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SIMULATION AND CONTINGENCY ANALYSIS OF A DISTRIBUTED NETWORK IN IRAQ

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Abstract: This paper presents the contingency analysis to study the impact of forced or planned outages on electrical distribution system. The mathematical modeling of contingency analysis includes; the load flow analysis and the power restoration analysis. The power restoration is formulated as a constrained multi-objective optimization problem, based on the ranking search method. The method performs load flow simulations and utilizes the analytical information obtained to maximize the amount of total power restored and to minimize the number of required switching operations.In this work the contingency analysis is based on the advanced CYMDIST software as a tool for the simulation of a distribution network and performing the required analysis. CYMDIST software is practical and efficient analysis software used by many electrical companies worldwide as well as by the Iraqi ministry of electricity. The distribution network simulation and contingency analysis proposed in this paper were implemented on Al_Amereah 11 kV network which is a part of Baghdad city distribution network. The results show that full power restoration under contingency conditions after fault isolation without violating constraints was achieved in three steps: optimal switching, addition of a feeder, and optimal capacitor placement.

Keywords: *Contingency analysis in distribution network, CYMDIST software, power restoration, network reconfiguration, capacitor placement.*

محاكاة وتحليل الطوارئ لشبكة توزيع في العراق

الخلاصة: تقدم هذه الورقة تحليل الطوارئ لدراسة أثر انقطاع التيار القسري أو المخطط له على منظومة التوزيع الكهربائية. التمثيل الرياضي لتحليل الطوارئ يشتمل على تحليلات سريان الحمل و تحليلات استعادة القدرة الكهربائية. استعادة القدرة الكهربائية تم صياغتها على شكل مسألة أمثلية متعددة الاهداف مقيدة،وذلك بالاستناد الى طريقة البحث حسب الترتيب الطبقي ranking search method. هذه الطريقة تعمل محاكاة لسريان الحمل وتستخدم المعلومات التحليلية التي يتم الحصول عليها لاستعادة اعظم قدرة كهربائية للمستهلكين وبأقل عدد من عمليات التبديل (فتح وغلق المفاتيح).في هذا العمل استند تحليل الطوارئ على برامجيات CYMDIST المتقدمة كأداة لمحاكاة شبكة التوزيع الكهربائية وإجراء التحليلات المطلوبة. برنامج CYMDIST برنامج تحليل عملي وفعال يستخدم من قبل العديد من شركات الكهرباء في جميع أنحاء العالم، وكذلك من قبل وزارة الكهرباء العراقية. محاكاة شبكة التوزيع الكهربائية وتحليل الطوارئ المقترح في هذه الورقة تم تنفيذه على شبكة توزيع كهرباء العامرية 11 kV والتي تمثل جزءاً من شبكة توزيع كهرباء بغداد-الكرخ. وتشير النتائج أن استعادة الخدمة كاملة بعد عزل العطل، بدون أي انتهاك للقيود في ظل حالة الطوارئ، تم تحقيقه في ثلاث خطوات: التبديل (فتح وغلق المفاتيح) الامثل، اضافة مُغذي، والتوزيع الامثل للمتسعات.

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1. Introduction

Due to the huge expansion of electric power systems the distribution systems have been more complex and hence fault events are unavoidable. These faults affect the system's reliability. Contingency analysis studies the impact of outages of network elements and investigates the resulting effects on bus voltages and power flow for the remaining system.

In case of feeder outage in a power distribution system, the supply of power is isolated from the feeder to certain loads. Most feeders are provided with tie circuits to neighboring feeders from either the same or different substations in order to restore power to out of surface consumers following a fault. Restoring power using these ties requires a number of switching operations [1].

The objective of power restoration is to restore the maximum possible loads by supplying power to the out of service areas from other distribution feeders by finding the optimum switching plan (changing the status of normally closed sectionalizing switches and normally open tie switches) this process is known as network reconfiguration.

Restoring power to the whole out of service area is not always possible, sometimes substations located at the borders of the utility service area may have no alternative feed to its feeders. Sometimes alternative feed is possible however it may not be possible to restore power at peak load intervals without causing over load or voltage drop problems [2]. The capacity of networks must be expanded over time to cope with increasing demand arising from population and economic growth. Feeders, transformers and other network appliances need to be upgraded to support the load growth and peak load level. However, upgrading the transformer and feeder rating may not be cost benefit. To avoid extra upgrades, area planning is needed to provide means for restoring the abnormal system to its normal working condition through [3]:

1) Load balancing in the network, by transferring some loads from heavily loaded feeders to lightly loaded feeders by switching operations.
2) Placement of shunt capacitors.
3) Replacing the existing conductors with higher capacity conductors.
4) Addition of new feeder to carry some of the loads from the existing feeders.

2. Mathematical Model

2.1 Load Allocation Method

In this work the connected kVA load allocation technique provided by CYMDIST software is used which distributes the substation load demand (entered by the user in amperes for each phase) along the feeder according to the connected kVA of the distribution transformers.

The connected kVA algorithm [4].

$$\mathrm{kVA_T} = \sum_{i}^{n} \mathrm{KVA_{C(i)}} \times \mathrm{LF} \qquad (1)$$

$$kW_{a(i)} = kW_d \times \left[\frac{KVA_{C(i)} \times LF}{kVA_T}\right] \quad (2)$$

$$kVAr_{a(i)} = kW_{a(i)} \times \sqrt{(\frac{1}{P.F})^2 - 1} \quad (3)$$

Where:

i : is the section number. kW_d : is the demand (kW).

kVA_c: is the connected (kVA). kVA_T: is the total connected (kVA).

$kW_{a(i)}$: kW allocated on section (i). $kVAr_{a(i)}$: kVAr allocated on section (i).

2.2 Load flow method (Backward/Forward sweep algorithm)

The Backward/Forward sweep algorithm solves the load flow equations of radial distribution networks iteratively in two stages:

In the first stage the node and branch currents are calculated by the backward sweep starting from the end nodes back to the source node using Kirchhoff's Current Law (KCL). The end nodes currents are calculated as a function of the end nodes voltages and the given loads.

$$I_n = \left(\frac{S_n}{V_n}\right)^* \quad (4)$$

For the first iteration the initial end nodes voltages are taken as the nominal bus voltages at these nodes.

The backward sweeps calculates branch currents and voltage drop in branches to update nodes voltages back to the source node.

$$V_k = V_n + Z_{k,n} \times I_{k,n} \quad (6)$$

The calculated branch currents are saved to be utilized in the following forward sweep calculations.

Finally as a convergence criterion the calculated source voltage is compared to the specified source voltage for mismatch calculation.

$$Error = \left||V_s| - |V_1|\right| \quad (7)$$

In the second stage by the forward sweep starting from the source node to the end nodes the voltage is calculated at each node as a function of the branch currents, using the currents calculated in the previous backward sweep using Kirchhoff's Voltage Law (KVL), with the nominal voltage taken as the source voltage at the starting of each forward sweep**.**

$$V_k = V_n - Z_{k,n} \times I_{k,n} \quad (8)$$

The forward and backward sweeps continues until the calculated source voltage becomes within a specified tolerance with the nominal source voltage [5].

2.3 Power restoration method

In this work the ranking based search method is employed to solve the power restoration problem as a multi objective function multi constraint optimization problem, as illustrated in Figure (1). The method acts to find the optimum switching plan that gives the optimum network configuration which satisfies the objective functions of maximizing power restoration, minimizing the number of switching operations, and load balancing to minimize the risk of overload. Without violating constrains of voltage drop limits, line/transformer capacity limits, and feeder load limits. Also, the radiality of the feeders should be kept. The constrained optimum power restoration algorithms are formulated as follows:

2.3.1 The objective functions are

1. Minimization of out of service area:

$$\min f_1(\bar{x}) = \sum_{i=1}^{n} L_i - \sum_{i=1}^{n_R} L_i \quad (9)$$

Where,

$\bar{x}$: is the switch status vector of the network,

$$\bar{x} = [SW_1, SW_2 \ldots SW_{Ns}]$$

SW_i: is the status of i^{th} switch, closed = 1 and open = 0.

N_s : is the number of switches in the network.

n : is the number of energized buses in the network before fault.

L_i : is the load on i^{th} bus.

n_R: is the number of energized buses in the restored network.

In equation (9), it is assumed that all the buses in the network from 1 to n are energized before fault case. While n_R is the number of the energized buses after fault condition.

2. Minimization the number of switching operations:

$$\min f_2(\bar{x}) = \sum_{j=1}^{Ns} \left| SW_j - SWR_j \right| \quad (10)$$

Where,

$\bar{x}$: is the switch status vector of the network,

$$\bar{x} = [SW_1, SW_2 \ldots SW_{Ns}]$$

Ns: is the number of switches in the network,
SW_j: is the status of j^{th} switch in network just after fault.
SWR_j: is the status of j^{th}switch in the network after restoration.

2.3.2 The constraints

1. Radial network structure: For fault locating and isolation, and the coordination of protective devices, a radial network structure must be retained after power restoration.
2. Bus voltages should not violate their limits:

$$|V_{min}| \leq |V_j| \leq |V_{max}| \tag{11}$$

Where: V_j , is the voltage at bus j; V_{min}, is the minimum acceptable bus voltage; V_{max}, is the maximum acceptable bus voltage.

3. Feeders should not be overloaded:

$$I_j \leq I_{j_{max}} \tag{12}$$

Where: I_j , is the load current in line j; $I_{j_{max}}$the maximum acceptable load current in line j.

4. Power source limit constraint: The total loads of a certain partial network cannot exceed the capacity limit of the corresponding power source.

$$P_t \leq P_s^{max.} \tag{13}$$

$$Q_t \leq Q_s^{max.} \tag{14}$$

Power factor constraint, harmonics constraint, and voltage angle constraint has not been taken into consideration to avoid the complexity of the problem.

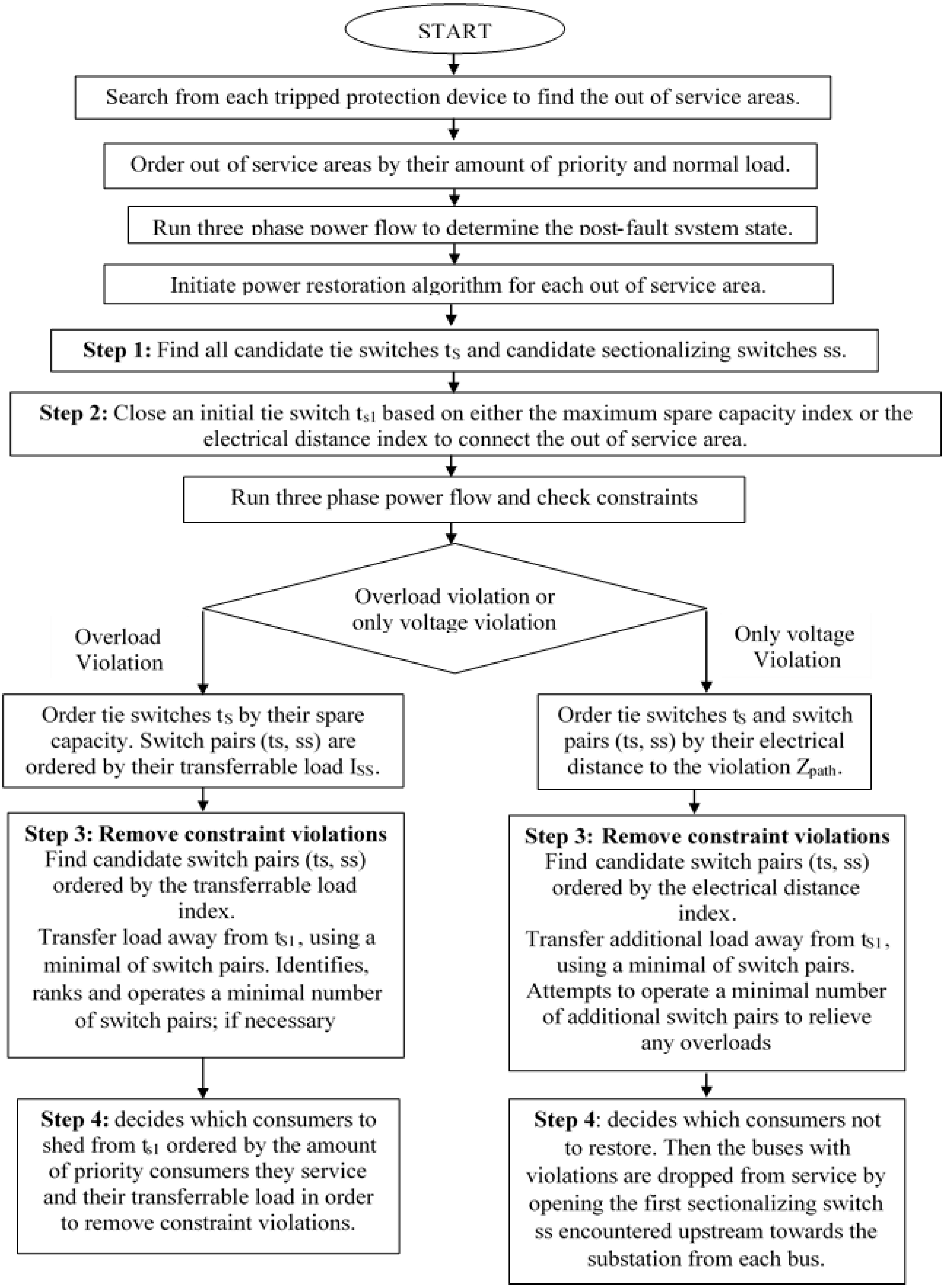

Figure 1. Demonstrates the ranking based search method for power restoration after a contingency case in a distribution network [6].

2.4 Optimal capacitor placement and sizing

Full Power restoration for the out of service area from adjacent feeder may not be possible because extra power flow on the feeder may lead to over load condition on this feeder. Placement of controlled capacitor bank can increase the power transfer capacity of the feeder and increase the possibility of full power restoration. The problem is formulated to determine the optimal shunt capacitor size and location in a radial distribution network by minimizing the ohmic losses. At the same time, the choice is restricted by electric network constraints. The sizes of capacitor banks are given by standard size, which makes the set of solutions to be discrete. Therefore, the problem is classified as a discrete optimization problem [7]. Providing reactive power compensation for a primary distribution network. CYMDIST module is used to determine an optimal compensation solution which also enables variation of the solution when the network configuration changes. Applying compensation using the CYMDIST module helps in saving additional power, improves the voltage profile, and causes lesser load shedding during restoration

2.4.1 Capacitor placement algorithm

The optimal capacitor size and placement at proper node should minimize the objective function in equation (15):

$$P_{loss(k+1)} \leq P_{loss(k)} \quad (15)$$

Where: $P_{LOSS\ (K+1)}$, Power losses after capacitor placement; $P_{LOSS\ (K)}$, Power losses before capacitor placement.

And satisfy the following constraints:

1. Bus Voltage Limits:

$$V_{min} \leq |V_i| \leq V_{max} \quad (16)$$

Where: V_{min} Lower bus voltage limit; V_{max} Upper bus voltage limit; $|V_i|$ rms value of the ith bus voltage.

2. The line flow limits: The line load current (I) should be less than the line rated current (I_{rated}).

$$I \leq I_{rated} \quad (17)$$

3. Power Conservation Limits: The algebraic sum of all incoming and outgoing power including line losses over the whole distribution network should be equal to zero:

$$P_G - \sum_{i=1}^{n} P_D - P_{lt} = 0 \quad (18)$$

Where: P_G is power generation; P_D is power demand; P_{lt} is total power losses

4. The number and Sizes of permissible capacitor banks constraint:

$$\sum_{i=1}^{m} Q_c \leq Q_t \tag{19}$$

Where: Q_c, kVAr obtained from the capacitor bank; Q_t total reactive power flow requirement; m total number of capacitor banks.

The proposed method for capacitor placement in a radial distribution feeder is summarized by the flowchart in Figure (2).

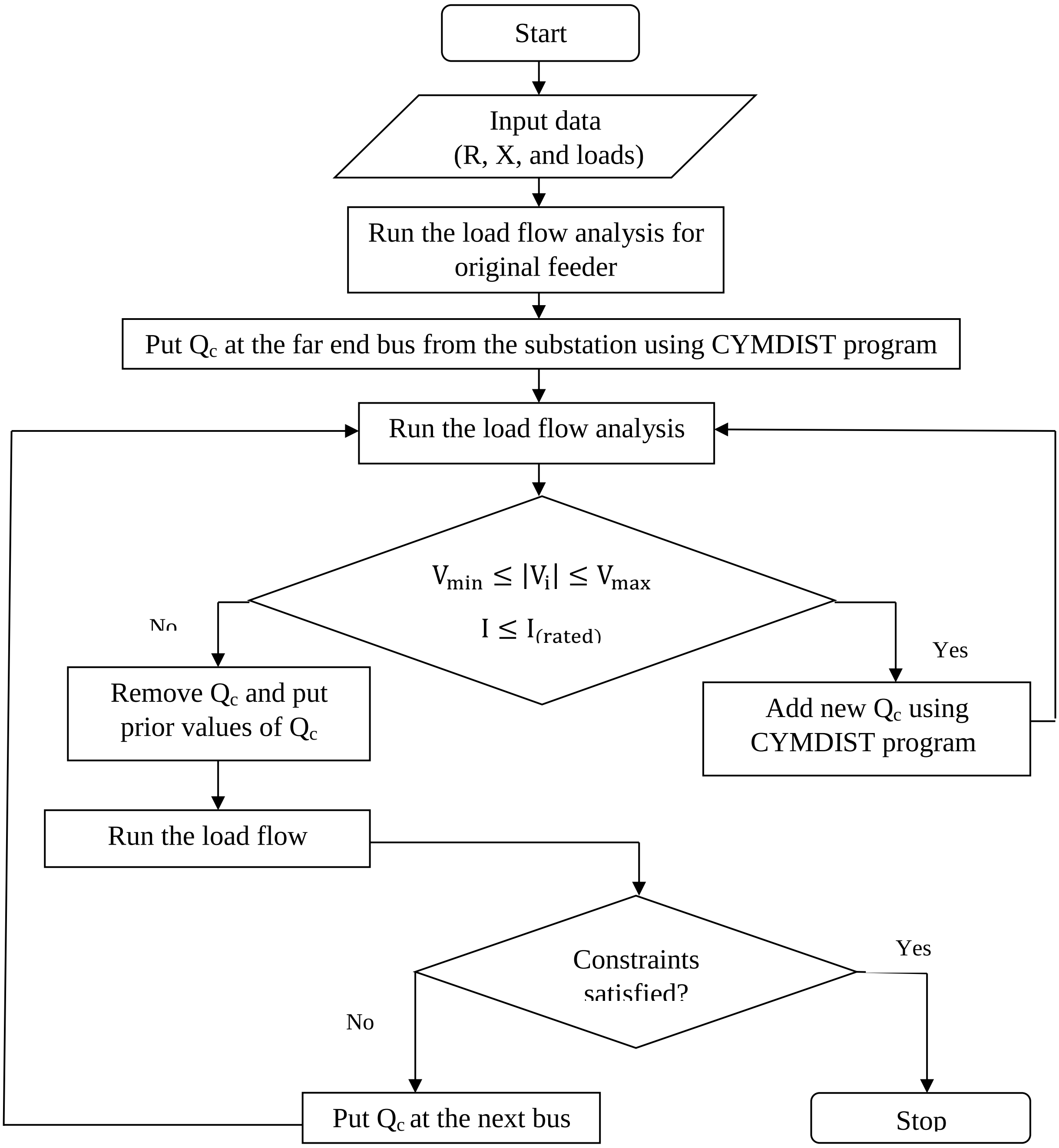

Figure 2. Flowchart of capacitor placement in a radial distribution feeder using CYMDIST program [8].

3. Proposed Network Model

The modeling process begins with acquiring all the input data required for the modeling, and the combined processed data are entered or imported from GIS software into CYMDIST to create the distribution system model, with the single line diagram automatically generated.

4. Contingency Analysis Methodology

The Contingency analysis methodology in this paper is illustrated by the flowchart in Figure (3). The methodology acts to find the optimal configuration that will maximize the electrical power restoration to consumers in a distribution network, after fault isolation, without violating the operational constraints.

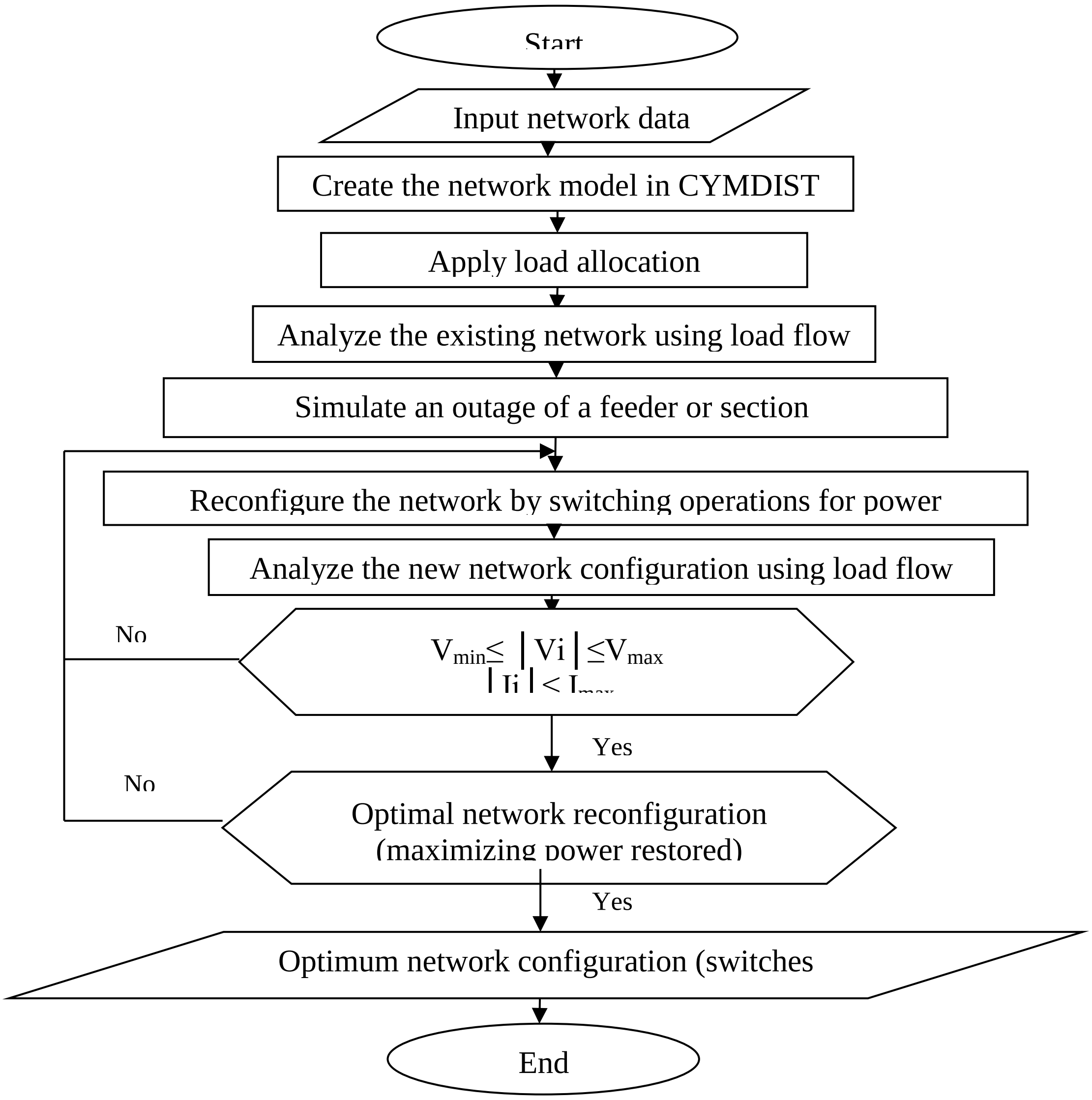

Figure 3. Flowchart representing the contingency analysis methodology using CYMDIST software.

5. Case Study

The analysis is implemented, using the CYMDIST 4.5 (Rev.6) software, on Al_Amereah distribution network which is a part of the distribution system in Baghdad city. The network consists of 11 outgoing feeders from Al_Amereah substation (33/11kV, 2×31.5 MVA) serving a large area of mixed residential, commercial, and industrial loads. The network is rated at 11 kV, base 100MVA, 50 Hz, with 323 line sections, 313 buses, and 11 tie switches. The modeling of Al_Amereah network is based on the actual coordination's taken from Iraqi Ministry of Electricity (MOE) depending on the Global Positioning System (GPS) and Geographic Information System (GIS), as shown in Figure (4).

Loads allocation: Loads are allocated on all sections by using the connected kVA method depending on the load current at the head of each feeder as given in Table (1). The secondary (11/0.4 kV) (Delta-Grounded wye) transformer capacities are given in Table (2).

Figure 4. Al_Amereah network model based on (GPS) and (GIS) data.

Table 1. The load current of the 11 outgoing feeders from Al_Amereah substation.

Main substation transformer (1) 33/11 kV, 31.5 MVA			Main substation transformer (2) 33/11 kV, 31.5 MVA		
Feeder name 11kV	Current/ph (A)	P.F.	Feeder name 11kV	Current/ph (A)	P.F.
Amereah_80	10	0.85	Amereah_87	190	0.85
Amereah_81	130	0.85	Amereah_88	200	0.85
Amereah_82	200	0.85	Amereah_89	260	0.85
Amereah_83	220	0.85	Amereah_90	10	0.85
Amereah_84	160	0.85			
Amereah_85	260	0.85			
Amereah_86	100	0.85			

Table 2. 11\0.4 kV transformer capacities of Al_Amereah network.

Spot load number	Transformer capacity(kVA)
51,158,193,224,227,243,245,255,271	100
8,14,15,17,19,21,22,29,30,34,35,43,45,46,47,48,50,52,53,57,58,61,62,63,65,66,69,	
71,73,76,78,80,81,83,85,,86,88,92,94,95,96,97,98,99,106,108,109,110,111,112,116	250
118,119,120,122,127,129,130,131,132,134,135,136,138,140,141,143,145,146,150,	

155,156,160,164,168,183,190,194,204,206,207,208,209,211,213,215,220,221,222, 223,230,237,246,249,250,256,258,260,261,263,265,266,270,275,278,280,283,286, 289,291,297,300,309,313,315,319	
13,44,55,60,67,74,75,82,104,105,115,117,125,152,172,180,181,182,202,225,226, 236,238,242,264,267,269,272,273,274,276,279,295,299,305,308,310,317,318	400
9,11,12,68,77,89,176,179,185,187,191,192,195,199,232,233,235,244,247,248,301, 302	630
2,3,6,103,157,175,282,285	1000

5.1 Load flow study of Al_Amereah during normal operation

Voltage levels and load currents are calculated using backward/forward sweep load flow method in CYMDIST during normal operating conditions for the original configuration, as shown in Figure (5). The load summary and voltage drop results are given in Table (3).

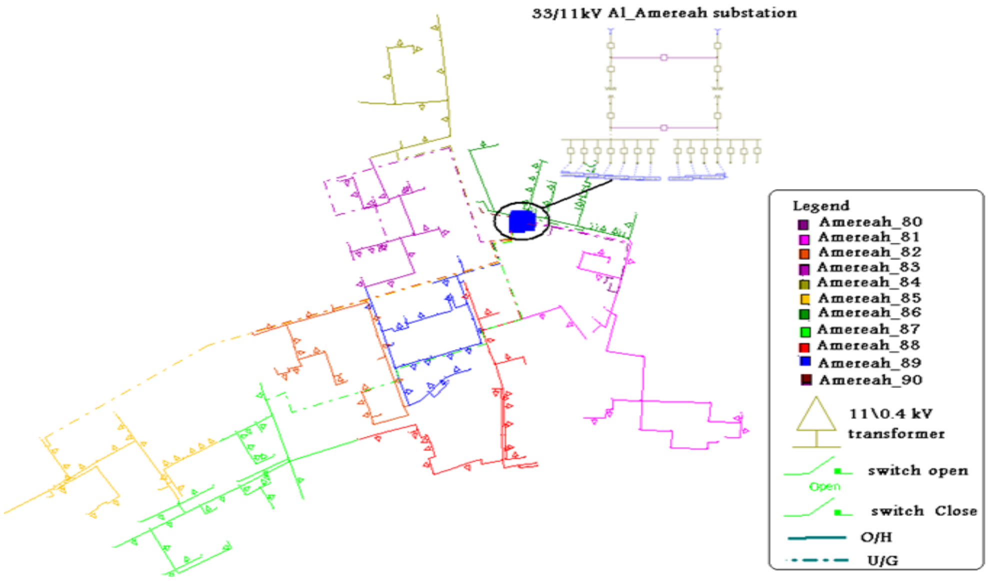

Figure 5. Single line diagram of Al_Amereah network during normal operating conditions.

Table 3. Load summary and voltage drop of Al_Amereah network during normal operating conditions.

Feeder name	Current A/ phase	Feeder current loading (%)	Total Load		P.F.	Minimum voltage on feeder (p.u.)	Location of minimum voltage
			kW	kVAr			
Amereah_80	10	2.9 %	161.94	104.35	0.8406	0.999	Section _6
Amereah_81	130	37.68 %	2095.61	1299.84	0.8498	0.994	Section _41
Amereah_82	200	57.97 %	3194.18	1976.22	0.85	0.98	Section _71
Amereah_83	220	63.76 %	3512.49	2178.69	0.8498	0.98	Section _99
Amereah_84	160	46.38%	2573.5	1597.02	0.8497	0.98	Section _112
Amereah_85	260	75.35%	4100.4	2531.86	0.85	0.963	Section _152
Amereah_86	100	29 %	1616.88	1004.6	0.849	0.995	Section _213
Amereah_87	190	55.07 %	3025.56	1874.01	0.85	0.976	Section_251

Amereah_88	200	57.97 %	3198.75	1971.48	0.85	0.98	Section _286
Amereah_89	260	75.4%	4154.27	2557.04	0.85	0.98	Section _319
Amereah_90	10	2.9%	161.95	101.22	0.85	0.999	Section _321

The results obtained in Table (3) show that all the feeders are within their current carrying capacities, the voltage levels are within their 5% limit, and the network is in a healthy state.

5.2 Contingency analysis of Al_Amereah distributed network

To perform the contingency analysis, feeder outage is simulated assuming 3-phase fault on one feeder at a time.

Feeder Amereah_81 outage is simulated by assuming a fault on section_7 which is the main outgoing line (underground cable) from substation Al_Amereah to supply the rest of the feeder. The contingency program opens switch (Sw_7) to clear the fault, this results in loss of power supply to sections (7 to 41), as shown by the darker black line in Figure (6). The total load for the unserved consumers is 2905.6 kW.

Similarly for feeders Amereah_82, Amereah_84, and Amereah_85 a fault is assumed on the main section of each feeder, which is the outgoing line (underground cable) from substation Al_Amereah to supply the rest sections of the feeder. The total load for the unserved consumers for each case is given in Table (4).The contingency program opens the corresponding switch to clear fault, this results in loss of power supply to the rest of the feeder, as shown by the bold black line in Figures (7) to (9).

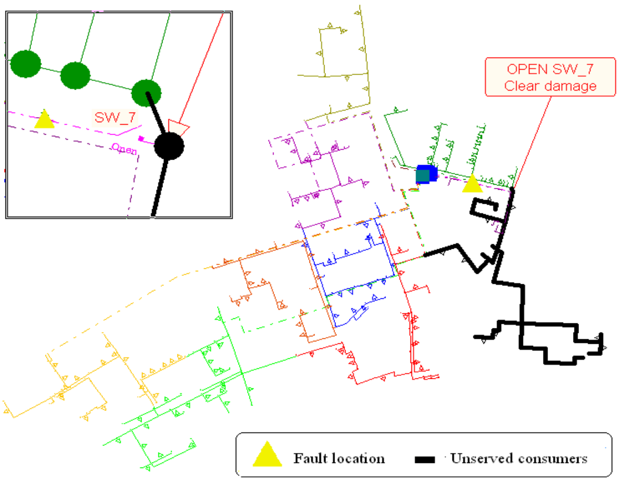

Figure 6. Single line diagram of Al_Amereah network showing the outage of feeder Amereah_81.

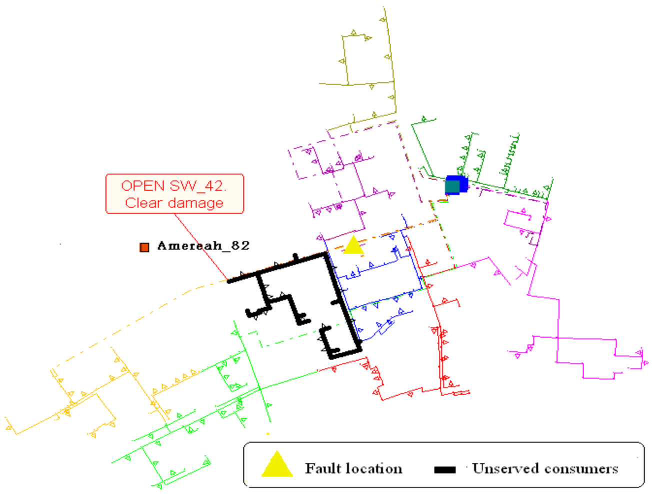

Figure 7. Single line diagram of Al_Amereah network showing the outage of feeder Amereah_82.

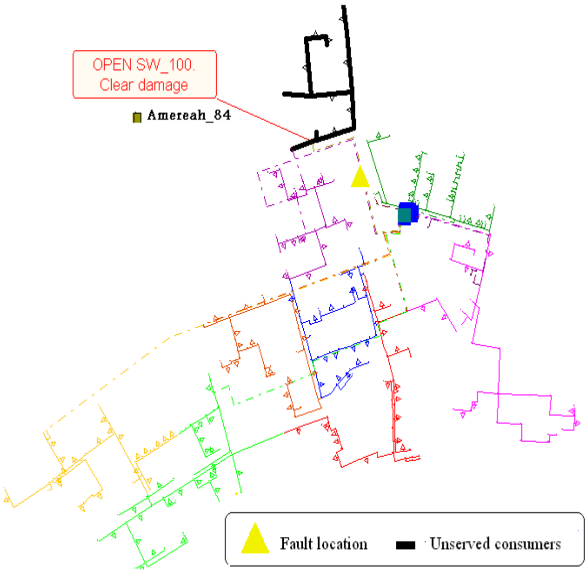

Figure 8. Single line diagram of Al_Amereah network showing the outage of feeder Amereah_84.

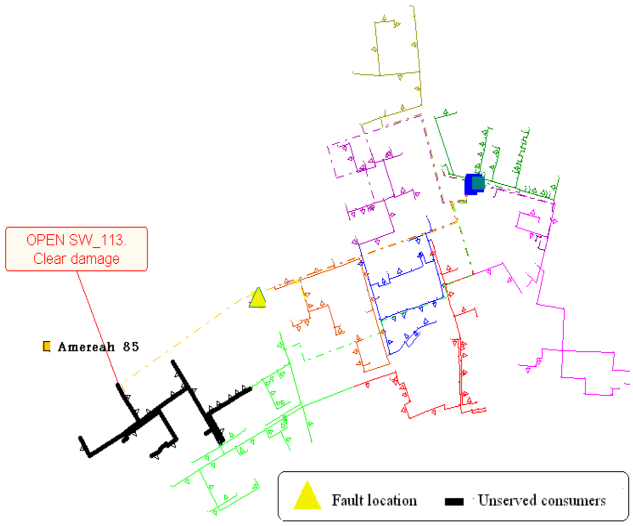

Figure 9. Single line diagram of Al_Amereah network showing the outage of feeder Amereah_85.

Table 4. Summary of contingency analysis following feeder outage.

Feeder outage	Fault location	Switch opened to clear fault	Section outage		Consumers unserved (kW)
			From	To	
Amereah_81	Section_7	Sw_7	7	41	2095.6
Amereah_82	Section_42	Sw_42	42	71	3194.18
Amereah_84	Section_100	Sw_100	100	112	2573.5
Amereah_85	Section_113	Sw_113	113	152	4100.4

5.3 Service restoration by network reconfiguration after fault isolation

The program carries on network reconfiguration by opening and closing switches according to the switching optimization technique to restore power to consumers affected by the feeder outage. The optimum configurations of feeders Amereah_81, Amereah_82, Amereah_84, and Amereah_85 are obtained as follows:

1. For the contingency case of feeder Amereah_81, the network was reconfigured by closing N/O tie-switch (Tie_Sw_212), as shown in Figure (10). Closing tie-switch (Tie_Sw_212) allow transfer of load 2095.6 kW from feeder Amereah_81 to feeder Amereah_86 after fault isolation.
2. For the contingency case of feeder Amereah_82, the network was reconfigured by closing N/O tie-switch (Tie_Sw_70), as shown in Figure (11). Closing tie-switch (Tie_Sw_70) allow transfer of load 1301 kW from feeder Amereah_82 to feeder Amereah_89 after fault isolation. Opening N/C switches (Sw_58), (Sw_62), (Sw_66) and (Sw_71) splits load to avoid overloading on feeder Amereah_89**.**
3. For the contingency case of feeder Amereah_84, the network was reconfigured by closing N/O tie-switch (Tie_Sw_101), as shown in Figure (12). Closing tie-switch (Tie_Sw_101) allow transfer of load 1486.1 kW from feeder Amereah_84 to feeder

Amereah_83 after fault isolation. Opening N/C switch (Sw_105) split load to avoid overloading on feeder Amereah_83.

4. For the contingency case of feeder Amereah_85, the network was reconfigured by closing N/O tie-switch (Tie_Sw_228), as shown in Figure (13). Closing tie-switch (Tie_Sw_228) allow transfer of load 2361.2 kW from feeder Amereah_85 to feeder Amereah_87 after fault isolation. Opening N/C switches (Sw_125), (Sw_126), and (Sw_137) splits load to avoid overloading on feeder Amereah_87.

The summary of power restoration is given in Table (5).

Table 5. Summary of power restoration following contingency analysis for feeders of Al_Amereah network.

Section Id	Switch Id	Action	Reason	Power restoration(kW)	Consumers unserved(kW)
Feeder Amereah_81					
Section Id	Switch Id	Action	Reason	Power restoration(kW)	Consumers unserved(kW)
Amereah_7	Sw_7	0pen	Clear fault	0	2095.6
Amereah_212	Tie_Sw_212	Close	Transfer load	2095.6	0
Total				**2095.6**	**0**
Feeder Amereah_82					
Section Id	Switch Id	Action	Reason	power restoration(kW)	Consumers unserved(kW)
Amereah_42	Sw_42	0pen	Clear fault	0	3194.2
Amereah_66	Sw_66	0pen	Split load	0	3194.2
Amereah_70	Tie_Sw_70	Close	Transfer load	1301	1893.2
Amereah_58	Sw_58	0pen	Split load	0	1893.2
Amereah_71	Sw_71	0pen	Split load	0	1893.2
Amereah_62	Sw_62	0pen	Split load	0	1893.2
Total				**1301**	**1893.2**
Feeder Amereah_84					
Section Id	Switch Id	Action	Reason	Power restoration(kW)	Consumers unserved (kW)
Amereah_100	Sw_100	0pen	Clear fault	0	2573.5
Amereah_101	Tie_Sw_101	Close	Transfer load	1486.1	1087.4
Amereah_105	Sw_105	0pen	Split load	0	1087.4
Total				**1486.1**	**1087.4**
Feeder Amereah_85					
Section Id	Switch Id	Action	Reason	Power restoration(kW)	Consumers unserved (kW)
Amereah_113	Sw_113	0pen	Clear fault	0	4100.4
Amereah_125	Sw_125	0pen	Split load	0	4100.4
Amereah_126	Sw_126	0pen	Split load	0	4100.4
Amereah_228	Tie_Sw_228	Close	Transfer load	2361.2	1739.2
Amereah_137	Sw_137	0pen	Split load	0	1739.2
Total				**2361.2**	**1739.2**

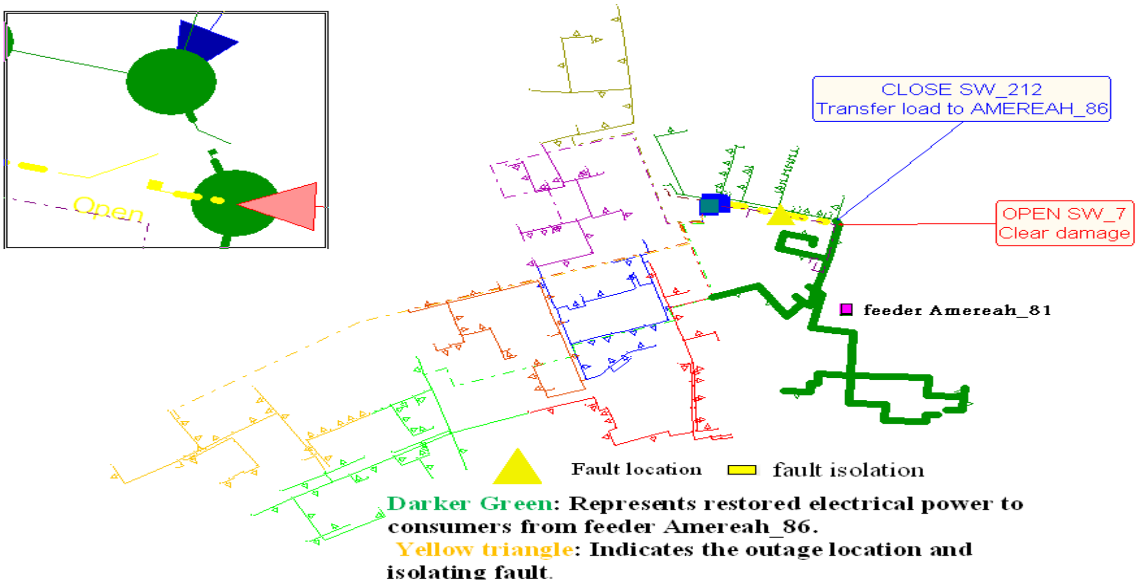

Figure 10. Single line diagram of Al_Amereah network showing the outage of feeder Amereah_81.

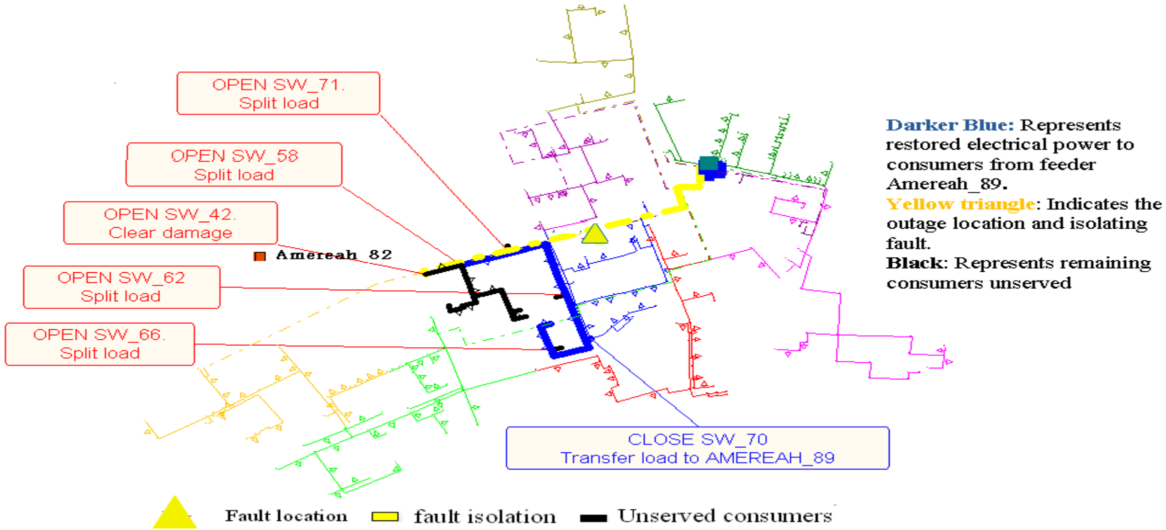

Figure 11. Single line diagram of Al_Amereah network showing the outage of feeder Amereah_82.

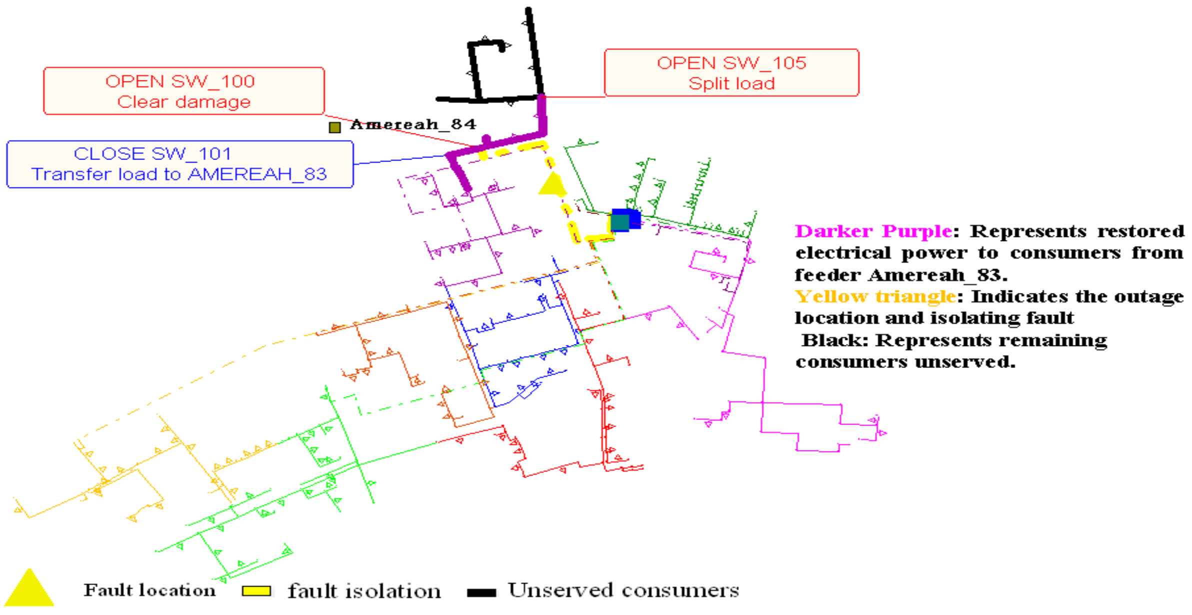

Figure 12. Single line diagram of Al_Amereah network showing the outage of feeder Amereah_84.

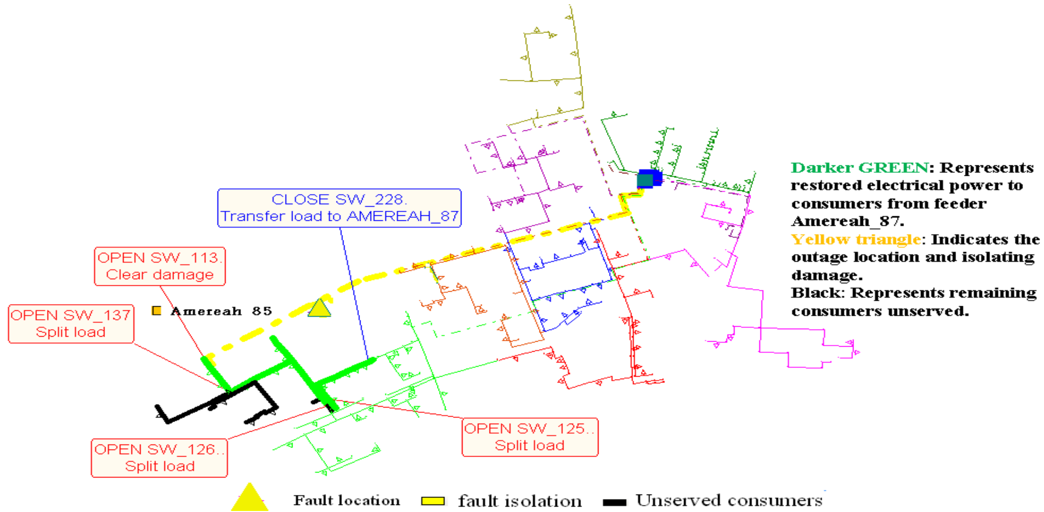

Figure 13. Single line diagram of Al_Amereah network showing the outage of feeder Amereah_85.

The results of power restoration following contingency analysis for the 9 feeders of Al_Amereah network are summarized in Table (6).

Table 6. Power restoration following contingency analysis for the 9 feeders of Al_Amereah network.

Feeder name	Total load before fault (kW)	Power restored after fault clearing (kW)	Consumers unserved (kW)
Amereah_81	2095.6	2095.6	0
Amereah_82	3194.2	1301	1893.2
Amereah_83	3512.5	2082.5	1430
Amereah_84	2573.5	1486.1	1087.4
Amereah_85	4100.4	2361.2	1739.2
Amereah_86	1616.9	1616.9	0
Amereah_87	3025.6	697.1	2328.4
Amereah_88	3198.7	3198.7	0
Amereah_89	4154.3	4154.3	0

5.4 Remedial action for further power restoration

Table (6) illustrates that power restoration following contingency analysis for feeders Amereah_82, Amereah_83, Amereah_84, Amereah_85, and Amereah_87 needs more remedy. Achieving further power restoration in the distribution system requires; addition of new switching, or addition of new feeder, or addition of capacitor to the network.

5.5 Addition of new switches in the network

Feeder Amereah_82: The proposed plan is by adding N/0 switch (Sw_216) between node Amereah_216 and node Amereah_50 to restore the electrical power from feeder Amereah_87 to recover the maximum possible consumers load in the affected areas of feeder Amereah_82, during contingency case. For this contingency case, the network was reconfigured by closing N/O tie-switches (Tie_Sw_70) and (Tie_Sw_216) and opening N/C switch (Sw_63) . Closing (Tie_Sw_70) and (Tie_Sw_216) allow transfer of 985.4 kW and 2208.8 kW from feeder Amereah_87 and Amereah_89 respectively to feeder Amereah_82 after fault isolation. Opening N/C switch (Sw_63) split load to avoid overloading on feeder Amereah_89**.** The reconfiguration is shown in Figure (14). The summary of power restoration is given in Table (7).

Table 7. The proposed switching plan for feeder Amereah_82 after addition of tie-switch (Tie_Sw_216).

Section Id	Switch Id	Action	Reason	Power restoration (kW)	Consumers unserved (kW)
Amereah_42	Sw_42	0pen	Clear fault	0	3194.2
Amereah_63	Sw_63	0pen	Split load	0	3194.2
Amereah_70	Tie_Sw_70	Close	Transfer load	985.4	2208.8
Amereah_216	Proposed Tie_Sw_216	Close	Transfer load	2208.8	0
		Total		**3194.2**	**0**

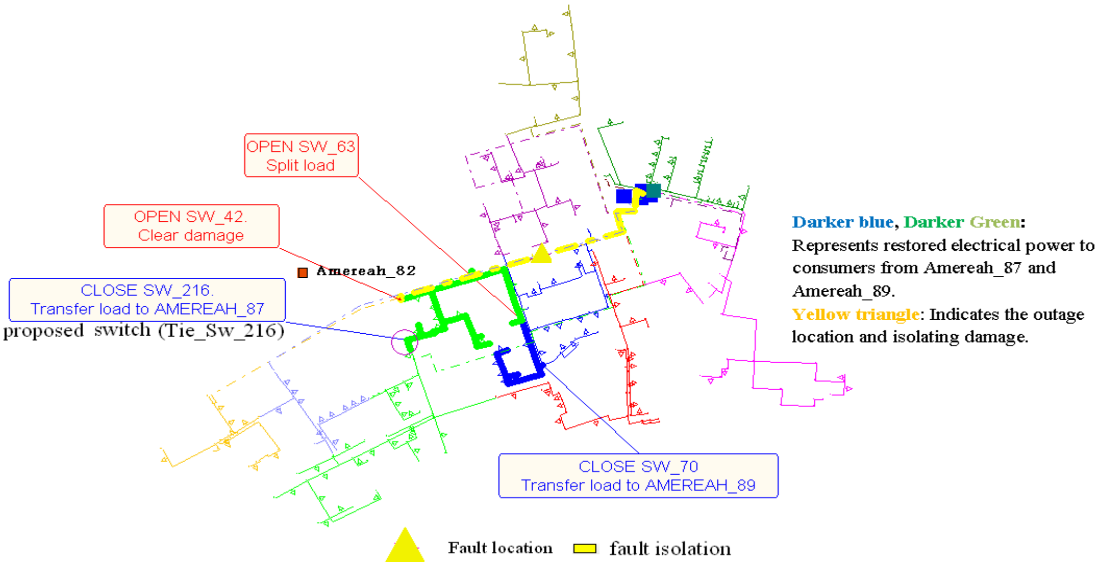

Figure 14. Single line diagram of the network after applying the proposed tie-switch (Tie_Sw_216) to restore electrical power to consumers of feeder Amereah_82 after isolating fault.

5.6 Addition of new feeder in the network

Feeder Amereah_85: The remedy of feeder Amereah_85 using optimal switching and network reconfiguration did not restore the total power during the contingency case. By investigating the network we proposed addition of a new outgoing feeder from substation Al_Amereah. This feeder named Amereah_91 is an underground cable, 2850 m length according to GIS data, as shown in Figure (15). This feeder will reduce load on feeder Amereah_85. The maximum load current on feeder Amereah_85 before addition of the proposed feeder was 260 A, and after the addition of the proposed feeder became 123.8 A, and the maximum load of the proposed feeder is 131.8 A. The load for feeder Amereah_85 before addition was 4100.4 kW and after addition became 1982.06 kW and the load for feeder Amereah_91 is 2108.86 kW.

The contingency analysis was implemented assuming a fault occurrence on feeder Amereah_85. In this contingency case, the network was reconfigured by closing N/O tie-switch switch (Tie_Sw_118) allow transfer of load 1982.1 kW from feeder Amereah_85 to proposed feeder Amereah_91 after fault isolation as given in Table (8). The reconfiguration is shown in Figure (16).

Table 8. Optimal switching plan for feeder Amereah_85 after addition of the proposed feeder Amereah_91.

Section Id	Switch Id	Action	Reason	Power restoration (kW)	Consumers unserved (kW)
Amereah_113	Sw_113	0pen	Clear fault	0	1982.1
Amereah_118	Tie_Sw_118	Close	Transfer load	1982.1	0
	Total			**1982.1**	**0**

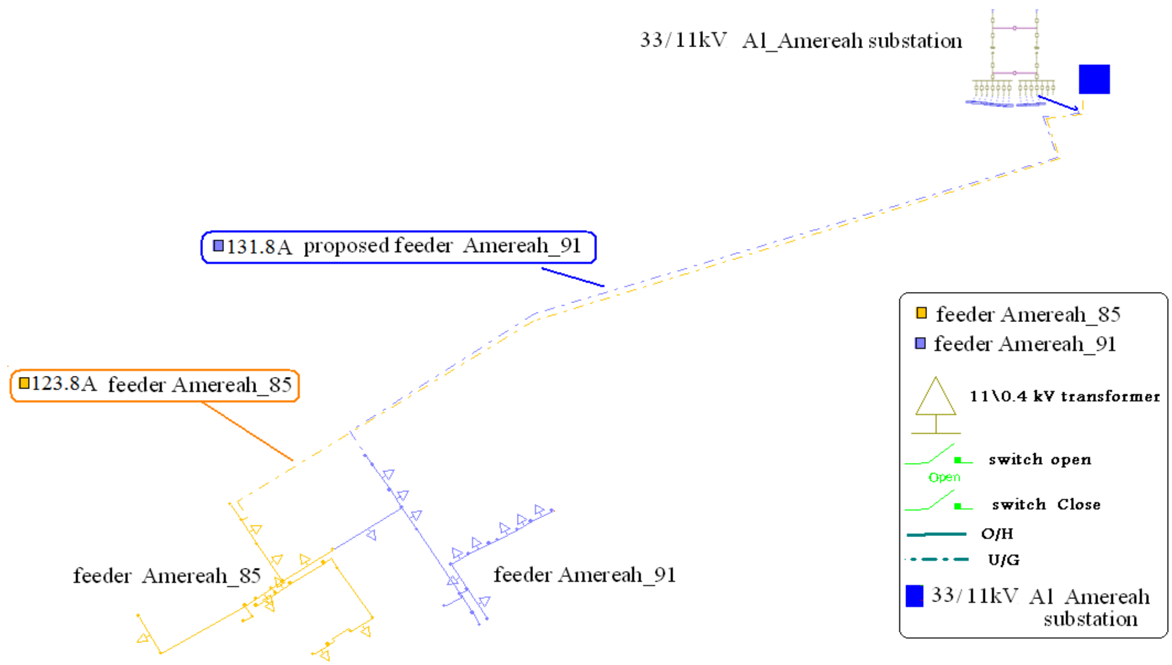

Figure 15. Shows the addition of the proposed feeder Amereah_91 to Al_Amereah network.

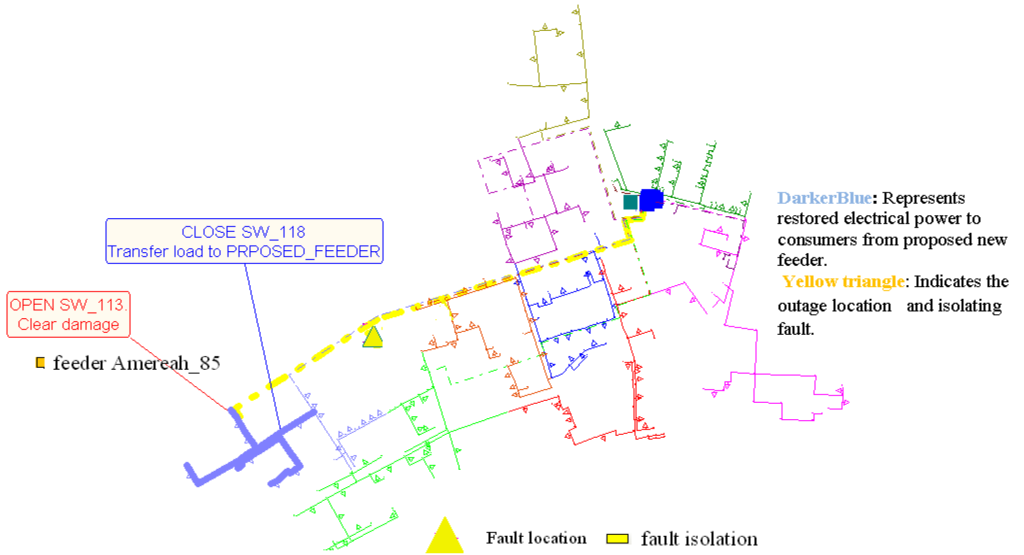

Figure 16. Single line diagram of the optimal switching plan to restore electrical power to consumers on feeder Amereah_85 after isolating fault.

5.7 Addition of capacitor to the network

After the proposed switching plan for feeder Amereah_84 by addition of switch (Sw_106), still there are unserved consumers 1087.4 kW as given in Table (6). As a solution to this problem we proposed addition of capacitors on feeders Amereah_83 and Amereah_84. By using CYMDIST program /capacitor placement analysis the optimum capacitors required for network remedy are as follows:

1. Addition of 300 kVAr and 200 kVAr capacitors on sections Amereah_79 and Amereah_87 respectively to feeder Amereah_83.
2. Addition of 450 kVAr capacitor on section Amereah_102 to feeder Aaereah_84.

This capacitor placement restores all power to feeder Amereah_84 after fault, as shown in Figure (17).

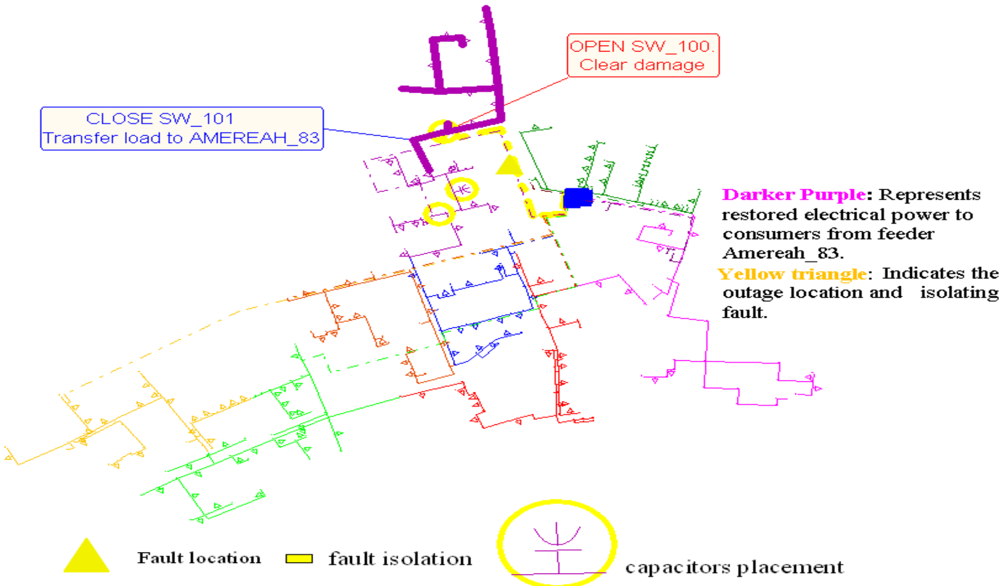

Figure 17. The optimal switching plan following capacitor placement to restore electrical power to consumers on feeder Amereah_84 after isolating fault.

The network was reconfigured by closing N/O tie-switch (Tie_Sw_101) allowing transfer of 2573.5 kW from feeder Amereah_83 to Amereah_84, after fault isolation. The reconfiguration is summarized in Table (9).

Table 9. Optimal switching planAmereah_84 after addtion of capacitor placement.

Section Id	Switch Id	Action	Reason	Power restoration (kW)	Consumers unserved (kW)
Amereah_100	Sw_100	0pen	Clear fault	0	2573.5
Amereah_101	Tie_Sw_101	Close	Transfer load	2573.5	0
	Total			**2573.5**	**0**

6. Al_Amereah Network Voltage Profile

The voltage profile obtained before and after optimum configuration (after fault isolation) of feeders Amereah_81, Amereah_82, Amereah_84, and Amereah_85, as shown in Figures (18) to (21) for each case.

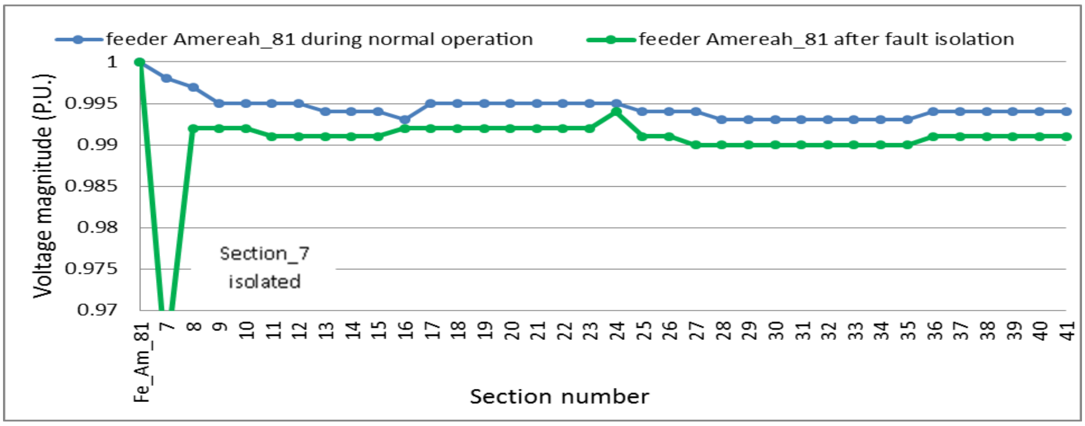

Figure 18. Voltage profile of feeder Amereah_81, during normal operation and after fault isolation.

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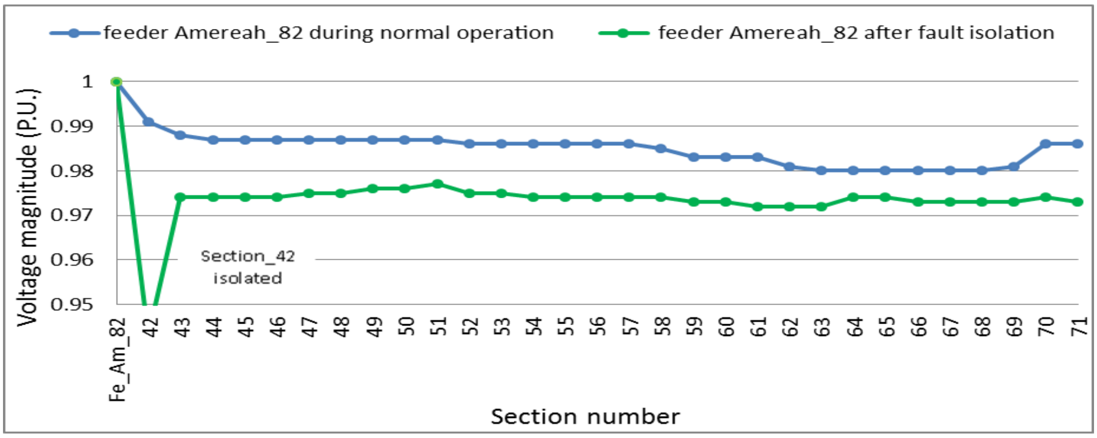

Figure 19. Voltage profile of feeder Amereah_82, during normal operation and after fault isolation.

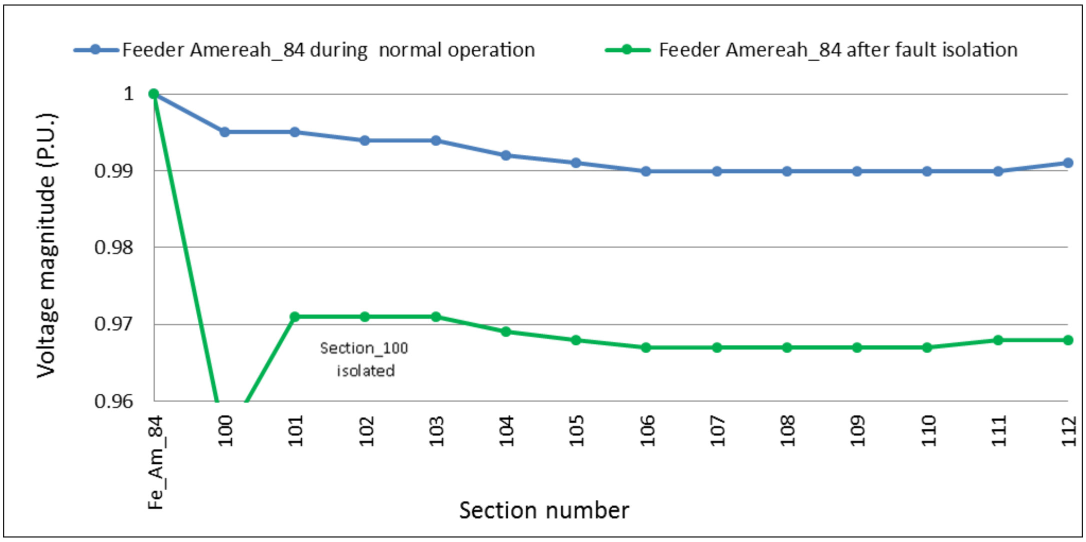

Figure 20. Voltage profile of feeder Amereah_84; during normal operation and after fault isolation.

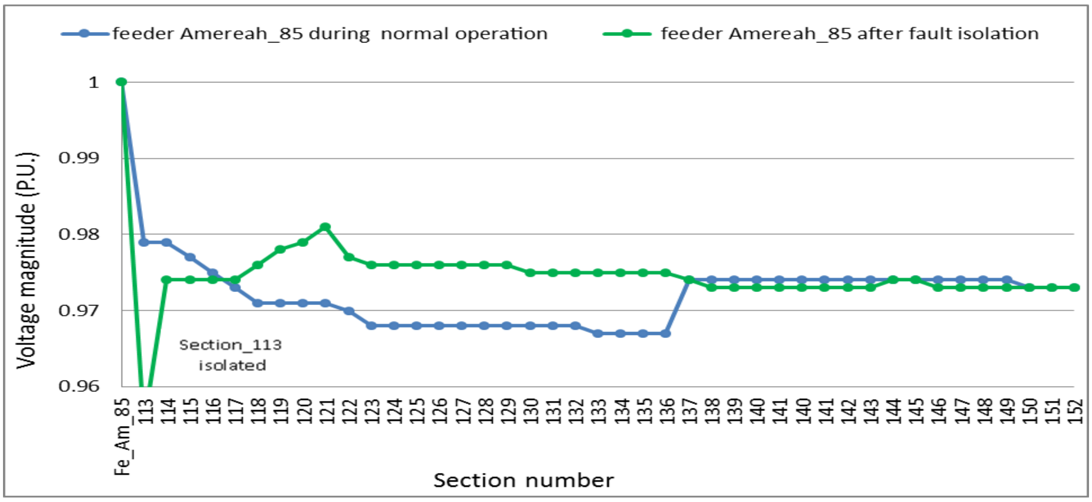

Figure 21. Voltage profile of feeder Amereah_85; during normal operation and after fault isolation.

7. Current Loading of Al_Amereah Network

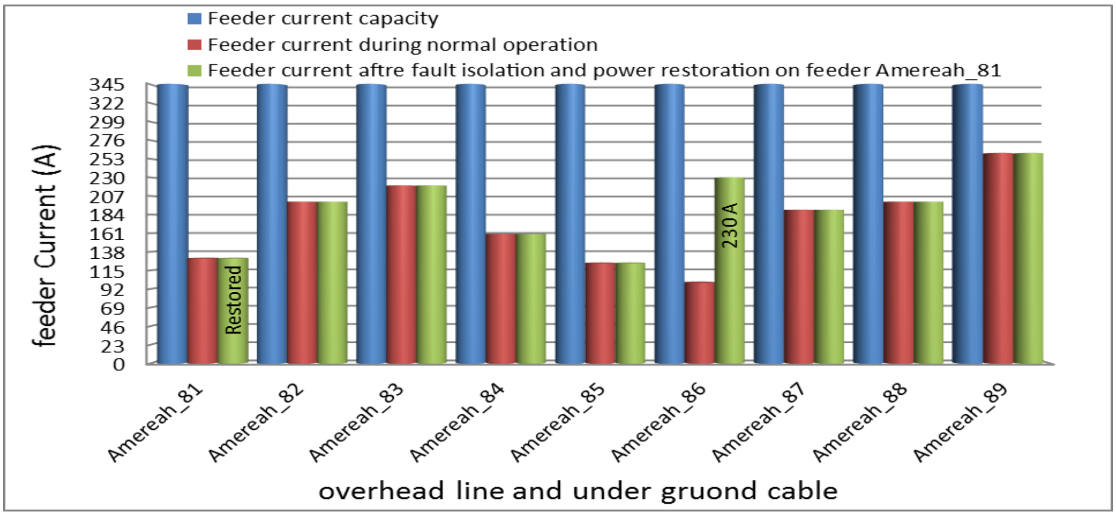

Figure 22. Current loading for feeder of Al_Amereah_81 network.

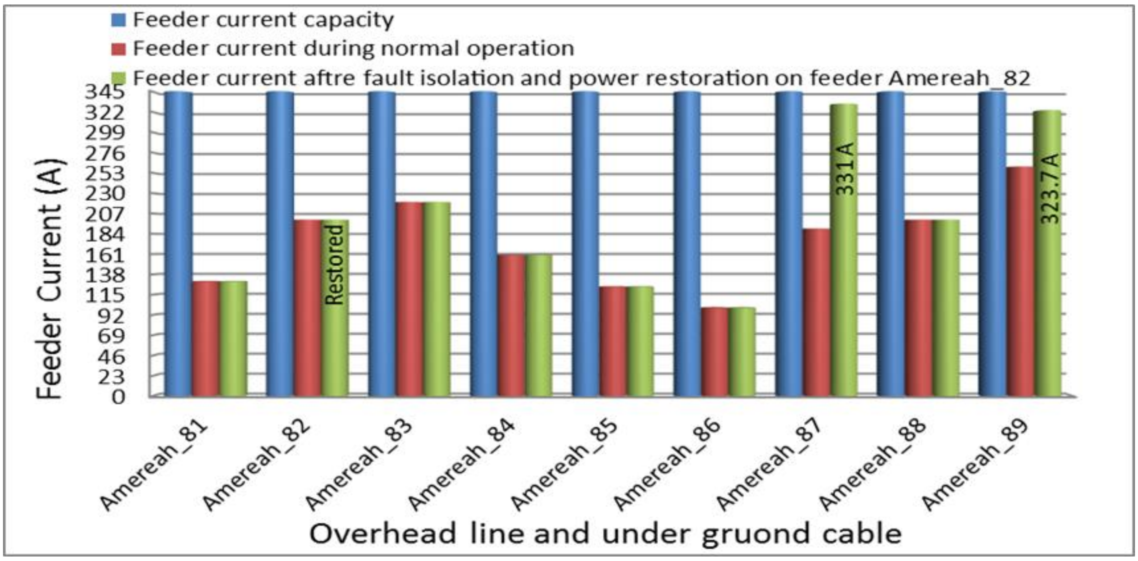

Figure 23. Current loading for feeder of Al_Amereah_82 network.

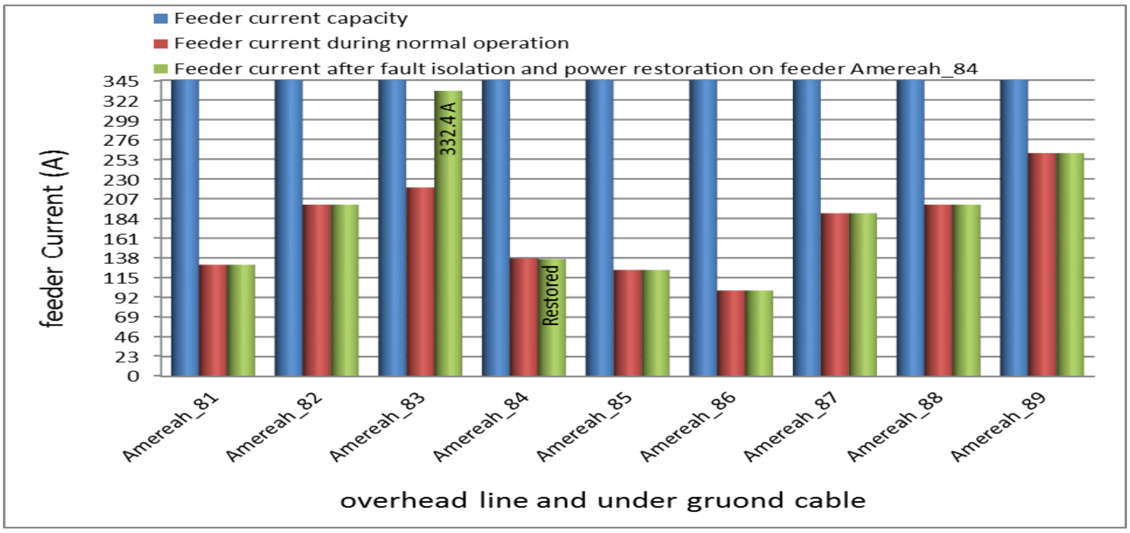

Figure 24. Current loading for feeder of Al_Amereah_84 network.

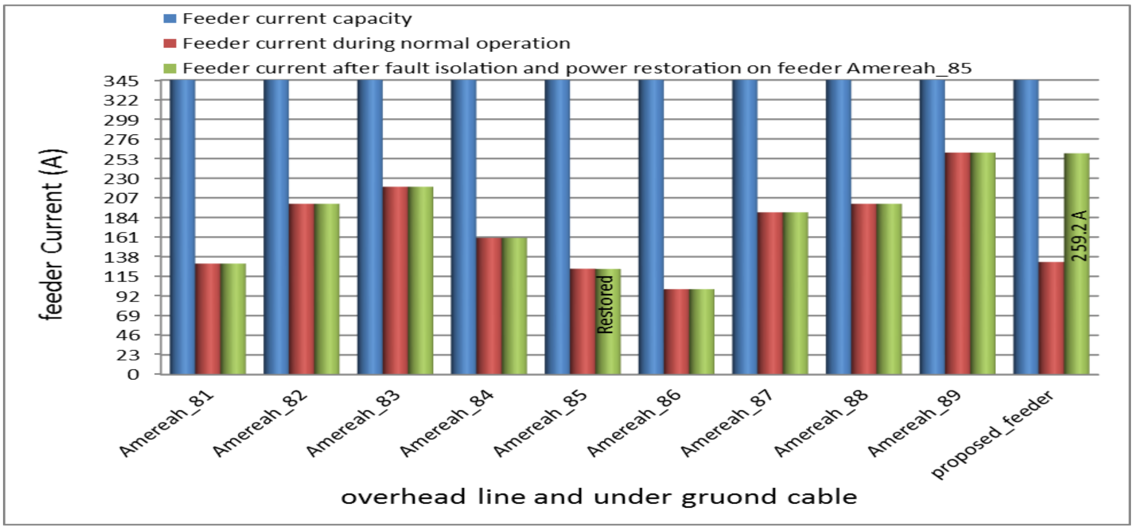

Figure 25.Current loading for feeder of Al_Amereah_85 network.

8. Reactive Power Compensation for Feeder Amereah_83 and Feeder Amereah_84

Table (10) presents current loading, real power, reactive power, and voltage profile before and after capacitor placement on feeder Amereah_83 and feeder Amereah_84. Figures (26) to (29) show the downstream reactive power profile with respect to distance for feeders Amereah_83 and Amereah_84 before and after capacitor placement.

Table 10. Presents current loading, power, and voltage profile after capacitor placement on feeder Amereah_83 and feeder Amereah_84.

feeder Amereah_83	Total load used before compensation				Total load used after compensation			
	Current A/phase	kW	kVAr	Minimum voltage (p.u.)	Current A/phase	kW	kVAr	Minimum voltage (p.u.)
System load	220	3512.49	2178.69	0.98	190.3	3512.4 9	2178.69	0.9868
Total adjusted shunt capacitor	---	0.0	---	---	---	---	1465.59	---
conductor capacities	---	0.0	9.29	---	---	---	9.42	---
System losses	---	50.02	38.74	---	---	37.59	29.18	---
feeder Amereah_84	Total load used before compensation				Total load used after compensation			
	Current A/phase	kW	kVAr	Minimum Voltage (p.u.)	Current A/phase	kW	kVAr	Minimum voltage (p.u.)
System load	160	2573.5	1597.02	0.98	136.5	2573.5	1597.06	0.9915
Total adjusted shunt capacitor	---	0.0	---	---	---	---	1338.57	---
conductor capacities	---	0.0	5.82	---	---	---	5.83	---
System losses	---	17.68	14.57	---	---	13.82	11.64	---

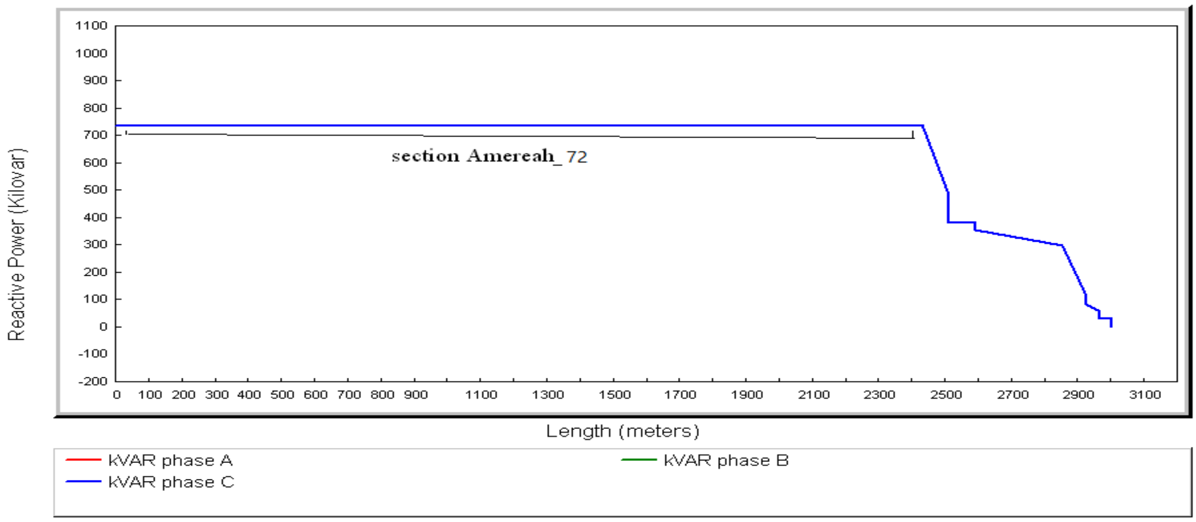

Figure 26. kVAr profile of feeder Amereah_83 before capacitor placement.

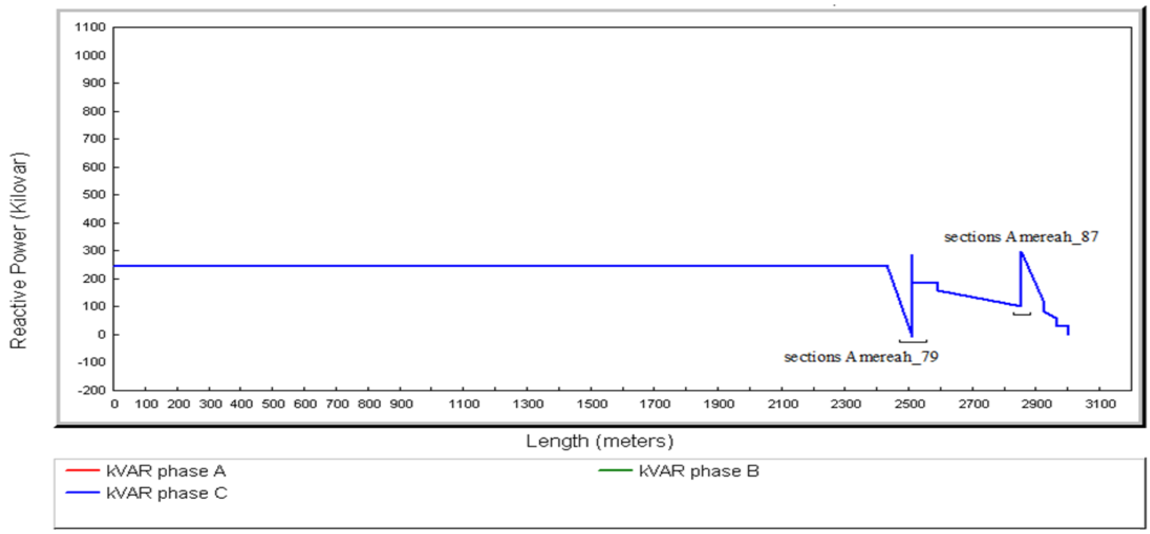

Figure 27. kVAr profile of feeder Amereah_83 after capacitor placement.

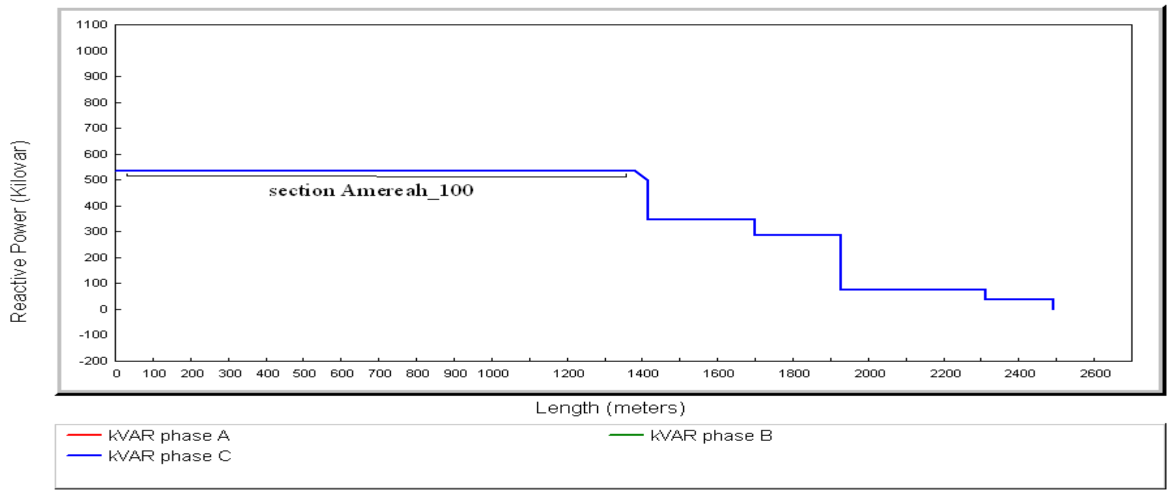

Figure 28. kVAr profile of feeder Amereah_84 before capacitor placement.

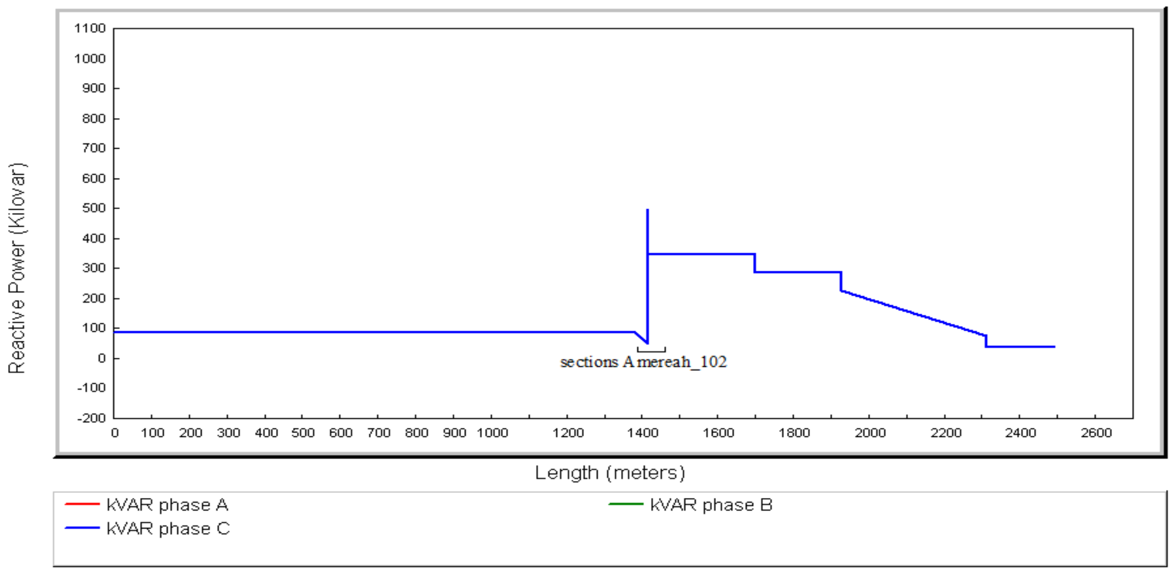

Figure 29. kVAr profile of feeder Amereah_84 after capacitor placement.

Section Amereah_72 (2436.71 m length) has 727.79 downstream kVAr /phase before compensation; this value is reduced to 238.82 kVAr /phase after applying capacitors placement. Also, Section Amereah_100 (1379.5 m length) has 533.53 downstream kVAr /phase before compensation; this value is reduced to 87.273 kVAr /phase after applying capacitors placement. The sections that have capacitors become a source of reactive power, the overall active and reactive power losses will be reduced and lead to increasing conductor capacities. The overall P.F. of each feeder is improved as illustrated in Table (10).

9. Conclusions

Due to the increasing size and complexity of distribution networks, using practical software for the simulation and analysis of such networks become a necessity. Contingency analysis is an important analysis since faults cannot be avoided. In this paper the CYMDIST software is used as a tool for this analysis. The results show that performing optimal switching operations to isolate a fault and restoring the power for maximum number of consumers can only be achieved by proper simulation of the actual distribution network, accurate load flow analysis, and optimal reconfiguration of the network.

Power restoration to all consumers cannot be achieved due to many constraints such as lines capacity and operating current and voltage limitations, so different approaches have been considered in this work for increasing this power restoration, such as addition of switches in the network, addition of a new feeder, or addition of capacitors. These remedial actions for the contingency case can also enhance the overall performance of the network during normal operation.

Abbreviations

I_n	Load current (Amp) at node n
N/C	Normally close
N/O	Normally Open
P_t	Total active power (kW)
Q_t	Total reactive power (kVAr)
ss	Sectionalizing switches
t_S	Tie switches
t_{S1}	Tie switch with the largest spare capacity
V_1	voltage calculated at node 1
Z_{path}	Electrical distance

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