Enhancement of Iraqi Power Distribution Systems Performance using Optimal System Reconfiguration

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Abstract:

This paper presents a method to enhance the performance of Iraqi power distribution systems using an optimal system reconfiguration strategy. The objective of the proposed method is to minimize the active power losses and then improve the voltage profile with considering the current-carrying capacity of the system branches. In order to determine the optimal system configuration, a new optimization method, called selective water cycle optimization method, is also proposed in this paper. The proposed method is based on the traditional water cycle optimization method, but it is modified to consider the selective search space required in the reconfiguration problem. The proposed methods were evaluated and tested on an actual distribution system nominated by the Directorate of Electricity Distribution in Babylon/Iraq, based on repeated consumer complaints about the poor quality of the power supply.

Keywords: distribution systems, distribution systems reconfiguration, power losses, voltage profile, water cycle optimization method.

الخلاصة

يقدم هذا البحث طريقة لتَحسين أداءِ أنظمة توزيع الطاقة الكهربائية العراقية باستخدام استراتيجية إعادة التشكيل المثلى لأنظمة التوزيع. ان الهدف من الطريقة المقترحة هو تقليل خسائر الطاقة ومن ثم تحسين مستوى الفولتية مع مراعاة سعة تحمل افرع النظام للتيار الكهربائي. ومن اجل تحديد التشكيل الامثل للنظام، يقترح ايضا في هذا البحث طريقة جديدة لتحقيق الأمثلية، تسمى طريقة دورة المياه الانتقائية. تستند طريقة تحقيق الأمثلية المقترحة على طريقة دورة المياه التقليدية، ولكنها عُدِلت للأخذ بنظر الاعتبار مجال البحث الانتقائي المطلوب في مشكلة إعادة التشكيل. ان الطرق المُقتَرَحة قُيّمتْ وإختبرتْ على نظام توزيع حقيقي الذي رشحته مديرية توزيع الكهرباء في بابل / العراق، استنادا إلى شكاوى المستهلكين المتكررة حول سوء نوعية تجهيز القدرة الكهربائية.

الكلمات المفتاحية: أنظمة توزيع الطاقة الكهربائية، إعادة تشكيل أنظمة التوزيع، الخسائر الكهربائية، مستوى الفولتية، طريقة دورة المياه لتحقيق الامثلية.

1. Introduction

During the last ten years, irregular residential buildings have been widely established in some agricultural fields located in centers of Iraqi cities. These buildings have been supplied by electricity from the nearest electrical distribution feeders without previous planning since such buildings do not exist in future planning developed by General Directorate of Urban Planning in Iraq.

As a result, most of the feeder lines supplied the mentioned buildings suffer from overloading and poor voltage profile which causes malfunction in the operation of customer electrical devices (Kjolle *et.al.*, 2008). Moreover, the power losses are also increased in some parts of these feeders due to the presence of insufficient cables sizes for the load current. In order to solve this problem, several strategies have been proposed by electric power distribution utilities in Iraq to enhance the power distribution system. The most utilized strategies are listed below:

- Upgrade the cable size of the overloaded feeder lines.
- Installation of shunt capacitors along the distribution feeder to compensate the load inductive power.

However, these strategies are very expensive and are not applicable in this time due to Iraqi economic crisis. Therefore, it is very important to develop an alternative strategy to decrease the power losses and improve the voltage profile with less cost.

The proposed strategy presented, in this paper, is the reconfiguration of distribution feeders (RDF). The main idea of RDF strategy is based on changing the topological structure of distribution feeder by altering the status of open/close switches to achieve minimum power losses and acceptable voltage profile. The main advantage of the proposed strategy is represented by the low investment requirement since it uses the switches which are already available in the distribution systems. Although this strategy is very attractive, it requires an accurate optimization method to obtain the optimal configuration structure of the system. In addition, it requires an optimization method with selective search space to search among only the available system switches (Aman *et.al.*, 2016).

Many RDF methods have been developed using different optimization methods, such as simulated annealing (Su *et.al.*, 2001), genetic algorithm (Taher *et.al.*, 2014), bee colony (Ganesh, 2014), immune systems (Alonso *et.al.*, 2015), Ant colony (Tolabi *et.al.*, 2015), Particle swarm (Balakrishna *et.al.*, 2014), evolutionary programming (Aman *et.al.*, 2013). However, most of these methods were tested using simple and theoretical radial networks.

Water cycle optimization method (WCOM) (Eskandar *et.al.*, 2012; Sadollah *et.al.*, 2015), which is based on water cycle phenomenon, is recently developed. During the previous two years, WCOM shows superior performances compared to other optimization methods for different applications (Jahan *et.al.*, 2015; Khodabakhshian *et.al.*, 2016; Heidari *et.al.*, 2017). However, WCOM was formulated for continuous or discrete optimization problems using free search space which is not applicable to RDF problem.

In this paper, optimal reconfiguration of distribution systems is proposed to enhance the performance of Iraqi power distribution systems. The optimal radial configuration is determined using selective water cycle optimization method which is also proposed, in this paper to consider the selective search space required in the reconfiguration problem. The objective of proposed system reconfiguration method is to minimize the power losses and then improve the voltage profile with considering the current-carrying capacity of the system branches. An actual distribution system selected from Hillah city network is used, in this paper, to test and verify the effectiveness of the proposed methods. Superiority of the proposed methods compared with other methods is also verified.

2. Proposed Distribution System Reconfiguration Method

In Iraq, the distribution systems are constructed as weakly meshed, but are operated with radial configuration using the switches located in the end of each branch. Two types of switches are available in the systems, which are normally closed switches (sectionalized switches) and normally open switches (tie switches). By changing the state of these switches, different radial configurations can be obtained. The main purpose of the mentioned switches design is to manage the system configuration at contingency and fault conditions.

In this paper, an optimal reconfiguration method is proposed for Iraqi power distribution systems to minimize the active power losses and then improve the voltage profile with considering the current-carrying capacity of the system branches. The optimal radial configuration of the distribution system is obtained by determining the optimal state of the system switches. Since the real power distribution system consists of many branches and open/closed switches, many candidate-switching combinations are possible to form the radial structure. Therefore, efficient optimization method is required to solve this complicated problem. In this aspect, a new efficient optimization method is proposed in this paper to solve the reconfiguration problem.

The objective function and constrains are described as:

$$objective\ function = f(P_{Loss}) \tag{1}$$

Subjected to the following system constrained:

$$V_{min} \leq |V_i| \leq V_{max} \tag{2}$$

$$|I_j| \leq I_{j,max} \tag{3}$$

where P_{Loss} is the system active power losses. $|V_i|$ is the bus voltage magnitude of the i^{th} bus. V_{max} and V_{min} are the maximum and minimum bus voltage limit, respectively. $|I_j|$ and $I_{j,max}$ are the current magnitude and the maximum current-carrying capacity of the j^{th} branch, respectively. The power losses and the system constrains are determined in this paper using Newton-Raphson load flow algorithm (Glover *et.al.*, 2017).

A simple distribution system, as shown in Figure (1), is used to illustrate the formulation of the proposed reconfiguration method. This system consists of two feeders, 11 buses, 3 tie switches and 10 sectionalized switches. By closing the three tie switches, three loops are obtained. In order to find the optimal radial configuration that minimizes the active power losses and satisfies the system constrains, one branch in each loop should open. The open branches are obtained using the proposed optimization method which will be subsequently presented in the next section.

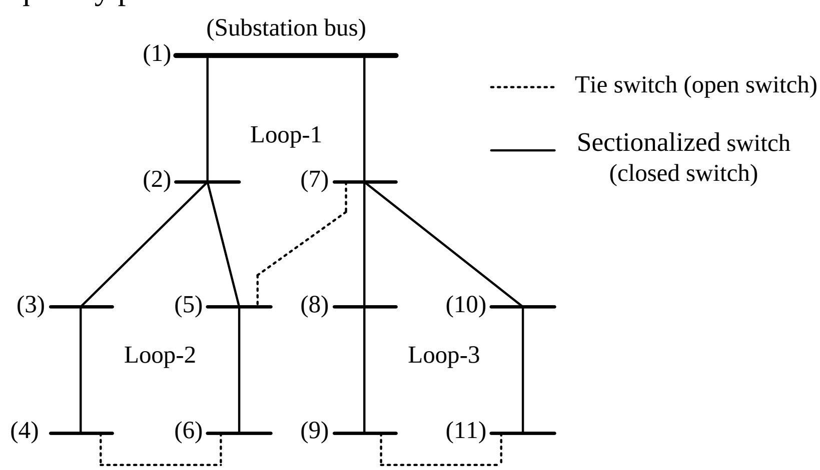

Figure (1): Simple distribution system

Accordingly, the number of control variables in the optimization problem is equal to the number of loops, while the branches of the i^{th} loop represent the search space of the i^{th} control variable. However, the branches which are common to the more than one loop should be randomly presented only in the search space of one control variable (Aman *et.al.*, 2016). Table (1) lists the search space for each control variable in the optimization problem for the system shown in Figure (1).

Table (1): Search space for each control variable

Control variable	Search space (Branches)
1st	1-2, 1-7, 2-5, 5-7
2nd	2-3, 3-4, 4-6, 5-6
3rd	7-8, 7-10, 8-9, 9-11, 10-11

3. Proposed Selective Water Cycle Optimization Method

The water cycle method represents one of the best meta-heuristic optimization methods. It was firstly originated from the observation of the water cycle process in nature by Eskandar *et.al.* in 2012 and it was modified to consider the multi objective optimization problems in 2015. Both method versions were formulated for continuous or discrete optimization problems using a random selection of control variable values (free search space).

However, most of engineering applications need to select and upgrade values of the variables according to their standard values. One of these applications is the reconfiguration of power distribution systems. In such application, an optimization method is used to determine the status (open/close) of specific switches which are already existed in the system to find the optimal system configuration.

Therefore, this paper proposes a modification to the WCOM to search in a selective space for the values of control variables. The proposed modified method is called selective water cycle optimization Method. This method starts by the raining process and then the raindrops will create sea, rivers and streams. Rivers and streams directly or indirectly flow to the sea as the most downhill point, or in optimization method, this represents the optimal point (Eskandar *et.al.*, 2012). Detailed description of the proposed method will be presented in the following subsections:

i.Initialization

After the raining process, an initial population of raindrops is randomly selected from the given search space of the control variables (S_{CV}). In this method, the search space (S_{CV}) is a set of m values obtained from the standard values of the control variables given in the optimization problem:

$$S_{CV} = [S_{CV1} \quad S_{CV2} \quad S_{CV3} \quad \cdots \quad S_{CVm}] \tag{4}$$

The initial population is formulated as a matrix. The dimension of the population matrix is based on the population size (N_P) and the number of design control variables (N_v) as shown in Eq. (5).

$$\text{Population of raindrops} = \begin{bmatrix} x_{1,1} & x_{1,2} & \cdots & x_{1,N_v} \\ x_{2,1} & x_{2,2} & \cdots & x_{2,N_v} \\ \vdots & \vdots & \vdots & \vdots \\ x_{N_p,1} & x_{N_p,2} & \cdots & x_{N_p,N_v} \end{bmatrix} \tag{5}$$

Each row in the population matrix represents a single solution for the optimization problem (raindrop) while the number of rows represents the population size.

ii. Cost Determination

Using the cost function (objective function), the cost of each individual solution can be obtained.

$$Cost_i = P_{Loss_i} = f\left(x_{i,1}, x_{i,2}, \dots, x_{i,N_v}\right) \quad \text{where } i = 1, 2, 3, \dots, N_p \tag{6}$$

iii. Formulation of Sea, Rivers and Streams

After determining the cost of each candidate solution, the candidates are organized in descending order according to their cost. A number of best candidates (N_{bc}) are chosen as the sea and rivers while the other candidates are considered as the streams (N_s) as shown in Eqs. (7) and (8). Among the best candidates, the one which has lowest cost value is selected as the sea.

$$N_p = N_{bc} + N_s \tag{7}$$

$$N_{bc} = \underbrace{1}_{Sea} + \underbrace{N_r}_{Rivers} \tag{8}$$

iv. Flow of Rivers and Streams

In the water cycle optimization method, the cost value of each candidate represents the magnitude of the flow while the variables value of each candidate represents its location. Depending on the flow magnitude, the streams may flow to the rivers or may directly flow to the sea while all rivers will directly flow to the sea. The numbers of streams which flow to the sea and to the specific river are calculated using Eqs. (9) and (10), respectively.

$$No.of\ steams\ which\ flow\ to\ the\ sea = \left\| \left| \frac{cost\ of\ the\ sea}{\sum_{j=1}^{N_{bc}} Cost_j} \right| \times N_s \right\| \tag{9}$$

$$No.of\ steams\ which\ flow\ to\ the\ i^{th}\ river = \left\| \left| \frac{cost\ of\ the\ i^{th} river}{\sum_{j=1}^{N_{bc}} Cost_j} \right| \times N_s \right\| \tag{10}$$

Because of the flow of streams and rivers toward the downhill point, their locations change with time. The new location of the rivers which flow to the sea can be determined using Eq. (11):

$$\vec{X}_{River}(\mathrm{t}+1) = \vec{X}_{River}(t) + \alpha \times \beta \times \left(\vec{X}_{Sea}(t) - \vec{X}_{River}(t)\right) \tag{11}$$

The new location of the steams which flow to the river can be determined using Eq. (12):

$$\vec{X}_{Stream}(\mathrm{t}+1) = \vec{X}_{Stream}(t) + \alpha \times \beta \times \left(\vec{X}_{River}(t) - \vec{X}_{Stream}(t)\right) \tag{12}$$

The new location of the steams which flow to the sea can be determined using Eq. (13):

$$\vec{X}_{Stream}(\mathrm{t}+1) = \vec{X}_{Stream}(t) + \alpha \times \beta \times \left(\vec{X}_{Sea}(t) - \vec{X}_{Stream}(t)\right) \tag{13}$$

where β is a random number between 0 and 1, α is a number between 1 and 2, and t is an iteration index.

However, the control variables values of the new raindrops locations determined from Eqs. (11), (12) and (13) may be not within the standard search space given in Eq. (4). In order to change values of the variables to be within search space, the proposed process of the selected search space is utilized using Eqs. (14) and (15):

$$\vec{X}_{Updated\_River}(\mathrm{t}+1)=\begin{cases} S_{CV1} & if \quad Sig\left(\vec{X}_{River}(\mathrm{t}+1)\right)<1 \\ S_{CV2} & if \quad Sig\left(\vec{X}_{River}(\mathrm{t}+1)\right)<2 \\ S_{CV3} & if \quad Sig\left(\vec{X}_{River}(\mathrm{t}+1)\right)<3 \\ \vdots \quad \vdots & \qquad \vdots \\ S_{CVm} & if \quad Sig\left(\vec{X}_{River}(\mathrm{t}+1)\right)\leq m \end{cases} \tag{14}$$

$$\vec{X}_{Updated\_Stream}(\mathrm{t}+1)=\begin{cases} S_{CV1} & if \quad Sig\left(\vec{X}_{Stream}(\mathrm{t}+1)\right)<1 \\ S_{CV2} & if \quad Sig\left(\vec{X}_{Stream}(\mathrm{t}+1)\right)<2 \\ S_{CV3} & if \quad Sig\left(\vec{X}_{Stream}(\mathrm{t}+1)\right)<3 \\ \vdots \quad \vdots & \qquad \vdots \\ S_{CVm} & if \quad Sig\left(\vec{X}_{Stream}(\mathrm{t}+1)\right)\leq m \end{cases} \tag{15}$$

where m is the number of selected location in the given search space, and Sig is the sigmoid function which is determined as:

$$Sig\ (\Upsilon)=\frac{m}{1+\exp(-\Upsilon)} \tag{16}$$

After updating the new location of the streams and rivers, the cost is determined for each of them. If the cost obtained by a stream is better than that of its connected river, the locations of river and stream are exchanged. Similar change can be utilized for the sea and the river.

v. Evaporation and Raining Processes

According to the nature of the water cycle process, the waters evaporate from sea to create clouds which then back to earth in the raining process. This stage of water cycle starts when the water of specific stream/river reaches to the sea or is close enough. Equation (17) is used to check the occurrence of the evaporation condition for the case of rivers. Similar criteria are used for streams.

$$\begin{cases} if\ \left|\vec{X}_{Sea}-\vec{X}_{River}\right|<\ \rho \\ \text{then} \\ \text{evaporation is occured} \end{cases} \tag{17}$$

where ρ is a small number near to zero. This number is iteratively reduced using the following equation:

$$\rho(\mathrm{t}+1)=\rho(\mathrm{t})-\frac{\rho(\mathrm{t})}{\text{Max Iteration}} \tag{18}$$

As results to the evaporation process, the streams/rivers which are close to the sea are eliminated from population.

After that, all constraints are checked for each available solution (sea, rivers and streams) of the remaining population. A set of feasible solutions are obtained. Based on the cost of each feasible solution, new sea, rivers and streams are formulated. For the next iteration, the population is updated to create new raindrops instead of the eliminated ones and the procedure goes back to Step-2 (cost determination).

These procedures are repeated until the maximum iteration is satisfied and the location of the sea will represent the optimal solution.

4. Case Study

In this paper, the case study is an actual distribution system selected from Hillah city network. It was nominated for this study by the Directorate of Electricity Distribution in Babylon/Iraq based on repeated consumer complaints about the poor quality of the power supply. The topology and the single line diagram of this system are given in Figures (2) and (3), respectively. It consists of two 11 kV distribution feeders connected to the same substation, 77 sectionalized switches, 5 tie switches and different sizes of 11kV/380V transformers. The measured power at the substation bus for the two feeders is (8.95+j4.19 MVA). The load at each load bus is determined based on the total power and the transformer size using the algorithm presented in (Pereira *et.al.*, 2009). According to the formulation of the proposed reconfiguration method presented in Section-2, the number of control variables (or the number of loops) for the given case study is five variables and the search space for each variable is presented in Table (2).

Table (2): Search space for each control variable in the system

Control variable	Search space (Branches)
1st	1-2, 2-3, 3-5, 5-6, 6-7, 7-40, 1-39, 39-40
2nd	2-8, 8-9, 9-10, 10-11, 11-12, 12-55, 40-41, 41-42, 42-43, 43-44, 44-46, 46-47, 47-48, 48-54, 54-55
3rd	48-49, 49-51, 51-52, 52-53, 53-62, 55-57, 57-61, 61-62
4th	21-59, 58-59, 57-58, 10-13, 13-15, 15-17, 17-18, 18-19,19-20, 20-21
5th	29-57, 20-22, 22-23, 23-24, 24-27, 27-28, 28-29

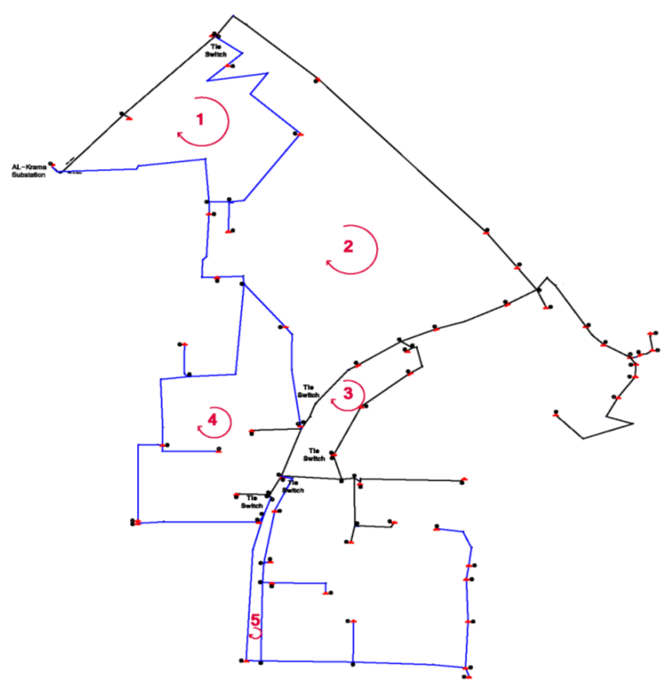

Figure (2): Topology of an actual distribution system selected from Hillah city network

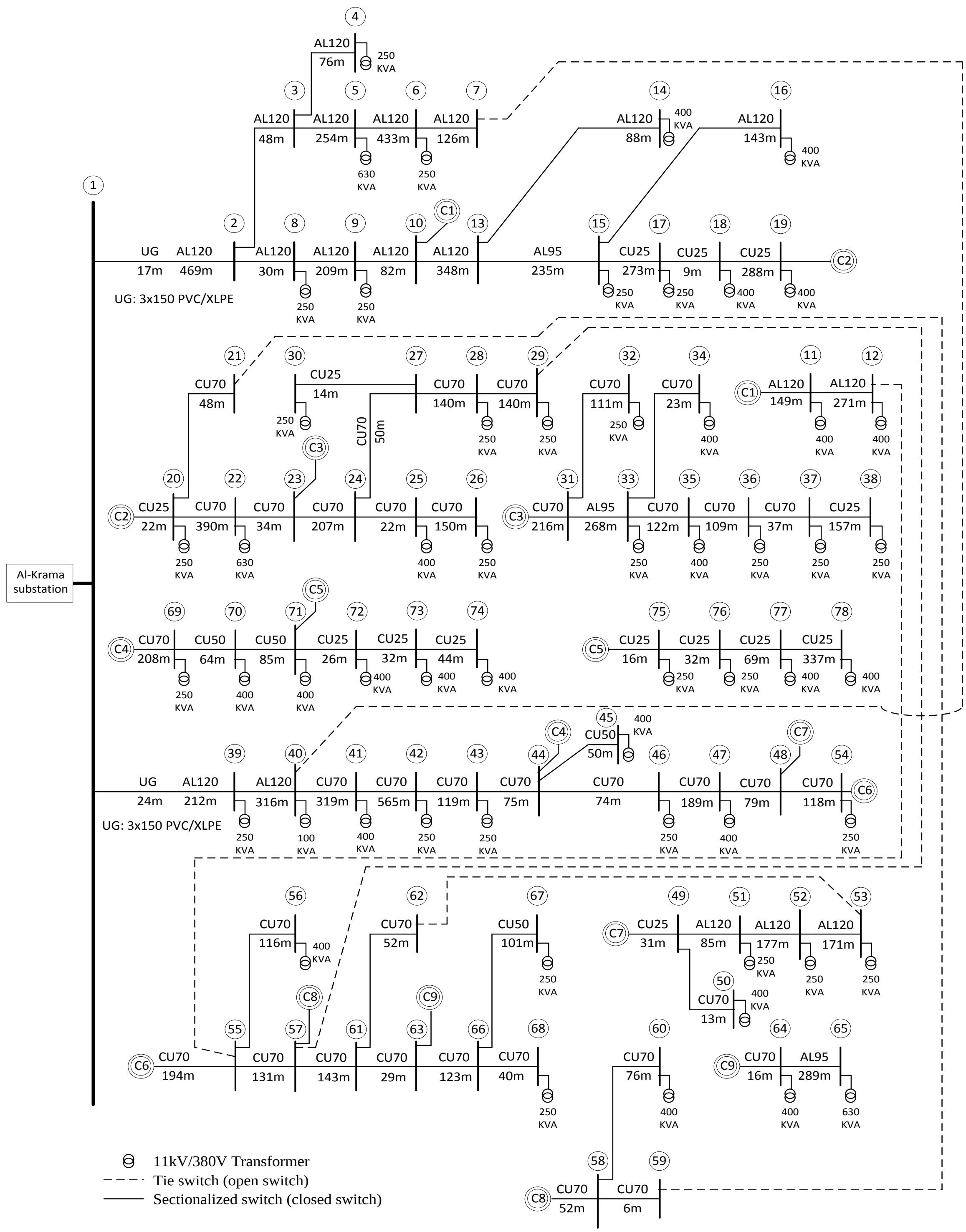

Figure (3): Single line diagram of an actual distribution system selected from Hillah city network

5. Results and Discussions

In order to find the optimal reconfiguration for the given large distribution system, the proposed reconfiguration method is implemented in MATLAB environment. The reconfiguration results are listed in Table (3). It can be seen from this table that the optimal radial configuration is obtained by opening the switches (5, 54, 60, 58 and 21).

Table (3): Distribution system reconfiguration results

	Existing system configuration		Proposed system configuration	
Open switches	78	(from bus-7 to bus-40)	5	(from bus-5 to bus-6)
	79	(from bus-12 to bus-55)	54	(from bus-54 to bus-55)
	80	(from bus-53 to bus-62)	60	(from bus-57 to bus-61)
	81	(from bus-21 to bus-59)	58	(from bus-58 to bus-59)
	82	(from bus-29 to bus-57)	21	(from bus-20 to bus-22)
Power Loss	0.26 MW		0.17088 MW	

5.1 Performance Tests

The performance of the proposed method is analyzed based on its impacts on the active power losses, the voltage profile and the branches currents.

i. Power Loss

It can be seen from Table (3) that the power loss determined for the existing system configuration was 0.26 MW while it was decreased to 0.17088 MW for the case of the optimal system configuration obtained from the proposed method. These results verify the effectiveness of the proposed method to decrease the power loss without additional cost.

ii. Voltage Profile

The voltages determined at each bus for the existing system configuration and for the optimal system configuration are presented in Figures (4) and (5), respectively. It can be seen from these results that minimum voltage obtained after reconfiguration was 0.9703 p.u., whereas in the case of the existing system configuration, the minimum voltage was 0.943 p.u. which is lower than the acceptable voltage limits (0.95 p.u.-1.05p.u.). These results verify the ability of the proposed method to improve the voltage profile for a large distribution system.

iii. Branches Currents

It is well known that each branch in the system has a current-carrying capacity based on the size of the branch cable. If the branch current increased higher than its capacity, progressive or immediate damage would occur in the branch cable. In order to analyze this problem, the branches currents are determined for the existing system configuration and for the case of the optimal system configuration obtained from the proposed method. The comparisons between the branch current and the maximum current-carrying capacity of each branch for the two cases are presented in Figures (6) and (7). It can be seen from Figure (6) that the transmitted currents in the branches (16, 17, 18, 19 and 40) are higher than their maximum current-carrying capacity. On the other hand, after system reconfiguration, the transmitted currents in all branches are within the permissible values as shown in Figure (7). These results verify the ability of the proposed method to solve the problem of overloaded branch in Iraqi power distribution system.

The preceding discussion demonstrates the effectiveness of the proposed distribution system reconfiguration method in conjunction with the proposed modified version of WCOM to enhance a complex and an actual power distribution system in Iraq.

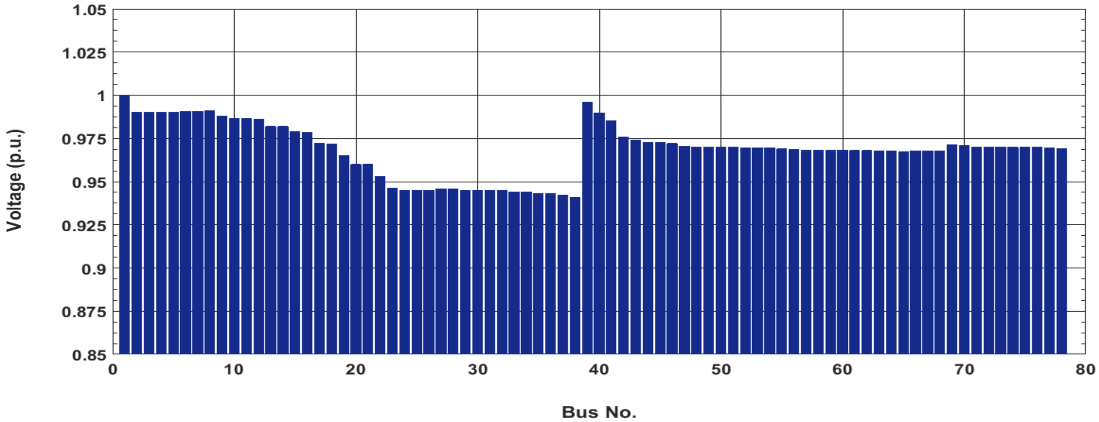

Figure (4): Voltage profile for the existing system configuration

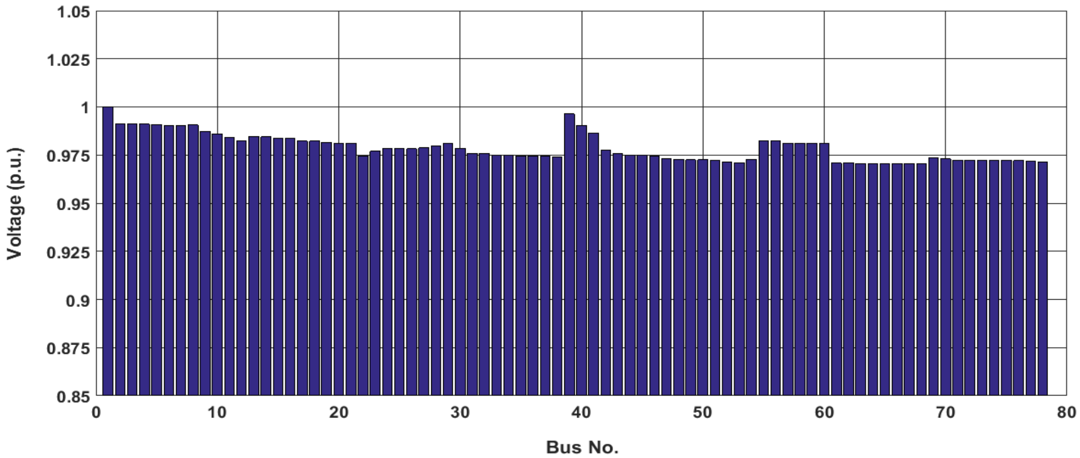

Figure (5): Voltage profile for the system after reconfiguration

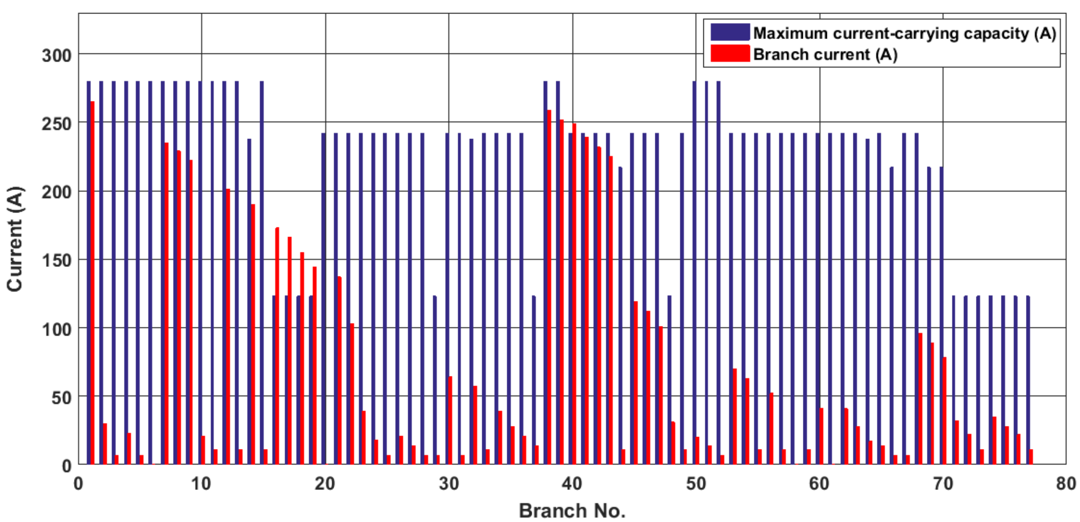

Figure (6): Currents and maximum current-carrying capacity of each branch for the existing system configuration

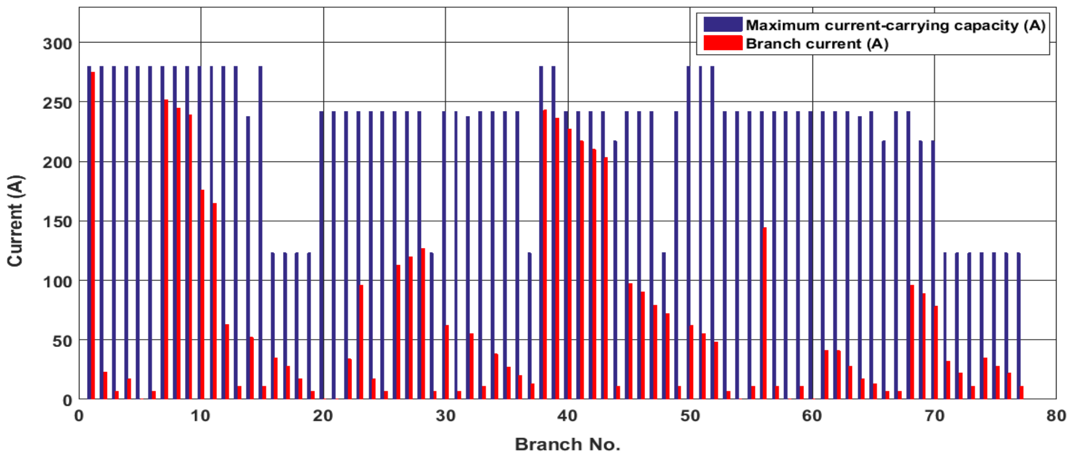

Figure (7): Currents and maximum current-carrying capacity of each branch for the system after reconfiguration

5.2 Comparison Tests

As mentioned before, the conventional solution to the problem of overloaded branch utilized by electric power distribution utility in Iraq is the upgrading of the branch cable size. For the actual case study analyzed in this paper, the overloaded branches are (16, 17, 18, 19 and 40), as shown in Figure (6), and the length of these branches is 1053m. Accordingly, high cost is required to apply the conventional method which includes the cost of 1053m cable as well as the installation cost.

On the other hand, the proposed method does not only solve the problem of overloaded branch but it also improves the voltage profile and decreases the power losses without any additional cost. It only requires changing the state of five tie-switches and five sectionalized switches in the system as shown in Table (3). These results verify the superiority of the proposed method over the conventional method.

In order to verify the superiority of the proposed selective water cycle optimization method over other optimization methods, a comparison between the proposed method and a genetic algorithm method proposed by Taher (Taher *et.al.*, 2014) is presented. The genetic algorithm was implemented in MATLAB environment using single point cross-over and single point mutation with probability of 0.8 and 0.02, respectively. The objective function and constraints presented in this paper were also used in the formulation of the genetic algorithm. The system reconfiguration results of the two methods are presented in Table (4).

Table (4): Comparison of the system reconfiguration results

	Genetic algorithm method (Taher *et.al.*, 2014)	Proposed method
Open switches	4 (from bus-3 to bus-5) 54 (from bus-54 to bus-55) 60 (from bus-57 to bus-61) 16 (from bus-15 to bus-17) 22 (from bus-22 to bus-23)	5 (from bus-5 to bus-6) 54 (from bus-54 to bus-55) 60 (from bus-57 to bus-61) 58 (from bus-58 to bus-59) 21 (from bus-20 to bus-22)
Power Loss	0.1717 MW	0.17088 MW

It can be seen from the results presented in Table (4) that the active power loss in the case of the proposed system configuration was 0.17088 MW while it was 0.1717 MW for the system configuration obtained using genetic algorithm. These results verify the accuracy and superiority of the proposed optimization method over other methods, to find the optimal system configuration.

6. Conclusion

Some distribution systems in Iraq suffer from high power losses, poor voltage-profile, and the excessive loading of the system branches. The strategies proposed by electric power distribution utilities in Iraq for remedying this problem are very expensive and are not applicable in this time due to Iraqi economic crisis.

This paper presented a distribution systems reconfiguration method to enhance the performance of Iraqi power distribution systems without any additional cost. A modification to the original WCOM was also proposed, in this paper, to consider the selective search space required in the reconfiguration problem. The proposed distribution system reconfiguration method in conjunction with the proposed modified version of WCOM was utilized to determine the optimal system configuration. The objective of the proposed methods was to minimize the active power losses with satisfying the system constraints. An actual distribution system selected from Hillah city network was used to evaluate the performance of the proposed methods. Test results verified the ability of the proposed methods to minimize the power losses, to improve the voltage profile and to solve the problem of overloaded branch in Iraqi power distribution system. Moreover, the superiority of the proposed methods over other methods was also verified.

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