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C4-210

CIGRE 2018

A novel approach to statistical analysis of slow front overvoltages in HVDC converter stations

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SUMMARY

The understanding of transient overvoltages has become a key factor in the development of HVDC converters. This is due to increasing demands for reliability, higher system complexity and the development of UHVDC. An important but often neglected aspect is the statistical nature of so-called slow front overvoltages, which typically originate from earth faults within the HVDC system. Many of the parameters affecting the severity of these overvoltages are by nature statistical.

In this work we propose a general approach to statistical analysis of slow front overvoltages. It is exemplified with a study of a DC side node of typical VSC HVDC converter station. The results are analyzed in terms of their statistical properties. A commonly used assumption in statistical transient studies in AC systems is that overvoltages can be well described by the normal distribution. We show that this assumption is not feasible in our case. The results of the study raise awareness of the statistical nature of slow front overvoltages, and are important in order to improve and maintain the historical high reliability of HVDC systems.

KEYWORDS

VSC, HVDC, Slow-front overvoltage, Statistical analysis

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1. INTRODUCTION

HVDC is a key technology for transferring electricity with low losses and high controllability. Increasing system complexity and higher voltage levels provide a number of new challenges, especially from an overvoltage point of view. Transient overvoltages of the type *slow front* play an important role in the insulation coordination process of an HVDC converter station and understanding of them is crucial in order to maintain and increase historically high operational reliability. However, the statistical nature of transient overvoltages in HVDC has not been rigorously explored. In this study some concepts and ideas have been directly taken from statistical insulation coordination for AC applications.

The IEC standard 60071-2 [1] proposes two methods of performing insulation coordination: the deterministic method and the statistical method. In many practical applications a combination of both methods are used, often called the *semi-statistical method* [2]. For instance, this is the case in applications of the deterministic method when some of the parameters result from probabilistic considerations. For HVDC applications, the IEC standard 60071-5 [3] recommends the deterministic method in order to determine the maximum overvoltage, that is the so-called *required withstand voltage,* U_{cw}.

A drawback of limiting the analysis to the maximum overvoltage is the difficulty of estimating how likely an overvoltage is. Knowledge of the overvoltage probability can support decisions regarding performance and reliability in the design of HVDC converters. By including the entire range of possible slow front transients, the probability density function (PDF) can be estimated. The PDF can be used to analyze and predict the probability of future overvoltage magnitudes.

The probability of a certain slow front overvoltage magnitude can be determined following the proposed statistical model:

- Determine the fault probability
- Determine the electrical pre-condition probability

In an HVDC converter there are several possible fault locations that are all associated with a certain probability. If a fault occurs in an operating HVDC system, it may induce transient overvoltages which can distribute throughout the system. The magnitude of the transient overvoltage depends on the electrical pre-condition and is also associated with a certain probability. The proposed statistical model is rather general and includes a lot of details. Therefore the purpose of this study is to introduce the electrical pre-condition probability. This is done by studying and analyzing a DC side node for a typical VSC HVDC converter station.

2. SYSTEM UNDER STUDY

The studied system is a symmetrical monopole VSC HVDC link, modelled in the time-domain simulation software *PSCAD*. The simulation model is based on detailed representation of both converters, two connecting AC networks and a DC connection in between. The modelling of the system closely follows recommendations in IEC standard [3]. A simplified single line diagram of the system is shown in Figure 1.

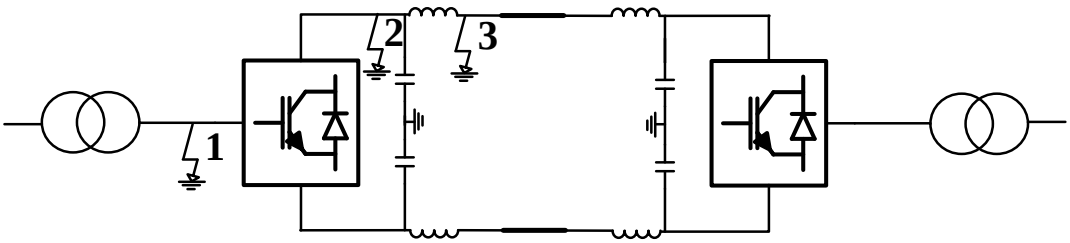

Figure 1**.** Simplified circuit diagram of the studied VSC-HVDC link including fault designation number.

The studied node is a DC side node on the inverter, located at the same electrical node as fault designation number 3. The node under study is subjected to slow front overvoltages caused by three types of faults, one AC bus fault and two D.C side faults. In Table 1 the fault designation number together with fault description is shown for the three types of faults.

Table 1. Summarizes the applied earth faults in the system. Compare with Figure 1.

Fault designation number	**Fault description**
1	AC bus fault
2	DC bus fault
3	DC pole fault

The fault initiation time is the stochastic parameter and the operation mode of the HVDC link is fixed, that is steady state operation at a fixed power level. For every applied fault the maximum slow front overvoltage is recorded according to the *Case-peak method* [1]. In Figure 2 the results from the simulation are shown for one period (20 ms) of the fundamental AC frequency during steady state operation.

As seen in Figure 2, the three different faults result in very different overvoltage behaviour. The resulting overvoltages for the A.C bus fault reach voltage levels as high as 1.640 p.u. That is at least 0.06 p.u. lower compared to the DC faults which both result in overvoltages as high as 1.692 p.u. for the DC bus fault and 1.694 p.u. for the DC pole fault. In addition to the voltage magnitude, observations regarding the periodic behaviour of the overvoltages becomes clear by studying Figure 2. The AC bus fault has two distinct periodic maximas as opposed to the multiple periodic maximas for the DC bus fault and the DC pole fault. The periodic pattern for the DC pole fault indicates how the overvoltages alternate between low and high voltage depending on fault initiation. This behaviour is due to the system configuration of the HVDC link. In following section the overvoltage data shown in Figure 2 are analysed in terms of their statistical properties.

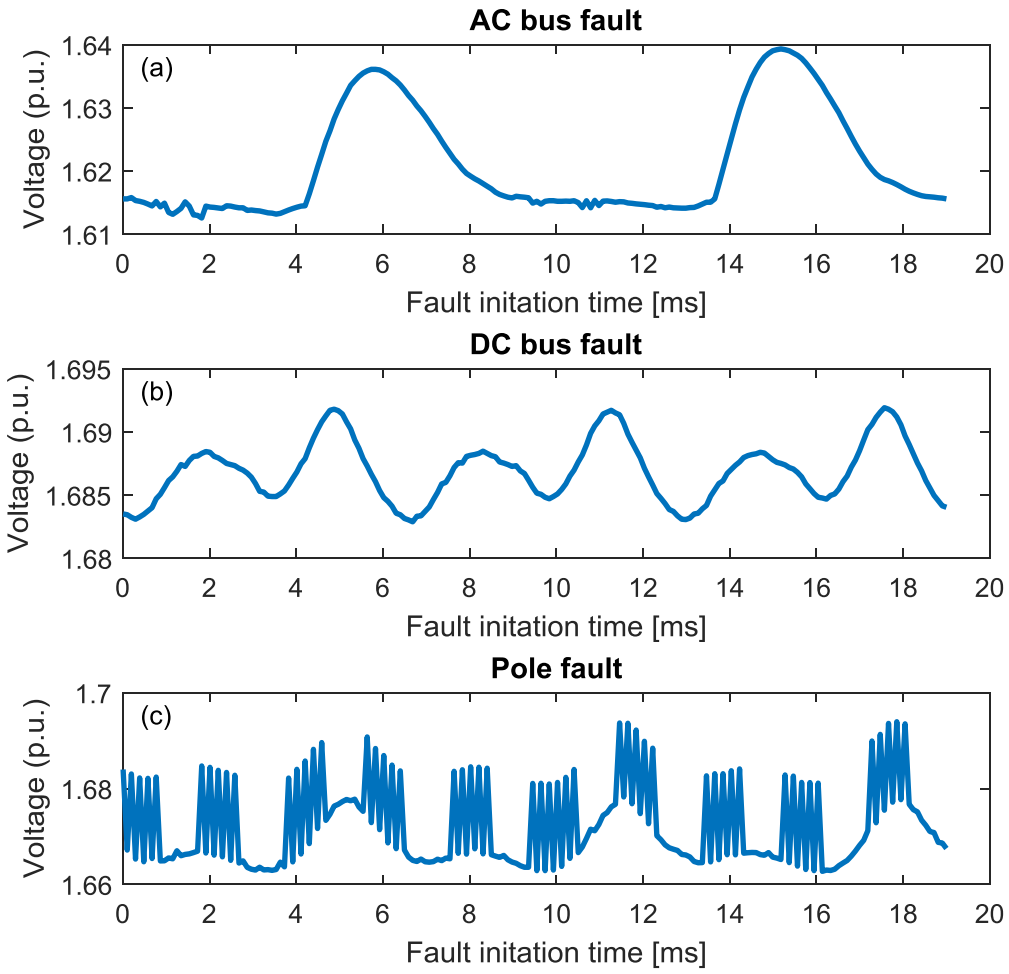

Figure 2. The maximum overvoltage at the inverter DC bus for three simulated faults over one period of fault initiation time. (a) corresponds to AC bus fault, (b) corresponds to DC bus fault, (c) corresponds to pole bus fault.

3. STATISTICAL ANALYSIS OF OVERVOLTAGE DATA

This section describes how transient overvoltages in general can be analysed together with applications to the simulated overvoltages shown in Figure 2. Traditionally in power systems, electrical stress is characterized using the normal distribution with the associated PDF

$$f(x|\mu,\sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{(x-\mu)^2}{2\sigma^2}},$$

where μ is the mean value and σ the standard deviation [1] [4]. Alternatives to the normal distribution are for instance the Weibull and positive extreme value distribution. Both distributions allows more flexibility in terms of non-symmetry [4].

A shared property between all mentioned distributions is unimodality. This means that the PDF has a distinct maximum. The purpose of assigning overvoltage data to a PDF is to create an interface between the electrical stress and potential applications, for example those

involving dielectrical strength calculations. In practice any distribution can be used as long as the high voltage region (the upper tail) of the stress is well characterized [4].

3.1 Examine overvoltage data using normal probability plot

Before assigning a probability distribution to data, it is important to carefully examine the properties of the data. A common starting point is to examine a normal probability plot (NPP). The NPP is a graphical technique used to determine whether or not data is approximately normally distributed. The idea is to plot the data against a theoretical normal distribution represented by a straight line and see how well data aligns to the line.

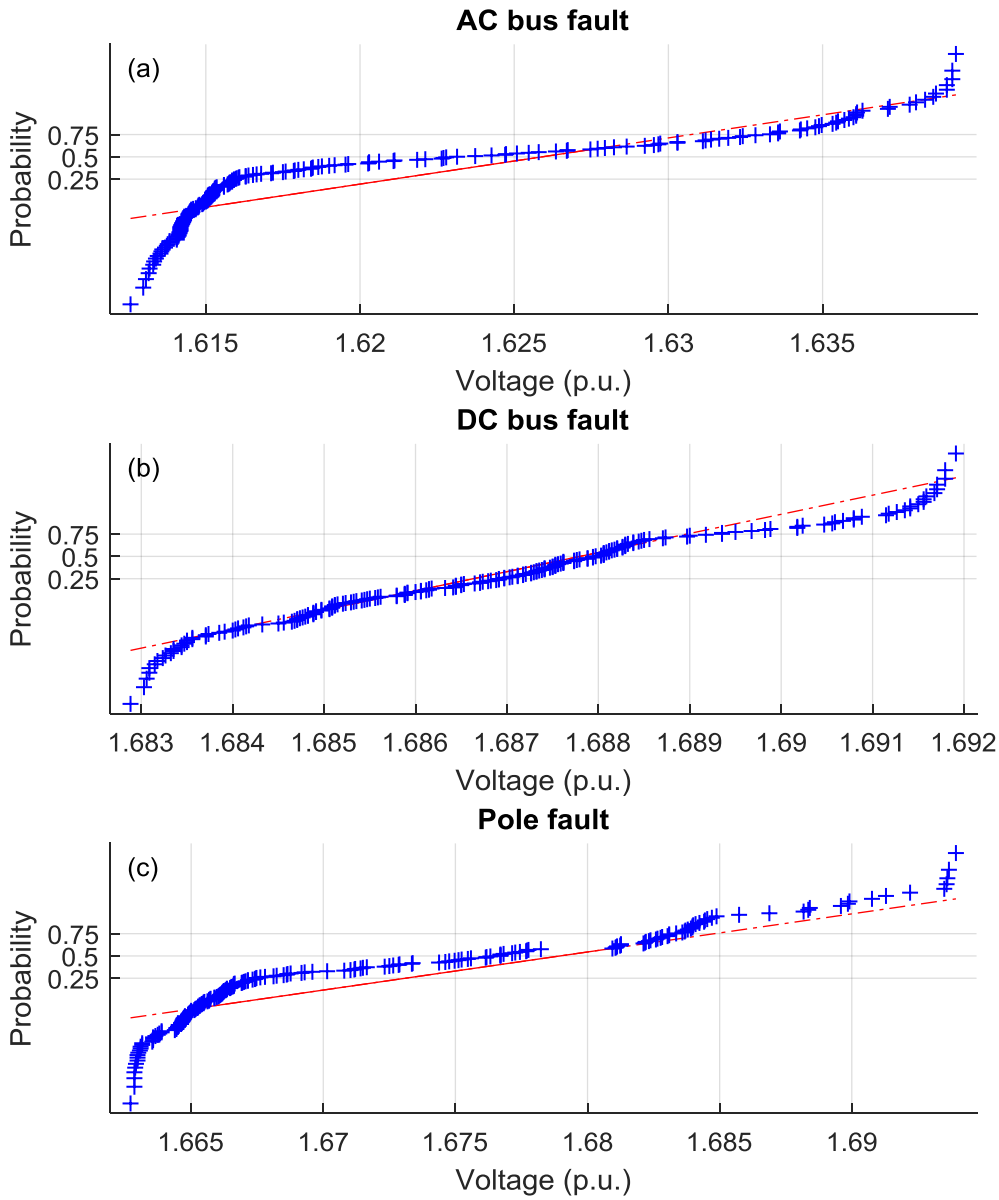

Figure 3 Normal probability plot showing slow front overvoltages for the three simulated faults. (a) corresponds to AC bus fault, (b) corresponds to DC bus fault, (c) corresponds to pole bus fault.

In Figure 3 the results from the simulation are shown in a NPP. In terms of electrical stress severity, the high voltage region is the most important and should therefore be carefully examined. Both the AC bus fault and the DC pole fault shows a non-linear pattern. Specifically, both shows overshoots in the lower voltage region, around 1.615 p.u. for the AC bus fault and 1.667 p.u. for the DC pole fault. This indicates that both distributions might be right-skewed (Positive Skewness). The DC bus fault shows a more linear pattern except from both tail ends (upper and lower). The same applies to the tail ends for the AC bus fault and the DC bus fault. Altogether this makes the normal distribution inappropriate to model the simulated overvoltage data.

3.2 Examine overvoltage data using histograms

Histograms can be used to extend the analysis of the overvoltages. Histogram is a graphical representation tool. It is used to estimate probability distributions. In Figure 4 the relative histograms are shown for the overvoltage data, with its estimated distribution superimposed. It is seen that the data does not align to any simple distribution. In particular, the local maxima between 1.691-1.692 p.u. for the DC bus fault needs to be handled properly [1].

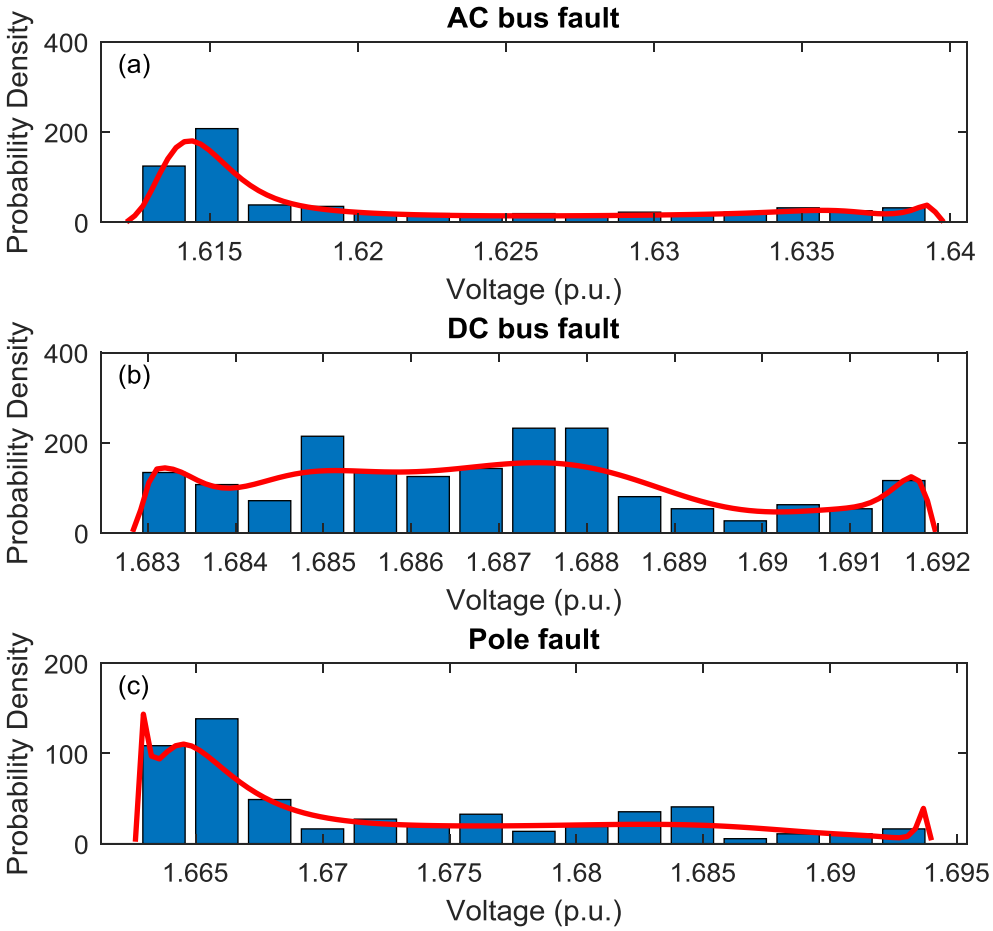

Figure 4. Histograms and estimate of PDF of slow front overvoltages for the three simulated faults. (a) corresponds to AC bus fault, (b) corresponds to DC bus fault, (c) corresponds to pole bus fault.

Due to lack of support for multimodal distributions, the probability distributions mentioned in the beginning of this section are disqualified. Instead of simply using a normal probability distribution, the problem requires more attention in terms of distribution fitting. One way is to build histograms, as already shown, and determine shape, symmetry and truncation by inspection. By matching the histogram with a distribution sharing the properties with the histogram, it is often possible to obtain a relatively close fit. When dealing with a large number of datasets, this method tends to be impractical. An alternative is to use different parametric distributions together with maximum likelihood to simplify and automate the analysis. Nonparametric methods such as kernel density estimation may also be an alternative.

Other interesting observations can be made from Figure 4. By strictly following the deterministic method and using the maximum overvoltage, the worst fault is identified to be the pole bus fault, followed by the DC bus fault. As seen in Figure 4, the overvoltages caused by the DC bus fault tend to occur in a more narrow range (1.683-1.692 p.u.) compared with the pole bus fault (1.663-1.694 p.u.). In addition the DC bus fault overvoltages are clearly more probable in the high voltage region (>1.690 p.u.). Therefore overvoltages caused by the DC bus fault are very interesting from a reliability point of view for example when designing HVDC converters. While not the highest, overvoltages caused by the DC bus fault may still be important for determining critical electrical stresses.

4. CONCLUSIONS

We have made a study showing how the statistical nature of slow front transients could be addressed in an HVDC system. The result indicates that statistical characterization of transient overvoltages should be carefully examined. This includes simple statistical tools such as histograms and normal probability plots, as well as more complex distribution fitting techniques.

It was shown that traditional unimodal probability distributions may be impractical for certain transient studies applied to HVDC. It was also shown that the highest overvoltage emerged from a pole bus fault with heavy tailed PDF. This observation is possible due to the use of a statistical method instead of a deterministic method. The benefits of using the statistical method become even more clear when comparing the approximated overvoltage PDF of the DC bus fault with the one of the pole bus fault. Both faults result in overvoltages that are almost equally high, but the tails in the PDFs differ significantly.

This study is raising awareness of the statistical nature of slow front transients within HVDC systems. Further research is necessary to describe the complete statistical behaviour of slow front overvoltages. Nevertheless, the presented approach provides the foundation for more extensive studies that will contribute to increased reliability and availability in future HVDC converters

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