EMTP as a protection planning tool for the series compensated lines between Finland and Sweden

Liisa Pottonen
IVO Transmission Services LTD
PO BOX 629
00101 Helsinki, Finland

Abstract - **The 400 kV tielines between Finland and Sweden will be series compensated. During the planning stage of the series compensation project a lot of EMTP simulations were made in order to find out the fault currents, MOV energy absorption demands and the substations where the correct operation of the distance relays is crucial. Afterwards the relays were tested to ensure the correct protection of series compensated and adjacent lines.**

Keywords : Transient Analysis, EMTP, Protection, Series Compensation, Relay Testing

I. THE SERIES COMPENSATION PROJECT

A. General features

The Finnish and Swedish networks are interconnected with two 400 kV ac lines in the north and with one HVDC link in the south. The transmission companies Svenska Kraftnät in Sweden and IVO Transmission Services in Finland have started a project to series compensate the tielines in order to increase the transmission capacity between the countries. The series capacitors will be taken into operation in the late 1997. Fig. 1 presents the Finnish 400 kV network with the connections to abroad and the new series capacitors. The series compensated and adjacent lines are important lines from a stability point of view.

Series compensating some of the existing lines proved out to be the most cost efficient solution to increase the transmission capacity [1], [2]. The compensation degree of the lines will be as high as 70 %.

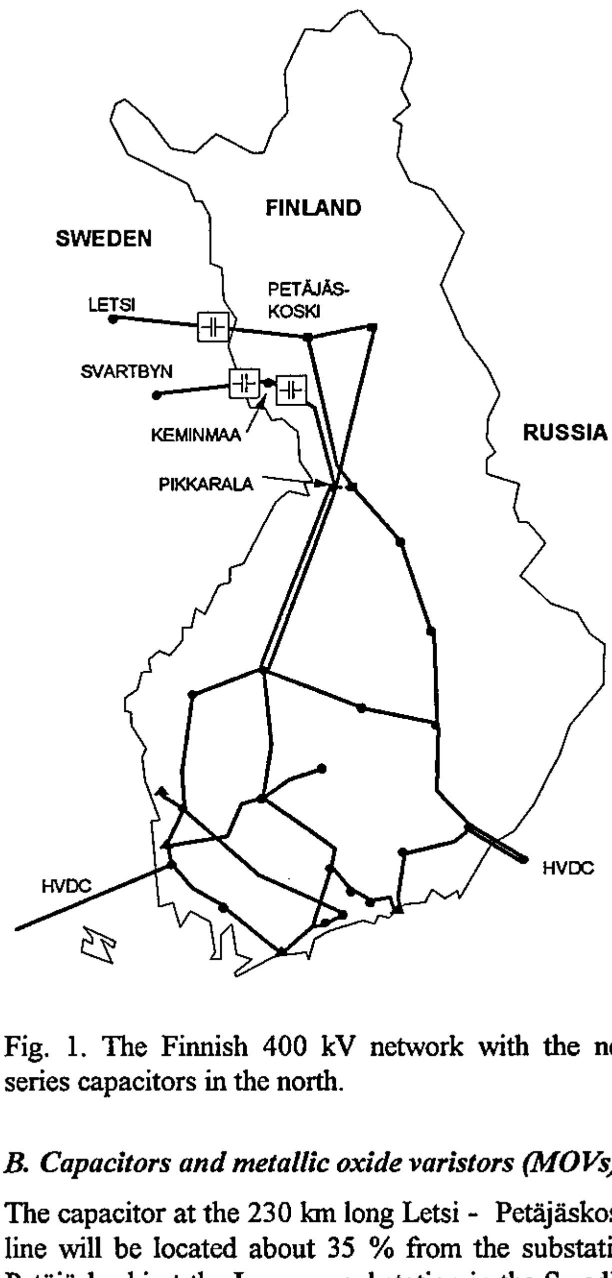

Fig. 1. The Finnish 400 kV network with the new series capacitors in the north.

B. Capacitors and metallic oxide varistors (MOVs)

The capacitor at the 230 km long Letsi - Petäjäskoski line will be located about 35 % from the substation Petäjäskoski at the Isovaara substation in the Swedish side

The sequential Svartbyn - Keminmaa and Keminmaa - Pikkarala lines (both about 140 km) will be compensated at the Keminmaa substation. The series capacitors will be equipped with metallic oxide varistors (MOV). The overvoltage protection level of the capacitors will be 2.3 p.u. Parallel to MOV branches there will be spark gaps which can be triggered during internal faults (i.e. faults at the compensated line) when the energy absorption capability of the MOVs is exceeded.

C. Preliminary studies with EMTP

The EMTP used was EPRI/DCG version 2 at VAX workstation. At the beginning EMTP was used for the fault simulations at the series compensated lines and the adjacent lines to see the fault currents, the best capacitor locations and the MOV energy absorption during the different faults.

II. THE PROTECTION PROBLEMS WITH THE SERIES COMPENSATION

The protection of the 400 kV lines in the north will become more complicated with the erection of the series capacitors. Ref. 3 tells more about the protection problems of series compensated lines.

A. Voltage inversion

Voltage inversion at the substation busbar occurs when the total impedance between the voltage source and fault is inductive but simultaneously the impedance between the busbar and the fault is capacitive (= fault behind the capacitor). The fault beyond the capacitor in forward direction and the fault in reverse direction both lead to a negative reactance, but in the first case the relay should trip and in the second it must not trip. This leads to the requirement that the relay must locate the fault by using the memory voltage to get the direction correctly. Also the relay must be capable to trip during all negative reactance values when the fault is in forward direction.

The voltage inversion will occur to some extent in some Finnish substations. Because the voltage transformers at the Keminmaa substation will be located on the line side of the capacitors instead of the

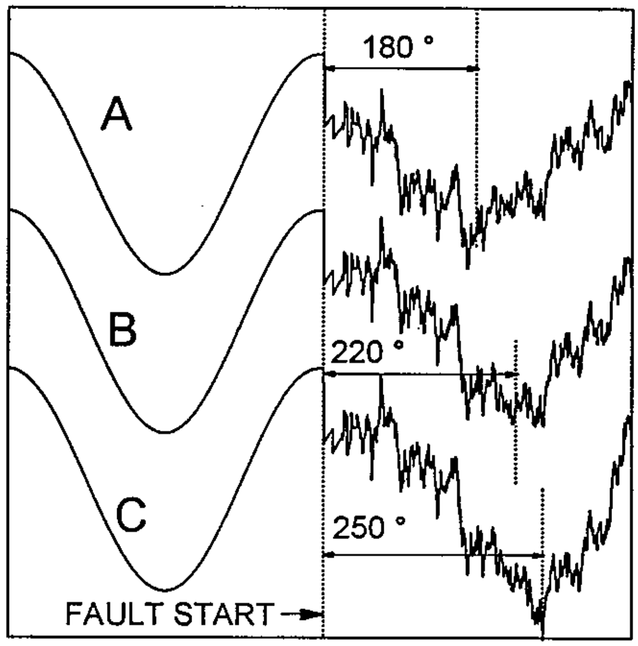

Fig. 2. The phase voltages at Petäjäskoski before and during a 3-phase fault at 85 km from Petäjäskoski to Letsi (fault in Fig. 3). Curves:
A - Inductive line (no series capacitor, no MOV).
B - series capacitor + MOV.
C - series capacitor, no MOV.

busbar, the voltage inversion at the Keminmaa does not create problems for the protection when the fault is on forward direction.

At the Letsi - Petäjäskoski line the faults located near the capacitor create some voltage inversion. The MOVs however reduce the voltage phase shift because part of the fault current goes through the MOV branch and thus reduces the compensation degree. In Fig. 2 there is a comparison of the simulated Petäjäskoski phase voltages during a 3-phase short circuit located at the line part Letsi - capacitor at 5 km distance from the capacitor. There are three different simulations: one without series compensation (A), one with series capacitor equipped with MOV (B), and one with series capacitor without MOV (C). In the cases where there is no series capacitor at the line the fault location corresponds to case where the fault is 85 km (37 %) from Petäjäskoski. The phase lag of curve C compared to the inductive case A is about 70° and in the case B about 40°. It can be seen that the modeling of MOV characteristics is important to ensure that the voltage curves will be correct.

B. Current inversion

Current inversion occurs in the cases when the total impedance between the voltage source and fault becomes capacitive. In this case the distance relays see that the fault is located in reverse direction. There will not occur current inversion problems, because the capacitors are either situated at the weak Keminmaa substation or far from the strong Letsi substation. Also the MOVs prevent the line to be capacitive with big currents and thus prevent the current inversion.

C. MOV effect to the resistive reaching of the relays

During the faults the current bypasses the capacitor partly or totally and thus creates a resistive component to the fault loop.

III. THE MAIN PROTECTION SCHEMES

A. Main protection of the ordinary 400 kV lines

The ordinary main protection of the Finnish 400 kV lines is redundant. It includes 2 distance relays, which are of different type.

B. Protection of the Finnish adjacent lines and the series compensated Keminmaa - Pikkarala line

All the Finnish adjacent lines and the series compensated Keminmaa - Pikkarala line are equipped with fiber optic telecommunication. The new protection for these lines will consist of a differential relay and two different distance relays. One differential relay and one distance relay suitable for series compensated lines will be added. The other distance relay is one of the existing distance relays and its purpose is to be a back-up relay. The first zone of the back-up will be turned off and thus it will have a delay of 0.4 s in its overreaching setting which is 120 % of the line.

C. The protection of the tielines between the countries

The telecommunication system for the tielines between the countries is power line carrier. This prevents the use of differential relays. The relay protection of the

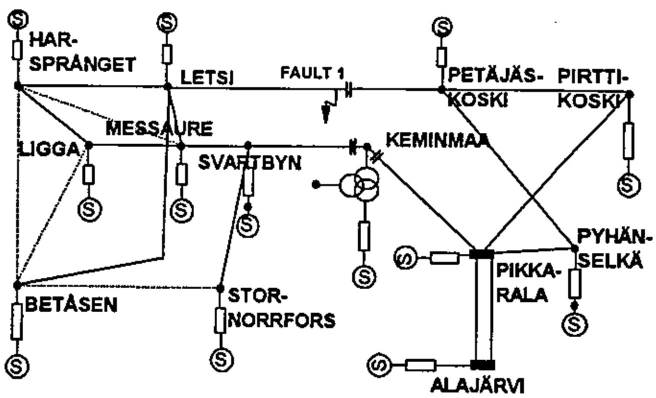

Fig. 3 One line diagram of the EMTP model of the northern Finnish and Swedish network.

two tielines will include two different distance relays suitable for series compensated lines.

IV. EMTP MODEL

The network model for the EMTP simulation includes the series compensated lines and the adjacent lines both in Sweden and in Finland. The lines are modeled as distributed lines. The 400/110 kV transformer at Keminmaa substation is modeled with its saturation characteristics. The series capacitors are modeled as lumped capacitors. The MOVs are modeled as true nonlinear zinc oxide arresters. The damping circuits of the capacitor by-pass breakers are modeled in order to prevent the oscillation after the by-pass breaker is closed. The other parts of the network are modeled with voltage sources behind the equivalent positive and zero sequence impedances. Before the simulations the correctness of the EMTP model was checked by simulating the 3-phase and 1-phase faults (without series capacitors) at all the substations and comparing the fault currents with the load flow program fault currents. The one line diagram of the EMTP network model is in Fig. 3.

V. MATLAB CALCULATIONS

It is laborious to validate the reactance that the distance relay measures at a substation by looking only the voltage and current output curves by EMTP simulations.

With the MATLAB the currents and voltages from EMTP simulations were filtered so that the harmonics were eliminated and the phase difference between the current and voltage could be calculated. After these modifications the impedance, resistance and reactance at all the line ends where the distance relays are situated were calculated. During the 3-phase fault the voltage divided by the current (both peak values, u_{AB}/i_{AB}) gives the impedance value Z. The phase angle is calculated from the time difference between the filtered voltage and current peak values.

The reactance X is calculated as $Z\sin\phi$ and resistance R is $Z\cos\phi$. During earth faults the measured impedance of the relay was calculated with $Z=u_A/(i_A+k_0*3*i_0)$, where k_0 is the line constant $k_0 = (Z_0 - Z_1)/3Z_1$.

The modern relays have the polarizing voltage in the memory in order to decide the fault location. At first simulations the only voltage used in the impedance calculations with MATLAB was the voltage during the fault. This gave results where the reactance seemed to be inductive instead of capacitive also during the reverse faults. This is not correct but at the first stage it helped to find out the relay locations where the relays must be tested in order to ensure the correct tripping.

During the additional simulation the MATLAB calculations were improved in such a way that the phase fault location (forward or reverse) was calculated by the memory voltage but the impedance, reactance and resistance values were calculated by the voltage during the fault. These MATLAB calculations did not try to model any specific relay but instead give an idea how the relay sees the fault.

VI. EMTP SIMULATIONS FOR PROTECTION PLANNING

A. First group of fault simulations

At first only 3-phase faults with zero fault resistance at the series compensated lines were simulated. The faults were located either in the middle of the line (or line part) or near the capacitor (10 % distance from the capacitor).

The same faults were simulated both with a strong network (all lines in use) and with a weak Finnish network (lines Pikkarala - Pirttikoski, Pikkarala - Pyhänselkä and Pikkarala - Alajärvi eastern line out of operation) and with a weak Swedish network (Letsi - Messaure line out of operation).

The spark gaps or by-pass breakers were not used for bypassing the varistors. The reason for this was the fact that the parallel connection of the capacitor and the MOV to the protection of the lines was interesting. If the varistors were by-passed, there would remain no series compensation, which would be easier for the protection.

The busbar voltages and the line currents were the simulation outputs. The voltages and currents were taken at the places where the current and voltage transformers are located. The aim of the simulations was to study the possible problems for the distance relay protection of the lines. The typical curves received of these simulations can be seen in Fig. 4, where the phase-to-phase voltage at Keminmaa on the line side of the capacitor (on the line to Pikkarala) and the current Keminmaa - Pikkarala are presented. The fault location was 50 % from Keminmaa substation to Pikkarala at a weak Finnish network.

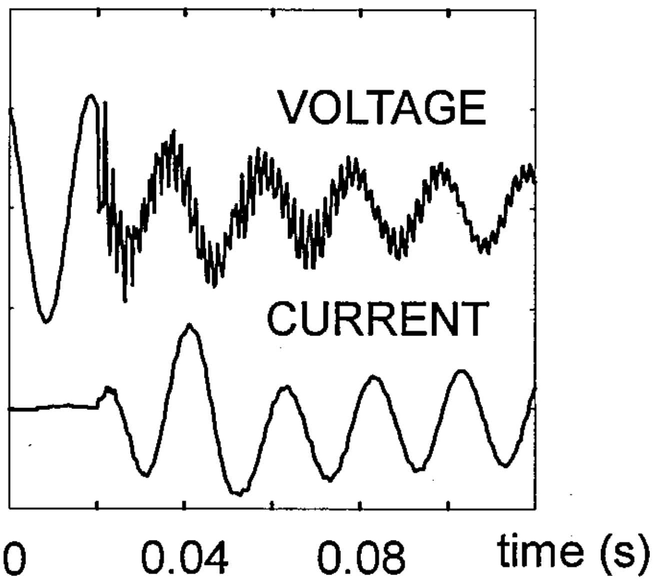

Fig. 4. Simulated phase-to-phase voltage at Keminmaa on the line side of the capacitor (on the line to Pikkarala) and the current Keminmaa - Pikkarala. The fault location was 50 % from Keminmaa substation to Pikkarala at a weak Finnish network.

The result of these simulations was that at all the northern Finnish 400 kV substations and at the Swedish Svartbyn substation the behavior of the relays should need more precise study. The reactances were calculated with the voltage during the fault and it seemed that the relays measured very small reactances and resistances also when the fault was at reverse direction or at the other line.

VII. ADDITIONAL EMTP SIMULATIONS

A. Simulated faults

A selection of other fault simulations was made in order to study more precisely the effect of the fault resistance and external faults. 1-phase and 3-phase faults with different fault resistances were simulated with intact network and weak network.

B. Effect of the MOV to the resistive setting of the relays

The only place where the MOV has effect to forward fault measurement is at the Letsi - Petäjäskoski line. When the fault was located at 10 % distance from capacitor to Petäjäskoski the measured fault resistances at Letsi and Petäjäskoski were very different as can be seen at the Table 2. When simulating the same fault with capacitor and MOV by-passed the relay at Letsi measured the resistance of 1 Ω. The effect of MOV greatly enlarges the resistive zone needed in the relay settings.

Table 2. Calculated resistances at Letsi (LT) and Petäjäskoski (PT) substations during a 3-phase faults at different fault resistances at the 10 % distance from capacitor to Petäjäskoski.

Rf (Ω)		LT-PT	PT-LT
0	C + MOV in use	25 Ω	-4 Ω
1	C + MOV in use	26 Ω	10 Ω
5	C + MOV in use	32 Ω	15 Ω
1	C + MOV by-passed	1	9

C. Problems during external faults

The 3-phase external faults near Pikkarala substation at Pikkarala - Pirttikoski line at different locations near the Pikkarala substation demonstrated that the simulated reactance at non faulted lines at Letsi (to Petäjäskoski), and at Svartbyn (to Keminmaa) were less than the line reactance and the fault direction was forward. The reason for this phenomenon is the fact that the currents via the series capacitors were less than the values at which the MOVs start to conduct. As a consequence the measured reactances at Letsi and Svartbyn were very small. This phenomenon reduces the allowed zone 1 of the relay.

VIII. THE RELAY TESTING

A. Test preparation

To ensure the correct and selective tripping during the faults the new distance relay candidates were decided to be tested. The relay testing could be possible either by using the EMTP simulation output files as the inputs of the relays or by a TNA (transient network analyzer). The tests were decided to perform by using TNA at a Canadian test laboratory. The main reason to choose the TNA instead of the EMTP simulations was because it was less laborious to make statistical analysis with different fault incident angles, fault resistances etc. during the tests.

B. Tests and results

Three distance relays supplied by different manufacturers were received for the tests. The test fault locations were at the series compensated lines or at the substations Petäjäskoski, Svartbyn, Keminmaa and Pikkarala. The faults were: 3-phase-to-ground faults, 2-phase faults and 1-phase-to-ground faults. Every fault was made 20 times in different fault ignition angles. The behavior of the relay was checked at several substations during each fault to ensure that only the right relays trip. One of the three relays passed the tests without problems and it was selected. The other relays had some difficulties: one tripped during a reverse fault and the other did not trip during a forward fault.

C. Analysis of the tests

The test results of the relay, which did not trip during a forward fault was analyzed afterwards. The relay was protecting the Petäjäskoski - Letsi line at Petäjäskoski substation during the fault behind the capacitor (fault 1 in Fig. 3). The zone 1 reactive setting was the maximum allowed: $X1= 0.85*(X_l - X_c)$, where X_l is the reactance of the line and X_c is the reactance of the capacitance. The relay did not trip. With increased resistive setting it tripped after carrier receive (zone 2). With increased resistive and reactive settings it always tripped at zone 1.

The simulations showed that the fault was near the resistive axis near the zone 1 limit (point 1 in Fig. 5). Increasing the reactive reach of the zone 1 changes slightly the angle of the resistive limit and point 1 becomes to zone 1 area and the relay trips.

With this analysis it also occurred that this relay inherently has similar negative and positive reactive reaches. The simulations indicated that the limited reactive reach can be a problem: with a weak network the relay measures such a big negative reactance (point 3 in Fig. 5) that it is at the negative border of the zone 1. The tripping is not guaranteed.

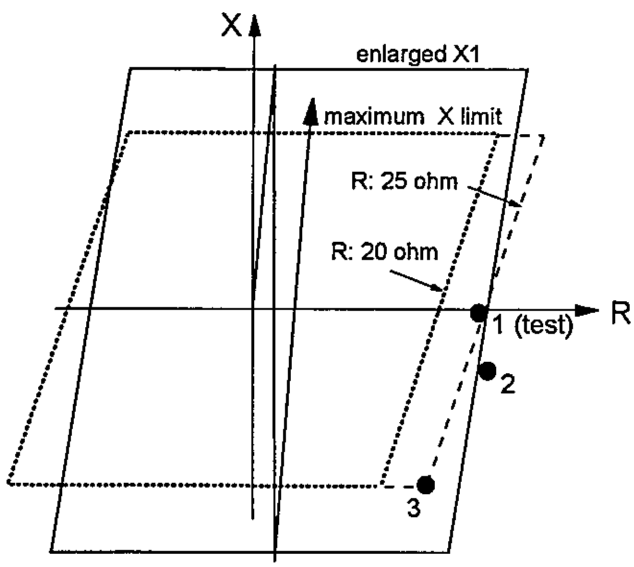

Fig. 5 Impedances measured by the relay at Petäjäskoski during a 3-phase fault behind the capacitor with different network connections.
1 - intact network
2 - Petäjäskoski - Pirttikoski line out of use.
3 - Petäjäskoski - Pirttikoski and Petäjäskoski - Pyhänselkä lines out of use

IX. CONCLUSIONS

The simulations confirmed the fact that the distance relays which do not use the memory voltage as the polarizing voltage are not suitable for protecting the series compensated or adjacent lines.

The importance of modeling the MOVs in simulations was also clarified. The MOV has an effect to the voltage phase and to the reactance measured by the relay. It also increases the resistive part of the measuring loop.

The simulations helped to prepare the relay tests, which occurred to be useful when selecting the relay to the lines, because the problems were found out before the selection of the relays. The tests showed that the negative reactive and the positive resistive zones must be large enough to enable the relay to trip during voltage inversion.

X. REFERENCES

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