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Inrush current mitigation in three-phase transformers with isolated neutral

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ABSTRACT

In this paper, a new method for inrush current mitigation of three-phase transformers with isolated neutral is presented. The method uses controlled switching and requires independent-pole-operated circuit breakers. Two switching operations are proposed at time instants that achieve optimal mitigation of inrush current.

1. Introduction

Uncontrolled energization of power transformers can create large flux asymmetries and saturation of the transformer magnetic core. This saturation results in high current magnitudes with a wide harmonic spectrum and a high direct-current component [1].

Inrush currents can cause false operation of protective relays [2,3], reduce transformer lifecycle [4,5], and usually reduce power quality on the system [6,7]. The magnitudes reached by these currents depend on two principal factors: the point on the voltage waveform at which the switches are closed; and the residual fluxes in the transformer core [8].

Several methods, such as series compensator [9,10], sequential phase energization with a grounding resistor [11,12] and controlled switching [1,8,13,14], have been developed to reduce the inrush current. Among these, the controlled switching that takes into account the core residual flux constitutes the most promising method. Its basic principle is to guarantee that the residual fluxes are equal to the prospective fluxes at the instant of energization. A prospective flux is the steady-state flux if the supply source is already connected to the transformer.

The success of the controlled switching techniques requires independent pole operated circuit breakers, whose closing characteristics are stable and repeatable. The desired closing time deviations are less than ±1 ms [13]. This could result in an additional cost which may be offset by the reduction of maintenance costs of the breaker and transformer [15]. However, when the safety and reliability of the power system are involved, the incremental cost of implementing controlled switching is negligible.

In particular, in [1,8], controlled energization has been applied to three-phase transformers whose neutral is earthed. In these cases, one phase is energized at the optimal point on the voltage waveform, and the remaining two phases are energized later. This method is widely used in earthed-neutral systems but cannot be applied when the neutral is isolated, since, in this case, closing one pole of a three-phase breaker applies no voltage to any transformer winding.

A controlled switching method for isolated neutral systems has been described in [16]. This method is based on prospective and residual fluxes computed from phase-to-phase voltages, but it does not provide an analytical expression of the proper closing instants. In this paper, optimal switching instants are determined analytically based on the solution of a min-max problem in order to minimize flux asymmetry during transformer energization.

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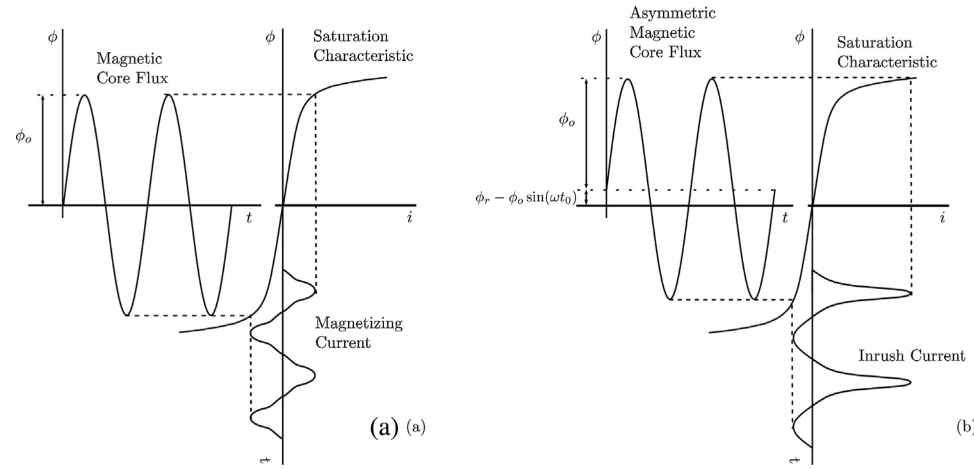

Fig. 1. Inrush current generated when flux exceeds saturation limit.

Furthermore, residual fluxes are computed from phase-to-ground voltage. The voltage signals needed by the controller for this process may be taken from Voltage Transformers (VTs) or Capacitor Voltage Transformers (CVTs) which are commonly installed adjacent to the transformer. This new approach achieves optimal mitigation of inrush current.

Section 2 focuses on the controlled switching principles to reduce inrush current. Section 3 describes the residual flux measurement in ungrounded transformers using phase-to-ground voltage. Section 4 describes the proposed controlled energization method, while Section 5 presents the simulation results which verify inrush current elimination during energization. The results of this paper are summarized in Section 6.

2. Controlled switching principles

Suppose a voltage $u(t) = U_o \cos(\omega t)$ is applied to an unloaded transformer at instant t_0. It is well known that the core flux is the integral of the applied voltage and can be expressed as

$$\phi(t) = \phi_r + \frac{1}{N}\int_{t_0}^{t} u(\tau)d\tau = \phi_r - \phi_o \sin(\omega t_0) + \phi_o \sin(\omega t) \qquad (1)$$

where $\phi_o = U_o/(N\omega)$ is the sinusoidal flux amplitude, and ϕ_r is the residual flux prior to instant t_0. ϕ_r is a permanent magnetization of the core that remains due to hysteresis of the ferromagnetic material when the transformer is de-energized.

From (1), the maximum possible value of the flux $\phi(t)$ upon energization is $2\phi_o + \phi_r$. Power transformers are designed to operate at a rated voltage and flux close to the saturation knee point (Fig. 1a). The core enters deep saturation as soon as the core flux exceeds the rated value, resulting in a large magnetizing current (Fig. 1b).

Fig. 2 illustrates the basic principle for the elimination of the core flux asymmetry: the prospective flux (indefinite integral of the applied voltage) at the instant of energization must equal the residual flux. This is equivalent to selecting the energization instant t_0 such that $\phi_r = \phi_o \sin(\omega t_0)$, in accordance with (1).

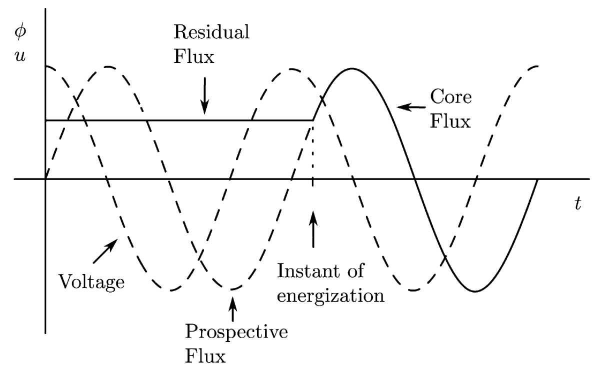

Fig. 2. Optimal energization to eliminate core flux asymmetry.

3. Measurement of residual magnetic fluxes in ungrounded transformers

The residual fluxes can be obtained by integrating the corresponding phase voltages during de-energization, in accordance with Faraday's law. For this purpose, the three voltages between the lines and the transformer neutral point are required. For economic reasons, the neutral may not be located outside the tank, thereby saving the cost of a bushing. Therefore, the transformer neutral point is occasionally inaccessible. However, the phase voltages of the transformer can be obtained from the phase-to-ground voltages. Fig. 3 shows a simplified system to energize the ungrounded transformer. The following equations hold:

$$\begin{aligned} u_{AN} - u_{BN} &= u_{AG} - u_{BG} \\ u_{BN} - u_{CN} &= u_{BG} - u_{CG} \\ u_{CN} - u_{AN} &= u_{CG} - u_{AG} \end{aligned} \qquad (2)$$

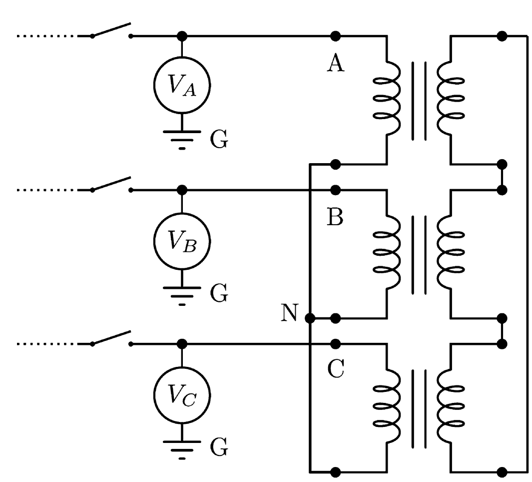

Fig. 3. Simplified system to energize the ungrounded transformer.