Reliability analysis of Pneumatic Control Valve in Process Plant Using Simulated Failure Data

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Abstract—Performance monitoring is an important part of process plants. As it is very well known that process plants consist of many control loops to operate. Although, single downtime in a process plant can cause huge loses in production and financially. Hence it is required to understand the behavior of controllers, such as control valves to avoid the downtime and to reflect the reliability analysis. Valve stiction is the most common and reoccurring problem in pneumatic control valves. Since many existing models define the valve stiction and how to control stiction effect, but how the stiction is going to affect the reliability of the process and how does stiction can occur at different stages of valve opening is still missing to consider. So, there is a need to understand the reliability behavior and effects on the whole process plant and also including the maintenance of the plant. This paper focuses on the prediction of reliability analysis using Weibull distribution and visualizing the maintainability on the bathtub curve to estimate and calculate the life of control valves.

Keywords – Control Valve, Reliability, Valve Stiction, Weibull distribution.

I. INTRODUCTION

In today’s digital era of the industrial revolution, Industry (4.0) or (I4.0) is the latest trend, which is leading technology to the next level ahead. Global promising of best delivery output or results had made machine and software more complicated and hence, more challenging to sustain their reliability. Since it fails in performance or become incapable to continue performing operations as promised by manufacturers.

Process plant typical consist of thousands of control loop. To make operation conditions smooth it is required to make control loop design more stable. The quality of the plant operations is directly proportional to the loops with their efficiency and performances. Therefore, a platform is required to keep a steady watch on all plant operations along with depending controllers. Since there are many controller devices which are assembled to construct a single process plant. The most common control used is “control valve”, which is used to regulate and manipulate the process. A control valve is amassed by following parts, such as valve body, valve seat and valve plug. As per some research, 30% of loops in process plant get suffer due to valve non-linearity problems, which are stiction, hysteresis, and deadband [1].

A pneumatic control valve are still utilized most broadly in the process industry, because of their lower cost and effortlessness maintainance [2]. Thus, it is required to develop a tool that would notify the early stage of failure with visualization of failure on the bathtub curve (Life expectancy curve). To keep performing the control valve, its reliability and all its related issues should be considered. Since, Fault detection and diagnosis has fascinate the researchers, however faults can be major divergence [3]. The scholarly community has responded to valve stiction issue by showing several results which are referenced in [4]. Stiction produces a vast scope of symptoms because of the vast decent variety of control loops. Moreover, the valve operational process, the control parameters and the plant components affects the quality of oscillation created by stiction [5]. Research review of current valve stiction recognition strategies mentioned in [6]–[8] presumed that single planning is not enough to analyze stiction for all cases.

This paper presents the reliability prediction of control valve performance under several opening and closing of valve plug from 10% to 100%. In the first stage, it will detect the working behavior of control valve under several loads for a single tank system. In the second stage, the failure data is collected using the simulation for valve stiction. In the fourth stage, the reliability model is implemented and validated to predict up to 95% accuracy of prediction. This research paper is formed as follows sections, Section II will define the control valve stiction and factors affecting it. Section III will define the failure mode and failure of data collection. Section IV will discuss the implementation of the reliability model and followed with section V for results. Finally, Section VI will conclude this research paper work.

II. CONTROL VALVE AND CONTROL VALVE STITION EFFECTING PERFORMANCES

This section will define the working of control valves and how stiction is effecting in reducing reliability.

A. Working of Control Valves

As it is well known for process plant consist of hundreds of control loop. Each control loop is dedicated to controlling some important variable in control such as pressure, flow, level, temperature, etc. So to keep all these processes go smoothly without getting any failure control valve are used to control the output.

To decrease the impact of these load disturbance, sensors and transmitters gather data about the procedure variable and its relationship to some ideal set point. A controller at that point forms this data and chooses what must be done to recover the procedure variable to where it ought to be after a load unsettling influence happens. At the point when all the estimating, comparing, and figuring are done, some sort of definite control component must execute the system chosen.
Fig. 1: Control Valve arrangements in process plant. Image source (http://in.ari-armaturen.com/in/home.html)

by the controller. Fig.1 shows how the control valve is placed and used to control the rate of flow in a line.

The control valve typically comprises of the valve body, the bonnet, the valve seat and valve plug or interior trim parts, an actuator (a pneumatic, water driven or electrically controlled gadget that provisions power and movement to open or close a valve), valve shaft which associates with the actuator, fixing course of action between the valve stem and the bonnet and extra valve accessories. Fig. 2 demonstrates a diagrammatic representation of a single seat two-port pneumatic valve.

Fig. 2: Working of penuamtic control valve.

B. Stiction Symptoms

Stiction is a situation which describes a valve stem position response in increasing (overshoot) controlled output which can happen in flowing three stages [5].

- The position of the valve remains unchanged while the valve input steadily increase,
- The valve stem starts movement abruptly by jumping from one point to another,
- The valve stem moves smoothly according to increase in the input signal.

Fig 3. shows the typical input-output behavior of a valve under stiction.

Fig. 3: Valve stiction behavior [9]

III. CONTROL VALVE FAILURE MODE

To justify the failure mode of a control valve, there are two aspects to be considered. The first strategy can be considered as the method which is discussed and appraised to define the technique for failure mode. The second approach can focus on the application of failure mode and classification to control valves for a specific evaluation [11]. The two most likely critical faults are:

- The valve stiction and,
- The valve plug wear

In control valves, the nonlinear phenomenon is the main source to degrade the process and that nonlinearity causes from friction phenomena. Few formation of failure process in control valve are such as stick-slick motion, hysteresis (backlash), actuator control saturation, dead band [10]. As per the research finding, nonlinearity with first-order linear dynamic model is the most critical situation in formation of stiction [13].

IV. METHOD

The method section will define how the reliability for control valve can be estimated by applying algorithm and visualizing on bathtub curve.
A. Failure Data for Control Valve

This research is based on simulation since data was collected using simulation in MATLAB environment. In this research single tank plant was considered. Data set is listed in two parts, first is the rate of flow, and second is a failure in the rate of flow. After that rate of flow was divided into two parts, first in which gate valve opening was kept till 30% of the control valve. In the second, gate wall opening was fixed till 90%. This process was done to understand the working behavior for the initial stage and the final stage of control valve control ability. In the final stage of data collection, data censoring process was performed to define the failure occurrence in the rate of flow.

B. Analysis Model

In the process to predict and to obtain the reliability, we assumed some parameters from data to compute as a censored data set. TTF (Time to Fail) measurement was satisfactorily predicted by using 2- parameter Weibull distribution as described in the result section. Since some assumptions were made depending on data and different kind of sampling performed. Now, calculating the Weibull distribution CDF (cumulative density function), which can be expressed as:

\[ Pr(T \leq t; \eta, \beta) = 1 - \exp\left(-\left(\frac{t}{\eta}\right)\right), t > 0 \]  

where, \( \beta > 0 \) is a shape parameter and \( \eta > 0 \) is a scale parameter in particular, if \( T \) has a Weibull distribution, then \( Y = \log(T) \cdot SEV(\mu, \sigma) \), where \( \sigma = 1/\beta \), is the scale parameter and \( \mu = \log(\eta) \) is the location parameter. Lets say, \( T \) has a Weibull distribution, which can be represented by \( \text{TWEIB}(\mu, \sigma) \), where SEV is the smallest extreme value distribution. [12]

Now the Weibull cdf, pdf and hf can be written as:

\[ F(t; \mu, \sigma) = \Phi_{sev}\left[ \log\left(\frac{t - \mu}{\sigma}\right) \right], \]  

\[ f(t; \mu, \sigma) = \frac{1}{\sigma} \Phi_{sev}\left[ \log\left(\frac{t - \mu}{\sigma}\right) \right] = \beta \frac{t}{\eta} \exp\left[-\left(\frac{t}{\eta}\right)\right] \]  

\[ h(t; \mu, \sigma) = \frac{1}{\sigma \exp(\mu)} \frac{1}{\exp(\mu)} \frac{1}{\sigma} = \frac{t}{\eta} = \beta \frac{t}{\eta} \beta^{-1}, t > 0. \]

where, \( \Phi_{sev} \) is the standardized smallest extreme value cdf.

1) Maximum Likelihood Estimator: Maximum likelihood estimator (MLE) is more assuring to use for reliability estimations of Weibull parameters than other methods such as Median Rank Regression (MRR) [12]. To find the MLE for complete data, the maximum of the following likelihood function with respect to the unknown parameter \( \theta_1, ..., \theta_k \) is found:

\[ L(\theta_1, ..., \theta_k) = \prod_{i=1}^{n} f(t_i; \theta_1, ..., \theta_k) \]  

The main objective of using MLE is to estimates the values of \( \theta_1, ..., \theta_k \), that will render the likelihood function as large as possible for given values of \( t_1, ..., t_n \).

2) Weibull MLE: MLE for two-parameter Weibull distribution must be calculated numerically. It can be computed for both singly censored data, the estimate for the shape parameter, \( \beta \), can be derived as follows:

\[ g(\hat{\beta}) = \sum_{i=1}^{r} t_i^\beta \ln t_i + (n-r) t_i^\beta \ln t_i - 1 - \frac{1}{\beta} \sum_{i=1}^{r} t_i^\beta = 0 \]  

V. RESULTS

This section will show the results on the prediction of the reliability in the pneumatic control valve and visualizing it. As shown in Fig 4, it represents the failure data simulated from MATLAB SIMULINK. In here it visualize the censored data formation at valve gate opening of 30% and 90%.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>lower value</th>
<th>estimated value</th>
<th>upper value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta )</td>
<td>2.4118</td>
<td>2.564</td>
<td>2.726402</td>
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<tr>
<td>( \eta )</td>
<td>15.68169</td>
<td>16.19037</td>
<td>16.71555</td>
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After representation of data, Weibull values for shape and size which are \( \beta \) and \( \eta \) were calculated. Table I and Table II shows the values for \( \beta \) and \( \eta \) focusing for lower estimated, main estimated and upper limit estimated values for reliability prediction. As shown in Fig. 5 (a) it visualizes the reliability plot for 30% of the gate valve opening. Here it can also be visualized about bathtub curve. In 5(b) Reliability plot shows the rapid fall in a curve, which mean the reliability failure chances are higher than in comparison to 5(a). Fig 6 shows the failure rate based on hazard function depended on time.

After computing the values, estimation was validated by using bootstrapping for 1000 samples to calculate the estimated values of failure rate. The calculated values as displayed in Table III and IV. To validate the curve fitting E(T) function was superimposed to get 95% of accuracy, which can be visualized in Fig 7. Hence, in Table III and IV, shows the limits which define the range for availability and maintainability by looking at the stage of lower and upper. Which also shows the reliability analysis of the control valve in different operation limits.

VI. CONCLUSION

This paper presents the extraction of the failure data by performing simulation for stiction. The system aimed...
(a) Cumulative Frequency Distribution (CDF) of the failure rate upto gate valve opening 30%.

(b) Cumulative Frequency Distribution (CDF) of the failure rate upto gate valve opening 90%.

Fig. 4: Representation of failure data used.

(a) Reliability plot vs time which visualize the (β) values for 30% operation of control valve.

(b) Reliability plot vs time which visualize the (η) values for 90% operation of control valve.

Fig. 5: Reliability plot for 2 parameter Weibull distribution

(a) Failure rate plot vs time which shows the shape parameter (β) values for 30% operation of control valve.

(b) Failure rate plot vs time which visualize the (η) values for 90% operation of control valve.

Fig. 6: Failure rate plot visualization for Weibull 2 parameters (β) and (η)

TABLE III: MTTF estimated values with using Weibull distribution

<table>
<thead>
<tr>
<th>Parameters</th>
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<th>estimated</th>
<th>upper</th>
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<tbody>
<tr>
<td>MTTF</td>
<td>14.37472</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MTTF (Bootstrap)</td>
<td>13.92188</td>
<td>14.37472</td>
<td>14.86119</td>
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<td>Bootstrap Statistics</td>
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<td>Bias</td>
<td>Std. Error</td>
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<td>14.37472</td>
<td>-0.006359</td>
<td>0.23487</td>
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<tr>
<td>Mean</td>
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<td></td>
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</tbody>
</table>

TABLE IV: MTTF estimated values with using Weibull distribution

<table>
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<th>Parameters</th>
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<th>estimated</th>
<th>upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTTF</td>
<td>90.3966</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MTTF (Bootstrap)</td>
<td>89.7012</td>
<td>90.3921</td>
<td>91.1456</td>
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<tr>
<td>Bootstrap Statistics</td>
<td>Original</td>
<td>Bias</td>
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<tr>
<td></td>
<td>90.3966</td>
<td>0.00103</td>
<td>0.3764</td>
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<tr>
<td>Mean</td>
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to collect the data and to do reliability analysis. Weibull distribution was used to perform the reliability analysis. Specifically, this research divides the data collection at two major functioning points of control valve. In first situation control valve behavior with 30% of gate valve opening along with stiction was implemented to recorded failure data. Another situation was observed at 90% gate valve opening was considered. In this manner the operation behavior of pneumatic control valve was understood.

The results disused about the prediction of the reliability analysis. However, the results of the Weibull shows reliability prediction. 95% of accuracy fitting was imposed to attaining the best analysis. Hence, the method was able to show the reliability prediction, along with indicating the maintenance required time. Moreover, the failure of the control valve was be visualized on the bathtub curve which is the most suitable cure to define the working-age of instruments. However, research is still required to make understand the reliability analysis. Hence, this research will help system engineers to take correct steps, to avoid unplanned downtime.

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