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The role of load harmonics in audible noise of electrical transformers

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ABSTRACT

Harmonic components in load currents have a larger impact on the load noise level of transformers than might be expected from their amplitude. There are several reasons for this larger impact: (a) the interaction of higher harmonics with the large fundamental load current at power frequency, (b) the increasing sound radiation efficiency with increasing frequency, and (c) the greater sensitivity of the human ear to higher frequencies, which is considered in sound measurements by applying the A-weighting filter. This paper describes the process of generation, transmission, and emission of load noise in the presence of load harmonics. A calculation scheme is presented that is able to estimate the noise increase and the noise spectrum of electrical transformers under non-sinusoidal load conditions. The proposed calculation scheme is applied to three practical examples.

1. Introduction

Electrical power and distribution transformers operating in the field regularly show significant noise level deviations from the sound measurements made by the manufacturer under the controlled and standardised measurement conditions applied in a test field. The main reasons follow: (a) the acoustical ambient conditions are changed on-site by sound reflection and diffraction caused by nearby obstacles; (b) the structural and acoustical resonances are altered; and (c) the principal operating conditions on-site are different. While the first factory test for load noise applies a pure sinusoidal current with short-circuited secondary winding, transformers on-site operate at power load factors that change (phase angle between voltage and load current), loading beyond the rated power (overload, partial load) and harmonics in the load current.

Harmonic components in the power grid are caused primarily by non-linear loads and by the non-linear transfer characteristic of the power grid [1]. Any electrical device that shows a non-linear consumption of active power or a non-linear change of the source impedance draws a distorted current waveform, even if the supply voltage is sinusoidal. With the continuously growing use of electrical and electronic devices, waveforms distorted by harmonics in the power supply grid have increased sharply within the past years. Devices such as variable speed drives (VSD), six-pulse bridge rectifiers used in power electronics, and switched mode power supplies (SMPS) draw a non-sinusoidal but pulsating current. While most electric devices generate solely odd harmonics, some devices with fluctuating power consumption generate odd, even, and inter-harmonic currents [2].

Recently, transformer load harmonics and the related sound emissions have been the focus or research because of the increasing use of renewable energy sources. Variable speed wind turbines inject harmonic currents in the grid-side power converters, which create harmonic distortion problems in the network [3,4]. In urban areas with a high photovoltaic population, the current harmonics from inverters were found to exceed the nationally permitted limits of system perturbation in low and medium voltage power systems [5].

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Transformer load noise is generated by electromagnetic forces acting on the transformer windings. The forces are proportional to the square of the load current (Section 2.2). This quadratic response behaviour generates winding vibrations at frequencies higher than the power frequency. In the case of harmonics in the load current, the resulting magnetic force and noise components have harmonics with a more complex frequency spectrum. The related increase in the load noise level must be considered in the estimation of the total noise level of transformers under real load conditions. The question arises about how to predict the resulting noise level under these loading conditions to guarantee that the sound level at the transformer site does not exceed the maximum allowed by legislative regulations or the owners specification.

The fundamental process of load noise generation, its characteristics and contribution to the total transformer noise as well as the measurement and estimation of load noise levels are presented in [6–10]. In more detail, the parameters affecting the load noise levels and their variability are treated in [11–14]. By investigating the relevance of load noise emission over time, it can be noticed that the contribution of load noise to the total noise level of power transformers has increased or even become dominant [15]. This observation is based on the continuous improvements in transformer core design and core material (electrical steel). Here, the related magnetic and magnetostrictive noise of transformer cores (no-load noise) has been greatly reduced over the last three decades.

The literature shows that the formation of harmonic distortions in power grids has been intensively studied [2,16,17]. In contrast, publications about the interaction of power system harmonics with transformers are mainly limited to heating effects based on frequency dependent eddy current losses and core hysteresis losses [1,2]. Rarely, publications can be found dealing with the impact of load harmonics on load noise. A systematic approach describing the generation of load noise harmonics as well as predicting the related changes in the load noise level of power transformers in the presence of power system harmonics is currently not available.

Starting from basic principles, this paper describes and quantifies the fundamental generation process of harmonics in winding forces, winding vibrations, and load noise in electrical power transformers caused by load harmonics. A calculation scheme for a physically based and fast estimation of the increase in the load noise level for a given load current spectrum is presented. This scheme includes the magneto-mechanical coupling at the transformer windings as well as the fluid–structure coupling of the sound transmission and emission process at the fluid-filled transformer tank.

Furthermore, the frequency-dependent sound radiation efficiency of a transformer is included using a different weighting of harmonic sound components. The frequency-dependent sensitivity of the human ear is considered by applying the A-weighting filter. Because of its practical relevance, the effect of the phase relations of load current harmonics to the resulting harmonic noise components and the overall sound level is investigated in detail. Finally, three practical examples of load noise increased by load harmonics are given.

2. Load noise generation with respect to load harmonics

2.1. Description of load current harmonics

Consider a transformer in operation with power supply at an operating frequency, f_1, with a load current amplitude, $\hat{I}_1$, and phase, φ_1. In the case of superimposed harmonics, the transient load current $I(t)$ has the general form

$$I(t) = \sum_{i=1}^{N} \hat{I}_i \sin(\omega_i t + \varphi_i), \tag{1}$$

where N denotes the total number of harmonics. Thus, a harmonic component of order i is completely described by its angular frequency, $\omega_i = 2\pi f_i$, amplitude, $\hat{I}_i$, and phase angle, φ_i.

2.2. Generation of magnetic forces on windings

The magnetic coupling of the windings is imperfect in a real transformer; thus, a magnetic leakage flux field arise between the concentric windings if the transformer is at load. According to Ampere's law in the quasi-static case, the load current in the transformer windings generates a magnetic field that is proportional to the current density

$$\nabla \times \mathbf{H} = \mathbf{J}, \tag{2}$$

where $\mathbf{H}$ denotes the vector of the magnetic field strength and $\mathbf{J}$ the current density vector. Because the windings are located in air or immersed in an oil-filled tank, the constant relative magnetic permeabilities $\mu_r \approx 1$ in these non-ferromagnetic materials dominate the magnetic field properties in any closed contour of magnetic flux crossing the windings [18]. Thus, the vector of the magnetic flux density, $\mathbf{B}$, is proportional to the vector of the magnetic field strength:

$$\mathbf{B} = \mu_r \mu_0 \mathbf{H}, \tag{3}$$

where $\mu_0 = 4\pi \times 10^7$ Vs/Am denotes the magnetic constant and μ_r the relative permeability. Consequently, the magnitude B of the leakage flux next to a winding can be estimated by

$$B \approx \mu_0 \frac{NI}{l}, \tag{4}$$