An Improved Service Restoration Algorithm under Consideration of Abnormal Conditions in Distribution Automation Systems

Namhun Cho†, Insung Kim, Sungwoo Lee

KEPCO Research Institute, Korea Electric Power Corporation,105 Munji-Ro, Yuseong-Gu, Daejeon 34056, Korea
† ncho@kepco.co.kr

Abstract

The most important function in distribution automation system (DAS) is the service restoration. KEPCO's current service restoration provides a very effective restoration service. However, it has been developed without the consideration of unexpected abnormal conditions that may occur while processing the sequence of switching operations. The objective of this paper is to provide practical service restoration schemes under consideration of abnormal conditions. The proposed service restoration schemes have been integrated to a branch office (B/O) in KEPCO. The proposed method strongly supports the conventional service restoration and adds to its value.

Keywords : DAS, Service Restoration, Abnormal Condition, Contingency Support, Distribution System

I. INTRODUCTION

With an application of the smart grid (SM) technology, power utilities are interested in the area of Distribution Automation to make their own distribution systems more intelligent, efficient, reliable and cost-effective.

Distribution Automation System (DAS) has the responsibility of finding a solution within several seconds (based on a real time mode) while satisfying the conflicting goals and constraints during contingency situations. KEPCO, which is the sole electric utility in Korea, has been pushing forward the outage-free techniques [1]. Due to a difference in the features of distribution systems with other countries: 22.9 kV-Y 3 phase 4 wire multi-grounded system, KEPCO developed its own domestic DAS [2].

To recapture the investment cost through application of service restoration, since 2000, KEPCO has focused on developing KEPCO DAS (KDAS) based on a large scale centralized system with full automated mode. Now, it has expanded to all 191 branch offices (B/Os) all over South Korea. DNP communication protocol is used and the major media is optical fiber up to 95%. About 54.3% of the nodes in KEPCO grid are connected via communication to the control center.

KEPCO's Distribution Automation System (KDAS) provides a very effective restoration solution based on a expert decision-making method, but it does not consider various unexpected uncertainties during contingencies.

To implement the fully automated mode without operators' intervention, it has been learnt through discussions with the operators, that they have concerns regarding the abnormal conditions that may occur during Fault Detection, Location, Isolation and Service Restoration (FDLISR).

Unexpected conditions cause FDLISR to come to a stop before the mission is complete. In case FDLISR stops in the middle of a switching operation, operators have to take on the responsibility of the service restoration. It is difficult for operators to keep track of and identify such problems since FDLISR process is very fast. They are hesitant to take over a half complete mission since they cannot complete the task in such a short time. It is a heavy burden for operators.

Therefore, operators experienced in dealing with abnormal conditions are reluctant to use FDLISR. Without considering unexpected conditions, it is hard to implement FDLISR to the field with confidence.

Although there has been a lot of research on FDLISR schemes [1][3]-[7], authors couldn't find studies regarding abnormal conditions based on a centralized DAS. Note that there is a significant difference in FDLISR between theory and practice since FDLISR is achieved using computer and communication technology, advanced software, and remotely operable high voltage switch gear based on real-time.

In this paper, novel fault isolation and service restoration schemes are proposed. In case of abnormalities (unexpected failure of communication links and automated switches) during contingencies, the proposed schemes enable the conventional FDLISR to find a substitute switching operation sequence so that FDLISR process does not stop. Test results that show effectiveness of the proposed schemes are presented, and the basic concept of the FDLISR of KDAS is briefly described as well.

This paper is organized into five sections. Section 1 is the introduction. Section 2 describes the current FDLISR concept. Section 3 shows the proposed schemes and Section 4 show test results. Conclusions are presented in Section 5.

II. BASIC CONCEPT OF FDLISR IN KEPCO

In this section, the concept of the conventional FDLISR in KDAS and terms are introduced since the proposed schemes have been developed based on the conventional FDLISR. FDLISR automatically detects a fault from protective devices, locates the faulted section by collecting fault indicators, isolates the faulted section by opening the boundary switches and restores service to the healthy un-faulted outage zone in the faulted feeder. As can be seen in Fig. 1, boundary switches S1, S2 and S8 remain closed during un-faulted conditions. When a

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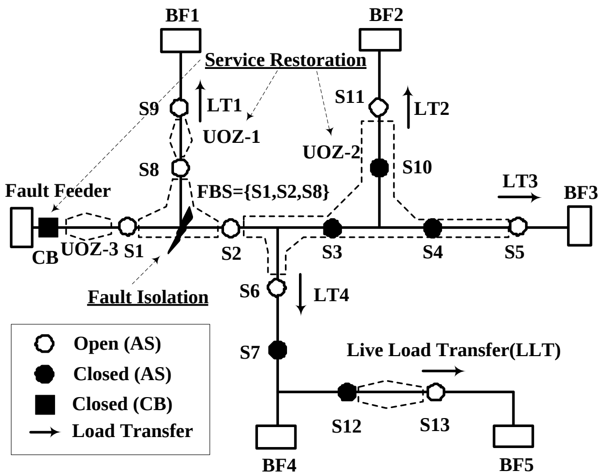

Fig. 1. Conventional FDLISR schemes

fault occurs, circuit breaker CB trips to interrupt fault current, and FDLISR sends commands to open S1, S2 and S8 to isolate the fault. Restoration occurs by first closing CB and then restoring the un-faulted outage zones step by step.

Level of Backup Feeder

In most cases, backup feeders (BFs) directly connected to the un-faulted outage zone (UOZ) are utilized. These are referred to as "level-1 backup feeder” or “Level-1 BF” in this paper. In some cases, when Level-1 BF is short of margin, a feeder connected to Level-1 BF (Level-2 BF) is utilized in order to secure the extra margin for Level-1 BF by load transfer (LT) to Level-2 BF. Similarly, Level-3 BF can be also defined as a feeder that serves as backup to Level-2 BF, and so on. From the viewpoint of operators, a service restoration plan involving only Level-1 BF is preferred to that involving Level-2 BF because of lesser switching. In Fig. 1, the faulted feeder has four Level-1 BF (BF1, BF2, BF3, BF4), and one Level-2 BF (BF5).

Fault Isolation and Un-faulted Outage Zone

A fault creates a faulted section encircled by switches (in this paper, it is referred to as the set of the faulted section boundary switch (FBS)). All members of FBS set should be opened to isolate the faulted section. After fault isolation, with FBS set as reference, the members of UOZ set are generated. All members should be restored by load transfer (LT) according to priority. Note that the number of members in UOZ set is the same as that in FBS set.

By closing the protective device (UOZ-3), one member of UOZ set is restored as shown in Fig. 1. Assume priority of UOZ-1 to be higher than UOZ-2. Service restoration is first performed on UOZ-1. The full load of this zone is transferred to Level-1 BF1 by LT1. Service restoration is then performed on UOZ-2. When the amount of outage load in UOZ-2 is larger than the sum of three Level-1 BFs (BF2, BF3, BF4), some load of BF4 can be transferred to Level-2 BF5 to find a service-restoration solution within three Level-1 BFs. This is called as the live load transfer (LLT).

Service Restoration

Six basic service restoration schemes applied to KDAS based on only single feeder-level contingency support are

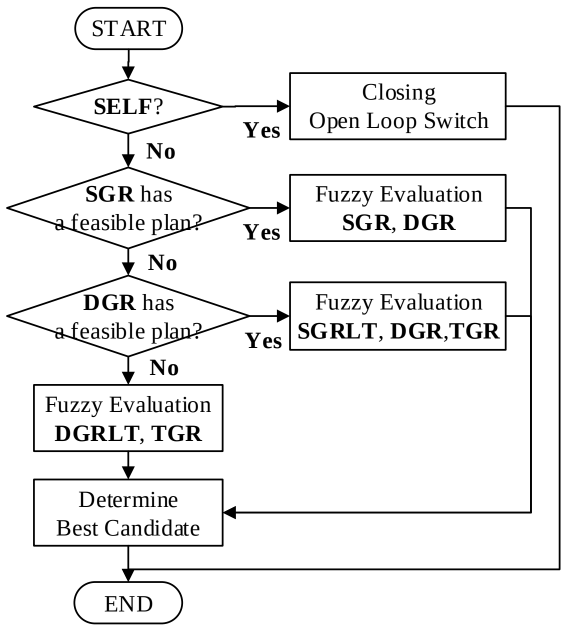

Fig. 2. Service Restoration Schemes

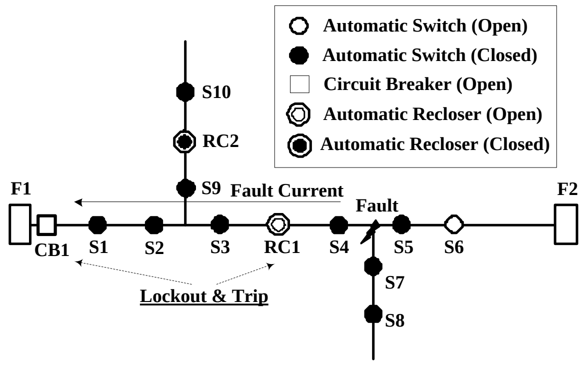

Fig. 3. Simultaneous Tripping of Protective Devices

shown in Fig. 2. More detailed explanations of these essential concepts can be found in [3].

1) Self Restoration (SELF)
2) Single Group Restoration (SGR)
3) Double Group Restoration (DGR)
4) Triple Group Restoration (TGR)
5) Single Group & Live Load Transfer (SGRLT)
6) Double Group & Live Load Transfer (DGRLT)

III. FDLISR WITH ABNORMAL CONDITIONS

This section proposes four FDLISR schemes to improve the conventional FDLISR : a) simultaneous tripping of protective devices, b) unexpected interruption by operators, c) failure of fault isolation, and d) failure of service restoration.

A. Simultaneous Tripping of Protective Equipment

There are several causes for miscoordination between protective devices. These include settings errors, misapplications, erroneous short-circuit studies, and unforeseen circumstances.

An example of miscoordination of protective devices during a permanent fault is shown in Fig. 3. Due to the fault

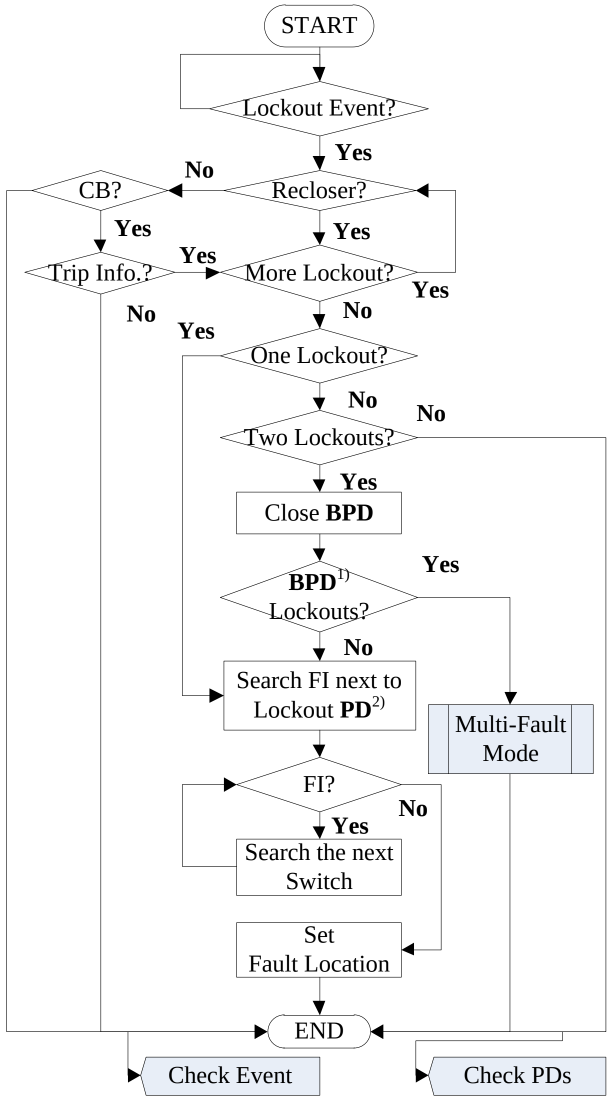

Fig. 4. Scheme for Protection Failure

current flowing from CB1 to S4, the recloser (RC1) will lockout, and then the fault indicator of S4 will be set and sent to DAS. FDLISR can recognize that the fault is between S4, S5 and S7 from fault indicator information with 'Yes-No' logic [1].

A simultaneous tripping can be caused in case of both miscoordination of protection and a multi-fault. Under these conditions, both protective devices will send lockout indications, as can be seen in Fig. 3. To ensure the completion of FDLISR, a scheme for protection failure has been proposed (As shown in Fig. 4).

In case of miscoordination, the lockout events generated from two protective devices are immediately sent to the control center via communication media without time delay. First, the type of protective device that generates the lockout event, is identified - circuit breaker (CB) or recloser. Once it is identified as CB, the proposed scheme identifies the CB name from the trip event. For practical purposes, the scope of the scheme limits the number of simultaneous tripping of protective devices to two. Once the type of protective devices is identified, the backup protective device (BPD) is closed to restore the un-faulted

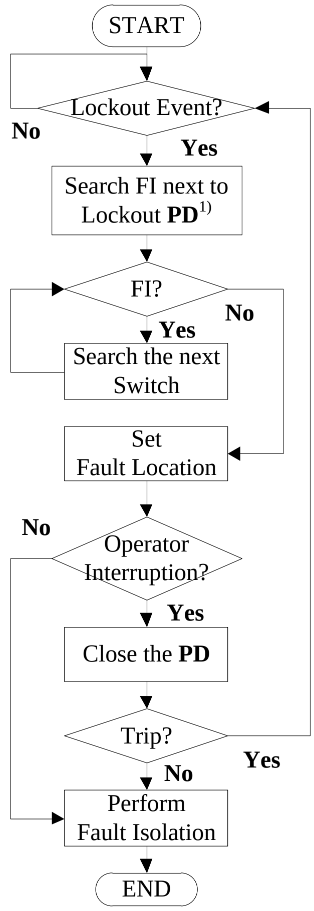

Fig. 5. Fault Detection with Operators' Interruption

outage zone. After closing the protective device (PD), there is no more tripping. The scheme begins to search for the faulted section with information of the fault indicators as usual. If the reclosed backup protective device trips again, it indicates the existence of a second permanent fault. The multiple fault case can be treated with sequential restoration mode [4].

B. Operators' Interruption

Currently, KEPCO is trying to implement the fully automated mode without operator intervention. After fault detection, FDLISR immediately isolates the faulted section to restore the un-faulted outage zones without interruption by operators. However, sometimes operators reclose the protective device expecting the fault to clear before the process of fault isolation. Fig. 5 shows the scheme under consideration of unexpected interruption by operators. After identifying the faulted section, if operators reclose the protective device and if the fault is cleared, the protective device will not trip and there is no fault indicator (FI) from switches. Otherwise the protective device will trip again and FIs are sent by switches, and then FDLISR begins to detect the faulted section.

C. Failure of Fault Isolation

Immediately after finding the fault location, FDLISR will activate Fault Isolation to isolate the faulted section. Members of FBS set are determined with the assumption that all automatic switches are operating without any failure. Even

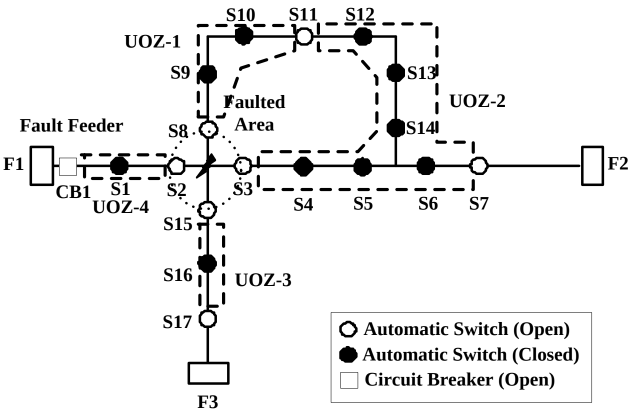

Fig. 6. Fault Isolation without Abnormal Conditions

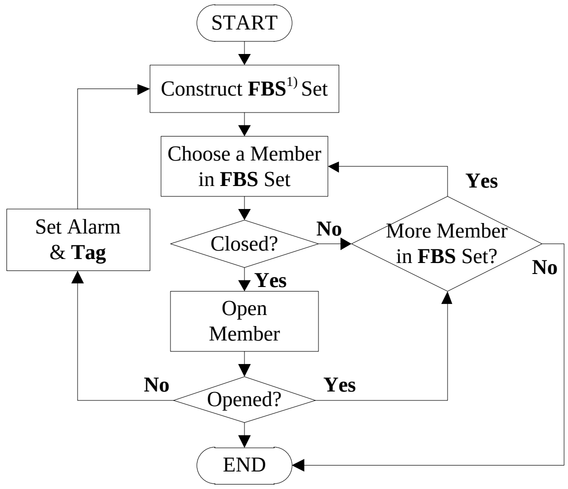

Fig. 7. Fault Isolation Scheme for Abnormal Conditions

though the unstable automatic switches with bad history have been excluded prior to the construction of FBS set, sometimes a switch does not operate because of an abnormal situation. Fig. 6 shows the result of Fault Isolation and UOZ set created from the members of FBS set. FBS set contains S2, S3, S8 and S15. S8 causes an UOZ-1. S3 causes UOZ-2 and S15 causes UOZ-3. S2 causes UOZ-4.

The proposed scheme for failure of Fault Isolation is shown in Fig. 7. When an abnormality occurs, the proposed scheme sends an alarm to operators regarding the abnormal switch, and then tags the abnormal switch so that it is excluded from the search space until the end of the process of FDLISR. The scheme will attempt to determine a substitute automatic switch in place of the abnormal switch under constraint of the minimization of the isolated section

By assuming S1, S2 and S15 to be abnormal in Fig. 6, the result is as shown in Fig. 8 in accordance with Fig. 7. By comparing the size of FBS between Fig. 6 and Fig. 8, it is clearly seen that the size of FBS has increased compared to Fig. 6.

D. Failure of Fault Isolation

The scheme for service restoration should be designed in accordance with the conventional service restoration scheme shown in Fig. 2. To develop a service restoration scheme under consideration of abnormal conditions, the conventional six schemes are re-categorized into two schemes according to the features of switching sequence of each scheme: a) the schemes

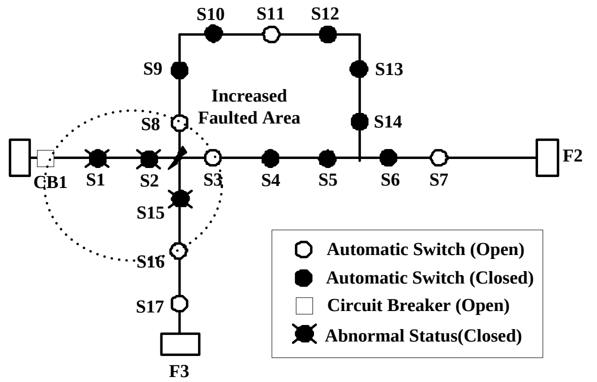

Fig. 8. Fault Isolation with Abnormal Conditions

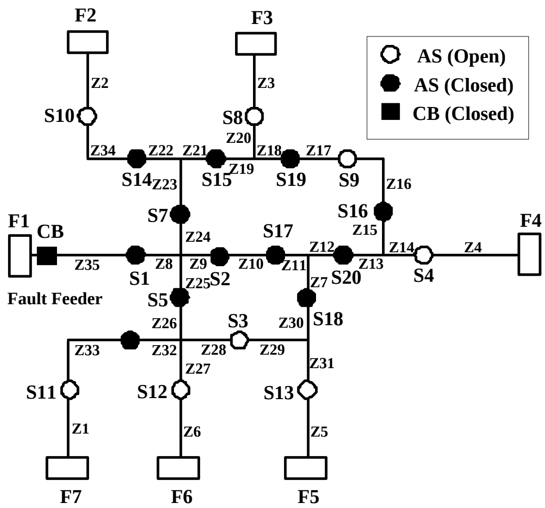

Fig. 9. Example Feeder System for Service Restoration

Table 1. Data of Example Feeder System

Zone No.	Zone Length	Load[1)] Case I	Load[1)] Case II	Line Impedance
1	10 Km	250 A	270 A	o 22.9 kV-y 3 phase 4 wire Multi-grounded system o ACSR-OC 160/N95 - Z1=6.94+j14.92 - Z0=23.98+j58.52 o Maximum Capacity : 330A
2		250 A		
3		250 A		
4		170 A		
5		250 A		
6		240 A		
7 - 35	0.5 Km	8.0 A		

1) Uniformly spatially distributed loads with 1.0 PF for simplification

of switching sequence involving only the closing of switches (SELF, SGR) b) the switching sequence that involves both opening and closing of switches (DGR, TGR, SGRLT, DGRLT). An example feeder system with six Level-1 BFs and load flow data based on the faulted feeder F1 are shown in Fig. 9 and Table 1, respectively.

Switching Sequence of Closing Operations

The conventional schemes for SELF and SGR can be implemented by closing a set of open switches. While performing SELF scheme, if an abnormal condition occurs, SELF scheme is discontinued and a tag for abnormal condition is put on the abnormal switch. The SGR scheme is then activated. In the same manner as the proposed fault isolation scheme, the abnormal switch is excluded from the search space until FDLISR is completed. After completion of FDLISR, a dispatcher is sent to investigate and fix this tagged switch.

A simplified model of Fig. 10 just by reducing the number

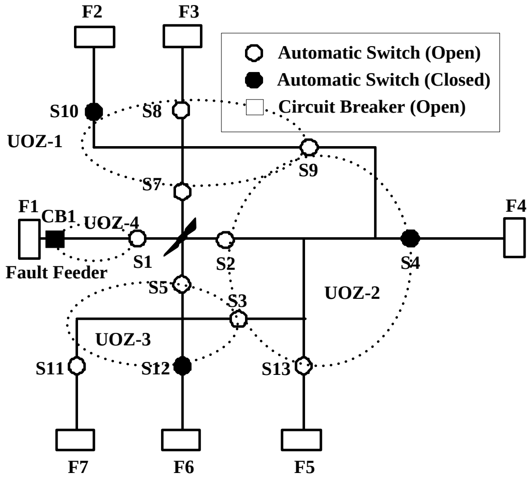

Fig. 10. Example Feeder System for Switching Sequence of Closing Operations

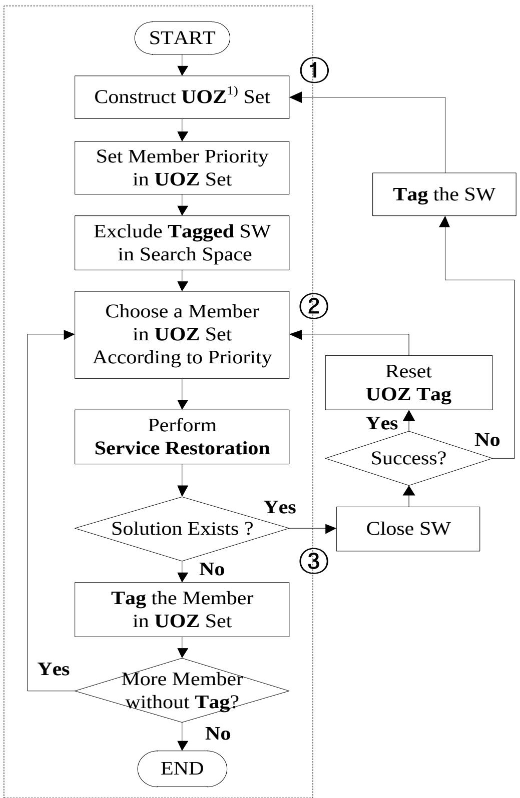

Fig. 11. Scheme for Switching Sequence of Closing Operations under Abnormal Conditions

of switches is shown in Fig. 7. Four members of the UOZ set are generated by this fault. To handle multi-UOZs, the sequential restoration scheme [1] is applied to the proposed service restoration scheme because of the following features: a) operators use this method, b) simple to implement according to priority of the UOZs. However, the disadvantage is that the search space may be reduced. Without consideration of abnormal conditions, switching sequence of closing operations at each UOZ is performed by closing the normally open tie switches such as F4, F2 and F6 for UOZ-2, UOZ-1 and UOZ-3, respectively. The worst voltage drops are 3.6% at S3, 3.9% at

Table 2. Service Restoration in Fig. 10.

No	BF	Load Capacity[kVA]		MaxV$_d$(%)		SW Operation	
		Before	After	SW	V_d[1)]		
1	F4	6,743	10,233	S3	3.7	S4	Success
2	F2	9,916	12,454	S9	3.9	S10	Abnormal
3	F3	9,916	12,454	S10	3.9	S8	Abnormal
4	F4	10,233	12,771	S10	5.2	S9	Success
5	F6	9,519	11,106	S11	3.2	S12	Abnormal
6	F7	9,916	11,502	S12	3.3	S11	Success

* Uniformly spatially distributed loads with 0.95 PF

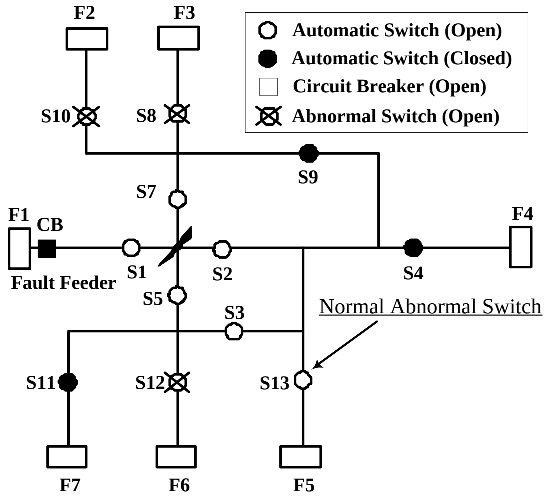

Fig. 12. Solution for Switching Sequence of Closing Operations under Abnormal Conditions

S9 and 3.2% at S11 for UOZ-2, UOZ-1 and UOZ-3, respectively.

In Fig. 11, the members of UOZ set are determined by using the members of FBS set as reference. Priority of each member of UOZ set is assigned according to the priority of outage load size in this paper. Before starting service restoration, the tagged abnormal switches are excluded from the search space. If there is no candidate for a chosen UOZ member, it is tagged so that the proposed scheme does not try to find a solution for this UOZ. However, the tagged UOZ member is reset if there is a change in network topology due to a switching operation. The process of the proposed scheme for service restoration will be repeated until there is no UOZ member without tag. Note that there are two types of tags for abnormal conditions in the proposed scheme. Fig. 12 shows the solution of service restoration evaluated by the proposed scheme with assumptions of three unexpected abnormal switches (S8, S10, S12) and a normally abnormal switch (expected abnormal switch) S13 with Fig. 10. Note that the original UOZ area will not split up in case of failure of switching operation.

Table 2 shows details of service restoration in Fig. 10 in accordance with Case I in Table 1. BF in Table 2 refers to the name of the backup feeder in accordance with each UOZ. Consider BF F4, the location on the feeder corresponding to maximum voltage drop (V_d) is at SW3. Load capacity before and after refers to the capacity before and after transfer of a part of UOZ.

IV. TEST EXAMPLE

Table 3. Restoration Result without Abnormal Conditions

UOZ ID	BF	Load Capacity[kVA]		MaxV$_d$(%)		No	BF Level
		Before	After	SW	V$_d$		
1	121	9,900	12,946	TieSw23	2.1	6	Level-1
	131	9,900	12,946	S1T2D2S3	2.4		Level-1
	322	9,900	12,946	S1T2D2R5	3.0		Level-1

Table 4. Switching Sequence with Normal Condition

No	SW	SW Status		Control Comment	Result
		Present	Operation		
1	S1T2D2S1	Close	Open	Fault Isolation	Success
2	S1T2D2S3	Close	Open	Separate Outage Load	Success
3	TieSw31	Open	Close	Transfer Outage Load	Success
4	S1T2D2R5	Close	Open	Separate Outage Load	Success
5	TieSw42	Open	Close	Transfer Outage Load	Success
6	TieSw94	Open	Close	Transfer Outage Load	Success

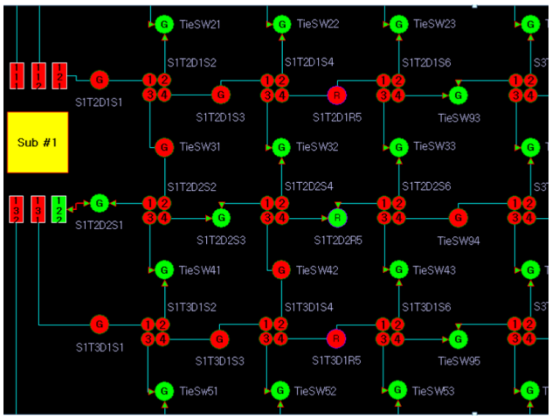

Fig. 13. Restoration Result without Abnormal Conditions

In Appendix, a test example is shown with four substations (S/S). Each substation (S/S 1 and S/S 3) is connected to 3 transformers : MTR 1, MTR 2 and MTR3. Each transformer, in turn, is connected to 2 feeders through a CB. The number representing the CB also represents the feeder name. S/S 2 and S/S 4 have the same structure as described above. Each feeder has a normal operating capacity of 10,000 KVA based on 22.9 kV nominal voltage, and is divided into 13 sections such that the load for each section is 770 KVA. The length of each section is 1 Km.

Maximum operating capacity of every feeder is 13,000 KVA leaving a margin of 3000 KVA that can take 4 sections from neighboring feeder during contingency. The features of the test system are as follows:

1) Due to the symmetrical nature of the system readers can easily understand its structure, and can intuitively and immediately determine if the solution is correct.

2) The system is flexible. By switching operation, this test system can implement various topologies.

3) By using multi-circuit switches that are generally used in underground distribution systems, search space can be greatly increased so that complexity is sufficient for testing.

The purpose of this section is to demonstrate the results of service restoration through test examples that are identical except for the presence of abnormal switches in one example. In this way, differences between both solutions can be found intuitively.

Table 5. Restoration Result with Abnormal Condition

UOZ ID	BF	Load Capacity[kVA]		MaxVd (%)		No	BF Level
		Before	After	SW	V$_d$		
1	121	9,900	12,946	TieSw43	3.2	7	Level-I
	131	9,900	12,946	TieSw32	2.4		Level-I
	331	9,900	12,946	S1T3D1R5	3.3		Level-II

Table 6. Switching Sequence with Abnormal Condition

No	SW	SW Status		Control Comments	Results
		Present	Operation		
1	S1T2D2S1	Close	Open	Fault Isolation	Success
2	S1T2D2S3	Close	Open	Separate Outage Load	Fail
3	S1T2D2R5	Close	Open	Separate Outage Load	Success
4	TieSw94	Open	Close	Transfer Outage Load	Fail
5	TieSw95	Open	Close	Loop for Load Transfer	Success
6	S1T3D1R5	Close	Open	Live Load Transfer	Success
7	TieSw41	Open	Close	Transfer Outage Load	Success

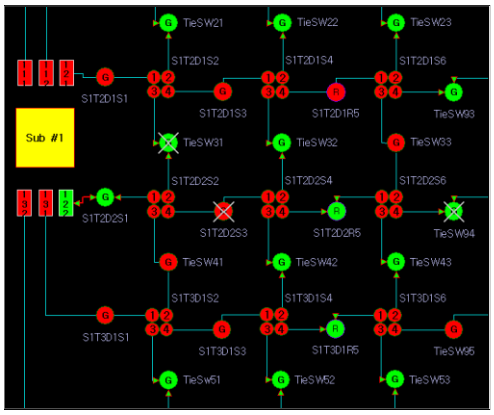

Fig. 14. Restoration Result with Abnormal Conditions

A. Service Restoration without Abnormal Conditions

In the test system, consider a fault occurring between 122 and S1T2D2S, which is the worst case scenario of the feeder-level contingency. The results of service restoration and detailed information are shown in Fig. 13 and Table 1 respectively.

The fault causes outage area as shown in Fig. 13 - a total of 12 sections. 4 sections are transferred to BF 121 by closing TieSW31. After picking up these loads, BF 121 reaches maximum operating capacity and has no margin remaining. In the same way, 4 sections are transferred to BF 131, and the last 4 sections to BF 322 (not shown in the example due to space constraints).

Table 3 shows details. Consider BF 121, the location on the feeder corresponding to maximum voltage drop (V_d) is at TieSW 23, 93, 33. These 3 points have equal voltage levels and are the weakest points on the feeder.

UOZ ID refers to ID of the un-faulted outage zone. BF refers to the name of the backup feeder - 121 131 and 322. Load capacity before and after refers to the capacity before transfer and after transfer of a part of UOZ.

Table 4 is the switching sequence report for operators. There are 6 sequences each corresponding to a switch. Column 2 shows the name of the switch. Column 3 shows the status of the switch: Present status of switch and the operation that needs to be performed on it. Control comment displays the function of the switching operation i.e. fault isolation, load transfer etc. Result indicates if the operation is successful or not.

B. Service Restoration with Abnormal Conditions

To investigate the effectiveness of the proposed method in handling worst-case situations, 3 abnormal switches are set with a cross as shown in Fig. 14. All system conditions are exactly the same as the previous example (normal condition) with the exception of these three abnormal switches.

The 8 outage sections of 12 are transferred to BF 131. In order to receive 8 sections, 4 sections of BF 131 are transferred to Level-2 BF 331. Through this Level-2 BF transfer, the load on BF 131 is reduced and it has sufficient capacity to receive 8 outage sections. The remaining 4 outage sections are transferred to BF 121. Table 5 summarizes the results. Table 6 is the switching sequence report for operators.

By comparing the results of service restoration without and with abnormal conditions (Table 3 and 5), the differences can be seen. The worst V_d under normal conditions (3%) is lower than V_d with abnormal conditions (3.3%).

This means that the length of load reach with abnormal conditions is higher compared to the normal case. The number of switching operations has also increased from 6 to 7.

V. CONCLUSIONS

In this paper, new schemes, which enable the conventional FDLISR to find substitute switching operation sequence under unexpected abnormal conditions, have been reported.

The proposed schemes have been designed for each stage of fault isolation and service restoration in FDLISR. With the application of the proposed methods, FDLISR can fulfill its objective without stopping in between. The software implementing the proposed schemes has been integrated into an operating DAS of KEPCO, and the concept of the multi-zone contingency support in KEPCO has been briefly reported in this paper. The proposed schemes could help operators to operate DAS more confidently, accurately and efficiently.

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Appendix : Test System for FDLISR