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Abstract

Analysis by means of simulation studies is essential for providing useful information to distribution engineers and researchers regarding high frequency switching transients in cable systems. The behaviour of transients due to switching is strongly dependent on the pole closing span of the circuit breaker and also the closing angle of the power frequency voltage. This behaviour requires the study of overvoltage magnitude distributions to be carried out using a statistical approach. This paper presents an analysis of overvoltage sensitivity due to circuit breaker operations when energising an unloaded 132 kV underground cable system. Based on two approaches, the overvoltage values at the sending and receiving end tends to vary between approximately 1.8 p.u. to up to 2.1 p.u. respectively. Other related information is presented especially the useful data for consideration of protective schemes as well as the coordination of insulation systems.

Keywords

analysis, overvoltages, statistical, 132, cable, kv, due, energisation, underground

Disciplines

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Statistical Analysis of Overvoltages due to the Energisation of a 132 kV Underground Cable

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***Abstract*—Analysis by means of simulation studies is essential for providing useful information to distribution engineers and researchers regarding high frequency switching transients in cable systems. The behaviour of transients due to switching is strongly dependent on the pole closing span of the circuit breaker and also the closing angle of the power frequency voltage. This behaviour requires the study of overvoltage magnitude distributions to be carried out using a statistical approach. This paper presents an analysis of overvoltage sensitivity due to circuit breaker operations when energising an unloaded 132 kV underground cable system. Based on two approaches, the overvoltage values at the sending and receiving end tends to vary between approximately 1.8 p.u. to up to 2.1 p.u. respectively. Other related information is presented especially the useful data for consideration of protective schemes as well as the coordination of insulation systems.**

I. Introduction

Switching operations in distribution and transmission networks can cause significant overvoltages in the system. Studies to determine the switching overvoltage are considered to be of primary importance in electric power insulation coordination. Their role in insulation coordination has been widely researched [1]–[5]. The closing of a circuit breaker to energise a high voltage underground cable system introduces oscillatory transients which are characterised by their magnitude, duration and spectral content. Normally, their frequency can increase up to the range of tens of kilohertz and last several milliseconds before settling down to the steady state condition [6], [7].

Such studies are normally performed with particular interest in avoiding breakdown, or minimising transient stress on the insulation systems as well as the transmission and distribution equipment. The varying characteristics of transients induce different levels of failure of electrical equipment [6]. In general, characterisation of overvoltage stress may be performed by the following means [8]:

- The maximum peak values
- A statistical overvoltage of the peak values
- A statistical overvoltage value generated by particular events with a peak value that has a 2% probability of being exceeded

For an underground cable system, such as to perform dielectric strength test, such data can easily be presented based on simulation using a reliable cable model. Other than the dedicated simulation approach, the particular general consideration which is confirmed by different measurement in field also can be adopted. The latter method has been used in [2] in studying the influence of the cable length and type of insulation compound on the risk of insulation failures on MV and HV lines.

Some statistical switching studies have also been performed in EMTP-type simulator such as a large scale statistical switching analysis by Lee and Poon [3] and case studies on the impact of protective devices carried out in [4]. For the case of a long, cross-bonded cable system, studies on the overvoltage sensitivity stress on the insulation can be found in [5]. Some general and specific modelling guidelines in relation to switching overvoltage studies are also provided [1], [9].

From the literature it has been found that the evaluation of switching overvoltages is an important task for planning and design of power systems, as it has a direct bearing on insulation characteristics and coordination, cost and reliability of particular projects. Also, accurate simulation by means of electromagnetic transient program is the most convenient way to undertake such studies. This paper presents a statistical analysis of overvoltages due to switching operation of a circuit breaker during energisation of a 132 kV underground cable system. Documents in relation to statistical switching overvoltage studies will be outlined in Section II. The power system network model in PSCAD®/EMTDC™and simulation approaches will be presented in Section III. The results obtained are discussed in Section IV followed by conclusions in the Section V.

II. Statistical Switching

Switching surges are random in nature as they are affected by many different factors. Such impacts may be due to the network structure, line parameters as well as the circuit breaker performance. Other than those factors, the circuit breaker's pole span which is the time between the first and the third pole to close and also the point-on-wave (POW) of switching angles on the 3-phase also greatly influence the behaviour of the transients introduced. The latter two cases are considered in this paper and detailed in the following section.

A. Circuit Breaker Pole Span and Closing Angle

The closing condition of a circuit breaker strongly affects the transient overvoltages. In the real world, simultaneous

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close of contacts or poles will rarely occur. This is due to the following reasons [10]:

1) Circuit Breaker Pole Span: The closing of the contacts of circuit breaker at high speed and the closing times are governed by their mechanical tolerances. This gives the different closing times of poles for each phase. Normally the difference between the first pole to close and the third pole especially in EHV and UHV systems fall in the order of 3 ms to 5 ms.

2) The Closing Angle: This refers to the point-on-wave (POW) where the circuit breaker starts to close. The phase with highest power frequency voltage during the switching instant is likely to generate higher transient peak. Pre-arc also might occur and affect the behaviour of the transient at the circuit breaker terminals. Strong coupling effects between phases cause unexpected high magnitude and frequency overvoltages. In general, statistical assessment on switching overvoltages are studied over the entire range of a cycle [1].

Apparently, the initial conditions for the transients are characterised by the two phenomena described above. In addition, the severity of the transient magnitude and frequency are also affected by system's capacitive and inductive parameters whereas the resistive elements help the transient to settle down faster. Accurate simulation of transients affected by these parameters will be based on the accuracy of the frequency dependence modelling of the power system network.

B. Statistical Method

Due to the random behaviour of circuit breaker pole closure, probability analysis is the most practical way in providing useful data on switching overvoltages. The methods on evaluation of switching overvoltages can be categorised as the following [11]:

1) Statistical study approach
2) Statistical maximisation approach
3) Optimisation approach

The first approach is considered the most fundamental method based on probability concepts and is adopted in this paper. Statistics are used to evaluate the switching surges to obtain mean amplitude and standard deviation of overvoltages. Normally, normal distribution (Gaussian) is assumed for the scattering characteristics of circuit breaker poles. Cumulative probability distribution of overvoltages is then calculated to be compared with the system's ability to withstand transient overvoltages. Assessment using several statistical methods such as Gaussian, Uniform and Systematic switching approaches can be found in [12]. The detailed explanation of the other two approaches are presented in [11].

III. Modelling and Simulation

A. Cable and Power System Network

An accurate prediction of the overvoltages generated due to switching can be achieved provided that the distributed nature and the frequency dependence of the system components are accounted for in the simulation. The power system network is adopted from [7] and has been modified to make use of multiple run systems in PSCAD®/EMTDC™. This allowed the statistical analysis of overvoltages to be applied such as using the normal distribution. The modelling of transmission lines and underground network was based on the Universal Line Model (ULM), which is stable and accurate for predicting high frequency transients. The other system component and settings remain unchanged as detailed in [7].

B. Simulation Time Step

For analysis of this class of transient, the simulation step size is based on the recommendation in [9] given by:

$$\Delta t = \frac{1}{10 \times F_{max}} \tag{1}$$

where F_{max} corresponds to the highest frequency range expected. It has been found, from previous research, that the frequency due to energisation of this cable system was up to several tens of kHz [7]. Thus, the simulation time step of at least 10 us would be adequate. However, as the shortest, small section cross-bonded cable considered is around 0.8 km, the simulation time step smaller than 2.6 us is the best choice as suggested in [13]. In this simulation, 1 us was used as the simulation time step and can be considered adequate.

C. Simulation Approaches

The statistical analysis of overvoltages generated due to energisation of the cable system considered was based on two approaches. In the first approach, the circuit breaker poles closing times from actual measurements were applied uniformly over the full cycle of the power frequency voltage. This method is also known as systematic switches [12] which also has been applied in [4] to identify the worst case switching overvoltage. The four sets of circuit breaker poles closure schemes used are shown in Table I.

TABLE I
Circuit Breaker Poles Switching Settings

Tests	Ph-A (ms)	Ph-B (ms)	Ph-C (ms)
Test 1	0.0095	0.0655	0.1295
Test 2	0.0168	0.5288	0.5968
Test 3	0.0174	0.3894	0.4574
Test 4	0.0173	0.7652	0.8332

In general, at least 100 simulations of different sets of circuit breaker closing times are considered adequate for evaluation of statistical switching overvoltages [9]. With an incremental time of 0.1 ms, each set of tests will generate 200 overvoltage data sequences for a complete cycle of the power frequency voltage. The poles closing sequence also considered which results in up to six combinations applied to each of the tests in Table I.

The second approach was based on probabilistic techniques. The random nature of the closure of circuit breaker poles are simulated using a random-normal distribution and applied in every aiming point sectionalised over the entire cycle of power frequency voltage. Each aiming point is assumed to generate more than 100 sets of overvoltage data from random and iterative runs. Different pole span settings are also considered and varied from as small as 0.8 ms to up to 3 ms. An 0.8 ms minimum span has been selected to make it identical to the largest possible pole span used in the first approach. Statistical analysis of each pole span setting is then applied to generate data of the overvoltage probability at sending end (SE) and receiving ends (RE). Figure 1 shows an example of aiming points for the case of 2 ms pole span.

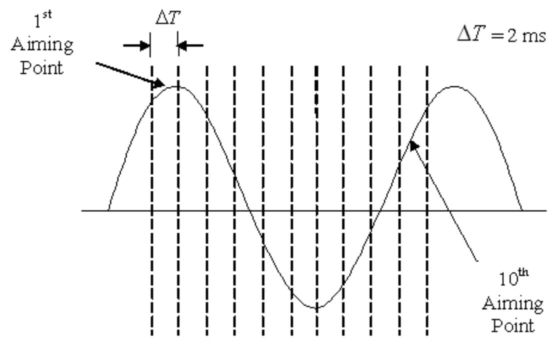

Fig. 1. Single phase view of aiming point settings for 2 ms pole span.

IV. Results

The sending and receiving end absolute value of phase-to-earth overvoltage peaks generated due to energisation of a 132 kV unloaded underground cable system considered were processed in MATLAB and presented in this section.

A. Simulation Results of Overvoltages from First Approach

Based on the systematic switchings applied in this approach, the overvoltage transients are presented in Figure 2.

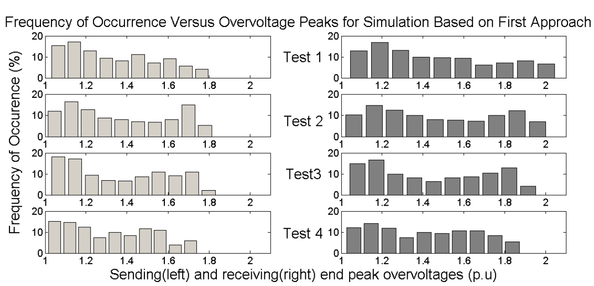

Fig. 2. Frequency of occurrence of overvoltage peaks from first approach.

In general, the larger the poles span, the more prone the overvoltage peaks (at the circuit breaker terminals) to increase up to the high level. In contrast, simultaneous close of circuit breaker poles is likely to introduce relatively lower overvoltage peaks [4], [9]. However, from Figure 2, it can clearly be seen that the smallest pole span settings in Test 1 has generated higher overvoltage peaks rather than the larger gap applied in the case of Test 4. This deficiency is expected due to the inaccuracy of power system model used to simulate the high frequency phenomena such as the pre-arc and the strong coupling effects between the phases. However, only 1.5% difference of sending end overvoltage peaks between the first and the fourth case can still be considered as a small deficiency.

The significant overvoltage peaks for each phase at sending and receiving ends are summarised in Table II.

TABLE II
Significant Overvoltage Peaks from First Approach

	SE Peaks(p.u)			RE Peaks (p.u)		
Tests	Ph-A	Ph-B	Ph-C	Ph-A	Ph-B	Ph-C
Test 1	1.80	1.76	1.77	2.04	2.06	2.01
Test 2	1.79	1.80	1.82	2.01	1.97	2.00
Test 3	1.84	1.80	1.78	1.96	1.95	1.88
Test 4	1.77	1.75	1.74	1.86	1.84	1.88

At the sending end, the highest overvoltage peak is 1.84 p.u. generated from the third case. Travelling wave phenomena causes the most severe overvoltage peaks at receiving end when no loads are connected. For instance, the overvoltage peak magnitudes, especially in the case of Test 1 and Test 2 energisation schemes, all fall in the range of 2 p.u. Overall, in all of the cases, the sending and receiving end overvoltage peak values fall between the range of 1.74 to 1.84 p.u. and 1.84 to 2.06 p.u. respectively.

The overvoltage peaks of sending and receiving ends seems most significant in the case of Test 1 and Test 3 energisation schemes respectively. Consequently, the Cumulative Distribution Function (CDF) plots are derived for these cases as shown in Figure 3. This enables a closer statistical analysis of the overvoltage transient.

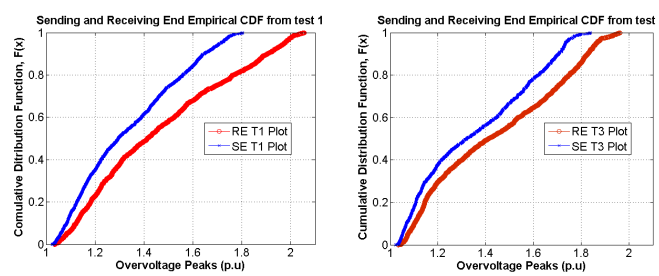

Fig. 3. CDF for Test 1 and Test 3 energisation schemes

From Figure 3, 2% of the switching cases are likely to produce overvoltage magnitude value in the range of 1.75 to 1.77 p.u at the sending end and as high as 1.9 to 2.0 p.u at the receiving end.

B. Simulation Results of Overvoltages from Second Approach

In the second approach, the more realistic method has been applied. The random-normal distribution considered for the scattering effects of circuit breaker poles are more suitable over the uniform and systematic switching approaches, especially for studies on line energisation [12]. The peak overvoltage frequencies of different pole span settings are as shown in Figure 4.

For approximately 1% of the time, the overvoltage peak magnitudes are likely to vary between 1.83 to 1.86 p.u. at

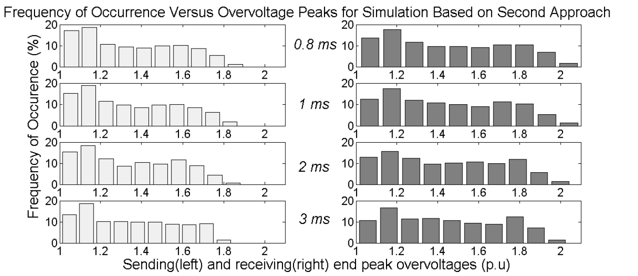

Fig. 4. Frequency of occurrence of overvoltage peaks from second approach.

the sending end. Similarly, around the same frequency, the overvoltage at receiving end tends to vary between 1.98 to 2.09 p.u.. These values are slightly higher than those expected based on the first approach. Again, the peak magnitudes are decreasing with increasing pole span settings. However, there is only small percentage difference in terms of the 0.8 ms span and 3 ms span.

To enable comparison with the first method, the most significant values from 0.8 ms pole span settings have been used. It has been found that the 8th aiming point generates the highest sending and receiving end peak magnitude (the worst case scenario). The Probability Density (PD) and Cumulative Distribution Function (CDF) for 8th aiming point of 0.8 ms pole span settings are shown in Figure 5.

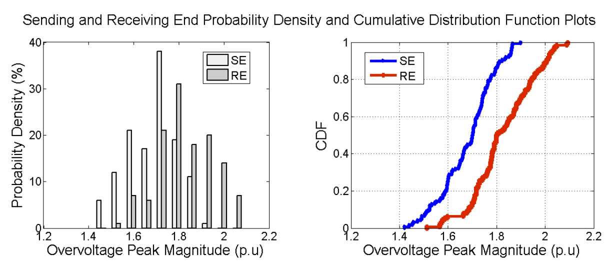

Fig. 5. PD/CDF of overvoltage peaks (8th aiming point of 0.8 ms pole span)

The sending end magnitude was 1.9 p.u., which is around 7% higher than the values approximated based on the 4th energisation schemes used in the first approach. Similarly, at the receiving end, the highest peak is around 2.1 p.u. which is 13% higher. The 2% overvoltage values are 1.86 p.u. and 2.05 p.u. at the sending and receiving end respectively which is close to the values obtained from first approach. The corresponding statistical information at sending and receiving ends are summarised in Table III.

TABLE III
STATISTICAL INFORMATION OF CDF IN FIGURE 5

Values	Sending End (p.u)	Receiving End (p.u)
Max	1.9006	2.0928
Mean	1.6842	1.8263
Std. Dev.	0.1094	0.1268

V. CONCLUSION

A statistical study has been carried out of the energisation transient overvoltage for a 132 kV underground cable system. Two approaches were adopted. The first approach employed the data from real energisation tests and allowing sequential runs which are uniformly distributed over the power frequency voltage angle. The second approach was based on normal probability for random operations of a circuit breaker. The significant overvoltage values have been extracted, such as the peak magnitudes, as well as 2% probability values. Not much difference can be seen for the values obtained from both approaches. However, the data from second technique are recommended since they were based on the approach which is closer to the real situation. The outcomes of this study will be of use to distribution system engineers as well as researchers for future planning and design of possible protective levels related to this class of cable systems.

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