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Optimal Water Distribution Network Design Accounting for Valve Closure

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Abstract

Flow regulation is always carried out by means of flow controlling devices like valves, flow meters etc.Valve closure is carried out in a pipe network for planned or unplanned operating conditions (e. g. pipe failure) in order to isolate a part of the network. It creates unusual working conditions in the network due to topological modifications. Analysis of distribution system for isolation by means of valve closureshould always be performed as a part of the assessment of system reliability. Thus, a challenge for network designers is to optimize pipe diameters versus system management under these abnormal working conditions. The present study accounts for the mechanical reliability with respect to pipe failures due to valve shutdown, and deliver a strategy for the optimal design. The network modification considering valve shutdown is aimed at changing the hydraulic capacity of the connected network by modifying the pressure at the critical nodes. Two types of analysis namely, Demand driven and Pressure driven analysis were performed in this study. A real network in Thrissur district is selected to test the developed strategy for the optimization.Optimization results provide us with four sets of diameter values, which are to be adopted to avoid a condition of pressure deficiency for any type of isolation.

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*Keywords:*Water Distribution Networks (WDN); Optimal Design; Isolation Valve System (IVS)

1. Introduction

Among the various natural resources available on earth, water is one of the most important natural resource. It is an essential commodity for human life and indeed for all life on earth. Hence, every human has an important role in

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water-caring. Public water services provide more than 90 per cent of water supply in the world. A well maintained conveyance system is a critical component of a safe drinking water supply system and it plays an important role in the distribution of potable water to the consumers. In this condition, the design and analysis of a water distribution network gains prime importance.

Optimal water distribution network design is a classical issue. [1] and [2] first introduced the idea of solving pipe sizing optimization problem using genetic algorithms (GA). Several other studies done in this area also concluded that GA can be used as an efficient tool for the reliability based optimization of water distribution networks [3].

For isolating subsystems in water distribution systems, valves play a major role in the system reliability and security by providing a shutoff function.For knowingthe system reliability, isolation valve system should always be analysed first.

The word reliability refers to the ability of the distribution system to provideadequate services for the customers undervarious abnormal operating conditions [3]. It is usually studied according to two general classes of failure events: mechanical and hydraulic failures [4]. Mechanical failures includes system components failures, such as pipe breaks and pumps out of service, whereas the hydraulic failures includes variability of demands and/or pipe hydraulic resistances etc.

For the optimal design of WDNs considering the mechanical reliability, various reliability measures (like network resilience, WDN nodal capacity reliability) andstrategies were developed [5,4]. Similarly, several strategies were formulatedin the design procedure to account for the hydraulic reliability [6,7].

For computing the approximate values of the capacity reliability of WDNs, the first-order reliability method (FORM) based algorithm was first introducedin [3]. [6] presented a methodology for the least cost design of water distribution networks under uncertain water demands. It related the uncertainty in the nodal head with the system performance. Similar study made in this area used FORM for an adaptive surface response method for performing the reliability analysis of WDNs [7].

For the design of a water distribution network, a multi-objective genetic algorithm model was used in[5]. The objectives considered are, the minimization of the network cost and the maximization of network resilience. A multi-objective strategy was used to achieve optimal design and operational solutions [4]. This study considers a deterministic modelling of multi-objective optimization problem to account the network reliability.

Distribution network should be divided into various subsystems in order to repair broken components such as pipes or to perform maintenance works. There may be situations where one pipe or segments of pipes need to be removed from the rest of the network for some hydraulic needs. So, in order to separate a portion of a network from the rest, isolation valves must be included in the network. Many studies have been conducted, for the development of methodologies for the optimal design of water distribution systems. Valve closure is carried out in a pipe network for planned or unplanned operating conditions (e.g. pipe failure) in order to isolate a part of the network. The use of isolating valves causes the disconnection of distribution system into various segments consisting of isolated pipes and nodes. Methods to analyse the isolation valve system (IVS) and the generated network configurations have been proposed in[8].

So far, no optimization studies have been taken place considering the actual modification of the network layout resulting from the isolation of network segments [9]. Therefore, the present study accounts for the mechanical reliability with respect to pipe failures due to valve shutdown, and deliver a strategy for the optimal design. The network modification considering valve shutdown is carried out by changing the hydraulic capacity of the connected network by modifying the pressure at the critical nodes.

Two types of analysis namely, ‘Demand Driven’ and ‘Pressure Driven’ analysis (DDA and PDA) were performed in this study. In demand driven analysis, the demands are fixed in the model as a basic assumption. The assumption on demand which is independent of pressure, simplifies its algorithm and computation. In pressure driven analysis, the demands are not fixed a priori but they are dependent on pressures in the network. This analysis takes into account the relationship between pressure and demand.

As a case study, a large sized network (Kunnamkulam Water Supply Scheme in Thrissur district composed of 204 pipes and 167 nodes) is taken to carry out the optimization.

2. Optimal Design Accounting for Valve Shutdowns

Optimal pipe sizing of water distribution systems considering the objective of minimal network cost is a classical issue. Many works have addressed the subject to develop efficient and reliable optimization strategies. Others focussed on the issue of hydraulic system reliability. In both cases the optimization was performed using classical demand-driven modelling, because the maximum demands required in the model are fixed a priori as a planning assumption. Consequently, several measures of system reliability were developed based on DDA. Also, the network topology was assumed as fixed despite the presence of isolation valves, whose shutdown during planned or unplanned works can significantly modify the network topology and the hydraulic behaviour of the system.

WDNetXL implements the classical optimal pipe sizing by using a multi-objective strategy of minimization of network cost and pressure deficit with respect to a normal working condition. Both classical DDA and pressure-driven analysis (PDA) are allowed.

Also, WDNetXL implements the optimal pipe sizing accounting for system reliability with respect to network topological changes due to valve shutdowns (mechanical reliability). For which, the isolation valve system (IVS) of the network is considered. This means that the optimization strategy accounts the isolation valve shutdowns in order to disconnect a portion of the hydraulic system. In fact, an emerging management issue is to improve the system reliability of existing hydraulic systems with respect to abnormal working conditions.

After valve shutdowns, since pressure-deficient conditions occurs in the regions of network that are still connected to the source of network as a result of reduction in pressure below the required pressure, Pressure-driven analysis (PDA) of the distribution system should be given more importance. The assumption of fixed demands in the optimization model is not consistent with the occurrence of a pressure-deficient condition in some nodes. Since the model fails to predict the actual demand depending on actual pressures,the demands required by the customers are not satisfied in these nodes.

Also, in DDA it is assumed that leakages are a fixed percentage of the customer-based demands. This is a rough assumption for nodes because the percentage varies node by node depending on the pressure.In PDA, the demands are dependent on the pressure in the network which is closer to the actual situation. Hence the simulation of the hydraulic system using PDA and pressure-dependent leakages has more practical importance.

The optimization problem includes both the hydraulic system modelling strategies i.e., DDA and PDA. It is solved using a MOGA strategy named the Optimized Multi-objective Genetic Algorithm (OPTIMOGA) [10].

3. Software used: WDNetXL

The various functions under the Analysis and Design functions of the software WDNetXL are shown in the Fig. 1. In this study, “Pipe Sizing” function under the design part is used and for verifying the results of each isolation “Pipe Failure” function under the analysis part is used.

Fig.1. Functions of WDNetXL

4. Case Study: Kunnamkulam Water Supply Scheme

In order to check the mechanical reliability for isolation valve system, the Kunnamkulam water supply scheme in Thrissur district is selected which is composed of 204 pipes and 167 nodes.The Kunnamkulam network layout drawn in EPANET (which is exported in .inp format) can be directly imported to WDNetXL by its in-built options.

The Kunnamkulam network was designed by considering mechanical reliability assuming two isolation valve systems as follows:

- Two valves for each pipe located close to its terminal node, named N-valve rule (or single pipe isolation). Thus, the system is composed of 406 valves determining 203 pipe segments (as 203is the total numbers of pipes in the network).
- An isolation valve system, named as Parsimonious (or segment isolation), composed of 34 isolation valves whose shutdown generates 20 segments (segment isolation) as in Fig. 2.

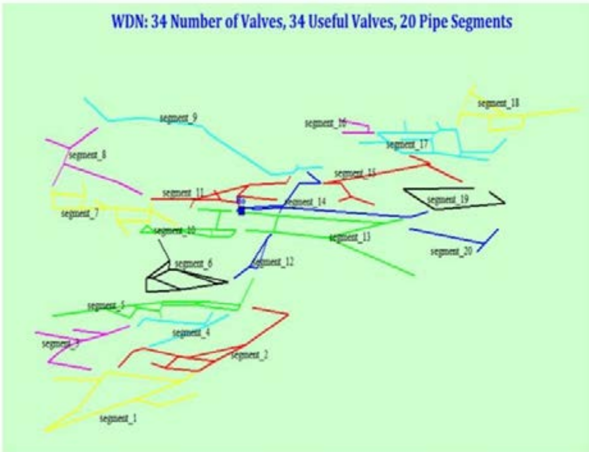

Fig.2. Segments generated by valve shutdowns by Parsimonious system

Kunnamkulam network is composed of 204 pipes, 167 nodes and an overhead tank as the source of water. The parameters used for the leakage modelare $\alpha = 1.2$ and $\beta = 2.07 \times 10^{-8}$(corresponding to an averageleakage level of approximately 25% with respect to nodal demand).The pressure-demand relationship was satisfied by settingthe minimum pressure for any service and for a correct service as equal to 0 and 10 m for the entire network.

All the tests were performed using WDNetXL. OPTIMOGA, was run 5000 generations for all the four optimal reliable runs.

Excel files are generated as outputs for each run. Four optimal designs considering for system reliability were performed using the two isolation valve systems (N-rule/ single pipe isolation and parsimonious/ segment isolation) and Demand driven analysis or Pressure driven analysis. After the optimization run, a number of solutions are available (satisfying the initial condition of a maximum $P_{deficit}$ = 2m). The solution corresponding to a null pressure deficit is selected. The values of pipe diameters which we adopted, based on null pressure deficit solution are displayed in column J of the excel file.

Thus, for four optimal runs (N-rule & DDA, N-rule & PDA, Parsimonious & DDA, Parsimonious & PDA), four sets of diameter values are obtained corresponding to a null pressure deficit. These values of diameters are to be adopted inorder to avoid a condition of pressure deficiency for any type of isolation.

5. Comparison of Diameters

Comparison of diameters of the Kunnamkulam network with the actual diameters has been carried out. It is found that, there is a considerable increase in diameters of the network for some pipes. Thus by increasing the pipe diameters, the condition of pressure deficiency can be avoided for any type of isolation (N-valve rule/single pipe isolation and Parsimonious/segment isolation).

The comparison of diameters is performed to verify the applicability of the increase in diameters of the pipes in the Kunnamkulam network. Hence the obtained optimized diameters of the Kunnamkulam network are compared with the available pipe sizes in market. It is found that, the obtained values of diameters are available in market. This proved the applicability of the results, in actual case.

6. Analysis of Pipe Network

Pipe network analysis is the analysis of the fluid flow through a hydraulic network. The final aim of pipe network analysis is to determine the flow rates and pressure in the individual sections of pipe network. The modern method of solution for this is to use specialized software in order to solve the problems automatically. In this study, for the validation purpose the software EPANET is used.

6.1 Validation of Pressure and Flow Rate in the Network

The diameters obtained from WDNetXL are validated by inputting those values in EPANET to carry out the analysis. It is found that, the pressure developed at the nodes and the flow rates in the pipes are greater than the minimal values (i.e, values obtained by inputting the actual pipe diameters).

6.2 Verification of Pressure in Segments Isolated by "Actual Isolation Valve System" (IVS)

In the present case study, for getting the solution set which corresponds to the number of isolation valves and network segments, the "Valve System" function under the design head in WDNetXL is to be performed first. The results of this design, generated an excel sheet comprising 50 sets of solution. For each solution set, corresponding values are to be entered in the column segment ID (pipes), 16th and 17th column of the Table of Pipes and in the excel sheet named 'Valve Policy' in WDNetXL. After doing the analysis for each solution set, the optimum number of isolation valves and network segments are obtained. So, the Kunnamkulam network is designed for this solution set, composed of 34 isolation valves whose shutdown generates 20 segments of the network as shown in Fig. 2.

The Kunnamkulam network was designed by considering mechanical reliability assuming the isolation valve system (IVS) for the above solution set. It is necessary to check the pressure at any node should not go below the required minimum pressure for any of the 20 isolated segments.

For that, one has to isolate one segment at a time and check the values of pressure at all the nodes in the regions that are still connected. This check can be done in the "PIPE FAILURE" function present in the Analysis part of WDNetXL. An example of segment isolation is shown below taking Segment 1.

The pipe in red colour indicates the pipe in that segment which has failed. The pipe in blue colour indicates the pipes which have failed unintentionally because of the failure of red coloured pipe. The output figure showing the pressure values at the still connected nodes using a colour code is shown in Fig. 3.

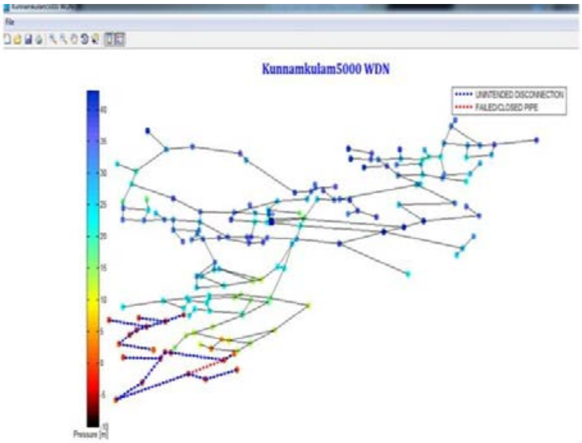

Fig.3. Segment 1 Isolation

Fig. 4.shows a graphical representation of segment_1 isolation. From the graph which connects node number and Nodal Pressure-Head, it can be inferred that, the pressure values in the disconnected regions (from nodes 139 to 166) have a zero value and all other nodes have a pressure value greater than the minimum required (i.e., minimum pressure set for the model=10 m of water).

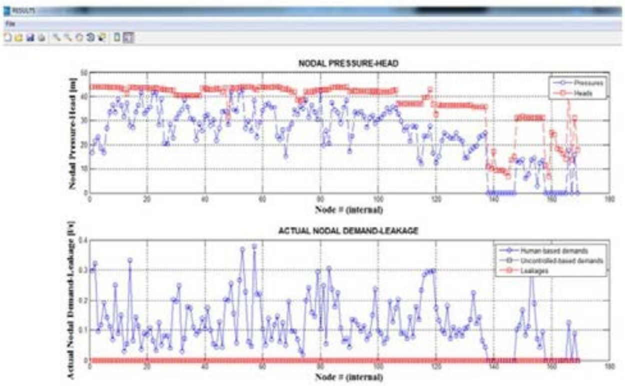

Fig.4. Graphical representation of Segment 1 Isolation

[Note: In Fig. 4. the output (node number and Nodal Pressure-Head, Nodal Demand Leakage versus node number) represented as a continuous line. But, in the actual case the figure represent discrete values corresponding to each node numbers.]

Similar results can be obtained for all the other 19 segments. From the result, it can be concluded that, even though each segment is isolated separately, all the other connected nodes have their pressure values greater than 0. This is because of the use of optimized diameter values in the pipes (for Demand Driven and Pressure Driven analysis).

Thus, the results of pipe size optimization using WDNetXL is validated and found that the use of this changed diameter will not create a condition of pressure deficiency for any type of isolation.

7. Conclusion

Optimization of Kunnamkulam network was done for two isolation valve systems (namely N-rule and Parsimonious) and also for DDA or PDA using the software WDNetXL. The optimization outputs clearly shows, that in some pipes the diameters need to be increased to avoid pressure deficit condition for any type of isolation.The results of pipe size optimization using WDNetXL is validated and found that the use of changed diameter will not create a condition of pressure deficiency for any type of isolation.

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