including part load and up to full gate operation.
- Deferring planned and unplanned maintenance

### 3.1. STARTS AND STOPS

The costs associated with starting and stopping generators are considered in the one model as having a start will inevitably lead to a stop. Starting and stopping a machine can be a source of high maintenance cost. Some components are used principally during the start/stop, for example the main inlet valve, brakes, or auto-synchronizer. Some components undergo stresses that principally occur due to a start/stop, for example thermal expansion of the stator coils. The whole machine can be affected by being operated in a rough-running zone on the way to the scheduled operating load. There are many sources of cost for start/stops and they needed to be identified.

### 3.1.1. IDENTIFYING SOURCES OF STOP-START COSTS

Questionnaires and interviews were found to be a common method used for identifying sources of costs and estimating their value based on anecdotal evidence[5, 6]. This is a subjective method drawing on operating and engineering experience. A more obective approach involves statistically analysing maintenance records and finding correlations with operating conditions. However, it is generally agreed that the academic approach utilising available data would be difficult given the diversity of machine design and the relatively low frequency of major maintenance. Furthermore, the inaccuracies developed have been shown to be greater than the errors from the anecdotal approach[5, 6].

Results from the questionnaires and interviews produced some common conclusions, including: loss of water during a start did not contribute significantly to the overall start-up cost; cost due to wear on the main valve during a start-up was unexpectedly high; and wear on generator components, such as stator winding, stator core, etc, contributed the most to the start-up cost. Table 1 is a summary of two investigations (one Norwegian the other Sweden) into start-up costs:

| | Eliasson[5] | Nilsson[6, 7] |
|---|---|---|
| Size | 92 Norwegian units | 8 major Sweden power generators |
| Capacity | 27, 300MW | 21, 903MW |
| Start-up costs: Item contributing the most | Labour costs | Wear of stator windings due to temperature stresses |
| ↓ | Generator wear | Wear of mechanical equipment |
| | Cost of failed start | Malfunctions in control equipment |
| | Main Valve | Loss of water during maintenance |
| | Turbine wear | Loss of water during start-up |
| Item contributing the least | Loss of water | |

Table 1: Comparison of identified start-up costs

It has also been indicated that the cost of mechanical wear may be hidden by a high frequency maintenance schedule or upgrades[6-8].

It can be seen that failures and increased wear make up a large portion of the costs. The costs associated with start/stops could be broken down into the following:

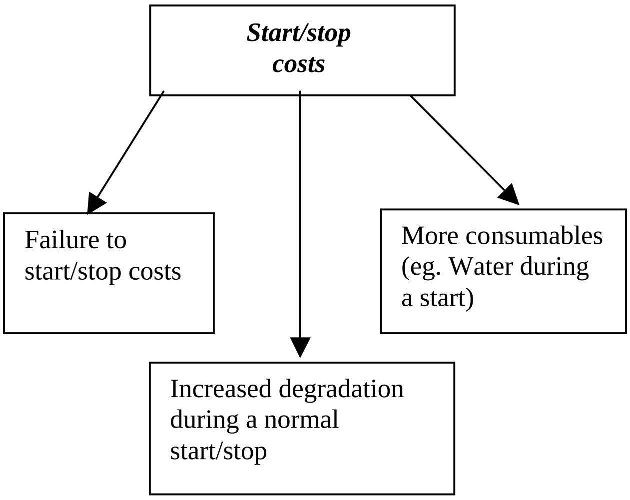

Figure 4: Breakdown of start/stop costs

The risk cost of a failed start is equal to the consequence of a failed start multiplied by the chance of a failed start. For example a cost associated with the lost opportunity for not starting would be included. Note that the risk cost should not include the cost of the actual breakdown and subsequence maintenance. The reason for this is that some failures occur independently of the number of starts. If a failure is dependent on the number of starts, then this will be picked up in the increased degradation section of the model.

The fuel source used in hydropower generation is water. The amount of water utilized during a start is relatively small. The reason for this is the short start-up time, generally in the order of of minutes, and the low flow required to get a machine up to speed and synchronized with the mains.

The cost due to increased degradation is complicated and is dependent on the type of maintenance as well as the failure distribution.

For OTF, since there is no maintenance and failure is inevitable, the cost of degradation is equal to the cost of the failure being brought forward.

For FTM, there is an increased chance of a breakdown failure, assuming same interval between preventative maintenance activities. Alternatively, the interval between the preventative maintenance activities could be shortened to keep the same reliability.

For CBM, the PF interval may shorten, increasing the chance that the PF might not be picked up. Alternatively, if the condition-monitoring interval is short enough, it may mean that the repair might be required sooner.

## 3.2. OFF-DESIGN POINT OPERATION

### 3.2.1. THE EFFICIENCY CURVE OF A HYDRO TURBINE

The efficiency curve of a typical Francis turbine is shown in figure 5. The graph is made up of a rough running zone, an on-design range (usually small), and an area up to maximum flow. Pelton turbines do not have a rough running zone. Generally, to maximize energy production and minimize degradation of the asset, the turbine should be run at the maximum efficiency flow point. However, there are times when it might be desirable to run either in the rough running zone or up to and including maximum flow. If the demand is high or the storage is on spill, then the station might need to run up to full-gate. Running in an off-design zone can increase degradation as well as lower efficiency.

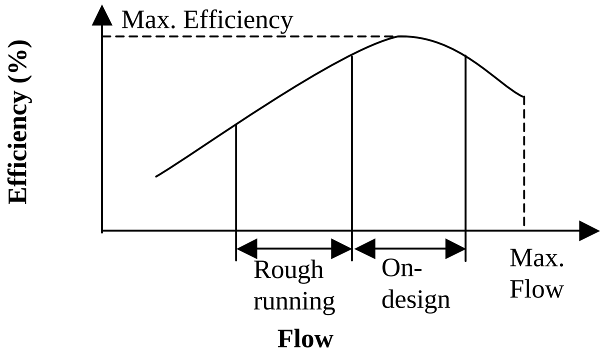

Figure 5: Efficiency curve for a Francis turbine

### 3.2.2. CAVITATION

Cavitation occurs when the local fluid dynamic pressure in areas of accelerated flow drops below the vapor pressure of the liquid[9]. Generally, cavitation occurs more readily during off-design operation. However, the exact loads where cavitation occurs varies between machines. Cavitation can cause significant damage to solid surfaces when the bubbles collapse back to liquid. This is most significant on the runner blades of the turbine and on or around protrusions into the suction cone beneath the turbine. The extent of the damage also varies between machines.

### 3.2.3. BREAKDOWN OF OFF-DESIGN POINT COSTS

A breakdown of off-design point operation costs is shown in figure 6.

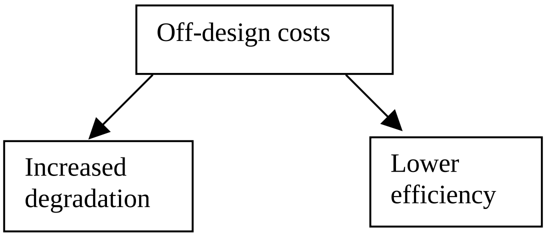

Figure 6: breakdown of off-design costs

The increased degradation is similar to the stop/start model, and the lower efficiency is already captured in the model used to determine the value of the bids.

## 3.3. DEFERRAL OF MAINTENANCE

### 3.3.1. PLANNED VS. UNPLANNED MAINTENANCE

Planned maintenance consists of all the routine maintenance and condition monitoring, while unplanned maintenance refers to failures and repairs for detected potential failures. The unplanned maintenance can be broken further down to the jobs which need to be done immediately, the jobs which require substantial downtime scheduled, and the jobs which can logged and completed on an opportunity basis.

The cost associated with deferral of maintenance is sensitive to the type of maintenance employed. It may need to include contract penalties if the maintenance is outsourced, and lost opportunity if a failure does occur. Also the scope of the work required might increase, meaning longer downtime and increased cost for the maintenance activity. Deferring the maintenance might mean running at lower efficiency until the maintenance is done, reduced reliability and/or increased risk of plant failure. Deferral of maintenance could result in the maintenance being undertaken at a less opportune time, for example when there is a high market price.

# 4. MODEL OF DEGRADATION COSTS

Cost of degradation is a common aspect of all the models and has become the focus of this project. This cost needs to cover the increase in downtime and maintenance due to increased chance of failure. This depends not only on the distribution of the failure, but also on the type of maintenance activity assigned to the failure mode.

### 4.1. PROBABILISTIC VS. DETERMINISTIC

There are two general approaches to modeling the costs previously mentioned, probabilistically or deterministically. The probabilistic approach was chosen because of the inherently random nature of many of the parameters and because although it might be harder to construct and interpret the results, probabilistic models generally give more credible conclusions and also allow for exceptions and refinements than deterministic models[10].

### 4.2. MARKOV VS. MONTE CARLO

A Markov model[4, 10-12] is a probabilistic model commonly used in reliability engineering to look at repairable systems, systems with several components and systems with spares. Markov models have a lot of advantages including that they are a commonly used technique, they are able to reveal a lot of information about the system, they are able to handle both discrete and continuous stochastic processes, and they can be easily and definitively solved on a digital computer.

The stochastic process modeled needs to be memoryless and stationary. In other words the failure rate needs to be constant with time. There are however a few techniques that can be used if the hazard rate is not constant. One way is break the process down into a series of deteriorated states, each with a different constant failure rate. However, Markov models cannot cope with fixed time interval events easily. Also, as the number of components increases the size of the model goes up exponentially. In fact the size of the model is equal to $m^n$ where m is the number of states each component can take on and n is the number of components. However, combining some states can reduce this number.

Another model which is commonly used in reliability engineering is the Monte Carlo simulation model[13]. This technique has a number of advantages including good flexibility and relatively fast computation times for a large number of components.

### *4.3.* A BRIEF DESCRIPTION OF THE MODEL.

The model developed for determining the costs associated with deteriorated states is based around the RCM approach to reliability. It takes in the failure distribution of a component, the type of maintenance (FTM, CBM, or OTF), the interval of the maintenance, information about the PF interval and the condition monitoring, and the costs associated with the failures and the maintenance.

As mentioned previously for OTF, since there is no maintenance and failure is inevitable, the cost of degradation is equal to the cost of the failure being brought forward. This can be calculated using accounting based discounting technique[14]. The amount of time the failure will be brought forward will be equal to the change in MTBF.

For FTM, an array of failure times can be randomly generated (based on the failure distributions). All the times less than the FTM interval will be counted as failures and a cost can be associated with those. Also, if required, random costs can be generated for those failures. All generated times larger than the FTM interval are set to the FTM interval and treated as a scheduled maintenance. Random costs can also be generated for the scheduled maintenance. The advantage of using the Monte Carlo technique is demonstrated in the ease of modifying the model.

For CBM maintenance, PF interval times can be randomly generated and the inspection interval compared. This model can also incorporate imperfect inspections which may either produce false positives or negatives (ie. either detecting a failure when there is not one, or missing a failure).

Data for the costs and times for inspections, repairs, and maintenance can be easily derived from operating history. The failure distributions and rates will need anecdotal input from experienced engineers.

## 5. CONCLUSION

Cost of high-impact operations of hydropower generators needs to be considered when optimizing revenues.

Maintenance strategies have a large effect on the high-impact operating costs. RCM was briefly reviewed as it forms a good basis for the cost model.

Increased degradation was identified as a common factor in the cost model. A model for the increased degradation cost was discussed.

A Monte Carlo approach was selected for its adaptability and flexibility. The model simulates Fixed Time Maintenance (FTM), Condition Based Maintenance (CMB), and Operate To Failure (OTF) maintenance strategies as defined in the Reliability-Centered Maintenance (RCM) process. Lost opportunity costs and discounting are also included.

## 6. ACKNOWLEDGMENTS

I would like to take this opportunity to thank Charles Peacock and staff at Hydro Tasmania for their support and expert knowledge.

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