Modelling of Inrush Currents in Power Transformers by a Detailed Magnetic Equivalent Circuit

A. M. Miri , C. Müller
Universität Karlsruhe, Institut für
Elektroenergiesysteme und Hochspannungstechnik
Kaiserstr. 12, D-76128 Karlsruhe, Germany
miri@ieh.etec.uni-karlsruhe.de

C. Sihler
Max-Planck-Institut für Plasmaphysik (IPP)
EURATOM Association
Boltzmannstr. 2, D-85748 Garching, Germany
sihler@ipp.mpg.de

Abstract - **Static power converters powered by flywheel generators are used to feed the magnet coils of the ASDEX Upgrade tokamak – an experimental device for nuclear fusion research. The largest converters have a nominal power in the range of 100 MVA in pulsed operation (S_N about 20 MVA in continuous duty). About twenty power transformers must be energised on a daily basis to get the pulsed power supply operational for plasma experiments. Nuisance interaction of inrush currents with the protection system of the synchronous machines, other on-line transformers or vacuum-switched static var compensators (SVC) must be avoided in present and future configurations. In order to investigate the effects of inrush transients in various configurations a detailed simulation model for one of the power transformers was derived. The paper describes the model which is based on an equivalent magnetic circuit representation of the transformer, results of simulation and measurement and gives an outlook on future activities.**

Keywords: Transformer inrush currents, equivalent magnetic circuit, saturation, isolated network, transient analysis

I. INTRODUCTION

IPP's <u>a</u>xially <u>s</u>ymmetric <u>d</u>ivertor <u>ex</u>periment (ASDEX Upgrade) belongs to the tokamak family. In this device the ring-shaped hydrogen plasma carries an electric current up to 1.4 MA. The magnetically coupled poloidal field coils of the experimental device, the largest one with a diameter of 7 m, require an electric power up to several hundred MVA for about 15 s [1].

The poloidal field power supply of ASDEX Upgrade consists of the two flywheel generators EZ3 (500 MJ / 144 MVA), EZ4 (650 MJ / 220 MVA) and 11 thyristor converters to feed the magnet coils (Fig. 1). Together with the high-voltage converters of the additional heating systems more than 20 power transformers must be energised on a daily basis to get the pulsed power supply operational for plasma experiments.

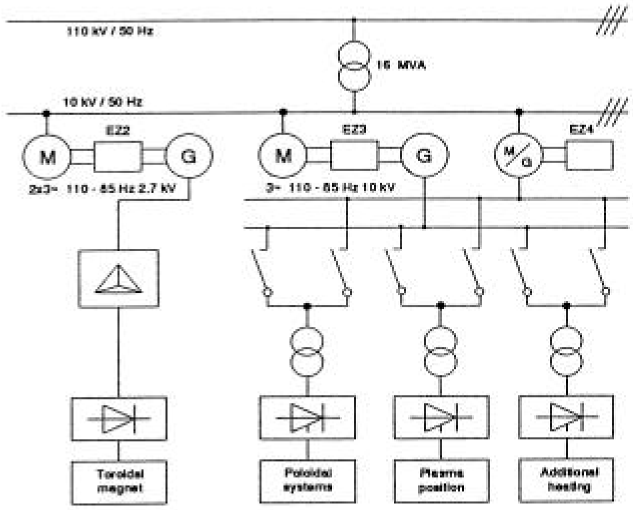


Fig. 1. Simplified representation of IPP power supply

The converter transformers are directly connected to the synchronous machines. The resistance available to damp out the inrush currents is quite small and the inrush transients from connecting the unloaded transformers can be sustained for seconds. The inrush current amplitudes can reach values in the range of 20 kA for large transformers of the experimental power supply. In order to investigate the effects of inrush transients in various configurations a detailed simulation model for one of the power transformers was derived.

II. INRUSH CURRENT MEASUREMENTS

Inrush current measurements were performed at switching-on of the converter transformer shown in Fig. 2.

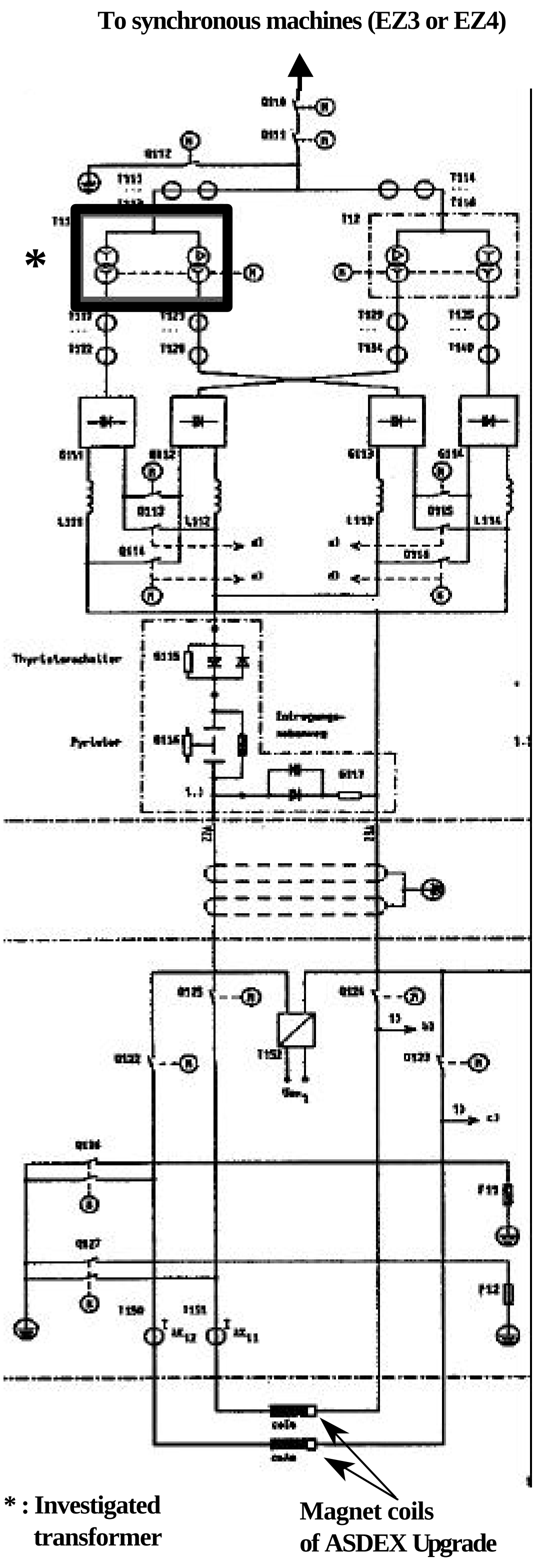


Fig. 2. Electric circuit diagram of investigated converter transformer

Because of lacking data with respect to the frequency dependence of the B-H characteristic of the core material at frequencies between f_1 = 85 Hz and f_2 = 110 Hz ([f_1, f_2]: nominal frequency in the IPP flywheel generator networks), the measurements were performed at frequencies of 90 Hz and 100 Hz. The points of measurement were located at the 10.5 kV busbars of the synchronous machines, i. e. the measured inrush currents shown in Figs. 3 and 4 are the currents at switching-on of two identical star-star/star-delta transformers, each of them designed for 11 MVA in pulsed duty (nominal power in continuous duty about 2 MVA).

A. Results from measurements at 90 Hz

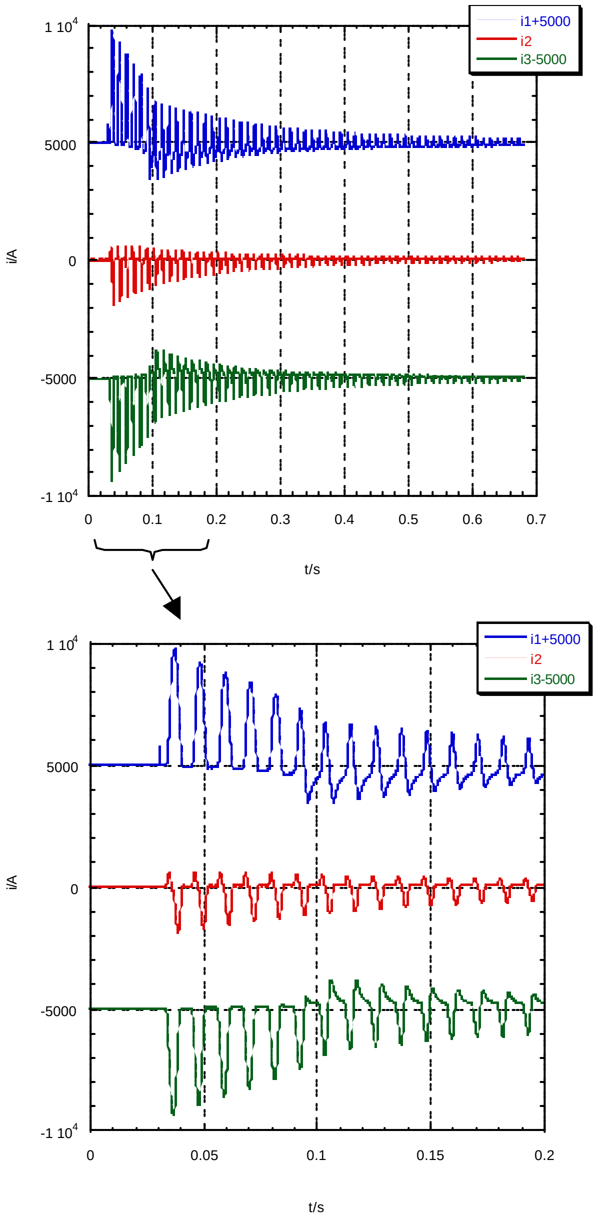
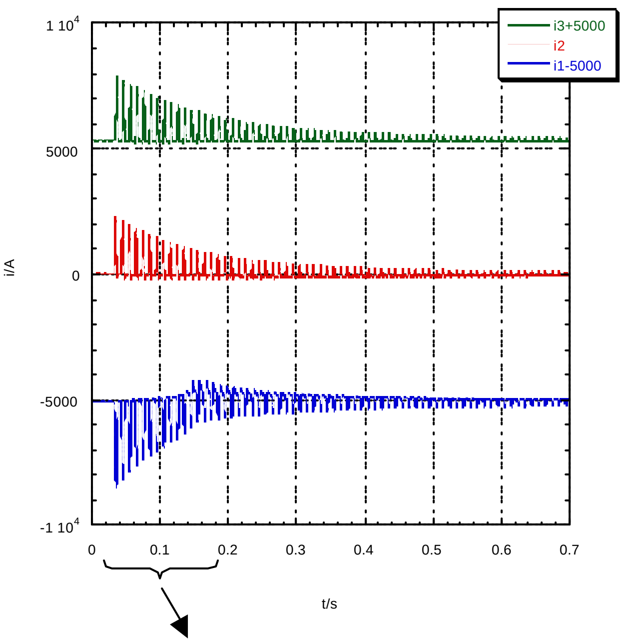


Fig. 3. Switching-on at 90 Hz network frequency (at positive zero-crossing of phase 1)

After the 6th current peak there is a difference to the ideal inrush current time history which can be explained by the generator voltage controller starting to influence the transient response after about 70 ms.

B. Results from measurements at 100 Hz

Whereas the inrush currents reached maximum values up to 5 kA at network frequencies of 90 Hz, they were about 1.5 kA smaller in worst-case switching at a network frequency of 100 Hz (see Fig. 4). Inrush currents reach higher values at lower network-frequencies (non-linear



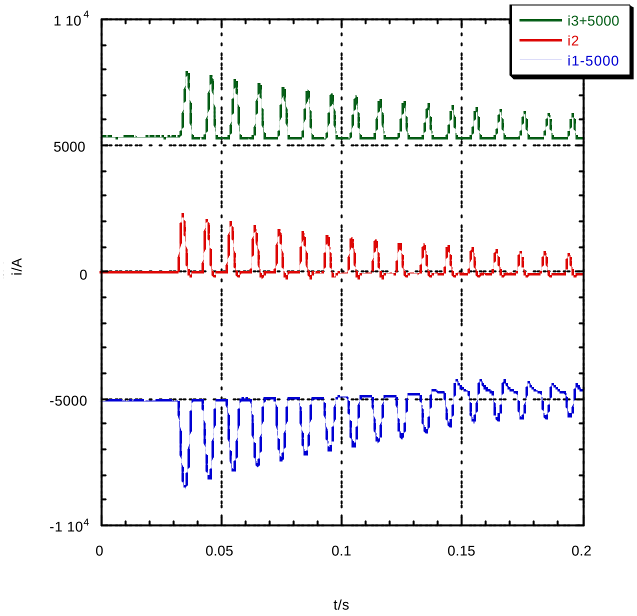


Fig. 4. Switching-on at 100 Hz network frequency (at negative zero-crossing of phase 1)

connection) since at lower frequencies the transformer's iron-core is saturated at lower magnetic field strengths.

The maximum amplitude of 5 kA is more than 20 times higher than the nominal current in continuous duty (i. e. more than four times the nominal current in pulsed duty). In previous measurements performed on a larger converter transformer inrush currents with amplitudes up to 20 kA had been observed in the system.

III. MODELLING OF TRANSFORMER

An equivalent magnetic circuit representation of the transformer shown in Fig. 2 was chosen. That way direct dependencies of the transformer design and the inrush transients can be investigated. The electrical and magnetic transformer circuits were modelled within a single, coupled circuit simulation using the Simplorer code [2].

A major problem was to model the nonlinearity of the iron core since not much information was available on the core material. Finally, the B-H characteristic of the core material was approximated by straight lines as shown in Fig. 5.

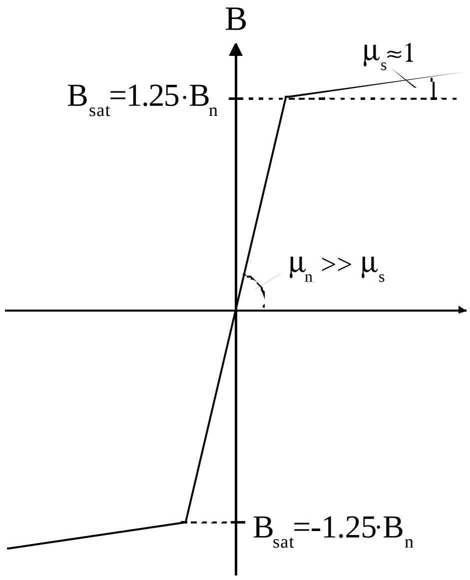


Fig. 5. Approximation of the B-H characteristic of the core material

The reluctances of the equivalent magnetic circuit can be derived by means of the magnetic variables given in equation system (1)

$$f = \int_A B dA$$

$$B = m \cdot H \qquad q = R_m \cdot f = \frac{l}{mA} \cdot f$$

$$q = w \cdot i = \oint_s H ds$$

(1)

$$q = f \cdot R_n \qquad \text{für} \;\; -f_{sat} < f < f_{sat}$$

$$q = f_{sat} \cdot R_n + (f - f_{sat}) \cdot R_s \qquad f > f_{sat}$$

$$q = -f_{sat} \cdot R_n - (f + f_{sat}) \cdot R_s \qquad f < -f_{sat}$$

R_s, R_n: Saturated, non-saturated reluctances of iron core
q: Ampere-turns; f: Flux; w: Turn number

The three-phase transformer shown in Fig. 6 [3]

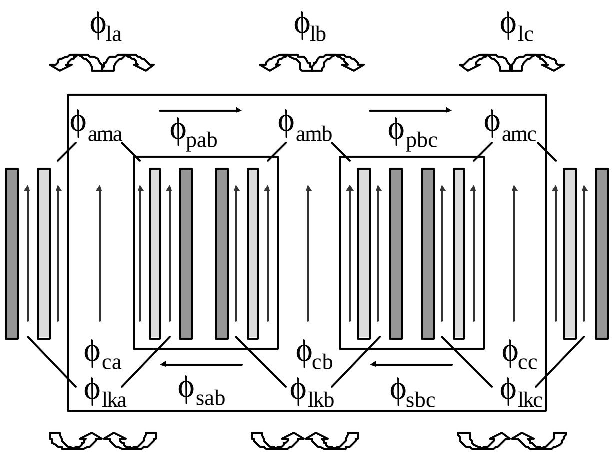


Fig. 6.Cross-section of a three-limb transformer

was modelled using the magnetic equivalent circuit representation which is given in Fig. 7.

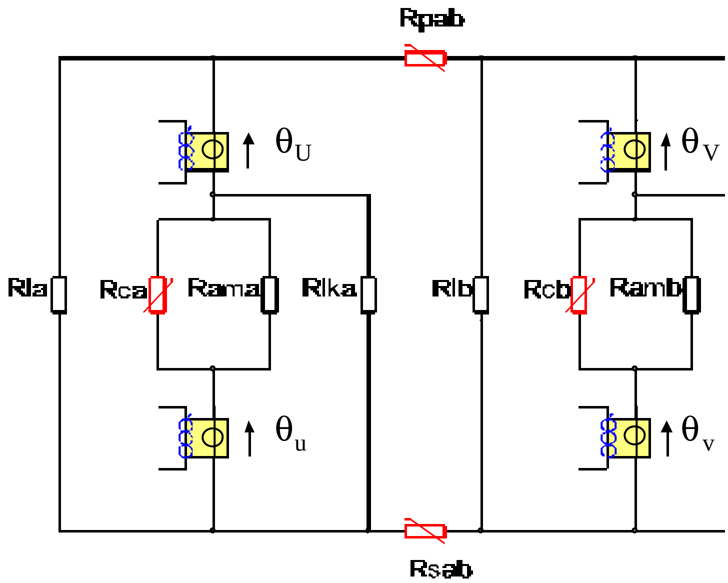


Fig. 7. Magnetic equivalent circuit of the three-lim

The non-linear magnetic resistances R_{pab}, R_{pbc}, R_{sab} and R_{sbc} represent the linking yoke sections of length l_J. The non-linear magnetic resistances R_{ca}, R_{cb} and R_{cc} represent the limb sections of length l_s. In parallel to the limb resistances the linear magnetic resistances R_{ama}, R_{amb} and R_{amc} have been installed which represent the stray fluxes between the low-voltage windings and the transformer core. The linear magnetic resistances R_{lka}, R_{lkb} *and* R_{lkc} represent the flux paths between the low-voltage and the high-voltage windings. The stray fluxes that close in free space are represented by the linear reluctances R_{la}, R_{lb} and R_{lc}. The coupling elements in Fig. 7 are used for the mutual transformation of electrical and magnetic energy.

The equation system completely describing the transformer behaviour depends on the transformer's vector group [4], [5]. In the general case the transformer is described by voltage equation system (2):

$$[u] = [R] \cdot [i] + [w] \cdot \left[\frac{df}{dt}\right] \qquad (2)$$

$[u]$, $[i]$, and $[df/dt]$: Column vectors of the terminal voltages, currents and flux changes in the windings. $[R]$ and $[w]$ are the diagonal matrices representing the winding resistances and the number of turns. The vector of magnetomotive forces generated by the windings can be expressed by equation (3) or (4), in which $[R_m]$ is

$$[q] = [w] \cdot [i] \qquad [3]$$

$$[q] = [R_m] \cdot [f] \qquad [4]$$

the matrix of equivalent magnetic resistances and $[f]$ is the matrix of magnetic fluxes.

The remanence in the transformer core was realised in using magnetic starting resistors R_V in the model, as shown in Fig. 8. By means of a state graph definition in Simplorer sufficiently high initial values were given to the magnetic resistances in the model.

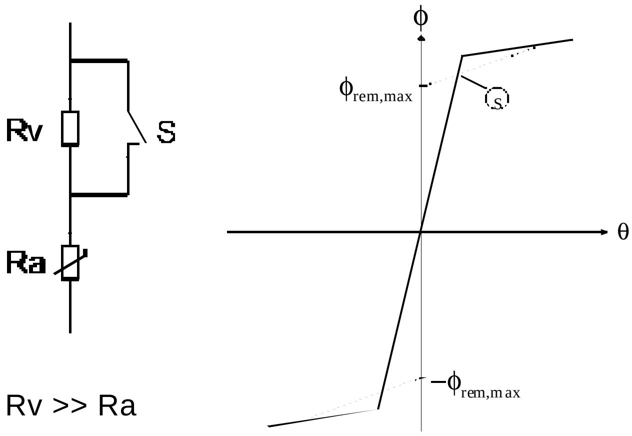


Fig. 8. Modelling of remanence in using magnetic starting resistors

IV. SIMULATION RESULTS

The amplitudes of the inrush currents calculated with the simulation model presented in section III strongly depend on the degree of remanence assumed for the transformer core. Since the remanence of the cores of the transformers shown in Fig. 2 is unknown, a direct comparison of simulated and measured inrush currents cannot be performed. The amplitudes of the simulated inrush currents correspond to the measured ones if remanence values in the order of 60-80 % are assumed. Since problems occurred with the Simplorer code in performing simulations with a transformer model of vector group Dy5, two parallel Yy0 transformers were used in the simulations instead.

For a qualitative verification of the simulation model, inrush currents simulated with the Yy0 model are compared to results from literature, achieved on a star-star connected transformer with a nominal power of 1060 MVA [6]. The smaller amplitudes in the left diagram of Fig. 9 represent inrush currents without, the higher amplitudes inrush currents with remanence. They are compared to simulated inrush currents assuming a remanence of 60 % in the model.

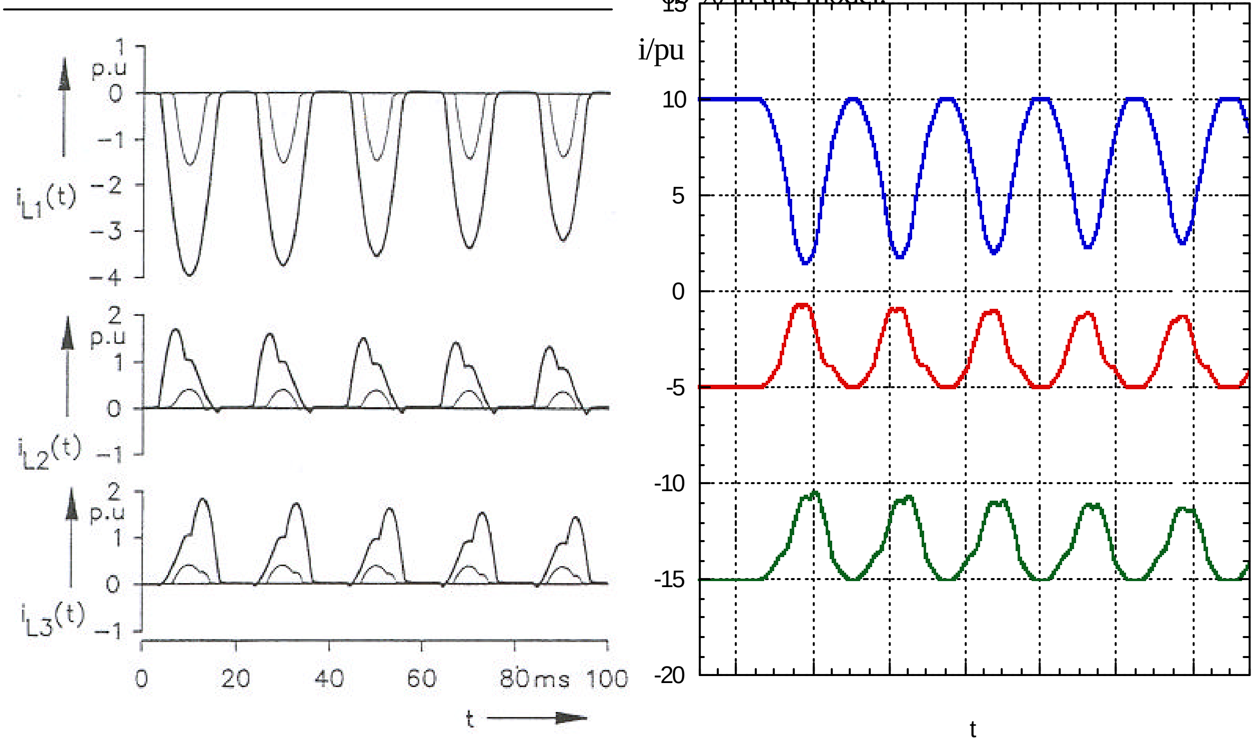


Fig. 9. Comparison of the inrush currents of two transformers of vector group Yy0. Left diagram: 1060 MVA transformer [6], right diagram: simulation model with 60 % remanence

The simulation model is being used to investigate nuisance interactions of inrush currents with the protection system of the synchronous machines, other on-line transformers or vacuum-switched static var compensators (SVC) in the IPP variable frequency network. Especially the potential interference of inrush currents and resonances in the SVC system must be excluded. The lowest natural frequency of the SVC system is in the order of the 2^{nd} harmonic [7]. The first curve in Fig. 10 is a capacitor current in the SVC system that has been excited to resonances before a transformer is connected to the network (lower three curves: corresponding inrush currents).

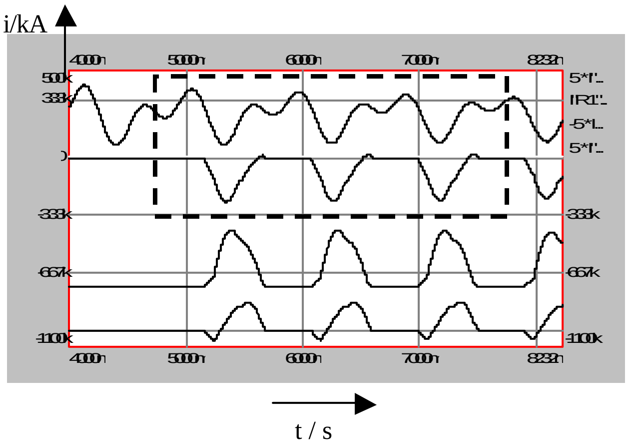


Fig. 10. Simulated mutual interference of SVC system (upper current) and transformer inrush currents* (lower three curves)
(* multiplied by a factor of 5, for illustrative reasons)

Although the first two curves are in phase, inrush currents of smaller and medium-sized transformers (as shown in Fig. 2) do not seem to be able to excite the SVC system to resonances (decreasing amplitude of the first curve). On the other hand, resonances in the SVC system seem to retard the decay of inrush currents (preliminary result to be investigated in more detail).

V. CONCLUSION

Inrush transients of power transformers in a flywheel generator network were investigated by simulation and measurement. A detailed simulation model of one of the power transformers was derived for analysing the effects of inrush currents in future configurations. An equivalent magnetic circuit representation of the transformer was chosen so that direct dependencies of the transformer design and the inrush transients can be investigated. First simulations were performed to exclude nuisance interactions of transformer inrush currents and a 120 MVAr reactive power compensation system (SVC) which is under construction. They indicate that the SVC installation cannot be excited to resonances by the inrush currents of small and medium-sized transformers. Investigations for larger transformers are being prepared.

VI. REFERENCES

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