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## Investigation of transformers for power electronic converters

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# Investigation of transformers for power electronic converters

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**Abstract.** A transformer is an integral part of power electronic equipment and it is usually the input stage of a high power converter. A good model of the transformer is needed to evaluate the performance parameters of power converters. This work represent 2 new methods for short-circuit test of single-phase transformers. The paper offers measurement methods that do not require powerful adjustable AC sources. Short circuit parameters can be determined by measuring the parameters of the transient when switching on: i) capacitor under zero initial conditions to an idle transformer or ii) by a transient process when connected to a non-powered short-circuit transformer of a capacitor under non-zero initial conditions. In order to accurately determine the period and the transition process in the event of a short circuit, it is suggested to include a parallel connected battery. *PSpice* is being used as a simulation tool for analysis and design of power electric circuits.

## 1. Introduction

A number of industry applications require Specific Industrial Transformers due to the usage of power (current) as a major resource for production. High-current Rectifier and Converter Transformers need a specific design to supply the necessary power at a low voltage level. These transformer types (EAF Transformers and Ladle Furnace Transformers), as well as converter transformers for large drive applications are called special-purpose or Industry Transformers, whose design is tailor-made for high-current solutions for industry applications [1, 2, 3].

The electromagnetic chokes and transformers are elements in the structure of almost all electronic energy converters.

The increasing utilization of power converters in power electronics requires fundamental analysis and design of power converters. These studies could provide wide opportunities for electromagnetic chokes and transformers at higher frequency exploitation in power electronic circuits [4].

Magnetic components such as chokes and transformers constitute together with the control and the semiconductor components, the main parts in the design of power electronic converters. In today's power electronics, the power electronic converters can withstand high switching frequencies [2, 5].

Comparing the modern power switches used in power supplies with those from older generations, the new switches have significantly reduced switching times, leading to faster and faster rise and fall times for the voltage and current waveforms. These fast edges produce significant energy at surprisingly high frequencies [5, 6].

Transformers supplying converter applications are connected on their secondary side to a converter. The converter input can be a passive rectifier or have an active front end using controllable semiconductor switches. These elements create a lot of harmonic frequencies. Different drive types are quite diverse in the amount of harmonics produced [7].



Therefore, normal transformers, designed and dimensioned for electricity distribution duty do not work satisfactorily in a converter system. Harmonic frequencies increase the thermal, mechanic and dielectric stresses and therefore the transformers must be specially designed for this duty. Overdimensioning of a normal distribution transformer is not an adequate measure [8].

Aside from power ratings and power losses, transformers often harbor other undesirable limitations which circuit designers must be made aware of. Like their simpler counterparts - inductors - transformers exhibit capacitance due to the insulation dielectric between conductors: from winding to winding, turn to turn (in a single winding), and winding to core. Usually this capacitance is of no concern in a power application, but high-frequency applications may not tolerate this quirk well [9].

The current work proposes not to use the conventional way to determine the short-circuit parameters of transformers and rather use a transitional regime of capacitor's discharging through a transformer. It is also suggested to use a transitional regime in order to determine the frequency of the coils for parameters at elevated frequencies taking into account the capacity of the coils.

In order to determine the parameters of a transformer such as voltage regulation and efficiency, the open circuit and short tests are carried out. These tests are very convenient, as they furnish the required information without actually loading the transformer. Also the power required to carry out these test is very small as compared to full load output of the transformer.

The short circuit test is used to determine the values  $R_s$  and  $X_s$  of the series branch of the equivalent circuit and is carry out with current  $1.25xI_n$ . These impedances are usually very low, but appear higher in value when referred to the high voltage side. This test is consequently performed on high voltage side of the transformer in order to keep the current drawn by these impedances at a manageable level [2, 10, 11].

Common short-circuit test method for power transformers are presented in many in the references. Some testing methods use capacitance and power factor/dissipation factor measurement.

Regularly performing a range of standard electrical tests has proven an effective way to gain a reliable insight into the operating condition of power transformers. Mechanical changes to windings, contact problems in the tap changer or at other connections, shorted windings/coils, as well as interruptions or short-circuit of parallel lines can all be diagnosed early by using conventional testing methods. Severe and costly damage can be thereby prevented. These conventional testing methods include measuring a number of parameters, such as the short circuit impedance, transformers ratio, magnetizing current, etc. Tayeb et al. represents numerical method based on Visual basic language to get the operating characteristics of power transformer, including short circuit parameters [12]. =

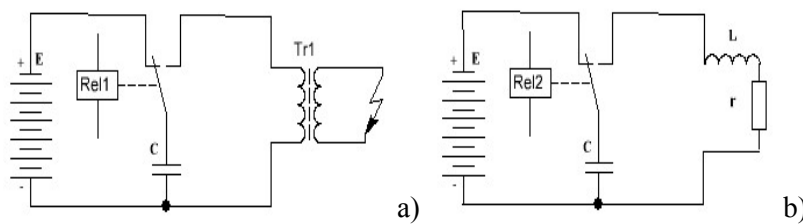
## 2. Experimental investigation

Present work proposed new method for short-circuit parameters determination of transformers for electronic converters to be determined by cause a transient discharge process of preloaded capacitor through the secondary transformer coil.

Work measurement methods that do not require powerful adjustable AC voltage sources are available. The short-circuit parameters are determined by measuring the parameters of the transitional process by switching in:

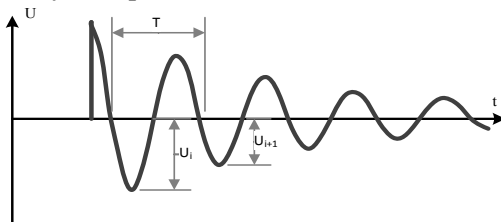
- a capacitor at zero initial conditions to an idle running transformer;
- or through a transitional process when switching in a non-powered transformer with a capacitor's shading coil at non-zero initial conditions;
- and the third possibility is to determine the short-circuit parameters on basis of measuring processes in commutation phenomenon of converters, more particularly of rectifiers.

The shown equivalent circuit is used to represent the transformer for experimental study. In short circuit mode the equivalent circuit of the transformer is reduced to inductance and equivalent resistance of the windings in a series connected, Figure 1.



**Figure 1.** Electrical circuit (a) and equivalent circuit (b) of the transformer used for experimental investigation.

The idea of the proposed method is to cause a transient discharge process of preloaded capacitor  $C$  through the coil of the transformer when the other coil is short-circuited. For the experimental part electrolytic capacitor was selected:  $U = 400\text{ V}$  and capacitance  $C = 1\ \mu\text{F}$ .



**Figure 2.** Transient discharge process of preloaded capacitor.  $T$  is time period and  $U_i$  is the amplitude.

The parameters of the transitional process, which is a damped sine wave, allow to measure the period  $T$  of own fluctuations and attenuation - by the ratio of the amplitudes of two consecutive periods  $U_i/(U_{i+1})$ , Figure 2. The measured parameters and the value of the used capacitor  $C$  determines the inductance of the short circuit.  $L_{1,2}$  and the equivalent resistance of the transformer aligned to the used coil.

A similar approach is used in the so called "diagnostics of automation objects", even for more complex objects.

The study was carrying out by using the following formulas and mathematical dependencies:

- Voltage across the capacitor in equivalent circuit:

$$U_C(t) = U_C(0) \cdot \cos \beta t, \quad (1)$$

where  $\alpha$ - attenuation coefficient of own fluctuations;

- angular velocity  $\beta = 2\pi f$ . If we use frequency equation:  $f = 1/T$  we get next dependence:

$$\beta = \frac{2\pi}{T} = \sqrt{\omega_0^2 - \alpha^2}, \quad (2)$$

where  $\omega_0$  is resonance frequency,  $T$  is time period;

At considered use of transformers for electronic converters, the damping ratio of own fluctuations  $\alpha$  is much smaller than the resonant frequency  $\omega_0$ . Then expression (1) is simplified to:

$$\beta = 2\pi f = \frac{2\pi}{T} = \sqrt{(\omega_0^2)} = \sqrt{\frac{1}{LC}}. \quad (3)$$

The inductance value is calculated by the following formula [1]:

$$L = \frac{T^2}{4\pi^2 C} \quad (4)$$

To account for the impact of the active resistances that cause the attenuation it is suggested to determine the ratio  $U_i/(U_{i+1})$  and after that to determine the attenuation coefficient of the own oscillations  $\alpha$  by using the following mathematical expression [2]:



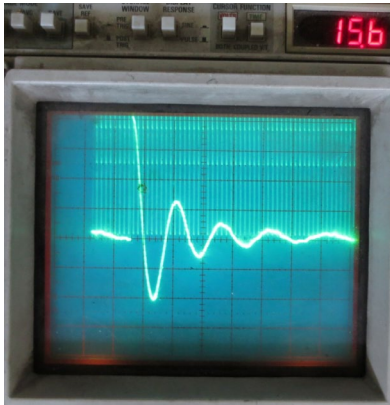
**Figure 3.** Type of appearance of transformer used in experimental investigations: type ETB 400-10/0.4, voltage 10000/400V, current 23.09/577.4 A,  $f = 50$  Hz, 3-phase step-down transformer.

$$\begin{aligned} P &= 400 \text{ kVA}; & P_{1F} &= 133.3 \text{ kVA}; \\ P_F &= 133.3 \text{ kVA}; & U_{2F} &= 5780 \text{ V}; \\ I_{2F} &= 23.09 \text{ A} & U_{sc} &= 3.95 \%; \\ Z_{sc} &= 9.9 \Omega; & L_{sc} &= 63.06 \cdot 10^{-3} \text{ H} \end{aligned}$$

$$\alpha T = \ln \frac{U_i}{U_{i+1}} \quad (5)$$

Experimental tests verification were carried out on a transformer with the following data and type of appearance, shown on Figure 3.

For the studied power transformer, an experiment has been conducted and a waveform of the transitional process has been recorded by oscilloscope, Figure 4. The inductance value have been determined analytically and compared with the experimental data. Also, the error value has been determined:  $\varepsilon = -2.25\%$ .



**Figure 4.** Capacitor discharging waveform connected to power transformer. The waveform was used to determine the period  $T$ .

$C_1 = 100 \mu F$  – discharge capacitor connected to the secondary side of a power transformer

$T = 15.6 \text{ ms}$  value representing the transient capacitor discharge process through the secondary side of a power transformer

$$T = 2\pi \sqrt{LC}$$

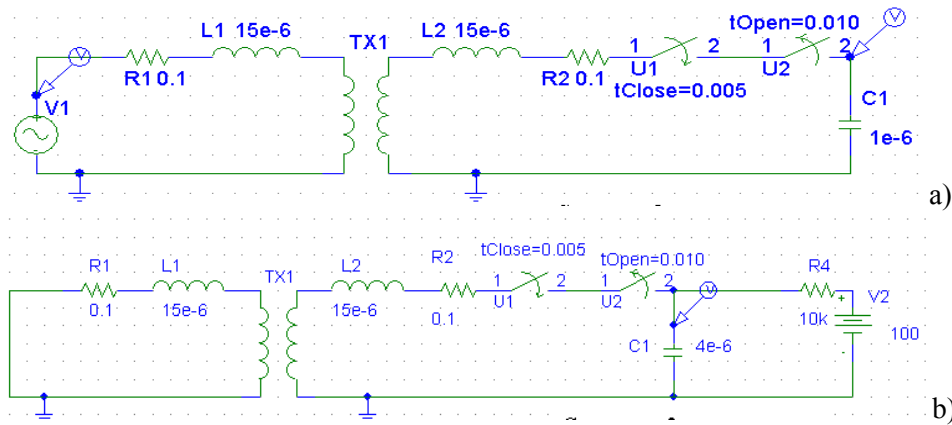
$$L = \frac{T^2}{(2\pi)^2 C} = 0.06164 \text{ H} - \text{inductance value}$$

### 3. Simulation results

This article proposes an analogy between a three-phase medium voltage transformer and a single-phase low voltage transformer for short-circuit testing. For this purpose the article uses a traditional model of a single-phase transformer in a *Pspice* environment, which includes a source of sinusoidal voltage, serial connected resistance and inductance, Figure 5. L1 and L2 are respectively the inductances of the primary and secondary windings of the transformer under test. R1 and R2 are the active resistances of the primary and secondary windings. The inductance L1 models the magnetizing inductance and the resistor R1 models the core losses. The two switches included in the transformer secondary circuit are required to simulate the on and off process. The short circuit mode is achieved by diluting a electrolytic capacitor C1 ( $U = 400 \text{ V}$ ,  $1 \mu F$ ) connected to the secondary coil of the studied transformer. We use ideal transformer model where the coupling coefficient is set to 1. The *Pspice* schematic is as shown on Figure 5a.

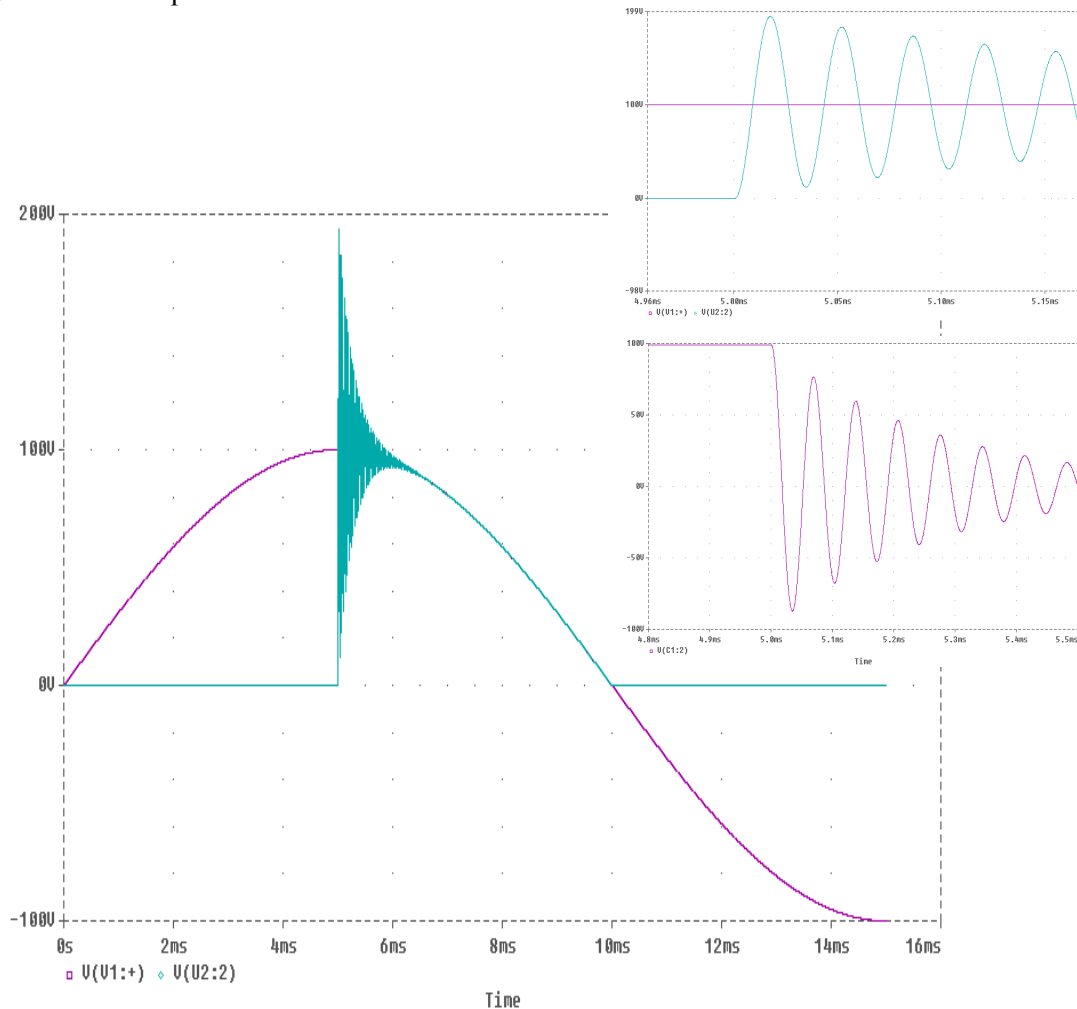
The electrical circuit shown in Figure 5b enables the simulation and the experimental evaluation of the transient and the process of the capacitor to be simulated several times. The selected voltage source has a value of  $100 \text{ V}$  and a resistance of  $10 \text{ k}\Omega$ .

The article also offers the possibility for precise determination of the period  $T$  by parallel connection to the capacitor C1 of an additional voltage source.



**Figure 5.** Equivalent *PSpice* circuit model of the transformer (a) and equivalent circuit with additionally included voltage source (b).

The results of the simulation are given in Figure 6. Figure 6 shows voltage waveforms of U1, U2 and voltage across the capacitor C1 obtained when a short circuit occurs.



**Figure 6.** Simulated waveforms of discharge process of preloaded capacitor C1 (U2).

#### 4. Conclusions

Experimental studies of gamma transformers have been carried out and the results of a 400 kVA transformer are presented in the article. The experiment was performed by diluting an electrolytic

capacitor connected to the secondary side of the transformer, the primary winding being short-circuited. The paper offers measurement methods that do not require powerful adjustable AC sources. Parameters for short circuit are determined by measuring the parameters of the transient when switching on: *i*) capacitor under zero initial conditions to an idle transformer or *ii*) by a transient process when connected to a non-powered short-circuit transformer of a capacitor under non-zero initial conditions. The proposed method cause a transient discharge process of preloaded capacitor through the coil of the transformer provides sufficient accuracy – 2.25 %. The method is easily applicable to transformers for the needs of electronic converters operating at a wide range of frequencies and powers. Short-circuit testing transformers for high-power should be performed with a high-power source as well. These conditions are difficult to achieve, so the proposed method avoids this disadvantage. In the research laboratories are necessary small investments by applying the proposed method for short-circuit transformer parameters determination. The article proposes two simulation models of a single-phase low-power transformer. The first model, Figure 5a, proposes that a short circuit test be performed with a capacitor simulating the short circuit process. The second model, Figure 5b, adds a voltage source to the capacitor in parallel to charge the capacitor periodically. In conclusion, it can be said that there is a coincidence between the experimentally obtained results and the data provided by the manufacturer for the voltage and inductance of the short circuit. The simulation data obtained confirm the transient process and show the voltage damping by allowing the relationship to be determined  $U_i / (U_i + I)$ .

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