RESEARCH ON CLASSIFICATION OF VOLTAGE SAG SOURCES BASED ON RECORDED EVENTS

Pengfei WEI
NCEPU – China
weipengfei930602@163.com

Yonghai XU
NCEPU – China
yonghaixu@263.net

Yapen WU
NCEPU – China
wuyapen2010@163.com

Chenyi LI
NCEPU – China
1903539506@qq.com

ABSTRACT

In recent years, with the widely application of power electronic devices and stringent requirement of industrial process, voltage sag has caused much attention in many countries. To design effective and efficient mitigation and management strategies, it is essential to have accurate classification of voltage sag sources. In this paper, based on the analysis of massive voltage sag events in the grid recorded by online power quality monitoring systems in several different regions in China, a more extensive and practical classification of voltage sag sources is given. The voltage sags are divided into eight categories due to short circuit faults with symmetric and asymmetric faults included, transformer energizing, induction motor starting, lightning faults, self-extinguishing faults, the combined action of short circuit faults and heavy load starting, upgrade faults and multistage voltage sags. For each category of the voltage sag sources, both the instantaneous value and the root mean square (RMS) value of the waveform of the typical recorded events are given. In addition, the reasons are analysed and the waveform characteristics are summarized for each category of the voltage sag sources. Finally, the frequencies of eight categories under different voltage levels and the statistical result analysis are given.

INTRODUCTION

Voltage sag refers to a temporary reduction of the root mean square (RMS) voltage at a point in the electrical system below a threshold [1]. In many regions, voltage sag has become one of the most concerned power quality problems. And the huge economic loss caused by voltage sags has been the most important problem that many consumers are faced with [2].

In recent years, lots of experts and scholars have done research on the classification (e.g. [3]-[4]), detection and identification (e.g.[5]-[8]) of voltage sags. In [3], the voltage sag events obtained from surveys in medium and low voltage networks were classified. The events were mainly classified into five categories due to short circuit faults, induction motor starting, transformer energizing, self-extinguishing faults and multistage voltage sags. The voltage waveforms of the instantaneous value and the fundamental frequency magnitude were given. In [4], an expert system was presented to classify different categories of power system events. Voltage sags were mainly classified into three categories due to short circuit faults, induction motor starting and transformer energizing. And the waveforms of fundamental voltage magnitude were given as well. In view of the detection and classification of voltage sags, three voltage sag sources including fault induced voltage sag, starting of induction motor and three phase transformer energization were chosen in [6], while four sources including short circuit faults, transformer energizing, induction motor starting and self-extinguishing faults were used in [7].

In existing papers, voltage sags are mainly classified into three categories due to short circuit faults, induction motor starting and transformer energizing. And the classification of actual voltage sag sources was not comprehensive. In actual power systems, the sags caused by lightning are not the same with short circuit faults. Besides, a part of sags may be caused by the combined action of several reasons including short circuit faults, upgrade faults, heavy load starting and relay protection. Therefore, a more extensive and practical classification of voltage sag sources are necessary. In this paper, based on the voltage sag events recorded in the online power quality monitoring systems in several different regions of China, the voltage sag sources are classified more extensively and specifically. Reason analysis and waveform characteristics are summarized for each category of sags, and the typical waveforms of each category are given. Finally, the 369 effective voltage sag events under different voltage levels are classified and the statistical results are analysed as well.

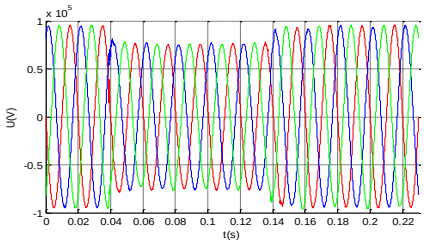
CLASSIFICATION OF VOLTAGE SAG SOURCES

A. Voltage sags due to short circuit faults

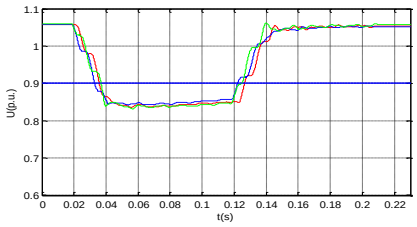
In actual power systems, more than 70% of voltage sags are caused by short circuit faults. During the process of power system operation, short circuit faults may occur due to the operation overvoltage, the natural aging insulation material, equipment defects caused by poor design and installation, etc. After the occurrence of short circuit faults, the magnitude of the point of common coupling (PCC) connected to the short circuit point and its connecting branches may decrease, and the voltage sag occurs. With the action of relay protection, the short circuit point is insulated with the whole system, the voltage goes back to the normal level and the sag is over. Therefore, the sag duration depends on the time of fault removing. Voltage sags due to short circuit faults can be classified into two categories: the symmetrical voltage sags caused by three-phase short circuit fault and the asymmetric voltage sags caused by single-phase grounding fault, two-phase grounding fault and two-phase fault.

Fig.1 shows the recorded waveform of a symmetrical voltage sag occurring in a 110kV bus and Fig.2 shows the

recorded waveform of an asymmetrical voltage sag occurring in a 110kV bus. It can be seen that the RMS value waveform of this category is approximate to a rectangle.

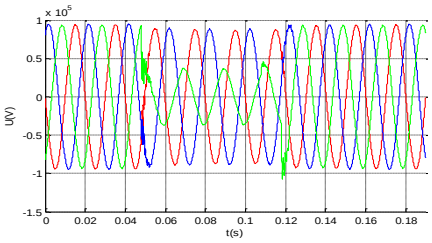


a) The instantaneous value

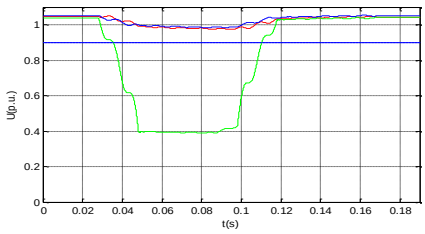


b) The RMS value

Fig.1 The recorded waveform of a symmetrical voltage sag due to short circuit faults



a) The instantaneous value



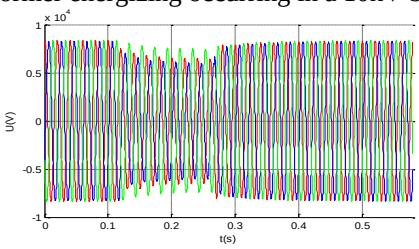
b) The RMS value

Fig.2 The recorded waveform of an asymmetrical voltage sag due to short circuit faults

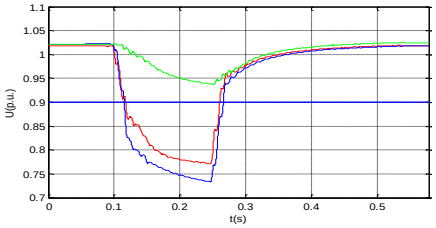
B. Voltage sags due to transformer energizing

When a transformer is put into operation, due to the saturation effect of the core, the inrush current will produce up to 8-10 times the rated current. The magnitudes of the inrush current and the voltage sag are both related to the initial phase angle of no-load transformer. For a three-phase transformer, the magnitude of each phase is always unbalanced due to the 120° phase difference. A different extend of inrush current may appear in at least two phases by no-load transformer in any cases. That is to say, voltage sags may appear in at least two phases. For a large capacity transformer, which has small resistance and large reactance, it may cost a long time to reach steady state when the sag is over.

Fig.3 shows the recorded waveform of a voltage sag due to transformer energizing occurring in a 10kV bus.



a) The instantaneous value



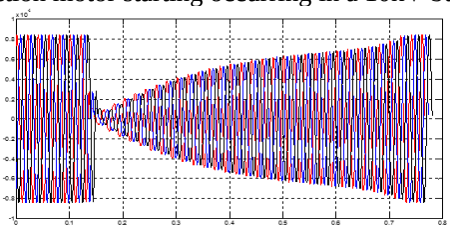
b) The RMS value

Fig.3 The recorded waveform of a voltage sag due to transformer energizing

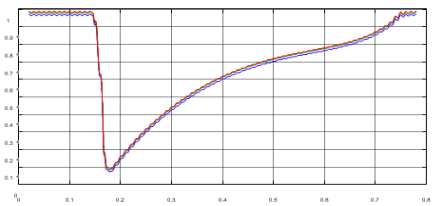
C. Voltage sags due to induction motor starting

As a large number of induction motors are used in actual power system, the voltage sags due to induction motor starting cannot be ignored. When an induction motor starts, the current drawn from the power grid is 5-6 times the current of the full load operation. When the current flows through the system impedance, a sudden voltage drop in the PCC point may be caused, and the voltage sag occurs. The extent of voltage sag is determined by the starting capacity of the motor, the residual capacity of the superior transformer and local power network. If the starting capacity of the motor is close to the residual capacity of the superior transformer, the magnitude of the voltage sag may be smaller.

Fig.4 shows the recorded waveform of a voltage sag due to induction motor starting occurring in a 10kV bus.



a) The instantaneous value



b) The RMS value

Fig.4 The recorded waveform of a voltage sag due to induction motor starting

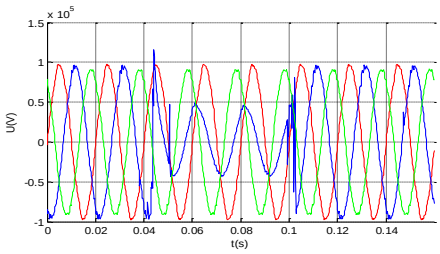
The following conclusions can be drawn in Fig.4. With respect to the voltage sags due to induction motor starting, the magnitudes of the three phases are the same. The voltage drops suddenly in the starting moment and recovers slowly. The recovery duration is long, and there is no obvious end point of the voltage sag. Besides, the voltage after the sag may be a little different with the voltage before the sag.

D. Voltage sags due to lightning faults

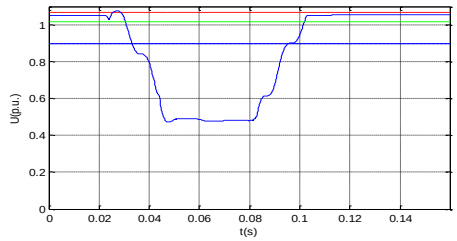
As a large part of the overhead line is exposed in nature, it is very easy to be affected by lightning in thunderstorm season. When the transmission line is stricken by lightning, if the lightning current exceeds the protection level of the transmission line, the impulse flashover may appear in the line insulation. The lightning current flows into the ground along the flashover channel, and the action may not be taken by line switch because the time is only a few tens. The power frequency short-circuit current continues to flow through the flashover channel and the stable arc is established, then the ground fault happens and the line trips. When the line is stricken by lightning, the lightning travelling wave will be produced and propagate in the system. The voltage of each site in the system may rise and fluctuate due to the wave propagation and the reflection of the traveling wave. After the ground fault caused by the insulator flashover happens, the voltage sag may propagate in the system, and the site voltage will first rise and then fall.

The sags due to lightning are not the same with short circuit faults. When a line fault is stricken by lightning, the lightning waves propagate in the system and high frequency component is consisted in the bus voltage signal. However, when it comes to common circuit faults, high frequency component is not contained in the bus voltage signal, and the bus voltage waveform does not rise but directly drops. More than 90% of the faults caused by lightning are single-phase grounding faults. Considering that the atmospheric overvoltage may be caused by the lightning in the three-phase wires, there is the possibility of two-phase and three-phase grounding faults. Besides, the power frequency short-circuit current flows into ground along the flashover channel, therefore, most faults caused by lightning are grounding faults and the probability of two-phase faults is very small.

Fig.5 shows the recorded waveform of a voltage sag due to lightning occurring in a 110kV bus.



a) The instantaneous value



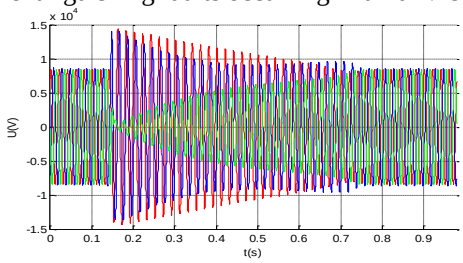
b) The RMS value

Fig.5 The recorded waveform of a voltage sag due to lightning faults

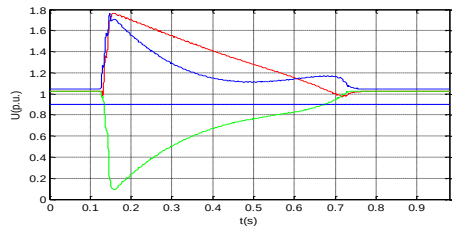
E. Voltage sags due to self-extinguishing faults

Self-extinguishing fault is a fault that has disappeared before the circuit breaker closest to the fault acting. This category of faults will not cause the action of the circuit breaker, but the swell may occur.

Fig.6 shows the recorded waveform of a voltage sag due to self-extinguishing faults occurring in a 10kV bus.



a) The instantaneous value



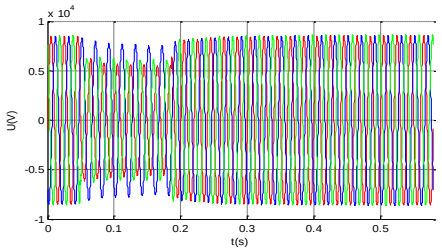
b) The RMS value

Fig.6 The recorded waveform of a voltage sag due to self-extinguishing faults

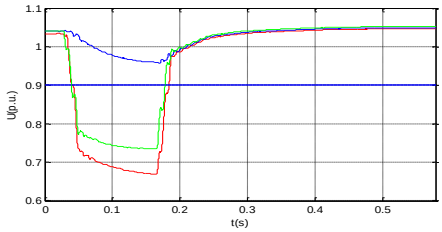
F. Voltage sags due to the combined action of short circuit faults and heavy load starting

When a short circuit fault occurs in the system, the induction motors closing to the fault point will lose most of the air gap magnetic field energy and slow down. When the fault is removed, a large current will be absorbed from the grid by induction motors. As a result, the voltage recovers slowly and the duration is long. This phenomenon is common in the power lines with heavy loads. Its difference to short circuit faults is the longer voltage recovery time and grater damage to the power system. Similarly, once the fault is removed, the transformer closing to the fault point goes into saturation state and the recovery characteristics of voltage sags are similar to the voltage sags due to transformer energizing.

Fig.7 shows the recorded waveform of a voltage sag due to the combined action of short circuit faults and heavy load starting occurring in a 10kV bus.



a) The instantaneous value

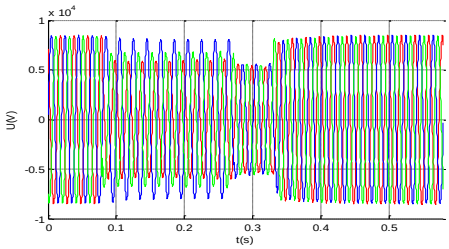


b) The RMS value

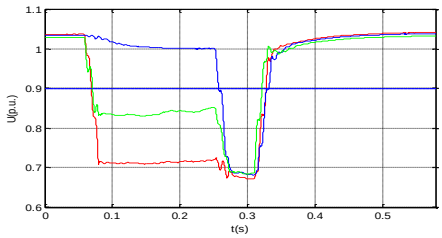
Fig.7 The recorded waveform of a voltage sag due to the combined action of short circuit faults and heavy load starting

G. Voltage sags due to upgrade faults

In actual power system, single-phase faults and two-phase faults will develop into three-phase faults due to the influence of arc or other factors. Fig.8 shows the recorded waveform of a voltage sag due to upgrade faults occurring in a 10kV bus.



a) The instantaneous value



b) The RMS value

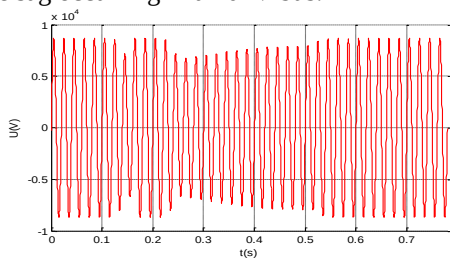
Fig.8 The recorded waveform of a voltage sag due to upgrade faults

Compared with the voltage sags due to short circuit faults, the fall and recovery process of sags due to upgrade faults is complicated. It is equivalent to a voltage sag occurring in another voltage sag which has not finished yet. The fall of sag magnitude can be divided into two processes. And the sag magnitude of the second process is smaller than the first generally. Therefore, the whole duration is longer and the influence on sensitive equipment is greater.

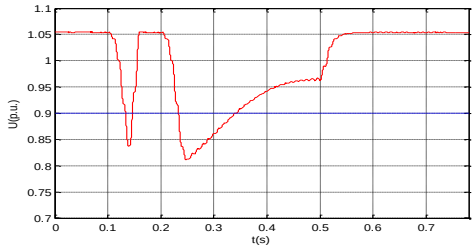
H. Multistage voltage sags

In actual power system, voltage sags do not occur randomly throughout the year, and their distribution is related to the weather condition. In bad weather condition, the probability of sag occurrence is higher than the normal weather condition. Therefore, two or more voltage sags may occur within a short time one after another, and a multistage voltage sag may occur. Multistage voltage sags can be caused by automatic reclosing device as well. Two similar voltage sags may be caused by an unsuccessful reclosing operation. Besides, even the reclosing operation acts successfully, another voltage sag may be caused by transformer energizing when the fault is removed. And a multistage voltage sag is formed by the two sags.

Fig.9 shows the recorded waveform of a multistage voltage sag occurring in a 10kV bus.



a) The instantaneous value



b) The RMS value

Fig.9 The recorded waveform of a multistage voltage sag

When two or more voltage sags occur within a short time one after another, sensitive equipment may be immune to the previous sag but may break down due to the second similar or more various sag. Besides, if sensitive equipment breaks down or runs wrongly during the first sag, then it will not be influenced by the second sag. The multistage voltage sag is described mostly on the basis of duration and magnitude or on the selection of the most serious sag in the multistage voltage sag. Therefore, the influence of multistage voltage sags on sensitive equipment cannot be reflected completely and special consideration should be taken in the evaluation of sensitive equipment to multistage voltage sags.

STATISTICAL RESULT ANALYSIS

In this paper, according to the eight categories of voltage sag sources, the 369 effective voltage sags recorded by online power quality monitoring systems in several regions of China are classified and analyzed. The voltage levels of the sag events are 10kV, 35kV, 110kV and

220kV. The statistical results are shown in Tab.1.

Tab.1 The frequencies of eight categories under different voltage levels

Sag Category	Voltage level(kV)				Percentage
	10	35	110	220	
A	99	23	86	88	80.22%
B	16	3	0	4	6.23%
C	2	0	0	0	0.54%
D	0	0	1	0	0.27%
E	15	0	0	0	4.07%
F	5	1	2	1	2.44%
G	2	2	0	0	1.08%
H	17	0	2	0	5.15%

The following conclusions can be drawn from Tab.1. First of all, the probability of Category A is 80.22% in all of the sag events, the conclusion that short circuit fault is the main cause of voltage sags can be proven. And the higher the voltage level, the higher the probability of voltage sags due to short circuit faults. In the voltage level of 220kV, the probability of Category A is up to 94.62%. Although the probability of Category A is high, other categories cannot be ignored as well. For example, in the voltage level of 10kV, other categories except A is 36.54%, which is large enough to be paid attention to. As a whole, Category B and F may happen at each of the voltage levels, while Category C, E, G and H may happen mostly under the voltage level of 10kV.

In the existing voltage sag evaluation method [1], the magnitude is defined as the ratio of the minimum voltage to the rated voltage during the sag process and the duration is defined as the time of the whole sag process. As the periods of starting and finishing in Category A are relatively short and the time at the minimum voltage is relatively long, the existing method can be applied to Category A. However, it may be not suitable for other categories. Take Category C as an example, the time at the minimum voltage is almost close to 0. It may cause excessive evaluation using existing method. Therefore, a new method according to the waveform characteristics should be proposed to evaluate the other categories accurately.

CONCLUSION

In this paper, eight categories of voltage sag sources including short circuit faults, transformer energizing, induction motor starting, lightning faults, self-extinguishing faults, the combined action of short circuit faults and heavy load starting, upgrade faults and multistage voltage sags are introduced and analyzed in detail.

On the basis of the voltage sag events in the grid recorded by online power quality monitoring systems in several different regions in China, both the instantaneous value and RMS value of the waveform of the typical recorded events are given for each category of the voltage sag sources. The waveform characteristics of each category are analyzed and summarized. The frequencies of the eight categories under different voltage levels are given and the statistical results are analyzed. Category A is the most common voltage sag, while other categories cannot be ignored as well. Besides, it is suggested that a new method according to the waveform characteristics should be proposed for the accurate evaluation of other categories of voltage sags.

It has significance for further understanding of voltage sag source categories, and a theoretical basis for the detection and identification of the sources can be provided by the study of the voltage sag sources. Besides, the more extensive and practical classification of voltage sag sources can provide a theoretical basis for power grid workers and consumers to study and take corresponding control measures as well.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (No. 51277069).

REFERENCES

[1] IEEE Std. 1564-2014, *IEEE Guide for Voltage Sag Indices*, IEEE Press, New York, USA, 2014.

[2] K. Zhu, Y. Wang, P. Yin, and J. Ni, 2015, "Voltage sag source location technology based on corresponding sequence components", *IET Generation, Transmission & Distribution*, vol. 9, 820–827.

[3] E. Styvaktakis, M. H. J. Bollen, and I. Y. H. Gu, 2000, "Classification of power system events: voltage dips", *Proc. 2000 Ninth International Conference on Harmonics and Quality of Power*, 745-750.

[4] E. Styvaktakis, M. H. J. Bollen, and I. Y. H. Gu, 2002, "Expert system for classification and analysis of power system events", *IEEE Transactions on Power Delivery*, vol. 17, 423–428.

[5] N. Wang, S. Wang, and Q. Jia, 2014, "The method to reduce identification feature of different voltage sag disturbance source based on principal component analysis", *Proc. 2014 Transportation Electrification Asia-Pacific (ITEC Asia-Pacific), IEEE Conference and Expo*, 1-6.

[6] M. Manjula, A. V. R. S. Sarma, and S. Mishra, 2011, "Detection and classification of voltage sag causes based on empirical mode decomposition", *Proc. 2011 Annual IEEE India Conference*, 1-5.

[7] J. Yu, L. Wang, B. Zhou, and W. Tian, 2011, "An expert system based on s-transform for classification of voltage dips", *Proc. 2011 2nd International Conference on Artificial Intelligence, Management Science and Electronic Commerce (AIMSEC)*, 3732-3735.