부하 절환 스위칭을 이용한 방사상 배전계통에서의 순간전압강하 대책

論 文
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Countermeasure of Voltage Sag in Radial Power Distribution System using Load Transfer Switching

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Abstract - In this paper, we propose a method for mitigating the effect of voltage sag in radial power distribution systems using load transfer switching (LTS). The term of LTS is defined that the weakness load points for voltage sag transfer to the alternative source during the fault clearing practices. The sequences of proposed LTS method is divided into the search of weakness points for voltage sag using the risk assessment model and transfer behavior of weakness points. The search of weakness point is carried out using the risk assessment model of voltage sag and the Monte Carlo simulation method and the historical reliability data in Korea Electric Power Corporation (KEPCO) are also used. Through the case studies, we verify the effectiveness of proposed LTS method and present the searching method of effective application points of LTS method using the risk assessment model.

Key Words : Voltage Sag, Voltage Quality, Load Transfer Switching, SSTS, STS

1. Introduction

According to the development of automatic process in customers and the change of distribution system topology to the short distance and the high load density, the concern for quality of electric power has been increased. Above of all, voltage sag that is the most representative voltage magnitude quality problem due to the faults in power system is more frequent than sustained interruption, and also the damage is not less than the sustained interruption for the some customer type.

The several methods to reduce the number and severity of voltage sag and to dull the sensitivity of equipment for voltage sag have developed. The main subject can be divided into the utility and customer side countermeasures[1]. Utilities concentrate their effort to prevent the faults and to modify the fault clearing practice in power system. These efforts may reduce the number and duration of voltage sags. However, the faults in power system can never be completely eliminated. To increase the bus voltage during voltage sags, G. T. Heydt proposes the series voltage booster [2]. And Detroit Edison Power Co. utilize the static transfer switch (STS) to solve the power quality problems [3]. Customer side solutions usually involve the power-conditioning equipment for sensitive loads. They present the enhancement of ride-through capability for voltage sag using the power-conditioning devices [4-5]. These methods have merit of showing direct and clear effect for the individual equipment. However, the customer side solutions cannot be applied to whole customers' loads because the power conditioning devices have restriction for capacity and price. Therefore, it is necessary to develop the mitigation method that considering the sufficient capacity and inexpensive price in utility side.

This paper presents a mitigation method of voltage sag using load transfer switching (LTS) method in radial power distribution system. The term of LTS is defined that the weakness load points for voltage sag transfer to the alternative source during the fault clearing practices. This method is basically utility side solution of voltage sag. The proposed LTS method is carried out using the switching behavior for the sectionalizing points of distribution networks. It consists of two main sequences. One is the search of weakness point for voltage sag. It is carried by the reliability evaluation using risk assessment model of voltage sag. The other is the transfer behavior of weakness points of voltage sag to the alternative source during the fault current exist. The Monte Carlo method and the historical reliability data in Korea Electric Power Corporation (KEPCO) are used for search of weakness points. Through the case studies, we

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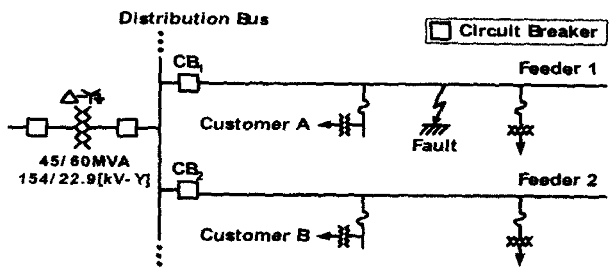
find the most effective point of LTS method for model system.

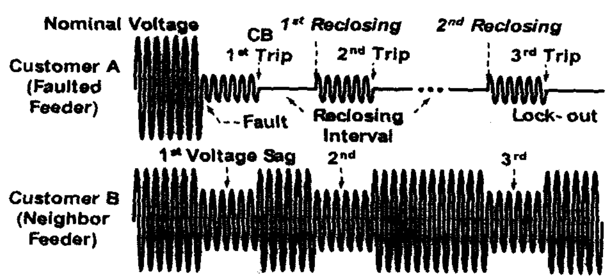
2. Voltage Sag in Radial Power Distribution System

2.1 Source and Generation Mechanism

Voltage sags are mainly associated with a fault somewhere on the power system [6]. When a fault occurs on distribution system in Fig. 1(a), the circuit breaker CB1 opens to clear the fault and automatically recloses after a time delay. These operation schemes enhance the reliability for a temporary fault, but the neighbor feeders in same main transformer experience a voltage sag or successive voltage sags. Fig. 1(b) shows the voltage waveform during a permanent fault.



(a) Radial distribution system model



(b) Waveform of voltage during permanent fault

Fig. 1 Generation mechanism of voltage sag

2.2 Decision of Parameters of Voltage Sag

2.2.1 Definition of Magnitude and Duration

In this paper, the definitions of the duration and magnitude of voltage sag follows the IEEE Std. 1159 (1995) because it presents the most precise division. According to the IEEE Std. 1159, the magnitude of voltage sag range is 10[%] ~ 90[%] of nominal voltage and its duration is 0.5[cycles] ~ 1[min].

2.2.2 Count of Phases

Voltage sags normally affect each phase of a three-phase system differently. One, two, or all three phases may see voltages low enough to be called sag for any one-fault event. We assumed that all three phases have an equal probability of a fault [7]. Therefore, we counts as 1/3 for each phase.

2.2.3 Calculation of Duration and Magnitude

The duration of voltage sag is determined by the clearing time of the protective device. If a temporary fault occurs in the model distribution system of Fig. 1(a) and the fault is cleared during the first reclosing with the circuit breaker CB_1, then the duration of first voltage sag for the fault in model distribution system is calculated as (1). The t^1_{TD}, t^1_{Re} and t^1_{CB} in (1) represent the duration of first voltage sag, the operation time of relay and circuit breaker, respectively. The superscript 1 in (1) represents the status of no-reclosing.

$$t^1_{TD} = t^1_{Re} + t^1_{CB} \quad (1)$$

In overheads distribution system, automatic reclosing is commonly used. In this paper, we account the successive voltage sags due to the reclosing with circuit breaker or recloser as one if they occur within a certain fault [7]. And also, the duration of voltage sag is assumed the longest one as (2). The superscript n in (2) represents the order of voltage sags that occurred within a fault.

$$t_{TD} = \mathrm{Max}(t^n_{TD}) \qquad ;\ n=1,\ 2,\ 3,\ \ldots\ ,k \quad (2)$$

Where,

t_{TD} : total duration of voltage sag within a fault

t^n_{TD} : n^{th} voltage sag duration within a fault (n=1...k)

t^1_{TD} : voltage sag duration due to the no-reclosing

t^k_{TD} : voltage sag duration due to the $(k-1)^{th}$ reclosing

The magnitude of voltage sag is related with fault current. For the radial distribution system in Fig. 1(a), it assume that the magnitude of voltage in neighbor feeders is almost equal to the distribution bus voltage [6]. Therefore, we calculated the voltage sag magnitude as follows:

1) Calculate the voltage on the faulted point and fault current

2) Compensate the voltage from faulted point to the distribution bus

3) Calculate the magnitude of voltage sag. It is defined by the M_{VS} in (3). The M_{VS} is the percentage of voltage sag magnitude in faulted phase. The V^{fp}_{Bus} in (3) is the magnitude of bus voltage in faulted phase. When a fault occurs, the lowest one among the three phase voltages for each event is selected as the magnitude of voltage sag (M_{VS}) [7].

$$M_{VS} = (1 - |V^{fp}_{Bus}|) \times 100[\%] \quad (3)$$

2.3 Decision Parameter of Customers' Effect

As mentioned in reference [8], the parameters of customers effect by voltage sag is divided into the duration and magnitude of voltage sag and the customer type.

1) Duration and magnitude of voltage sag : These are factors that can directly decide the shutdown or malfunction of customers loads. The CBEMA (Computer Business Equipment Manufacturer Association) curve is used to analyze the customers' effect for voltage sag. Fig. 2 shows the experiment result [8]. The solid and dotted lines represent the effect boundaries of sensitive loads for individual and successive voltage sag, respectively. The successive voltage sag is generated with 0.5[sec] of time interval. The 0.5[sec] of time interval is equal to the first reclosing interval by circuit breaker (or recloser) in the overhead distribution system of KEPCO. The weighted impact in the X axis (voltage sag duration) can be shown in Fig. 2.

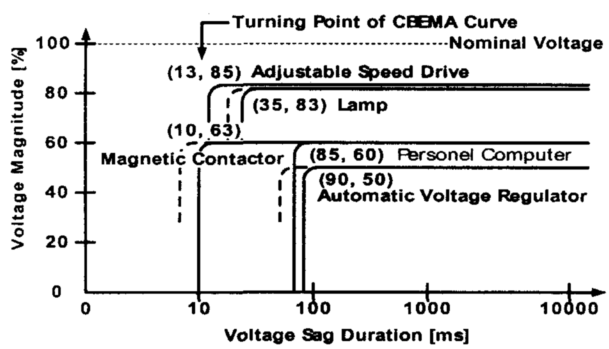


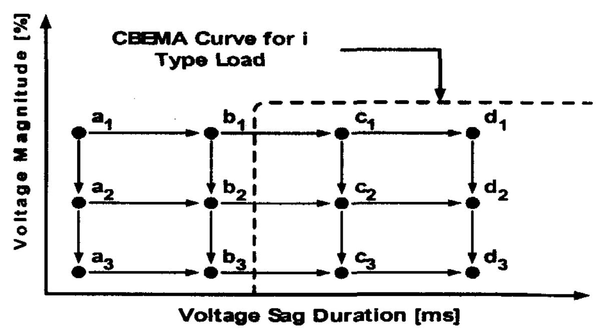
Fig. 2 Experiment result for sensitive loads

2) Customer type : we assume two voltage sags with the same magnitude and duration. One is generated in a residential and the other is generated in an office building, respectively. For this case, the latter is generally severe than the former. It means that the difference of customer load composition exists. We already know that office buildings generally are equipped with more sensitive loads than residential customers. we surveyed customers' opinions from September '96 to March '97 through the questionnaire called "Survey of Power Quality". The survey result shows the different effect of voltage sag for each customer types [8].

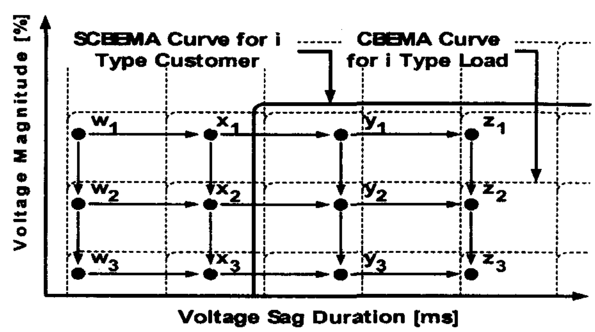
The CBEMA curve that represents the effect of each load due to the voltage sag cannot be directly applied to the decision of customers' effects for voltage sag, because a type of customer is composed of various load types. To reflect the effect of voltage sag for each customer, we propose the SCBEMA (Specified CBEMA) curve as mentioned in [8]. The SCBEMA curve means the representative susceptibility curve by voltage sag for each customer type.

As shown in the experiment results of Fig. 2, the duration and magnitude of voltage sag do not individually affect. When the duration and magnitude of voltage sag simultaneously occur in the inside of a CBEMA curve, the equipment will be shutdown. Therefore, the risk of the load due to the voltage sag at points a_1, a_2, a_3 and b_1, b_2, b_3 for the CBEMA curve in Fig. 3(a) is 0. And then, the risk of the load due to the voltage sags at points c_1, c_2, c_3 and d_1, d_2, d_3 points is 1. Although the duration of voltage sag from points of b, d to a, c is shortened, respectively, the risk does not decrease. Also, if the magnitude of voltage sag from point a_1, c_1 to a_3, c_3 is expanded, respectively, then the risk does not increased. Therefore, the relationship between magnitude and duration of voltage sag is perfect logical AND in the CBEMA curve.

However, this relation is not correct at the SCBEMA curve, because the SCBEMA curve contains a lot of types CBEMA curve of individual load shown in Fig. 3(b). The risk of the customer due to the voltage sags at points w_1, w_2, w_3 and x_1, x_2, x_3 is not 0 and the risk of the customer at points y_1, y_2, y_3 and z_1, z_2, z_3 is not 1. If the duration of voltage sag from points of x, z to w, y is decreased, respectively, then the risk decrease.



(a) CBEMA curve



(b) SCBEMA curve

Fig. 3 Comparision of CBEMA with SCBEMA curve

For this reason, we conclude the characteristics of customers' effect due to the voltage sag as follows.

1) If the duration of voltage sag is only reduced, then the risk of customer due to the voltage can be also reduced.
2) The risk of the customer has a different value according to the magnitude and duration of voltage sag. Therefore, the relation between magnitude and duration is not perfect logical AND in the SCBEMA curve.

3. Mitigation Method of Voltage Sag in Radial Power Distribution System

3.1 Basic Concept

Through the above parameters, we decide the fundamental idea for mitigation method of voltage sag as follows.

1) The relation between magnitude and duration is not perfectly logical AND in the whole customer loads. Therefore, if the duration of voltage sag is only reduced, the customers risk due to the voltage sag is also reduced as shown in Fig. 3. In this paper, we propose the mitigation method through the duration of voltage sag reduced.

2) From the survey result for power quality in Korea [8], the all types of customer are not seriously affected by voltage sag. The mitigation method is not necessary to reduce the damage of voltage sag for all customer. Therefore, the proposed mitigation method must contains the searching routine of weakness points for voltage sag in specific distribution system.

3.2 Load Transfer Switching (LTS) Method

The proposed mitigation method in this paper is named load transfer switching (LTS) method. The LTS method is that the sensitive customer for voltage sag transfers to the alternative distribution source during the fault current exists. The LTS method is entirely carried by utilities side. It has several advantages in conventional radial distribution systems as follows.

1) For enhancing the reliability of distribution system, utilities have already employed the alternative sources. For example, the normal close and open switches have been utilized for connecting the feeders of other main transformer.
2) The location of LTS operation, where the load capacity and protection scheme has been taken into considerate, has been designed already.

The proposed LTS method is composed of two parts as follows.
1) Search of weakness load point for voltage sag
2) Transfer behavior of weakness load points

3.2.1 Search of Weakness Load Points for Voltage Sag

In this paper, we use the risk assessment model of voltage sag as mentioned in [8] for the weakness points search of voltage sag. The risk assessment model is designed considering the customer type and the duration and magnitude of voltage sag as mentioned the factors of customers effects by voltage sag. The assessment model is basically composed of the fuzzy model for each customer types and the membership functions of fuzzy model obtained from the SCBEMA curve for each customer types. The assessment procedures of proposed model are composed of three steps. The Monte Carlo method is used for random number generation [9].

Step 1) Random number generation: Fault location, fault type and reclosing situation are generated within the constraint conditions and historical reliability data.
Step 2) Risk assessment for each fault: Magnitude and duration of voltage sag are calculated for each case of step 1 and the risk for individual voltage sag (R_{VS}) is computed [8].
Step 3) Risk assessment of customer per year: Total risk is summed and the average risk of customer per year (SAVSRI) is computed.

The final result of the assessment method is defined as system average voltage sag risk index (SAVSRI) as (4). The SAVSRI represents the risk of voltage sag per year per customer for specific distribution system. If the SAVSRI is 1, it means that the whole loads of customer may experience at least one time of shutdown or malfunction per year caused by voltage sag.

$$SAVSRI = \frac{\sum R_{VS}}{\text{Total No. of Customer}} \tag{4}$$

3.2.2 Transfer Behavior Mechanism of LTS

To explain the transfer behavior mechanism of proposed LTS method, we illustrate the Fig. 4. It is assumed that the sensitive customer of voltage sag is the customer 4 in feeder 2. The LTS method consists of following steps.

1) A fault occurs in feeder 1 of Fig. 4. The relay of CB_1 measures the fault current. And the switch controller in feeder 2 simultaneously measures voltage sag.

2) The switch controller in feeder 2 transmits the switching operation signal to S/W_1 and S/W_2.

3) The normal open switch S/W_2 closes and the normal close switch S/W_1 simultaneously opens in Time T_1. At this time, the clean power is supplied to the

customer 4 from the feeder 3 in neighbor bank. The circuit breaker CB_2 trips in Time T_2.

4) The circuit breaker CB_2 recloses after a time delay. If the fault is temporary in nature, then the fault is cleared when the circuit breaker CB_2 recloses. If the fault is permanent in nature, then the circuit breaker CB_2 locked out

5) When the voltage sag in feeder 2 clears, the switch controller in feeder 2 transmits the switching operation signal to S/W_1 and S/W_2 in Time T_3 which is set.

6) Switch S/W_1 close and S/W_2 open in Time T_3. At this time, the clean power is supplied to the customer 4 from feeder 2.

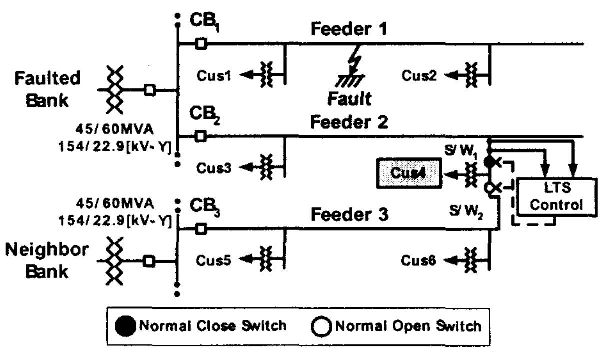


Fig. 4 Model radial distribution system applied the LTS

The voltage waveform of customer 4 during the LTS operation is shown in Fig. 5.

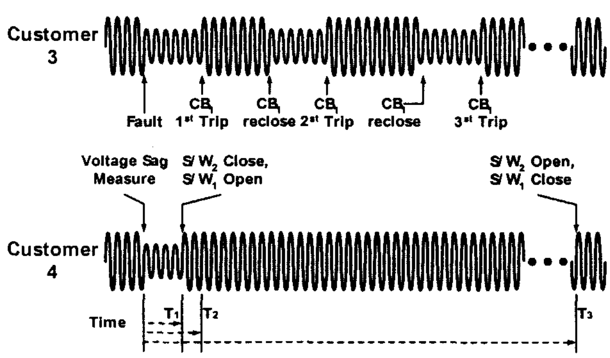


Fig. 5 Voltage waveform of customer with feeder transfer switch

The high speed switching device is required for transfer behavior of LTS method as above mentioned. In these day, field application cases of high speed switching device is presented by several utilities. The static transfer switch (STS) [3] and solid-state transfer switch (SSTS) [10] are most representative one. In this paper, the SSTS is selected as a switch device of proposed LTS method.

The principle configuration of SSTS is shown in Fig. 6. The SSTS is composed of two hybrid switches. For the hybrid switch device, line current is by-passed through the parallel switch (PS) during normal operation and the thyristor switch (TS) does not conduct the load current. When an opening operation is required, PS is opened and TS is turned on, simultaneously. The AR in Fig. 6 represents the surge arrester.

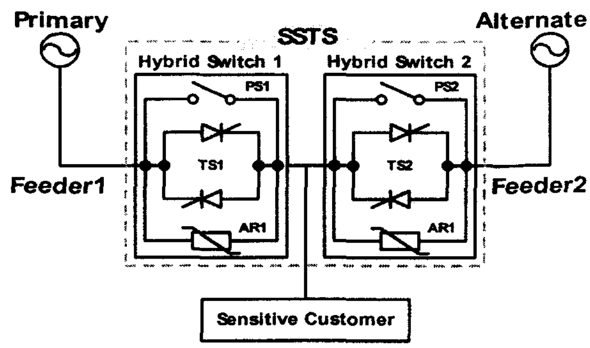


Fig. 6 Configuration of SSTS using the hybrid switch device

For the SSTS, a pair of hybrid switch devices are utilized for the LTS scheme. During normal operation, line current is by-passed by the parallel switch (PS1). When the transfer operation is required, PS1 is opened and TS1 is turned on, simultaneously. Consequently, the current is commutated to TS1 immediately and blocked by the TS1 at the first zero crossing of the current. Immediately after completing the blocking of current, the opposite side thyristor switch (TS2) beings to conduct the current to the load from the alternative source. The parallel switch (PS2) is then closed and bypasses the load current. Upon sensing the voltage disturbances, the operation time of SSTS is made within 0.5[cycles].

4. Case Studies

4.1 Test System Model

The test system is the modified distribution bus 2 of RBTS (Roy Billinton Test System) [8, 11]. This system consists of four overhead 22.9[kV] feeders fed from two main transformers and serves 22 load points (LP1-LP22). Fig. 7 shows the test system topology.

4.2 Data for Simulations

The historical reliability data used for case studies are shown in Table 1 [12]. This data is obtained from KEPCO distribution system in Kyung-in province. We assume that the reliability data of SSTS is equal to the normal switch data.

Fig. 8 shows the fuzzy membership functions that are used for risk assessment model of voltage sag [8]. the data related with the SSTS is shown in Table 2 [10] and the data related with the calculation of duration and magnitude of voltage sag is shown in Table 3 [8].

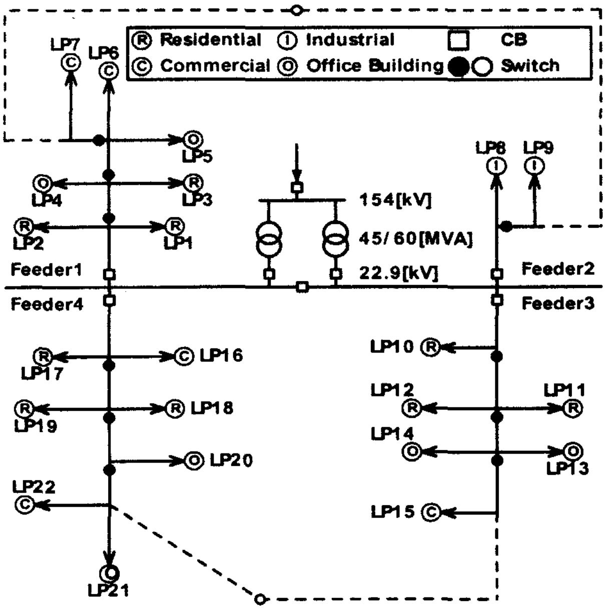


Fig. 7 Topology of test system model

Table 1 Reliability data(KEPCO's distribution system in Kyung-in province, Korea)

Fault Rate(λ) / Component	Sustained[/yr]	Momentary[/yr]
Overhead Line	0.017/km	0.080/km
Circuit Breaker	0.005	0.000
Switch	0.002	0.000
SSTS	0.002	0.000

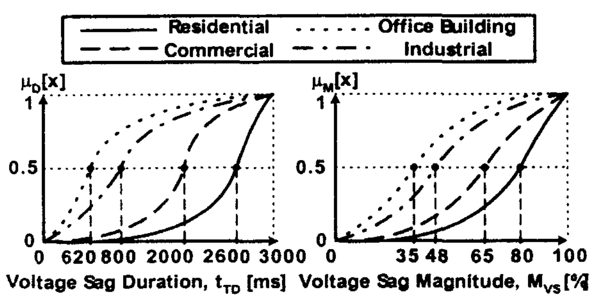


Fig. 8 Fuzzy membership functions used in case studies

Table 2 Data for SSTS

Items	Contents
Rated Current	600/1200[A]
BIL	95[kV]
Cooling Method	Natural Cooling
Overall Operation Time	0.25~0.5[cycles]

Table 3 Data for the calculation of voltage sag magnitude and duration

Items		Contents
Fault Resistance		Ignore(0[Ω])
Reclosing Number		1 Fast, 1 Delay
Successful Ratio of Reclosing		1st: 70[%], 2nd: 15[%]
Ratio of Fault Type		Phase-to-Ground Fault: 80 Phase-to-Phase Fault: 15 Three Phase Fault: 5
Fault Clearing Time	OCR /OCGR Fast	1.5~2.4[cycles]
	OCR /OCGR Delay	$T_{Re}=\left(\frac{39.85}{I^{1.95}-1}+1.084\right)\times 6\times M$[c I : Multiples of Tap Value Current M : Multiples of Time
	CB	4[cycles]
System Impedance [%](100 [MVA] Base)	Line	Z0: 9.87 + j22.68 Z1(=Z2): 3.86 + j7.42
	Tr. (45/60 [MVA])	Z0(=Z1=Z2): j31.9 (self base: j14.3)
	Source	Z0: 0.27 + j 1.52 Z1(=Z2): 0.09 + j0.96

4.3 Simulation Case

The case studies are composed of three parts as follows.

Case 1) Comparison of the SARFI with SAVSRI : The SARFI is proposed by R. C. Dugan in 1998 [13] and it is based on the frequency of voltage sag. This case is carried out to show the different of proposed assessment index (SAVSRI) and conventional assessment index (SARFI).

Case 2) Comparison of the SAVSRI with SAVSRI applied the LTS method. The location of LTS is the carried out at the LP9 and LP21 in Fig. 6. This case is carried out to show the effectiveness of proposed LTS method.

Case 3) Effectiveness comparison of the LTS method for each load points of Fig. 6. We calculate the risk reduction of each points due to the LTS method. This case is carried out to search the most effective point of proposed LTS method.

4.4 Simulation Results

The simulation results of Case 1 are shown in Table 4. This result shows that the SAVSRI reflect the difference of customers' type because the SAVSRI has different risk for customer type. However, the SARFI

Table 4 Simulation results of case 1(comparison of SARFI and SAVSRI)

Customer	SAVSRI	SARFI	Customer	SAVSRI	SARFI
Feeder1	0.0614	3.352	LP10	0.0359	2.715
Feeder2	0.1725	4.188	LP11	0.0359	2.715
Feeder3	0.0366	2.715	LP12	0.0359	2.715
Feeder4	0.0625	3.185	LP13	0.1509	2.715
LP1	0.0595	3.352	LP14	0.1509	2.715
LP2	0.0595	3.352	LP15	0.0554	2.715
LP3	0.0595	3.352	LP16	0.0933	3.185
LP4	0.3041	3.352	LP17	0.0606	3.185
LP5	0.3040	3.352	LP18	0.0606	3.185
LP6	0.0919	3.352	LP19	0.0606	3.185
LP7	0.0919	3.352	LP20	0.3067	3.185
LP8	0.1725	4.188	LP21	0.3068	3.185
LP9	0.1725	4.188	LP22	0.0933	3.185

Table 5 Simulation results of case 2(applied LTS to LP9 and LP21)

Customer	SAVSRI	SAVSRI Applied LTS	Customer	SAVSRI	SAVSRI Applied LTS
Feeder1	0.0614	0.0615	LP10	0.0359	0.0359
Feeder2	0.1725	0.0866	LP11	0.0359	0.0359
Feeder3	0.0366	0.0366	LP12	0.0359	0.0359
Feeder4	0.0625	0.0622	LP13	0.1509	0.1508
LP1	0.0595	0.0596	LP14	0.1509	0.1508
LP2	0.0595	0.0596	LP15	0.0554	0.0554
LP3	0.0595	0.0596	LP16	0.0933	0.0935
LP4	0.3041	0.3041	LP17	0.0606	0.0608
LP5	0.3040	0.3041	LP18	0.0606	0.0608
LP6	0.0919	0.0921	LP19	0.0606	0.0608
LP7	0.0919	0.0921	LP20	0.3067	0.3067
LP8	0.1725	0.1724	LP21	0.3068	0.0009
LP9	0.1725	0.0008	LP22	0.0933	0.0935

Table 6 Simulation results of case 3(comparison of effectiveness of LTS method for each load point)

Selected LTS Point	SAVSRI (for Whole System)	Risk Reduction [%]	Selected LTS Point	SAVSRI (for Whole System)	Risk Reduction [%]
LP1	0.0785	5.6529	LP12	0.0803	3.5051
LP2	0.0785	5.6811	LP13	0.0832	0.0651
LP3	0.0786	5.6311	LP14	0.0832	0.0601
LP4	0.0832	0.1070	LP15	0.0830	0.3325
LP5	0.0832	0.1070	LP16	0.0828	0.4849
LP6	0.0829	0.4777	LP17	0.0785	5.7066
LP7	0.0829	0.4195	LP18	0.0785	5.6965
LP8	0.0618	25.7775	LP19	0.0792	4.8305
LP9	0.0618	25.7402	LP20	0.0831	0.1351
LP10	0.0805	3.2605	LP21	0.0832	0.0768
LP11	0.0804	3.4234	LP22	0.0829	0.4770

does not reflect the difference of customer type. For the customers of same feeder, SARFI has same one because this index is based on the frequency of voltage sag. From this result, we show that the SAVSRI is more adequate than SARFI for assessing the risk of voltage sag and the effect of mitigation method at load point.

The simulation results of Case 2 are shown in Table 5. Above of all, this result shows the dramatic risk reduction at the LP9 and LP21 which is applied the LTS method. The effect of risk reduction in Feeder 2 is larger than Feeder 4, because the results are the average risk due to the difference of the number of customer.

The simulation results of Case 3 are shown in Table 6. The SAVSRI of Table 6 represents the average value of entire system. The percentage of risk reduction shows the difference between the normal operation(not applied LTS) and the case that applied LTS for each load point. In Table 6, the dark areas show that the percentage of risk reduction is relatively large. On the other hand, it means that these areas have an advantage for LTS method in given system. If the darkness is deeper, then the advantage for LTS method is larger. The simulation results show that the LP8 and LP9 are most effective point of LTS for this system.

5. Conclusions

This paper presents a mitigation method of voltage sag using load transfer switching (LTS) in radial power distribution systems. The proposed method is carried out by the switching operation at the sectionalizing points of distribution networks. For the search of weakness points of voltage sag, we use the risk assessment method of voltage sag. Through the case studies, we find the several results. First, the SAVSRI that is the index of proposed assessment model for voltage sag is more practically than SARFI that is the conventional index to assess the risk of voltage sag and mitigation method at load point, because the SAVSRI can reflect the difference risk of voltage sag due to the customer type. Second, the SAVSRI of load points are dramatically reduced in case of employing the proposed LTS method. And finally, the effective utilizing points of LTS method can be selected using the proposed assessment method. The proposed LTS method could be used to enhance the power quality of entire distribution system.

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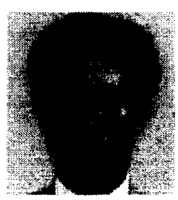

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