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Comparison between two Hydraulic Control Valves Systems for Leakage Minimization in Water Distribution Networks Using Multi-Objective Memetic Algorithm

المقارنة بين نظامين من محابس التحكم الهيدروليكية لتقليل تسرب شبكات توزيع المياه باستخدام الطريقة الخوارزمية الميماتيكية متعددة الأهداف

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KEYWORDS:
Water distribution networks, Multi-objectives memetic algorithms, Throttle control valves, Flow control valves, Leakage reduction.

الملخص العربي:- يهدف هذا البحث إلى تطبيق نظامين من محابس التحكم الهيدروليكية على شبكات توزيع المياه والمقارنة فيما بينهما بغرض تقليل تسرب المياه من تلك الشبكات. النظام الاول يشتمل علي المحابس الخانقة (TCVs) و النظام الثاني يحتوي على محابس التحكم في السريان (FCVs). خلال كل نظام من النظامين يتم تحديد العدد الأمثل للمحابس، أماكن تواجدها على مواسير الشبكة، بالإضافة إلى تحديد الفتحة المثلى لكل منها بهدف تقليل كل من التسرب و عدد المحابس الكلي كبديل للتكلفة وذلك باستخدام الطريقة الخوارزمية الميماتيكية متعددة الأهداف. تم إعداد نموذج رياضي للمشكلة محل الدراسة و كتابة كود بلغة الفورتران للنموذج الرياضي المعد. اثبتت كفاءة هذا الكود بالتطبيق على شبكة مياه شائعة الاستخدام في الدراسات السابقة ومن ثم تم التطبيق على شبكة مياه بإحدى المدن الجديدة بجمهورية مصر العربية. أوضحت النتائج أن أداء نظامي المحابس المقترحين في تقليل التسرب من شبكات المياه يكون تقريبا متماثل لنفس العدد من المحابس مع الافضلية النسبية لنظام المحابس الخانقة (TCVs).

***Abstract*—This paper optimizes the selection, number, location, and sizing of hydraulic devices with the purposes of leakage reduction in water distribution network (WDN). A multi-objective memetic algorithm is adopted to effectively minimize the leakage problem in WDN through the regulation of two different hydraulic control valves systems: throttle control valves (TCVs) and flow control valves (FCVs). Two objective functions are simultaneously considered: the first one is to minimize the total leakage in the network and the second objective function is represented by the minimization of the number of valves (a surrogate for establishing valves cost) while accomplishing the required nodal pressure head restrictions. The great advantage of this study is that, in one run, several trade-off optimal solutions are acquired with a different level of compromise between the two objectives. Each solution from these optimal ones consists of minimum number of suggested valves, the best locations for the valves and optimum valves settings. The performance of the developed optimization model is evaluated by its application on a well-known WDN from literature. Then, the developed optimization model is applied on a real WDN of a new city, Egypt. Results show that the hydraulic performances of the two hydraulic control valves systems in leakage reduction are almost agreement for the same valves number, and the TCVs system is relatively better than the FCVs system.**

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I. INTRODUCTION

LEAKAGE in WDN, which depends on the age and deterioration of the network, represents a large portion of total supplied water [1]. A distinction is found between total water loss and leakage. Total water loss is the difference between the all-out provided water and the expended water. Leakage is one of the water loss components due to physical losses from joints, fittings, and pipes and also overflows from service reservoirs. It is necessary to supply water at suitable pressure head to end users as the pressure head excess may cause water leakage. As the WDN aged and deteriorated, leakage values may reach 50% of the total water provided [2]. Hence, network pressure heads should be adjusted to a satisfactory level. Pressure head regulation and consequently leakage reduction can be accomplished in various ways, from the control of water level in storage tanks [3], reduction of pump heads for variable speed pumps [4, 5], installation of break pressure tanks or establishing pressure zones through the use of a variety of valves, for example, TCVs [6, 7], FCVs [8], and pressure reducing valves [9, 10]. Pressure head regulation and leakage reduction using valves is normally solved in two stages: the first one, both the number and location of valves are optimized by considering pseudo valves randomly located in each pipe which was simulated by extra roughness that minimized pressure heads in each node of the WDN. It is realized that, for increasing the heading loss of any pipe its Hazen–Williams coefficient decreases, hence the pipe of unrealistic Hazen–Williams coefficient value is suitable to install a valve. Thus, the reasonable number of pseudo valves is equivalent to the quantity of pipes which have unrealistic Hazen–Williams values. The subsequent stage establishes the optimum settings (opening sizes) for these valves at the chosen locations [1, 11, 12].

Stochastic optimization algorithms joined with pipe flow simulation have been broadly adopted to manage network pressure head and leakage. Genetic Algorithm (GA) is widely used in the literature to manage this issue [6, 7, 9, 13, 14]. As by reviewing the literature, this problem was tackled using different optimization algorithms, for example, particle swarm optimization [10], sequential addition [15], and shuffled complex evaluation algorithm [16]. There is no report of the use of memetic algorithms (MA), ant colony optimization, differential evolution, and simulated annealing for solving such optimization problem. Decision variables are related to the location of valves [17, 18], the location and setting of valves [19] and also the number, location and setting of valves [8, 12, 20]. This is carried out by using a single objective function [21] or a multi-objective functions [8, 14, 20] with the aim of minimizing the average nodal pressure head [14, 22], the number of valves [6, 8, 12], the leakage rate [9, 14] and the cost or energy dissipation [23].

TCVs are utilized to minimize the excess pressure heads through changing the demand pattern. The pipe valves have different degrees of closure which diminish the capacity of pipe and accordingly the pressure head loss increases [11]. Several models have been developed for leakage control using TCVs, for example, Awad et al. [16] developed an optimization model using shuffled complex evaluation algorithm and artificial neural networks to find the suitable settings of preexisted electrical motor TCVs. The suggested model was applied on a real WDN of Fukuoka city, Japan, with the purpose of pressure heads regulation and leakage reduction. Zidan et al. [6] presented a model for optimal pressure head regulation in WDN through identifying the number, locations, and opening size of TCVs. Multi-objective GA model was adopted to minimize both the TCVs number and the difference between nodal pressure heads and minimum reasonable pressure heads. The developed model was applied on Damnhour city WDN, Egypt, to compare volume of leakage in the cases of controlled and uncontrolled pressure heads. Gençoğlua and Merzib [7] adopted a GA optimization model to minimize excess nodal pressure heads in WDN by determining the optimal location and opening setting of TCV. They solved the leakage problem in two phases: determining the optimum location for the pre-specified number of valves; and the optimum settings (opening sizes) for these valves at the selected locations.

FCVs can be utilized to minimize the excessive pressure heads and consequently leakage reduction. Usage of these valves can make a decrease of leakage up to 20-30% [11]. Tremendous research works have been adopted FCVs for leakage reduction, such as given by Jowitt and Xu [2] who developed an optimization model by joined both the linear theory and linear programming techniques. They determined the optimum FCVs settings with the purpose of minimizing the relationship between the volume of leakage and average service pressure heads throughout the WDN. Reis et al. [1] adopted a GA model to determine an optimum location for a given number of FCVs as well as their opening percentages for leakage decrease. They concluded that, leakage can be controlled by using fewer valves optimally located in the network. El-Ghandour and Elansary [8] developed multi-objective GA model to minimize water system leakage and number of FCVs (a surrogate for valves cost) in WDN. They used the model to determine a set of Pareto optimal solutions; each solution consists of number, best locations and optimum openings of FCVs at each time period during the day. They concluded that, the maximum leakage reduction can be obtained by optimal locating a few numbers of FCVs.

In the present paper, a multi-objective memetic algorithm optimization model is developed and coded using the FORTRAN. Two different hydraulic control valves systems utilized for leakage decrease are examined and compared. The novelty of this study stems from: a set of Pareto optimal solutions are obtained, where each solution comprises of the number, best locations and optimum settings for a set of valves; and The objective functions include minimization of both WDN leakage and number of valves (a surrogate for valves cost). The developed model was verified against widespread WDN from literature. Then, it was applied on a real WDN of a new city, Egypt.

II. MATHEMATICAL FORMULATION

The leakage problem, under consideration, has been formulated to minimize both the total WDN leakage and the total number of valves (a surrogate for establishment cost of valves). Equation 1 is an empirical relationship utilized for estimating the amount of leakage which based on the orifice flow equation and was verified using a set of field experimental data [2]. This equation has been broadly utilized in literature [8, 20]. The two objective functions can be expressed numerically as follows:

$$\text{minimize} \quad f_1 = \sum_{i=1}^{N_p} C_{Li} L_i \left(\frac{h_{ui} - h_{di}}{2} \right)^{1.18} \tag{1}$$

$$\text{minimize} \quad f_2 = N_V \tag{2}$$

in which, f_1 and f_2 are the two considered objective functions; N_p is the number of pipes in the WDN; C_{Li} is a coefficient corresponding to pipe *i* depends on the age and deterioration of the pipe and the soil properties (it is taken equal to 10^{-5} for all pipes [20]); L_i is the length of the pipe *i*; h_{ui} and h_{di} are the pressure heads of upstream and downstream nodes of pipe *i*; and N_V is the number of valves.

The set of constraints are divided into: implicit bound, explicit variable and implicit system constraints. The implicit bound constraints contain restrictions on nodal pressure heads as follows:

$$h_j \geq H_{min\, j}, \quad j = 1, \ldots\ldots, N_n \tag{3}$$

in which, h_j is the pressure head at node *j*, $H_{min\ j}$ is the minimum allowable head at node *j*, and N_n is the number of nodes in the WDN.

The explicit variable constraint can be utilized to set limits on opening size for both TCVs and FCVs as follows:

$$0 \leq \theta_k \leq 100, \quad k = 1, \ldots\ldots, N_{TCV} \tag{4}$$

in which, θ_k is the percentage of TCV opening size corresponding to valve *k*, and N_{TCV} is the number of TCVs.

The loss coefficient (K_v) corresponding to TCV is proportional to the valve opening size (θ) and calculated from Eq. 5 [6, 16]:

$$K_{vk}(\theta) = \begin{cases} 165226 \times 10^{-0.18\theta} & (0 \leq \theta < 13) \\ 3696 \times 10^{-0.06\theta} & (13 \leq \theta < 40) \\ 221 \times 10^{-0.03\theta} & (40 \leq \theta \leq 100) \end{cases} \tag{5}$$

The behavior of a fully closed FCV is represented by setting β_l equal to zero, whereas a unity value occurs when the valve is fully open which there is no head loss beyond that in the pipe. Consequently, β_l has a value in the range between zero and unity as follows [2, 11]:

$$0 \leq \beta_l \leq 1, \quad l = 1, 2, \ldots\ldots\ldots, N_{FCV} \tag{6}$$

in which, β_l is the opening size corresponding to FCV of number *l*, and N_{FCV} is the number of FCVs.

The relationship between the flow (Q_i) through pipe *i* and head loss (h_{fi}) across this pipe in case of located FCV is given as follows [2, 11]:

$$Q_i = \beta_l \frac{\alpha C_{HWi} D_i^{2.63} h_{fi}^{0.54}}{L_i^{0.54}} \tag{7}$$

in which, Q_i is the flow through a FCV of opening percentage β_l located in pipe *i*, D_i is the diameter of pipe *i*, C_{HWi} is the Hazen-Williams coefficient for pipe *i*, L_i is the length of pipe *i*, h_{fi} is the head loss across pipe *i*, and α is a constant whose value depends on the used unit.

The implicit system constraints include mass nodal conservation and energy conservation and can be represented as follows:

$$\sum Q_{in\, j} - \sum Q_{out\, j} = Q_{e\, j}, \quad j = 1, \ldots\ldots\ldots, N_n \tag{8}$$

(for each node other than the source)

in which, $Q_{in\, j}$ is the node inflow *j*, $Q_{out\, j}$ is the node outflow *j*, and $Q_{e\, j}$ is the external inflow or demand at the node *j*.

$$\sum_{i=1}^{N_p} h_{fim} = \begin{cases} 0 & \text{(around each loop for no pump)} \\ E_p & \text{(if there is a pump)} \quad m = 1, \ldots\ldots, N_l \end{cases} \tag{9}$$

in which, h_{fim} is the frictional head loss in a pipe *i* and loop *m*, E_p is the energy supplied by a pump, and N_l is the number of loops in WDN.

III. MEMETIC ALGORITHM TECHNIQUE

Memetic Algorithm (MA) [24] generally represents a solution utilizing chromosomes, everyone comprises of set of memes, having values for the unknowns optimization problem (i.e. decision variables). MA works with a random population of chromosomes (solutions). Typically, every chromosome is assessed against objective functions to decide the corresponding fitness. Each produced chromosome is exposed to a local search to enhance its experience and in this manner a population of local optimum solutions can be acquired. Thereafter, the MA operators are applied (i.e. selection, crossover and mutation), to produce offspring chromosomes. Through these three operators, chromosomes of high fitness values, in the population, have a high likelihood of being chosen for combination with other chromosomes of high fitness. Then, a combination is accomplished through crossover between chosen chromosomes. Mutation allows for the random change of bits information in individual memes. As such, Mutation introduces new memtic material to the evolutionary process, perhaps thereby avoiding stagnation or being trapped in local minima. Then the offspring chromosomes are subjected to local search so that local optimality is maintained.

The multi-objective memetic algorithm (MOMA) consists of the following steps:

1- A randomly initial population of chromosomes is generated (father pool).

2- Objective functions and the corresponding constraints are evaluated for each chromosome utilizing the pipe flow simulation model.

3- Each created chromosome is exposed to a local search to improve its experience and subsequently a population of local optimum solutions can be acquired. The local search is done, in this paper, by swapping two elements (memes) in the chromosome as appeared in Figure 1. After each swap, the change is kept if the chromosome's performance improves; otherwise, disregard the change.

4- The fitness of each chromosome is determined utilizing layer classification strategy, in which all chromosomes are steadily arranging utilizing Pareto dominance. A solution is called Pareto optimal if it beats all other solutions at least in one objective [25]. The accompanying steps show the technique for figuring of the Fitness for every chromosome [26]:

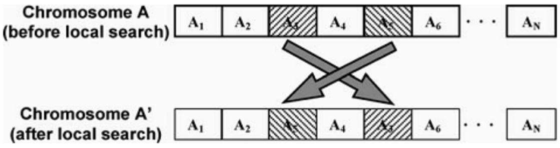

Fig. 1. Applying local search using pair-wise interchange

- A set of Pareto optimal solutions (chromosomes) is determined from the population through objective functions' comparisons. A rank of one is assigned to each solution in this set.
- The identified set of Pareto optimal solutions is set apart, and another set of Pareto optimal solution is determined from the remaining solutions. A rank of two is assigned to each solution in this current set.
- This process is continued until the entire chromosomes' population is ranked.
- The Fitness of each chromosome is determined based on its rank, as follows [26]:

$$Fitness_m = 1/\ rank_m \tag{10}$$

where, $Fitness_m$ and $rank_m$ are the fitness and the rank number of chromosome m.

5- Normalization of chromosomes probabilities are performed.

6- MA Operators (i.e. selection, crossover, and mutation) are applied to create a new population of offspring chromosomes (children pool).

7- Replacement strategy is done to supplant the weakest chromosome in the current generation with the randomly selected one located in the PF of previous generation.

8- Replace the chromosomes in the fathers' pool with the corresponding ones in the children pool.

9- The steps from (2) to (8) are continued for a large number of generations to convergence criteria are satisfied.

The MA parameters which affect its performance are population size, number of generations, crossover ratio, mutation ratio, type of cross over, and number of swaps. The flow chart of the proposed MOMA algorithm is shown in Figure 2.

IV. MODEL VERIFICATION

The developed MOMA model is verified through the application on a widespread benchmark WDN from literature [1, 2, 8, 20] to minimize both the total volume of network leakage and number of valves. Two distinct hydraulic control valves systems are considered to optimally control the leakage (i.e. TCVs, and FCVs). The results of every valves system are compared with the corresponding ones from the literature. The selected benchmark WDN comprises of 25 node, 37 pipes, and three reservoirs having levels equal to 54.66 m, 54.60 m, and 54.50 m at nodes 23, 24, and 25 respectively (Figure 3). The pipes and nodes data are summarized in Table 1. The appropriate values for the MA parameters are determined after several trial runs: population size = 300, maximum number of generations = 2000, crossover ratio = 0.7, mutation ratio = 0.08, type of cross over is uniform and maximum number of swaps = 10. The minimum allowable head (H_{min}) is taken as 30 m [1, 2, 8, 20].

Figure 4 shows a comparison among the obtained Pareto fronts, for each suggested hydraulic control valves system, and the corresponding ones given by previous researchers [8, 20]. Each Pareto front consists of a set of Pareto optimal solutions which represents a relationship between the leakage volume and number of valves. Each optimal solution gives an appropriate number of valves, best locations and optimum valves settings.

It can be noticed that from Figure 4, the obtained Pareto fronts are nearly very close to the corresponding one given by El-Ghandour and Elansary [8] while, they gives relatively minimum leakage volume compared with the Pareto front given by Nicolini and Zovatto [20] for the same number of valves. Also, Figure 4 shows that when the number of valves reaches 6 the reduction of leakage volume is insignificant. As such, the reduction of leakage can be obtained with the smallest valves number when they are optimally located in the network. This is the same noticeable given by several previous researchers [1, 8, 20]. Consequently, the results of the four Pareto fronts are summarized in Table 2 corresponding to the number of valves from 1 to 6. It can be seen from this table, the best location for one valve is pipe number 11 as given by Nicolini and Zovatto [20] with a leakage volume equals 25.03 l/sec while, both the study given by El-Ghandour and Elansary [8] and the suggested TCVs system, in the present study, determine the best location is pipe number 27. The best location for one valve in the suggested FCVs system is pipe number 16. The corresponding leakage volumes, in this case, are 24.57 l/sec and 24.48 l/sec, 24.51 l/sec for the study of El-Ghandour and Elansary [8] and the suggested two systems, respectively. While, the suggested system 1 and the study given by Nicolini and Zovatto [20] agree with the best location for two and three valves (pipes numbers 11, 20) and (1, 11, 20), the obtained leakage in system 1 is the less. Both the suggested system 2 and the study given by El-Ghandour and Elansary [8] agree with the best location for two valves (pipes numbers 1, 27). The comparison between the hydraulic performances of the two suggested valves systems in leakage reduction shows that they have the same trend, and the TCVs system is relatively better than the FCVs system. Consequently, from the results demonstrated in Table 2, the MOMA model, in the two suggested hydraulic control valves systems, is able to determine the minimum number of valves, best valves locations, and optimum valve settings to minimize both the leakage volume in WDN and number of valves.

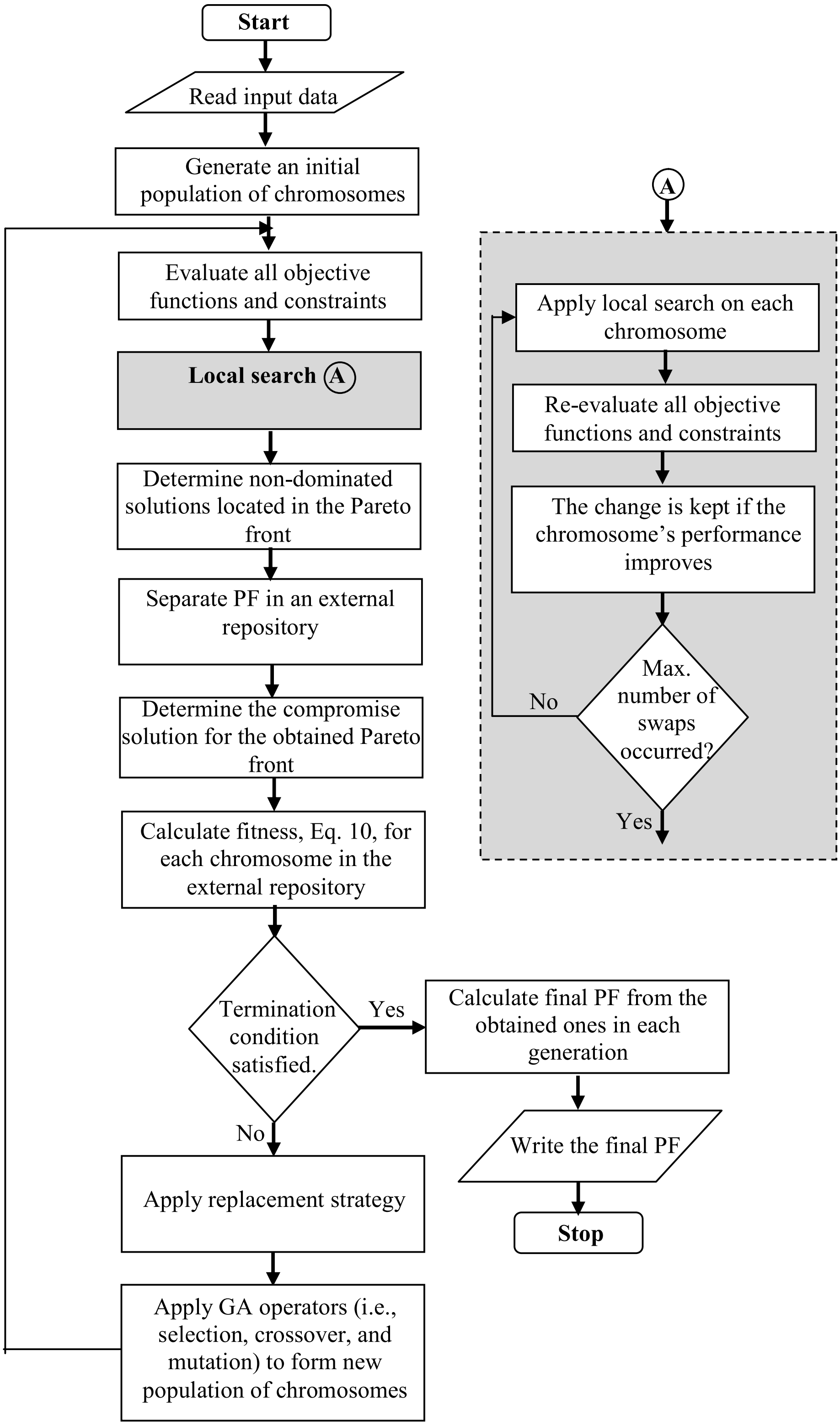

Fig. 2. Flowchart describing MOMA model

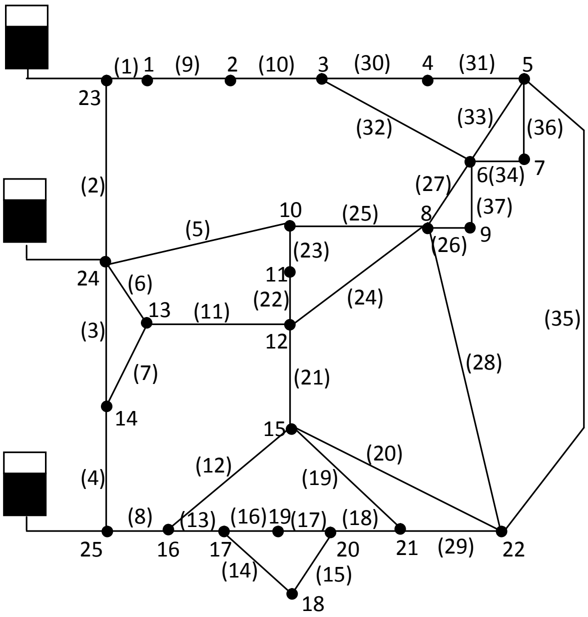

Fig. 3. Layout of the well-known benchmark WDN used in the verification process

TABLE 1

DATA OF NODES AND PIPES FOR THE WELL-KNOWN BENCHMARK WDN

Node number (Maximum Demand [l/s], Level [m])			
1 (7, 18)	2 (14, 18)	3 (0, 14)	4 (7, 12)
5 (42, 14)	6 (14, 15)	7 (0, 14.5)	8 (28, 14)
9 (0, 14)	10 (7, 15)	11 (14, 12)	12 (0, 15)
13 (0, 23)	14 (7, 20)	15 (28, 8)	16 (0, 10)
17 (0, 7)	18 (7, 8)	19 (7, 10)	20 (0, 7)
21 (7, 10)	22 (28, 15)		
Pipe number (Length [m], Diameter [mm], Hazen-Williams coefficient)			
1 (606, 457, 110)	2 (454, 457, 110)	3 (2782, 229, 105)	4 (304, 381,135)
5 (3382, 305, 100)	6 (1767, 475, 110)	7 (1014, 381, 135)	8 (1097, 381, 6)
9 (1930, 457, 110)	10 (5150, 305, 10)	11 (762, 457, 110)	12 (914, 229, 125)
13 (822, 305, 140)	14 (411, 152, 100)	15 (701, 229,110)	16 (1072, 229, 135)
17 (864, 152, 90)	18 (711, 152, 90)	19 (832, 152, 90)	20 (2334, 229, 100)
21 (1996, 229, 95)	22 (777, 229, 90)	23 (542, 229, 90)	24 (1600, 457, 110)
25 (249, 305, 105)	26 (443, 229, 90)	27 (743, 381, 110)	28 (931, 229, 125)
29 (2689, 152, 100)	30 (326, 152, 100)	31 (844, 229, 110)	32 (1274, 152, 100)
33 (1115, 229, 90)	34 (615, 381, 110)	35 (1408, 152, 100)	36 (500, 381, 110)
37 (300, 229, 90)			

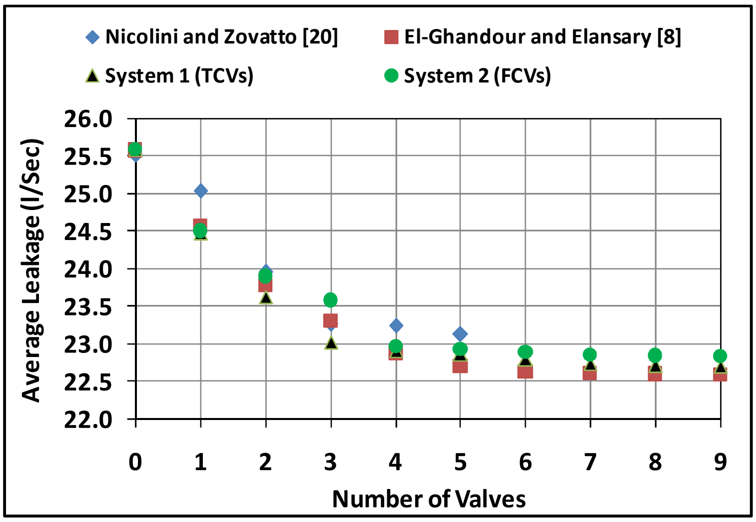

Fig. 4. Pareto fronts given by the present and other studies

TABLE 2
RESULTS OF PARETO OPTIMAL SOLUTIONS OBTAINED BY BOTH THE MODEL VERIFICATION AND THE CORRESPONDING ONES GIVEN BY PREVIOUS STUDIES

Pareto front given by	Valves type	Pipe number-Valve location	Leakage volume (l/sec)
Nicolini and Zovatto [20]	**Pressure reducing valves**	11	25.03
		11, 20	23.96
		1, 11, 20	23.26
		1, 11, 20, 21	23.24
		1, 11, 20, 21, 27	23.13
		------	-----
El-Ghandour and Elansary [8]	**FCVs**	27	24.57
		1, 27	23.78
		1, 5, 20	23.30
		1, 5, 20, 27	22.88
		1, 5, 8, 20, 27	22.70
		1, 5, 8, 20, 27, 31	22.64
System (1)	**TCVs**	27	24.48
		11, 20	23.63
		1, 11, 20	23.03
		1, 8, 20, 27	22.91
		1, 8, 20, 22, 27	22.87
		8,17, 20, 22, 27, 31	22.80
System (2)	**FCVs**	16	24.51
		1, 27	23.90
		1, 13, 27	23.58
		1, 8, 12, 27	22.97
		1, 6, 8, 20, 36	22.93
		1, 8, 20, 27, 35, 36	22.90

V. MODEL APPLICATION

The verified MOMA model is applied on an existing real WDN of a new city, Egypt, [27] to minimize both the total network leakage volume and number of valves, considering the two suggested hydraulic control valves systems. The WDN is a gravity-driven and draws water from a reservoir, of total head equal to 313.0 m, to the downstream network. After performing the simplification process for the network, the simplified network (99 pipes and 89 nodes) mimics the behavior of the current large network (1411 pipes and 1283 nodes), Figure 5. The simplified network data are given by El-Ghandour and Elansary [27] including pipe data and nodal requirements. The values of MA parameters are chosen as the same taken in model verification and H_{min} is taken 30 m.

Figure 6 shows the obtained Pareto fronts corresponding to each suggested valve system. From this Figure, the Pareto fronts corresponding for the two valves' systems are nearly coincide and the TCVs system is relatively better than the FCVs system as noticed in Figure 4 for a well-known WDN. It is also noticed that the contribution of a number of valves greater than 7 is marginal to the reduction of leakage volume. Consequently, the results of the two Pareto fronts are listed in Table 3 corresponding to the number of valves from 1 to 7.

From this table, system 1, it is noticed that the MOMA model identifies the optimal control for only single valve in pipe number (P-1807) can reduce the leakage volume by about 6.39 l/sec (equal to 201515 m^3/year) while, 8.04 l/sec (equal to 253549 m^3/year) reduction in leakage volume is occurred for optimal control of two valves in pipes (P-1809, P-1777). The best locations of other five solutions (i.e. from three to seven valves) are summarized in Table 3. Increasing in leakage reductions for these five solutions are marginally compared with the first two solutions (i.e. 8.50 l/sec, 8.92 l/sec, 9.31 l/sec, 9.51 l/sec, and 9.69 l/sec), Table 3.

For system 2, the MOMA model identifies the valve in pipe number (P-1809) as the optimal single valve whereas the two valves are in pipe numbers (P-1809, P-1777) are the best two valves solution. It is noticed that, the suggested two systems agree with the best locations for two valves solution. Optimal control for only single valve in pipe number (P-1809) can reduce the leakage by about 5.40 l/sec (equal to 170294 m^3/year). The valves combination in pipes (P-1777, P-516, P-1800) is the best three valves solution. By optimal location and regulation of these three valves, 8.30 l/sec (equal to 261749 m^3/year) reduction of leakage volume is achieved. The best locations of other four solutions (i.e. from four to seven valves) are summarized in Table 3. Leakage reductions for these four solutions are 8.77 l/sec, 9.05 l/sec, 9.49 l/sec, and 9.61 l/sec, respectively, Table 3.

Figure 7 shows a comparison between the percentage of leakage reduction corresponding to each valve solution for the two valves systems. The percentage of leakage reduction is calculated from $[(LV_{un} - LV_c)/ LV_{un}]$, in which, LV_{un} is the uncontrolled total leakage volume through the network (i.e. leakage volume in case of there is no valves in the WDN) and LV_c is the controlled total leakage volume through the network (i.e. leakage volume in case of there is valves in the WDN). It can be noticed from this Figure, the hydraulic performances of TCVs (System 1) in leakage reduction is better than FCVs (System 2) from one to five valves' solutions then they are nearly the same for the other two valves solutions.

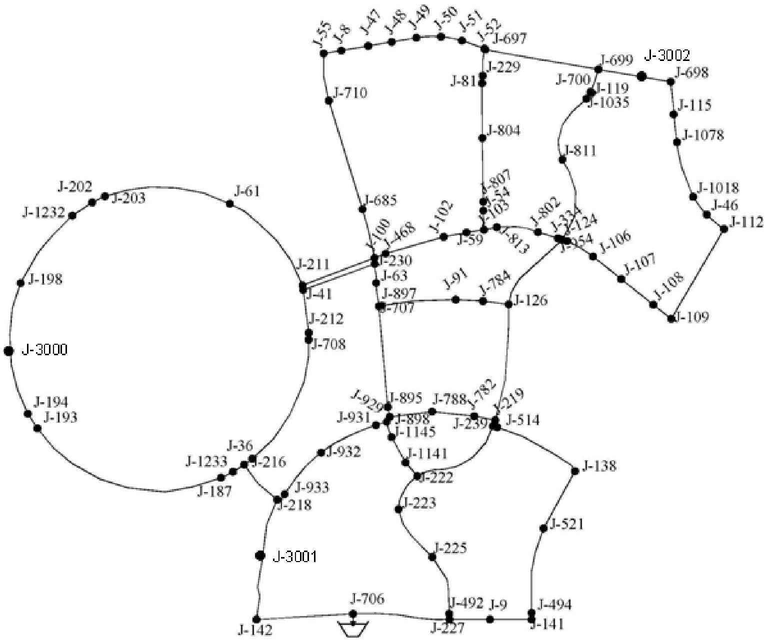

Fig. 5. Layout of the WDN of a new city, Egypt

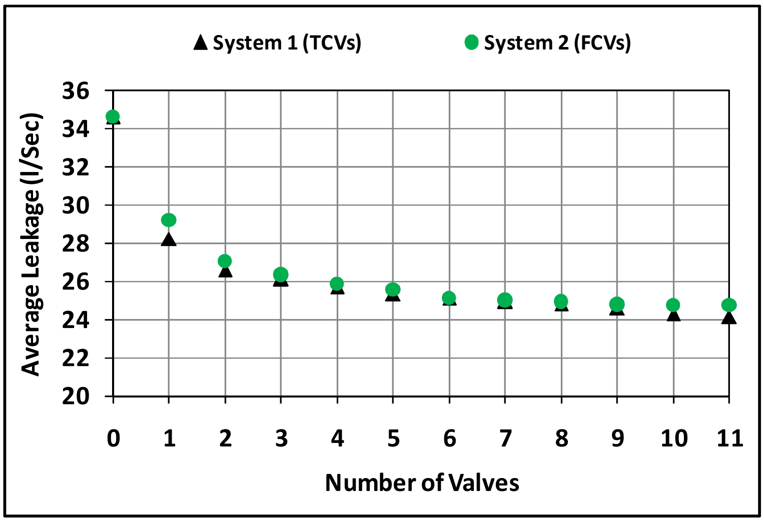

Fig. 6. Pareto fronts given by the application of the two hydraulic control valves systems

TABLE 3
RESULTS OF PARETO OPTIMAL SOLUTIONS OBTAINED IN THE MODEL APPLICATION

Pareto front	Valves type	Pipe number-Valve location	Leakage Volume (l/sec)	Leakage Reduction (l/sec)
	Zero valves	-----	34.61	-----
System (1)	TCVs	P-1807	28.22	6.39
		P-1809, P-1777	26.57	8.04
		P-1777, P-1779, P-4001	26.11	8.50
		P-1807, P-1814, P-1777, P-1805	25.69	8.92
		P-1807, P-1788, P-1777, P-1823, P-1779	25.30	9.31
		P-1807, P-139, P-1777, P-1779, P-1805, P-1810	25.10	9.51
		P-1809, P-139, P-1777, P-1823, P-516, P-1779, P-1805	24.92	9.69
System (2)	FCVs	P-1809	29.21	5.40
		P-1809, P-1777	27.05	7.56
		P-1777, P-516, P-1800	26.31	8.3
		P-1809, P-1777, P-1769, P-1779	25.84	8.77
		P-1809, P-835, P-1777, P-1823, P-1779	25.56	9.05
		P-1809, P-1777, P-1823, P-1769, P-1779, P-1805	25.12	9.49
		P-1809, P-1777, P-1823, P-516, P-1769, P-1779, P-1805	25.00	9.61

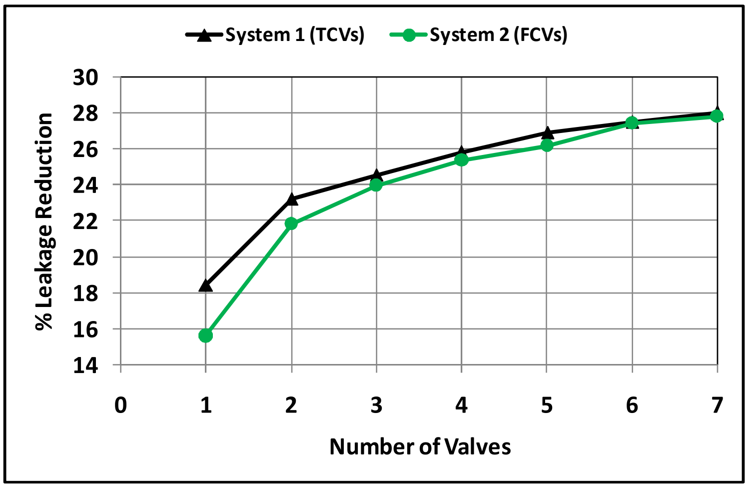

Fig. 7. Leakage reduction versus number of valves for the two hydraulic control valves systems

VI. CONCLUSIONS

Both TCVs and FCVs can be considered as possible technology in WDN to limit the leakage volume. This paper aims to optimize the selection, number, location, and sizing of hydraulic valves with the purposes of minimizing the total water leakage from the system and the number of valves (a surrogate for establishment costs). A multi-objective memetic-algorithms optimization model is developed and originally coded using FORTRAN language to facilitate its use. The model can determine, a set of optimal solutions (Pareto front) representing the trade-off between the two objective functions. Each solution in the optimal ones contains the appropriate number of flow control valves, their best locations, and valves' settings. A comparison is carried out between the two valves systems (i.e. TCVs and FCVs). Application results on an existing real WDN of a new city, Egypt, show that the hydraulic performances of the two valves' systems are almost agreement for the same valves number, and the TCVs system is relatively better than the FCVs system. In general, reduction of total leakage can be obtained with the smallest valves number when they are located optimally in the network.

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