Identification of Stiction Nonlinearity for Pneumatic Control Valve using ANFIS Method

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Abstract-Valve stiction is one of the prominent stand-alone reasons for oscillatory behavior in process industry. Stiction is a common problem in spring diaphragm type valves, which are widely used in the process industry. This behavior leads control valves to deliver accurate feed and thereby allowing wastage of utility. Recently, there have been many attempts to understand, define, model and detect stiction in control valves. Most of the available methods cannot simultaneously detect and quantify stiction. The paper presents an Adaptive Neuro-Fuzzy methodology for identification of stiction. For a vertical two tank level process with Kano's model of stiction is considered to obtain necessary required data to formulate objective function. The proposed methods for detecting and quantifying stiction are applied on the flow control valve using MATLAB/Simulink platform.

Keyword-ANFIS, Control-Valve, Dead-Band, Identification, Modelling, Nonlinear, Stick-Band, Stiction,

I. INTRODUCTION

Stiction in control valves and inadequate controller tuning are two of the major to measure of causes for degradation in the performance of the control loop. Stiction in a control valve appears as a hard non-linearity in the control loop dynamics [1] and is a sophisticated non-linear phenomenon. Its detection and quantification has been identified as a highly challenging academic as well as industrial problem. The presence of control valve nonlinearities, e.g., stiction, backlash and dead-band, is a major cause of oscillations in control loops. The presence of oscillation in a control loop increases the variability of the process variables thus causing inferior quality products, larger rejection rates, increased energy consumption, reduced average throughput and decreased profitability. Among different nonlinearities in control valves, stiction is the most common and is one of the long-standing problems in the process industry. It hinders proper movement of the valve stem and can easily be detected using invasive methods such as valve travel or bump test. However, applying such invasive methods across an entire plant site is neither feasible nor cost-effective because of their labor and time intensive nature.

There are several non-invasive methods for detection of stiction that have been reported in the literature [1-6]. The cross-correlation method [2] is widely used in detecting valve stiction in flow control loops. It cannot be applied for loops involving an integrator or those carrying compressible fluids. However, [20] suggested another method called the 'camel method' based on the distribution of the second derivatives of the controlled variable to detect valve stiction in an integrating plant. The 'camel method' is sensitive to the noise and requires designing of a good filter. The methods described in [3], [4], [7] depend on the qualitative shape of the time trends of the data which is often distorted by the presence of noise and disturbances. Also, in real life the shape of the time trends of data is heavily affected by the process and controller dynamics. A Model based segmentation method [6] described to detect stiction in control valves. All the above methods are cumbersome and do not used valve model explicitly to quantify the amount of Stiction. It is necessary to detect and estimate the amount of stiction so as to feed correct amount of input to the process as manipulated variable. Usual conventional model also fails to map nonlinear behavior of Stiction in pneumatic control valve.

In this paper, the ANFIS method is used for modeling and identification of the control valve stiction. The rest of the paper is organized as follows: A review of literature for detection of stiction is given in Section II. Section III explains different models to detect stiction in control valves. The widely used Kano's stiction model is explained in detail in section IV. Section V explains the process coupled two tank system were control valve is used as flow valve. Section VI and VII explains the proposed modeling of the system. Experiments and results of the proposed work are discussed in Section VIII. The summary and discussion of the paper is in Section IX.

II. DETECTION OF STICTION: A BRIEF REVIEW

Numerous research works on stiction nonlinearity in control valve are available in literature based on their modelling, identification, estimating and controlling. There have been many attempts to understand, define, model and detect stiction in control valves, but quantification of the actual amount of stiction still remains a challenge. The definition and modeling of control valve stiction [13] have discussed and they demonstrated a method to detect and quantify the actual amount of valve stiction using routine operating data. The proposed method was completely data-driven model. No additional excitation or experimentation of the plant was required.

Separable least-squares and global search algorithms [14] has presented a procedure for quantifying control valve stiction in control loops. Measurements of the controlled variable PV and controller output OP were used to estimate the parameters of a Hammerstein model structure, consisting of a connection of a two-parameter stiction model and a linear low-order process model. As the objective function was non-smooth, gradient-free optimization algorithms, i.e., pattern search PS methods or genetic algorithms GA were used for fixing the global minimum of the parameters of the valve stiction model, subordinated with a least-squares estimator for identifying the linear model parameters. Different approaches for selecting the model structure of the linear model part were discussed. Their results show that this optimization-based technique recovers accurate and reliable estimates of the stiction model parameters, dead-band + stick-band S and slip-jump J, from normal operating data for self-regulating and integrating processes. The robustness of the proposed approach was proven considering a range of test conditions including different process types, controller settings and measurement noise.

The causes of control valve stiction oscillations [15] have discussed in industrial process control loops. Such oscillations can degrade the overall performance of the loop and eventually the final product quality. The detection and quantification of valve stiction in industrial process control loops was thus important. From the discussion, a sticky valve has been shown to have a distinct signature of the stiction phenomena in its valve positioned data. However, the position of the modulating control valves was seldom available. They considered the problem of estimating the valve position as an unknown input estimation problem. They proposed an application of the unknown input estimator in order to estimate the valve position for a given process model and the data of the process variable and controller output. Using the estimated valve position, they could detect and also quantify the amount of stiction. They demonstrated the efficacy of the method through simulation examples where a sticky valve was deliberately introduced in the closed loop using a two-parameter stiction model. Application of the proposed methodology to a laboratory scale flow control loop was presented.

A novel one-stage procedure to estimate stiction parameters is proposed using a two-parameter stiction model [16] were discussed. Thus, detecting and quantifying this valve problem was essential to ensuring plant profitability. The optimization problem was computed using a global optimization algorithm. These two propositions make the stiction computation more efficient and computationally faster than the currently available method. The applicability of the proposed approach was illustrated using a large number of simulated and industrial valves. Moreover, to isolate the impact of each proposition, the method was compared with the currently available technique, which was based on a two-stage scheme.

Compensation of control valve stiction through controller tuning [17] have presented and suggested this method is applicable for a limited problem. They proposed a stiction compensation framework which was based on the oscillation condition introduced. This condition was used as a tool to predict occurrence and severity of stiction-induced oscillations in control systems. The aim was to suggest re-tuning guidelines for controllers with regard to the presence of stiction in the control valve, to eliminate or to reduce oscillations. A variety of processes and controllers were studied and recommendations were made in order to eliminate the stiction-induced oscillations. The known and unknown model [18] have proposed for stiction detection in nonlinear process control loops based on frequency response of stiction phenomenon and second order volterra process using a physical stiction model. For stiction detection, the proposed robust approach assumes that stiction nonlinearity is discontinuous while the process model is continuous.

III. MODELING OF STICTION FOR CONTROL VALVE

The modeling of stiction is a preliminary approach for analyzing the valve stiction of process industries. The general block diagram of process control valve with stiction is illustrated in Fig 1. In the process control diagram, the controller gain is denoted as G_c, the control valve gain is denoted as G_v and the process gain is denoted as G_p. Measurements of the process variable PV and controller output OP were used to estimate the parameters of a Hammerstein system, consisting of a non linear control valve stiction model and a linear process model. The process output is denoted as 'y_b' and the external disturbance is denoted 'y_d'. Finally, the Process variable PV is denoted 'y' and the expression of output is described as,

$$y = y_b + y_d \quad (1)$$

$$y = N(u) + y_d \tag{2}$$

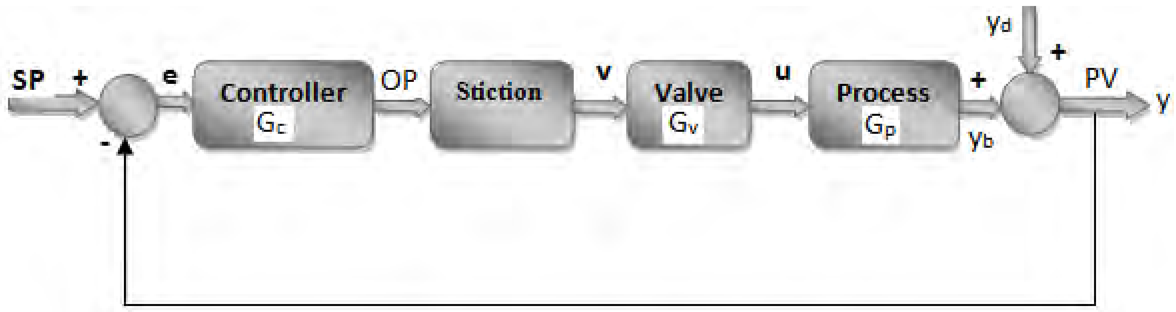

Fig 1: Control loop with sticky valve represented by the nonlinearity

Where, y_b is the process component which written in equation (2) in terms of valve output 'u' and process transfer function 'N'. The identification of the linear dynamics (valve and process) is decoupled from the nonlinear element (stiction). The decoupling between the nonlinear and the linear component is achieved by an iterative procedure [8]. "Stiction is a property of an element such that its smooth movement in response to a varying input is preceded by a static part (dead-band + stick-band) followed by a sudden abrupt jump called 'slip-jump'. Slip-jump is expressed as a percentage of the output span. Its origin in a mechanical system is static friction which exceeds the dynamic friction during smooth movement".

Different people or organizations have defined stiction in different ways. Some of these definitions have been presented in [8]. Based on careful investigation of real process data a new definition of stiction has been proposed by [4] and is summarized as follows. The phase plot of the input-output behavior of a valve "suffering from stiction" can be described as shown in Fig.2. It consists of four components: dead-band, stick-band, slip-jump and the moving-phase. When the valve comes to a rest or changes the direction at point A, the valve sticks as it cannot overcome the force due to static friction. After the controller output overcomes the dead-band (AB) plus the stick-band (BC) of the valve, the valve jumps to a new position (point D) and continues to move. Due to very low or zero velocity, the valve may stick again in between points D and E in Fig.2 while travelling in the same direction. In such a case the magnitude of the dead-band is zero and only the stick-band is present.

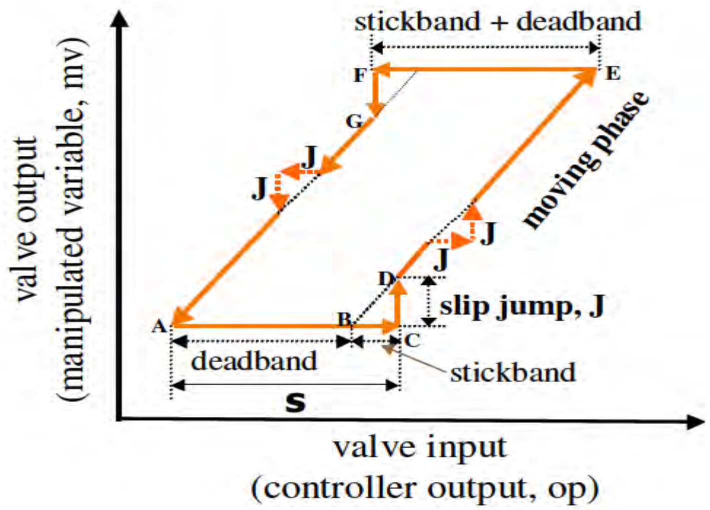

Fig.2. Typical input-output behavior of a sticky valve

The following Fig.3 to Fig.5 represented for various level of stiction obtained from the sticky control valve using Kano's model. For example, Fig. 3 represents the case of strong stiction S=0.8 and jump J=0.3. The stiction model graph indicates the OP verses MV as trapezoidal curve and OP verses PV indicates as elliptic curve. Fig. 4 represented for weak stiction S= 0.1 and jump J=0.3. The stiction model graph indicates the OP versus MV as reduced trapezoidal curve and OP versus PV indicates reduced elliptic curve. Fig. 5 represented for no stiction control valve S= 0 and jump J=0. Now the stiction model graph indicates the OP verses MV as non-trapezoidal curve and OP verses PV indicates more reduced elliptic curve. It can be found from these figures from 3 to 5 that with different slip and jump conditions the trapezoidal nature of the stiction between OP and MV changes its shape. The thickness of OP versus MV curve and the spread of OP and PV curves are found to be thinner with different values of slip(s).

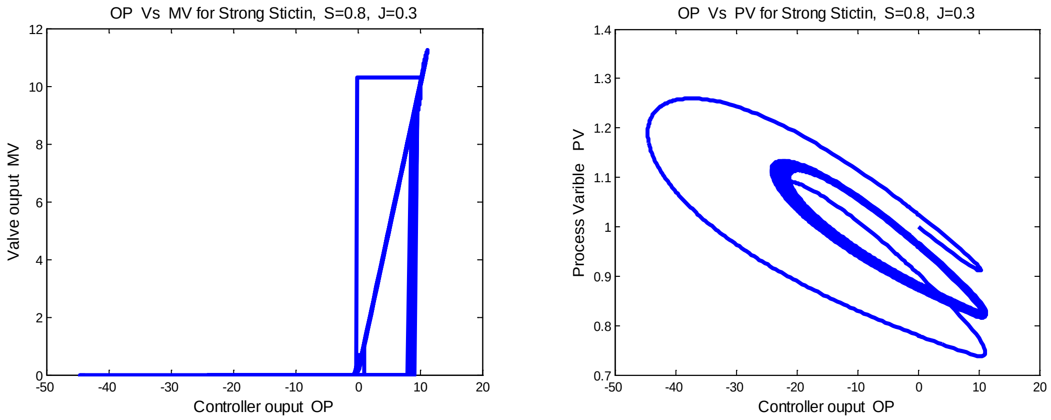

Fig.3 Performance of the OP versus MV and OP verses PV for strong stiction (S=0.8; J=0.3)

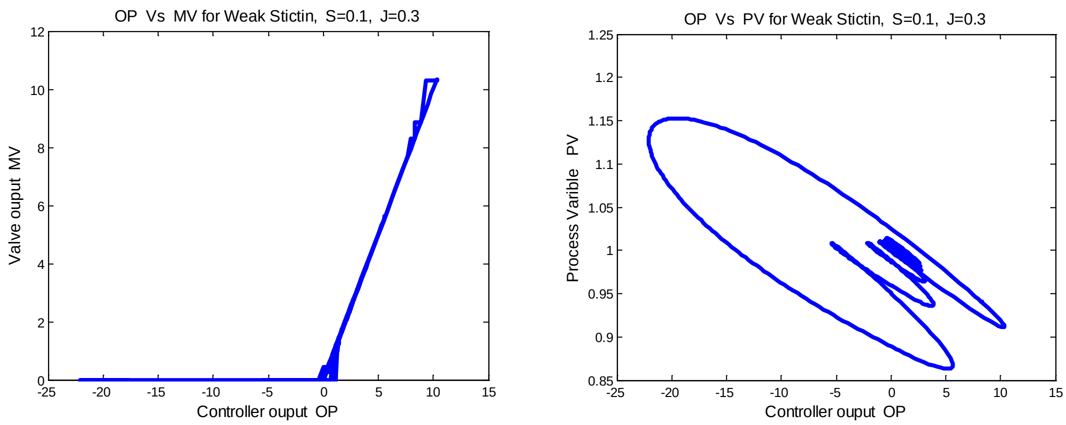

Fig.4 Performance of the OP versus MV and OP verses PV for weak stiction (S=0.1; J=0.3)

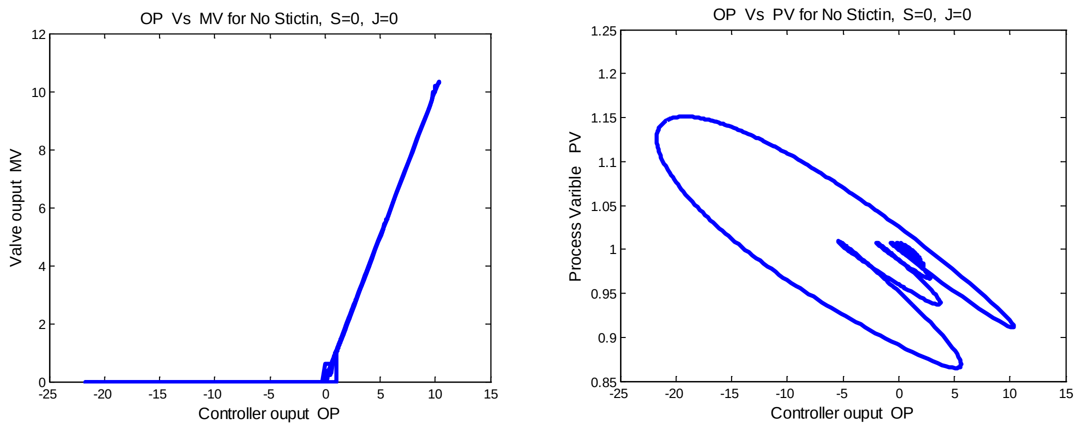

Fig.5 Performance of the OP versus MV and OP verses PV for no stiction (S=0; J=0)

IV. KANO'S STICTION MODEL

The two-parameter model as discussed in [10] has been modified in [11] attempted to relate *S* and *J* to the elastic force, air pressure and frictional force. In Kano's model, *S* corresponds to the summation of static and dynamic friction and *J* corresponds to the difference between the static and dynamic friction. Having this in mind, they offered an alternative flow chart for simulating stiction. The flowchart for stiction simulation is presented in Fig. 6. The input and output of this valve-stiction model are the controller output *u* and the valve position *y*, respectively. Here, the controller output is transformed to the range corresponding to the valve position in advance.

In Kano's model, two states of the valve are explicitly distinguished, denoted by the variable *stp*. In the moving state *stp* has the value 0, while in the resting state *stp* is 1. In addition, the controller output at the moment the valve state changes from moving to resting is defined as u_S. The u_S is updated and the state is changed to the resting state (*stp* =1) only when the valve stops or changes its direction ($\Delta u(t) - \Delta u(t-1) \leq 0$) while its state is moving (*stp*=0). Then, the two conditions concerning the difference between $u(t)$ and u_S are checked unless the valve is in a moving state. The first condition judges whether the valve changes its direction and overcomes the maximum static friction.

$$y(t) = u(t) - df_d = u(t) - \frac{d(S-J)}{2} \tag{3}$$

Here, $d = \pm 1$ denotes the direction of frictional force. The second condition judges whether the valve moves in the similar direction and overcomes friction.

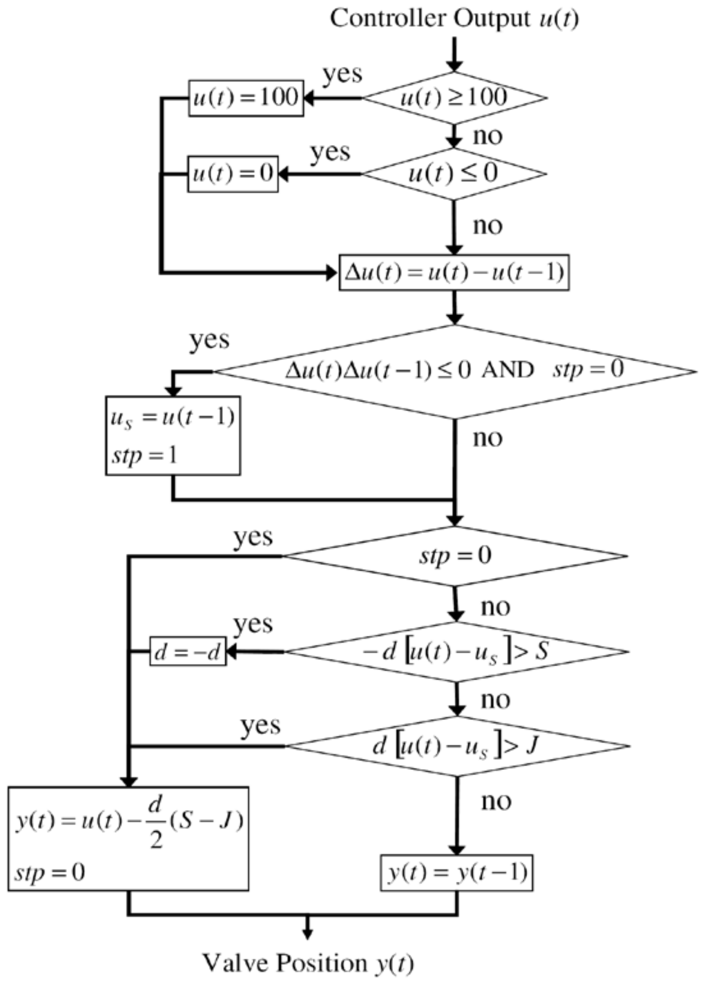

Fig. 6 Flow chart of Kano's valve-stiction model

If one of these two conditions is satisfied or the valve is in a moving state, the valve position is updated using above equation. On the other hand, the valve position is unchanged if the valve remains in a resting state.

V. COUPLED TWO TANK SYSTEM

The control of liquid level in tanks and flow between tanks is a basic problem in the process industries. In vital industries such as petro-chemical industries, paper making industries, water treatment industries have coupled tanks processes of chemical or mixing treatment in the tanks. The level of fluid in the tanks and interacting between the tanks must be controlled. It is essential for control system engineers to understand how coupled tanks control systems work and how the level control problem is solved. The problem of level control in coupled tanks processes are system dynamics and interacting characteristic. The State Space equation of the two tank coupled system is represented as below

$$\mathrm{A} = \begin{bmatrix} -1 & 1 \\ 1 & -2 \end{bmatrix}, \qquad \mathrm{B} = \begin{bmatrix} 1 & 0 \end{bmatrix}, \qquad \mathrm{C} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \text{ and } \mathrm{D} = \begin{bmatrix} 0 & 0 \end{bmatrix} \tag{4}$$

VI. PROBLEM STATEMENT AND PROPOSED METHODOLOGY

For stiction modeling there are number of methods used to identify such as curve fitting method, cross correlation method, relay fitting method, Hilbert method, Fourier method, etc. These methods works based on the principle of either by decomposing the signal or comparing or over lapping the signal with sinusoidal or triangular reference wave forms. The objective function used here is to determine the stiction level is based on the least square error or mean error of the signal. The existing methods are having major drawbacks to determine the percentage of stiction presence in the system. Presence of Stiction is classified as week stiction, strong stiction and no stiction category. Results obtained by these methods having poor accuracy (classifying either no stiction or week stiction as strong category or strong presence of stiction is identified as week or no stiction category) / determining level or difficulties in algorithm establishment.

Many control loops in process plants perform poorly due to valve stiction which is one of the most common equipment problems. It is well known that valve stiction in control loops causes oscillations in the form of periodic finite-amplitude instabilities, known as limit cycles. This phenomenon increases variability in product quality, accelerates equipment wear, or leads to control-system instability. Several methods have been developed to detect valve stiction in the last decade. However, all these methods require either detailed process knowledge or user interaction which is not desirable for automated monitoring systems. Since, at present there is no method to quantify these performance problems.

The proposed methodology will be having the ability to overcome those discussed disadvantages and having an advantage of ability to determine the percentage of stiction level presence in the system. As we discussed above/earlier to overcome those disadvantages the proposed methodology uses adaptive neuro fuzzy (ANFIS) inference system for determine the presence as well as percentage of stiction present in the system. Adaptive neuro fuzzy inference system is a kind of neural network that is based on Takagi–Sugeno fuzzy inference system. Since it integrates both neural networks and fuzzy logic principles, it has potential to capture the benefits of both in a single framework. The proposed ANFIS can construct an input-output mapping based on human knowledge and appropriate membership functions to generate the stipulated input-output data pairs. In the simulation, the ANFIS is employed to model nonlinear functions, and predict a chaotic time series, all yielding a remarkable result.

VII. MODELLING OF PROPOSED SYSTEM

System is designed to be having a data logging units at the places, marked in error, controller output, and valve output. Objective/cost function is defined to be ratio of above mentioned variables, expressed in equation (5) below.

$$input\begin{cases} \dfrac{error}{input}\dfrac{e(t)}{i(t)} \\ \dfrac{controller\ \mathrm{var}iable}{input}\dfrac{co(t)}{i(t)} \\ \dfrac{Manipulated\ \mathrm{var}iable}{input}\dfrac{mv(t)}{i(t)} \end{cases} \qquad output\begin{cases} stiction\ \ (0-1) \end{cases} \tag{5}$$

Using the above cost function training results can be obtained with intervals of 10%, 15%, or 25% of stiction level.

VIII. SIMULATION RESULTS AND DISCUSSION

A vertical two tank system (level process) is considered for our test case. To introduce stiction presence in the test case system Kano's stiction model is taken into consideration; similarly other models (Choudhary's Model, He's Model, etc…) can also possibly to be implemented. Proposed system is established in MATLAB/Simulink environment. Results are obtained with interval of 10% of stiction increment. The required values of input and output are estimated using equation (5). For test case fuzzy system is designed as three input (error, OP & MV) and single output (stiction). There are three membership function were selected for each variable (error, OP & MV) to process the system and the membership function areas are defined as Gaussian surfaces. Along with the obtained fuzzy system MATLAB 'anfis' function is used to create an adaptive neuro fuzzy structure required to determine the percentage of stiction level . To prove the efficiency of the proposed system, it is executed with different stiction level (from 0 to 100% with 1% increment). Using ANFIS structure the amount of stiction in percentage is obtained and compared.

The graph represented in Fig.7 shows clearly, there is non-oscillatory response when stiction is not introduced in control valve. From the graph it is understood that the control valve is performing in a smooth way and it is also understood that the closed loop performance of the system is acceptable one. On the other hand if a small stiction introduced in control valve, it leads continues oscillations both in process variable (PV) as well as in the controller output (OP). Hence, it is clearly understood that the control valve is not functioning in a systematic manner and valve needs identification of stiction level in it. Fig.8. Express the graphical representation between actual stiction level and calculated stiction level using ANFIS algorithm. Fig. 9 indicates the error level presence in proposed methodology.

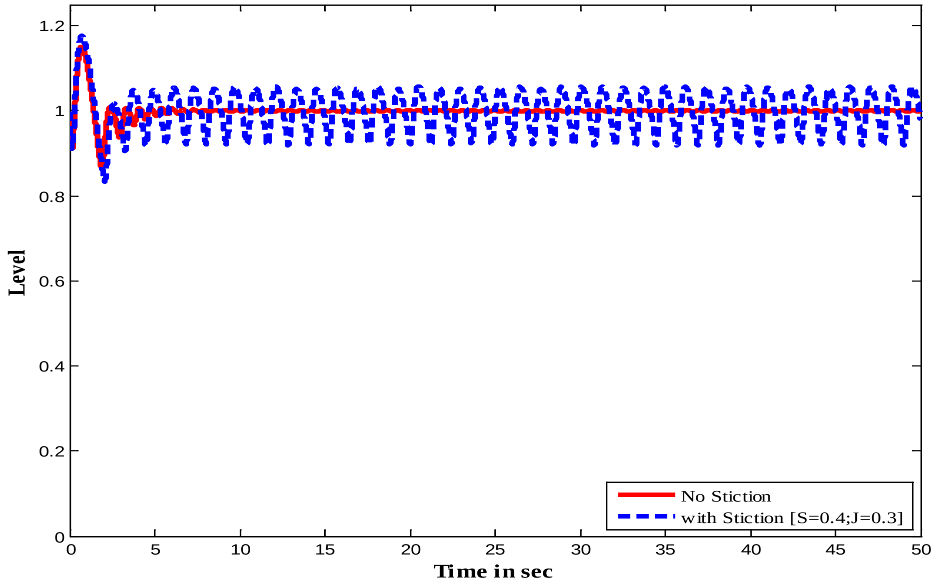

Fig.7 Waveform obtained with and without the presence of stiction

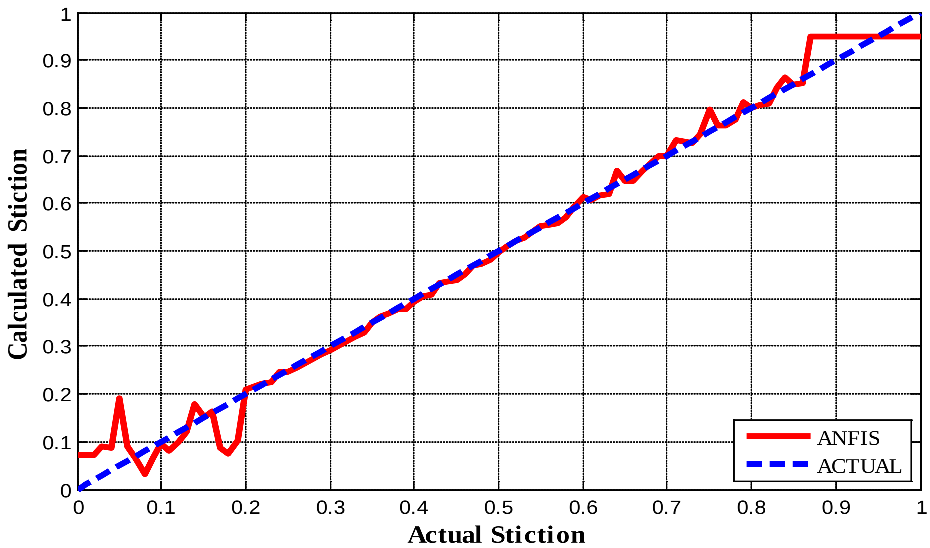

Fig.8 Wave form obtained actual and calculated stiction level

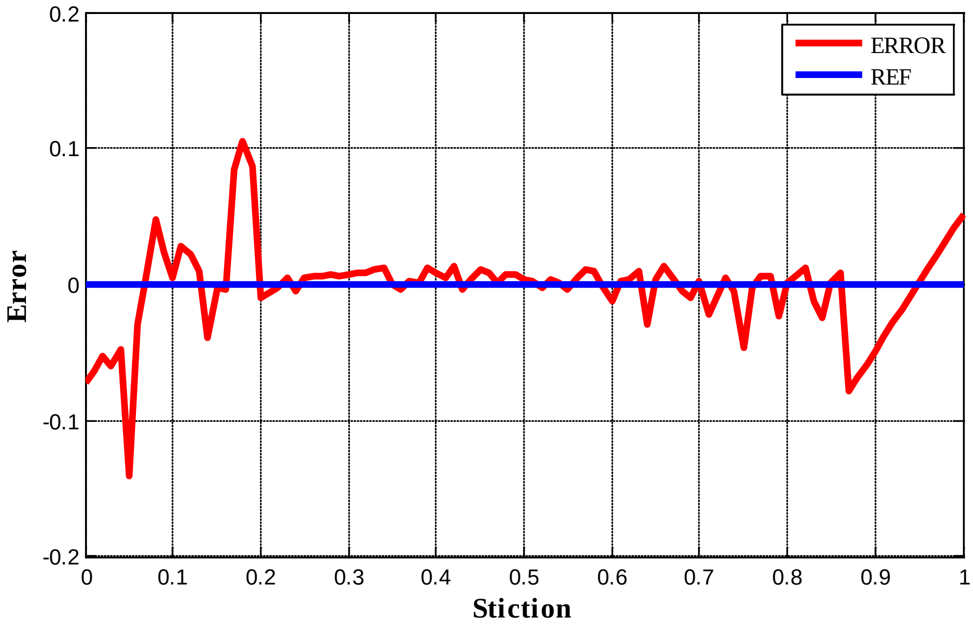

Fig.9 Wave form obtained between stiction and the error.

IX. SUMMARY AND CONCLUSION

Stiction in control valve produces oscillation thereby degrades the closed loop performance of the system. A detailed study on detection, identification and quantification of stiction in control valves is presented here. Stiction is detected and identified using different conventional methods and the same is presented using ANFIS techniques in this work, where reliable results were obtained. Two tanks system in series are used for this work to study the closed loop behavior using a flow control valve with stiction. From the obtained results it is clear that proposed methodology is superior over existing methods used for stiction detection. The ability of proposed method to detect and estimate the exact level of stiction present is also proved. From Fig.9 it is clear that the proposed method have a peak error of 10% and average error of 3% which is in the acceptable range compared with existing methods used to determine the stiction level in the system.

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