Reducing the magnetizing inrush current by means of controlled energization and de-energization of large power transformers

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***Abstract* – Energization of unloaded transformers results in magnetizing inrush current (IR) very often with high amplitude. These currents have many unfavorable effects, including operation failure of transformer differential protection, deterioration of the insulation and mechanical support structure of windings and reduced power quality of the system. Without controlled switching the energization may occur at any time on the voltage wave producing high inrush current peak when the transformer core is driven into saturation. The control strategy presented in this paper has been elaborated to eliminate the inrush currents of 132/15 kV, 155 MVA Y_n/Δ generator step-up transformers switched very often in two quick start gas-turbine power station. Existing control methods proposed by former papers could not be applied here, because the transformer breakers are mechanically staggered common drive types (3-pole operated breaker with single spring drive and fixed time delay between the operating poles). The paper proposes a new control method to minimize the residual flux by controlled transformer de-energization combined with the traditional point-on-wave controlled energization. The new concept has been tested by several field tests and the elaborated new point-on-wave controller has been put into service in two new substations in Hungary.**

Keywords – Controlled switching, inrush current, residual flux, simulation, transformer model, ATP-EMTP.

I. INTRODUCTION

Uncontrolled energization of large power transformers may result in large dynamic flux and saturation in one or more cores of the transformer. The saturation results in high amplitude magnetizing inrush current that are rich in harmonics and have a high direct current component.

The amplitude of the magnetizing current depends mainly on two factors: the residual flux in the magnetic core and the transient flux produced by the integral of the sinusoidal supply voltage. When energizing a transformer at zero crossing of the sinusoidal voltage the prospective magnetizing current and the flux have their maximal values, and delay by 90 electrical degrees. To satisfy the principle of the flux steadiness, it is necessary to build an equalizing flux with the same magnitude, but opposite polarity to the prospective flux. This way the transient flux starts from the residual flux and reaches its highest amplitude a half period later. At that point the flux saturates the core and a high amplitude inrush current appears because the inductance of the magnetic core is very small in that region. A typical core saturation characteristic is illustrated in Fig. 1.

Fig. 1 correctly describes the flux-current relationship of a single phase transformer, but not easily applicable for three-phase, two- or three winding Y/y, Y/Δ or Δ/Δ coupled transformers of different core and winding structure, or for bulk transformer banks consisting of single phase units.

This paper gives a brief survey of existing controlled switching methods to energize of large power transformers. Unfortunately none of them were applicable to eliminate the inrush current of the 155 MVA, 132/15 kV generator step-up transformers operating in two gas fired, secondary reserve power stations because of the mechanically staggered circuit breakers. But as is shown in the paper, the residual flux can be influenced by means of controlled de-energization of the transformers and the inrush transient can be completely eliminated this way (i.e. by controlling both the opening and the closing breaker operations). Considering the practical aspects of controlled switching, such as the mechanical scatter of the drive mechanism, pre-strike between the moving contacts and current chopping characteristics of the breaker, this theoretical optimum can not be achieved. Although the inrush current amplitude can be easily kept below or in the range of the transformer nominal current making the stresses caused by the energization less or equal to that of the normal, steady-state operation.

II. UNFAVORABLE CONSEQUENCES OF THE MAGNETIZING INRUSH CURRENT

The magnitude of the magnetizing inrush current is in the range of the short circuit current and may occur severe dynamical stress in the transformer windings [1]. The inrush current amplitude usually does not exceed the fault current withstand capability of the transformer, however the duration of these stresses are significantly longer and occurrence is more frequent than that of the short circuit which is cleared by the relay protection within some tens of ms. Fig. 2 shows a long duration magnetizing inrush current of the generator step-up transformer.

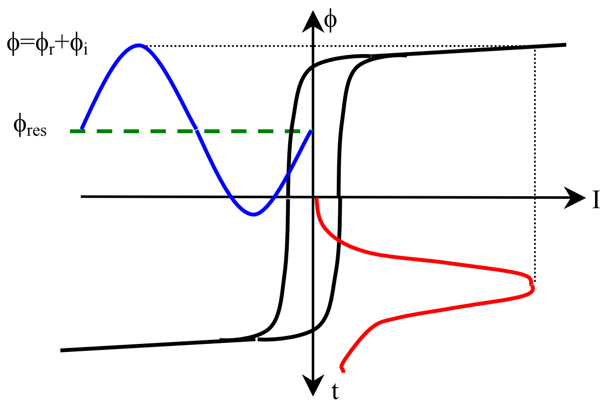


Fig. 1 - Flux current relationship.

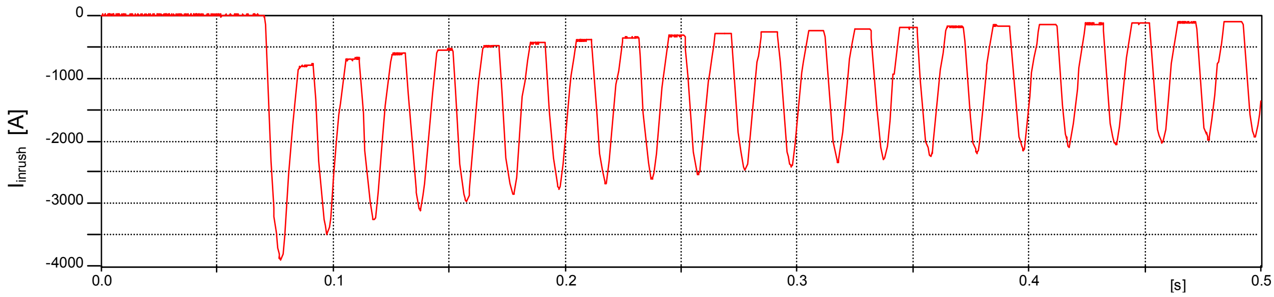


Fig. 2 – Long duration inrush current of the 155 MVA, 132/15 kV, Y_nd11 transformer (measured).

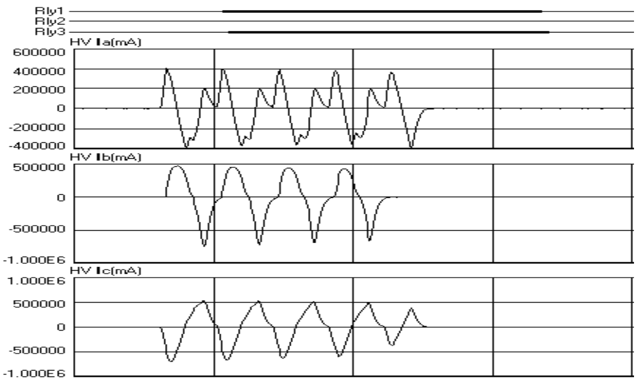


Fig. 3 – False trip in phase A and C produced by the differential protection of the 4 MVA auxiliary transformer.

Besides the long duration exposure to the mechanical support structure of the windings, these currents reduce the power quality, because the voltage drop on the source impedance is considerable during the inrush period, which produces voltage swell in both side of the transformer. A high amplitude inrush current may cause false differential protection operations, as shown in Fig. 3. Additionally, a false relay trip may result in dangerous overvoltages if the inrush current is interrupted by a breaker having high current chopping level before the natural current zero.

III. PREDICTING THE INRUSH CURRENT PEAK

When a transformer is energized at instant of voltage zero, the iron core is mostly driven into saturation because the core flux density exceeds the saturation limit. Following saturation the magnetizing branch can be considered as an air-core inductance and the inrush current peak be predicted by Eq. (1):

$$i_{peak} = \frac{B_{air}\, l}{\mu_0 N} = \frac{l}{\mu_0 N} \cdot \frac{A_c}{A_{air}} \cdot \left(2 \cdot B_n + B_r - B_s\right) \qquad (1)$$

where: B_{air} magnetic flux density outside the saturated core [Vs],
B_n nominal peak core magnetization [Vs],
B_r, B_s residual and saturation magnetization [Vs],
l length of the magnetic flux path in air [m],
N number of turns of the energized coil,
A_c cross section of the iron core [m^2],
A_{air} cross-section of the air-core inductance [m^2],
μ_0 permeability of the air (oil) = $4 \cdot \pi \cdot 10^{-7}$[Vs(A/m)$^{-1}$]

Substituting the geometrical and magnetic parameters of the 132/15 kV transformer, the highest inrush current peak yields 5.12 kA (5.35 p.u.) at unfavorable conditions. If no residual flux is to be expected and energization is made at voltage zero the inrush current peak yields 2.3 kA (2.4 p.u). When energization is made at voltage peak, the inrush current peak yields 2.1 kA (2.2 p.u).

Table -1

Nameplate data of the transformer	Parameters of the coil and the magnetic core
Rated voltage: 132±5%/15 kV Rated current: 678 / 5966 A Rated power: 155 MVA Connection: Y_nd11 Short circuit reactance:14 % Magnetizing current:0.3/2.7A	A_c = 0.535 m^2, A_{air} = 1.21 m^2 N=375 (at tap: -5%), l = 2 m Nominal core magnetization: B_n=1.62 Tesla, Saturation level: B_s=2.03 Tesla Residual flux:B_r=1.52 Tesla ($B_s \approx 1.25\, B_n$, $B_r \approx 0.75\, B_s$)

Eq.(1) expects that short circuit capacity of the supply network is infinite. In real circumstances the voltage wave is significantly distorted by the inrush current. Additionally, the core saturation in case of multiphase, multi-winding transformers is more complex due to the galvanic and magnetic coupling between the phases. If the breaker poles are operated with less than 10 ms time delay, the peak value of the flux in the first energized phase might be influenced by the delaying phase(s), too. At the same time there is a counter effect: the magnetic induction produced by the first energized phase may superimpose onto the residual flux of the not yet energized phases.

IV. CONTROL SWITCHING STRATEGIES FOR MULTIPHASE Y_n/Δ TRANSFORMERS

In order to achieve inrush current free energization of large power transformers, the operating time of the circuit breaker poles must be controlled individually and contacts closing performed in a proper sequence. There are several control strategies published in the literature [2,3] and realized in the practice [4]. Point-on-wave controlled transformer energization is probably the most widely used controlled switching technology today [5].

A) Controlled switching with no residual flux

Transformers with *single-phase core* and without delta winding can be considered as three single-phase transformers. Majority of power transformers are however manufactured with at least one delta winding, which accomplish interaction between the phases. In presence of a delta winding the energization of the first phase at the Y side will change the static residual flux in the other phases. If the *residual flux is zero* in all phases, the sinusoidal voltage peak makes the optimal instant for the first phase to close at the HV side. After closing the first phase, a dynamic core flux appears in the other two phases. To achieve inrush free switching in all phases, the second and third phases must be energized 5 ms later simultaneously, when the prospective flux is equal to the dynamic core flux in each phases [6].

The instant of optimal energization of Y_n/Δ transformers with *three-phase core* is identical with that of the single core transformers. Energization of the first phase at the effectively grounded HV side will directly create dynamic core flux in the other two phases.

B) Controlled switching with residual flux

It is known that the sum of the residual flux must be zero for core-type (3-leg) transformers or if the transformer has at least one delta winding. It is not the case for transformers without a delta winding or having 5-leg or shell-type cores.

If the residual flux pattern is known, the best strategy is to energize first the phase with the lowest residual flux first. Depending on the polarity of the residual flux in the other two legs, the dynamic core flux and prospective fluxes will be equal in certain moments following the first pole to close. These instants offer an opportunity to energize the remaining phases without core saturation. This closing strategy is called *rapid closing*.

There are other closing strategies such as *delayed closing*, where the second and third phases are energized with a significant delay (20-40 ms) and *simultaneous closing,* where all phases are closed at the same time [3]. The application of the latter strategy is limited to cases where the residual flux equals to zero in one phase and high in the other two with opposite polarity.

C) Considering practical aspects: pre-strike, scatter of the operating time, common drive breakers

Theoretically, the inrush transient can be eliminated completely by using an appropriate synchronous controller. In practice, several factors prevent the complete elimination of the inrush current. These factors are:

- Scatter of the operating time of circuit breakers
- Pre-strike between the moving breaker contacts
- Residual flux pattern is not exactly known
- Dependent operation of circuit breaker poles (e.g. in case of staggered, common drive breakers)

Existing control methods proposed by former papers unfortunately were not applicable to reduce the inrush current amplitude of the step-up transformers investigated in this paper, because transformers are switched with mechanically staggered circuit breakers (3-pole switch operated by a common spring drive with fixed time delay between the opening/closing poles).

V. EMTP MODEL FOR THE INRUSH CURRENT STUDIES

The 132/15 kV step-up and the 15/6.9 kV auxiliary transformers are energized together in these quick start power stations. The plant supplies a nearby 400/220/120 kV substation through 400 m long 120 kV overhead line or XLPE cable. The transformer breakers are located at the remote end of the line/cable. The complete EMTP model is shown in Fig. 4 (using the new compress feature of ATPDraw [7]) and in Fig. 5 (without object customization). As it can be seen the *Compress* feature (available only in version 3.5 and later) of ATPDraw is a powerful tool which makes the circuits more readable.

There are several transformer models available in the ATP version of EMTP [8] for an inrush study. If the iron-core provides low reluctance path for the return of the zero-sequence flux (i.e. for 3-phase, 3-leg shell-type or 4-5 legs core type transformers) the zero sequence parameters of the transformer are identical with the positive sequence ones. In case of 3-phase, 3-leg core-type transformers the zero sequence flux is forced to return through the air and the tank, making the zero sequence magnetizing inductance high and linear. The steady-state performance of different transformer models in ATP has been compared in [9]. The main conclusions can be summarized as next:

- if the transformer has at least one delta winding, the BCTRAN and STC (saturable transformer component) models are both suitable.
- if no delta winding exists, only high homopolar models are acceptable (TRANSFORMER THREE PHASE, or #Sat. Y/Y 3-leg object of ATPDraw). The BCTRAN model can be also applied if the user specifies the zero sequence parameters properly.

The transformer model for the residual flux and inrush current simulations presented in this paper consisted of a linear BCTRAN object (Fig. 6) and three delta coupled, hysteretic Type-96 inductors to represent the nonlinear magnetizing branch.

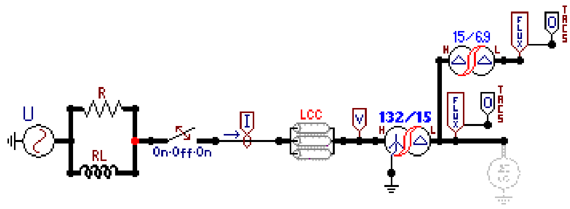


Fig. 4 - ATPDraw circuit with compressed objects.

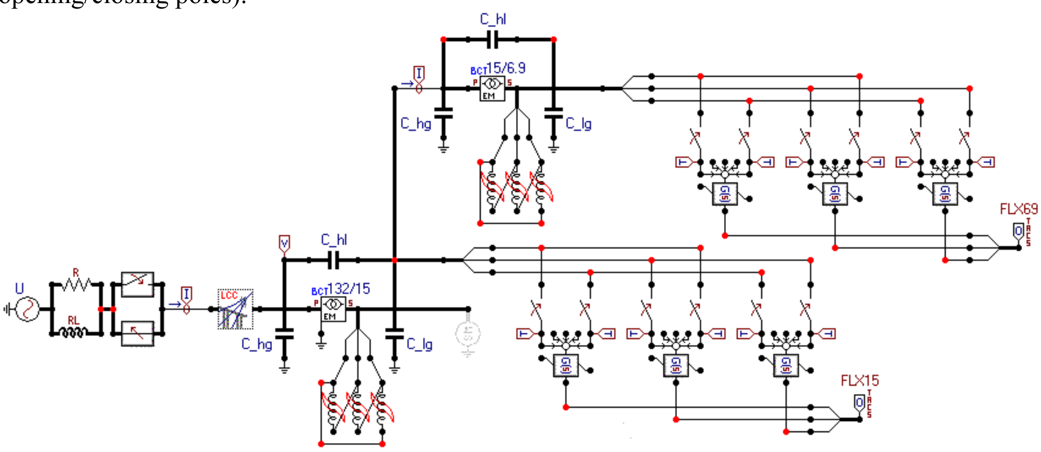


Fig. 5 - ATPDraw circuit without customized objects.

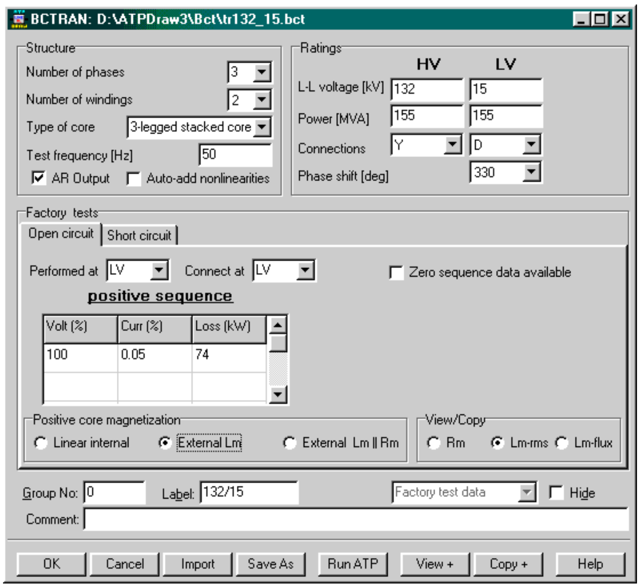


Fig. 6 - Input dialog of BCTRAN object in ATPDraw.

VI. RELATIONSHIP BETWEEN THE RESIDUAL FLUX AND INSTANT OF DE-ENERGIZATION

The relationship between the residual flux and the moment of transformer de-energization has been established by this study. The instant of first pole to open has been varied systematically in 1 ms steps. The current chopping characteristics of the breaker has been set according to the "chopping number" of the SF_6 breaker. The following cases have been analyzed:

- pole separation sequence is B-C-A, time delay between the opening poles is 0-3.3-6.6 ms
- pole separation sequence is AC-B with 5 ms delay between the simultaneously opening first two and the third poles.

Fig. 7 shows the calculated residual flux patterns for both cases as function of the first pole opening instant along a power frequency cycle. As it can be seen, the highest residual flux value may reach 72 % of the rated induction. Additionally, two 2-3 ms narrow window can be observed in both diagrams, where the residual flux is low in all phases.

This study confirmed that the residual flux can be managed effectively by means of controlling the breaker operations when disconnecting an unloaded transformer.

VII. CONTROLLED SWITCHING WITH STAGGERED, COMMON DRIVE CIRCUIT BREAKERS

The EMTP model presented in section V has been used successfully to develop a new point-on-wave control method and to investigate the differential protection maloperations experienced by the utility at the automatic start-up of the power station many times.

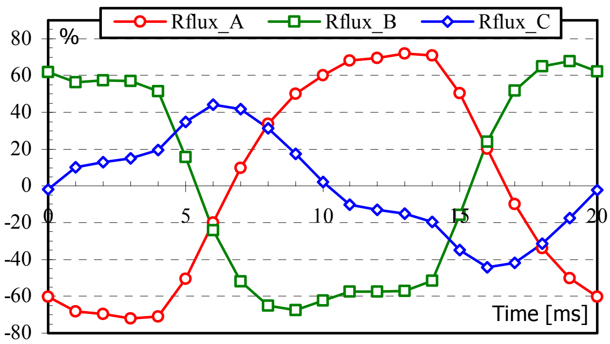
The transformer circuit breakers in these power stations are a common drive type with 60 electrical degrees phase shift. i.e. the making sequence is A-C-B with 3.3 ms delay and the breaking sequence is B-C-A with the same time delay. The 15/6.9 kV auxiliary transformers are energized and disconnected simultaneously with the main transformer because no switching device has been built between them (see Fig. 4). Consequently, if the step-up transformer is energized from the 120 kV bus, the auxiliary transformers are also producing an inrush phenomena.

Fig. 8/a shows the typical inrush current recorded when the first phase of the main transformer has been energized close to the voltage zero and the residual flux pattern has been approx. +70, -70, 0 % in phases A-B-C, respectively. This worst case scenario resulted in inrush current peak of 4.2 p.u. in the 132 kV winding and 6.4 p.u in the line current of the auxiliary transformer. The recorded signals of the auxiliary transformer are shown in Fig. 9/a.

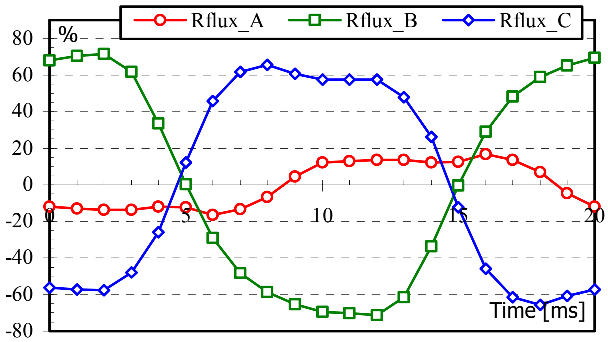
The voltage and current curves in Fig 8/b and 9/b have been obtained by EMTP simulation by setting the simulation conditions identical with that of the measurements. The amplitude and wave shape of the measured and computed voltages/currents agree fairly well, which proves the correctness of the digital model.

Fig. 10 shows the energization of the main transformer/auxiliary transformer block using the new point-on-wave electronic controller developed and manufactured as part of this research. This time the *controlled energization* of the transformer has been preceded by a *controlled de-energization* to keep the residual flux low and flux pattern (polarity and amplitude of flux in each phase) known. As can be seen in Fig. 10, the synchronous controller operated the first pole of the breaker at the voltage peak. Thanks to the controlled energization the inrush current has been eliminated.

The elaborated control strategy has been put into service in two power plant in Hungary and have been in operation since 2002.



a) switching sequence B-C-A, time delay 0-3.3-6.6 ms



b) switching sequence AC-B, time delay 0-0-5 ms

Fig. 7 - Residual flux vs. instant of the first pole opening along a whole power frequency cycle.

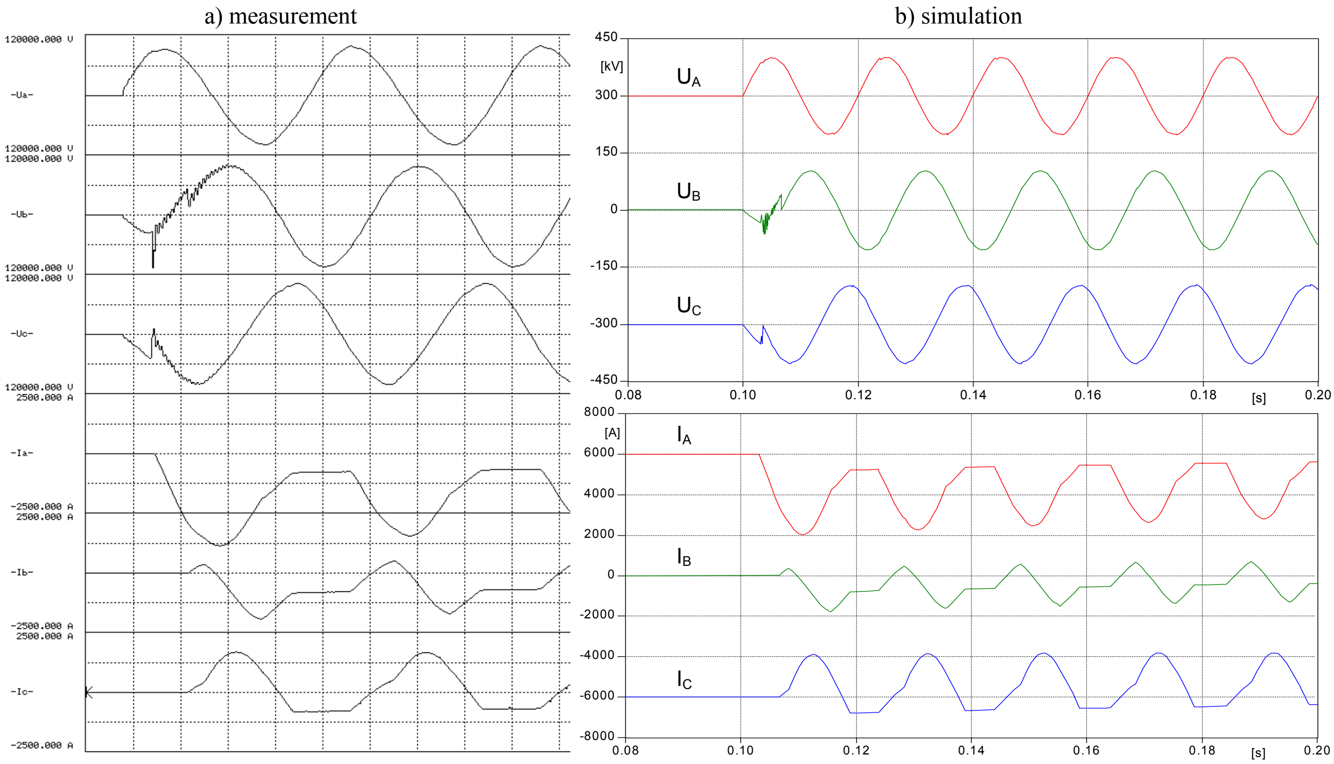


Fig. 8 - Measured and calculated phase-to-ground voltages and inrush current of the 132/15 kV transformer at worst case scenario.

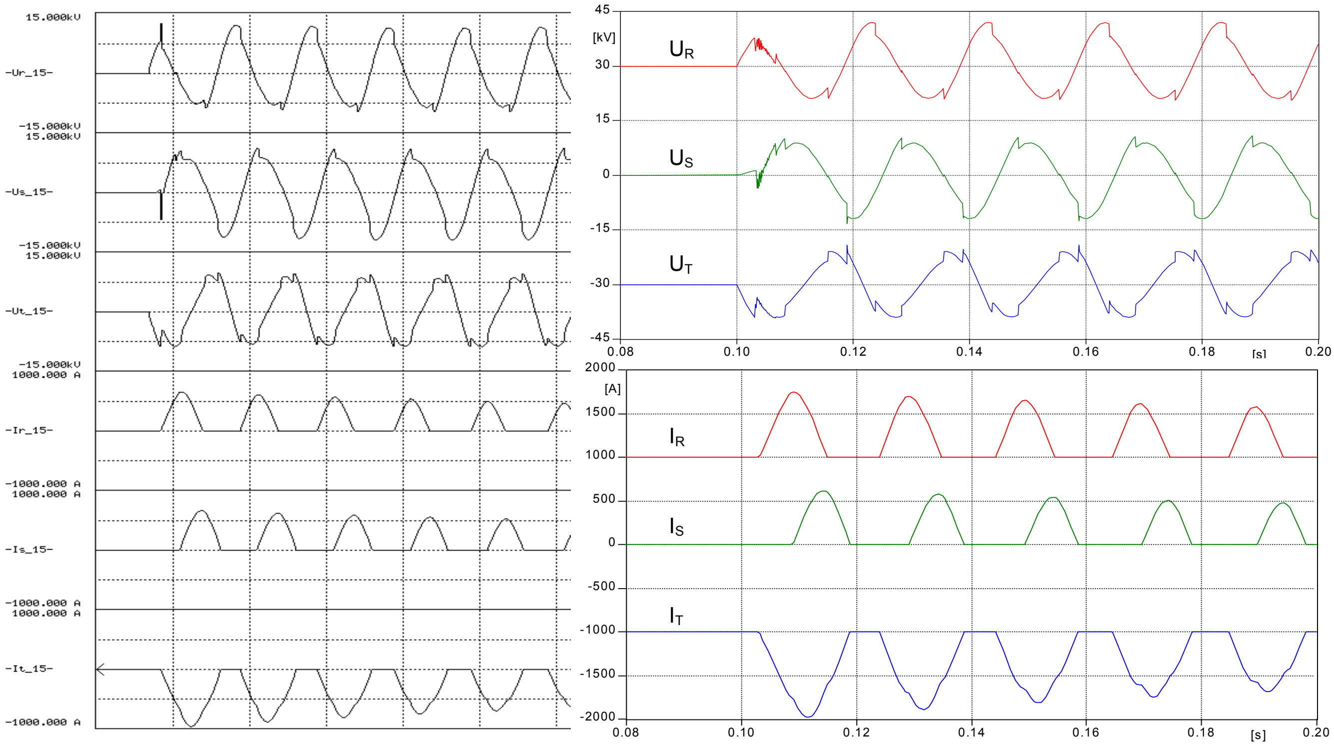


Fig. 9 - Measured and calculated phase-to-ground voltages and inrush current of the 15/6.9 kV transformer at worst case scenario.

VIII. IMECHANICAL STABILITY OF THE DRIVE

The influence of the mechanical scatter of the drive, the electronic controller and of the pre-strike has been analyzed in this study. The pre-strike plays a significant role in transformer controlled switching, because it produces a breakdown of the closing contact gap before metal-to-metal contact of the poles.

Table-2 shows the amplitude of the inrush current peak vs. operating time deviation from the optimum. This optimum is highlighted as gray row. As it can be seen, the requirements against the mechanical stability are not severe. If the opening time deviation is less than 1 ms and the closing time deviation does not exceed 2 ms, the amplitude of the inrush current can be kept below 1.1 p.u.

Modern spring drive circuit breakers easily fulfil these requirements. Published data by manufacturers confirms that switching time deviation from the rated values does not exceed ±0.5 ms. A larger value must be expected only if the circuit breaker is put into operation following a longer out of service period. In this case the closing time may become 1-2 ms longer.

IX. CONCLUSIONS

The residual flux plays a significant role in development of the magnetizing inrush current. The residual flux can be influenced by means of point-on-wave controlled de-energization of the transformers, supposing that the phase-to-ground capacitance seen from the transformer terminal is known and does not exceed some nF.

The EMTP studies proved that the residual flux pattern is function of the magnetizing characteristic of the core material, the current chopping characteristics of the breaker, the mechanical stability of the drive and basically the capacitance of the winding, the bushing and the bus-bar which connects the transformer and the breaker.

The field tests proved that the magnetizing inrush current of generator step-up transformers can be reduced effectively, by means of controlled switching. Energization with low inrush current can be achieved even with circuit breakers having built-in time delay in the operating time of the opening/closing poles.

If optimal residual flux pattern is ensured by means of controlled de-energization, the accuracy requirements against the mechanical stability of the drive and the controller at a subsequent energization is not very strict.

The new synchronous controllers hardwired with the control strategy presented in this paper have been in operation since 2002 in two substations.

X. ACKNOWLEDGEMENT

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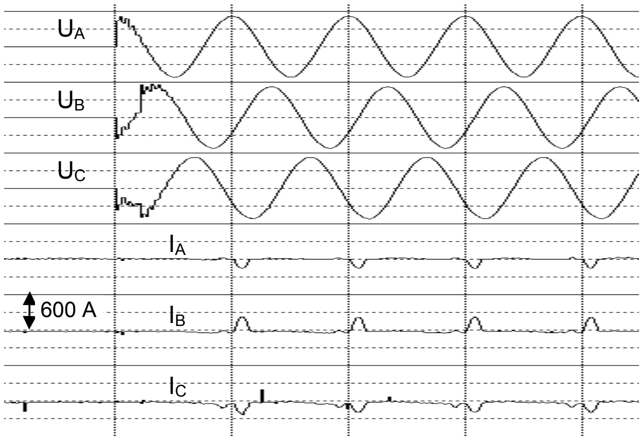

Fig. 10 – Controlled energization of the 132/15 kV generator step-up transformer at voltage peak with optimal residual flux pattern. Upper curves: phase-to-ground transformer voltages. Lower curves: magnetizing inrush current (on site measurement).

Table -2
Inrush current of the 132/15 kV transformer if the opening and closing time deviates from the optimum.

Opening time	**Inrush current peak in [p.u.]** (simulation) opening sequence: B-C-A, closing sequence: A-C-B with time delay 0-3.3-6.6 ms											
	Closing at voltage peak			Closing 1 ms before			Closing 1 ms after			Closing 2 ms after		
t_B [ms]	I_A	I_B	I_C	I_A	I_B	I_C	I_A	I_B	I_C	I_A	I_B	I_C
1	-1.03	1.32	-0.67	-0.79	1.27	-1.11	-1.47	1.37	0.65	-1.92	1.07	0.78
3	-1.07	1.30	-0.64	-0.77	1.32	-1.02	-1.53	1.39	0.70	-1.99	1.08	0.98
5	-0.52	0.69	-0.34	-0.38	0.77	-0.43	-1.05	0.63	0.52	-1.51	0.76	1.17
6	0.00	0.06	-0.03	0.17	0.17	-0.34	-0.53	0.26	0.30	-1.08	0.50	1.07
7	0.00	0.00	0.00	0.47	0.33	-0.26	-0.14	-0.14	0.28	-0.59	-0.49	0.98
8	0.30	0.03	-0.06	1.00	0.61	-0.30	0.07	-0.13	0.08	-0.39	-0.39	0.78
9	0.67	0.18	-0.13	1.36	0.77	-0.49	0.08	-0.17	0.08	-0.28	-0.40	0.55
11	1.07	0.40	-0.53	1.77	0.90	-1.00	0.39	-0.12	-0.12	0.13	-0.25	0.13
13	1.16	0.43	-0.51	1.85	0.93	-1.08	0.48	-0.12	-0.12	0.12	-0.25	0.12
15	0.67	0.25	-1.04	1.37	0.76	-1.58	0.11	0.11	-0.30	0.00	0.00	0.00
17	-0.86	0.73	-1.40	-0.92	0.85	-2.09	-0.58	0.97	-0.58	-0.91	0.70	-0.49
19	-0.87	1.22	-1.01	-0.96	1.21	1.64	-1.27	1.25	-0.73	-1.73	0.94	0.70