International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-3 Issue-1, October 2013

Neural Network Observer Based Leak Detection and Localization System for Oil Transporting Pipelines

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Abstract—This paper considered with the design of two leak detection and localization systems in oil transporting pipeline. The first one based on mass balance principles and second one based on pressure gradient intersection. The main distinction of the both methods, thy have an intelligent observer structured by artificial neural network. Every system has been tested individually, and satisfactory results have been obtained with accurate and good performance. These methods collected together to work in parallel implementing a combined system, this system gives better performance and reduce the false alarm level.

Index Terms— intelligent observer, LDS, leak detection and localization, leakage classifier, neural network observer, oil transporting pipeline,.

I. INTRODUCTION

More than three million kilometers of high pressure liquid and gas pipelines are installed all over the world. Generally steel pipelines provide the safest means to transport large quantities of oil, oil related products and natural gas.[1]

In Iraq recently, pipeline leakage accident frequently occurs due to pipeline quality problem, and ancient of the pipe, conduit age growth, inevitable corrosion, wear , artificial damage,[2] and devastation actions, which not only cause severe environmental pollution , great resource waste and large economic losses, but also threaten people's life. In order to get safe operation and reduction the economic losses and environmental pollution as much as possible installing pipeline leak detection and localization system (LDS) has important significance.

In general there are two types of LDS :

1- External systems. External based LDS (due to API 1130 2nd Ed.) use local leak sensors to generate a leak alarm. Acoustic emission detectors, fiber optical sensing cable, vapor sensing cable and liquid sensing cable based systems.[3]
2- Internally based (LDS) utilize field sensors to monitor internal pipeline attributes such as flow rate, temperature, density, viscosity, etc. The use of computers permit the application of important information processing methodologies.[3]

For example the following methods have been implemented by Regulatory Framework:

- Line balance
- Volume balance
- modified volume balance
- Real time transient model
- Acoustic/negative pressure wave, and
- Statistical analysis. [4]

The main idea of LDS systems based on comparing physical quantities with its predefines thresholds values, the results of this comparing refers to leak accident occurs or not, an addition algorithms utilized to determine the location of the leak .

Usually the thresholds not constant, so the mathematical model is a significant solution to calculate these thresholds at free leak condition, this model usually called pipeline observer. In classical models like real time transient model (RTTM) which explained in section II the observer determines the thresholds by using the numerical solution for complicated partial differential equations(PDE), while in this paper the observers designed by using artificial neural network ANN. The designed system consist of two detections methods first one depend on mass balance principles and second one depend on pressure drop calculations

II. REAL TIME TRANSIENT MODEL (RTTM)

The most sensitive, but also the most complex and costly leak detection method in use is real time transient modeling (RTTM). RTTM involves the computer simulation of pipeline conditions using advanced fluid mechanics and hydraulic modeling.[5]

RTTM models the fluid dynamic characteristic (flow, pressure, temperature, and density). A no-linear pipeline model is obtained by using the equation of continuity, momentum, and energy.

$$\frac{1}{a^2}\frac{\partial p}{\partial t} = -\frac{\partial q}{\partial s} \qquad (1)$$

$$\bar{\rho}\frac{\partial q}{\partial t} + \bar{\rho}g\ sin\alpha + \frac{\bar{\rho}\lambda(q)|q|q}{2D} = \frac{\partial p}{\partial s} \qquad (2)$$

Where p pressure ,q the flow , A the cross section area , $\bar{\rho}$ is the is the density of homogeneous fluid, α is thepipeline inclination , λ the friction coefficient and D the diameter of the pipeline the continuity and momentum equations 1 and 2 form a pair of quasi – linear hyperbolic partial differential equations in term two dependent variables , flow (velocity) $q(s,t) \equiv V(s,t)$ and pressure p(s,t) and two independent variables , distance along the pipeline s and time t .[4]

The general solution of this PDE's not available, so the numerical solution attended depending on the power of modern digital computer.

This system estimates the flow at inlet $(\bar{f_I})$and outlet $(\bar{f_O})$ according to measured values for transient and steady state as a leak free condition.

Manuscript published on 30 October 2013.
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RTTM software can predict the size and location of leaks by comparing the measured data for a segment of pipeline with the predicted modeled conditions.[5]

III. ARTIFICIAL NEURAL NETWORK

Artificial Neural Network (ANN) is a computing tool that is inspired by the capabilities of human brains. An ANN is constructed of interconnected basic elements called nodes or neurons.

A schematic diagram of this neuron is shown in Figure (1). Similar to their biological counterpart, these neurons are capable of processing incoming information and transferring them to other neurons.

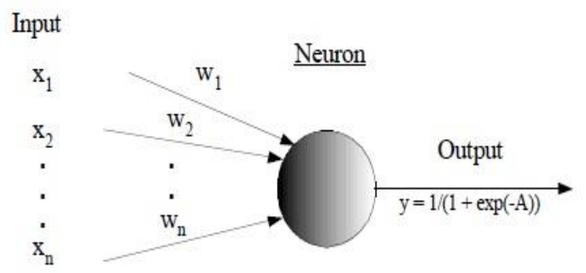

Fig 1.An Individual Neural Network Processing Unit (Neuron).

The input signals come from either the environment or outputs of other neurons through connections as specified by the network architecture. Within each neuron, input signals are summed and transformed using a specified activation function before being sent to other neurons. Such transformations are needed to impart pattern-mapping capability to the networks.[6]

IV.UTILIZEDLEAK DETECTION AND LOCALIZATION METHODS

1. Dynamic mass balance

In this method mass balance conservation principles applied, same as in RTTM the estimated flow at inlet and outlet respectively compared with the measured values and the deviation result refers to leak accident occurs or not but in this method the designed observer build by using ANN depend on the set point value which limited by the operator according to operation requirement. In Iraqi pipelines and from the historical data which refer to no leak occurs at transient time (starting or step change) never at all because of using smoothly starting procedure, so that the designed leak detection LDS in this paper consider for steady state only, especially the transient time is short proportionally, for example in pipeline extended from Baiji to Kirkuk which used to transport gasoline and benzene need to less than three minutes at starting and less than one minute at step change. Then at any change in set point the system will be paused leak calculations for small period time equal or greater than transient time, and then check again if leak occurs in this period of time.

V. FLOW PIPELINE OBSERVER

The heart of the leak monitoring system is the pipeline observer. It represents the flow mechanics and thermo dynamics along the length of the leak-free pipeline. For this purpose the pressure pi and po are measured at inlet and outlet respectively , in addition the temperature of the fluid (batch) and the ground are required .The flow rates$(\overline{f_I})$and$(\overline{f_O})$of the inlet and outlet calculated from these values . in these paper the observer did not estimates $(\overline{f_I})$ and $(\overline{f_O})$ from real time transient model (RTTM), but depend on the set point value of flow controller, while the flow control system in Iraqi pipelines is an open loop control system, so the output of controller don't affected by the dynamic changes in the pipeline, so the output of the controller refer to the flow rate at leak free case.

Here the set point from 0 to 100% considered as an input for ANN and flow rate as a target for ANN, with a good training the observer is ready to use with high efficiency and low cost because of the reduction in the number of the sensors. The estimated $(\overline{f_I})$ and $(\overline{f_O})$ will be more accurate at steady state . The set point based LDS is fastest than LDS with RTTM because there is no PDE need to solve numerically.

VI. FLOW LEAKAGE CLASSIFIER

The leakage classifier is a software module that runs on the LDS monitoring computer common is used to determine whether or not a leak occurred. It also calculates leakage rate, determines the location of the leak and gives suitable delay time when set point changed. The estimated values obtained by observer are compared with the measured actual values the results called the residuals

$$X = fi - \overline{fI} \qquad (4)$$

$$Y = fo - \overline{fo} \qquad (5)$$

In the leak-free case (X and Y)≈0 , if leak occurs deviation will occurs from which both the leak position XL and leakage rate (speed, volume flow or mass flow) F_{leak} can be derived [7]

$$F_{leak} = X - Y \qquad (6)$$

$$XL = \frac{-Y}{X-Y} L \qquad (7)$$

Where: L is the length of the pipeline.

VII. APPLICATION DYNAMIC MASS BALANCE

This method has been realized and applied by using MATLAB Simulink simulation, the constructed system consist of pipeline with length 101.05 Km with central fugal pump, ideal flow rate sensors at the inlet and outlet respectively. The simulated system has been tested by creating different leak distances and flow rates of the leak as shown in table I. The result shows that F_{leak} has been determined accurately and X_L determined with average error 0.637% of total distance.

Table I

Leak location /Km	Estimated leak location	Error percent in leak location	Flow rate of leak	Estimated flow rate of leak	flow rate of leak of total flow
63.5	64.11	0.6%	88.25	88.25	1.4%
50.5	51.11	0.6%	45.8	45.8	0.733%
70.5	71.22	0.712%	217.6%	217.6%	3.48%

Also this method applied on real pipeline in North Refineries Company in Baiji /Iraq on water stainless steel pipeline, with length $L = 490\ m\ and\ D = 8\ inch$. The result shows that flow rate of the leak determined accurately, it's about 1.5% of total flow rate, the error of leak location about 2% of total pipe length, as shown in table II

Table II

Pipeline length /m	Leak location /m	Estimated leak location	Error percent in leak location	Estimated flow rate of leak/ m^3/h	flow rate of leak of total flow
490	293	283.2	-2%	1.005	1.5%

VII. PRESSURE GRADIANT INTERSECTION METHOD

For a simple horizontal pipeline Pressure drops linearly if friction factor f and pipe diameter D are constant along the pipeline and in absence of a leak. If a leak occurs at leak location x_{leak}, upstream pressure drop will increased and downstream pressure drop will decreased as shown in fig (2-a). Practically the pressure drop can be determined by using double sensor s_1 and s_2 with known distance between them l_{12} at upstream and another pair s_3 ,$s_4$with distance l_{34} at downstream as shown in fig (2-b)

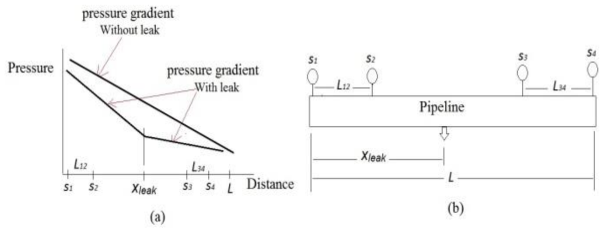

Fig 2.a. pressure drop before and after leak occurrence
b. distribution sensors on pipeline

as a mathematical relation for the realization of partial derivative can be written as:

$$-\frac{\partial p}{\partial x}\Big|_{inlet} = \frac{s_1-s_2}{l_{12}} \qquad (8)$$

$$-\frac{\partial p}{\partial x}\Big|_{outlet} = \frac{s_3-s_4}{l_{34}} \qquad (9)$$

In case of leak – free case (without leak),

$$\frac{\partial p}{\partial x}\Big|_{inlet} = \frac{\partial p}{\partial x}\Big|_{outlet}$$

while if leak occurs thy will differ and we can say.

$\frac{s_1-s_2}{l_{12}} = \frac{s_1-p_l}{x_l}$ and $\frac{s_3-s_4}{l_{34}} = \frac{p_l-s_4}{L-x_l}$ so equations (8) and (9) can be written as:

$$-\frac{\partial p}{\partial x}\Big|_{inlet} = \frac{s_1-p_l}{x_l} \qquad (10)$$

$$-\frac{\partial p}{\partial x}\Big|_{outlet} = \frac{p_l-s_4}{L-x_l} \qquad (11)$$

By using the numerical solution with sampling for leak location XL and pressure at leak, equations (10) and (11) can be written as:

$$-\frac{\partial p}{\partial x}\Big|_{inlet} - \sum_{i=p_o}^{i=i+0.01} \sum_{j=L}^{j=j-0.01} \frac{s_1-p_{li}}{x_{lj}} = a \qquad (12)$$

$$-\frac{\partial p}{\partial x}\Big|_{outlet} - \sum_{i=p_o}^{i=i+0.01} \sum_{j=L}^{j=j-0.01} \frac{p_{li}-s_4}{L-x_{lj}} = b \qquad (13)$$

$(i_{max} < p_i\ and\ i_{min} > p_o)$

$(\ j_{max} < l\ and\ j_{min} > 0\ )in\ ideal\ case\ (a = b = 0)$

When applying this technique in MATLAB Simulink many results of leak locations appears that satisfy these equations, and a lot of these results where didn't represent the actual location. The invention in this paper is an elimination of incorrect results by limiting the range which a and b lie on it, this technique gives very accurate leak location estimation with accurate estimation of pressure at leak point.

VIII. PRESSURE PIPELINE OBSERVER

This observer estimates the range of comparing the measured pressure drops at Inlet and outlet respectively with computed pressure drops (range which include a and b), this observer designed by using ANN where the input of ANN is a set point of flow controller Sp same as in flow pipeline observer the target of ANN is comparing range $[R_1,R_2]$ where $o \leq R_1 < R_2 \leq 1$. By applying the results from this observer in leakage classifier the estimated leak location was very accurate, in addition the accurate estimation of pressure at leak point p_l that is very useful in maintenance process, this manner not used before.

IX. PRESSURE DROP LEAKAGE CLASSIFIER

The pressure drop leakage classifier is a software that determined the leak accident occurs or not, and if occurs it estimates the location of the leak and pressure at leak point p_l , by comparing the pressure drop at inlet with pressure drop at outlet if the difference between them passes the predefined threshold value (th) that is refer to leak accident occurrence.

$$\frac{\partial p}{\partial x}\Big|_{inlet} - \frac{\partial p}{\partial x}\Big|_{outlet} = x\ , \begin{cases} x < th & \Rightarrow No\ leak \\ x > th & \Rightarrow\ leak \end{cases} \qquad (14)$$

The another significant task of this classifier it gives suitable delay time at starting or at any desired operation changes, this delay benefit in reducing the false alarm.

X. APPLICATION OF PRESSURE GRADIENTINTERSECTION METHOD

This method has been realized and applied by using MATLAB Simulink simulation, the constructed system consists of pipeline with length 13.7 Km with central fugal pump, ideal pressure sensors at the inlet and outlet respectively. The simulated system has been tested by creating different leak distances and flow rates of the leak (about 40 tests) some of these tests shown in table (3). The result shows X_L determined with average error 0.465% of total distance.

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Table III

Sp %	Actual leak location /km	Estimated leak location / km	Error percent of leak location	Actual pressure at leak point/kpa	Estimated pressure at leak point /kpa	Error percent of pressure at leak point
40	4	4.07	0.51%	10.3	10.29	0.10%
60	4	4.09	0.65%	23.64	23.56	0.33%
80	6	6.03	-0.51%	37.34	37.61	0.72%

This method applied on real pipeline in North Refineries Company in Baiji /Iraq on water stainless steel pipeline, with length $L = 490\ m\ and\ D = 8\ inch$ .The result shown in table IV.

Table IV

Pipeline length /m	Leak location /m	Estimated leak location	Error percent in leak location
2375	913	930	0.71%

XI. COMBINED SYSTEM

This system include the dynamic mass balance method and pressure gradient intersection method to gather to get powerful LDS system with lowest false alarm level, every system can work as a redundant to another with increasing the reliability and authority of the system.

XII. LEAKAGECLASSIFIEROFCOMBINED SYSTEM

This leakage classifier is a software program estimates the leak accident by checking the output oftwo utilized system states, if one of them gives leak alarm and the another not that is mean either false alarm or another system fail, so if this false alarm will eliminating by this software else the classifier will gives failing system alarm, but if the two systems gives leak alarm the classifier will take the estimated distance of every leakage classifier and then optimized the accurately leak location with estimating flow rate of the leak and pressure at leak point.

XIII. PREVENTIONFALSEALARMS

The false alarm usually occurs at transient time in case of a sudden changes in operation state (change set point or operation requirement like opening circulating valve) all this changes can be measured then sending their signal to LDS computer and take it in account to eliminate the false alarm by using either statistical methods or by given a delay time equal or greater than transient of the effective change then operate leak classifier again .

XIV. SCADA/COMMUNICATIONS

The Supervisory Control and Data Acquisition (SCADA) system is a computer-based communications system that monitors, processes, transmits, and displays pipeline data for the controller.[5]

The utilized SCADA system is an internet based, that is benefit because of the internet available everywhere and cost effective, the SCADA system receives data from remote terminal units RTU which usually programmable logic controller PLCs, while in this system the RTUs designed by using microcontroller, that is very cost effective and powerful. Fig(3) shows block diagram of a combined system.

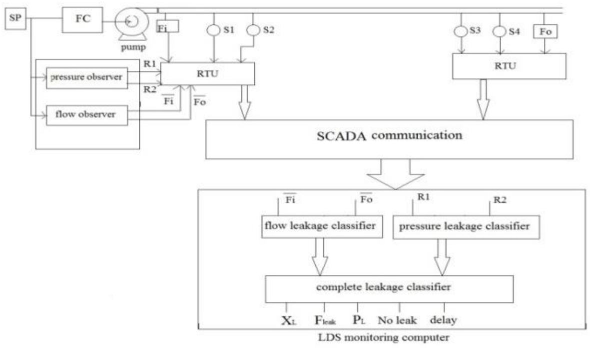

Fig. 3 combined system

XV. CONCLUSION

In the dynamic mass balance the ANN observer has been implemented to detect the leak location along the Iraqi pipeline with acceptable percentage error. The major property of ANN is that it does not need numerical solution of PDEs.

In the pressure gradient intersection method the benefit ANN observer to introduce the comparing range [R1,R2] between the computed pressure gradient and measured pressure gradient to eliminate the incorrect results.

The SCADA system has been constructed utilizing the availability of internet wireless communication. The benefit of SCADA system is to monitor the state of the pipeline. The combined system LDS suitable only for pumping systems that are controlled by open loop control system as in Iraqi pipelines, and the transported fluids should be single phase.

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