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Quantitative Evaluation of the Impact of Low-Voltage Loads due to Repetitive Voltage Sags

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Abstract - Automatic reclosing is a typical protection method in power distribution systems for the clearing of temporary faults. However, it has a fatal weakness in regards to voltage sags because it produces repetitive voltage sags. In this paper, we explored the repetitive impact of voltage sag due to the automatic reclosing of power distribution systems. The actual tests of low voltage loads were carried out for obtaining the susceptibility of voltage sags. The final results of the tests yielded power acceptability curves of voltage sag, and the curves transformed the 3-dimensional CBEMA (Computer Business Equipment Manufacturer Association) format. For the quantitative evaluation of the impact of repetitive 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 repetitive voltage sags.

Keywords: Automatic reclosing, power acceptability curve, power quality, repetitive voltage sags, voltage sag contour

1. Introduction

Over the past few decades, the impact of voltage sags has continued to grow with the increase in the use of electronic and precision instruments by customers and the topology of distribution systems becoming shorter and higher in density.

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 testing 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 the entire outages. In spite of these merits, some weaknesses in regard to the power quality still remained, owing to repetitive voltage sags. The impact of repetitive voltage sags due to the automatic reclosing is not dealt with in the above mentioned studies.

In this paper, we explored the repetitive impact of voltage sags due to the automatic reclosing of power distribution systems. Actual tests of the sensitive loads were carried out for obtaining the susceptibility of voltage sags and the quantitative approaches were also accomplished by using the performance contours of voltage sag. In 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 section 3, the actual tests and their results for obtaining the power acceptability curves of the low voltage loads are presented. In section 4, we propose the assessment formulation of the impact of repetitive voltage sags using the performance contour of voltage sag and case studies 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 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 effort to establish a continuous service for a temporary fault. If the

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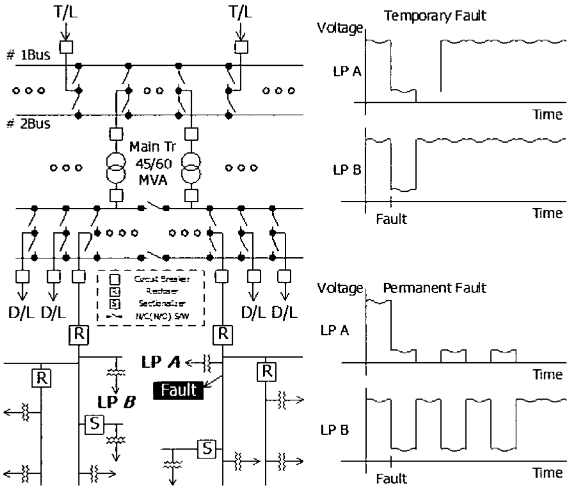
fault is temporary in nature, the reclosing operation of the breaker should be successful and the interruption will only be momentary. For this case, the customers of LP (Load Point) A on the faulted feeder will experience a momentary interruption and the customers of LP B on the neighbor feeder will experience a voltage sag or repetitive voltage sags and this is shown in the right-side of 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 of voltage sags respectively as shown in Fig. 1. As presented in these examples, the automatic reclosing of power distribution systems could produce repetitive voltage sags.



(a) (b)

Fig. 1 Occurrence of voltage sag during a fault clearing

2.2 Evaluation Methods of Voltage Sag Impact

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

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

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 denotes the safety area for voltage variations and the curves are composed with the magnitude and duration axis of a voltage variation. The form of the CBEMA curve is continuous, but the ITIC curve has a discrete shape.

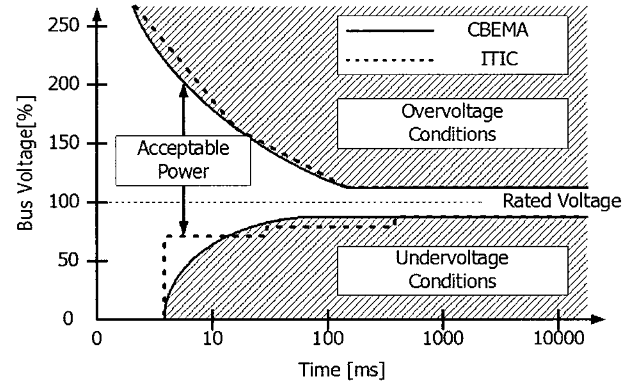


Fig. 2 Typical power acceptability curves

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 duration and magnitude and the power acceptability curve of a load should be combined. Fig. 3 depicts an example of the voltage sag contour. In Fig. 3, the oblique lines are sag contours. In this example, the voltage sag having 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 repetitive voltage sag, respectively.

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

$$N_{ID} = X_1 + X_2 - Y_1 \tag{3}$$

where, X_1 and X_2 are the number of voltage sags that intersect the knee points of the non-rectangular curves, and Y_l 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, (3) is generally formulated as follows.

$$N_{ID} = \sum_{i=1}^{n} X_i - \sum_{i=1}^{n-1} Y_i \tag{4}$$

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

$$N_{SU} = \sum_{i=1}^{n} \alpha_i - \sum_{i=1}^{n-1} \beta_i \tag{5}$$

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

$$N_T = (\sum_{i=1}^{n} X_i - \sum_{i=1}^{n-1} Y_i) \times P_{r1} + (\sum_{i=1}^{n} \alpha_i - \sum_{i=1}^{n-1} \beta_i) \times P_{r2} \tag{6}$$

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

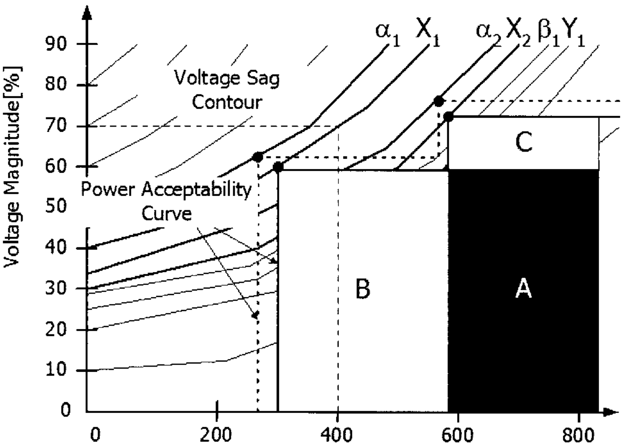


Fig. 3 Voltage sag contour and CBEMA curves

3. Actual Tests for Repetitive Voltage Sags

For the test of the proposed evaluation method, we performed the actual experiment. The object of this test was to obtain the power acceptability curve of the low-voltage sensitive loads for individual and repetitive 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 tests 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	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 repetitive voltage sags. Fig. 4 illustrates these procedures.

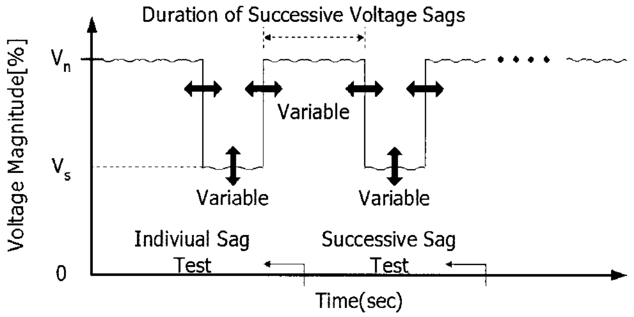


Fig. 4 Test procedures for the generation of repetitive voltage sags

The configuration of the test system is shown in Fig. 5. As mentioned above, generated sags can be divided into two types; individual sag and repetitive sag. The generation time interval of repetitive voltage sags was set to be changed from 0.5s through 2s because it is a typical reclosing interval employed by the 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.

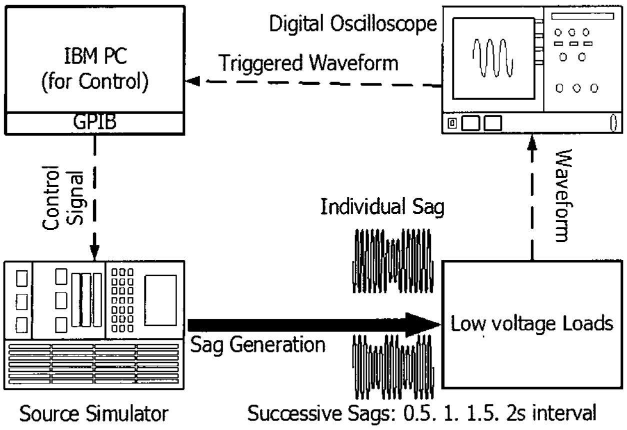


Fig. 5 Configuration of the test system

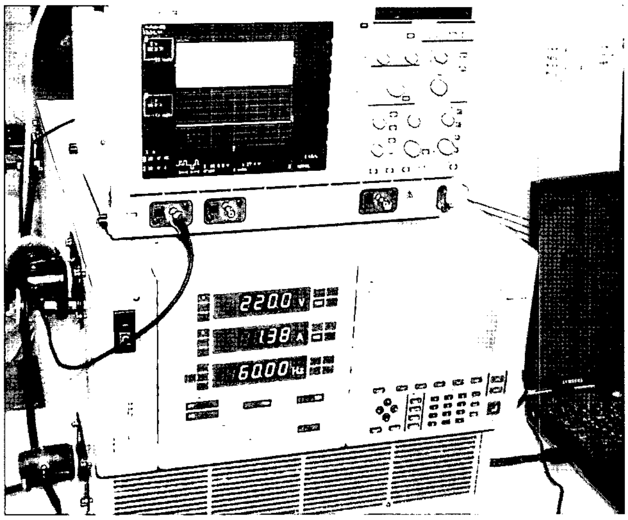
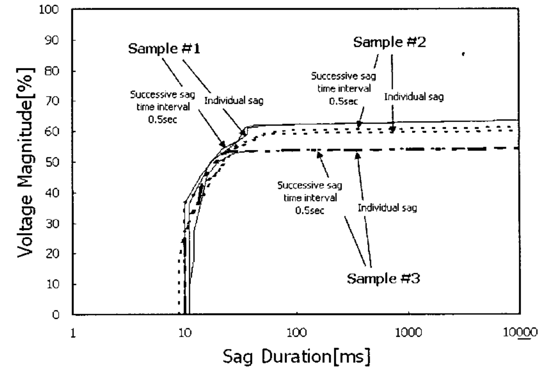


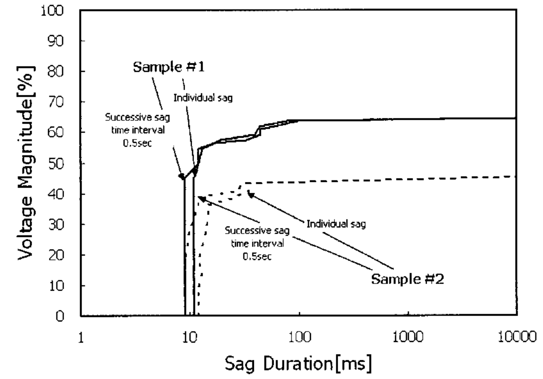
Fig. 6 Photo of the actual test scene

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 in logarithmic scale. The CBEMA format curves in Fig. 7(a)~(b) illustrate the impact of individual and repetitive voltage sags for the magnetic contactor and the automatic voltage regulator. The average values of the curves for individual and repetitive voltage sags are shown in Fig. 7(c). As can be seen in these figures, we can find the cumulative impact of some loads.

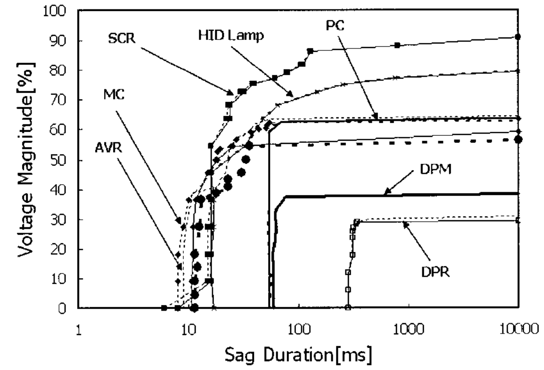
From the test results, the SCR controller can be regarded as the most sensitive single-phase load among the test samples. But the digital power meter and digital protective relay are not sensitive to voltage sags compared to the other equipment. In regards to the impact of repetitive voltage sags, the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



(a) Magnetic contactor



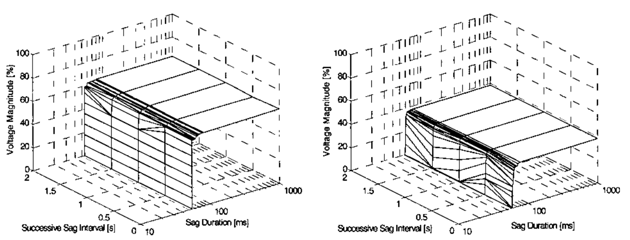
(b) Automatic voltage regulator



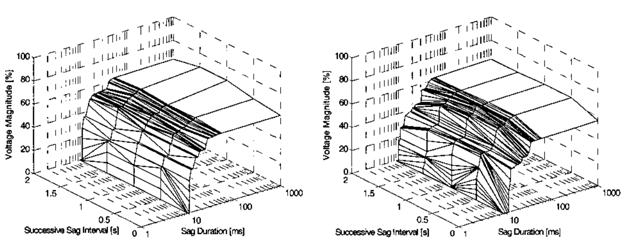
(c) Average results

Fig. 7 Test results

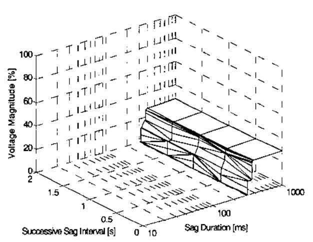
However, it is obvious that some devices which are not affected by the individual sag could malfunction during repetitive voltage sags. Although the x-axis of the CBEMA curve presents the duration in logarithmic scale, it is not easy to make a comparison between the impact of individual voltage sag and the repetitive sags. A more effective method that makes it easier to compare these plots is necessary. In this paper, a 3-dimensional CBEMA curve is proposed. Fig. 8 shows 3-dimensional CBEMA curves of repetitive sags that 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 Contour

In order to perform a quantitative analysis of the impact of voltage sag, voltage sag coordination charts were used [2]. Sag coordination charts illustrate 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 indicates supply sag performance contours that were derived from the 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 repetitive 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 repetitive voltage sag will occur 5.1 times per year.

For the magnetic contactor, the solid line is approximated by a shape with three knees. Considering 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.

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

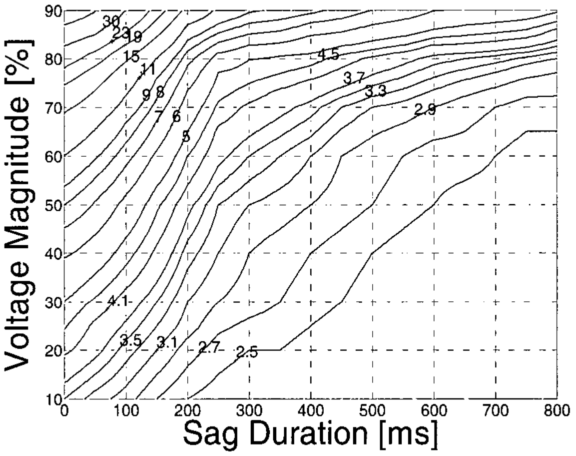
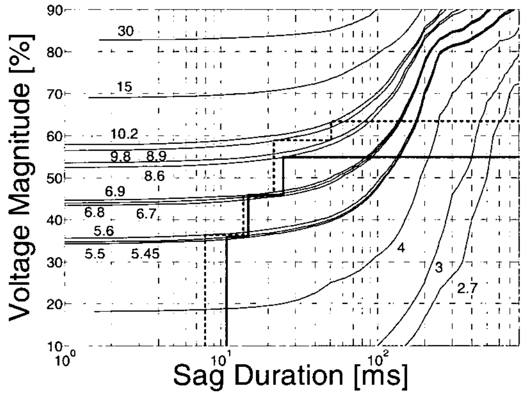


Fig. 9 Voltage sag contour

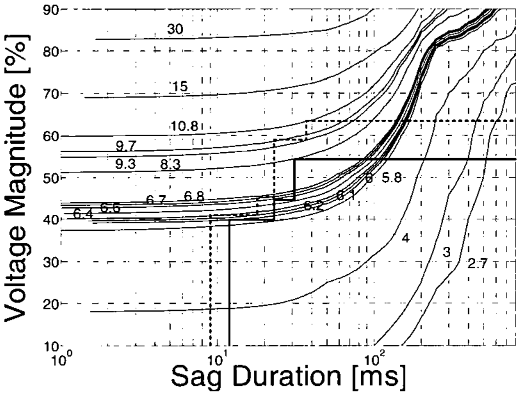
Table 2 presents the number of disruption events from voltage sags for each load. That is to say, each number on the table means the possible number of disruption events from voltage sags for each load. According to [11], it is assumed that P_{r1} and P_{r2} are 0.7 (70%) and 0.3 (30%), respectively.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

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

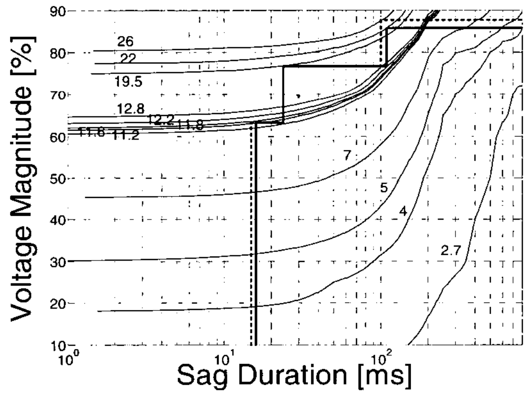
The SCR controller is predicted to be disrupted 29.7 times per year by individual voltage sags, 32.3 times per year by repetitive sags and 30.48 times per year by total voltage sags. The number of disruption events for high intensity discharge lamps is also high. Therefore, we can say that SCR controllers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



(a) Magnetic contactor



(b) AVR



(c) SCR controller

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

Table 2 Number of the disruption events for each load

Event type	N_{ID}	N_{SU}	N_T	Cumulativ
PC	9.90	9.70	9.84	-0.61
DPM	5.00	5.10	5.03	0.60
M/C	8.85	11.30	9.59	8.31
AVR	8.70	11.40	9.51	9.31
DPR	2.76	2.78	2.77	0.22
HID	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 repetitive voltage sags.

5. Conclusions

In this paper we proposed the quantitative evaluation method of the repetitive impact of voltage sags due to the automatic reclosing of distribution systems. For this purpose, we carried out actual tests of the low voltage sensitive loads for obtaining the susceptibility of voltage sags. From the results of the test, we produced the CBEMA format curves for individual and repetitive voltage sags, and the 3-dimensional power acceptability curves were presented. We proposed the assessment formulation of the repetitive 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 as per 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 repetitive voltage sags.

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