INTERNAL RESONANT TRANSFORMER WITH DISTRIBUTED OPEN MAGNETIC CORE

Andrei MARINESCU[1], Aurelia SCORNEA[2], Ionel DUMBRAVA[2]

[1] ASTR Member, ICMET Craiova, [2] ICMET Craiova

Abstract: The on-site dielectric tests on cables and high power electric machines requires the achievement of some medium voltage testing facilities with reduced dimensions and weights, allowing the compensation of the important reactive energy required by the own capacitance of the device under test (DUT) and which could be supplied from low power and low voltage networks. Until now, by using the classical transformers with closed magnetic core and external resonance, these desiderata could not be accomplished. The solution proposed in the paper, applicable to testing voltages up to 60 - 80 kV, appeals to air core or distributed open magnetic core transformers that operate with internal resonance at variable frequency, within the narrow limits (45-65 Hz) imposed by the standards in force. The possibilities offered by the diagram with parallel resonance and variants of open magnetic cores are analyzed by simulation and experiment, aiming at the maximization of the ratio between the reactive power of the DUT and the apparent power absorbed from the variable frequency source.
Keywords: resonant transformer, capacitive load, open core.

1. INTRODUCTION

AC tests of insulation for cables and electric generators (important capacitive loads) both at the factory and in operation, demands special equipment, able to generate high reactive powers. The classical testing systems contain expensive, heavy equipment (about 5-10 kg/kvar) with large dimensions that lead to difficulties and high costs for transporting them on site.

The standards in force related to the alternating voltage tests [1], with special requirements for cables [2] and electrical rotating machines [3], impose low frequencies of the testing voltage, within the range 45 - 65Hz.

The solution proposed in this paper refers to a testing system that utilizes a transformer with internal resonance and open magnetic core, supplied from a low power and variable frequency static source, designed to be used instead of the classical system with external resonance and closed magnetic circuit.

2. BRIEF DESCRIPTION OF THE TESTING SCHEMES WITH RESONANT SYSTEMS

The resonant systems, used for compensating the reactive energy required by the own capacitance of DUT, depending on the way of obtaining resonance, are divided into [4]:

- *external resonance systems*, presented in (Fig.1a,b), which utilize a classical construction test transformer with closed magnetic core, supplied from a power frequency adjustable voltage source, the resonance being obtained using an iron-cored coil having adjustable inductance, connected in parallel with the transformer secondary or primary;
- *internal resonance systems*, which utilize either a test transformer with closed magnetic circuit and variable air gap, supplied from an adjustable voltage source with frequency of 50Hz (Fig.1c), or an open core transformer, supplied from a variable frequency voltage source (Fig.1d).

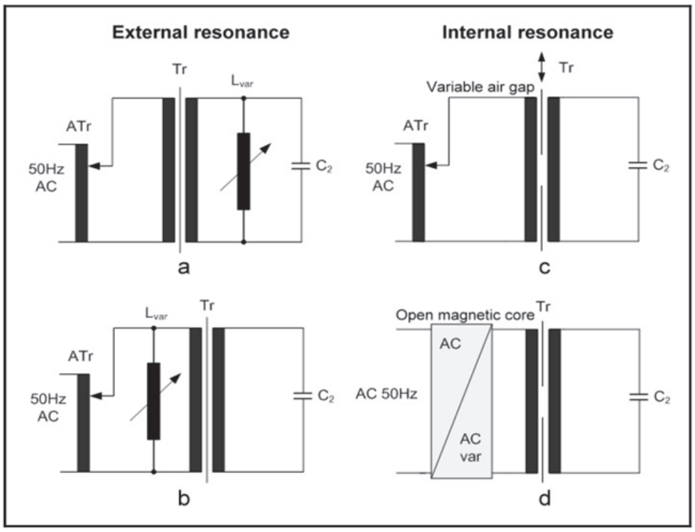


Fig.1 Technical solution for resonant systems

The disadvantage of the technical solution presented in Fig.1a consists in the necessity of a continuously variable inductance L_{var} to compensate the capacitance C_2 at the mains frequency, which leads to high material consumptions and costs plus transport difficulties. In the case of the resonant system from Fig.1b, the disadvantage consists in the fact that the entire reactive power required by the test will pass through the transformer Tr, the adjustment being done on its low voltage side.
The solution of obtaining resonance using a closed magnetic circuit with adjustable air gap, presented in Fig.1c, involves achieving a complicated mechanical system for changing the air gap, included in the transformer.
In the above presented cases, obtaining resonance at low frequencies for high values of the capacitance C_2 is hindered by the high value inductance of the secondary winding, specific to the use of a closed magnetic circuit.
A significant weight reduction and a lower secondary inductance, able to resonate with high capacitances at low frequencies, could be obtained by using either an air core transformer or an open magnetic circuit transformer, supplied from a variable frequency static source (Fig.1d).

3. THE MODEL OF AIR CORE TRANSFORMER

This step-up air core transformer, rather rarely encountered in engineering practice, is achieved in a construction with cylindrical windings, the secondary being made of multi turn disk windings like in Fig.2, three in number, series connected, over which the primary winding is wrapped in only one layer on the whole length of the secondary winding (Fig.3).
The main geometrical and electrical characteristics of the air core transformer are presented in Table 1.

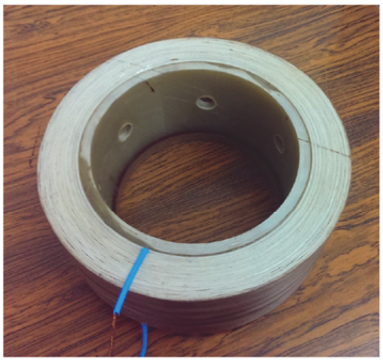


Fig.2 Multi turn disk winding

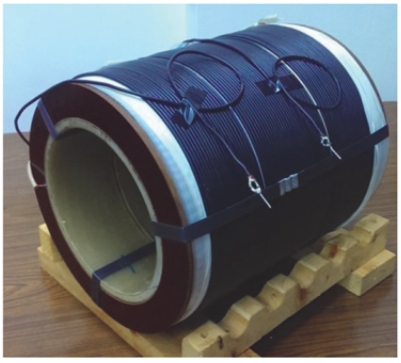


Fig.3 Air core transformer with cylindrical windings

Table 1 Geometrical and electrical characteristics of the air core transformer

Dimensions		Primary		Secondary	
Outer diameter [mm]	284	Number of turns N_1	70	Number of turns N_2	2520
Inner diameter [mm]	190	Wire section [mm^2]	4	Wire section [mm^2]	1.5
Total length [mm]	324	Ohmic resistance R_1 [Ω]	0.476	Ohmic resistance R_2 [Ω]	19.5

The transformer was sized for a power of about 25 kVA at operating in air, under short time duty (5 minutes) specific to insulation tests and it has a turns ratio n_{tr}=36. For an output voltage of 20 kV, no special elements for making uniform the electric field were provided. The total weight of the assembly is 39 kg and the volume is 12 dm^3.
When sizing the transformer, it was taken into account the fact that the secondary winding supplies directly a capacitive load (Q_2=25 kvar) similar to a MV cable or to a synchronous motor/generator that must be tested with applied voltage, in the factory or at commissioning, or after repairs on site, respectively. Instead, due to the parallel resonance in secondary, the primary winding is sized for a much lower power, thus contributing to the maximization of the coupling between windings.
Experimental model parameters identification consisted in determining the self inductances of the transformer windings L_1 and L_2, mutual inductance M, coupling factor k and real transformation ratio n; the obtained results are presented in Table 2. Experimental determination was performed by the method of applied voltages, respectively induced voltages in primary and secondary, taking into account the winding resistances; this engineering method is more accurate than that based on measuring the self inductances in additional and differential arrangement, when the inductances L_1 and L_2 are very different as regards the order of magnitude.

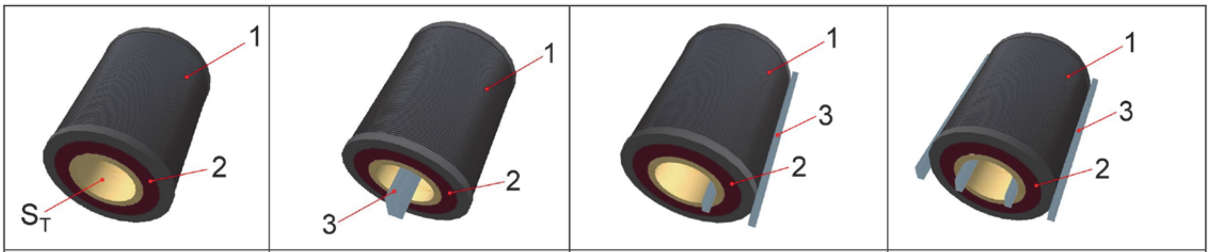
Table 2 Air core transformer parameters (n_{tr}=36)

L_1 [H]	**L_2 [H]**	**M [H]**	**k**	**n**
$1.5 \cdot 10^{-3}$	0.84	0.024	0.68	24.5

It is noted that the coupling factor value is relatively high for an air core transformer, fact pursued by its design.

4. DISTRIBUTED OPEN CORE TRANSFORMER

Starting from the air core transformer (Fig.4a), for being possible to use it in as many as possible practical applications, at the same time maintaining the narrow frequency range (45 - 65 Hz) imposed by the standards in force, regardless of the capacitance of DUT, one may appeal to the classical solution with bar-type core (Fig.4b). In this paper other solution was used, in which distinct packs of ferromagnetic sheets were placed inside and outside the windings, like in Figs 4c and 4d, aiming at maximizing the magnetic core effect by reducing the leakage flux.



a. air core S_T=283 cm^2; (K_S = 0) | **b.** bar-type core | **c.** 2 ferromagnetic sheets packs (K_S = 15%) | **d.** 4 ferromagnetic sheets packs (K_S = 30%)

Fig. 4 Spatial view of the air core/distributed open core transformer
1 – primary winding; 2 – secondary winding; 3 – ferromagnetic sheets pack

The total section of the sheets packs S_{Fe} was chosen so as to be much smaller than the total section available inside the transformer windings S_T, for keeping the transformer linearity within a wide range of supply voltages.
The transformer parameters variation with the filling factor $K_S = (S_{Fe}/S_T) \cdot 100$ [%] was experimentally studied, and the obtained results are presented in Table 3.

Table 3 Air core / open core transformer parameters

	Air core	**Distributed magnetic core**	
	K_S=0	K_S=15%	K_S=30%
L_1 [H]	$1.5 \cdot 10^{-3}$	$4.2 \cdot 10^{-3}$	$6.4 \cdot 10^{-3}$
L_2 [H]	0.84	4.49	7.3
M [H]	0.024	0.125	0.205
k	0.68	0.91	0.95
n	24.5	32.8	34.2

It is noticed that the ferromagnetic packs determine increasing the coupling factor k from 0.68 to 0.91 for K_S=15% and from 0.68 to 0.95 for K_S=30%, the last value of k being closed to the case of closed magnetic circuit. The figure of merit of the secondary winding increases also, without increasing the number of turns, and the specific weight of the assembly decreases about 10 times as compared to the case of classical constructions with closed magnetic circuit.

5. EVALUATION OF OPEN CORE TRANSFORMER PERFORMANCES AT PARALLEL RESONANCE

The use of open core transformer in the circuits for alternating voltage test of capacitive loads raises a number of questions on the resonant system energy efficiency, calculated as a ratio between the reactive power from the secondary Q_2 and the apparent power S_1 absorbed from the primary power supply, which is influenced by many factors such as: constructive variant of magnetic open core (utilized quantity of ferromagnetic material), internal resistance of the power supply, dielectric losses of DUT a.s.o.

The parallel resonance duty at variable frequency of the distributed open core transformer was studied both experimentally [5] and by simulation [6] within the technical solution from Fig.1d and testing scheme from Fig.5, in which the resonance of the inductance L_2 of the secondary winding of the transformer with the capacitive load C_2 is obtained by adjusting the frequency of the supply voltage U_s.

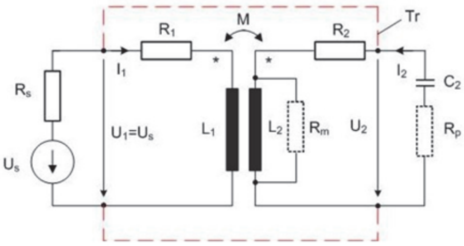


Fig.5 Testing scheme with open core transformer and parallel resonance

The calculation of this circuit was presented in previous papers [5,7].
To this end, recordings of the electric quantities (voltages, currents) were performed in the transformer primary and secondary respectively, at different frequencies; derived quantities, such as input impedance, powers, transformation ratio a.s.o. were then determined by calculation.
By using the previously identified transformer parameters, it was passed to the circuit simulation and determination of the electrical quantities, which afterwards were compared with the experimentally obtained values. The simulation allowed estimating the influences of some factors, which cannot be neglected in practice, on the transformer performances; such factors are, for instance, the internal resistance of the power supply and the dielectric losses of DUT.
In Figs. 6 and 7, there are presented the diagrams of the primary current I_1 and transformation ratio U_2/U_s variations with frequency, obtained for a supply voltage $U_s = 10\ V_{eff}$, $C_2 = 2\ \mu F$ in the case of the variant of magnetic core from Fig.4c ($K_S = 15\ \%$), containing also the experimental curves.

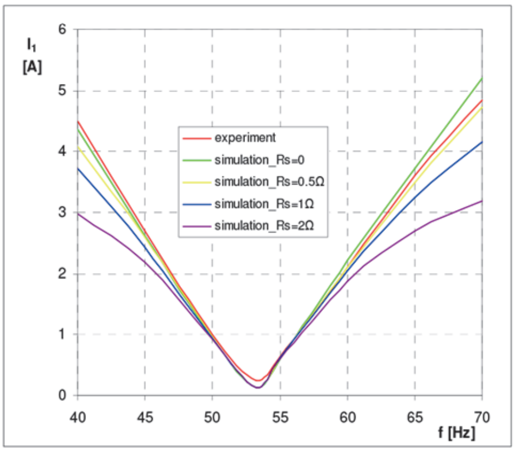


Fig.6 Transformer primary current I_1 versus frequency

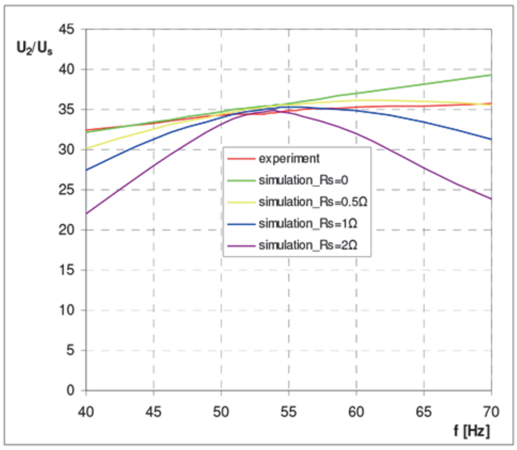


Fig.7 Transformation ratio U_2/U_s versus frequency

The resonance was obtained for the frequency f = 53 Hz, at which the value of primary current I_1 is 0.12 A at simulation (regardless of the internal resistance R_s of the power supply) and 0.25 A experimentally. Instead, there is a good compliance within the branches of the experimental and simulated resonance curves for the presumed source resistance of 0.5 Ω. From Fig.7 it is noticed that at resonance, the same transformation ratio, both experimental and simulated, is obtained, and this value is close to the ratio of the number of turns n_{tr}=36. For studying the dielectric losses influence of DUT on the resonant system energy efficiency, the simulation of the circuit from Fig.5 was done, first without dielectric losses (ideal case) and then taking into account the dielectric losses of DUT (R_p being the equivalent resistance corresponding to $\tan\delta = 1\ \%$), to obtain $U_2 = 20$ kV on the capacitance $C_2 = 1.5\ \mu F$, the constructive variant of the distributed open core being that from Fig.4d ($K_S = 30\%$).
The results obtained at resonance frequency f = 49.96 Hz are presented in Table 4, from which the dielectric losses influence of the DUT on the energy efficiency could be observed.

Table 4 Dielectric losses influence on energy efficiency

No losses	With dielectric losses (tanδ = 1%)
I_1 = 2.97 A	I_1 = 6.36 A
S_1 = 1.7 kVA	S_1 = 3.6 kVA
Q_2 = 187.6 kvar	Q_2 = 185.3 kvar
Q_2/S_1 = 110 kvar/kVA	Q_2/S_1 = 51.5 kvar/kVA

If the open core losses (through the resistance R_m), estimated so as the input impedance of the simulated circuit to be equal with that calculated on the basis of the experimental data, are also taken into account, after the simulation of the circuit from Fig.5, the resonance curves presented in Fig.8 are obtained. It is noticed the increase of the resonance current value from 2.97 A, in the absence of losses, to 6.36 A due to the dielectric losses of the DUT and to 7.13 A, if the iron losses are added, too.

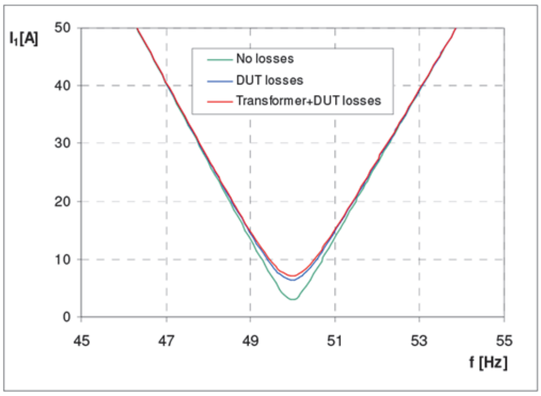


Fig.8 Losses influence on the resonance curves

However, the testing scheme does not loose its practical importance, because the reactive power generated for supplying the load remains almost unchanged.

6. CONCLUSIONS

1. Different technical solutions for generating some important reactive powers were presented, emphasizing a solution that uses a parallel internal resonance transformer with distributed open core and supplied from a variable frequency static source; the assembly is easily transportable and has a specific weight below 1kg/kvar.
2. The parameters of air core / distributed open core transformer were identified, and its performances were determined by experiment and simulation.
3. The energy efficiency of the resonant circuit is between 50 and 150 kvar/kVA, depending on the load parameters, without requiring additional compensation inductances.
4. Starting from the presented system, there are prospects for achieving some systems for industrial tests at medium voltage cables and generators.
5. Further on, the possibilities offered by this solution will be used for achieving some variable inductances with no moving parts, for compensating the cable networks.

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