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Review

Reliability prediction of control valves through mechanistic models

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A Nuclear Power Plant (NPP) consists of normally operating and emergency standby systems and components. The failure of any operating component will lead to a change in the state of the plant. Control of the processes in the plant is an essential part of the plant operation. The most common control element in the process control systems is the control valve. The control valve manipulates a flowing fluid, such as steam, water, gas, or chemical compounds, to compensate for the load disturbance and keep the regulated process variable as close as possible to the desired set point. In order to ensure the high reliability of the system, component reliability should be ensured. In this paper working principle of control valve and different failure modes by which control valve can fail has been discussed. Reliability of the control valve has been estimated from the mechanistic models by using structural reliability methods.

Key words: Control valves, reliability, mechanistic models, FORM.

INTRODUCTION

Nuclear power plants consist of hundreds of control loops, each of these control loops is designed to keep some important process variable such as pressure, flow, level, temperature, etc. within a required operating range to ensure the quality of the process. For example, there must be enough water in the steam drums (4 steam drums in a typical Advanced Reactors) to act as a heat sink for the reactor. The level of the steam drum must be kept within a certain range. Each of these loops receives load disturbances that detrimentally affect the process variable. To reduce the effect of these load disturbances, sensors and transmitters collect information about the process variable and its relationship to some desired set point. A controller then processes this information and decides what must be done to get the process variable back to where it should be after a load disturbance occurs. When all the measurements, comparisons, and calculations are done, some type of final control element must implement the strategy selected by the controller. The most common final control element in the process control industries is the control valve. The control valve manipulates a flowing fluid to compensate for the load disturbance and keep the regulated process variable as close as possible to the desired set point.

OPERATING PRINCIPLE OF CONTROL VALVE

The control valve assembly typically consists of the valve body, the bonnet, the valve seat and valve plug or internal trim parts, an actuator (a pneumatic, hydraulic or electrically powered device that supplies force and motion to open or close a valve), valve spindle which connects to the actuator, sealing arrangement between the valve stem and the bonnet and additional valve accessories. Figure 1 shows a diagrammatic representation of a single seat two-port globe valve. In this case the fluid flow is pushing against the valve plug and tending to keep the plug off the valve seat. The difference in pressure upstream (P_1) and down stream (P_2) of the valve, against which the valve must close, is known as the differential pressure (ΔP). Hence, the force required

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Abbreviations: FORM, First order reliability methods; **SORM,** second-order reliability methods; **NPP,** nuclear power plant.

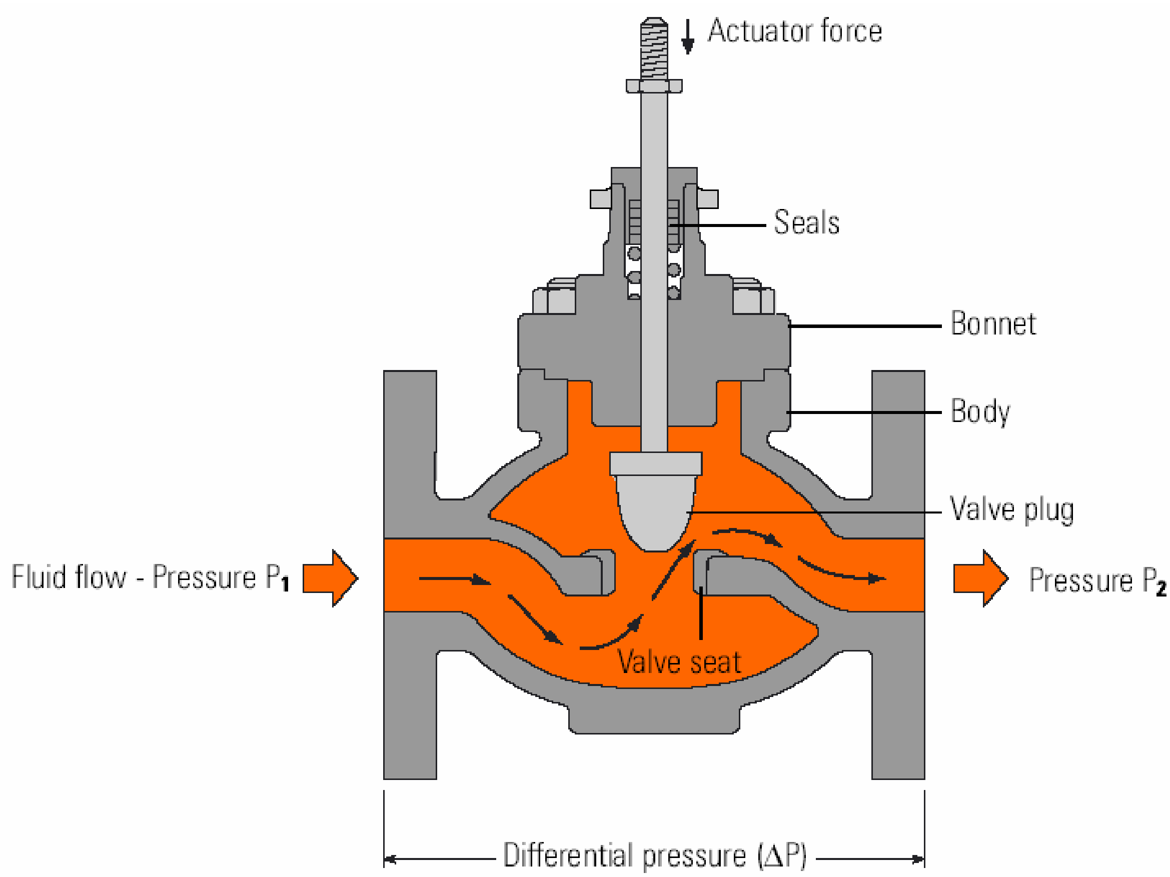

Figure 1. Flow through a single seat two-port globe valve SC-GCM-58 (2005).

from the actuator to close the valve can be calculated from the following equation SC-GCM-58 (2005):

$$F = (A \times \Delta P) + Friction\,Allowance \quad (1)$$

Where, 'A' is the valve seating area.

Depending on the flow requirements actuator force acts and the valve plug will move accordingly to provide the required amount of flow.

THE CONCEPT OF STRUCTURAL RELIABILITY METHODS

Structural reliability concept has evolved from component reliability theory. The first step in evaluating the reliability or probability of failure of a structure is to decide on specific performance criteria and the relevant load and resistance parameters, called the basic variables X_i, and the functional relationships among them corresponding to each performance criterion. Mathematically, performance function can be described as:

$$Z = g(X_1, X_2, ..., X_n) \quad (2)$$

The failure surface or the limit state of interest can then be defined as $Z = 0$. This is the boundary between the safe and unsafe regions in the design parameter space, and it also represents a state beyond which a structure can no longer fulfill the function for which it was designed. The failure surface and the safe and unsafe regions are shown in Figure 2, where, R and S are the two basic random variables. The limit state equation plays an important role in the development of structural reliability analysis methods. From the above Equation 2, it can be found that failure occurs when $Z < 0$. Hence, the probability of failure, P_f, can be given as follows:

$$P_f = \int \ldots \int_{g(\,)<0} f_X(x_1, x_2, \ldots, x_n)\, dx_1\, dx_2 .. dx_n \quad (3)$$

in which $f_X(x_1, x_2, \ldots, x_n)$ is the joint probability density function for the basic random variables $X_1, X_2, \ldots, X_n$ and the integration is performed over the failure region, that is g( )< 0. Performing of these integrations is complex therefore one approach is to use analytical approximations of this integral that are simpler to compute. These methods can be grouped in to first order reliability methods (FORM) and second-order reliability methods (SORM) Achintya and Sankaran (2000). The limit state of

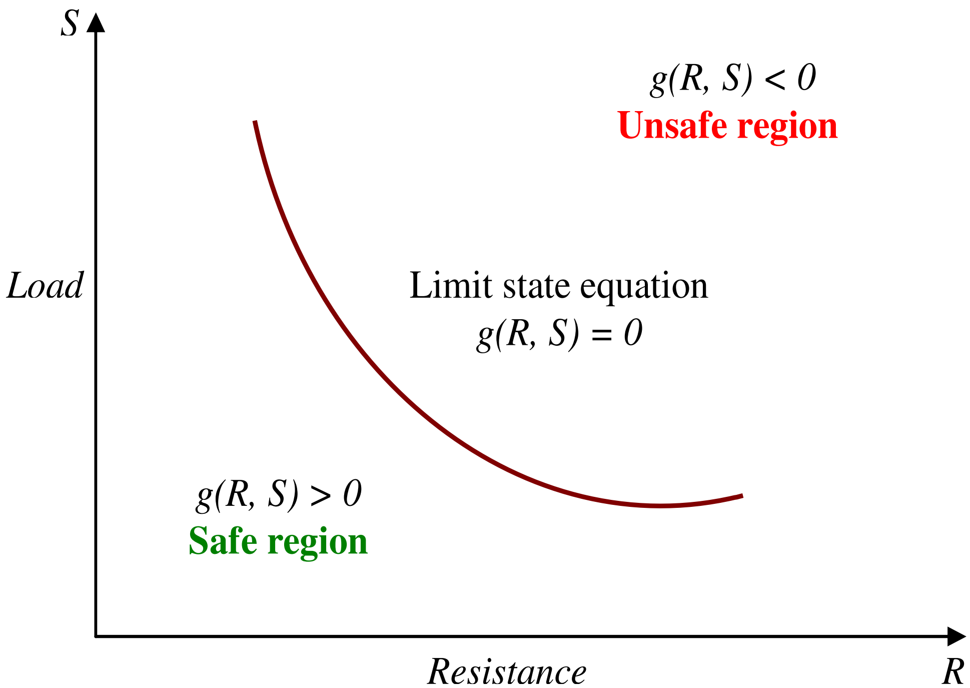

Figure 2. Limit state concept.

interest can be linear or nonlinear functions of the basic variables. FORM can be used when the limit state function is a linear function of uncorrelated normal variables or when the nonlinear limit state function is represented by a first order (linear) approximation with equivalent normal variables. SORM estimates the probability of failure by approximating the nonlinear limit state function, including a linear limit state function with correlated non normal variables, by a second order representation. In all these the concept of reliability index is used which is defined as the shortest distance from the origin to the limit state function in the space of standard normal varieties. The probability of failure in terms of the reliability index is given as follows Achintya and Sankaran (2000):

$$P_f = 1 - \Phi(\beta) \quad (4)$$

The flow chart which represents the different steps involved in performing the reliability analysis is shown in Figure 3.

FAILURE MODES

Failure mode can be defined as a manner in which the component or equipment failure takes place. Although, there are limited common control valve failure modes, the dominant problems are usually related to leakage, speed of operation or complete valve failure Mobley (2002). A control valve can have different failure modes namely: fails to open fully, fails to open partially, fails to close fully and Leakage. Different failure modes of control valve and their causes are shown in the Table 1.

ESTIMATION OF RELIABILITY

This section provides reliability analysis of control valves. Mechanistic model has been used to find the reliability of control valve instead of getting from the generic data-bases. With the help of these mechanistic models one can estimate the reliability of the control valve at all operating positions rather only at fully open or closed conditions. Failure of the control valve takes place if the supplied pressure is less than the required pressure for lifting the valve plug. Hence, the failure function can be represented as Probability of failure = P (Supplied Pressure < Required Pressure)

$$P_f = P(\sigma_S < \sigma_R) \quad (5)$$

For a diaphragm type control valve required pressure can be calculated as follows: The spring force required to lift the valve to a height of H is

$$F = K\,H \quad (6)$$

Where, K is the stiffness of the spring.

The valve lift can be calculated from the following expressions based on the flow requirements Emerson Process

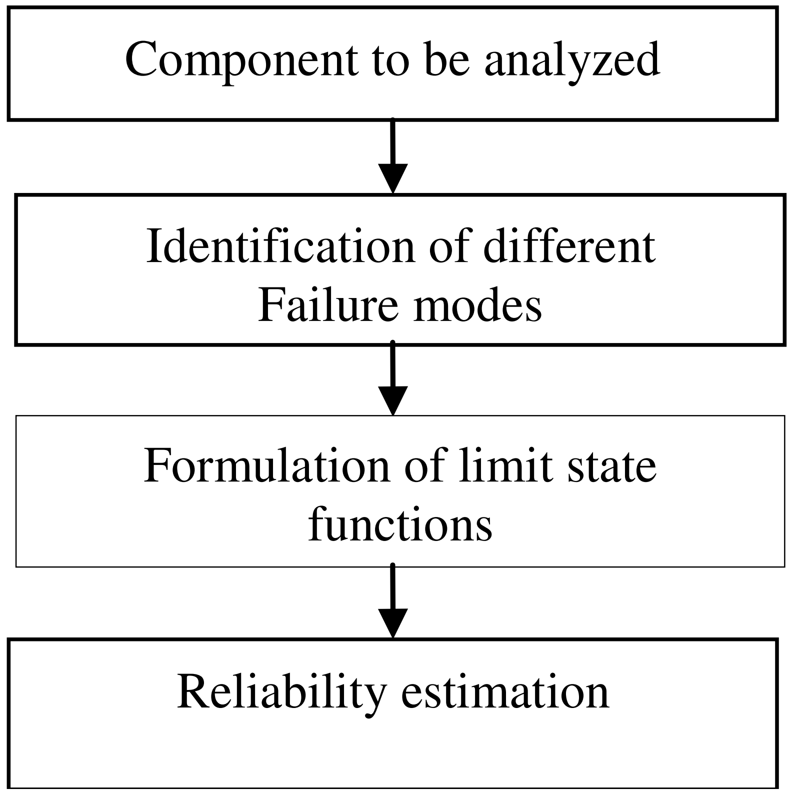

Figure 3. Flow chart representing the steps involved in performing the reliability analysis.

Table 1. Different failure modes of control valve.

Failure mode	Causes
Fails to open Fails to close Leakage	Corrosion, dirt/debris trapped in valve seat, line pressure too high, mechanical damage etc.

Management (2005).

$$H = \frac{\ln\left[\frac{\dot{V}}{\dot{V}_{max}}\tau\right]}{\ln\tau} \quad (7)$$

Where,

$\dot{V}$ = Volumetric flow through the valve at lift H

$\dot{V}_{max}$ = Maximum Volumetric flow through the valve

τ = Valve rangeability (ratio of maximum to minimum controllable flow rate)

Hence, for lifting the valve to a height of "H" the actuator force required is "F". From the above the required pressure that should act on the diaphragm can be calculated as follows:

$$\sigma_R = \frac{KH}{A_D} \quad (8)$$

where

A_D = Area of diaphragm

$= \frac{\pi}{4}D^2$

D = Diameter of diaphragm

Supplied pressure depends on the compressor and control signals. Hence, the probability of failure can be written as follows:

$$P_f = P\left(\sigma_S < \frac{4KH}{\pi D^2}\right) \quad (9)$$

In the above equation, K, D, σ_S have been considered as

Table 2. Random variables considered in the analysis.

Variables	Mean (μ)	Coefficient of variation (C.O.V)	Distribution
K (kg/cm)	85	0.01	Truncated normal
D (cm)	32	0.01	Truncated normal (Appendix 1)
σ_S (kg/cm^2)	1.004	0.01	Uniform
H (cm)	9.5	-	Constant

Table 3. Failure probabilities of different components.

Component	Failure probability
Compressor	2.42e-2
Pump	3.05e-3
Pressure Transmitter	3.51e-3
Orifice Flow Meter	3.02e-4

random variables and H is considered as a constant. The data used in the analysis is shown in the Table 2. By using the second order reliability methods (SORM), the reliability index (β) has been estimated as 1.918 and the probability of failure (P_f) has been estimated as 2.75e-2. This value is comparable with the value given in the generic data bases like IAEA-TECDOC 478 IAEA-TECDOC 478 (1988) which is given as 2.5e-2/demand. Once the design parameters of a control valve is known, one can use the above methodology for finding out the failure probability of a control valve instead of using the one generic value for all ranges of control valves. This methodology can be applied in all the process control loops where the functioning of control valve is sought, not only fully open or closed but also partial opening (% of opening). The similar approach has been applied for some more components and the results are shown in Table 3 and the values are comparable with the generic data bases like IAEA-TECDOC 478.

Conclusions

In all the process control systems control valves are being used to control the process variables. In order to ensure the high reliability of the system component reliability should be ensured. In this paper control valve failure probability has been estimated from the mechanistic models instead of getting from the generic data-bases. With the help of these mechanistic models one can estimate the failure probability of the control valve at all operating positions rather only at fully open or closed conditions.

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Appendix 1

Consider X follows normal distribution. Hence, the range of X varies from -∝ to +∝.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right] \qquad -\infty < x < +\infty$$

$$Let,\ \chi = \frac{x-\mu}{\sigma}$$

$$\therefore f(\chi) = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{\chi^2}{2}\right]$$

When X gets truncated at 3σ level then the expression gets changed and can be given as follows

$$f^1(\chi) = C\, f(\chi) \qquad \mu - 3\sigma < x < \mu + 3\sigma \ \ and \ \ -3 < u < +3$$

$$C\int_{-3}^{3} f(\chi)d\chi = 1 \qquad \Rightarrow C = \frac{1}{\int_{-3}^{3} f(\chi)d\chi}$$

$$But,\ \Phi(\chi) = \int_{-\infty}^{\chi} f(\chi)d\chi \qquad (Cumulative\ \ distribution\ \ function)$$

$$\therefore \int_{-3}^{3} f(\chi)d\chi = \int_{-\infty}^{\infty} f(\chi)d\chi - \int_{-\infty}^{-3} f(\chi)d\chi - \int_{3}^{\infty} f(\chi)d\chi$$

$$= 1 - \Phi(-3) - \int_{-\infty}^{-3} f(\chi)d\chi = 1 - 2\Phi(-3)$$

$$\therefore C = \frac{1}{1-2\Phi(-3)}$$

Hence,

$$f^1(\chi) = \frac{1}{1-2\Phi(-3)} \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{\chi^2}{2}\right] \quad -3 < \chi < +3$$

$$\therefore \Phi^1 = \int_{-3}^{\chi} f^1(\chi)d\chi = \frac{1}{1-2\Phi(-3)}\left[\int_{-\infty}^{\chi} f(\chi)d\chi - \int_{-\infty}^{-3} f(\chi)d\chi\right]$$

$$\Phi^1 = \frac{\Phi(\chi) - \Phi(-3)}{1-2\Phi(-3)}$$

By using the above formula one can calculate the cumulative distribution function value for the truncated normal distribution.