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Forecasting Thrust Bearing Temperature of 100 MW Francis Turbine

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Abstract: Thrust bearing plays a significant role in the smooth & efficient running of turbines. Its overheating is one of the major problems for the continuous operations of hydropower plants. A reliable forecast of thrust bearing temperature helps designers in preparing future thrust bearings and setting up the operating range of thrust bearing temperatures. In this study, a multiple regression model using SPSS software to forecast thrust bearing temperature of 100 MW Francis turbine was developed. The model integrates fifteen important independent variables. Data sets of all variables were collected followed by formulation of statistical model for a period of one year ranging from May 2012 to May 2013 used for the training whereas the proposed model was tested against the real dataset for June to July 2014. The predicted thrust bearing temperature values were compared with the actual thrust bearing temperature values in order to verify the performance of the model. The model offers a good predictive power with an adjusted R² value of 0.98 and a RMSE of 2.78°C.

Key Words: Thrust Bearing, Multiple Regression Method, SPSS, Ambient temperature.

1. Introduction

Hydro power contributes about 20% of the world electric power generation. Global installed capacity of Hydropower generation (electrical) is approximately 777GW (2998TWh/year) [1]. It is economical and pollution free source of energy. Round about 88% of the world’s renewable energy sources comprises of it [2]. In Pakistan about 35% of electricity is generated by hydropower in which three major power projects including Tarbela, Mangla and Warsak are contributing mostly [3].
Currently the shortfall of electricity in Pakistan is more or less 6000-8000 MW. Hence, obtaining the maximum possible share from hydropower would be great saving to the national economy. In context to the current scenario of electricity production in Pakistan, it is essential to obtain the maximum output from the existing hydro power plants by minimizing the downtime through regular and continuous monitoring of the performance of hydro power plant. In that perspective, predicting the availability of hydroelectric generating units for fault free operation is one of the crucial factors.

In Pakistan, power produced is 35% by Hydel power, 57% by thermal power, 5% by Nuclear power and 2% by others. [4]. Mangla dam, the world’s 7th largest dam located on the Jhelum River in the Mirpur District of Jammu & Kashmir, Pakistan is a multipurpose project designed to make up the deficiency of irrigation water in Pakistan as a consequence of Indus water treaty. Figure 1 shows the Mangla power station. It also conserves and controls the flood water of river Jhelum through significant reduction in flood peaks and volume at downstream by incidental use of available storage space [5]. The other by-products are power generation to meet the power demand of the country.

The construction of Mangla dam started in 1962 and was completed in 1967. The dam has two spillways (i.e. main and emergency spillway) for out flow regulations and has an intake structure with five tunnels. At the tail race canal, Mangla Power House is located. Capacity of this power house is 1000MW with 10 Francis turbines each of 100 megawatt) [5]. Since its completion in 1967, the gross storage capacity of Mangla reservoir has reduced by 20% due to sediments deposition. To counter this issue, Mangla dam was raised by 30 ft to regain its reservoir capacity. After rising of Mangla dam first impounding has been achieved up to 1240 feet in 2013 and its electricity generation capacity has also increased to 1200 MW [6].

![Mangla Power Station](image)

Figure 1 Mangla Power Station

At Mangla Power House, hydroelectricity is generated by converting potential energy of water to kinetic energy through its hydro turbines and coupled generators. A typical arrangement of a vertical shaft driven turbine, generator unit is shown in Figure 2 [7].
Hydro-turbine bearing applications typically have relatively low operating speeds and high thrust loads. Depending on the requirements, the thrust bearings may be fixed geometry or have tilting pads. At Mangla hydro power plant, thrust bearings of hydro turbines are of tilt pad type and contain 10 pads and support the axial load on a revolving vertical shaft. On a vertical shaft of hydro turbine unit, thrust bearing chains the entire rotating weight of the unit, as well as any hydraulic down thrust from the turbine itself [9]. A typical arrangement of the bearings in a vertical shaft generator-turbine unit of a hydropower plant is shown in Figure 3.

Bearing temperature plays a vital role in continues operation of the turbines. Stable bearing temperatures in the turbine and generator are essential for their successful continues operations [8]. Typical temperature ranges for thrust bearing is about 70-80°C. Under certain circumstances, where
the sensor for thrust bearing temperature becomes faulty, turbine operators must be able to estimate the running temperature of thrust bearing with minimum efforts. This study aims to provide a simple, quick and a reliable equation which could be used to forecast thrust bearing temperature of a hydro turbine. This equation is developed using Multiple Regression (MR) technique through SPSS software. Historical data for dependent temperature i.e. thrust bearing temperature and various independent variables such as running load, water flow rate, speed etc. were collected from the office of the chief engineer at Mangla Power House. MR technique was used for identifying different significant variables having a significant effect on the thrust bearing temperature and a forecasting model for thrust bearing temperature has been developed. This proposed model also helps in scheduling periodic maintenance of the thrust bearing.

2. Literature Review

Sternlicht et.al were among the first to publish solutions coupling the Reynolds and the energy equation. They realized the importance of oil temperature passing over the leading edge was a key parameter and that this temperature was heavily influenced by the oil/gas mix produced in the groove between the pads of a thrust bearing [10]. Sienkiewicz measured a 2D plane lubricant film, in the same case conference he showed in his results, the first THD explanation of the oil film distance from the ground [11]. J.H Vohr introduced the idea of an energy balance approach via a control volume that includes the entire pad of the thrust bearing. He adjusted the heat transfer coefficient of each surface to match with experimental data. Vohr suggests that Ettles solution may not properly address the thermal effects and ensured in his energy balance that it obtains more precise predictions [12]. Ettles presented a method for the temperature calculation in the thrust bearings assembly. The method included reverse flow phenomenon and simplifies the hot oil carry calculation. Transient thermo-elastic effects were also considered [13]. Heshmat and Pinkus presented a paper about the mixing inlet temperatures in the groove. They joined the restricted difference and restricted element methods in an iterative process to model gas lubricated thrust bearings and concluded that the load carrying capacity can be steadily increased by reducing the film thickness [14]. Ferguson continued studying the importance of oil viscosity and its relevance on the power loss from spring supported thrust bearings [15]. Wang reported the effects of different spring patterns and pad firmness on spring supported thrust bearings, taking pad thermo-elastic distortion into account [16]. Brown and Medley went further on the limits of hydrodynamics lubrication at low rotor speeds and angular velocities; the lubrication is basically hydrodynamics rather than thermodynamics [17]. Ancy M Alias and Amey George used guide bearings, turbine guide bearings, thrust bearings and winding temperatures of generator and transformer of hydroelectric generating unit for modeling & simulation of dynamic variation of temperature. They concluded that temperature of bearing is depending upon multiple variables such as ambient air temperature, cooling water temperature, cooling water flow rate and initial bearing temperatures. Increase in temperature in ambient air or cooling water would increase the temperature level of
bearing [18]. Brown discussed approach of spring supported thrust bearings including hydrostatic and hydrodynamic lubrication. He left behind the biharmonic plate bending finite difference method to calculate the deformation material layers on the pad and also model the springs without violating the thin plate assumptions assuming isothermal fluid flow [17]. The same year Sergi Glavatskih explained how to measure the oil film thickness and the temperature on fluid film bearings simultaneously [19]. Wodtke, Schubert and Fillon diagnosed about the hydrodynamic thrust bearings used to carry axial loads in load shafts of water power hydro turbines could reach aspect of outer diameter even over five meter also enlarged thrust bearing dimensions will decreases their operation capability at once. They couldn’t develop suitable agreement between bearings and concerned predictions obtained by using both theoretical models and experiments data [20]. Xiaodong Yu 2014 in his study on dynamic pressure of hydrostatic thrust bearing under the different recess depth and rotating velocity discussed the solution of the loading capacity of the hydrostatic thrust bearing a numerical simulation concerning dynamic pressure of multi pad hydrostatic thrust bearing under the different recess depth and rotating velocity. He also discussed three dimensional dynamic pressure field of gap fluid between the rotation worktable and the base has been simulated by using the computational fluid dynamics [21]. Andrew M. Mikula in 1989 discussed in his research paper that oil temperature was found to be the least likely to reflect bearing operating conditions, he further discussed that bearing operating temperature is used to measure the performance of a thrust bearing in the thermocouple junction [22]. John K. Whalen discussed that the intent herein was to launch a state of the art thrust bearing program and he further confer thrust bearing design option available to explain installed thrust bearings. He discussed three major design variables and assessed with the programs [23]. Gardner went deeper into the linkage between bearing power loss and pad operating temperatures on the oil flow. The importance of the temperature distribution on thrust behavior and its effect on the other variables as the load carrying capacity were pointed out [24].

3. Methodology

Hourly data of the following 16 variables (one dependent and fifteen independent) were collected in an MS excel ® file on a USB for the period June 2012 to 2013. Table 1 shows all the variables considered in this study.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Denoted by</th>
<th>Variable type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust Bearing temperature</td>
<td>(y)</td>
<td>Dependent</td>
</tr>
<tr>
<td>Upper guide bearing temperature</td>
<td>(x_1)</td>
<td>Independent</td>
</tr>
<tr>
<td>Lower guide bearing temperature</td>
<td>(x_2)</td>
<td>Independent</td>
</tr>
<tr>
<td>Main guide bearing temperature</td>
<td>(x_3)</td>
<td>Independent</td>
</tr>
<tr>
<td>Stuff box temperature</td>
<td>(x_4)</td>
<td>Independent</td>
</tr>
</tbody>
</table>
Next step was to develop a model. SPSS software is used in model development after selecting independent and dependent variables. We use multiple regression method (MRM) for the forecast of thrust bearing temperature. However, the accuracy of a regression model depends widely on the size of the data sample [13].

A typical MR model’s equation is presented in equation 1.

\[ Y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n \]  

(1)

Where;

- \( Y \) = thrust bearing temperature
- \( x_1 \) to \( x_n \) = Independent variables
- \( \beta_1 \) to \( \beta_n \) = Regression coefficients

4. Model Development

Using MR technique in SPSS software, an MR model was developed to estimate the thrust bearing temperature of a 100MW Francis turbine. A summary of this preliminary model is presented in Table 2.

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.990 *</td>
<td>.981</td>
<td>.981</td>
<td>0.78</td>
</tr>
</tbody>
</table>

It is evident that the model offers a good predictive power with an adjusted \( R^2 \) value = 0.98 which indicates that the 98% variance in thrust bearing temperature could be explained by the independent variables considered in this study.

In statistical analysis, a variable is considered a significant variable if its t-stat value is equal or
greater than 1.96. T-stat values for $x_3$ and $x_8$ variables were found less than 1.96 and therefore these two variables were eliminated and the regression analysis was repeated without these two variables. Table 3 below shows the t-stat values of different variables considered in the development of MR model.

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Stand. Coeff.</th>
<th>t-stat</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Constant)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Std. Err.</td>
<td>Beta</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40.5</td>
<td>.699</td>
<td>-0.016</td>
<td>57.892</td>
<td>.000</td>
</tr>
<tr>
<td>$x_1$</td>
<td>-.018</td>
<td>.003</td>
<td>5.060</td>
<td>.000</td>
</tr>
<tr>
<td>$x_2$</td>
<td>-.060</td>
<td>.008</td>
<td>7.429</td>
<td>.000</td>
</tr>
<tr>
<td>$x_4$</td>
<td>-.390</td>
<td>.009</td>
<td>42.423</td>
<td>.000</td>
</tr>
<tr>
<td>$x_5$</td>
<td>-.33</td>
<td>.010</td>
<td>31.649</td>
<td>.000</td>
</tr>
<tr>
<td>$x_7$</td>
<td>.50</td>
<td>.014</td>
<td>34.966</td>
<td>.000</td>
</tr>
<tr>
<td>$x_8$</td>
<td>-.026</td>
<td>.005</td>
<td>4.875</td>
<td>.000</td>
</tr>
<tr>
<td>$x_9$</td>
<td>-.16</td>
<td>.011</td>
<td>14.519</td>
<td>.000</td>
</tr>
<tr>
<td>$x_{10}$</td>
<td>1.53</td>
<td>.003</td>
<td>463.182</td>
<td>.000</td>
</tr>
<tr>
<td>$x_{11}$</td>
<td>.05</td>
<td>.003</td>
<td>15.417</td>
<td>.000</td>
</tr>
<tr>
<td>$x_{12}$</td>
<td>-.46</td>
<td>.011</td>
<td>42.856</td>
<td>.000</td>
</tr>
<tr>
<td>$x_{13}$</td>
<td>.061</td>
<td>.002</td>
<td>25.012</td>
<td>.000</td>
</tr>
<tr>
<td>$x_{14}$</td>
<td>-.022</td>
<td>.001</td>
<td>14.625</td>
<td>.000</td>
</tr>
<tr>
<td>$x_{15}$</td>
<td>-.81</td>
<td>.005</td>
<td>15.346</td>
<td>.000</td>
</tr>
</tbody>
</table>

The final equation of model is as follows:

$$Y = \alpha + \beta_1x_1 + \beta_2x_2 + \beta_4x_4 + \beta_5x_5 + \beta_7x_7 + \beta_9x_9 + \beta_{10}x_{10} + \beta_{11}x_{11} + \beta_{12}x_{12} + \beta_{13}x_{13} + \beta_{14}x_{14} + \beta_{15}x_{15} \quad (2)$$

Therefore, the final MR model equation for predicting the thrust bearing temperature is;

$$\text{Thrust Bearing Temperature} \ (Y) = 40.5 - 
0.018x_1 - 0.06x_2 - 0.39x_4 + 0.33x_5 + 0.5x_7 + 0.026x_9 + 0.16x_{10} + 0.05x_{11} + 0.05x_{12} + 0.01x_{13} + 0.022x_{14} + 0.81x_{15} \quad (3)$$

5. Results and Discussion

The data sets used for testing of model consist of duration of 1 Month from 16 June 2014 to 15 July 2014.

Table 4 shows a comparison between the Minimum, Maximum, mean and median values of actual and predicted temperature of thrust bearing.
The evaluation criteria for the performance of both models are the Mean Absolute Error (MAE), the Root Mean Square Error (RMSE), and the Mean Relative Error (MRE), which is employed to compare with the model’s forecasts. RMSE was found to be 2.78°C, MAE is 2.06 °C and MRE is 3.2 °C. The error analysis demonstrates that the MR model prediction will always be slightly higher than the actual values. Although the model predicts the thrust bearing temperature very well, some considerations must be taken into account. Some parameters were set constant to enable the analysis, such as turbine operating hours, thrust bearing activities and shape. Changing these variables would require additional studies to extend or revise the model’s equations.

6. Conclusions
In this study, a MR Linear Model was developed to forecast the temperature of thrust bearing of hydro turbine installed at Mangla Power Station in Pakistan in which 15 independent variables were evaluated. Final multiple regression model was tested against actual daily thrust bearing temperature data for the period of one month. A RMSE of 2.78 °C was observed between the actual and forecasted values. It is believed that the analysis and forecast would be helpful to operation and maintenance engineers and design engineers in maintaining and manufacturing of thrust bearing with a higher degree of accuracy. Therefore, this model must first provide a good fit to the current data, and secondly, is a reliable predictor of thrust bearing temperature, provided of course that the assumptions made in this study are unaltered.

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