DEVELOPMENT OF MATHEMATICAL MODEL FOR CONDITION BASED MAINTENANCE OF SMALL HYDROPOWER PLANTS

Ph.D. THESIS

by

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The overall development of any country is determined by its energy sources. Energy boosts up the socio economic progress of the country. Due to increased globalization, industrialization, population and living standards, the demand for energy is increasing in all the nations. This demand is even higher in the developing nations like India. According to IEA, 2015 total demand for energy is expected to increase by 21% by 2030. This fact can not be denied that the world is facing the energy crisis and almost all the countries are trying to develop new technologies to utilize the various sources of energy. The energy can be obtained from renewable and non-renewable resources. Renewable energy can be obtained from those resources that have a tendency to replenish themselves on their own like solar, hydro, wind, thermal and biomass. Fossil fuels like coal, petroleum belong to non-renewable resources of energy. The environmental consequences along with increased prices of fossil fuels have generated interest in the renewable sources of energy. Generation of energy from renewable sources can work as an unique opportunity to safeguard the environment without affecting the economic growth.

Hydro power is one of the oldest resources available. People have been benefiting from the power of water for more than two thousand years. Worldwide total hydropower capacity in operation was 1171 GW by the end of 2016 and presently, contributing more than 50 percent of electricity supply in about 60 countries. Hydro power is clean and stores both water and energy. The history of hydropower generation in India is more than 125 years old. The first hydropower station in India was a Small Hydro Power (SHP) station of 130 KW commissioned in 1897 at Sidrapong near Darjeeling in West Bengal state closely followed by the Sivasamudaram SHP station of 4500 KW in Mysore district of Karnataka state in 1902.

SHP plants in general can be classified on the basis of their capacity, head and their location or layout which are outlined in the thesis. As India is progressing in the generation of energy from SHP, the present study is devoted for modeling of

Condition Based Maintenance (CBM) for the cost optimization of SHP plant components and effect on the reliability.

From the detailed literature review, it has been found that lot of studies were carried on development of various techniques for maintenance of hydro power plants, estimating the remaining useful life and the failure numbers by comparing different types of maintenance. However, very few studies are available on comprehensive maintenance strategy for hydropower plants. The following gaps are identified in the earlier studies:

1. No comprehensive study is available on maintenance of small hydropower plant components. However, few studies were carried out for maintenance of large hydropower generating units.
2. Earlier authors have mainly focused for operation and maintenance on the radial bearing of the turbines.
3. In case of small hydropower plants, especially in hilly terrains, the maintenance of civil works components are also important. No study has been reported on maintenance of civil works of SHP plants.
4. No study has been reported on comprehensive maintenance cost of small hydro power plants.
5. Mathematical models, deterministic or probabilistic, are as of yet rarely used for maintenance cost of SHP plants because of complexity. This requires development of some user friendly model.

Considering above mentioned research gaps, it has been found that there is a scope for development of generalized models for the maintenance of SHP plants. The present study has been aimed to develop efficient CBM strategy for maintenance of high head run of river SHP plants with the following objectives:

1. To identify the components/parts affecting the overall cost for maintenance of SHP plants.
2. To study operation and maintenance of existing plants in the selected study area.
3. To analyze the collected data on the maintenance costs under different operating conditions of the SHP plants.

4. To optimize the maintenance cost of SHP plants by considering reliability and economics.
5. To develop a model for condition based maintenance of small hydropower plants.

In order to achieve the objectives of this study, following methodology has been adopted.

1. Selection of study area and SHP plants for the study.
2. Identification of major parts/components affecting the maintenance cost.
3. Field inspection of selected SHP plants and collection of data regarding maintenance of such plants.
4. Analysis of collected maintenance cost related data for development of cost correlation.
5. Life cycle analysis for prediction of useful life of SHP components.
6. Cost optimization for maintenance cost of SHP plants based on reliability and economics by financial analysis.

To carry out this study, RoR SHP plants in Himalayan region located in Kangra and Chamba districts of Himachal Pradesh state in India were selected. High head RoR SHP plants face many maintenance related problems as the rivers flow with high velocity and carry lots of silt, which adversely affect the mechanical parts and other connected components. The selected plants were visited several times, their actual operation and maintenance related problems were seen and discussed with the plant operating staff. The plant data related to problems occurring in components, major breakdowns, replacement time cycle of major components and repetition of major overhauling of the units and maintenance cost were observed /collected.

To predict the maintenance cost of components of high head RoR SHP plants, cost correlations were developed by considering head and capacity as cost sensitive parameters by regression analysis. The developed correlations were validated with the maintenance cost data obtained from the other hydropower stations.

The inspected/collected data were analyzed for the identification of maintenance problems in components of such SHP plants and found that the main components of the plants, which generally require frequent maintenance, major breakdown, replacement and major overhauling/capital maintenance are turbine and auxiliaries, cooling system, generator and auxiliaries, governor, control panel, switchyard and station auxiliaries.

The Life cycle analysis was carried out to determine the operational life of various components. The analyzed results of the average operational life of the SHP plant components are shown in Table 1.

Table 1. Average operational life of the SHP plant components

Components	**Runner**	**Nozzle**	**Deflector**	**Servomotor**	**Cooling system**	**DE/NDE bearing**	**Brakes and jacks**	**Governor**	**Control panel**	**Breakers**	**CTs/PTs**	**Power cables**	**Light Assistors**	**Isolators**	**DC battery/ chargers**	**Fire-fighting system**
Average operational life (Year)	12.2	7.8	5.5	5.4	19.5	5.7	8.6	18.5	19	9	8.7	16.7	16.3	16.5	5.9	16.8

The condition based maintenance (CBM) model was developed with mathematical techniques like gamma distribution, exponential distributed and Markov process model. For the development of CBM model, gamma distribution was used to determine the deterioration state of the components and an exponential distribution Markov chain was used to know the sequence of the virtual/sub states. The developed CBM model has been solved by the Monte Carlo simulation to find out the expected number of inspections, PM and CM, in the economical operational life of SHP plants which were further used in the cost model by considering discount rate (dr) as 0.09 and inflation rate (IR) as 6.7% per year.

The present value of total maintenance cost of all the components were determined for different maintenance strategies. It has been found that the maintenance cost of such plants by using CBM model is much lesser than annual/planned/scheduled maintenance strategy.

The reliability of the components based on the developed CBM model has been analysed and found that the reliability increases with the increase in perfect maintenance rate and after a long time it becomes constant. Further, the sensitivity analysis was also performed on the SHP components using the probability with expected operating time by the real deterioration data rate and changing the default parameters at first deterioration rate. It has been found that with the increased values of repair rate, perfect maintenance rate and common cause repair rate, the reliability of the components improves.

From this research work, following conclusions are drawn:

1. From the observations made at the power plants, collected data and also based on the literature, it has been found that the installation cost and maintenance cost of SHP plants varies with the head and capacity. Thus, head and capacity has been selected as cost influencing parameters for the analysis.
2. The maintenance cost correlations were developed considering head and capacity as cost sensitive parameters by regression analysis using cost data collected from the SHP plants. The developed correlations were validated with the maintenance cost data obtained from the other hydropower stations, and maximum deviation is found + 6.82% to – 6.68%. This shows that the correlations are in good agreement and can be used for assessment of maintenance cost of such plants.
3. A detailed analysis was carried out to determine useful life of high head RoR SHP plant components based on the details like maintenance problems, replacement of components, capital maintenance and major breakdowns. The useful life of some of the components is found from 5 to 20 years as given in the Table 1. The useful life of the components as analyzed was compared with the literature data and found that the determined average useful life of most of the components are near to the theoretical useful life.
4. Monte Carlo simulation of the CBM model has been carried out to obtain the expected number of inspections, PM and CM, in the economical operational life of SHP plants which were further used in the cost model.
5. The maintenance cost obtained by the CBM strategy is compared with cost by scheduled AM strategy for all the components. The results show that the

PV of total maintenance cost by CBM strategy is cost effective compared to annual/planned/scheduled maintenance strategy. The PV of total maintenance cost by CBM is found to be 5% to 48% lesser than PV of total maintenance cost by AM for the different SHP components.

6. It has been found that the components improve largely with the increased values of repair rate, perfect maintenance rate, and common cause repair rate.

The maintenance cost model developed by CBM strategy can be useful for the SHP plant owners and operators for minimizing the total maintenance cost of components and the plant.