DAMPING OF LOW FREQUENCY RESONANCE INDUCED OVERVOLTAGES IN A DISTRIBUTION NETWORK

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Summary A comprehensive study, employing time and frequency domain analyses, was carried out following a 3-phase-ground fault at a cable terminal connected to a large distribution substation. The fault developed high overvoltages that caused damage to potential transformers and cable sheath arresters in another substation. The overvoltages had a very high component at 127 Hz.

Frequency-domain analysis of the calculated network-to-earth impedance showed a main resonance frequency of 77 Hz, which corresponds to 127 Hz in the time-domain. The strongest resonance effect was found to be at the substation with the most damage.

The factors that affect the resonance have been identified to be the percentage of cable system portion with respect to overhead lines, the impedance of the grounding neutral reactors and the type of fault. The paper explains how each factor affects the low frequency resonance and shows how to solve the problem either by shifting the resonance frequency to a higher safe level or by directly increasing the resonance damping.

INTRODUCTION

The Nordostschweizerische Kraftwerke (NOK) is currently upgrading its sub-transmission network feeding the main distribution networks from 50 kV to 110 kV. During this process several parts of the 110 kV network are created as sub-networks that are successively interconnected.

This paper summarizes a comprehensive study carried out at NOK following a 3-phase-ground fault at a 110-kV cable terminal connected to a large distribution substation. The fault developed a particularly high overvoltage in another 110-kV substation, which entailed damage to potential transformers and cable sheath arresters. The initial analysis showed that the overvoltage had a very high component at 127 Hz.

This study was, therefore, necessary in order to clarify the source of this abnormal event and to define existing and future problems in the 110 kV network and offer solutions to prevent potential problems encountered during the several phases of the 50/110 kV network conversion.

THE FAULT EVENT

Figure 1 depicts the part of the network affected during the disturbance. Most of the shown interconnections are cables.

As shown in Figure 1, the 110 kV network is fed from the 220 kV transmission by Star-Star transformers with Delta tertiary windings. The neutral points on the 220 kV side are solidly grounded, whereas most of the neutral points on the 110 kV side are grounded through reactors to limit the zero-sequence short circuit currents. The 16 kV distribution network is directly fed from the 110 kV substations as shown in figure 1.

The disturbance course of events started by the inadvertent closing of the cable terminal grounding switch 'FT' while the breaker 'XB' at the other terminal 'B' is still closed. This developed a 3-phase-ground short circuit which was appropriately cleared by the relay action that activated the opening of the remote breaker 'XB' in about 400 ms.

Fig. 1 Schematic of network portion affected by the disturbance

Fig. 2 shows the 3-phase voltage traces produced by the disturbance fault recorder located at substation 'WA'.

Fig. 2 Three-phase voltage measured at substation WA (1 sec. duration)
However, after less than 20 seconds, several new phase-ground faults (phases c and a) occurred successively at substation 'WB' and on cables 'WB'-B' and 'WB'-F'. As a result, substation 'B' and all the 16 kV distribution networks fed from it lost all supply. Apparently, the overvoltages that followed clearing the fault were of such high magnitude that caused damage to the voltage measurement transformers and cable sheath arresters in substation 'WB'. As shown in Fig. 2, the voltage oscillates violently after the fault clearing with very high amplitudes and asymmetry between the phases. The oscillations and asymmetry are damped after approximately 250 ms.

**TRANSIENT SIMULATION**

The complete 110 kV network of NOK was simulated in details using the EMTP program with the configuration existing at the time of disturbance [1]. The 16 kV distribution networks connected to the substations in the vicinity of the disturbance were also represented.

In the model of the EMTP time simulations, low order filters were added before a disturbance event recorder model, in order to represent filtered measurements. This was necessary to reproduce the actual measured signals. Such a fault recorder model was simulated in substation 'WA'. The filtered signal is delayed by approximately 30 ms of the original signal.

Minor adjustments of the 16 kV load models were requisite in order to match the amplitude and damping of the measured voltage signals at substation 'WA'.

Figures 4 and 5 depict respectively the voltage waveform at substation 'WB' and the filtered voltage at substation 'WA' of the time simulations. A three phase to ground short circuit fault with 8.8 ohm impedance was simulated at location 'FT' of the opened line 'T'-B' at time $t = 0.148$ s. After 115 ms the remote breaker 'XB' was opened.

Although, in the actual disturbance, the fault lasted for about 400 ms due to back-up relay operation, only 115 ms fault was simulated to reduce the simulation execution time.

As shown in Fig. 4, the voltage at 'WB' have very large spikes, particularly in phases c and a, at the fault clearing instant. The peak voltages at 'WB' are generally slightly higher than at 'WA'. Note that 'WB' has no 16 KV feeders. Voltages at the other 110 kV substations in the vicinity are similar to those at 'WB' and 'WA' with small differences.
Figure 6 depicts the simulated voltage waveforms of the transformer neutral points at substations 'T', 'R' and 'F'. It is interesting to note the two different high frequency oscillations at fault commencement and after fault clearing. This phenomenon will be dealt with in the next sections.

**VERIFICATION OF NETWORK MODEL**

In order to make a meaningful comparison with the measured values, the simulated filtered voltage at 'WA' is split into two segments, namely at fault commencement and after fault clearing, and synchronized in time with the measured signal. The sampling rate for both signals is 1,666 ms. However, the measured signal is less accurate than the simulated one due to the low resolution used, i.e. high volt/bit ratio.

The comparison of the 3-phases (a, b, c) of measured and simulated filtered voltage at 'WA' for the two segments is shown in figures 7 and 8. Indeed, the similarity between the two signals is obvious and proves the accuracy of the model used for simulations.

**FREQUENCY ANALYSIS & NETWORK RESONANCE**

By scrutinizing figure 7, it is clear that the short-circuits in the three phases do not commence all simultaneously.

Similarly, the opening of the faulted line for fault clearing takes place for each individual phase successively, as shown in figure 8. This means that although the disturbance is categorized as a 3-phase fault, the network during fault commencement and fault clearing periods is asymmetrical.

This observation and the one made previously for figure 2 regarding asymmetry are very essential for the proper frequency domain analysis of the network. They entail that not only the frequency characteristics of the network positive sequence impedance should be analyzed but also the negative and, more importantly, the zero sequence impedances of the network. Therefore, in the following analytical method, the sum of network positive, negative and zero sequence impedances seen at substation 'WB' is calculated as a function of frequency. This is known as frequency scan and is usually used for the analysis of resonance problems in complex networks [2].

The frequency scan of the magnitude of total self impedance at substation 'WB' is shown in figure 9 during three stages of asymmetric operation of the network; commencement of short circuit at 'FT', opening breaker 'XB' and after clearing of the fault. Note the peaks of the impedance at certain frequencies that represent parallel resonance conditions. Such resonances are formed by the combined effects of the sequence impedances of the series reactance of lines, cables and transformers as well as the transformer neutral grounding reactors, the shunt capacitance of cables and lines and the load impedance.

As shown in figure 9, at fault commencement (curve 1), the resonance frequency is 100 Hz, whereas during opening the breaker 'XB' (curve 2) the resonance is exactly at 77 Hz. After clearing the fault (curve 3), the impedance resonance moves to 65 Hz but has an additional peak at 77 Hz. Due to the 50 Hz carrier frequency effect of the ac system, a 77 Hz resonance in the frequency domain shows as (77+50) 127 Hz in the time domain. Similarly, the 100 Hz resonance frequency shows as 150 Hz in the time domain.
The damping of such resonances is approximately inversely proportional to the peak impedance. It is clear that the 77 Hz (127 Hz in time domain) resonance is dominant, whereas the 100 Hz (150 Hz in time domain) resonance is well damped. This result explains the outcome of frequency analysis of the measured voltage in figure 3 and the source of neutral point voltage oscillations in figure 6.

To further elucidate the presence of voltage oscillations and asymmetry, the sum of the voltage three phases at each substation is made. Such a voltage, which equals 3 x the zero-sequence voltage, will be referred to as “Shift Voltage” Us. Figures 10 and 11 compare the Us of the measured and simulated filtered voltages at 'WA' respectively at fault commencement and after fault clearing. The similarity of the traces confirm the existence of the resonance phenomenon in the actual network.

In an attempt to explain why the equipment damages were confined to substation 'WB' and to cables 'WB'-B and 'WB'-F, the impedance frequency scan during short circuit and opening of breaker 'XB' is made for different sub-stations as shown in figure 12. It is evident that the strongest resonance effect for this particular fault location lies at 'WB', 'B' and 'F' substations. A resonance that led to a very high overvoltage with 127 Hz at those locations.

Fig. 10  Shift voltage Us of measured and simulated filtered voltages at 'WA' at fault commencement

Fig. 11  Shift voltage Us of measured and simulated filtered voltages at 'WA' after fault clearing

Fig. 12  Magnitude of network self impedance seen at different substations for asymmetric network operation as a function of frequency during short circuit and opening of breaker 'XB'

Figure 13 depicts the shift voltage Us at both 'WB' and 'WA' substations. The traces of Us show a damped 150 Hz oscillation at fault commencement and a poorly damped 127 Hz oscillation after fault clearing. In substation 'WB' the 127 Hz oscillation has a larger amplitude than in all other substations including 'WA'. This confirms the results of the frequency domain analysis. Note also how the amplitude of Us is much larger than the neutral-point voltages in the nearby substations (Fig. 6). Furthermore, the Us at substation 'WB' has a peak of 200 kV that decays slowly, is a voltage that certainly can cause damage to equipment. Therefore, the peak and damping of Us can be used as a criterion for quantifying the severity of resonance problem as will be discussed in the next sections.

Fig. 13  Shift voltage Us of simulated network voltages at 'WB' and 'WA'
Resonances in Other Regions

Using the same network model, simulations of similar faults at different locations in the network showed that the low frequency resonance problem is not limited to the network portion shown in figure 1 but is a problem inherent in the entire 110 kV Network. The overvoltages produced by the resonance and the resonance frequency are, however, different from one region to the other.

RESONANCE INFLUENCING FACTORS

Investigating the severity of the resonance problem at different regions gave the opportunity to determine the factors that affect the resonance. These have been identified to be the type of fault, the percentage of cable content in the region circuit and the reactance value of neutral point grounding reactors.

Effect of Fault Type

Both 3-phase-ground and 2-phase-ground faults can excite such low frequency resonances that can cause dangerous overvoltages. For single-phase-ground faults, although they show the same resonance phenomenon, however, no high overvoltages are produced.

Effect of Circuit Cable Content

It was observed from the simulation studies in different regions that, generally, with increasing the cable content in the circuit, the severity of the resonance problem rose. In some areas when all cables in an isolated sub-network were switched out, the resonance completely vanished. Due to the difficulty of isolating all the factors affecting the resonance and the arising overvoltages, a range of 25% to 30% of cable content was identified as being a critical limit regarding this phenomenon.

Effect of Neutral Point Grounding

Since the resonance is predominantly affected by the zero-sequence impedance of the network, the relatively high impedances of the neutral-point grounding reactors used throughout the network are the main cause of the low frequency (< 200 Hz) resonance problem.

Figure 14 depicts the 3-phase voltage at 'WB' for the same case discussed earlier (figure 4) but with all neutral point grounding reactors shown in figure 1 replaced by reactors having 1/3 of the original reactance. Note that the post-fault oscillations are still present but with less over-voltages.

Figure 15 depicts the corresponding shift voltages at substations 'WB' and 'WA'. It is quite evident that the Us oscillations has a reduced amplitude and a higher frequency compared with the original case in figure 13. The damping, however, remains unchanged.

DAMPING OF RESONANCE

Reducing the reactance of neutral-point grounding reactors can be a possible solution for alleviating the low frequency resonance problem [3]. However, the obvious disadvantage of this method is the increase in fault currents that may be beyond the existing switchgear design values. Which defies the reason for which such reactors have been utilized.

Another method for mitigating or completely eliminating the network resonance and its consequent high over-voltages, is by increasing the resonance damping, without changing its frequency of oscillations. This can be realized by adding a small resistance in series with the existing neutral point reactors or, equivalently, by adding a large resistance in parallel to those reactors.
For implementing a standard economic solution, it is proposed that all existing and future neutral point reactors in the network be fitted with parallel resistors having approximately 3 x the impedance value of such reactors.

In order to demonstrate the effectiveness of this solution, the same fault case discussed earlier (figures 4-6 and 13) is simulated but with all neutral point grounding reactors shown in figure 1 fitted with parallel resistors. For this case, figure 16 is presented to show the 3-phase voltage at 'WB'. Note how the overvoltage is reduced and all post-fault oscillations are practically eliminated.

Figure 17 shows the respective shift voltages at 'WB' and 'WA'. Comparing this figure to figure 13, note that the post-fault oscillations are still present but with much less amplitude and are quickly damped out. The same applies for the neutral point voltages depicted in figure 18.

The introduction of the parallel resistors provide, however, another path for short circuit currents. Because of the high resistance of the introduced resistors, the increase in fault currents is, nevertheless, limited to less than 10%.

This proposal has been examined in all parts of the network throughout all phases of the 50/110 kV network conversion, in order to prove its viability for solving the resonance problem.

CONCLUSIONS

Reactors used for earthing neutral points to limit fault currents in faulty phases and overvoltages in healthy phases can create low frequency resonances that lead to damaging post-fault overvoltages on all phases. The resonance phenomenon was mostly found in sub-networks that include underground cables.

As an effective and economic solution, the reactors are fitted with parallel resistors having approximately three times the respective impedance values of their reactances. Such resistors provide sufficient damping to the resonance oscillations without practically affecting the fault currents.

REFERENCES

