Assessment of controlled switching for no-load transformers, depending on constructive types and winding connections

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Abstract - **Substation switching operations cause transient disturbances and momentary power disruptions, that are sources of power quality problems in power system networks. A variety of technical options are available to prevent these effects; among them, an effective technology for reduction of switching transients is the so-called controlled switching that allows to independently close and open each pole of the circuit breaker at any desired value of the voltage and current waveforms. As a particular application of this technique, the paper addresses the problem of identifying the optimal switching strategy of unloaded transformers in order to limit the inrush current below the transformer rated current. An ATP model including the supply network, the controlled breaker and the transformer is considered allowing to derive the proper switching strategies for different types of transformers and winding connections. The procedures are then verified through both simulation and experimental tests.**

Keywords: controlled switching, no load transformer switching, transformer energisation.

I. INTRODUCTION

Controlled switching is more and more implemented for switching inductive and capacitive loads. This technique consists in independent pole operation of circuit breakers obtained by the action of a controller that identifies optimal opening/closing instants through monitoring of current and voltage waveforms in the network. The operation experience is, in general, good enabling to reduce transient overvoltages, inrush currents and electrical stresses. Consequently, the main advantages deriving from the application of this technology are the improvement of the overall system quality and a life extension of both the circuit breaker and the switched components (reactors, capacitors, transformers). A substantial requirement for the feasibility of synchronous switching is the clear identification of the opening/closing strategy and the accuracy of the circuit breaker controller. Particular attention must be paid by users and manufacturers, when actuating controlled switching, especially for unloaded transformer energisation. The need for controlled switching of transformers is not strictly necessary as transformers can withstand inrush current associated phenomena, apart from cases of frequent operations, as in arc furnace plants, where a higher reliability of the circuit breaker and transformer can be achieved.

Controlled switching is used to limit other related problems such as undue action of protection devices, resonance between the transformer and the connecting cable, voltage sags at the station buses.

Proper studies, related to transformer electromagnetic transients should be carried out to specify the breaker controller operational characteristics. Indeed, the breaker closure strategy strongly depends on the constructive type and winding connections of the transformer to be energised. In this context, the paper points out the critical features that must be addressed to limit the inrush current below the transformer rated load current. The approach regards both the simulation aspect through the ATP modelling of transformers in order to determine the switching instants and the experimental tests to verify the closing strategy. The aim is to assess, on the basis of the residual flux, a procedure for the energisation of unloaded transformers that takes into account all possible winding connections and the particular configuration of the magnetic circuit.

II. BEHAVIOUR OF TRANSFORMERS DURING ENERGISATION

The behaviour of a transformer during no-load energisation depends on its constructive type and on the way the primary and secondary windings are connected.

A three phase transformer can be composed of a bank of three identical single-phase units or more often of a three-phase unit where all the three phases share the same iron structure. Two basic designs are commonly used for three-phase units, the core and the shell type design, respectively. Owing to the different flux patterns inherent in the two designs, these two units respond differently to zero sequence voltages applied.

Consider a transformer with the coils not already connected to build up a Y or Δ winding: the distribution of the core fluxes depends on the constructive type only if, for any reason, the sum of the core fluxes is not zero, i.e. the fluxes are unbalanced [1].

In a three-phase shell-type transformer, the unbalanced flux finds an iron path to close its magnetic circuit, and therefore there is no difference between the operating characteristics of this type of three-phase transformer and a group of three single-phase transformers.

Instead, in a three-phase core-type transformer, unbalanced flux must close its circuit through an air (or oil) path and through the tank, i.e. through an high-reluctance path.

The result is that, in the first case, the zero sequence exciting current is nearly the same as the positive sequence value, whereas, in the second case, it presents a very high value, thus creating a magnetic coupling between the phases. These constructive differences emphasise when the transformer has both the primary and secondary windings Y-connected, with primary neutral solidly grounded.

If the transformer is Y-Y with the primary neutral isolated, the zero sequence currents cannot flow in the primary windings, but the constructive type influences the transformer response to the third harmonics and multiples. This fact reflects on the behaviour during the energisation process.

When there is at least one winding Δ-connected, the behaviour of the transformer is independent from the constructive type, because it's the delta that creates a low impedance circuit for the zero sequence components. In this case, the transformer behaviour during energisation depends only on the way the primary winding is connected, and not on its constructive type.

In the following, the term "coupled" will be used to describe a three-phase core-type transformer, in which the three phases are magnetically coupled, whereas the term "uncoupled" refers to a bank of three single-phase transformers, or to a three-phase shell-type transformer.

III. "CONTROLLED SWITCHING" STRATEGIES

In general, many factors determine the amplitude of the inrush current during transformer energisation. Among them, the two which can be directly influenced have been taken into account to establish the controlled switching strategies: the residual flux and the voltage phase at the closing instant.

The first strategy proposed, the **"zero residual flux"**, doesn't take into account the residual flux in transformer cores, and therefore gives the minimum transients if the residual flux is negligible and limited transients when the residual flux is unknown, due to a previous uncontrolled opening operation. This strategy is usually proposed in papers dealing with synchronous energisation of transformers [2]: the closing target is at maximum line-to-earth voltage, if the neutral of the primary winding is connected to ground, or at maximum phase-to-phase voltage, if the primary winding is isolated or Δ-connected. The closing instants of the remaining phases are chosen such that the core fluxes are generated without transients.

In the **"residual flux"** strategy, the knowledge of the residual flux magnitude is assumed: the procedure is set performing a controlled non simultaneous pole opening of the circuit breaker. The first pole being interrupted is phase S at current zero crossing, coming from negative to positive sign. The closing strategy is found evaluating the residual fluxes during an opening simulation (see section V) and then finding, for each phase, the closing instant for which the flux, calculated as the voltage integral, reaches its steady state waveform.

If the primary phase voltages of the transformer are:

$$v_i(t) = V_M \cos(\omega t + \alpha_i) \quad i = R,S,T \tag{1}$$

then the phase fluxes can be calculated as:

$$\varphi_i(t) = \Phi_{i\,res} + \int_{t_{close\,i}}^{t} v_i(t)dt = \tag{2}$$

$$= \Phi_{i\,res} + \frac{V_M}{\omega}\left[\sin(\omega t + \alpha_i) - \sin(\omega t_{close\,i} + \alpha_i)\right] \quad i = R,S,T$$

and therefore the conditions to be imposed are:

$$\Phi_{i\,res} = \frac{V_M}{\omega}\sin(\omega t_{close\,i} + \alpha_i) \quad i = R,S,T \tag{3}$$

For each of the equations above there are two solutions, i.e. two instants $t_{close\,i}$, that in general can be different for the three phases: the choice of one of these two values for each phase depends on considerations about the constructive type of the transformer.

To set general strategies, the closing instants cannot be expressed in seconds, because this assumes the choice of a time reference (i.e. a phase angle α_i), that will not be known in practical cases. For this reason, each closing instant is expressed in terms of the values of the three phase voltages at that instant.

We call this procedure the **"100% residual flux"** strategy.

In the cases Y-Y coupled and Y-Δ (or Δ-Y and Δ-Δ), the constraint $\sum_{i=R,S,T}\Phi_{i\,res} = 0$ enables to find a closing instant common for the three phases, whereas this condition is not achievable in a Y-Y uncoupled transformer. Obviously, to be practically implemented, the "100% residual flux" strategy requires the knowledge of the residual fluxes.

To overcome difficulties in achieving these data, the **"50% residual flux"** strategy has been proposed. Starting from the same opening operation, this procedure considers 50% values of the residual fluxes and could be implemented to take into account uncertainties and contingent reductions that can be due to stray capacitances.

This strategy has been found considering a transformer with the secondary winding Δ-connected and therefore it depends only on the way the primary winding is connected and not on the transformer constructive type.

IV. SYSTEM ATP MODELLING

The procedures previously outlined have been proven through both simulation using ATP and experimental tests.

As regard simulations, test system consists of a supply network, represented by its Thevenin equivalent, a circuit breaker, in which each pole can be operated independently from the others, and a distribution transformer, that has been modelled using the ATP supporting routine BCTRAN. This routine provides as output a linear matrix representation of a single or three-phase transformer, linking the time-dependent voltages and currents at its terminals. Three-phase transformers, both of the shell-type and of the core-type, can be handled. The model is derived by assigning the results of open-circuit and short-circuit tests, performed with positive and zero sequence voltages applied [3].

For the transient analysis of inrush currents, of ferroresonance and of similar phenomena it is necessary to include in the model the effects of saturation. Non linear behaviour can't be included in the matrix representation of BCTRAN and therefore the model requires extra non linear inductance branches, properly connected at the transformer terminals, to represent the shunt excitation branch.

Only the linear resistance R_m, representative of the no-load losses, is included in the BCTRAN matrix, specifying the active component of the exciting current.

For the core design, only, the homopolar data differ from those of the positive sequence. In this case, as already explained, the zero sequence flux returns outside the windings through the air and the tank and therefore the zero sequence exciting current presents a very high value: a reasonable value might be 100% of the rated current, if it is not available from test. As a consequence, the zero sequence magnetizing inductance L_0 can be considered linear (because of the air gap) and characterised by a very low value.

If the transformer has Δ-connected windings, independently from the constructive type, the value of the zero sequence exciting current is not critical: any reasonable value can be used since the Δ provides a low impedance circuit for zero sequence currents.

In Figs. 1 and 2, the equivalent circuits for the positive and the zero sequence for the Y-Y and Y-Δ transformers with neutral solidly grounded are reported, depending on constructive types.

For each case, the part inside the dotted box highlights the circuital representation of the matrix of the transformer calculated by the routine BCTRAN: R_1 and R_2 are the winding resistances, whereas L_1 and L_2 are the leakage inductances of the primary and secondary windings, respectively, calculated from the short-circuit test data.

As commonly assumed, the zero sequence short-circuit data and the zero sequence excitation losses have been considered equal to the correspondent values in the positive sequence tests.

The equivalent circuits for the Δ-Y and Δ-Δ transformers can be easily obtained modifying those of Figs. 1 and 2. The cases with neutral isolated are obtained substituting, in the zero sequence circuits, the connections to ground of the neutrals by open-circuits.

The non-linear magnetising branch has been added to the high voltage winding of the transformer: only in this way the behaviour of the transformer is correctly represented for all types of winding connections.

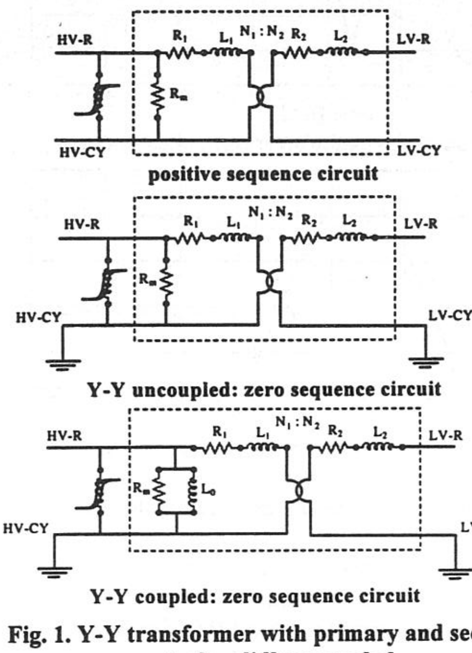

Fig. 1. Y-Y transformer with primary and secondary neutrals solidly grounded

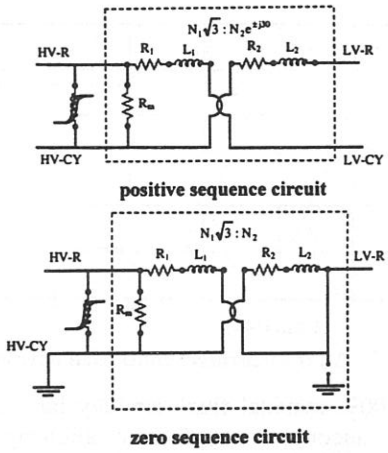

Fig. 2. Y-Δ transformer with neutral solidly grounded

V. SIMULATIONS RESULTS

Simulations have been performed to evaluate the opening and closing strategies for a distribution transformer: all different constructive types and winding connections have been considered in the ATP model. The simulations reported in this section refer to transformers with the primary Y-connected: the results relevant to the case with primary Δ-connected are similar to those of a coupled transformer with primary winding Y isolated. The "50% residual flux" strategies have not been simulated, since they assume relevance only in practical applications.

As transformer energisation tests showed that the mean circuit breaker time deviation from the closing target is limited to 0.2 ms and that this delay has not strong influence on the energisation transient, in the simulations an ideal circuit breaker has been considered.

Results are all in p.u. of the rated values.

A. Y- connected primary with neutral solidly grounded

As already outlined, after the opening the different types of transformer act quite different, causing the assessment of two "100% residual flux" strategies.

In the Y-Y uncoupled transformer there is no coupling between the phases: when only one phase is opened, the residual flux in this phase is not influenced by the others (Fig. 3).

In the Y-Y coupled and in the Y-Δ transformer, the magnetic circuits are a coupled system and, when only one phase is opened, the flux in that phase continues to vary to maintain the sum of the three fluxes equal to zero (Fig. 4).

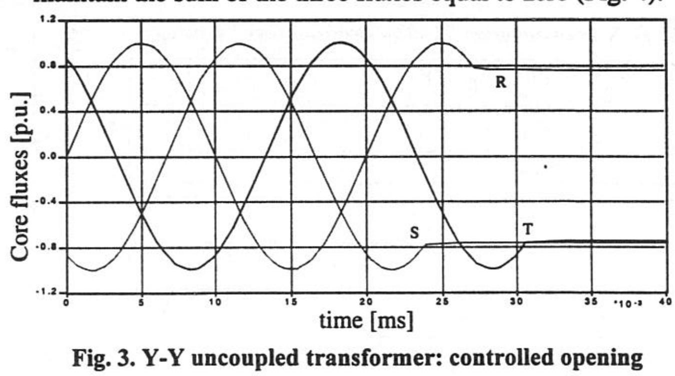

Fig. 3. Y-Y uncoupled transformer: controlled opening

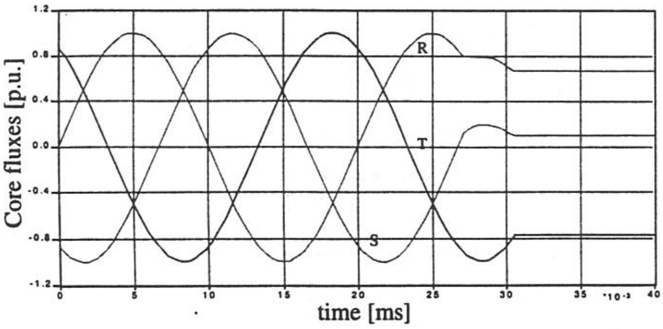

Fig. 4. Y-Y coupled (Y- Δ) transformer: controlled opening

In Fig. 5 the "100% residual flux" strategy has been applied to the Y-Y uncoupled transformer, allowing to obtain an inrush current peak equal to about 0.1 times the rated rms current value.

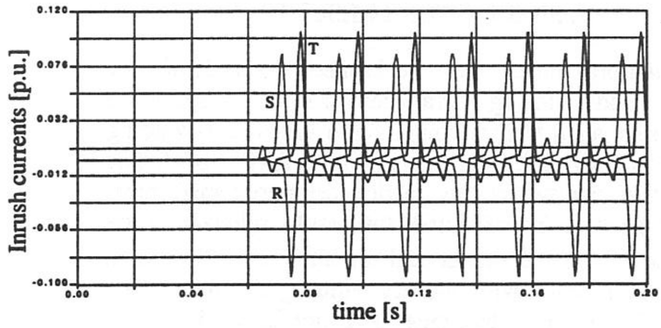

Fig. 5. Y-Y uncoupled transformer: "100% residual flux" strategy

In Figs. 6, 7 and 8 the "100%", the "zero residual flux" strategy, as well as an uncontrolled closing, have been applied to the Y- Δ transformer. The uncontrolled operation refers to a sample contemporary closing of the CB poles.

In the next section, these results will be compared with those obtained from experimental tests on a laboratory transformer with the same winding connections.

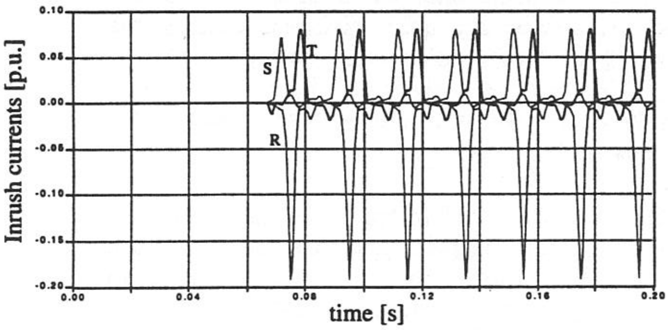

Fig. 6. Y- Δ transformer: "100% residual flux" strategy

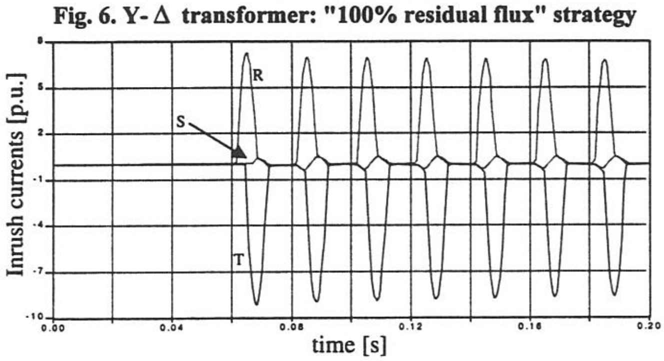

Fig. 7. Y- Δ transformer: "zero residual flux" strategy

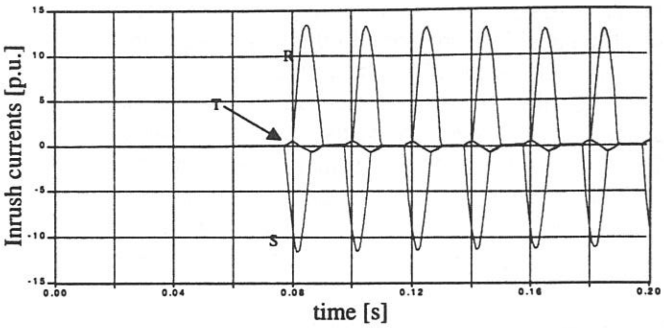

Fig. 8. Y- Δ transformer: uncontrolled closing

The "100% residual flux" strategy allows to obtain an inrush current peak about 0.2 p.u., against about 9 p.u. obtained with the "zero residual flux" strategy, and about 12 p.u. with an uncontrolled closing.

B. Y- connected primary with isolated neutral

In this case, independently from the type of transformer, when the first phase is opened, the other two phases don't interact with it.

Nevertheless, also in this case two different "100% residual flux" strategies have been found, one for the Y-Y uncoupled and one for the Y-Y coupled, Y- Δ transformer, because the core flux waveforms and consequently the residual fluxes are different (Figs. 9, 10) [4].

In the Y-Y uncoupled the core fluxes contain a large amount of third-harmonic components (Fig. 9), whereas in the Y-Y coupled and Y- Δ the core fluxes are nearly sinusoidal (Fig.10).

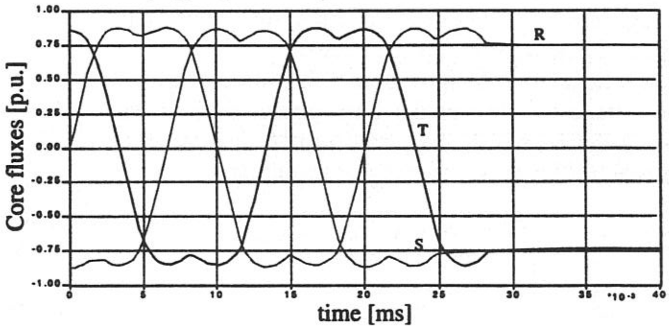

Fig. 9. Y-Y uncoupled transformer: controlled opening

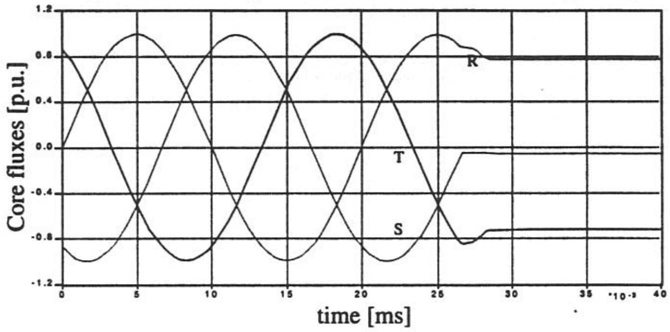

Fig. 10. Y-Y coupled (Y- Δ) transformer: controlled opening

In Fig. 11 the "100% residual flux" strategy has been applied to the Y-Y uncoupled transformer, obtaining a reduction of the inrush current to about 0.015 p.u., i.e. to a value very close to that of the magnetising current.

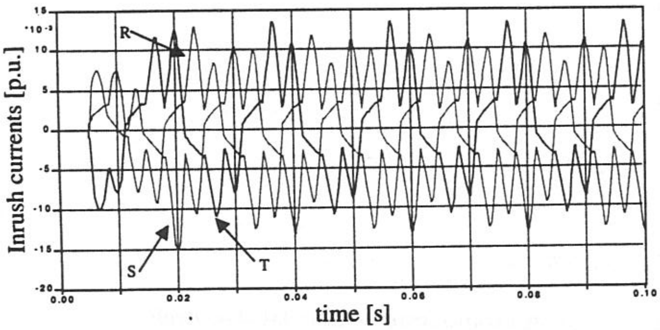

Fig. 11. Y-Y uncoupled transformer: "100% residual flux" strategy

In Figs. 12, 13 and 14 the results obtained performing respectively the "100% residual flux", the "zero residual flux" strategy and an uncontrolled closing are reported for the case Y-Y coupled, that will be analysed in the next section through experimental results.

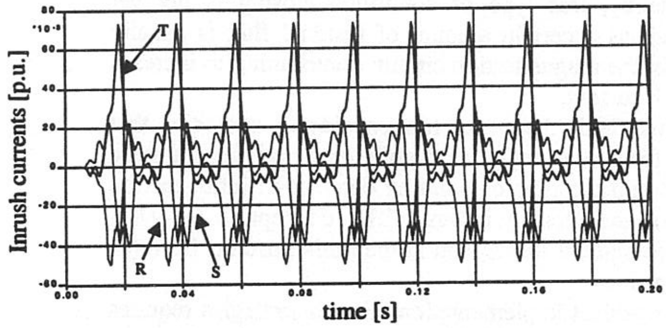

Fig. 12. Y-Y coupled transformer: "100% residual flux" strategy

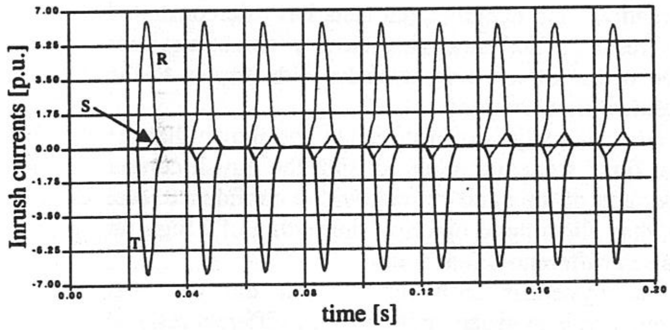

Fig. 13. Y-Y coupled transformer: "zero residual flux" strategy

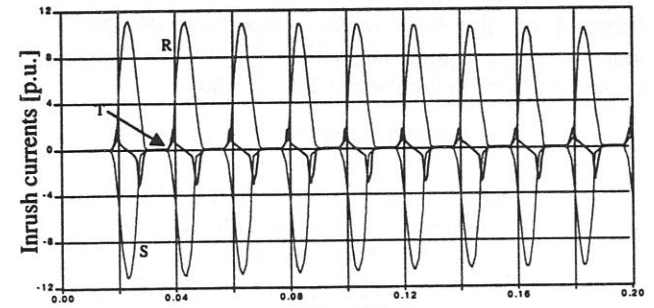

Fig. 14. Y-Y coupled transformer: uncontrolled closing

The maximum current peak with the uncontrolled closing is about 11 p.u.: the "zero residual flux" strategy allows to reduce this value to about 6 p.u., whereas with the "100% residual flux" strategy this value is reduced to 0.07 p.u.

VI. EXPERIMENTAL RESULTS

Experimental tests were performed on two different transformers. The first one is a laboratory transformer, with a Δ-connected secondary winding and whose primary winding can be Δ or Y-connected with grounded or isolated neutral. The second one is a distribution Y-Y coupled transformer with isolated neutral.

Being the residual fluxes not known, the two "residual flux" strategies outlined in section III, "100%" and "50%", should be tested to obtain the best results.

In the first case, all the strategies have been performed for all the primary winding connections.

In Figs. 15 to 18, the results of all the strategies and of an uncontrolled closing operation for the case Y-Δ with primary neutral solidly grounded are reported.

The "50% residual flux" strategy allows to obtain the best results, i.e. an inrush current peak about 0.2 p.u., against about 3 p.u. of the "zero residual flux" strategy and 9 p.u. of an uncontrolled closing operation. The "100% residual flux" strategy gives inrush current peaks higher than the "50%" one, meaning that in this case the residual fluxes are low. A comparison of the results of Fig. 16 with those of Fig. 6 shows that the experimental transient approaches the best results achievable by simulations.

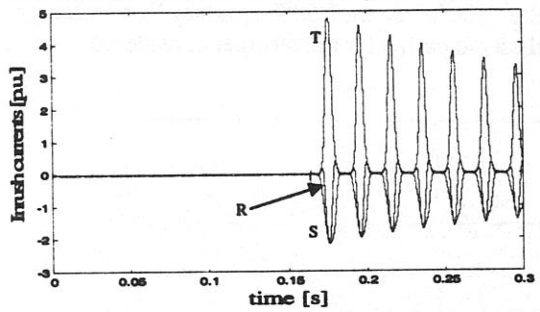

Fig. 15. Y-Δ transformer with neutral solidly grounded: "100% residual flux" strategy

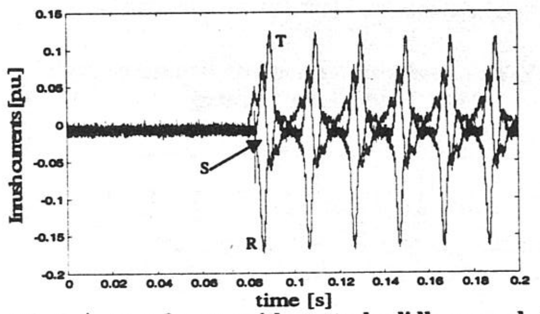

Fig. 16. Y-Δ transformer with neutral solidly grounded: "50% residual flux" strategy

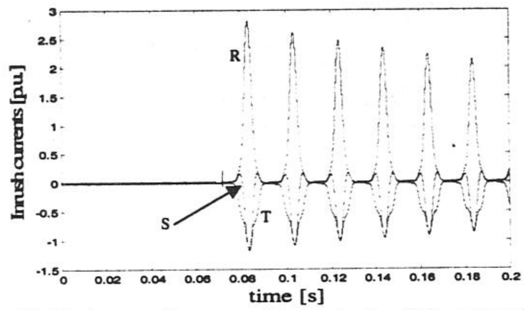

Fig. 17. Y-Δ transformer with neutral solidly grounded: "zero residual flux" strategy

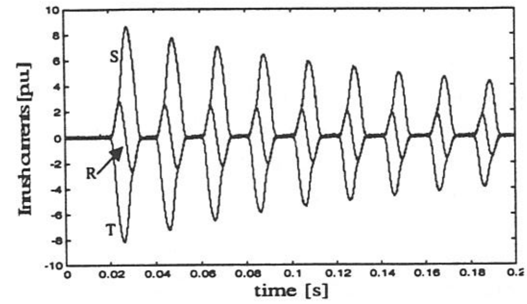

Fig. 18. Y- Δ transformer with neutral solidly grounded: uncontrolled closing

For the transformer Y-Y coupled with isolated neutral, the "50% residual flux" and the "zero residual flux" strategy have been performed (Figs. 19, 20).

The "50% residual flux" strategy is slightly better than the "zero residual flux" (0.3 p.u. against about 0.5 p.u.), but the results are close, meaning that in this case the residual fluxes are quite low.

With an uncontrolled closing operation (Fig. 21) the inrush current peaks are about 8 p.u.

As in the previous case, a comparison between simulations and experimental tests can be done: in both cases the "residual flux" strategy gives the best results; the choice of the "100%" or the" 50% residual flux" strategy will depend on the particular transformer considered.

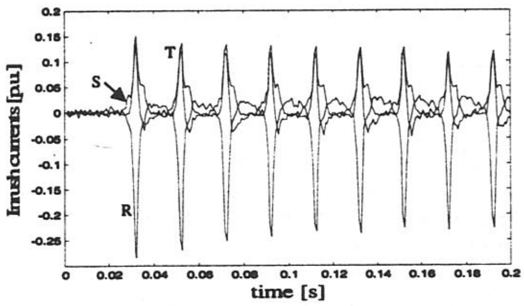

Fig. 19. Y-Y coupled transformer with isolated neutral: "50% residual flux" strategy

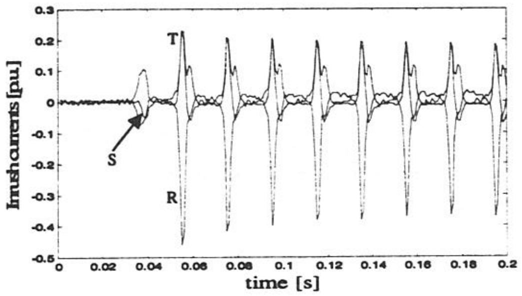

Fig. 20. Y-Y coupled transformer with isolated neutral: "zero residual flux" strategy

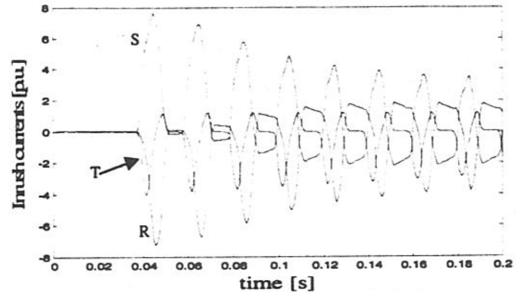

Fig. 21. Y-Y coupled transformer with isolated neutral: uncontrolled closing

VII. CONCLUSIONS

Controlled switching is increasingly used to operate transformers. As regard energisation, up to now the applied closing strategies are prevailingly based on the hypothesis that there is no residual flux in each transformer phase. Consequently, this type of controlled closing is not yet optimised, as a certain amount of residual flux is usually present in the magnetisation circuit, contributing to increase the inrush current.

In this field, the paper has considered strategies that account for the residual flux, highlighting how the magnetic structure and the type of winding connection influence the choice of the closing instants. The concept is to select closing so that the fluxes start at the initial instants from the residual values.

The practical implementation of such strategies requires the knowledge of the hysteresis loop and a proper control on the opening instants.

Simulations and experimental tests have demonstrated that the "residual flux" strategies allow to obtain a greater reduction of the inrush current peaks with respect to the "zero residual flux" strategy.

A statistical analysis of test results has shown that the "residual flux" strategies allow to limit the inrush current to 0.5 per unit of the rated current, with a confidence level of 98%, thus allowing to optimize the setting of a high-set unrestrained differential function.

As the hysteresis loop depends on the particular transformer and is in general not known, a different residual flux strategy, named "50%", has been considered to account for uncertainties in determining residual fluxes.

Experimental on site tests at the installation of the synchronous switching equipment will enable to tune the controller characteristics to the specific transformer.

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