

Influence of HV inductive voltage transformers core design to the ferroresonance occurrence probability

Danijel Krajtner, Igor Žiger

Abstract – The occurrence of ferroresonance oscillations of high voltage inductive (electromagnetic) voltage transformers (VT) has been recorded and reported in a number of papers and reports. Because of its non-linear characteristic, inductive voltage transformer has the possibility of causing ferroresonance with capacitances present in the transmission network, if initiated by a transient occurrence such as switching operation or fault.

One of the solutions for ferroresonance mitigation is introducing an air gap into voltage transformer core magnetic path, thus linearizing its magnetizing characteristic and decreasing the possibility of a ferroresonance occurrence.

This paper presents results of numerical ATP-EMTP simulation of typical ferroresonance situation involving inductive voltage transformers in high voltage networks - with circuit breaker opening operation after which the voltage transformer remains energized through the circuit breaker grading capacitance.

Main variable in calculating to the ferroresonance occurrence probability was the magnetizing characteristic change caused by the introduction of an air gap to the VT core, and separate diagrams are presented for VTs with different air gap length, including the paramount gapped transformer design – open core voltage transformers.

Keywords: ferroresonance, voltage transformer, air-gapped core, open core

I. INTRODUCTION

Ferroresonance including inductive voltage transformers (VT) in high voltage (HV) transmission system has been recorded in numerous cases, many of them described in [1], [2], [4]-[7].

The ferroresonance phenomenon has been analysed analytically, computationally, and experimentally in a rather extensive manner. Today, there are very thorough and up to date technical reports regarding ferroresonance in power systems, such as [2] and [3]. They provide comprehensive theoretical background on ferroresonance, sample cases recorded in service and mitigation and avoidance strategies.

One of the most common situations of HV voltage transformers ferroresonance is a set of inductive voltage transformers that remain energized only through the grading capacitors of open circuit breaker(s). Another situation

recorded includes two high voltage lines in a double-circuit line construction (on the same pylons), where VTs remain connected to the energized line through the coupling capacitance between two line sets. Ferroresonance of voltage transformers in ungrounded neutral systems, mainly in distribution systems (medium voltage level), being predominantly a three-phase phenomenon, is not within the scope of this paper.

Different measures and methods for avoiding or damping ferroresonance have been proposed and analysed: specifying circuit breakers without grading capacitors, disabling network conditions likely to result in ferroresonance, implementing additional passive or active damping devices (usually connected to VT secondary terminals) which ensure that energy is dissipated without causing sustained ferroresonant oscillations [2], [3].

Another possibility is to influence the transformer design – decreasing rated flux density moves the rated operating point further from the saturation area on the magnetizing characteristic, which reduces the possibility of ferroresonance.

The most radical approach is to use different VT technologies – capacitive, optical VT or capacitive dividers.

The main focus of this paper is to validate and confirm the ferroresonance avoiding method proposed in [3]. The proposed idea is to change the voltage transformer inductance by inserting an air gap into the magnetic core, or using open-core voltage transformers. Such intervention to the voltage transformer design linearizes its magnetizing characteristic and is supposed to decrease the possibility of ferroresonance occurrence.

II. MODEL USED IN THE SIMULATIONS

Many authors, while modelling ferroresonant situations in actual substations, have built impressively accurate models of the system in question. For the evaluation of VT design regarding its general ferroresonant behaviour most of these parameters are irrelevant. According to [2], ferroresonance is a localized phenomenon and, generally, large network models are not necessary. Therefore, only the main elements directly involved in the ferroresonant circuit need to be modelled in detail. These include the voltage source, the impedance of the supply system, two sets of capacitances – the capacitance of circuit breaker grading capacitors and stray capacitance of the part of substation fed by open CB, and most importantly, non-linear inductance – the voltage transformer itself.

Time-domain simulation, using EMTP has been chosen as the ferroresonance calculation method for a couple of reasons.

D. Krajtner is with Končar – Instrument transformers Inc., Zagreb, Croatia (e-mail: danijel.krajtner@koncar-mjt.hr).

I. Žiger is with Končar – Instrument transformers Inc., Zagreb, Croatia (e-mail: igor.ziger@koncar-mjt.hr).

Apart from authors being familiar with ATP-EMTP software, available references have also recognized advantages of such an approach, mainly because of the limitations of analytical solution methods regarding sub-harmonic and non-periodic ferroresonance [2], and their inability to take into consideration transient phenomena, such as the circuit breaker operation [8].

A. Model of the ferroresonant system

In high voltage systems, voltage transformers are almost exclusively single-phase units, and ferroresonance occurrences in transmission level systems are predominantly single phase ferroresonance oscillations, affecting elements in one phase. Therefore, it is enough to model only one phase for such considerations.

Some investigations have, however, shown the necessity to model the complete three-phase system in order to correctly cover all ferroresonant modes and situations [8]. Nevertheless, this investigation aims to give qualitative influence of the VT core parameter variation on ferroresonance occurrence, and therefore it is not crucial to cover all three-phase mutual inter-phase influences which can affect the final result. Instead, this investigation has covered a wide range of capacitance combinations and applied voltage values, and has therefore included the mentioned influences.

High voltage system with rated voltage of 220 kV has been chosen for this calculation, and schematic of the model in ATP-EMTP is given in Fig. 1.

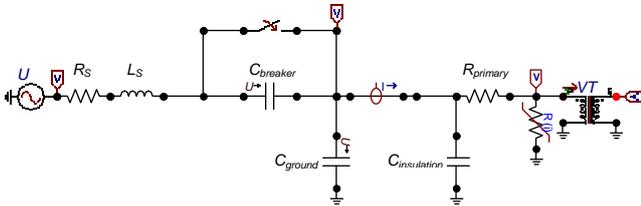


Fig. 1. ATP-EMTP model of the ferroresonant circuit used in calculations

B. Model of the high voltage apparatus

Although the correct modelling of ground capacitance of busbars and bay conductors, as well as stray capacitance of high voltage apparatus is important for correct simulation of a specific case, in this investigation they were instead modelled through their main parameters influencing ferroresonance occurrence - capacitance between phase and ground. Total capacitance, a lumped parameter including all HV apparatus of the isolated substation part, is a varying parameter in a wide range of values.

C_{ground} parameter marks the expected capacitance of the apparatus, HV cables, insulators and busbars of the proposed section in the HV station section which is isolated together with the VT. As this parameter depends on the rated voltage level, the expected capacitance is in the range of 500 pF up to 5000 pF, taking into account the 220 kV voltage level this paper is based on. The investigations in this paper used an even wider range - up to 10000 pF.

The circuit breaker is represented as ideal time-controlled switch, with a parallel capacitance connected to it [2], which is a variable parameter.

$C_{breaker}$ parameter marks the total capacitance of the circuit breaker (or multiple circuit breakers feeding isolated VT) grading capacitors. Range of values used in calculations was from 200 pF up to 10000 pF.

C. Model of the voltage transformer

As explained in the introduction, main aim is to compare ferroresonance performance of several transformer core design principles:

- closed core voltage transformer
- closed core VT with an air gap of 1 mm
- closed core VT with an air gap of 2 mm
- closed core VT with an air gap of 5 mm
- open core voltage transformer

An internal ATP-EMTP single phase saturable transformer model has been used for calculations. It incorporates T equivalent circuit model of the transformer, taking into account the rated voltages and transformation ratio, actual winding resistance, leakage inductance, piece-wise non-linear inductance and resistance modelled core losses.

Magnetizing characteristic of the non-linear inductance is certainly a crucial parameter for the correct modelling and simulation of ferroresonance, and therefore has been carefully prepared for this investigation.

Piecewise-linear representation of the magnetizing characteristics has been selected for a couple of reasons: it is incorporated into the saturated transformer model, point-by-point B-H characteristics of VTs were available, and finally, authors of [15] have concluded that polynomial curve can make significant errors in linear region slope, as well as in deep saturation.

Authors of [14] have proven that modelling the hysteresis loop of the VT magnetizing characteristic is important for obtaining correct simulation results, compared to modelling nonlinear inductance with steady-state piecewise-linear magnetizing characteristic. However, in this investigation the main aim was to observe air-gapped cores as well as the open core. Introducing an air gap into the magnetic circuit drastically reduces the remanence flux of the characteristic, thus making the hysteresis loop practically the same as the single-value magnetization characteristic. Therefore, for gapped cores and open-core, hysteresis loop modelling can be considered irrelevant. Even for conventional closed core transformers, neglecting the hysteresis loop is not expected to introduce significant errors. This is due to the fact that the aforementioned approximation introduces error in voltage values, but does not influence the ferroresonance occurrence in a significant way [14].

Magnetizing curves have been obtained by measurement, both for closed-core VT without an air gap, and for the open-core VT. For each core a separate measuring winding was constructed. The reason for this is to exclude the influence of

the main insulation capacitance, which would have otherwise been present.

Measured characteristics have been verified by analytical calculation of the magnetizing current, and then converted into linkage flux - current (ψ - i) characteristics using ATP embedded SATURATE procedure.

Finally, the last points of the obtained ψ - i characteristics have been additionally corrected in order to ensure adequate inductance in deep saturation, which is crucial for the correct behaviour of the transformer ferroresonance calculations, as per author's extensive experience with capacitor voltage transformers ferroresonance modelling and simulations in EMTP.

Magnetizing characteristics of closed core voltage transformers with an air gap have been calculated from the closed core magnetizing characteristics using analytical equations for magnetic resistance increase due to the presence of an air gap [17]:

$$I_n = \frac{H_n \cdot d_{Fe} + \frac{B_n}{1,257 \cdot 10^{-6}} \cdot d_{air}}{N_1} \quad (1)$$

$$U_n = \frac{B_n \cdot S_{Fe} \cdot N_1 \cdot \omega \cdot k}{\sqrt{2}} \quad (2)$$

where I_n and U_n are voltages for the n -th point of the U - I magnetizing characteristic, H_n and B_n are corresponding magnetic field strength and flux density of the n -th point, d_{Fe} is the average magnetic flux path in magnetic steel core and d_{air} is the length of the air gap inserted into the core. N_1 is the number of turns of the primary winding, S_{Fe} is core cross section and k is core stacking factor.

Figure 2 shows magnetizing characteristics used in EMTP simulations for the different core designs.

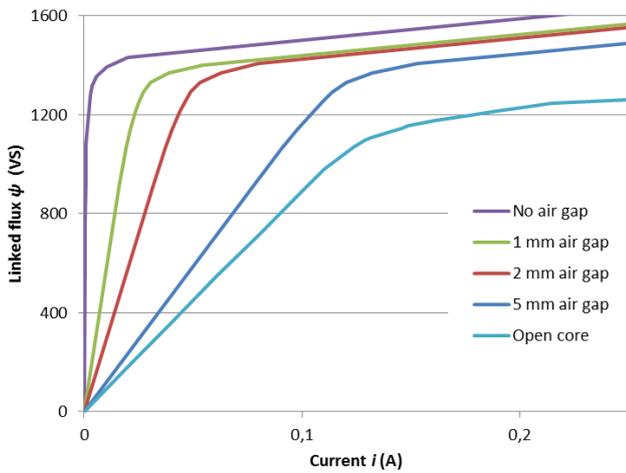


Fig. 2. Magnetization characteristics for VTs with different core design

Apart from the magnetizing characteristic, the core losses have to be modelled as well, as they can have significant

influence to ferroresonance simulation results. Constant value resistance ($R = 100 \text{ M}\Omega$) has been found adequate for representing losses in the open-core VT, based on the losses measurements performed. However, for closed core and air-gapped core models, an additional non-linear resistance was introduced in order to more correctly represent the core losses non-linearity. Due to the lack of measurement results, typical core losses for M4T27 steel were used to create non-linear resistance u - i characteristic shown in Fig. 3.

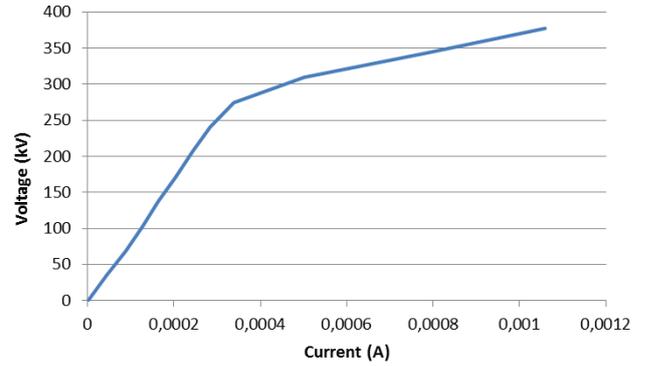


Fig. 3. Non-linear resistance characteristic used for the closed-core VT

Finally, since 220 kV voltage transformers normally have capacitively graded main insulation, which is basically connected in parallel to the primary winding of the transformer, insulation capacitance had to be added to the model. Measured value was used for open core VT and expected value was used for closed and gapped core VTs. Insulation capacitance was added as a separate capacitor between primary terminal and ground, marked with $C_{insulation}$.

D. Open core voltage transformer physical representation

As a special solution for the HV voltage transformers, open core voltage transformers have been used for decades in a number of power systems. They feature single limb core whose magnetic flux is closed through the surrounding non-magnetic material. Such core, provided it has a lean shape, corresponds to the equivalent closed core VT with air gap of 5 to 15 mm, according to analytical formulations based on Küchlers equation disclosed in [18]. Magnetizing current can then be calculated using (1), but with the equivalent air gap length:

$$d_{air} = 0,44 \cdot \frac{d_{Fe}^2}{d \cdot K_2 \cdot K_3} \quad (3)$$

where d_{Fe} is the diameter of the core limb, d is the average inner diameter of the primary winding, coefficient K_2 is determined from (4), and K_3 is determined from the diagram shown in Fig. 4.

$$K_2 = 1 + \frac{0,6 \cdot l_{Fe} - 0,5 \cdot l}{d_{Fe}} \quad (4)$$

where l_{Fe} is the total height of the core limb and l is the

height of the primary winding. Note that (4) is valid for designs where l_{Fe} has larger value than l , which is the case for open-core voltage transformers.

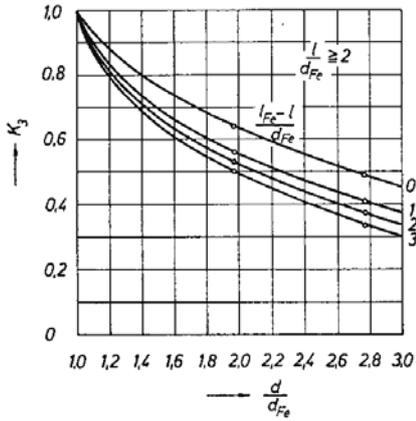


Fig. 4. Diagram for determining the K_3 coefficient

Apart from the described analytical check, the magnetizing current value is calculated by numerical calculation using the finite elements method (FEM), and results of both calculations are verified by measurements on actual transformers.

III. SIMULATION RESULTS

In a series of EMTP simulations, the phase to ground stray capacitance and circuit breaker capacitance, as well as the supply voltage value were selected as variables in a parametric study. The same set of simulations has been performed for each of the voltage transformers designs.

A. Simulation parameters

System transient was incepted by a circuit breaker switching off in instant $t = 0,2$ s, which has been found out to be the worst case scenario regarding oscillations intensity and ferroresonance occurrence.

Voltage transformers were unloaded in all cases, as this is also the worst case scenario that can happen in a power system. Further investigation has shown that significant load, larger than those normally connected to VT secondary windings, is needed to influence final state of the circuit.

Source voltage has been varied in range from 90% of rated voltage up to 120 %, as these values are expected as continuous in 220 kV systems.

B. Results

The results of the calculations are diagrams which show ferroresonance occurrence probability (steady state after circuit breaker opening) as a function of phase to ground capacitance and circuit breaker grading capacitance. Such diagrams have been constructed for different voltage values applied to the system, and for each type of voltage transformers core design.

Following circuit breaker opening and transient oscillations

period, a steady state was formed for each simulation, and its nature was verified by analysing each resulting waveform of VT voltage and current.

It is worth noting that these waveforms correspond with the waveforms seen in references [2], [4], [6], [7], either obtained by recording during ferroresonance or by time domain simulations.

Four different types of sustained voltage oscillations have been observed and marked in diagrams:

1. Damped transient oscillations and sustained sinusoidal voltage corresponding to the portion of source voltage defined by the ratio of capacitances $C_{breaker}$, C_{ground} and $C_{insulation}$. Example is shown in Fig. 5. In ferroresonance diagrams this outcome is marked with value 0 (green).

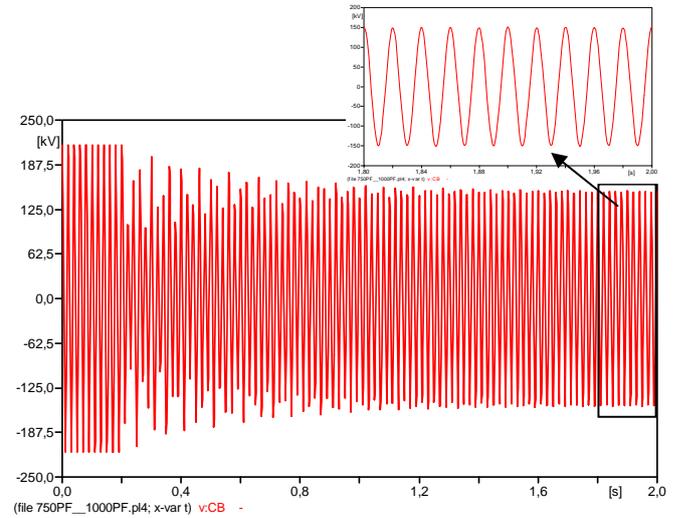


Fig. 5. Simulation result with damped transient oscillations voltage waveform at the voltage transformer primary terminals

2. Sustained fundamental ferroresonance (i.e. at rated frequency), with primary voltage reaching values of 3,5 p.u. and with extremely high magnetizing currents. Sample waveform is shown in Fig. 6, and such result is marked with value 1 (red colour) in diagrams.

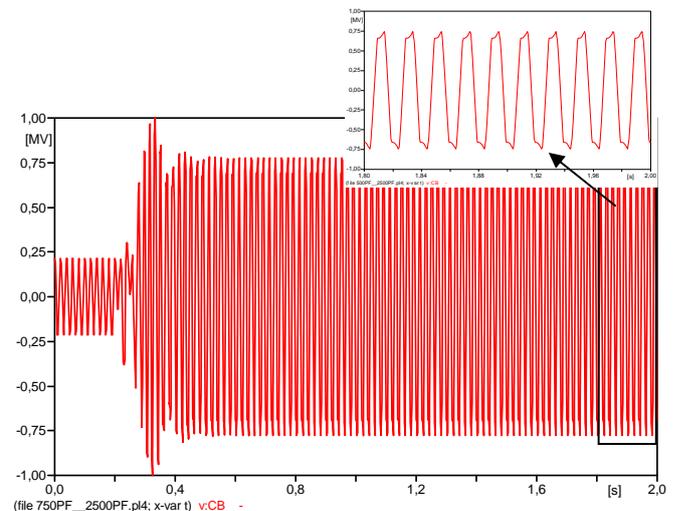


Fig. 6. Simulation result with fundamental ferroresonance voltage waveform at the voltage transformer primary terminals

3. Subharmonic ferroresonance with its order value (1/3 for 3rd subharmonic, 1/5 for 5th subharmonic etc.) indicated in diagrams (in yellow colour). Example is shown in Fig. 7. Although voltage reached at VT primary terminals was generally not much higher than the voltage source, the core reaches saturation state and magnetizing currents are high, which can present danger for the VT.

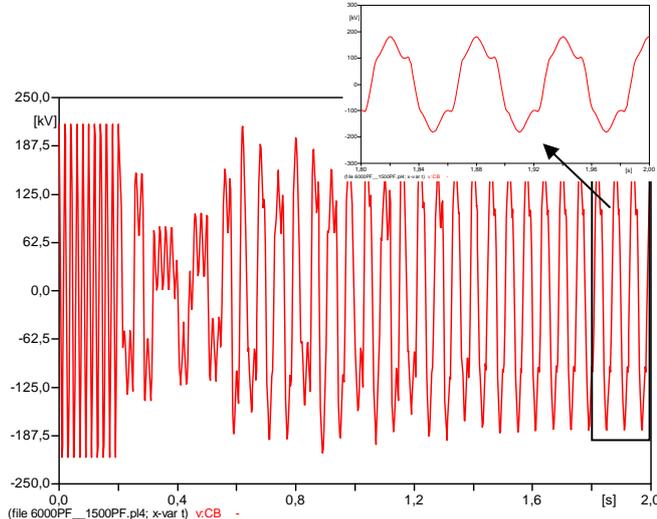


Fig. 7. Simulation result with subharmonic (3rd order) ferroresonance voltage waveform at the voltage transformer primary terminals

4. Oscillations occurrence difficult to be categorized into any of the above mentioned modes, sample of which is shown in Fig. 8. It could be characterized as non-periodic; although predominant is the 3rd subharmonic and a set of unstable lower subharmonics. Such occurrence has been marked with value 0,75 (orange colour), since normally voltage reached values higher than voltage source and thus has high severity if occurs.

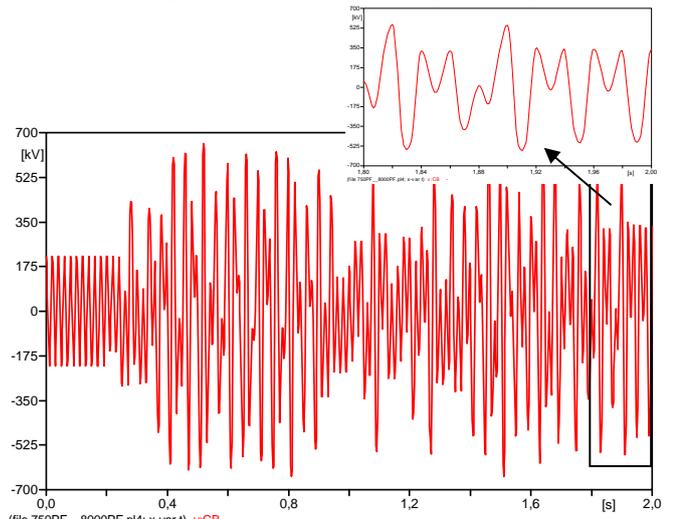


Fig. 8. Simulation result with non-periodic ferroresonance voltage waveform at the voltage transformer primary terminals

As a final result of the series of calculations, diagrams which show ferroresonance occurrence probability as a function of

phase to ground capacitance and circuit breaker grading capacitance, with applied voltage of 1,2 p.u., are shown in Fig. 9 to Fig. 13.

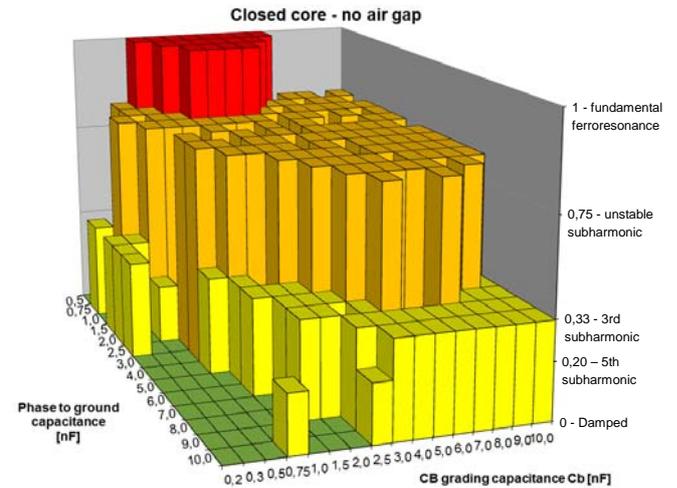


Fig. 9. Ferroresonance occurrence diagram – VT with closed core without gap; source voltage 1,2 p.u.

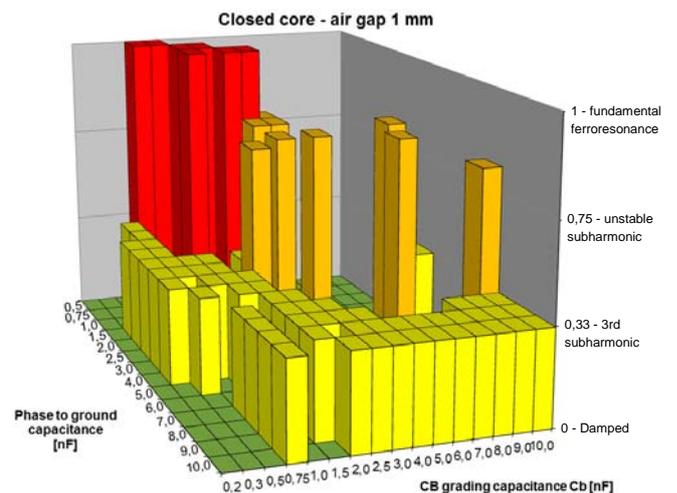


Fig. 10. Ferroresonance occurrence diagram – VT with closed core and 1 mm gap; source voltage 1,2 p.u.

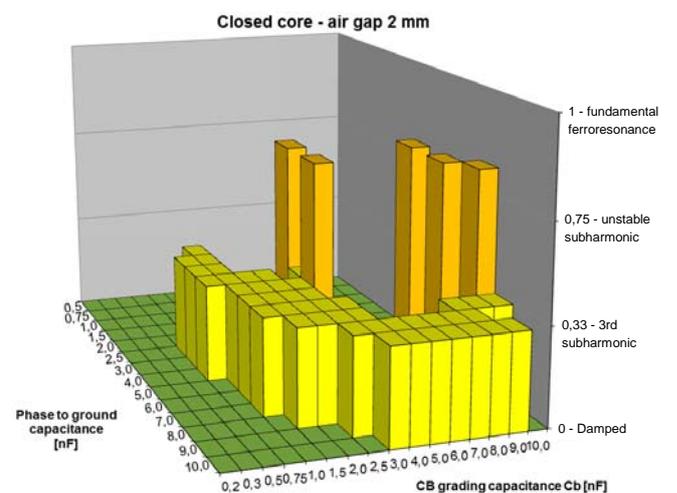


Fig. 11. Ferroresonance occurrence diagram – VT with closed core and 2 mm gap; source voltage 1,2 p.u.

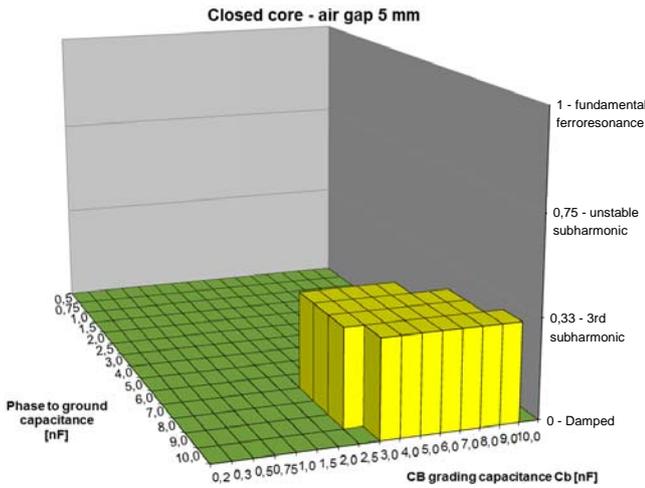


Fig. 12. Ferroresonance occurrence diagram – VT with closed core and 5 mm gap; source voltage 1,2 p.u.

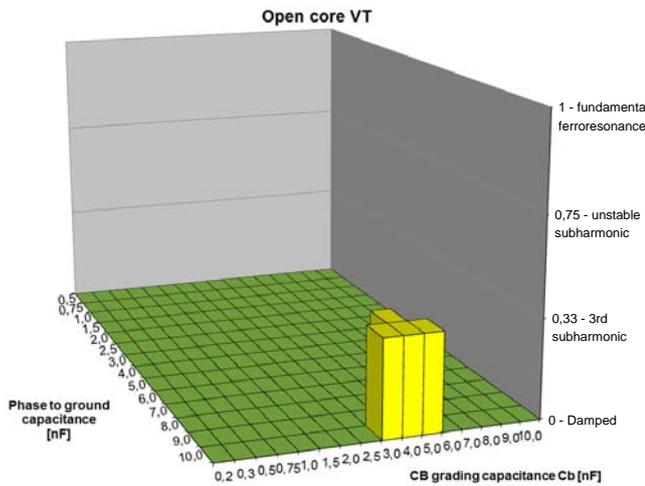


Fig. 13. Ferroresonance occurrence diagram – VT with open core source voltage 1,2 p.u.

Diagrams in Fig. 9 and Fig. 10 show wide area of capacitance combinations for which closed core VT can reach either rated-frequency or sub-harmonic frequency ferroresonance. Introduction of the 1 mm air gap does reduce the possibility of ferroresonance, but air gap increase to 5 mm is needed in order to reach stable non-ferroresonant state for most of the capacitances values combinations.

It can be seen from Fig. 13 that the open-core VT, having most linearized magnetizing characteristic, has practically no chance of ferroresonance inception, apart from couple of cases when extremely high capacitances were able to set a sub-harmonic sustained oscillations.

Diagrams in Fig. 9 to Fig. 13 clearly show a drastic decrease of ferroresonance occurrence possibility with the air gap introduction to the VT core and with air gap length increase.

Simulation results confirm that introduction of the air gap to the increase of the core gap length have a positive influence on the voltage transformer ferroresonance performance.

IV. RESULT DISCUSSION

Introducing an air gap into the voltage transformer magnetic core has a positive effect on the transformer ferroresonance performance. However, the introduction of the air gap into the closed core based VTs increases their magnetising current and consequently increases the phase displacement (phase error), thus making higher accuracy classes (i.e. 0,1 and 0,2) difficult to achieve. Therefore, only a limited air gap length can be used in the closed core VTs without disturbing their basic function – accuracy performance.

It is worth noting that open-core voltage transformers have this problem solved internally; thanks to specially designed secondary windings, which make it possible to compensate phase displacement created by magnetizing current and obtain the highest accuracy classes, while maintaining an excellent performance in terms of ferroresonance.

When increasing the air gap in the VT core, there is another issue that needs to be taken into consideration. With increasing magnetizing current and reducing voltage transformer inductance in linear region of the magnetizing characteristic, capacitance value required for a resonance (either for serial or parallel resonance) occurrence with VT inductance increases. With that, capacitance required to create resonance with VT can reach values that are equivalent to the realistic isolated substation part capacitance or $C_{\text{breaker}} + C_{\text{ground}}$ value. In such case, voltage increase is possible, even though ferroresonance does not occur.

Because of the predictive nature of resonance, it is rather simple to check resonance possibility for the given voltage transformer (using magnetizing current value at rated voltage provided by the manufacturer) and thus avoid possibility of VT resonance completely.

V. CONCLUSION

The aim of the paper was to show that the decrease of the magnetic core non-linearity, achieved by introducing an air gap into the main magnetic circuit has a very favourable effect on ferroresonance inception. Essentially, by smoothening the core non-linearity, one of the necessary conditions for ferroresonance occurrence is removed.

An extensive set of EMTP simulations was performed in order to verify this stipulation Closed core VT performance was compared to the same core design after the introduction of an air gap of different lengths.

The results of the calculations show ferroresonance occurrence probability as a function of phase to ground capacitance and circuit breaker grading capacitance for different applied voltages and different VT models (i.e. core designs).

Sustained ferroresonance oscillations were observed with fundamental and sub-harmonic ferroresonance in case of closed-core VT and air gapped core with 1 mm gap, while only sub-harmonic ferroresonant oscillations were observed

for 5 mm air gap VT and open core VT.

Simulation results clearly show a decrease of ferroresonance occurrence possibility with an increase of the air gap present in the magnetic core.

The increase of the air gap length further linearizes the magnetizing characteristic, and further drastically reduces the ferroresonance possibility.

Air gap length of 5 mm was found adequate to achieve satisfactory ferroresonance performance of the VT, proving the claims and recommendations proposed in [3] valid. However, the possibility of creating a VT with such a large air gap and maintaining accuracy performance at the same time is questionable.

Furthermore, the results have shown that the open-core voltage transformer has superior ferroresonance performance, as it can reach ferroresonance oscillations only for unrealistically large values of applied voltage and/or phase to ground capacitance, which essentially makes this type of design ferroresonance immune.

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