Limiting Sympathetic Interaction Between Transformers Caused by Inrush Transients

Simon Schramm, Christof Sihler, Sebastian Rosado

Abstract--**Sympathetic inrush current phenomena occur when a transformer is switched on in a power system network containing other transformers that are already energized. Although the amplitude the inrush current is higher during single transformer energization, the sympathetic inrush current is of special importance due to its unusual characteristics. The inrush current in a transformer decays, usually, within a few cycles, but the sympathetic inrush current can persist for seconds.**

Issues with sympathetic inrush currents were experienced when energizing two 20 kV / 3 MVA transformers of a converter test facility. To avoid a protective trip in the supply of the facility, an inrush current limitation resistor is used when energizing the transformers. The resistor causes the inrush current to decay within two periods when a single transformer is energized. Energizing the second transformer with the first transformer already connected to the 20 kV network, causes a sympathetic inrush transient in the 20 kV network that can last for more than 100 cycles, despite the use of an inrush current limitation resistor.

This paper deals with sympathetic inrush current phenomena between medium voltage transformers, investigates by simulation and measurement potential countermeasures, and gives recommendations concerning the limitation of inrush currents in applications where frequent switching of transformers is required.

Keywords: **Transient analysis; transformer switching; inrush current; sympathetic inrush current**

I. INTRODUCTION

THE High Power Electronics (HPE) Lab of GE Global Research Europe is currently extending its test facility for medium voltage converters. The existing infrastructure of the test facility comprises two medium voltage transformers that feed the rectifier and inverter side of a medium voltage converter, as shown in Fig. 1. In this test configuration medium voltage converters up to a nominal power of 3 MVA can be tested in a so-called pump back mode. During pump back tests the converters are controlled with a power factor close to 1, and the active power is circulated between S1-T1-TO-T2-S2-S1. Thus, only the losses must be supplied from the 20 kV grid supply, e.g. 150 kW for a total converter efficiency of $\eta_{tot} \sim 95\%$. Therefore the in-house grid supply was designed for a nominal power of only 1 MVA. The external 20 kV supply has a comparably small short-circuit power (160 MVA) [1]. The transformers T1 and T2 must be energized on a daily basis to get the converter test facility operational. To avoid protective trips or nuisance interactions in the 20 kV grid supply, a short-circuit current limitation resistor R was installed. R was designed for limiting short circuits when switching a single transformer and both transformers. To keep the inrush current amplitudes at an acceptable level, the 20 kV switchgear is controlled in such a way that the transformers can only be switched on one after another. Both transformers are switched on with S_R open, so that the inrush currents are limited and damped by means of R. R provides 100 Ohm in each phase during transformer switching. This is sufficient to limit the inrush current amplitudes to values below 150 A, and to damp out inrush transients in less than 50 ms, when switching a single transformer.

The converter transformers T1 and T2 are installed close to each other. When the second transformer is energized, it excites the first transformer to a long-lasting sympathetic inrush current [2]. Because of the proximity of the two transformers, the resistance available to damp the sympathetic inrush current between T1 and T2 is small. Therefore, the inrush transients caused by sympathetic interaction can be sustained for seconds, despite the damping resistor R in the supply line.

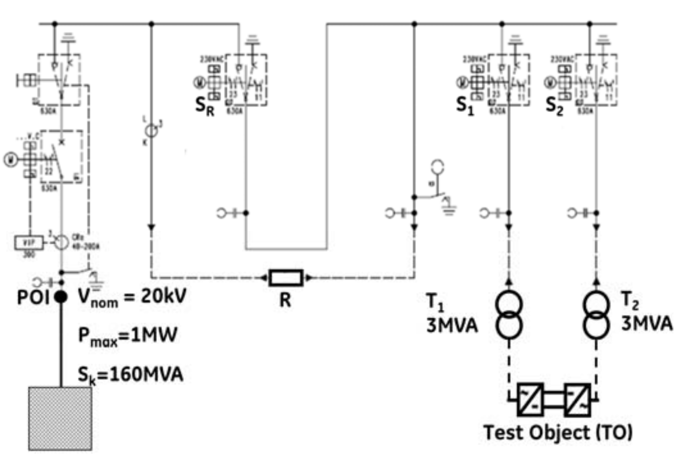

Fig. 1. One line diagram 20 kV supply system of converter test facility

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A model for investigating the sympathetic interaction phenomena was developed in order to understand better the measurement results and simulate inrush phenomena of larger transformers that are planned to be installed in 2011. These larger transformers will increase the capability of the medium voltage converter test facility.

II. Transformer Design and Modeling

A. Transformer Inrush Phenomenon

The behavior of a power transformer being energized must be analyzed by using a model that takes into account the inrush phenomenon. The large inrush created during the connection of a single transformer is a well-known phenomenon and has been described widely. A classical reference to this can be found in [3]. Here we just summarize it briefly for sake of completeness. The transformer current when a voltage step is applied is obtained from solving the following differential equation.

$$u(t)=\frac{d\psi(i,t)}{di(t)}\frac{di(t)}{dt}+R\cdot i(t) \qquad (1)$$

Where u is the applied voltage, i the circulating current, ψ the magnetic flux, and R is the winding resistance. Because of the nonlinear magnetic characteristic, the flux-current relationship is non-linear and therefore the flux derivative makes it difficult to solve equation (1). For this reason graphical methods have been classically used [4]; however, these are not accurate and provide mostly a qualitative description.

If we are only interested in finding the maximum value of the inrush current, [3] offers the approximated formula (2)

$$i_m=\frac{1}{\mu_0}\frac{A_c\cdot l_0}{A_d\cdot N}\left(2\cdot B_m+B_r-B_s\right) \qquad (2)$$

Where A_c is the cross sectional area of the core, A_d is the cross sectional area of the energizing winding (whether this is primary or secondary), l_0 is the length path to the magnetic field, N is the number of turns of the winding involved. Regarding the magnetic flux densities, B_m is the maximum value of the magnetic flux density due to the applied voltage, B_r is the remnant flux density, and B_s is the flux density saturation level. Some important conclusions can be extracted from equation (2). One is the influence of the constructive characteristics of the magnetic circuit in the value of the inrush current. This influence appears in the magnetic path length and cross sectional areas; these dimensions are determined by the core geometry indicated in Fig. 2. The transformer insulation type, e.g. oil or resin (dry), has also influence on the maximum inrush current, e.g. oil insulation does allow smaller A_c vs. A_d ratios, leading to lower maximum inrush currents.

Another conclusion is the influence of the energized coil cross-sectional area given by the size and position of the coil with respect to the core, shown in Fig. 3. The last aspect we will mention is the effect of the material magnetic characteristic given by the remanent and saturation flux density levels, B_r and B_s, and its relationship to the design choice of maximum magnetic flux in permanent operation, B_m.

Having analyzed the maximum value of the inrush current, another important aspect is how it decays with time. In other words, how long will the transformer and connected circuit have to withstand the effects of the increased current.

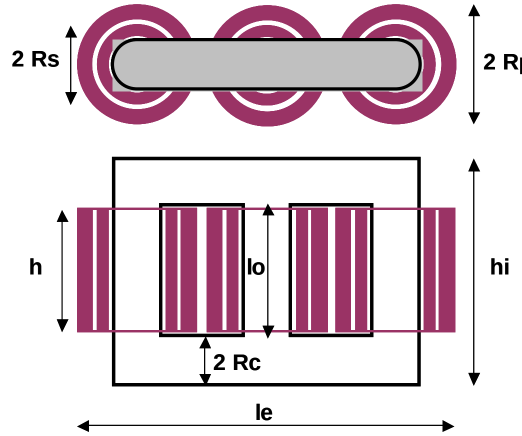

Fig. 2. Schematic of the construction of a three-phase transformer

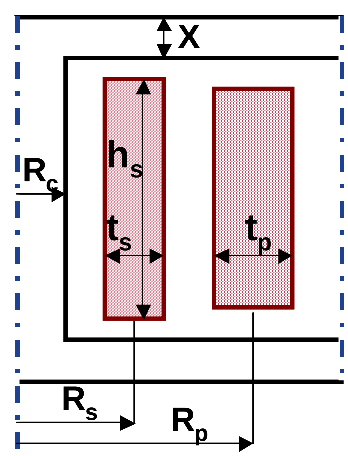

Fig. 3. Detail of the three-phase transformer magnetic circuit and dimensions involved in the peak value of the inrush current

The sympathetic inrush phenomenon has the effect of increasing the inrush current duration with time. In lack of an analytical solution of (1) we will point to the work in [5]-[6]. The magnitude and persistence of the inrush current is given by the core reaching and operating in the magnetic saturation region. Therefore, changes in the magnetic flux will eventually lead the core out of saturation. In [4] it is shown that the changes in the magnetic flux are given by:

$$\Delta\psi_{cycle}=-\frac{R}{\omega\cdot N}\cdot\int_{\alpha 0}^{\alpha 0+2\pi} i(\theta)\cdot d\theta \qquad (3)$$

Where R is the resistance of the input circuit, including the transformer winding, ω is the angular line frequency, and i is the circulating current. Solving the integral in (3) gives the flux change during a line cycle:

$$\Delta\psi_{cycle}=\frac{R\cdot I_{avg}}{N\cdot f} \qquad (4)$$

Where I_{avg} is the average value of the current during one line cycle. Equation (3) shows clearly the effect of the input circuit resistance on the transformer inrush. This fact has lead to the use of pre-insertion resistors as a method to damp inrush currents. The influence of the R value also points to the importance of including the external resistances when analyzing the inrush phenomenon. In this study the ratio of X/R in the transformer connecting circuit used for the study is shown in Fig. 4. It follows the recommendations of [1]; however, for worst-case type analysis the recommended values have been extrapolated in cases of larger power.

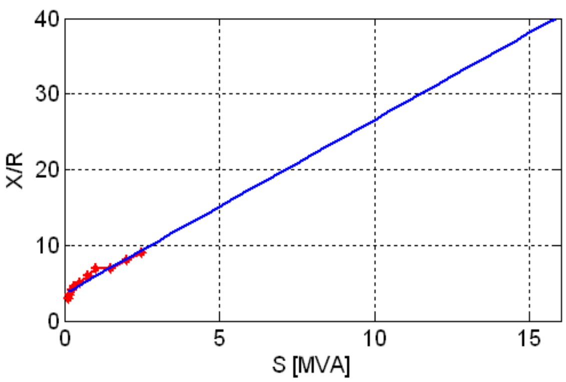

Fig. 4. $X/R(S) = 0.0023 \cdot S + 3.6126$ [1] red: IEEE 242 X/R reference ratios recommended for analysis of distribution systems. blue: X/R ratios used as reference for this work.

B. *Transformer design*

The transformer design process means primarily solving an optimization problem where a cost function must be minimized [7]. This cost function accounts for the materials and manufacturing labor involved in the equipment production and the losses during the lifetime operation. The minimization problem is subject to constraints given by the desired characteristics of the product. Some of those constraints are of the equality type given basically by the desired electrical parameters of the product such as output power, transformer ratio, or stray reactance. Moreover, some other constraints are expressed as an inequality, like the maximum flux density, current density, or total tank height. On the other side, the physical dimensions of the transformer core and windings are the design variables of the problem being considered. The inrush phenomenon then appears as a compromise assumed during the design process. In particular applications where a transformer is frequently connected, the inrush magnitudes acquire special relevance.

III. Sympathetic Inrush Phenomenon

The phenomenon of sympathetic inrush occurs when a transformer is energized and the inrush current produces interactions with other transformers, which are usually in close proximity. The sympathetic phenomenon usually worsen the inrush current behavior, mostly in terms of reducing the damping and producing a long current decay time. This increased duration of the inrush phenomenon can lead to false trip of differential currents as already reported in [8]. It also creates large stresses in the equipment involved; e. g. in the pre-insertion resistors used to mitigate the inrush effect, as it will be shown in this paper.

The sympathetic inrush phenomenon has attracted attention because of its effects in the distribution network power quality [9][10]. Modeling the phenomenon is quite complex as previously explained in II; nevertheless, some numerical approaches have been made lately [2]. For the simulations presented here we have used classical transformer models available in electromagnetic transient simulators package like [13]. The model provides magnetizing characteristic and initial condition. We have also measured the geometry of the core and have evaluated the influencing terms of equation (2).

IV. Model Verification by Simulation & Measurement

A. *Energizing Single Transformers*

Energizing a single transformer without inrush current limitation can result into inrush current amplitudes that are twenty times higher than the 1 MVA nominal power of the supply. Fig. 5 illustrates an example as a result of a simulation, where transformer T1 (

Fig. 1) is switched on at t=0.11s, at its worst case condition in terms of remaining flux vs. voltage phase (see Fig. 6).

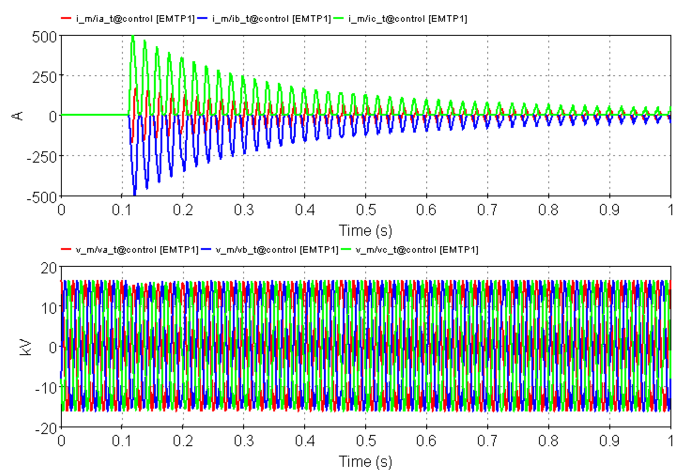

Fig. 5. Simulation result: Worst case inrush current and grid voltage at the point of interconnection (POI) shown in Fig. 1.

A voltage dip of 0.93 pu at the POI can result from an undamped inrush current. The decay of the inrush current is mainly defined by the effective resistance in the power circuit while energizing the transformer. The effect of remaining flux in the transformer core, as well as the effect of the voltage phase while switching on the transformer is indicated in Fig. 6. There will be always a significant inrush current when switching on transformers with no remaining flux, assuming that the switch is closing all three conductors simultaneously (Fig. 6-black curve). The relation between voltage and flux (1) indicates that there will be a maximum flux at the individual zero crossings of the three phases, resulting into six maxima for inrush currents within one period. The resulting inrush current for transformers with remaining flux in the transformer core (remanence) depends on the phase angle difference between the voltage when switching off and the voltage when switching on. A match of these phase-angles results into almost no inrush currents, whereas a phase angle mismatch will result into significantly higher inrush currents (see red curve in Fig. 6), more than twice as much as the resulting inrush current when the remanence of the core is not considered.

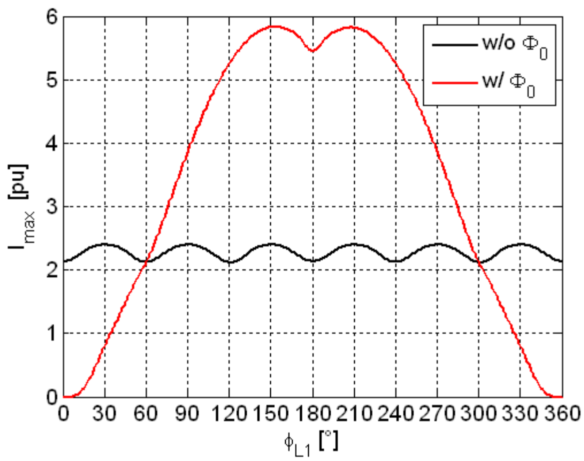

Fig. 6. Maximum inrush current as a function of the phase difference of the voltage when switching the transformer off and on (black curve: Core remanence Φ_0 not considered, red curve: Core remanence Φ_0 considered).

Fig. 6 only serves as a qualitative assessment because the absolute values strongly depend on the transformer design and parameters of the iron core (Section II).

B. *Energizing Two or More Transformers*

A simulation example illustrates the effects of sympathetic inrush currents: Energizing transformer T1 (

Fig. 1) results into a "standard" inrush current, whereas switching on the parallel connected transformer T2 can stimulate the already energized transformer T1 to participate in the inrush current drawn by transformer T2 (Fig. 7).

Driving the already energized transformer T1 into saturation is caused by a grid system voltage asymmetry, which is an effect of the inrush currents drawn by transformer T2. The result is a long lasting inrush current transient, seen by both transformers T1 and T2 and the grid. The decay of the inrush current is mainly defined by the resistance between the transformers vs. the resistance to the grid.

Fig. 7 shows that that the sympathetic inrush current can have an amplitude after one second that is still more than two times higher than the nominal current amplitude of this 20 kV line. This can cause protective trips of protection relays or nuisance interactions with other converter loads connected to the same 20 kV busbar.

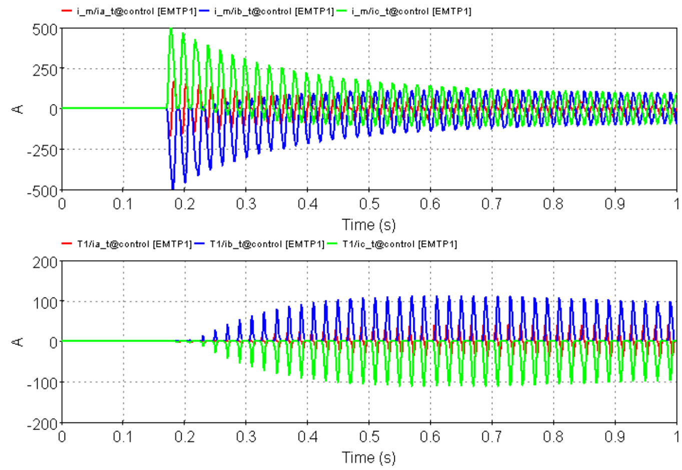

Fig. 7. Inrush current due to magnetizing transformer T2 (subplot 1) and sympathetic current in already energized transformer T1 (subplot 2)

In both transformers the inrush current stays at a high level of about 100 A after the first 500 ms, due to transformer saturation of both transformers. There is only a slow decay of the remaining inrush currents. This has been confirmed by measurements (see next section), where sympathetic inrush currents sustain for several seconds, despite the additional damping provided by inrush current limitation resistor R. This has also been observed during measurements.

V. Countermeasures Against (Sympathetic) Inrush Currents

The need to reduce inrush currents depends on the system configuration and the grid codes to be applied. In case of the HPE converter test facility, the limitation of inrush currents is required to comply with the grid codes (limited short-circuit power of the 20 kV supply) and to enable acceptable settings of protection relays. Several methods dealing with the mitigation of inrush currents can be found in literature [11-12], e.g. line synchronized switching of the single phases.

Fig. 8 gives an overview of the mitigation options that were investigated for the converter test facility.

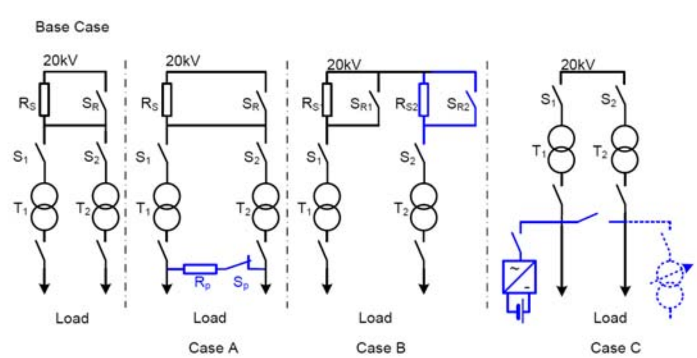

Fig. 8. Transformer energizing, different inrush current mitigation options

The first option (Base Case) and probably the most economic solution for most applications where inrush currents must be limited, is an inrush current limitation resistor, as shown in

Fig. 1. It can also be applied when connecting both transformers, for limiting the first and the sympathetic inrush current. A suitable switching sequence with this approach is illustrated in Fig. 9. What is different from using this approach, in comparison to limiting inrush current amplitudes for single transformers, are the time constants involved with the sympathetic inrush current – see Fig. 10. Transformer T1 is switched on at t=52.2s. The inrush current is very well damped, and disappears within one cycle. Transformer T2 is energized 60ms later, resulting into a comparably low inrush current amplitude, but with a low rate of decay of the currents.

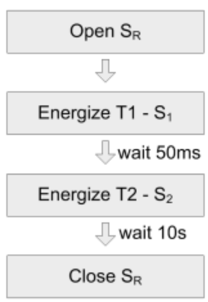

Fig. 9. Limitation of sympathetic inrush currents - energizing sequence for both transformers in Figure 1

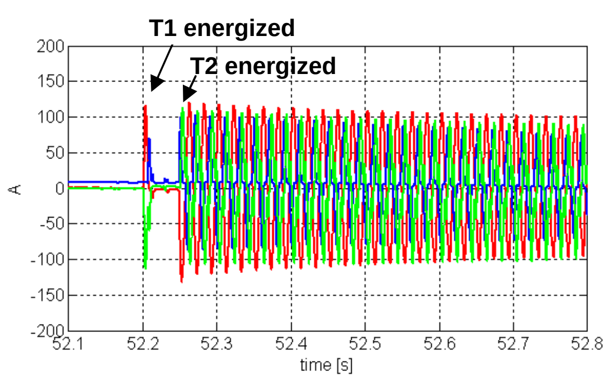

Fig. 10. Inrush currents measured at the POI of Fig. 1: T1 energized at ~52.2s, T2 at 52.26 s, both transformers energized with a 100 Ω resistance in the supply line

The measurement illustrates the main advantage of this approach, the need of only a single resistance stage together with a 20kV switchgear for both transformers to be energized. Drawback is the comparably long duration of the inrush currents due to the low ohmic resistance between the transformers, which significantly affects the required thermal capacitance of resistor R_s.

This case has also been investigated by numerical simulation, assuming worst case conditions for the energizing transformer. The simulation result in Fig. 11 shows that the measurement result in Fig. 10 is close to the worst case assumption. This last one has been used for dimensioning the resistor R_s.

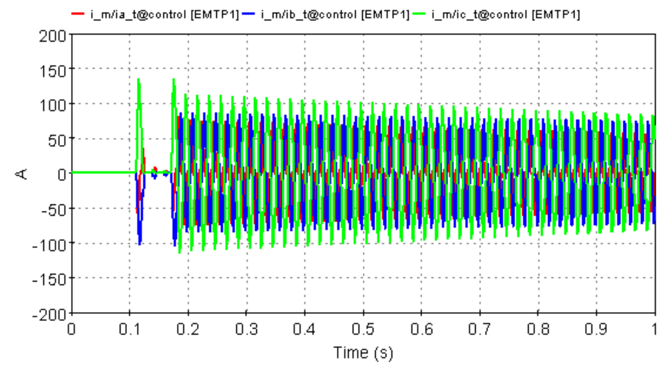

Fig. 11. Simulated inrush currents at the the POI of Fig. 1: T1 energized at ~0.11s, T2 at 0.17s with 100Ω series resistance activated

A straightforward approach for better damping of sympathetic inrush currents is shown in Fig. 8 – Case B with two independent inrush current limitation circuits. It is obvious that this approach would eliminate the sympathetic inrush current effect totally, as it introduces significant resistance between the two transformers. Fig. 12 confirms this assumption; the system behaves now as two independent transformers. Main advantage is the comparably low thermal capacitance of the individual resistors, drawback is the increased effort in switchgear and medium voltage cabinets as compared to Case A.

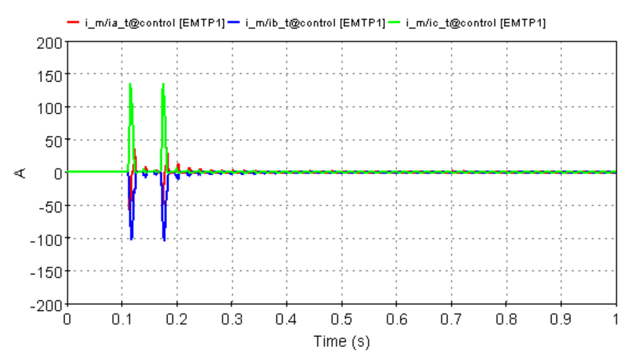

Fig. 12. Inrush current simulation: T1 energized at ~0.11s, T2 at 0.17s with two individual 100Ω series resistances activated

Another way of energizing the parallel transformer with limited inrush current phenomenon is indicated in Fig. 8 -Case A, by means of an additional (low voltage) switch S_p indicated with blue lines. The additional switch is used to energize the core of transformer T2 via T1 on the low voltage side, after Transformer T1 has been energized. Also in this case the inrush currents are not only limited through R_s, but the sympathetic inrush current can be totally avoided. The current flowing on the secondary side can be limited by a resistor R_P with small rating (in terms of thermal capacity and value), resulting into a smooth energization of the T2 transformer core, and afterwards switching in on the primary side without any inrush currents. The value of R_P has influences on the maximum current for energizing T2, lower values (e.g 1Ω) results in higher transient currents, significant larger values (e.g 100Ω) in a not fully established flux while switching in the primary side. This method works only for transformers with equal vector group, which is the case in

Fig. 1. The current capability of the (low voltage) switch is mainly determined by the magnetizing current on the selected voltage level, and will switch basically no current, as it will be opened after the primary side is connected to the power system. A simulation of this case is shown in Fig. 13.

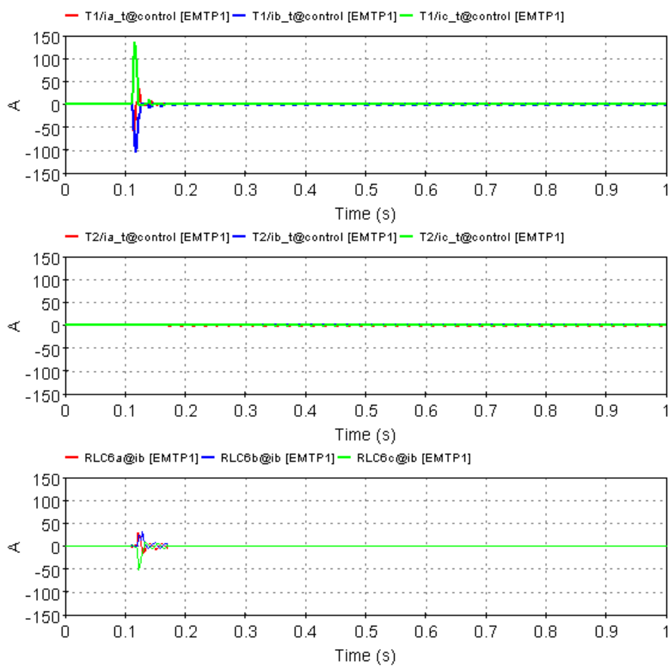

Fig. 13. Case A: S_p closed for t< 0.5s: Current measurements on T1-primary (subplot 1), on T2 primary (subplot 2) and through S_p (subplot 3) - no impact in the currents due to energizing T2. R_p = 20Ω.

The option shown in Fig. 8 – Case C is another possibility of mitigating inrush currents. Here the transformer cores are energized by means of a variable AC-source, e.g. a self-commutated converter or a variable transformer on the secondary side of the transformer before connecting the transformers on the primary side. The voltage amplitude on the secondary side can be controlled in such a way that the currents on the secondary side will be low. The effect of potentially remaining flux in the transformer winding can significantly be reduced by introducing a series resistances to the variable AC-source on the secondary side. The AC-source on the low voltage side of the transformer can have a comparably small rating. It must be synchronized with the three phases of the 20 kV supply.

VI. Conclusion

Sympathetic inrush currents have been investigated by simulation and measurement. Several mitigation methods have been investigated to avoid nuisance interactions with other loads and protective relays during daily switching of medium voltage transformers.

The theoretical background for single inrush and sympathetic inrush currents have been summarized, e.g. factors influencing maximum inrush current and the rate of decay, the influence of the effective switching on angle or the remaining flux.

Inrush current limitation resistors are an efficient method of limiting inrush current amplitudes. In case multiple transformers need to be energized, it is recommended to use several inrush current resistors. Alternatively a single inrush current limiting resistor can be used but it must be designed for long lasting inrush transients. The required thermal capacity of the single resistor may not be suitable for all applications. In case of identical transformers (vector group and voltage level), a single inrush current limitation resistor with low thermal capacitance can be used in conjunction with a simple closing switch on the secondary side of the transformer. This configuration avoids complexity in the medium voltage switchgear and effectively mitigates the inrush and sympathetic inrush current.

VII. Acknowledgment

The authors gratefully acknowledge the support of M. Kraus and C. Müller during commissioning of the medium voltage transformers and switchgear.

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