# Analysis of distance relay tripping an industry plant due to sympathetic inrush currents

H. Kr. Høidalen, V. Berg

***Abstract*—Sympathetic inrush current can cause unexpected transformer protection issues. In this paper we analyze an actual situation where this phenomenon caused the distance relay of a feeding line to trip after 2 seconds due to a very long inrush transient. From theory and simulations, it is shown that the duration of the inrush situation is governed by the transformers resistance and air-core inductance primarily, and not by the feeding network. Analysis of inrush currents is complicated in requires high precision in modelling and data. Two parameters of the transformers are in particular important; the air-core inductance of the transformer and the share of the winding resistance on the HV side. The most critical parameter is the tapping of the transformer. To prevent high inrush currents, the transformer should not be energized in low tap positions. Loading of the transformers seems also very important and should be studied more closely to identify a worst-case loading dependent on the distance relay zone shape.**

***Keywords*: sympathetic inrush current, distance relay, transformer modeling, measurements, ATP simulations.**

## I. Introduction

INRUSH currents occurs when transformers are switched in and can have an impact of protective relays. This is typically relevant for differential transformer relays and 2nd or 5th harmonic blocking in energization situation is normally used to avoid nuisance tripping [1, 2]. Switching in a transformer in parallel with an already energized or loaded transformer can cause sympathetic inrush current in this unit and cause unexpected transformer differential relay tripping. The sympathetic inrush current is smaller in amplitude but can last longer [3, 4]. The transient is dominantly damped by the small winding resistance in the two transformer units and not by the feeding network [3]. Effect of load was studied in [5] and various factors in [6].

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Less frequent and much less reported, inrush currents can also cause challenges for remote over-current or distance relays as shown in this paper. The paper is organized as follows. Section II summarizes sympathetic inrush theory and section III outlines an actual case. Section IV describes in brief the simulation model and section V shows simulation results with parameter variation in section VI. The results are discussed and conclusions are drawn in section VII.

## II. Sympathetic Inrush Currents

Sympathetic inrush currents can according to [1, 2] be divided in three steps. Step 1 is a pure inrush current caused by the switched in transformer while the current in the parallel transformer is zero. This period lasts for just a few cycles. Then comes Step 2 where the parallel transformer gradually is driven into saturation caused by the voltage drop across the feeding system resistance. At a certain point the transformers enters Step 3 where both transformers are in saturation each half period. The inrush current in Step 3 is independent on the feeding system and is only damped by the resistance in the loop between the transformers. Fig. 1 shows a sympathetic inrush case of unloaded parallel transformers compared with the case without parallel transformer. It is clearly seen that the sympathetic inrush has equal maximum inrush current amplitude and a much slower decay in Step 3. Fig. 2 shows the actual waveform of the inrush currents around the transition from Step 2 to Step 3. The currents in the two transformers (green and red curve) are nearly equal in magnitude but with opposite signs and shifted one half period. The current in the feeding network will thus oscillate between the two envelope curves.

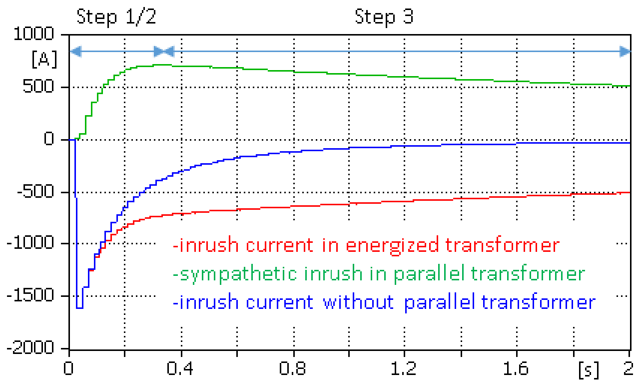


Fig. 1 Envelope of (sympathetic) inrush currents with the indication of Steps 1-3 [4]. Step 1 is very short in this case. The transformer is energized at voltage zero crossing (worst case).

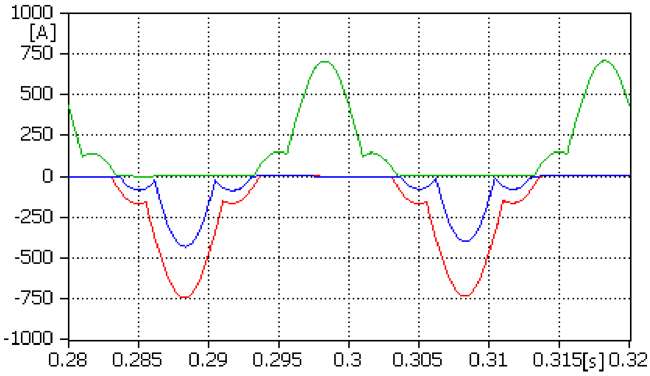


Fig. 2 Inrush current waveforms at the intersection of Step 2 and 3.

Schematically the sympathetic inrush case can be illustrate as in Fig. 3 with emphasis on the resistive parts.

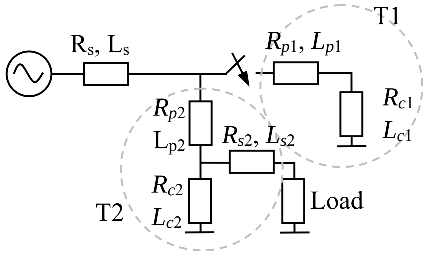


Fig. 3 Sympathetic inrush impedances.

According to [4] the fluxlinkage variation over one period T can be written for the three Steps 1-3:

$$\begin{bmatrix}\Delta\lambda_1\\ \Delta\lambda_2\end{bmatrix}_{Step1} = -T\cdot\begin{bmatrix}R_s+R_{T1}\\ R_s\end{bmatrix}\cdot i_{1f} \tag{1}$$

$$\begin{bmatrix}\Delta\lambda_1\\ \Delta\lambda_2\end{bmatrix}_{Step2} = -T\cdot\begin{bmatrix}R_s+R_{T1} & R_s\\ R_s & R_s+R_{T2}\end{bmatrix}\cdot\begin{bmatrix}-|i_{1f}|\\ |i_{f2}|\end{bmatrix} \tag{2}$$

$$\begin{bmatrix}\Delta\lambda_1\\ \Delta\lambda_2\end{bmatrix}_{Step3} = -T\cdot\begin{bmatrix}R_{T1}\\ R_{T2}\end{bmatrix}\cdot i_{f1} \tag{3}$$

where $R_{T1} = R_{p1} + R_{c1}$ and $R_{T2} = R_{p2} + R_{c2} \,||\, (R_{s2} + R_{load})$ are the transformer internal resistances of transformer T1 and T2 respectively. $R_{c1}$ is the series equivalent of the magnetization resistance and is thus small.

The average current $i_f$ can be obtained from the saturation characteristic in Fig. 4. Given the fluxlinkage $\lambda$ the instantaneous current is found graphically. The average of this current is next used in (1)-(3) to calculate an offset of the flux for the next period. The process is then repeated giving a new average flux $\lambda_0$ each iteration ($\lambda_0 = \lambda_0+\Delta\lambda$). The worst case starting point is $\lambda_0=\lambda_m+\lambda_R$, where $\lambda_R$ is the remanence ignored in this study. If we ignore the current when the flux is below the saturation point $\lambda_s$ the average current can be expressed as [7]

$$i_f \approx \frac{\lambda_m}{\pi\cdot L_{ac}}\left[\sqrt{1-\chi^2}-\chi\cdot\left(\cos^{-1}\chi\right)\right]\wedge\chi=\frac{\lambda_s-\lambda_0}{\lambda_m} \tag{4}$$

The feeding network sees the sum of the current in the two transformers. The two currents have opposite polarity and one is zero while the other saturates. Eq. (3) governs the long lasting sympathetic inrush current. The envelope of the Step 3 sympathetic inrush current can from (3, 4) be simplified as

$$i_1 \simeq -i_2 = A\cdot e^{-R/L\cdot t} \tag{5}$$

where $R$ is the equivalent resistance and $L$ is the air-core inductance ($L_{ac}$) of the transformer. $A$ is proportional to the feeding voltage divided by the total feeding impedance of the system and dependent on the more complex Step 2 process.

From Fig. 3 and (5) we see that that a loaded transformer will reduce the equivalent transformer resistance and thus potentially increase the inrush duration for the same terminal voltage. This will be investigated later via simulations.

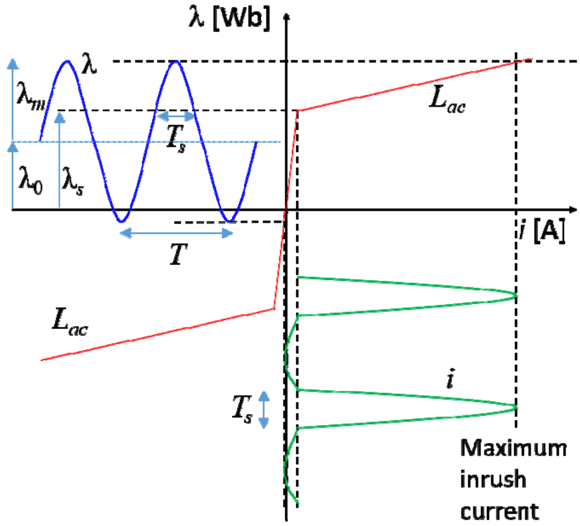


Fig. 4 Illustration of how to connect flux linkage and current.

## III. Distance Relay Tripping Case

This paper reports a case where energization of a 90 MVA transformer at 132 kV in parallel with four loaded transformers with a total capacity of 185 MVA, caused the feeding line to trip due to a nuisance distance relay operation. The entire load of 88 MW and 42.5 MVar was disconnected, affecting critical loads including several industry plants.

The event was recorded and captured by the distance relay and deeply analyzed. The relay plan was revised and the starting zone slightly reduced to avoid repetition of the event, but one uncertainty remained; Was the recorded event a worst-case situation or could an even worse situation still trip the adjusted relay?

### A. *System configuration*

Fig. 5 shows the schematic power system. The distance relay tripping the circuit breaker S1 was located at the remote end (BUS 1). The circuit breaker S2 energizing the 90 MVA transformer was located at BUS 2. The voltage at BUS 1 was reported to be 124 kV and the total load at this point was 88+j42.5 MVA. The impedance of the feeding line the equivalent source impedance are given in Fig. 5. The exact situation at BUS 2 is unknown, but 4 transformers were already energized. Two of them feeding industrial processes via rectifiers. Two seconds after switching in S2, S1 tripped.

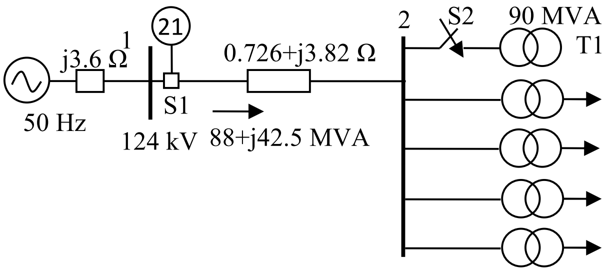


Fig. 5 Industry plant and supply configuration.

### *B. Measured impedance, currents and voltages*

The impedance trajectory recorded by the relay at BUS 1 is shown in Fig. 6. The trajectory stays within the starting zone for more than 2 seconds causing a trip as intended. The starting zone is extensive, as it has to cover the case when Bus 2 is connected to another parallel bus normally fed from a different source.

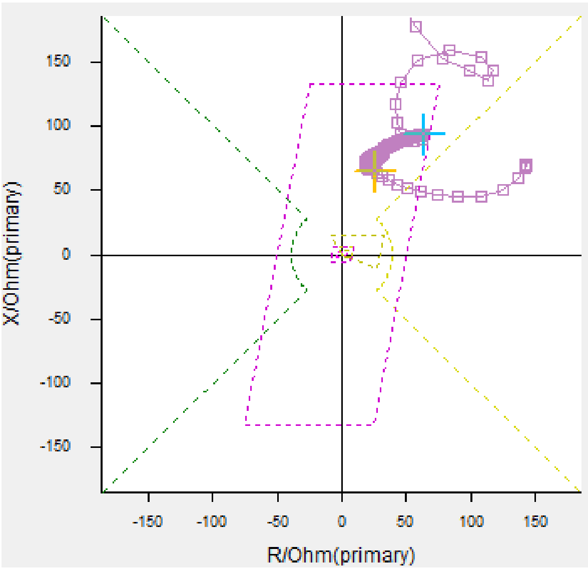


Fig. 6 Measured phase C impedance trajectory by distance relay at remote end: The trajectory enters zone 5 and cause a trip after 2 seconds marked by the blue cross.

Figures 7 and 8 show the recorded current and voltage waveforms seen by the relay. The red dashed lines mark the instance when inrush current first can be observed.

Maximum inrush current occurs when switching in at voltage zero crossing. After switching in is takes a few milliseconds before the flux saturates and the inrush current is observed. From Figures 7 and 8 it seems like the phase C voltage crosses zeros at the same time as the inrush current is observed. This thus does *not* indicate a worst-case situation. As the current and voltage are recorded by the distance relay at BUS 1 and the internal timing is uncertain, there might be an unknown phase shift in the measurements. When later studying the inrush current the measured power is used to obtain correct phase shift between voltages and currents and the shape of the inrush current at the time of onset is used to identify and replicate the switching instant in the simulations.

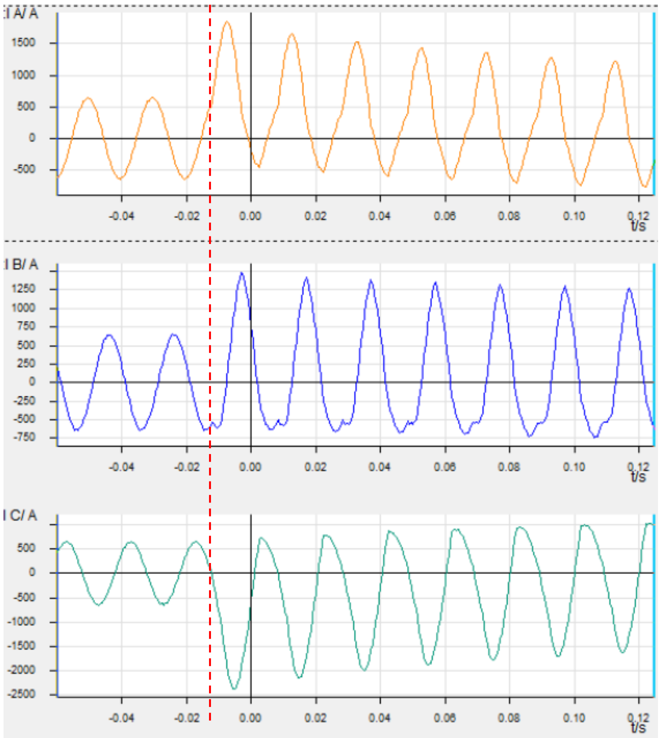


Fig. 7 Measure momentary values of inrush current at remote end.

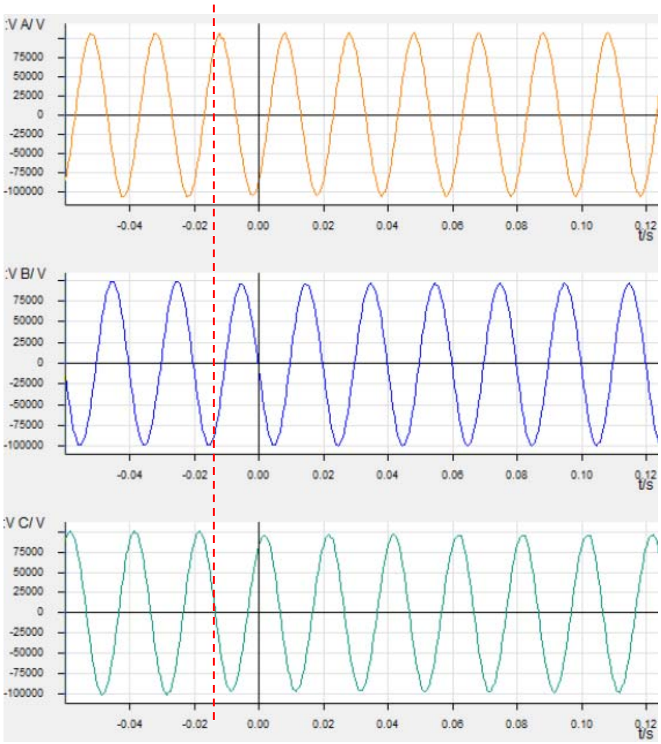


Fig. 8 Measure momentary values of voltage at remote end.

Fig. 9 shows the rms value of the inrush current seen by the relay at the feeding line.

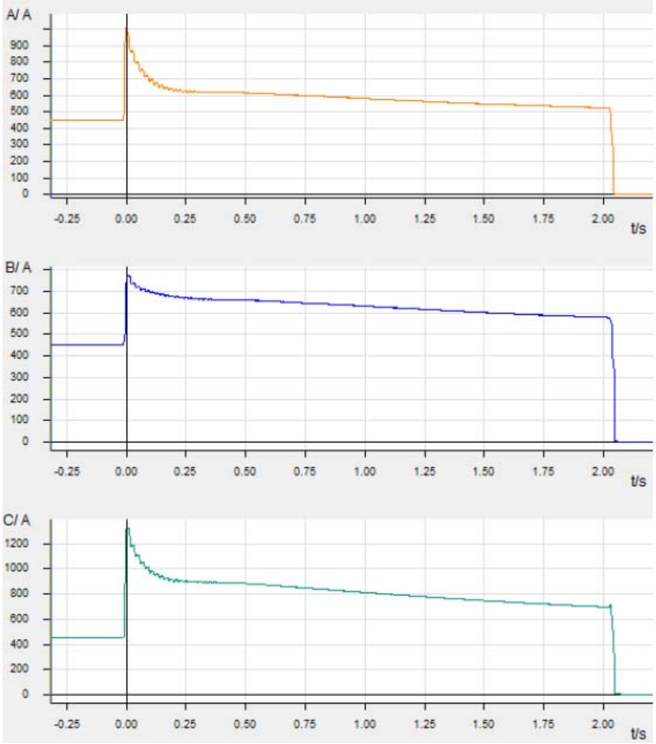


Fig. 9 Measure rms value of inrush current at remote end.

## IV. Method and Model

ATP-EMTP with the Hybrid Transformer Model [8, 9] in ATPDraw is used to simulate the case in Fig. 5. A PI-equivalent was used for the feeding line and constant impedance assumed for the loads. Some standard transformer data were available including a test report for the 50 MVA unit. For two units (90 and 70 MVA) only nameplate data were available, and for the remaining two units (2*34.4 MVA) some typical values were used. All nameplate data are shown Tabl. I. One fundamental problem in the study was that the transformers all had somewhat different voltage ratings. A fixed voltage rating of 122/22 kV was assumed in the simulations. All transformers are YNd5 coupled.

TABLE I Transformer Name plate data

| MVA | $Z_{SC}$ [%] | $P_{SC}$ kW] | $I_0$ [%] | $P_0$ [kW] |
|---|---|---|---|---|
| 90 | 12.3 | 252 | 0.05 | 38.7 |
| 70 | 11.6 | 266 | 0.28 | 49.2 |
| 50 | 11.7 | 191 | 0.21 | 35.9 |
| 34.4* | 6.0 | 205 | 0.4 | 40 |

*Typical values used

In order to reproduce the measured inrush current and its slow damping, two parameters where adjusted. One critical parameter that influences the maximum inrush current is the air-core inductance. A final slope of the saturation characteristic of 1 mH referred to the 22 kV side was used for all transformers. One critical parameter to obtain the correct damping of the sympathetic inrush current is the HV winding resistance. Instead of splitting this in 50 % pu on each side, only 25 % of the resistance was put on the HV side, the remaining 75 % on the LV side. The tap position of the transformer T1 switched in (90 MVA) was also a free parameter. Tap position 5 (117.5/22kV) was required to obtain the measured inrush current. The transformer operator claimed that in the actual case the transformer was switched in at a higher tap position.

## V. Simulation Results

This section shows the simulation results using ATP-EMTP. Emphasis is put on identifying the worst-case situation and the parameters that can influence this.

### A. Worst case switching scenario

Time zero $t$=0 is in the simulation the instance of maximum voltage of phase A of the source in Fig. 5. The voltage at the transformer T1 does not deviate significantly in angle. Phase C of the voltage crosses zero from positive to negative at the approximate instances

$T_{0C} = \frac{1}{f}\left(n - \frac{1}{12}\right)$ and $n$=6 is chosen in this case giving a zero crossing at $t$=0.1183s.

Based on this initial consideration, the switching instant was varied over the period and the maximum inrush current identified and plotted in Fig. 10. We see that the initial assumption is confirmed.

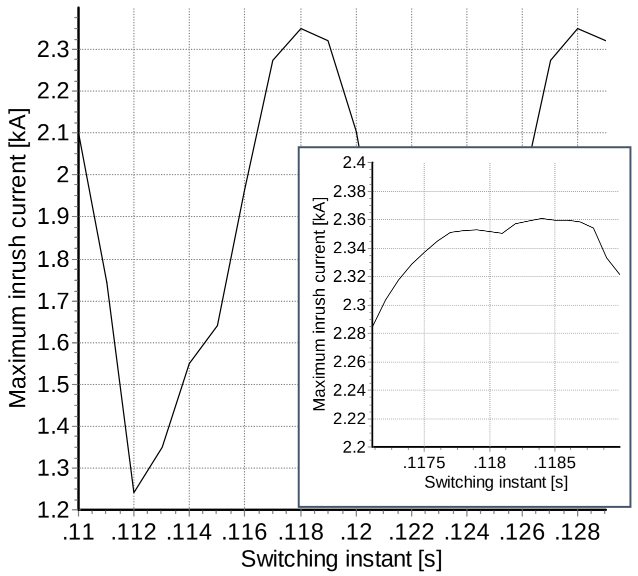


Fig. 10 Maximum inrush current seen at remote end as function of switching instance.

### B. Actual switching instance

Switching in at t=0.1183 s gives simulated inrush current waveforms that slightly deviate from the measured curves. Switching in at 0.1174 s, however, results in the simulated inrush currents shown in Fig. 11. This current is very similar to what was measured in Fig. 7.

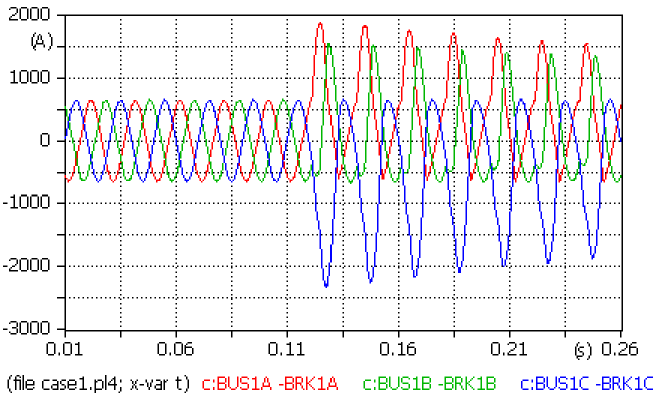


Fig. 11 Simulated inrush current when switching in at t=0.1174 s.

The impedance seen by relay is calculated and shown in Fig. 12. This is done by an FFT algorithm using 400 Samples/s in a one period moving window. As can be seen in the figure, the trajectory is close to what was measured, but goes out of the zone just prior to 2 seconds. The damping is thus too high in the simulations. This is also confirmed in Fig. 13 where the rms value of the inrush currents are calculated to be compared with measured quantities in Fig. 9.

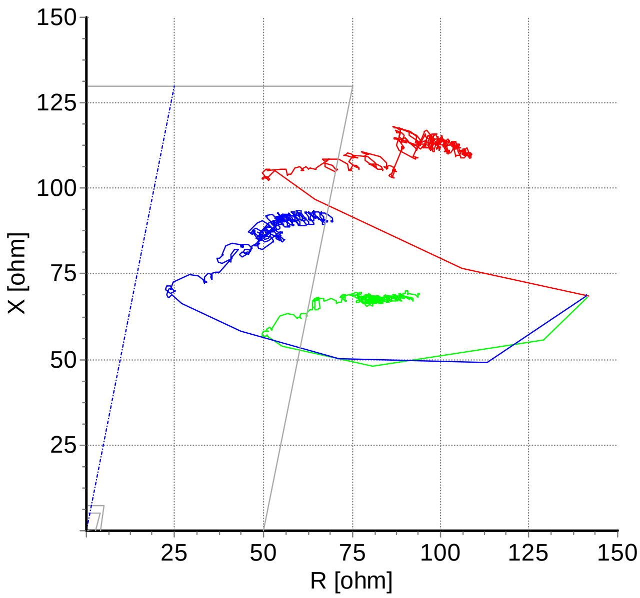


Fig.12 Calculated impedance trajectories (Blue is phase C) for switching instance t=0.1174 s.

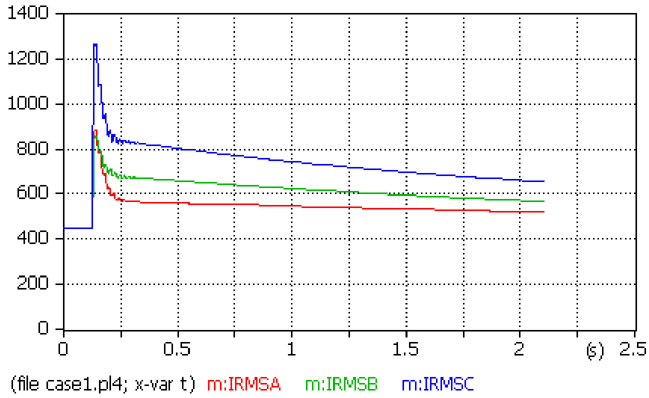


Fig. 13 Calculated rms value of the inrush current for switching instance t=0.1174 s.

## VI. Parameter Variation

Was the recorded event a worst-case situation? To address this a few system parameters are varied.

### *A. Switching instant*

Using the switching instance t=0.1183 instead of t=0.1174 gave a slightly higher inrush current but surprisingly not a lower apparent impedance later at 2 seconds. Variations of the switching instance between 0.117 and 0.119 did not give any lower impedance. This tells that the switching instance in the measurements is actually the worst-case situation for the distance relay.

### *B. Tap positions of transformer T1*

Setting the transformer in the lowest tap-postion tap 1 instead of tap 5 gave not surprisingly a higher inrush current peak and lower impedance at 2 seconds as shown in Fig. 14. The trajectory is now well within the starting zone at 2 seconds, but the effect is not dramatic.

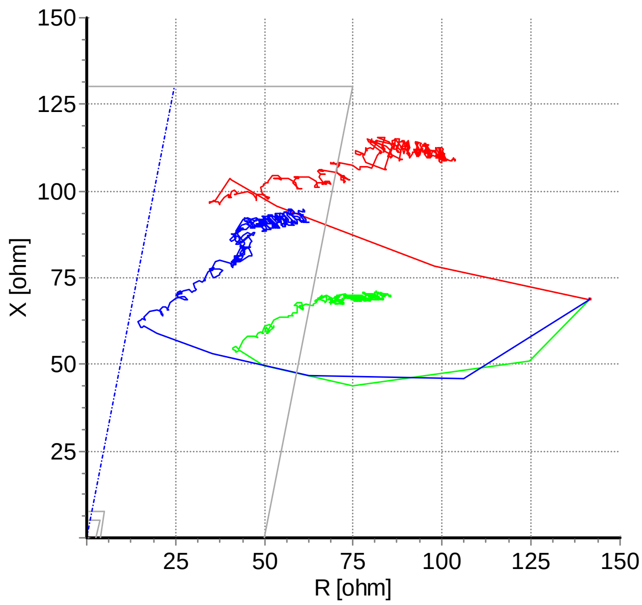


Fig. 14 Calculated impedance trajectory when the transformer is switched in at tap 1 (110 kV).

### C. *Increased and reduced load*

One hypothesis from theory is that increased load could prolong the inrush duration. The load was thus increased to 167 +j57.2 MVA and the source voltage increased so that BUS 1 was kept at 124 kV. As can be seen from Fig. 15, this gives indeed a lower impedance at 2 seconds, but as the inductive part also is reduced the trajectory falls out of the actual tripping zone. Fig. 16 shows the effect of reducing the load to 2.1+j0.34 MVA. The inductive part of the impedance goes high in this case and the trajectory goes well out of the zone.

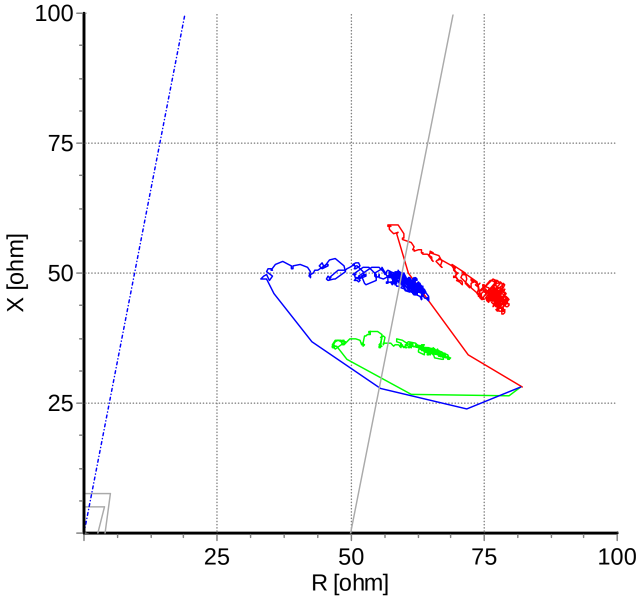


Fig. 15 Calculated trajectory showing the effect of doubling the load.

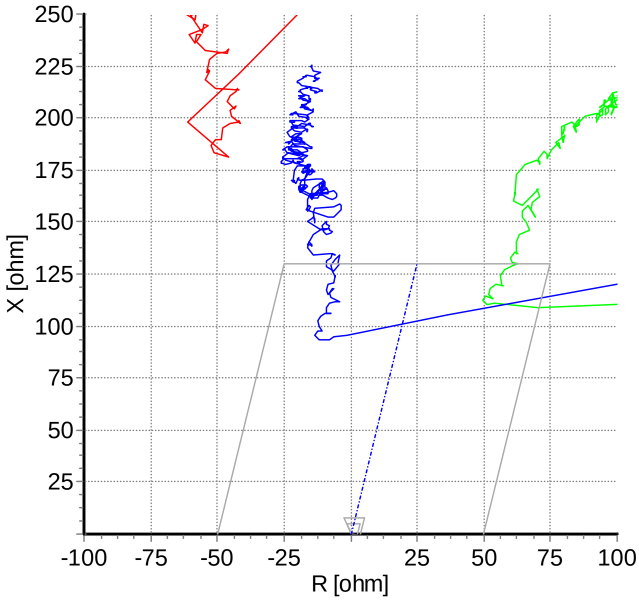


Fig. 16 Calculated trajectory showing the effect of reducing the load.

## VII. Discussion and Conclusion

In this paper we have shown an actual situation where sympathetic inrush currents caused the distance relay of a feeding line to trip after 2 seconds due to a very long inrush transient. The resistance of the involved transformers governs the duration of the inrush transient and not the feeding network.

Two parameters of the transformers are very important for the duration of the sympathetic inrush current; the air-core inductance of the transformer and the share of the winding resistance on the HV side. The manufacturer could provide such data.

Loading of the transformers seems very important and should be studied more closely to identify a worst-case loading dependent on the distance relay zone shape.

The most critical parameter is the tapping of the transformer. The transformer should not be switched on in low tap positions.

The program ATP-EMTP and ATPDraw was used to study the data case. The lack of a proper tap changer model added uncertainty to the simulations.

There are also some uncertainties in the measurements. The recorded current had apparently a few milliseconds time delay compared to the voltage. There could also be measurement errors in the connected CTs and VTs.

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