A HEURISTIC BASED METHOD TO DISTRIBUTION NETWORK RECONFIGURATION FOR LOSS REDUCTION AND SERVICE RESTORATION

استخدام طريقة تنقيبية لاعادة تهيئة شبكات التوزيع لغرض تقليل المفاقيد واسترجاع الخدمة

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الملخص العربي:

يقدم البحث طريقة مقترحة لتحقيق وضع مثالي لشبكة التوزيع معتمدا على استخدام الطرق التنقيبية لغرض تقليل المفاقيد فى الحالات الاعتيادية واسترجاع الخدمة للمستهلكين فى حالات القصر أو الصيانة مع تحقيق شروط التشغيل والتحميل لنظام التوزيع وضمان عمل نظام الوقاية بكفاءة ودقة وكذلك الحفاظ على مستوى عالى من الأعتمادية للنظام.
فى هذه الطريقة تم تعريف ثلاثة مؤشرات تؤثر فى اختيار الأماكن المناسبة لفتح حلقات التوزيع حيث تعتمد هذه المؤشرات على عاملين أساسين هما الأنخفاض فى الجهد والمقاومة الكهربائية للخط وسماحيته، وعن طريق اختيار مؤشر القرار الأكبر فى كل حلقة نستطيع الحصول على خطوط الربط التى يجب فتحها فى الحالات الأعتيادية لغرض الوصول الى وضع تشغيل مثالى يحقق أقل مفاقيد قدرة كهربائية حقيقية. أما فى حالة أسترجاع الخدمة فنختار من مجموعة الأحتمالات الموجودة مؤشر القرار الأقل قيمة حتى يمكن تغذية أكبر قدر ممكن من الأحمال المفصولة، وفى حالة فشل ذلك بسبب تجاوز قيود النظام نلجأ الى تخفيف الأحمال مع مراعاة الأحمال التى لها أولويات خاصة.
تم تطبيق الطريقة المقترحة على مثالين أحدهما (IEEE 16 –bus three-feeder system) والثانى نظام فعلى لشبكة التوزيع بمدينة المنصورة وتتكون من 33 قضيب منها محطة تحويل 11/33 ك ف وثلاثة محطات توزيع رئيسية (مفاتيح) و29 محطة توزيع فرعية 11/4و. ك ف و32 خط مغلق فى الوضع الأعتيادى بالأضافة الى 6 خطوط ربط.
وقد أظهرت النتائج مدى قدرة وكفاءة الطريقة المقترحة فى تقليل مفاقيد القدرة الحقيقية وتحسين جهود الشبكة وكذلك اعادة توزيع الأحمال على المغذيات والمحولات، كما طبقت الطريقة المقترحة لاسترجاع الخدمة عند حدوث أخطاء مختلفة بشبكة التوزيع.

ABSTRACT:

This paper presents a proposed solution method to the distribution network reconfiguration for the purpose of loss reduction in normal state and service restoration in the fault or maintenance state. The method is based on a heuristic approach for optimally reconfigure the network. The objective function for loss reduction is to minimize the total system real power losses, while satisfying the operational and loading system constraints. To achieve this objective a heuristic approach based on three switching indices is proposed. Meshed networks are created by closing all the tie switches. The optimal solution is obtained by opening the switch having a maximum decision index in each loop in normal operation state. Under service restoration state, the candidate switch to restore the service into disconnected loads is the switch with smallest decision index. If the system constraints are not satisfied, a load-

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shedding scheme is suggested considering the priorities of loads. Also, the proposed method takes into account the effect of reconfiguration process on the system protection scheme and the reliability level of the system. The method was applied to two test systems. The first is IEEE 16-bus three feeders system, and the second is a part of 11 kV distribution system in Mansoura city. The obtained results show the effectiveness of the proposed method in reducing the system losses, improving the system voltage profile, and relieving loads on feeders and transformers. Moreover, the method is successfully applied to restore electric supply into the faulted sections from alternative feeders.

1- INTRODUCTION

In a power system, the distribution system losses become more of concern due to the growth of load demand and the wide area served by this system. It was estimated that from 5 - 13 % of the total power system generation is wasted as power losses at the distribution level [1]. The optimum operating conditions of distribution networks can be obtained when the networks present minimum losses, minimum voltage deviations at the customer loading points, and maximum reliability. The means normally used to achieve these objectives are:

a) Network reconfiguration and,
b) Reactive power and voltage control by the installation of shunt capacitors and voltage regulators.

Network reconfiguration is the process of altering the topological structures of distribution feeders by changing the open/closed status of the sectionalizing and tie switches under both normal and abnormal operating conditions. During normal operating conditions, networks are reconfigured to reduce the system real power losses, relieve loads in the network and to increase network reliability. Another configuration management operation involves the restoration of service to as many customers as possible during a restorative state following a fault. When a fault occurs on a feeder, the faulted section has to be identified and isolated. The isolated sections will have to be fed from alternative feeders until the faulty branch is repaired. All switches would be restored to their normal positions after removal of the fault.

It is necessary that in the process of feeder reconfiguration, there is no overloading of feeders and transformers, and all system bus voltages are within the limits. Also, coordination of the protective scheme of the new configuration is very necessary and the system reliability level must be satisfied.

The problem of feeder reconfiguration is basically multi-objective, combinatorial and non-linear one with constraints. There have been many papers published in this area. They can be generally classified into three categories:

1) Optimization methods: The optimization methods are based on the application of various optimization techniques such as linear programming methods [1], mixed integer method [2], simulated annealing method [3], and network programming method [4]. Features of these methods are that the problem can be precisely defined in terms of the goal and the set of constraints. The short coming of these methods is that the nature of the problem is so complex that all aspects cannot be exactly taken into account. Moreover, the dimensions of the problem require extensive computer processing in real time. Finally, the convergence problems are such that in some cases only sub-optimal solutions are obtained.

2) Heuristic based methods: The heuristic based methods [1,3-14] have been proposed to find the optimal or near optimal solution with fast computational time. These methods are based on a superior understanding of the features of a distribution network (their radial configuration, multiple alternative supply sources, the concept of relay protection, and operation experience). In the heuristic approach, analytical methods are efficiently combined (estimation, load flow calculations, optimization methods and fuzzy logic). The heuristic approaches require a fewer number of iterations compared to any analytical methods.
3) Artificial intelligence (AI) based methods: In recent years the AI techniques such as ANN, genetic algorithms (GA), and expert systems have been used to determine the distribution reconfiguration [15]. The ANN is a potential candidate for on-line applications because of its fast computational performance. The major drawback is that it requires substational amount of accurate data for training. The training for ANN has to be conducted for each distribution network and any change in the network must be accounted. The GA methods can provide the solution which is independent from the initial system configuration but the computation speed is too slow to apply to large distribution systems. Expert systems are usually used for determining a restoration plan within a transformer station HV/ MV, for diagnosing faults. The other significant use of this approach is for simulation and for training of dispatchers. Because of the great complexity of the problems in distribution networks, expert systems have not been introduced as independent application. They are usually used in combination with other two methods.

2- FEEDER RECONFIGURATION FOR POWER LOSS REDUCTION

In normal operation of distribution networks, the feeders are reconfigured to reduce losses. The power loss in a branch in between two nodes i and j can be written as:

$$P_{L(i,j)} = R_{i,j} \,|\,I\,|^2 = R_{i,j} \,(|\,V_i - V_j\,\|\,y_{i,j}\,|)^2 \tag{1}$$

where

$R_{i,j}$: branch resistance between nodes i and j in p.u.
V_i, V_j: Voltage at nodes i, j in p.u.
y_{ij} : Branch admittance between bus i and bus j in p.u.

The loss reduction problem is formulated by minimizing the following objective function:

$$P_L = \Sigma P_{L(i,j)} = \Sigma R_{i,j} (|\,V_i - V_j\,\|\,y_{i,j}\,|)^2 \tag{2}$$

For all branches n in the system.

The minimization of objective function is subject to the following operational and loading constraints:

$$\left.\begin{aligned} &V_k^{min} \le V_k \le V_k^{max} \quad, k=1,2,\ldots,N \\ &I_m^{min} \le I_m \le I_m^{max} \quad, m=1,2,\ldots,n \\ &P_f^2 + Q_f^2 \le (S_f^{max})^2 \quad, f=1,2,\ldots,F \end{aligned}\right\} \tag{3}$$

where
N : number of system nodes.
n : number of branches.
F : number of feeders.
V_k : the voltage at bus k.
I_m : the branch current.
S_f : apparent power to feeder f.
S_f^{max} : maximum feeder capacity or that of its supply transformer.

The proposed algorithm starts with closing all tie switches to create a meshed network. This meshed network will contain many closed loops, and each loop should have a "best" opening point for minimum losses. Therefore, our goal in normal operation is to find the optimal opening switch for each loop. Eqn.2 indicates that, there are two factors affecting the power loss. These factors are the line parameters (R and Y), and the voltage drop.

2.1 The Voltage Index (I_V)

The minimization of equation (2) causes a low voltage drop that results in low losses. A voltage index (I_V) can be defined for a particular branch m (from i to j) by:

$$I_v(m) = \exp^{k_{Vm}} \tag{4}$$

and

$$kv_m = -\frac{\omega\,(\Delta V_m)^2}{(\Delta V_{av}^2)} \tag{5}$$

where ΔV_m is the voltage drop between two terminals of branch m, ΔV_{av}^2 is the mean square voltage drop of all branches for a chosen loop, and ω is the branch (switch) weighing factor.

2.2 The Line Index (I_L)

Line parameters R and Y can also be used to minimize equation (2). Low current flow is expected for high $R|Y|^2$ value. A line index (I_L) is then defined as :

$$I_L(m) = \exp^{k_{Lm}} \tag{6}$$

and

$$k_{Lm} = -\omega\,\left(\frac{R^i Y_i^2}{R_{av} Y_{av}^2}\right) \tag{7}$$

where R_{av} is the average branch resistance for a chosen loop, Y_{av} is the average branch admittance for a chosen loop and ω is the branch (switch) weighing factor.

2.3 Weighing Factor

For a loop ereated by closing a specific tie switch, a weighing factor ω is defined for each sectionalizing switch according to its distance to this specific tie switch. If there are m number of switches in a loop, the weighing factor for the tie switch and two neighboring switches are assigned the value 1/m. The second tie switch has a weighing factor 3/m and all the remaining switches can be assigned in a similar manner.

2.4 The Decision Index (I_d)

The decision index (I_d) can be defined for a branch m by the product of the two indices I_V and I_L as:

$$I_d(m) = I_V(m) \cdot I_L(m) \tag{8}$$

Under normal state, the optimal decision can be obtained by :

$$\text{Max } I_d(m) = \text{Max} \{ I_V(m) \cdot I_L(m) \} \tag{9}$$

2.5 Feeder Protection Scheme

Overhead distribution systems are subject to two types of electrical faults, permanent faults and temporary (transient) faults. The cause of permanent faults is usually a component damage, which must be repaired. Permanent faults are cleared by fuse cutouts installed at submain and lateral tap points. Temporary faults are cleared by service interuption which may be instantaneous or high-speed tripping and automatic reclosing of a relay-controlled power circuit breaker or the automatic tripping and reclosing of a circuit recloser.Network reconfiguration may require changes of the protection scheme.

The main features of the techniques used for the protection of overhead MV distribution systems can be summarized as follows:

1- Disconnectors or isolators are installed at judicious points along the main feeder. After the fault has been detected, the relevant disconnector can be opened and the circuit breaker reclosed.
2- Fuses are applied at the beginning of each lateral distributor. In this case a short circuit on a lateral distributor causes its appropriate fuse to blow which causes a disconnection of its load point until the fault is repaired.

A computer program based on the following principles has been developed:

a) The short circuit currents are calculated (minimum and maximum values), for phase and ground faults on the main feeder and each of the laterals.
b) The settings of the main feeder circuit breaker relays are selected (instantaneous and time delay).
c) For each lateral the proper fuse is selected according to the following rules:
   - The nominal current must be two times higher than the estimated peak load current of the lateral.
   - Coordination with the up-stream and down-stream protection devices must be satisfied.
   - Operation for minimum short circuit current must be obtained.

2.6 Reliability Indices

There are no industry wide standard outage reporting procedures, and each electric utility company has its own standards for each type of customer and its own methods of outage reporting. A unified scheme for the reporting of outages and the computation of reliability indices would be very useful but is not generally practice due to the differences in service areas, load characteristic, number of customers, and quality of service. Some utilities are using the EEI/IEEE approved indices [8] to monitor the duration and frequency of outages. The energy not supplied index (ENS) is considered as the most useful index of assessing the overall reliability performance of distribution system and is given by:

$$ENS = \sum La(i)\, Ui \qquad (10)$$

Where $La(i)$ is the average load connected to load point i and U_i is the annual outage time.

2.7 Solution Procedure

The solution procedure of feeder reconfiguration in normal operation state for power loss reduction is summarized as follows:

1- Close all tie switches to create a meshed network.
2-With the help of power flow calculations, the switching indices I_V , I_L and I_d are calculated.
3- Starting from the upstream loops to open the branch which has a maximum I_d in each loop.
4- Check the system constraints, if there is any violation, another branch with the second largest I_d is chosen and go to 3, otherwise, go to 5.
5- Check the protection scheme, if there is any problem, readjust the protection system, otherwise go to step 6.
6- Print out the results.

3. FEEDER RECONFIGURATION FOR SERVICE RESTORATION

A practical distribution system is mainly divided into a primary subsystem consisting only of system supply points and a number of secondary subsystems. To ensure a reliable operation of a distribution system, it is important to restore power to all customers rapidly on the occurrence of a fault. The restoration of supply is achieved in the following steps:

- Detection of the faulted components and isolation of the appropriate system sections by opening the suitable sectionalizing switches.
- Supply of power to the non-faulted out of service sections by closing the appropriate switches.
- The faulty section is to be repaired.
- Once the fault is repaired,.the system is to be restored back to the normal operating state.

As a matter of fact, the distribution system can be divided into three categories after isolating the fault:

(i) Unaffected load points with sources.
(ii) The source points.
(iii) The affected loads without sources.

Service restoration should find the best restoration strategy for the last type (category). As discussed in section 2, all the switching indices used are the ones obtained in the normal state. For restorative state, the optimal decision can be obtained by selecting the optimum path with minimum I_d from a selected group of paths. Therefore, our objective in restoration state is:

$$\text{Min}\,(\text{Max}\ I_d\,(m)) = \text{Min}\,(\text{Max}\,(I_V\,(m) \cdot I_L\,(m))) \qquad (11)$$

The minimization of Eqn. (11) must satisfy all system constraints and the protection scheme must operate properly. If one or more out-of-service sections cannot be completely restored, the load shedding procedure is implemented.

3.1 Load Shedding Scheme

Load shedding is the process of decreasing the load on the substation bus, transformer, or feeder. This may be accomplished by a procedure in which feeders are taken out of service for a relatively short period. Load shedding is performed to remove constraint violations by dropping a minimal amount of loads. If only voltage violation exist, then the buses with violations are dropped from service by opening the first violated bus toward the source. For overload violations, customers must be classified according to their priority. Priority loads, such as hospitals, military camps, and police stations, must be considered by identifying their buses. The low priority loads beyond the violated equipment need to be shedded first, step by step until all constraints are satisfied.

The load shedding strategy can be illustrated in the following steps :

Step 1: Identify all priority buses.

Stcp 2: Starting from the end sections of the violated feeders, the non-priority loads having small magnitudes are curtailed onc by one until the violations are climinated.

Step 3: Minimum loads have to bc shed to satisfy our constraints.

Step 4: If the system is still overloaded, the priority loads are curtailed according to their classification.

3.2 Restoration Solution Procedure

The following restoration algorithm is proposed to restore the eleetricity service to the out-of-service area:

1- Identify all the candidate tie switches Ns for restoration, and start with the first switch (i=1) with minimum I_d.
2- Close the next switch with minimum Id.
3- Check system constraints, if the system constraints are not satisfied, and i<= Ns reclose the selected switch and go to step 2.
4- If there is any violation and i>Ns, apply load-shedding scheme.
5- Check for protection scheme.
6- End

4- APPLICATION AND RESULTS

The proposed solution method introduced in the previous sections has been tested with two distribution systems. The first system is the IEEE 16-bus three-feeder, while the second is a 33-bus 11 kV typical distribution system.

4.1 IEEE 16-Bus Three-Feeder Test System

The first applieation of the proposed method is applied to IEEE 16-bus three-feeder test system [1]. The system consists of 3 feeders with 13 normally closed switehes and 3 tie switches. Closing all tie switches will create a meshed network with three loops. In the base case, switches at branches 14, 15 and 16 are normally opened. The values of switching indices

I_V, I_L, and I_d for each loop are computed and given in table 1. From table 1, we can see that the switches to be opened are 8,7, and 16 for the three loops respectively

Table 1 The values of switching indices for different loops

Loop #	Branches	I_V	I_L	I_d
1	1	0.41841	0.69108	0.28916
	2	0.92861	0.89497	0.83108
	14	0.99732	0.72561	0.72366
	8*	0.98143	0.88991	0.87339
	6	0.8153	0.71686	0.58445
	5	0.19436	0.70476	0.13698
2	5	0.13194	0.6775	0.08939
	7*	0.99754	0.87829	0.87613
	15	0.99633	0.69985	0.69727
	11	0.97003	0.89207	0.86534
	10	0.4211	0.6775	0.28529
3	6	0.16062	0.72694	0.11676
	7	0.96251	0.78707	0.75756
	15	0.94447	0.51765	0.48891
	11	0.75325	0.88124	0.6638
	12	0.70799	0.87225	0.61755
	13	0.99169	0.87661	0.86933
	16*	0.99116	0.95873	0.95026
	4	0.9957	0.87661	0.87284
	3	0.69337	0.93217	0.64634
	2	0.42621	0.87225	0.37177
	14	0.94973	0.51765	0.49163
	8	0.69787	0.78707	0.54928

* The maximum decision index branch number in a loop.

Table 2 summarizes the different benefits of feeder reconfiguration process. These include, system power loss reduction, improving the system voltage profile, relieving the loading of heavily loaded feeders (feeder #2).

Table 2 Results of IEEE 16-bus test system before and after switching process

Before switching			After switching		
Losses (MW)	Max. voltage regulation (%)	Loading of feeder #2 (%)	Losses (MW)	Max. voltage regulation (%)	Loading of feeder #2 (%)
0.5114	3.171	53	0.47096	2.926	47.4

4.2 Application to a Typical Distribution System

The second system is a part of distribution system of Mansoura City in Egypt. This system consists of one 33/11 kV (2 transformers) substation, three distribution points (switching stations), 29 transformer stations (11/0.4 kV), and 32 normally closed switches and 6 tie switches. The single line diagram of the system is shown in figure 1.

4.2.1 Application of Solution Method to Loss Reduction

The normally opened tie switches 3,7,13,20,30,and 35 are closed to form six loops. Table 3 gives the maximum values of I_d for the six loops. Based on the maximum value of Id for each loop, the branches # 3,21,6,12,30 and 36 are opened respectively for the six loops. Since branches 3 and 30 are already opened, there is no need to change the status of these switches.

The system power losses after reconfiguration is reduced by 5.7 % and 5.4 % for real and reactive power respectively as shown in figure 2. It is noted that the reduction is not so high, and this is because the system is not highly loaded. As shown in figure 3, the loading of feeder # 1 is decreased by 5.2%. The results of system voltage show that the system voltage profile is improved. The maximum voltage regulation for the system before switching is 0.917 % at bus # 19, and after switching process becomes 0.804 % at bus # 20.

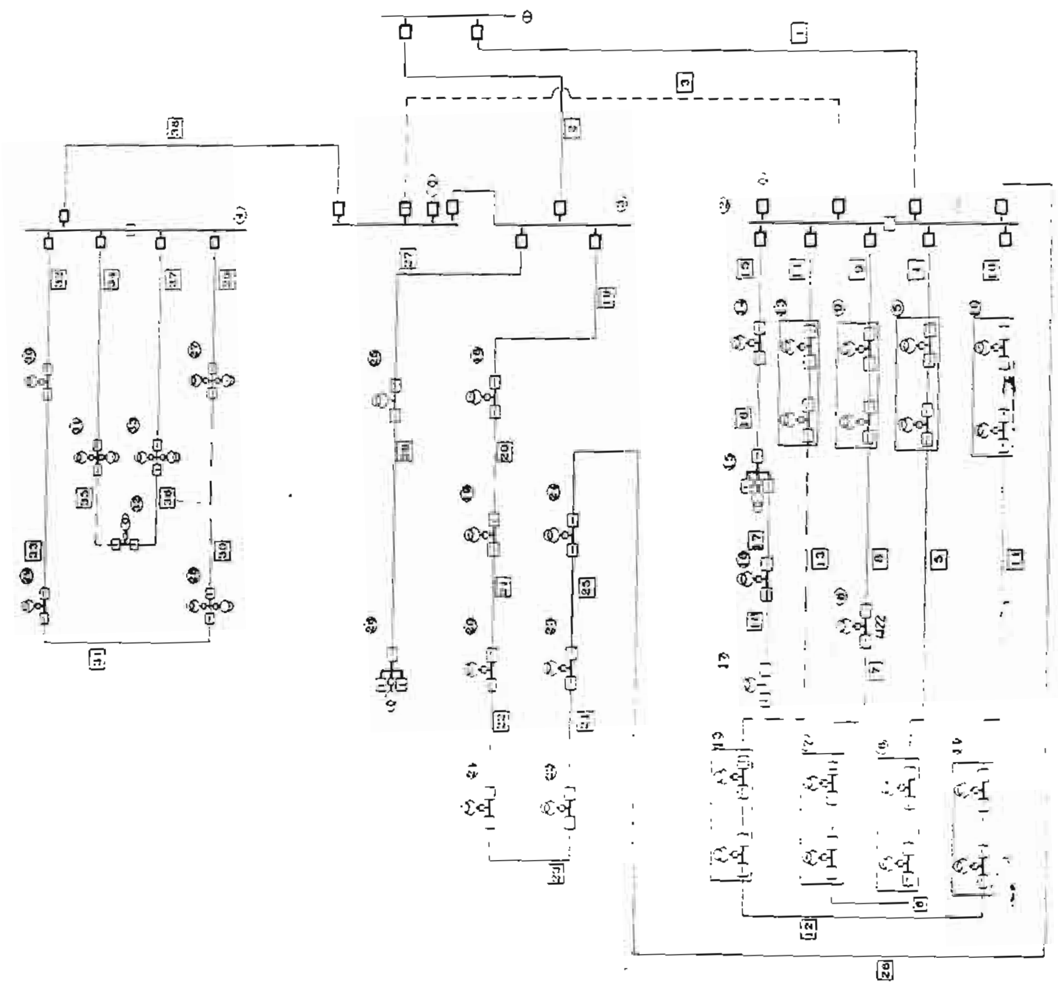

Figure (1) The single line diagram of the test system

Table 3 The switching operations process for different loops

Loop #	Switch to be closed	Max (I_d)
1	3	0.74249
2	21	0.89291
3	6	0.89804
4	12	0.82777
5	30	0.77927
6	36	0.82052

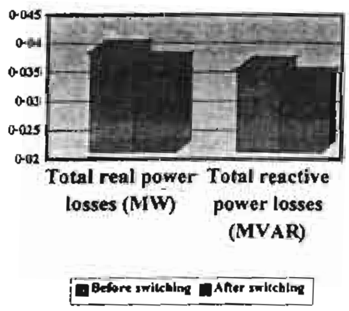

Figure (2) Effect on power losscs

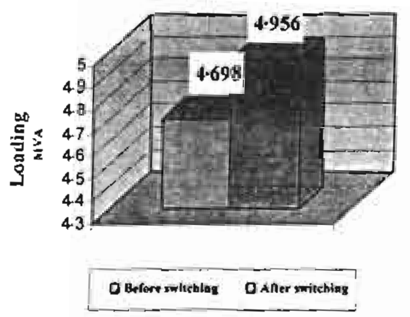

Figure (3) Effect on loading of feeder #1

Reliability consideration

The required data for reliability index evaluation are collected. Thesc data include number of customers for each bus and the area served by each bus. The failure rate, outage time, and annual outage time are calculated from the outage report. The time considered for isolating the fault and service restoration is considered 0.5 hr. The reliability results indicate that the energy not supplied index ENS is improved from 11.828 to 10.989 (MWh/year) after reconfiguration process.

4.2.2 Application to Service Restoration

The solution procedure of service restoration is applied to the test system shown in figure 1. Two fault cases are simulated on this system as follows:

(i) Multiple fault at branches # 9, 19

If a double fault is occurred at branches # 9 and 19, then after isolating the faults, the system is divided into three groups as shown in figure 1. Group 2 and 3 are the affected groups. Group 2 consists of buses # 7, 8, and 9, while group 3 consists of buses numbcr 18 and 19 only. Applying the restoration procedure mentioncd in section 3 shows that, there is only one path to restore each group. For group 2, the path is the branch # 6, while for group 3, the path is the branch # 21. The system constraints are satisfied and the protection scheme is operated properly, since there is no change in the main feeders 1, 2, 3, and 38.

(ii) The fault at branch # 1

The second fault is simulated on branch # 1 between bus 1 and bus 2. After isolating the fault, the system is divided into two groups. It can be seen that group 2 (which includes bus # 2,5-17,20-24) has load points without sources, which is considered as affected group. The restoration algorithm shows that the service can be restored through branch # 3 but this branch will be overloaded. Then, we returned to load shedding scheme. The service restoration can be achieved by shedding 53% of the load at bus number 10, with all system constraints are satisfied. The protection scheme is checked and it is found that the relays for branch # 3 must be readjusted.

5 - CONCLUSION

A proposed solution method has been presented for the distribution network reconfiguration to minimize power losses and restore service to the affected loads during a fault or maintenance state. The problem is formulated and solved using a heuristic multi objective algorithm. The obtained results of the method in normal operating state show great benefits for system operation.These include, system power loss reduction, improving the system voltage profile, relieving the loading of heavily loaded feeders and transformers.

The proposed method was applied also to service restoration of electric power supply on the occurrence of a fault or maintenance. The results show that the restoration of service to faulted sections has been achieved with minimum number of switching operations. Sometimes it may not be possible to feed all areas after a fault occurs. In such a situation it will be necessary to resort to load shedding and ensure that minimum load is to be shed taking into account a priority ordering of the loads.

Numerous tests of the proposed method show that it has less computational time, and it is suitable for both planning and operating purposes. Also, the method is practical in the sense that it satisfies the requirements for on line application especially the speed of computation and avoidance of unnecessary switching operations.

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