

Tracing Ground Path Resonances in a Sub-transmission Network with Cables

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This article summarizes a comprehensive study carried out by the Swiss Utility NOK following a 3-phase-ground fault at a 110kV cable terminal connected to a large distribution substation.

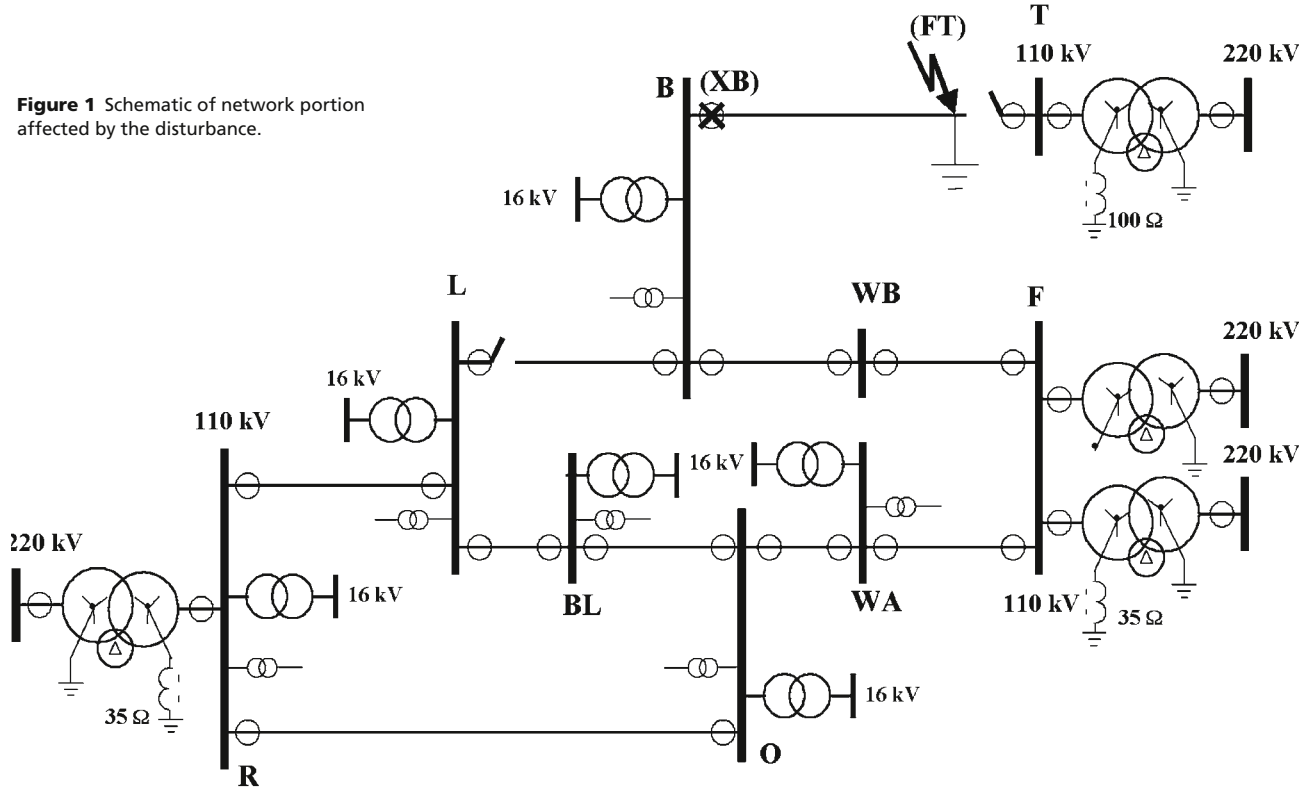
The fault developed a particularly high overvoltage in another 110kV substation, which entailed damage to potential transformers and cable sheath arresters. The initial analysis showed that the overvoltage had a very high component at 127Hz.

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

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

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 cleared by opening of the

Figure 1 Schematic of network portion affected by the disturbance.



remote breaker 'XB' in about 400ms. Figure 2 shows the 3-phase voltage traces produced by the disturbance fault recorder located at substation 'WA'. 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 16kV 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 Figure 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 250ms.

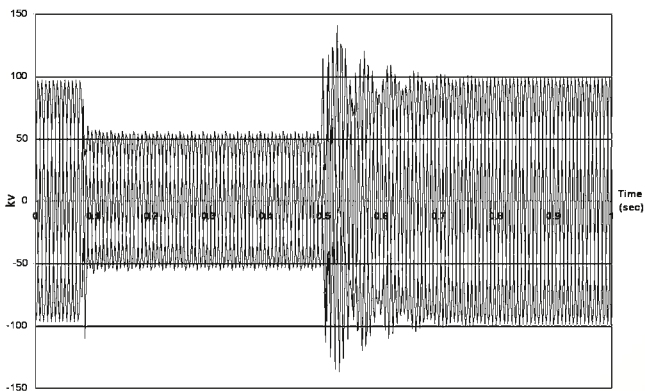
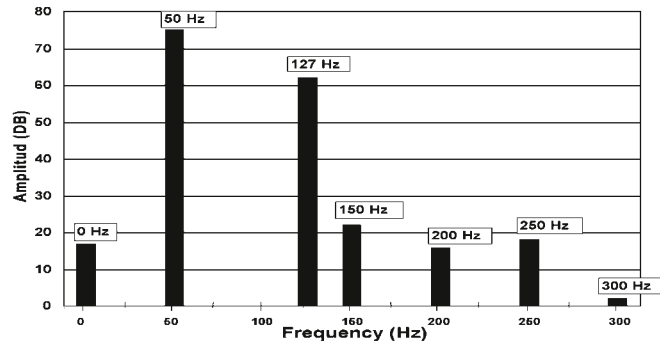


Figure 2 Three-phase voltage measured at substation 'WA' (1 second duration)

Figure 3 shows the Amplitude vs. Frequency of the measured voltage signal. Along with the 50Hz component and the DC offset one recognizes the very high component at 127Hz, followed by a smaller 150Hz component.

EMTDC™ Simulations The complete 110kV network of NOK was simulated in detail using PSCAD®/EMTDC™ simulations. The 16kV distribution networks connected to the substations in the vicinity of the disturbance were represented as well. Low order filtered measurements were also necessary to reproduce the actual measured signals. Minor adjustments of the 16kV

Figure 3 Frequency composition of the measured voltage.



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

As shown in Figure 4, the voltage at 'WB' has 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 16kV feeders. Voltages at the other 110kV substations in the vicinity are similar to those at 'WB' and 'WA' with small differences.

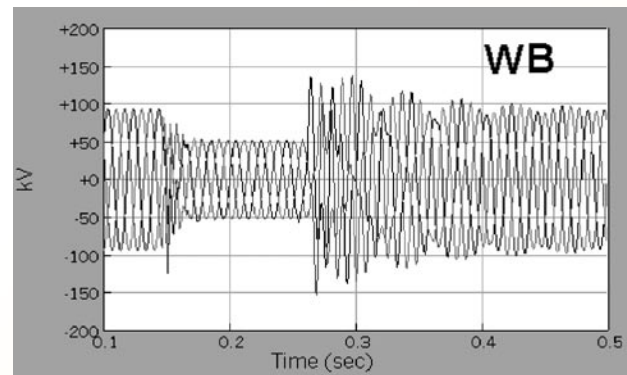


Figure 4 Simulated network voltage at substation 'WB':

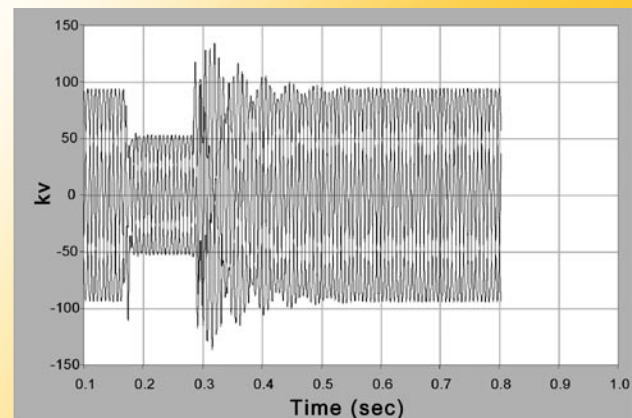


Figure 5 Simulated filtered voltage at substation 'WA':

...the network, during fault commencement and fault clearing periods, is asymmetrical.

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 comparison of the 3-phases (a, b, c) of measured and simulated filtered voltage at 'WA' for the two segments is shown in Figures 6 and 7. Indeed, the similarity between the two signals is obvious and proves the accuracy of the model used for simulations.

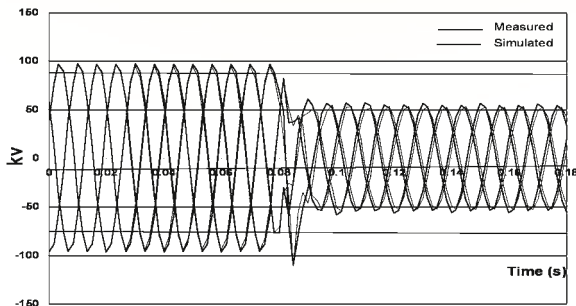


Figure 6 Comparison between measured and simulated filtered voltage at substation 'WA' at fault commencement.

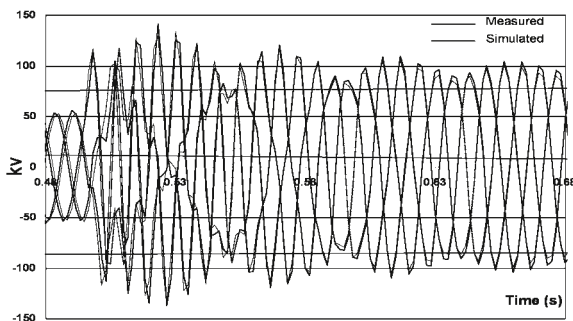


Figure 7 Comparison between measured and simulated filtered voltage at substation 'WA' after fault commencement.

Note that short-circuits in the three phases do not all commence simultaneously and the opening of the faulted line takes place for each individual phase successively. This means that the network during fault commencement and fault clearing periods is asymmetrical. Therefore, any frequency-domain analysis should consider all sequence impedances of the network. The frequency scan [1] for the sum of network positive, negative and zero sequence

impedances seen at substation 'WB' is shown in Figure 8 during three stages of asymmetric operation of the network; (1) commencement of short circuit at 'FT' with resonance frequency of 100Hz, (2) opening breaker 'XB' with resonance at exactly 77Hz and (3) after clearing of the fault where the impedance resonance moves to 65Hz but has an additional peak at 77Hz. Due to the 50Hz carrier frequency effect of the AC system, a 77Hz resonance in the frequency domain shows as (77+50) 127Hz in the time domain. Similarly, the 100Hz resonance frequency shows as 150Hz in the time domain. The damping of such resonances is approximately inversely proportional to the peak impedance. It is clear that the 77Hz resonance is dominant, where as the 100Hz resonance is well damped. This result explains the outcome of frequency composition of the measured voltage of Figure 3.

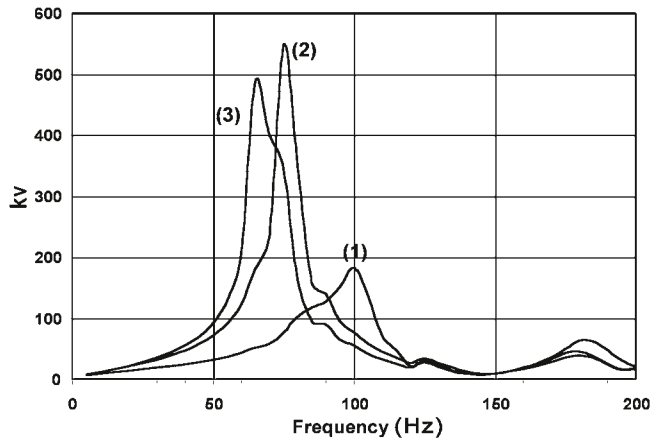


Figure 8 Frequency scan at substation 'WB' for asymmetric network operation: (1) during short circuit at 'FT', (2) during short circuit and opening of breaker 'XB', (3) after clearing of short circuit.

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 8. 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 overvoltages with 127Hz at those locations.

Editors' Note: It is our understanding that the frequency domain analysis is performed to capture resonant variations in fundamental frequency signals (i.e. similar to amplitude modulation). This translates to resonant frequencies f_0-f and f_0+f in real signals.

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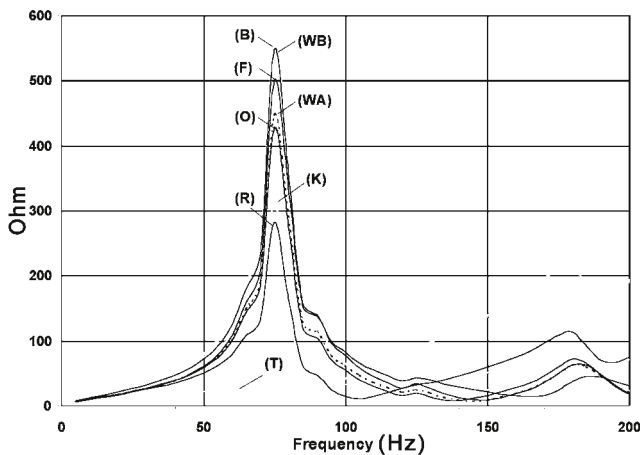


Figure 9 Frequency scan at different substations for asymmetric network operation during short circuit and opening of breaker 'XB'.

Resonance influencing factors:

Fault Type Both 3-phase-ground and 2-phase-ground faults can excite such low frequency resonances that can cause dangerous overvoltages.

Circuit Cable Content 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.

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

Damping of Resonance Reducing the reactance of neutral-point grounding reactors can be a possible solution for alleviating the low frequency resonance problem [2]. However, the obvious disadvantage of this method is the increase in fault currents that may be beyond the existing switchgear design values.

Another method for mitigating or completely eliminating the network resonance and its consequent high overvoltages 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. In order to demonstrate the effectiveness of this solution, the same fault case is simulated but with all neutral point grounding reactors shown in figure 1 fitted with parallel resistors having approximately 3 x the impedance value of such reactors. For this case, Figure 10 is presented to show the 3-phase voltage at 'WB'. Note how the overvoltage is reduced and all post-fault oscillations are practically eliminated.

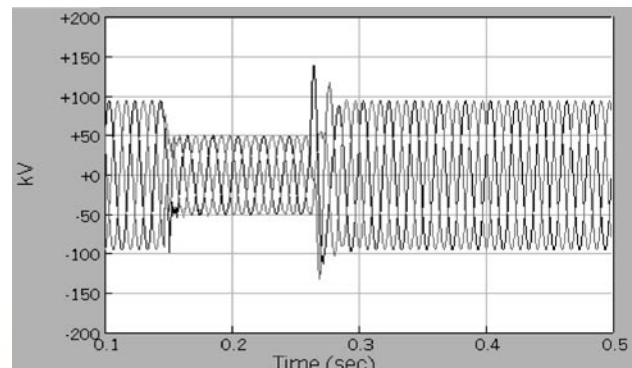


Figure 10 Voltage at substation 'WB' with parallel neutral point resistances.

For practical implementation of a standard economic solution, all existing and future neutral point reactors in the network are replaced with new reactors having very high inherent resistance by using different material other than aluminium.

References

- [1] A. Hammad, 1990, "Eigenvalue and Frequency Domain Analysis of Second Harmonic Resonance in a Complex AC/DC Network", *IEEE Power Engineering Society Special Publication*, No. 90, TH0292-3 PWR, 61-66.
- [2] S. Läderach and G. Köppl, 2001, "Beeinflussungsproblem bei Mehrfachleitungen", *Bulletin SEV*, 7/02, 9-12.