INVESTIGATION OF TRANSFORMER SYMPATHETIC INRUSH

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Abstract - **This paper deals with sympathetic inrush (or transferred saturation) between two transformers in parallel, a phenomenon which is of major interest for electric utility engineers. The problem studied has been reported several times in Hellenic remote MV/LV substations without having been clarified. This was the incentive for a research project investigating the influence of several parameters affecting the phenomenon; the initial results of this project are presented in this paper.**

Keywords : inrush, three-phase transformer modelling, transferred saturation

1. INTRODUCTION

Inrush current phenomena in single three-phase transformers [1-5] have been reported since a long time ago and they have been thoroughly investigated in order to improve the design of the protection schemes. However, more complicated phenomena, such as sympathetic inrush (or transferred saturation) have not been analysed to a comparative extent [6-7]. In this paper, an effort is made towards this direction.

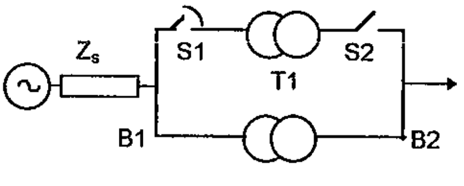

Fig. 1. Transferred saturation typical scheme

Assuming the arrangement of Fig. 1, the antenna-like part of an electric power system at busbar B1 can be fairly weak (the short circuit impedance Zs is of high value). The load is fed by two transformers in parallel, one of which is energised (switch S1 is turned on) while the other is normally operating. The inrush current phenomenon on the energising transformer affects the normally operating one. It is reminded that switch S2 is supposed to close after the decay of the transient.

In particular, due to the inrush of T1 an abrupt voltage drop on Z_s reduces the voltage of busbar B1. This tends to demagnetise transformer T2. However, in the next few periods, when inrush of T1 starts to damp, the voltage at B1 starts to recover, magnetising again transformer T2. Thus, T2 requires an inrush current, too, which is called sympathetic inrush [6-7], and might lead to tripping (the so-called sympathetic tripping) of its differential protection system and disconnection of the load.

The following parameters are expected to play an important role on the phenomenon:

- load value
- system impedance
- magnetising characteristic of both transformers
- instant of energisation
- remanent flux stored in the transformer being energised

The particular influence of these parameters is investigated. A transformer model (GMTRAN) that has already been used successfully for inrush current studies [8-9] has been chosen for this purpose. This model represents properly the combination of hysteresis and saturation effects dominating inrush phenomena. As a study case, a remote substation of the Hellenic system has been considered.

2. TRANSFORMER MODELLING

The dominant element of the study case discussed above is the transformer. Therefore, a three-phase transformer model, which has been proven appropriate for inrush current simulations [8-9], has been implemented. The model, named GMTRAN, standing for GeoMetrical Transformer model, takes inherently into account hysteresis and saturation effect of the iron core material, as [8,9]:

- regarding major and minor hysteresis loops, they are considered using a modified Preisach approach.
- saturation effect is taken into account either automatically by the modified Preisach approach within the major loop limits or as a simple single-valued flux density-magnetisation (B-H) relationship beyond these limits.
- during the simulation, at each time-step the magnetic core circuit is solved so that the fluxes at each core limb are defined. Thus, the operating points (B-H) of each limb are calculated. Then, an inductance matrix [L] representing the mutual winding coupling, is calculated. The iron loss resistances are updated, provided that a new hysteresis loop is introduced. Eddy current effect can be taken into account reducing the damping factors, however the dominant frequencies involved in inrush phenomena are lower than 1 kHz, where eddy currents begin to become important.

The GMTRAN transformer model is implemented in a stand-alone program solving the algebraic-differential equations of the entire electric circuit. However,on-going effort is currently made to incorporate it in ATP/EMTP [9] using the MODELS controlled 94-type multiphase elements.

3. STUDY CASE - INVESTIGATION

The problem is focused on the appropriate recognition of inrush current versus an internal fault. Differential protection scheme settings against tripping during inrush can be grouped as follows [4-5]:

- time-delayed tripping function, as inrush is damped fairly quickly. A simple technique which has been extensively used in the past.
- second harmonic restraint, which is based on the fact that during inrush a characteristic 2nd current harmonic of considerable value is recorded. This is the common practice in most actual applications.
- inrush identification using pattern recognition techniques. This most promising, but fairly expensive, technique has not yet been applied to great extent.

The investigation performed in this work could be exploited by all the three aforementioned techniques, however it has been adapted especially to the second method. Thus, the evolution of the 2nd harmonic in the current of the normally operating transformer, is calculated and presented as a means to evaluate the severity of sympathetic inrush.

As mentioned above, the phenomenon can be observed in *weak system locations*. A remote isolated 150/20 kV substation, comprising two similar transformers, has been chosen for this simulation, as it is considered a typical example to be studied. The corresponding study case data are listed in Table I, whereas the major hysteresis loop and the initial magnetisation curve of the transformer cores are depicted in Fig. 2.

Table I. Study case data

rated (transformer) power: 25 MVA
rated transformer voltage: 150/20 kV (in Dy0 winding connection, with the star earthed via a 12 Ω resistor)
transformer impedance:20 % with 120 kW rated copper losses
system impedance*(positive sequence)*:8.7%+j22.1% at 150 KV busbar
typical load value: 9.8 MW+j 1.8 MVAr

The following parameters have been investigated:

- regarding *load* value influence, simulations under no-load and full-load conditions have been performed.

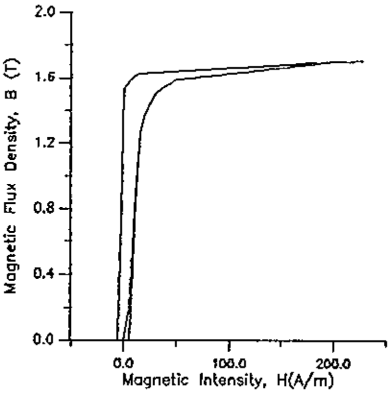

Fig. 2 Magnetisation characteristic of core material of transformers T1 and T2

- concerning *system impedance* influence, a variation between 10% and 100% of its actual value has been considered.
- regarding instant of energisation of the T1 transformer, time values along a fundamental period with a time-step interval of 5 ms have been selected.
- the influence of magnetisation characteristic, which is not a flexible parameter to treat, is investigated in two ways:
  - ◊ the deep-saturation part of the magnetisation curve has a slope of a multiple of μ_0 by 1,10 and 100 times,
  - ◊ furthermore, the remanent flux in T1 is set to values equal to the maximum, half and zero values. It is worth noting that in delta connected transformer windings, remanent linkage fluxes in the three phases are mutually dependent. Thus, during transformer inter-ruption, when the first phase is disconnected then two windings are set in series with the third being in parallel to them, while the system turns into single-phase operation. This means that the two windings in series have half the voltage of the third one, and finally they have half its remanent linkage flux.

4. DISCUSSION of RESULTS

The simulation results of the investigation performed are, mainly presented in the form of the progressive evolution of the characteristic 2nd harmonic of the current of operating transformer T2. This is done for all the three phase currents of T2, as different behaviour is expected by each of them. However, in several situations of particular interest, current waveforms are presented, too.

Thus, in Fig. 3, inrush current of phase "b" of transformer T1 is presented, whereas in Fig. 4 the corresponding *sympathetic* current of transformer T2 is shown. Transformer T2 is not loaded, while the remanence is equal to its maximum value. Finally, the slope of the deep saturation branch of magnetisation curve is equal to $10\mu_0$. Energisation takes place at instant t_o. In most cases t_o=50 ms with the exception of the simulations investigating t_o. The setup described above is the base case around which the sensitivity investigation is performed.

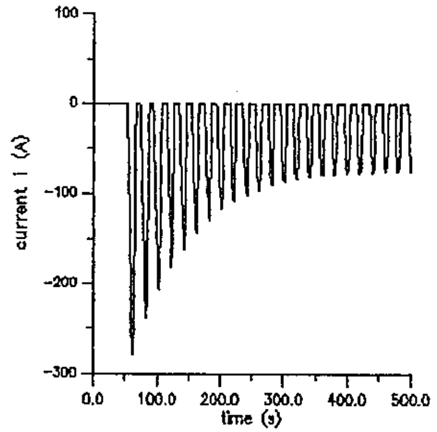

Fig.3 Inrush at transformer T1, being energised

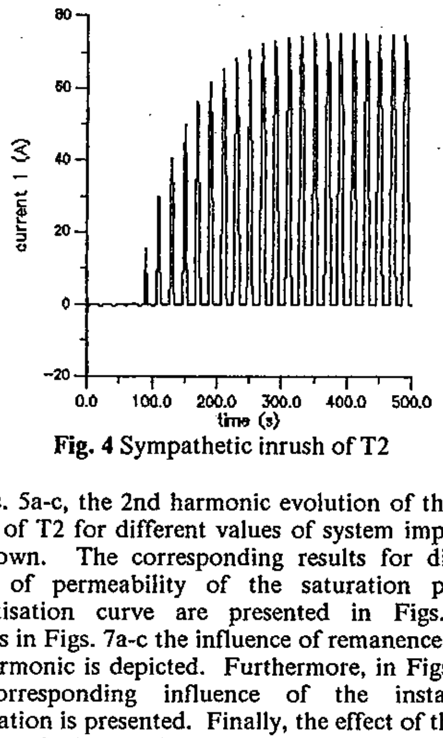

Fig. 4 Sympathetic inrush of T2

In Figs. 5a-c, the 2nd harmonic evolution of the three phases of T2 for different values of system impedance are shown. The corresponding results for different values of permeability of the saturation part of magnetisation curve are presented in Figs. 6a-c, whereas in Figs. 7a-c the influence of remanence on the 2nd harmonic is depicted. Furthermore, in Figs. 8a-c, the corresponding influence of the instant of energisation is presented. Finally, the effect of the load on sympathetic inrush is illustrated in waveforms of Figs. 9a-c. In all cases, the 2nd harmonic is scaled in % values of the corresponding fundamental. The remarks of the aforementioned results can be summarised as follows:

In general the phenomenon takes few periods to develop, depending on the values of the investigation parameters, but it can take more than 400 ms to begin to damp, see Fig. 4. It is interesting to note that no considerable differences are observed among the 2nd harmonic values of the three phases, regarding their order of magnitude as well as their rise time and their decay, see Figs 5-9. Focusing on each particular parameter that has been investigated, it can be seen:

System impedance: its influence is critical. The values play an important role, and the weaker the system, i.e. the higher the impedance, the more evident the phenomenon, [6]. Thus, as shown in Figs. 5a-c, the phenomenon seems to be of minor significance, when system impedance is low. However, it is worth noting that there is no considerable difference between the case of the actual system impedance and that of half of its value, with the exception of the rise-time of the 2nd harmonic. Therefore, in the case of Zs being 10% of the actual value, it can be argued that after a long time interval, the phenomenon would have become apparent, provided there had been no inrush damping mechanism.

Magnetisation: in Figs.6a-c, it is shown how important sympathetic inrush can be. In general, the closer the slope of B-H curve is to μ_0 the bigger the 2nd harmonic, reaching values up to 80% or even 120%. The remark that as permeability increases, sympathetic inrush decreases is confirmed in the case of $100\mu_0$.

Remanent linkage flux: as depicted in Figs. 7a-c, as remanent flux increases, without changes in polarity, sympathetic inrush increases. As already known [1-3], remanence causes a dc - offset to current curves and thus, drives high the magnitude of all the even-ordered harmonics, including the 2nd one. Furthermore, it is noted that the waveforms in each one of Figs. 7a-c, are of similar shape having different peak values, varying from 5% to 25%, and different rise-times. Finally, remanence influence is to be seen in conjunction with the time instant (point-on-wave) when the energisation occurs.

Instant of energisation: in Figs. 8a-c, it is shown that the point-on-wave of energisation in combination with the polarity and the value of the linkage flux can increase or eliminate completely the phenomenon. Thus, the worst case is when the switch closes at an instant when the instantaneous magnetic linkage flux to be installed in the windings is of opposite polarity to the remanent linkage flux. On the contrary, there is an instant, t_0+10ms in Figs. 8a-c, where the 2nd harmonic is of extremely small value. Finally, it is noted that due to the different phase-shift, the influence of energisation instant varies from phase to phase, but not significantly.

Load: as it can be seen in Figs. 9a-c, the phenomenon is less apparent when transformer T2 is loaded. Load existence causes differences to the values and, occasionally, to the rise-times of the 2nd harmonic. Thus, sympathetic saturation is to be more evident under no-load or low-load conditions, e.g. during the first electrification of a substation, or in post-black-out recovery situations.

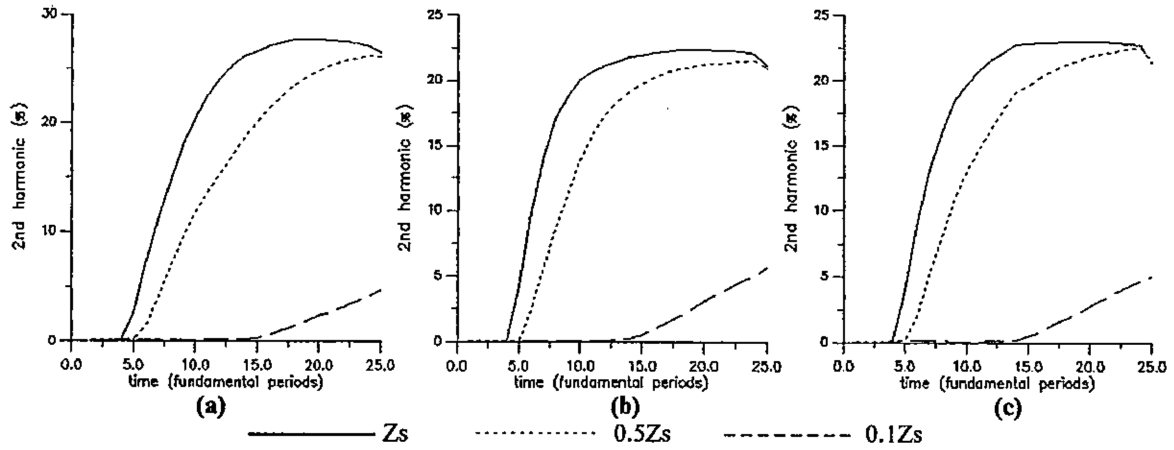

Fig. 5. 2nd harmonic of : (a) phase "a", (b) phase "b" , (c) phase "c" for different values of system impedance (saturation slope $10\mu_0$, maximum remanence, energisation at 50 ms, no-load)

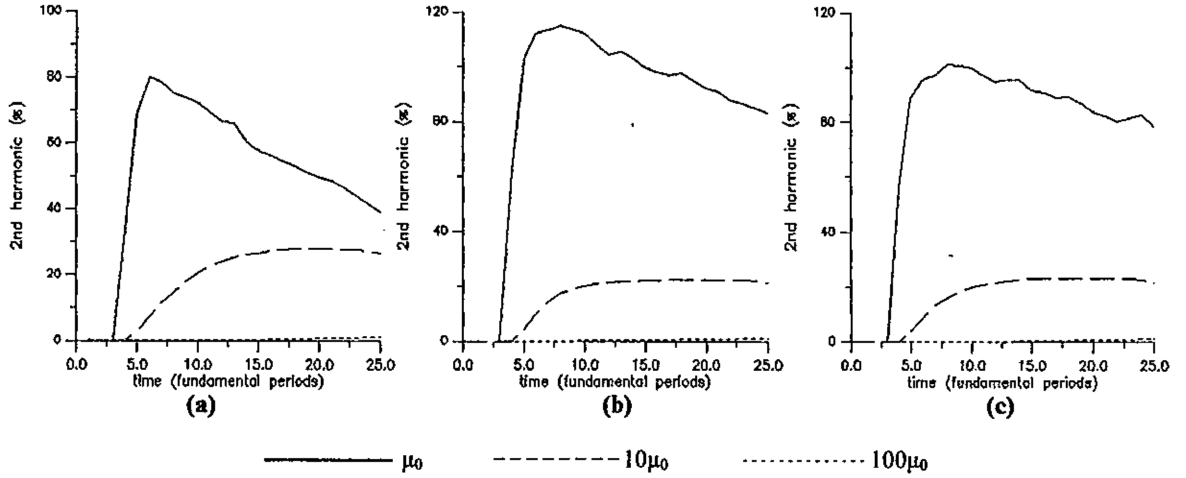

Fig. 6. 2nd harmonic of : (a) phase "a", (b) phase "b" , (c) phase "c" for different values of saturation permeability (actual system impedance, maximum remanence, energisation at 50 ms, no-load)

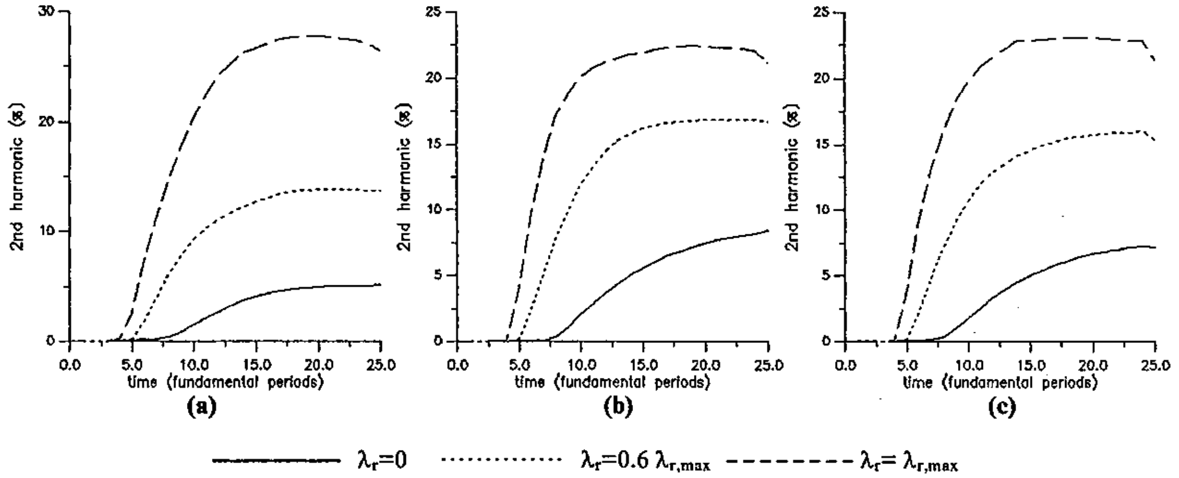

Fig. 7. 2nd harmonic of : (a) phase "a", (b) phase "b" , (c) phase "c" for different values of remanent flux, λ_r (actual system impedance, saturation slope $10\mu_0$, energisation at 50 ms, no-load)

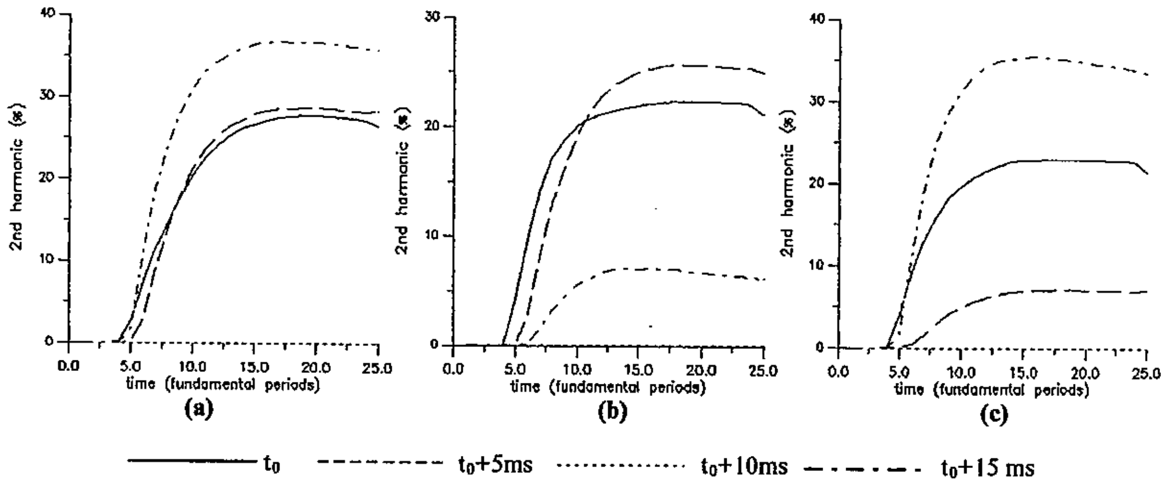

Fig. 8. 2nd harmonic of : (a) phase "a", (b) phase "b" , (c) phase "c" for different energisation instants (actual system impedance, saturation slope $10\mu_0$, maximum remanence, no-load)

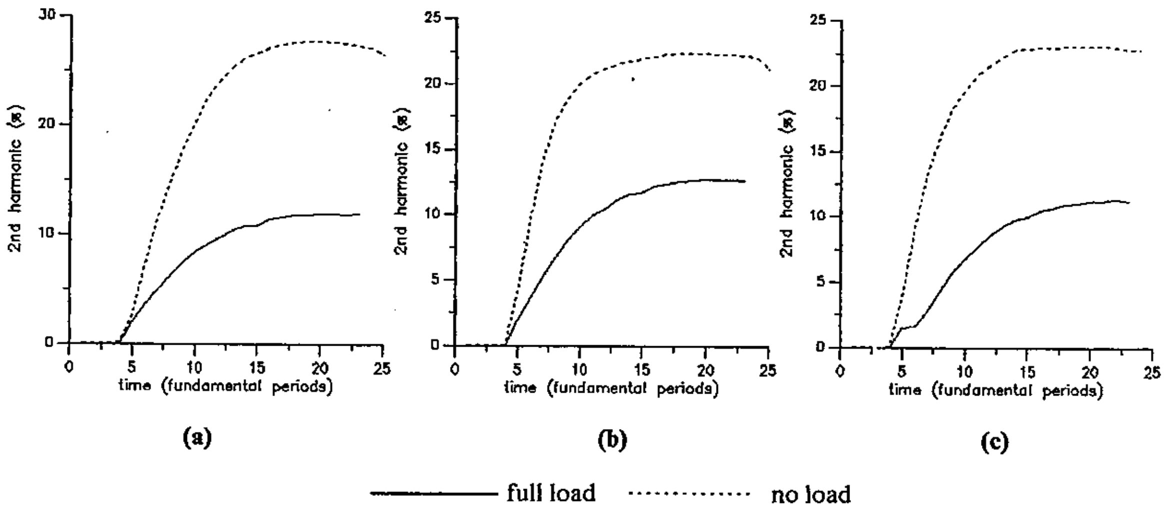

Fig. 9. 2nd harmonic of : (a) phase "a", (b) phase "b" , (c) phase "c" for different load values (actual system impedance, saturation slope $10\mu_0$, maximum remanence, energisation at 50 ms)

5. CONCLUSIONS

In this paper the influence of several parameters affecting the transferred saturation phenomenon between a transformer being energised and one already operating is investigated. It is shown that the phenomenon is more evident in weak system sites, in old core magnetic material transformers, while the combination of the remanent linkage flux and the instant of energisation can be critical. On the other hand, load damp tends to undermine the entire phenomenon. The possibility to distinguish sympathetic inrush from ordinary inrush or internal fault currents by appropriate setting of differential protection schemes, using the 2nd harmonic restraint method is finally investigated.

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