연속적인 순간전압강하에 의한 저압 부하의 정량적 영향 평가

論 文
53A-12-6

Quantitative Evaluation of the Impact of Low-Voltage Loads Due to the Successive Voltage Sags

文 鍾 必*・金 載 哲†・尹 尙 潤**・姜 奉 奭***
(Jong-Fil Moon・Jae-Chul Kim・Sang-Yun Yun・Bong-Seok Kang)

Abstract - Automatic reclosing is a typical protection method in power distribution systems for clearing the temporary faults. However, it has a fatal weakness in regards to voltage sags because it produces successive voltage sags. In this paper, we explored successive impact of voltage sag due to the automatic reclosing of power distribution systems. The actual tests of low voltage loads were accomplished for obtaining the susceptibility of voltage sags. The final results of the test yielded power acceptability curves of voltage sag, and the curves were transformed the 3-dimensional CBEMA(Computer Business Equipment Manufacturer Association) format. For the quantitative evaluation of the impact of successive voltage sags, an assessment formulation using the voltage sag contour was proposed. The proposed formulation was tested by using the voltage sag contour data of IEEE standard and the results of the test. Through the case studies, we verified that the proposed method can be effectively used to evaluate the actual impact of successive voltage sags.

Key Words : Successive Voltage Sags, Automatic Reclosing, Power Quality, Power Acceptability Curve

1. Introduction

Over the past few decades, the impact of voltage sags has continued to grow as more electronic and precision devices were used in customer-side and the topology of distribution systems became shorter and more high-dense.

Conrad et al. presented the assumption methodology of the magnitude and duration of voltage sag[1]. Conrad and Bollen proposed a method to assess the effect of individual loads using the contours of voltage sag performance [2] and some studies dealt with the assessment index of voltage variations[3,4]. In the reference[5-7], the power acceptability curves and the results of actual test for the susceptibility of voltage sags were presented.

Automatic reclosing is the most important protective method in power distribution systems, because it can eliminate temporary faults, which make up for about 80% of entire outages. In spite of these merits, some weaknesses in aspect of the power quality still remained. It is a successive voltage sags. The impact of successive voltage sags due to the automatic reclosing is not dealt with in above studies. In this paper, we explored the successive impact of voltage sags due to the automatic reclosing of power distribution systems. The actual tests of the sensitive loads were accomplished for obtaining the susceptibility of voltage sags and the quantitative approaches were also accomplished by using the performance contours of voltage sag. In the section 2, we summarize the mechanism of the voltage magnitude disturbances during the fault on the power distribution system and the conventional assessment methods of the voltage sag. In the section 3, the actual tests and its results for obtaining the power acceptability curves of the low voltage loads are presented. In the section 4, we propose the assessment formulation of the impact of successive voltage sags using the performance contour of voltage sag and case studies are performed using IEEE standard data and the test results.

2. Voltage Sags in Power Distribution Systems

2.1 Mechanism of voltage sag occurrence

When a fault occurs as shown in the model system of the Fig. 1, the automatic recloser will open to clear the fault and automatically reclose after a time delay. This reclosing behavior can take place several times in an

---

† 교신저자, 正會員 : 崇實大 工大 電氣制御시스템工學部 敎授・工博
E-mail : jckim@ee.ssu.ac.kr
* 正 會 員 : 基礎電力硏究員 電力시스템硏究室 先任硏究員
** 正 會 員 : LG産電 電力硏究所 先任硏究員・工博
*** 學生會員 : 崇實大 工大 電氣制御시스템工學部 碩士課程
接受日字 : 2004年 9月 16日
最終完了 : 2004年 10月 8日

effort to establish a continuous service for a temporary fault. If the fault is temporary in nature, the reclosing operation of the breaker should be successful and the interruption will only be momentary. For this case, the customers of LP(Load Point) A on faulted feeder will experience a momentary interruption and the customers of LP B on neighbor feeder will experience a voltage sag or successive voltage sags and it is shown in the right-side of the Fig. 1(b). However, if the fault is permanent in nature, reclosing operations on the automatic recloser should be failed and the reclosing operation will be locked-out. For this case, the customers of the LP A and the LP B will experience a sustained interruption and a series voltage sags respectively as shown in Fig. 1. As shown in these examples, automatic reclosing of power distribution systems could produce the successive voltage sags.

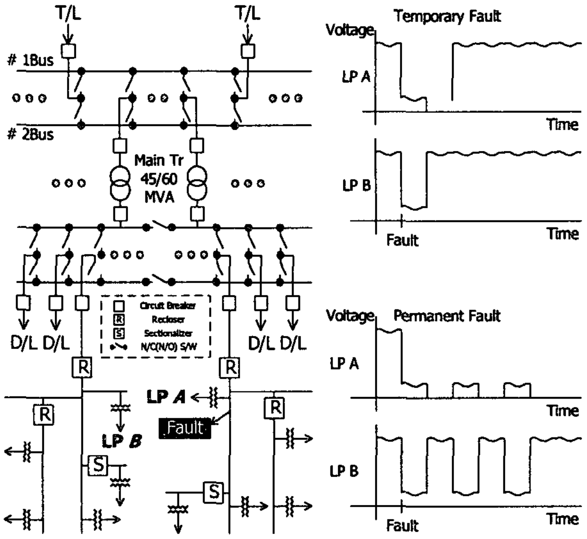


Fig. 1 Occurrence of the voltage sag during a fault clearing

2.2 Evaluation Methods of Impact of Voltage Sags

Several methods for assessing the impact of voltage sags are presented in this clause. These methods are divided into two parts. One is the assessment index. SARFI(System Average RMS Frequency Index) is based on the monitoring of a site for measuring the magnitude and duration of voltage sags[3].

$$SARFI_X = \frac{\sum NC_i}{NC_T} \tag{1}$$

where, X is the borderline value of voltage (i.e. 140, 120, 110, 90, 80, 70, 50, 10) and NC_i represents the number of customer that affected the voltage disturbances i over or under the borderline value $X\%$. NC_T is the total number of customer in system. SAVSRI(System Average Voltage Sag Risk Index) represent the annual average risk for voltage sags per customer[4]. The magnitude and duration of voltage sags and its risk are expected using a assumption formula of historical reliability data. Therefore this method is not required a monitoring system.

$$SAVSRI = \frac{Total\ Risk\ of\ Voltage\ Sags}{Total\ No.\ of\ Customer\ Served} \tag{2}$$

Another is the method that uses power acceptability curves. The most cited curves are the Computer Business Equipment Manufacturer Association (CBEMA) and the Information of Technology Industry Council (ITIC) curve as shown in Fig. 2[8]. The outside of each curve means the safety area for voltage variations and the curves are composed with the magnitude and duration axis of a voltage variation. The form of CBEMA curve is continuous, but the ITIC curve has the discrete shape.

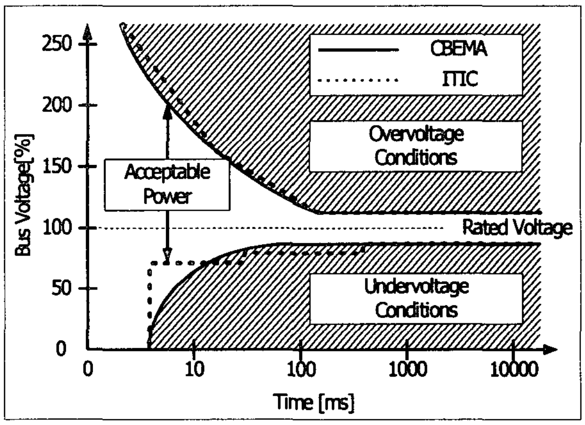


Fig. 2 Typical power acceptability curves

The third is the evaluation method that uses voltage sag contours[2,9]. For this method, the contour lines that represent the stochastic data of voltage sag occurrence for a duration and magnitude and the power acceptability curve of a load should be combined. Fig. 3 shows an example of the voltage sag contour. In the Fig. 3, the oblique lines are sag contours. In this example, the voltage sag which has 400ms duration and 70% magnitude can occur X_1 times in a year. The solid and dotted lines represent the power acceptability curve for individual and successive voltage sag, respectively.

The knee points of a power acceptability curve are used for calculating the number of impact of voltage sags in a year. If a equipment sensitivity is approximated by a shape with two knees as Fig. 1. The disruption region is the combination of all three shaded rectangular areas A, B, and C. Therefore, the total number of disruption of this equipment due to the individual voltage sags is

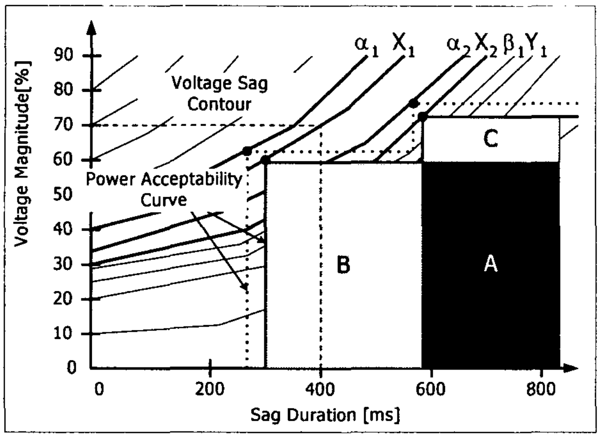


Fig. 3 Voltage sag contour and CBEMA curves

$$N_{ID} = X_1 + X_2 - Y_1 \quad (3)$$

where, X_1 and X_2 are the number of voltage sags which intersect the knee points of non-rectangular curve, and Y_1 denotes the overlap points of two rectangular shapes. These points are related to the power acceptability curve for individual voltage sag. If the number of knee points is N, Eq. (3) is generally formulated as follows.

$$N_{ID} = \sum_{i=1}^{N} X_i - \sum_{i=1}^{N-1} Y_i \quad (4)$$

The coordination chart of individual voltage sag predicts N_{ID} disruptions per year for this equipment sensitivity. As shown in the Fig. 3, the power acceptability curves of successive voltage sags are different from the curves of individual one. Therefore, the N_{SU} for the dotted line(power acceptability curve for successive voltage sags) is as follows.

$$N_{SU} = \sum_{i=1}^{N} \alpha_i - \sum_{i=1}^{N-1} \beta_i \quad (5)$$

where, α_i is the number of voltage sags which intersects the ith knee points of a non-rectangular curve for a successive voltage sags. β_i denotes the i-th overlap points of two rectangular shapes. The total impact of successive and individual voltage sag on a load is formulated as follows.

$$N_T = \left(\sum_{i=1}^{N} X_i - \sum_{i=1}^{N-1} Y_i \right) \times P_{r1} + \left(\sum_{i=1}^{N} \alpha_i - \sum_{i=1}^{N-1} \beta_i \right) \times P_{r2} \quad (6)$$

where, P_{r1} is the probability of first reclosing success and P_{r2} is the probability of second reclosing attempt.

For the verification of effectiveness of the proposed evaluation formulation in (6), we accomplish the actual test for obtaining the power acceptability curves of low-voltage loads and the case studies using voltage sag contours and the results of the actual test.

3. Actual Tests for Successive Voltage Sags

For the test of the proposed evaluation method, we accomplished the actual experiment. The object of this test was to obtain the power acceptability curve of the low-voltage sensitive loads for individual and successive voltage sags. The actual test for customers' loads is a very effective method to obtain the direct results, but it is impossible to accomplish the test of whole loads. Therefore, the reliability of the test was decided by the selection of representative sample loads. In this paper, some low-voltage loads were chosen for actual test based on [10]. The summary of test samples is shown in Table 1.

Table 1 Summary of actual tests

Type	Details	Confirmation of disruption
PC	P-III	rebooting
Magnetic contactor	110 and 220V	waveform
AVR	110 and 220V	waveform
HID lamp	Metal	relighting
Digital power meter	85-260V	resetting
Digital protective relay	110 and 85-260V	resetting
Adjustable speed driver	DC motor	waveform

Voltage sags were generated by a three-phase source simulator(AA-2000XG). Two different procedures were tested. One was the individual impact of voltage sag and the other was performed to obtain the CBEMA curve for successive voltage sags. Fig. 4 illustrates these procedures.

The configuration of the test system is shown in Fig.

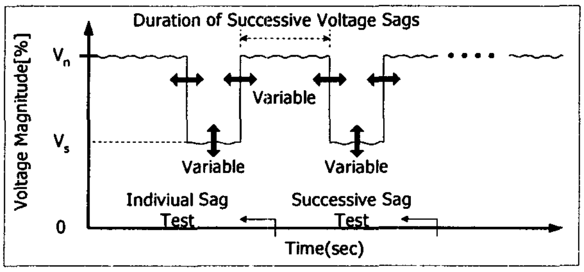


Fig. 4 Test procedures for the generation of successive voltage sags

5. As mentioned above, generated sags can be divided into two types; individual sag and successive sag. The generation time interval of successive voltage sags was set to be changed from 0.5s through 2s because it is typical reclosing interval which has employed in KEPCO(Korea Electric Power Corporation) distribution system. The source simulator was generating the voltage sags varying from 10% to 90% with 10% interval of normal voltage. Fig. 6 shows the digital oscilloscope and source simulator under the actual test.

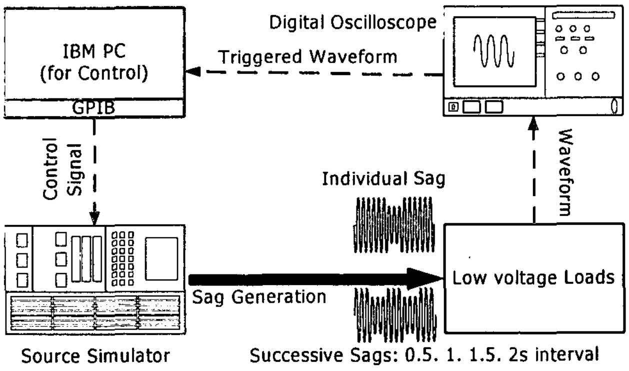


Fig. 5 Configuration of the test system

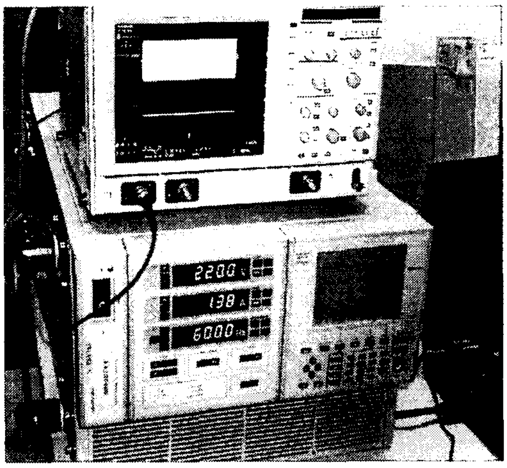
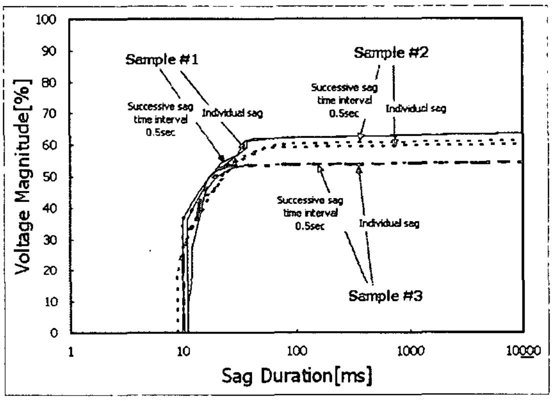


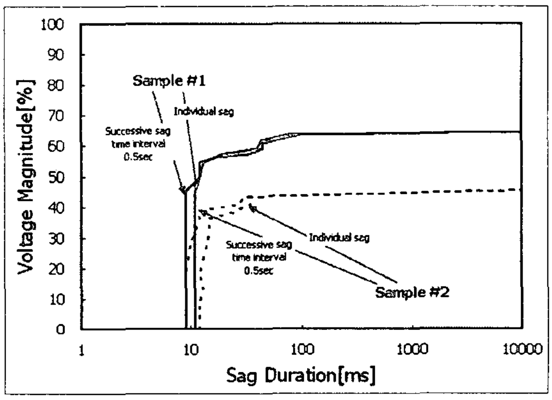
Fig. 6 Photo of the actual test scene

The results of the test are shown in Fig. 7. The vertical and horizontal axes represent the voltage magnitude and the sag duration, respectively. Voltage magnitude is in percent and sag duration is logarithmic scale. The CBEMA format curves in Fig. 7(a)~(b) illustrate the impact of individual and successive voltage sags for the magnetic contactor and the automatic voltage regulator. The average values of the curves for individual and successive voltage sags are shown in Fig. 7(c). As shown in these figures, we can find the cumulative impact of some loads.

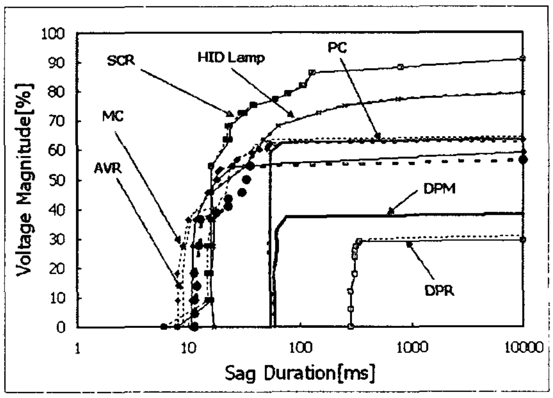
From the test results, SCR controller can be regarded as the most sensitive single-phase load among the test samples. But the digital power meter and digital protective relay are not sensitive to voltage sags compared to the other equipment. In regards to the impact of successive voltage sags, AVR and magnetic contactor are sensitive. It is turned out that other samples are not very affected by successive voltage sags.



(a) Magnetic contactor



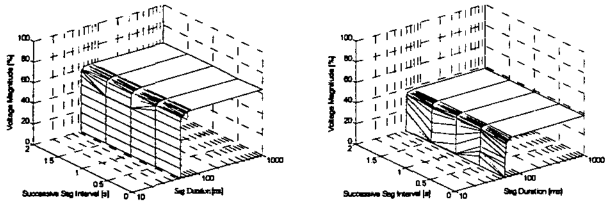
(b) Automatic voltage regulator



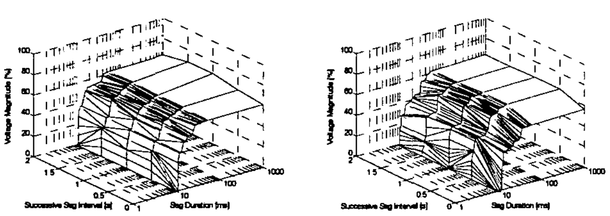
(c) Average results

Fig. 7 Test results

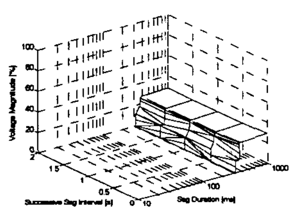
However, it is obvious that some devices which are not affected by the individual sag could malfunction during the successive voltage sags. Although x-axis of CBEMA curve presents the duration in logarithmic scale, it is not easy to make a comparison between the impact of individual voltage sag and successive one. More effective method that is easier to compare these plots is necessary. In this paper, 3-dimensional CBEMA curve is proposed. Fig. 8 shows 3-dimensional CBEMA curves of successive sags which have the sag generation time interval of 0.5s, 1s, 1.5s, and 2s for each load. The axes of these plots present the remaining voltage magnitude, the sag generation time, and the sag duration.



(a) PC (b) Digital power meter



(c) Magnetic contactor (d) AVR



(e) Digital protective relay

Fig. 8 3-dimensional CBEMA Curve

4. Case studies using Voltage Sag Contour

In order to perform a quantitative analysis of the impact of voltage sag, the voltage sag coordination charts were used[2]. Sag coordination charts show electric supply sag characteristics and utilization equipment response to voltage sags on a single graphical display. The foundation for the display is a 2-dimensional grid of sag magnitude on the vertical axis and the sag duration on the horizontal axis. Fig. 9 shows a supply sag performance contours which were derived from EPRI project[9]. We produced this contour curve by using interpolation. Each contour line represents the number of sags per year. In this paper, these contours were used for case studies.

Some ITIC curves that are derived from Fig. 7 (c) and turned out to have the most remarkable cumulative effect are shown in Fig. 10 (a)~(c). The solid lines represent individual voltage sag cases and the dotted lines represent successive voltage sag cases with the generation time interval of 0.5 [sec]. The number of disruption events from sags of rectangular equipment sensitivity such as PC, digital power meter, and digital protective relay can be determined rather easily. For the digital power meter case in Fig. 9 (b), the solid line knee intersects the 5 sag contour line at 56ms and 63[%] magnitude and the dotted line knee intersects the 5.1 sag contour line at the similar duration and magnitude. Therefore, in the case of the individual sag, process disruption will happen 5 times per year and process disruption caused by successive voltage sag will occur 5.1 times per year.

For the magnetic contactor, the solid line is approximated by a shape with three knees. Considered the areas shared by three knees, we can calculate the number of disruption events due to the individual voltage sags as follows. This means there will be 8.85 process disruptions per year for the individual voltage sags.

$$N_{ID}=(8.6+6.9+5.5)-(6.7+5.45)=8.85$$

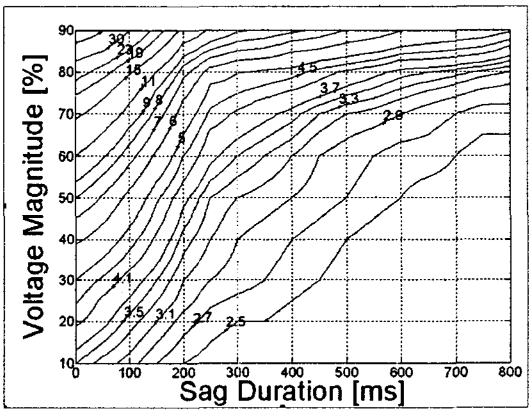
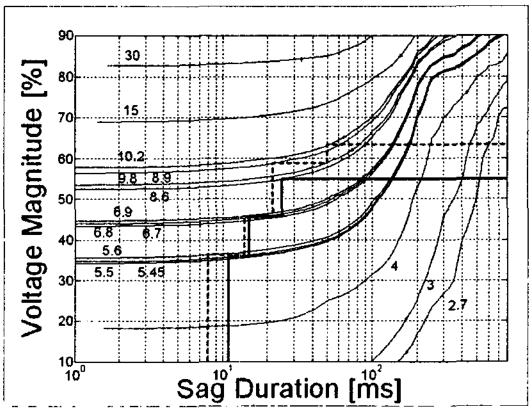
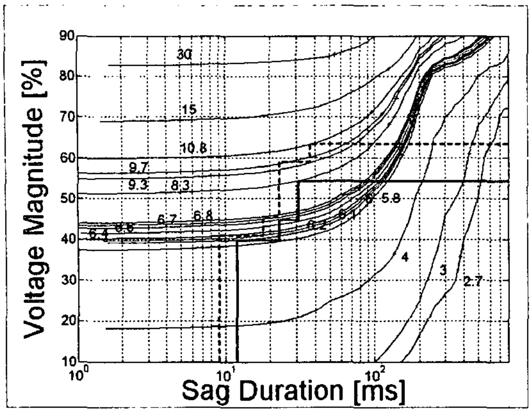


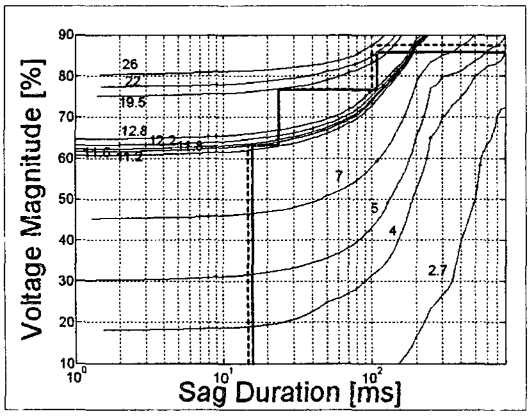
Fig. 9 Voltage sag contour



(a) Magnetic contactor



(b) AVR



(c) SCR controller

Fig. 10 Supply sag performance contours and ITIC curves for each load

Table 2 shows the number of disruption events from voltage sags for each load. That is to say, each number of the table means the possible number of disruption events from voltage sags for each load. According to the [11], it is assumed that P_{r1} and P_{r2} are 0.7(70%) and 0.3(30%), respectively. The number of disruption for individual and successive voltage sag, N_{ID} and N_{SU}, and the total number of the disruption due to the whole sags, N_T, are compared for each load type. The percentage of cumulative effect which compares N_{ID} with N_T is calculated as follows.

$$Cumulative\ Effect\ \% = \frac{N_T - N_{ID}}{N_{ID}} \times 100 \tag{7}$$

SCR controller is predicted to be disrupted 29.7 times per year by individual voltage sags, 32.3 times per year by successive ones and 30.48 times per year by total voltage sags. The number of disruption events for high intensity discharge lamp is also high. Therefore, we can say that SCR controller and high intensity discharge lamp is basically very sensitive to voltage sags. Although the number of disruption events for magnetic contactor is lower than for SCR controller's, magnetic contactor will disrupt 11.3 times per year by successive voltage sag while 8.85 process disruptions due to individual voltage sag will occur. AVR is also considerably affected by successive voltage sags. Therefore, for the cumulative effect, M/C and AVR have higher probabilities than the others.

Table 2 Number of the disruption events for each load

Event type / Load type	N_{ID}	N_{SU}	N_T	Cumulative Effect %
PC (personal computer)	9.90	9.70	9.84	-0.61
DPM (digital power meter)	5.00	5.10	5.03	0.60
M/C (magnetic contactor)	8.85	11.30	9.59	8.31
AVR (automatic voltage regulator)	8.70	11.40	9.51	9.31
DPR (digital protective relay)	2.76	2.78	2.77	0.22
HID (high intensity discharge) lamp	15.40	15.50	15.43	0.19
SCR controller	29.70	32.30	30.48	2.63

According to these results, we can expect the probability of the disruption of each load for a year and decide the cumulative effect of successive voltage sags.

5. Conclusions

In this paper we proposed the quantitative evaluation method of the successive impact of voltage sags due to the automatic reclosing of distribution systems. For this purpose, we accomplished the actual tests of the low voltage sensitive loads for obtaining the susceptibility of voltage sags. Form the results of the test, we produced the CBEMA format curves for individual and successive voltage sags, and the 3-dimensional power acceptability curves were presented. We proposed the assessment formulation of the successive voltage sag using the performance contour of voltage sags and the statistical probability of the reclosing successful ratio. The proposed formulation was tested by using the stochastic data of voltage sag contour in IEEE standard and actual test results. Through the case study, we verified that the proposed method can be used for expecting the probability of the disruption of each load for a year and deciding the cumulative effect of successive voltage sags.

Acknowledgement

This work has been supported by KESRI(02-jung-03), which is funded by MOCIE(Ministry of commerce, industry and energy)

References

[1] L. E. Conrad et al., "Proposed chapter 9 for predicting voltage sags (dip) in revision to IEEE Std 493, the Gold Book," IEEE Trans. Industry Applications, Vol. 30, No. 3, pp. 805-821, May/June 1994.

[2] L. E. Conrad and Math H. J. Bollen, "Voltage sag coordination for reliable plant operation," IEEE Trans. Industry Applications, Vol. 33, No. 6, pp. 1459-1464, November/December 1997.

[3] R. C. Dugan, D. L. Brooks, M. Waclawiak, and A. Sundaram, "Indices for assessing utility distribution system RMS variation performance," IEEE Trans. Power Delivery, Vol. 13, No. 1, pp. 254-259, January 1998.

[4] S.-Y. Yun and J.-C. Kim, "An evaluation method of voltage sag using a risk assessment model in power distribution system," International Journal of EP&ES(Elsevier Science), Vol.25, No.10, pp.829-839, December 2003.

[5] IEEE recommended practice for emergency and standby power systems for industrial and commercial applications, ANSI/IEEE Std. 446, 1987.

[6] Y. Sekine, T. Yamamoto, S. Mori, N. Saito, and H. Kurokawa, "Present state momentary voltage dip interferences and the countermeasures in Japan," CIGRE 36-206, September 1992.

[7] J. Lamoree, D. Mueller, P. Vinett, W. Jones, and M. Samotyj, "Voltage sag analysis case studies," IEEE Trans. Industry Applications, Vol. 30, No. 4, pp. 1083-1089, July/August 1994.

[8] J. Arrillaga, N. R. Watson, and S. Chen, Power system quality assessment, Chichester: John Wiley & Sons, 2000.

[9] IEEE recommended practice for evaluating electric power system compatibility with electronic process equipment, IEEE Std. 1346, 1998.

[10] IEEE guide for service to equipment sensitive to momentary voltage disturbances, IEEE Std. 1250, 1995.

[11] J. C. Kim and J. R. Shin, A study for the optimal reclosing method on the transmission and distribution line, Korea Electric Power Research Institute, Taejeon, Chung-Nam, Korea, Tech. Rep. TR.95YJ18.J1998.12, April 1998.

저자소개

문 종 필(文 鍾 必)

1977년 5월 27일생. 2000년 숭실대 전기공학과 졸업. 2004년 동 대학원 전기공학과 박사 수료. 현재 기초전력연구원 선임연구원.

Tel : 02-880-7587, Fax : 02-883-0827

E-mail : pichard@er.snu.ac.kr

김 재 철(金 載 哲)

1955년 7월 12일 생. 1979년 숭실대 전기공학과 졸업. 1987년 서울대 대학원 전기공학과 졸업(공박). 현재 숭실대 전기제어시스템공학부 교수.

Tel : 02-820-0647, Fax : 02-817-0780

E-mail : jckim@ee.ssu.ac.kr

윤 상 윤(尹 尙 潤)

1970년 8월 28일생. 1996년 숭실대 전기공학과 졸업. 2002년 동 대학원 전기공학과 졸업(공박). 현재 LG산전 전력연구소 선임연구원.

Tel : 043-261-6506, Fax : 043-261-6629

E-mail : syyun@lgis.com

강 봉 석(姜 奉 奭)

1978년 3월 25일생. 2003년 숭실대 전기공학과 졸업. 현재 동 대학원 전기공학과 석사과정.

Tel : 02-824-2416, Fax : 02-817-0780

E-mail : seogi23@ssu.ac.kr