Model Based Leak Detection in Pipe Networks Using Optimization Techniques

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Abstract: In the proposed work algorithms have been developed to minimise the placement of number of sensors to detect leaks in the looped pipe network using pressure sensitivity analysis. The proposed work starts with assumptions that leakages are constant demand that is assumed at junction and every node has a sensor. The algorithm of sensor placement uses the pressure sensitivity matrix which is the differences between the pressures calculated without leak and with leak values at nodes by EPANET simulation. The simulated pressure variations caused by all potential leaks are stored in the Fault Signature Matrix (FSM), with as many rows as sensors, ns, and as many columns as potential leaks, nl. Each value of the FSM matrix is binarized according to a threshold: '1' indicates that the sensor in row i truly detects a leak in column j ('0' indicates no detection).The minimum number of sensor is obtained using binarised matrix in such a way that every leak present in the network should be detected and isolated. The Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) techniques are used to find the minimal sensor placement for identification of leaks in pipe networks, further the comparison between the two techniques has made. The implementation of present algorithms shows the placements of sensors are minimized up to 15-20 % of total number sensor placed at nodes. The problem identifies the best location of minimum number sensors in the pipe network**.**

Keywords**—** Pressure sensitivity analysis; Isolability; Detectability; EPANET; GA; PSO.

I. Introduction

Leaks generate significant interest on water pipe distribution network. Such type of problem holds significant meaning to the society, struggling to supply the water supply of increasing demands. Thus managing this type of problem becomes an important aspect for managers of water supply networks [1, 2]. Acoustic listening and Ground penetrating radar device are the physical inspection of the leak in pipeline [3, 4]. These techniques require shutting down and isolating the effected part or whole system. The complete process may take few days to months with plenty of significant water wastage. The inspection of leaks has done on the observation on routine basis. When the fluctuation in demand is increased at night to day consumption abnormally or major losses are suspected, leak detection techniques are applied.

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Recent years have seen major advances in transient-based methodology; [5,6] presented a review that summarizes and compares the past and current contribution of transient based method. Alternatively, Leak detection and isolation techniques have also been studied using stationary models starting from seminal paper of [7], which used the least-squares optimization method to solve the problem. On the other hand, non-explicit non linear model have been observed when representing WDN as static, and causing problems in estimating related parameters.

Model-based leak detection and isolation techniques have started with the influential research work of Pudar & Ligget [8] and expresses as problem of least-squares estimation. The estimation of parameter of water distribution network model is difficult task [9]. Non-liner equation caused the difficulties in water distribution network system and for estimating the parameters very few measurement are available which causes the undetermined problem. Pérez et al. [10], developed a model-based method for detecting and localizing the leaks. This method used the pressure residuals) analysis and compared with a given threshold. Threshold has been used in keeping the model's uncertainty and noise. The comparison of the residual against the threshold shows the possible leak present at nodes. Due to demand uncertainty at node and noise in measurement, the performance of this approach decreases, while in ideal condition it shows good efficiency.

The application of GA (Genetic Algorithm) has been applied to the sensor placement problem using MATLAB's GA toolbox [11], where absence and presence of sensor at give node is depend on each chromosome. Sensor placement is based on the creation of binary genomes, which are required to allow population vectors to change between compatible presences ("one") or the absence ("zero") of sensors located in the corresponding node. GA established the parameters through experience of several trial and error tests and the most common configuration is taken into account. GA is permitted to use the crossover scattered function to create crossover children. A Gaussian function is selected to produce the mutation. The selection function is set as a stochastic uniform function.

On the other hand, PSO (Particle swarm optimization) has no mutation and crossover evolution operators like GA. In PSO, possible solutions, called particles, fly through the problem space by following the current optimal particles. In recent years, PSO-based methods have been applied to a wide variety of problems, leading to high efficiency [12, 13]. In present work PSO application depends on MATLAB tool box developed by [14] and introduce into the MathWorks, where presence and absence of sensor at a given node is determine through a particle.

This work proposed a model based strategy to detect and localise the leak. The aim of this research isto obtains the minimal pressure sensor placement in pipe network for detection and localization of leak. The method used the pressure variation at node which is produce due to uncertain change in demand [8]. The detection of leak is obtained by comparing pressure data of a network without leak and with a leak at time at all nodes of the network. The difference between measured and estimated pressure called residual which are evaluated to get signature matrix. The simulation model on EPANET is used to generate pressure data with a leak at time and without leak at all node. The present work proposed the analysis of threshold, independent of nodal pressure. The analysis of threshold in such a way that comparison of threshold to the sensitivity matrix give the same leak signature at each time and count the sensor available at the same time. The GA and PSO techniques are used to find the minimal sensor placement for identification of leaks in pipe networks, further the comparison between the two techniques has made. Different algorithms are developed and integrated to detect and localise the leak as well as sensor placement in this work.

II. Materials and Methodology/Study Area and Methods

A water supply network consists of pumps, tank/reservoir, and pipes. Pipe network may contain different component like flow control device, pressure regulating valve. The only aim of water supply system is to supply and satisfy consumers demand.

Two basic governing equation for steady state conditions are mass balance equation and energy equation. The inflows and outflows through the system are equal according to the law of conservation of mass.

$$\sum Q_{in} - \sum Q_{out} = Q_{dmd} \tag{1}$$

Where Q_{in} and Q_{out} are the inflow and outflow at junction and Q_{dem} is the junction demands. Law of energy conservation states that difference between two end points of pipe is equal to difference of addition of energy and frictional losses.

$$\sum_{i \in J_p} H_{P,j} - \sum_{i \in I_p} H_{L,i} = \Delta E \tag{2}$$

Where $h_{P,j}$ head increased by pump j, $h_{L,I}$ is the head loss across, $h_{P,j}$ pump head at j, and ΔE head loss in the path. The head loss for the path is represented as follows:

$$h_L = KQ^r \tag{3}$$

Where H_L is the head loss, Q^r is the pipe flow and K is pipe constant.

Water distribution system is modelled using EPANET software. Networks are simulated and pressures are calculated at each node with a leak at each node and without leak at node. In this paper leak assume at node. In such case leak can be seen as an additional demand at nodes and presented as 3% of total demand.

Methodology Of Leak Detection And Isolation

The present methodology is based on model based diagnosis that has already been used for the leak detection and localization [15, 16]. Two basic tasks are leak detection and leak isolation. Leak detection has check consistency of observed behaviour and isolation of faulty part has done by fault isolation. The check of consistency has done by evaluating the residual r(t) and obtained through measured input i(t) and output o(t) signals (pressure) using installed sensors.

$$r(t) = \Psi(i(t), o(t)) \tag{4}$$

Where Ψ residual generator function depended on of type detection technique [17] and "t" is the time instance. At each time "t" instant residual are compared with statically obtained threshold value taking noise and uncertainty in consideration. When the value of the residual is higher than the threshold then the fault is in the system otherwise system assume working fine.

In this paper, leak detection has been done by a passive method using threshold value. Residual evaluation provide observed fault signatures

Φ (t) = [Φ_1 (t), Φ_2 (t)…….. Φ_n (t)] where each elements are given as follows:

$$\Phi_i(t) = \begin{Bmatrix} 0 & if \ |r_i(t)| \le \tau_i(t) \\ 1 & if \ |r_i(t)| \ge \tau_i(t) \end{Bmatrix} \quad (5)$$

Where τ_i is threshold associated to the residual $r_i(t)$.

Leak sensitivity analysis

Use The effect of leak on pressure at node is evaluated in this section. If the process is repeated to each node with leak and compared without leak at is each time of a leak imposed in the node, the sensitivity matrix (8) is obtained as follows:

$$S = \begin{pmatrix} \frac{\partial p_1}{\partial f_1} \cdots & \frac{\partial p_1}{\partial f_n} \\ \vdots \cdots & \vdots \\ \frac{\partial p_n}{\partial f_1} \cdots & \frac{\partial p_n}{\partial f_n} \end{pmatrix} \quad (6)$$

Where s_{ij} measured the effect of leak f_j on pressure at junction p_i. Sensitivity matrix S cannot easily calculated by analytically because the water pipe network is a complex problem and have non-liner and non-explicit equation. The proposed work generates the sensitivity matrix by introducing the same leak in each node and measure the increment in the pressure. It implies n (number of node in network) number of node simulation for n number of pressure at node. Some of the sensor show more sensitivity for any of the leak present in network. Thus normalization of sensitivity matrix has done for the comparable information about the junction. The normalized sensitivity matrix is obtained by dividing the each element of each row of the sensitivity matrix to the corresponding maximum value of that row. This generate the normalize sensitivity matrix:

$$\bar{S} = \begin{pmatrix} \frac{s_{11}}{\sigma_1} \cdots \frac{s_{1n}}{\sigma_1} \\ \vdots \cdots \quad \vdots \\ \frac{s_{n1}}{\sigma_n} \cdots \frac{s_{nn}}{\sigma_n} \end{pmatrix} \quad (7)$$

Where σ_i =max (s_{i1}…….,s_{in}). It shows how a leak is most relevant to itself and maximum normalized sensitivity shown in diagonal. The column of this matrix corresponds to nodes with leak and row corresponds to nodes with sensors.

Algorithm for binarised sensitivity matrix

for each node i

calculate the simulated pressure without leak P_{wtl}

For each leak j

calculate the simulated pressure with same leak at each node for a leak P_{wl}

calculate the residual at each node of network for a leak at all node

$s_{ij}=P_{wtl}-P_{wl}$

end

end

for each row of matrix (sensor)

find the maximum value of this row (σ_i)

Calculate $\bar{s}_{ij} = \frac{s_{ij}}{\sigma_i}$

if $\bar{s}_{ij} < s_{th}$

$\bar{s}_{ij}{}^{b} = 0$

else

$\bar{s}_{ij}{}^{b} = 1$

end

end

end

The normalized sensitivity matrix used to formulate fault signature matrix (FSM). The element of the FSM equal to zero there is no fault or fault affected the pressure at node i and equal to 1 when fault effected pressure at node i.

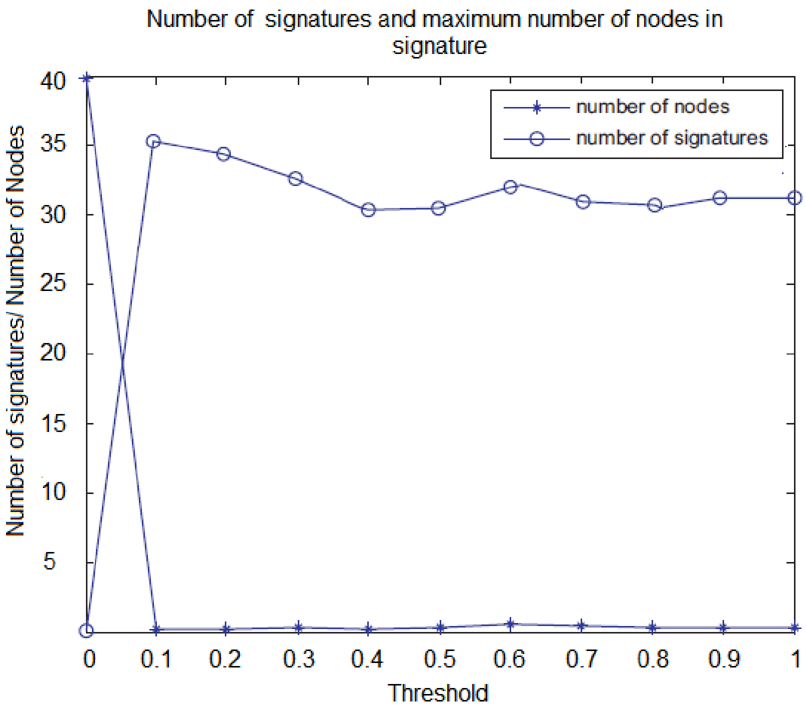

Figure 1 Evolution of the signature matrix depending on threshold

Sensor Placement Algorithm

A minimal sensor placement strategy is the configuration of sensors that minimise the total economical cost and considering identifying all faults in the system at the same time. A pipe network system considered as a graph network, where each edge represent the pipe of the network and Vertices are represented junctions such as, sources, demands of the pipe network.

The algorithm start with the binarization of normalized sensitivity matrix as describe in section 4.Each row of binarised sensitivity matrix corresponds to a location sensor at a junction and each column corresponds leak at a junction. Thus, if an element of binarised sensitivity matrix comprises ''1'', it means that sensor is install at the corresponding row would able to detect the single leak associated to column of this element. For any particular distribution, a set of groups of indiscernible leaks appear, each group with n_i leaks. The aim of the minimal sensor placement algorithm is to minimise the sensors by minimising the set of leak having same signature. In the present work sensors are minimised with the consideration that every column should present at one non-zero element.

Input: s_{th} is the binarisation threshold
$\bar{S}_{i,j}$ is the normalized matrix
$\bar{S}^b_{i,j}$ *binarised matrix*
$\bar{S}^b{}'$, *binary matrix after row zero*
S_n*Numbar of signature*
S_{n1} *number of signature of* $\bar{S}^b{}'$
s_{th}*=0.1: 0.01: 0.90*
for each s_{th}
if $\bar{S}_{i,j} > s_{th}$
$\bar{S}^b_{i,j}=1$
If $\bar{S}_{i,j} < s_{th}$
$\bar{S}^b_{i,j}=0$
Compute the number of signature for each binary matrix and save in an array
foreach column of $\bar{S}^b_{i,j}$
decimal value(j)=bi2de($\bar{S}^b{}_j$*)*
if decimal value(j)=decimal value(j+1)
decimal value(j+1)=0
end
end
S_n*=non-zero of decimal value array*
For each $\bar{S}^b_{i,j}$
For each row
$\bar{S}^b{}'$, *=make row zero of* $\bar{S}^b_{i,j}$
$S_{n1} = S_n$ *of* $\bar{S}^b{}'$,
If S_n *of* $\bar{S}^b{}'$, $<$ S_n *of* $\bar{S}^b_{i,j}$
Do note make zero that row
If any column of $\bar{S}^b{}'$, *become zero decimal value*
Do not make zero that row
End
End
End
Obtain sensor= Compute the non-zero row
Minimum number of sensors=min (obtain sensor)
end

Pseudo code for sensor placement based on GA and PSO

Require: the number of sensors n, the number of nodes m, the $s \times m \times m$ three-dimensional matrix R of residuals for the s leak magnitudes modeled and the maximum number of iterations it.

Ensure: a near-optimal sensor configuration x_{min} with error index ϵ_{min}.

1: Initialize the search with the previous solution.

2: Set the appropriate restrictions.

3: Choose the seed size.

4: **for** The number of iterations selected **do**

5: Build the initial population matrix with rows randomly initialized.

6: **Inputs:** The initial solution, restrictions, residuals and sensitivities. **//Start GA- or PSO-based search.**

7: **while** An optimization criterion is not reached **do**

8: Get a possible configuration.

9: Evaluate the solution using Equation (16).

10: **end while**

11: Evaluate the found solutions and choose the one with the minimal value. //End GA- or PSO-based search.

12: **end** for

13: Find the best solution x_{min} with the minimal error index ϵ_{min} between all of the iterations and save it as the near-optimal sensor placement.

III. Result and Discussion

A number of pipe networks are simulated for optimal sensor placement. Models are simulated using EPANET software. Model_1 shown in figure 1 has 35 nodes and 68 pipes are simulated with a leak at each node and without leak at each node to calculate pressure discrepancies at each node. The total demand of model_1 is746 LPS. The leak impose on each node is 3-4%of total demand of the network. The simulated leak for model_1 is 10 LPS.

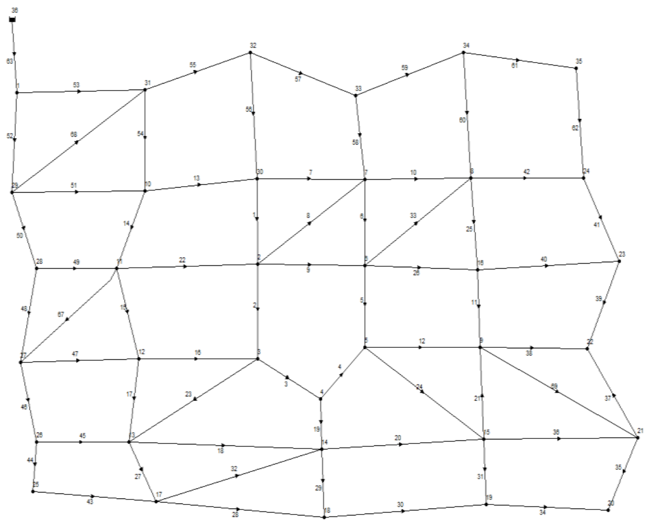

Figure 2 Pipe network of model_1

The differences between the pressure at each node with a leak and without leak at each node produce a pressure sensitivity matrix. The sensors are placed at each node to obtain the pressure fluctuation. Some leak shows more sensitivity to the pressure fluctuation. That is why the pressure sensitivity matrix is normalized row by row to the maximum value of the same row. Figure 3 shows the normalized sensitivity matrix of model_1.

The normalized sensitivity matrixes are binarised using different threshold (0.1:0.01:0.99) and saved. Each element of the binarised matrix is equal to '1' when the threshold is less or equal to the element otherwise its value will be zero. Element'1' of binary matrix shows the effect of leak at the respective nodes. Element of binary matrix '0' shows that there is no effect of leak at the respective position nodes."

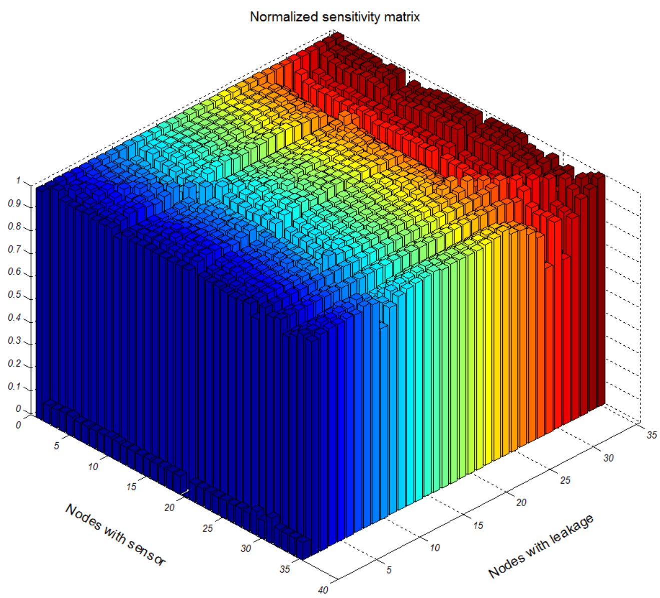

Figure 3 Normalized sensitivity matrix for Model_1

Each element of normalized sensitivity matrix compared with these thresholds. Elements of the binarised sensitivity matrix is equal to '1' when the threshold is less or equal to the element and it is equal to 0 when the threshold is greater than the threshold. The vertical axis shows the node with sensors and the horizontal axis shows the nodes with leaks. Every column in the binarised matrix shows leak with node and its leak signature at respective node. When the threshold is shorter 1 appears more, but when the threshold increases, then 0 more appeared. Leak signature is count after binarization of matrix of each leak. Leak signatures is the different combination of 0 and 1in each column for each node with leak. If two or more columns show the same kind of combinations, then they count the same leak signature.

The minimisation of sensors at nodes is based on the row deletion. The deletion of row is depends on the number of signature of leaks. Row deletion start with first row with the assumption, that the number of the signature of leaks after deletion are same and every column has at least 1 non-zero value. While deleting the rows, keep in mind that the number of leak signatures remains the same as before deleting the rows. While deleting the row, every column should at least one non-zero value. It is also required that the detectability and isolibility are checked at the same time.

Table-1 shows the how many sensors are required and sufficient for detecting all the leaks at different thresholds. Sensors required to detect the leaks are 3, 5, 5, 16 and 27 at different 0.5, 0.75, 0.84, 0.96 and 0.99 thresholds respectively. It has been observed that at threshold 0.5 only 3 sensors are required for detecting all the faults in the network.

Table -1 Sensors required detecting the leaks

Threshold	Number of sensors	Detection
0.5	3	All
0.75	5	All
0.84	5	All
0.9	16	All
0.99	27	All

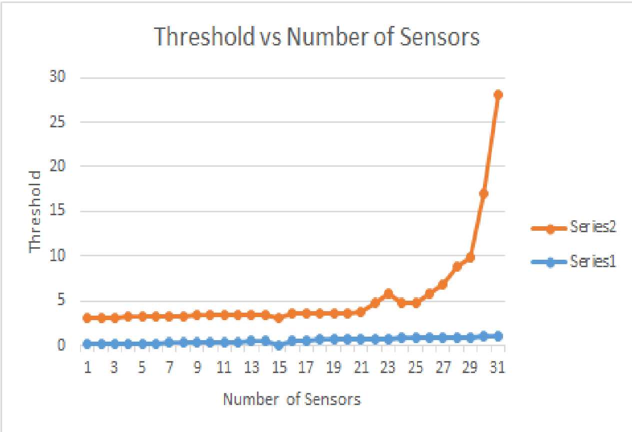

Figure 4 Threshold vs Number of Sensors

Figure 4 shows that, as threshold increase the number of sensors are also increases. An example of same network is tested with six leaks at different position of the node of the network. The positions of leaks are assumed at node numbers 1, 4, 9, 17, 28 and 33 in the network. The whole procedure repeated for the 6 leaks positions in the network. The test results show that only '2' sensors are required to detect the leaks at threshold 0.5 It shows different location of leak and can detect only by two sensors.

Application of GA and PSO Approaches

Prior to the application of the GA and PSO techniques, an analysis has been performed to determine the best parameter selection. The number of generation and seed matrix size are chosen in this analysis. The number of rows is defined by seed size which is used at initial search in algorithm in initialization matrix. First, a seed size is selected to run the test to select the appropriate number of generations. Then, the tests are repeated changing the size of the seed and taking into account the number of generations according to the previous result. Once the appropriate seed size and several generations have been selected, multiple executions of the optimization process with various seed initializations are performed to improve the search capability.

For example, placement of two sensors in current network running with ten iteration and five generation gives in each of them gives placement with 113 overlaps, while with one iteration and 25 generation gives best result of placement with 113 overlaps. In the current network, after testing the parameters are selected as follows: For the GA, the seed matrix has filled with random solution by setting 35 rows with 3 generations. To increase the efficiency only 3 iterations were allowed for GA. For the PSO, ten generations is allowed for 17 row seed matrix. In order to increase the efficiency of algorithm it runs 17 times.

Table 2 shows the number of sensor placement at different nodes.

Sensors	Node index		Overlap		Efficiency	
2	2, 34	2, 34	5	5	92.1	93.1
3	2, 34, 12	2, 16, 34	1	2	97.4	97.5
4	1, 34,12,21	1, 14 ,21, 34	0	0	100.0	100.0

IV. Conclusion

A minimal sensor placement method based on the pressure sensitivity analysis of nodes in a looped pipe network has been implemented. The minimal sensor placement methodology is developed using model based diagnosis.

In order to obtain maximum isolability with the reasonable number of sensors, a minimal number of sensor placement strategies have been proposed. The objective was to minimise the number of node with sensors, detecting the same leak with each sensor. The information about leakage has been obtained by pressure sensitivity matrix. The simulation of pipe network with leak at each node and without leak at node provides the pressure sensitivity matrix. The proposed work has been done to simulate leak value on each node. The pressure sensitivity matrix has been normalized row by row with maximum value of the respective row. The normalized matrix has been binarised using different threshold. The row of each binarised matrix has been deleted keeping leak signature constant. In this way minimal number of sensors has been obtained by calculating the remaining row in the binarised matrix. Leaks have been detected successfully by minimal number of sensors depending on the thresholds.

It should be noted that from the result PSO work more rapidaly than GA for less sensor installed but as the sensor installed more that is more combinations are possible GA f works better than PSO. From additional experiments not reported in the table, we have seen that PSO is implicated in a local suboptimal, even by increasing the number of iterations. It already reported in the literature [18]. It can be explained by the fact that PSO has the memory of past successes and prefers to search around the established configurations, whereas crossover operations like those in GA are usually favored when it is necessary to switch from one area to another remote region.

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