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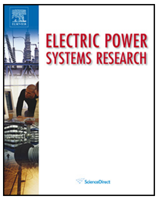

Influence of voltage harmonics on transformer no-load loss measurements and calculation of magnetization curves

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ABSTRACT

This paper investigates the voltage distortion phenomenon during no-load testing of transformers, its influence on no-load loss calculations, and a novel measurement technique that is unaffected by harmonics for obtaining transformer magnetization curves. Owing to economic reasons, no-load loss correction for distorted test waveforms has been addressed to some extent in existing standards, while not much has been done on the aspect of calculation of magnetization characteristics. This is important for parameter estimation and transformer modeling in power system transient simulations. Results from two test cases are presented, one is based on factory testing with 290-MVA, three-phase, three-legged power transformer and second is a more comprehensive analysis using a laboratory test setup with a 22-kVA single-phase transformer. Application of loss correction equations and limits based on existing testing standards was evaluated and found to result in overcompensation, while calculation of magnetization curves based on existing methods resulted in error up to 20%. Whereas, application of proposed measurement technique based on voltage "Zero-Crossing" detection is shown to result in negligible error. The proposed measurement technique uses the same input signals as in a standard no-load test procedure. Hence, it can be easily implemented in parallel with existing instrumentation.

1. Introduction

Transformers represent an important link in generation, transmission, distribution and utilization of electrical energy in power systems. Before leaving the production test facility, a series of tests are performed to inspect and certify the performance of a transformer in accordance with IEEE or IEC standards [1–4]. No-load or open-circuit testing of transformers is part of the routine test series and the outcome of the no-load test is typically a series of data points at different excitation voltage levels, with rms current and active power as shown in Table 1.

Even though no-load losses represent a small fraction of the transformer throughput, they are present as long as the transformer is energized and can contribute significantly to system-wide energy losses [5,6]. Hence, accurate measurement of no-load losses is of crucial importance. Another application of transformer test results is for parameter estimation and modeling in power system simulations such as electromagnetic transients program (EMTP) representing low-frequency or slow-front transient phenomenon [7–9]. In the last few years, EMTP simulations have gained lot of importance in predicting dangerous transient conditions involving the power system network, devices, and equipment. However, the first step is to reduce uncertainty in parameter estimation. Short circuit test results are used to identify leakage reactance and winding resistance of transformers; these parameters behave linearly, hence, their estimation is fairly simple. On the other hand, no-load test data is used to characterize the core losses and magnetizing inductance, which is intrinsically non-linear, thus their estimation is more challenging [10–14].

An effect of non-linearity of the core is the development of harmonics primarily in the current [15,16], however, due to the source and line impedance of the test circuit, the resulting voltage drop is affected and hence the voltage applied at the terminals of the transformer during the no-load test is distorted. Both IEEE and IEC recognize this limitation and propose correction formulas for moderate test voltage distortion within limits of 5% and 3% respectively for correction of measured no-load losses to a sinusoidal excitation voltage basis [1–4]. Further, IEEE standard C57.123 [3] recommends the terminal voltage Total Harmonic Distortion (THD) should be within 15% to avoid test waveforms with multiple zero-line crossings as it may result in additional hysteresis losses. However, the present standards do not allow any compensation for the excitation

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Table 1
290-MVA three-phase transformer factory test report data.

Main data	[kV]	[MVA]	[A]	Coupling
HS	432	290	388	YN
LS	16	290	10,465	d5
Open-circuit	E_0 [kV, (%)]	[MVA]	I_0 [%]	P_0 [kW]
LS	12 (75)	290	0.05	83.1
	14 (87.5)	290	0.11	118.8
	15 (93.75)	290	0.17	143.6
	16 (100)	290	0.31	178.6
	17 (106.25)	290	0.67	226.5
Short-circuit	[kV]	[MVA]	*ek*, *er* [%]	P_k [kW]
HS/LS	432/16	290	14.6, 0.24	*704.4*

current, as the 5% and 3% limit enforced on the magnitude of loss correction guarantees that the effect of voltage harmonics on the magnitude of rms value of the excitation current is small to cause it to exceed the manufacturer's guaranteed value [3]. While this may not pose any financial implications, it can introduce significant error in the calculation of transformer magnetization curves. As will be demonstrated in this paper, it is possible to violate the 5% and 3% loss correction limits even for waveforms with relatively low harmonic content (THD < 15%). Secondly, even for situations when the above recommended loss correction limits are met, application of IEEE and IEC correction formulas may result in corrected losses that deviate from the case with nearly sinusoidal voltage excitation [17,18]. Hence, objective of this paper is (1) to present a systematic investigation on the nature of terminal voltage distortion experienced during no-load testing of transformers, (2) to quantify the magnitude of IEEE and IEC recommended loss correction with varying levels of excitation and distortion, and (3) to demonstrate application of voltage "Zero-Crossing" detection as an enhanced method for calculation of magnetization curves.

2. Voltage distortion, no-load loss correction, and magnetization curves

2.1. Measurement of voltage distortion during no-load test

If $v_{ex}(t)$, represents the instantaneous excitation voltage waveform applied at the terminals of the transformer, with time period T and V_k represents rms magnitude of harmonic components, with $k = 2...N$ representing a finite number of harmonics, the following parameters (1)–(4) can be used to quantify distortion:

$$\text{True rms}: V_{rms} = \sqrt{\frac{1}{T}\int_0^T {v_{ex}}^2(t)dt} \tag{1}$$

$$\text{Average rms}: \quad V_{avg-rms} = \left(\frac{2}{T}\int_0^{T/2} v_{ex}(t)\,dt\right)\cdot\frac{\pi}{2\sqrt{2}} \tag{2}$$

$$\text{Total Harmonic Distortion}: THD = \sqrt{\frac{\sum_{k=2}^{N} V_k^2}{V_1^2}} \tag{3}$$

$$\text{Form Factor}: FF = \frac{V_{rms}}{V_{avg-rms}} \tag{4}$$

Harmonic decomposition can be performed using Fast Fourier Transform (FFT) with integer power of 2 samples and whole number of cycles to avoid spectral leakage effects [19]. Other quantities of interest such as active power and flux-linkage can be obtained using numerical integration as below in (5) and (6).

$$P = \frac{1}{T}\int_0^T v_{ex}(t)i_{ex}(t)dt \tag{5}$$

$$\lambda(t) = \int_0^T v_{ex}(t)dt \tag{6}$$

2.2. No-load loss correction

The problem of measuring no-load losses under influence of non-sinusoidal excitation is not unique to transformers and is a much broader issue encountered with design and application of magnetic materials [20–22]. However, most of the approaches proposed require access to magnetic and physical properties of the core and use empirical relations; hence, they are not practical for application in a factory testing environment. Secondly, very few references [23–25] actually address the problem of correction of no-load losses to a sinusoidal excitation basis for transformers. The approach recommended by present IEEE and IEC standards [1–4], based on the average-responding voltmeter method is used. In this method, the test voltage is adjusted based on the average-responding voltmeter to obtain hysteresis losses; however, readings of both true rms and average-responding voltmeters are necessary to correct the eddy current loss component to a sinusoidal basis using (7) and (8) for IEEE and IEC, respectively. Magnitude of loss correction can be calculated using (9).

$$IEEE: P_0 = \frac{P_m}{P_1 + kP_2},\ k = \left(\frac{V_{rms}}{V_{avg-rms}}\right)^2 \tag{7}$$

$$IEC: P_0 = P_m(1 + d),\ d = \frac{V_{avg-rms} - V_{rms}}{V_{avg-rms}} \tag{8}$$

$$\%correction = \frac{|P_0 - P_m|}{P_m} x100\% \tag{9}$$

where P_0 represents the corrected value and P_m represents measured losses.

The IEEE formula (7) also makes provision to account for separation of hysteresis and eddy current losses as P_1 and P_2 in per unit values respectively. If actual values are not available, IEEE recommends using 0.5 per unit for each. Both the IEEE and IEC formulas are equivalent when the Form Factor of the waveform approaches unity, as in the case of pure sinusoidal waveforms. As the Form Factor increases, the equations begin to deviate. If waveform distortion causes the magnitude of loss correction to exceed 5% and 3% for IEEE and IEC respectively, the test is subject to agreement between the manufacturer and purchaser [3,4].

2.3. Transformer magnetization curves

The third aspect of this paper deals with the calculation of transformer magnetization curves, which is critical for modeling transformers in power system transient simulation programs like EMTP and also harmonic load flow studies [7,26–28]. In order to describe the nonlinear characteristic of a transformer iron core, various approaches can be used [29–31]. However, the fundamental step involves calculation of the single-valued anhysteretic magnetization curve. Methods to convert rms quantities from the no-load test data into piece-wise nonlinear magnetization characteristic are described in Refs. [26,27] and is referred to as the "CONVERT" routine in EMTP [26] and "SATURA" routine in Alternative Transients