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Optimal gang-operated switching for transformer inrush current reduction

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ABSTRACT

Controlled switching technology with independent-pole-operated circuit breakers is an effective way to eliminate transient transformer inrush currents. This technique cannot usually be applied at lower voltage levels where three-pole-operated circuit breakers are more frequent. In this paper, the optimal instant for a simultaneous closing is obtained as a solution of a min–max problem. The proposed strategy has been evaluated in a test system using EMTP/ATP and has presented highly satisfactory results, even when actual characteristics of circuit breakers are taken into account.

1. Introduction

Power transformers are among the most important devices in power networks. Transformer energization may result in a high magnetization current, also known as inrush current, due to the saturation of magnetic flux in the core. The inrush current is asymmetric and unbalanced between the phases and can reach a value that is several times higher than the rated current of the transformer.

These transient currents have many unfavorable effects including: malfunction of protective relays or fuses [1,2], reduction of transformer lifecycle due to large current forces in windings [3,4], and temporary voltage drop due to impedance of the network between the sources and the energized transformer [5,6], thereby affecting the power quality of the network.

Various methods have been proposed to eliminate or at least reduce the inrush current, such as series compensator [7,8], sequential phase energization with a grounding resistor [9,10] and controlled switching [11–13].

Controlled switching systems have become a technically and economically suitable way to mitigate switching transients. In particular, in [11,13], this method has been applied to three-phase transformers. The fundamental aim is to energize the transformer windings at appropriate instants resulting in flux symmetry in consideration to the residual flux. An optimal energization, without core saturation or inrush transients, can be achieved following this method. Since each phase needs to be switched separately, independent-pole-operated circuit breakers are required. While this is normal practice above about 245 kV, additional mechanisms, and hence costs, may be incurred at lower voltage levels where gang operation is common [14]. Furthermore, this method can only be used in transformers whose primary winding has a wye connection and grounded neutral.

To achieve the total elimination of the inrush current using circuit breakers with one operating mechanism, it is necessary that the residual fluxes present a particular pattern [11], where the residual flux is equal to zero in one phase and is high in the other two with opposite polarity. Two different ways have been proposed to attain the desired pattern. In [15], DC auxiliary power supply is used to force the core magnetization to the desired pattern before simultaneous closing transformer energization. The DC supply must be disconnected during the transformer switch-on. The method requires a precise knowledge of the magnetization curve of the transformer core and the use of additional equipment. On the other hand, a synchronized switching method for a three-pole

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circuit breaker with fixed delay between poles (mechanically staggered) is presented in [16]. Optimal energization is obtained by setting the residual flux with controlled de-energization. The residual flux pattern is a function of many factors, such as the chopping-current value of the circuit breaker, the magnetic characteristic of the transformer core, and mainly of the capacitance of the winding and other capacitances connected to the transformer. For this reason, precisely controlling de-energization is a difficult task. Furthermore, in the case where there is an unplanned de-energization, for example when a fault occurs, any non-desired pattern can be found in the magnetic core.

In this paper, a simpler approach of controlled switching is used to avoid the drawbacks of the above methods and, particularly, to reduce the costs. As in commercial controlled switching devices for three-pole breakers, during uncontrolled de-energization, residual flux is computed by integrating the corresponding phase voltage, in accordance with Faraday's law. Considering the residual flux, a simultaneous closing instant can be chosen to reduce the inrush current. In [17], a non-optimal heuristic closing instant has been proposed. In this work, an optimal closing instant that results in the lowest possible inrush current is obtained by solving a min–max problem. The advantages of this approach are: three phases are closed simultaneously and hence no independent pole control is required, de-energization does not need to be controlled, and no additional device is required because the corresponding voltage signals needed by the controller for the residual flux calculation process may be taken from Voltage Transformers (VTs) or Capacitor Voltage Transformers (CVTs) which are commonly installed near to the transformer. This method cannot guarantee the complete elimination of the inrush current in all cases, but for its simplicity and low cost, this approach may be the most appropriate solution, especially at lower voltage levels where gang-operated circuit breakers are common.

Section 2 focuses on the principles of controlled switching to reduce the inrush current. Section 3 describes the proposed controlled energization strategy, while Section 4 presents the simulation results which verify that a higher reduction of inrush is obtained compared to uncontrolled energization. Practical considerations on how the characteristics of a real circuit breaker affect the proposed strategy are analyzed in Section 5. The results of this paper are summarized in Section 6.

2. Controlled switching principles

When a voltage $u(t)$ is applied on the primary winding of an unloaded transformer a flux $\phi(t)$ is established in the magnetic core. Neglecting winding resistance, the relationship between the applied voltage and flux is

$$u(t) = N\frac{d\phi(t)}{dt} \quad (1)$$

Suppose a sinusoidal voltage $u(t) = U_o\cos(\omega t)$ is applied at instant t_0, then the core flux can be calculated analytically as

$$\phi(t) = \phi_r + \frac{1}{N}\int_{t_0}^{t} u(\tau)d\tau = \phi_r - \phi_o\sin(\omega t_0) + \phi_o\sin(\omega t) \quad (2)$$

where $\phi_o = U_o/(N\omega)$ is the normal flux peak and ϕ_r is the residual flux prior to instant t_0. ϕ_r is a magnetic flux that remains after the transformer is de-energized.

From (2), the maximum possible value of the flux $\phi(t)$ upon energization is $2\phi_o + \phi_r$. In the worst case, when the transformer is energized at zero crossing of the voltage and prospective flux is of the opposite polarity as residual flux, then the peak value of

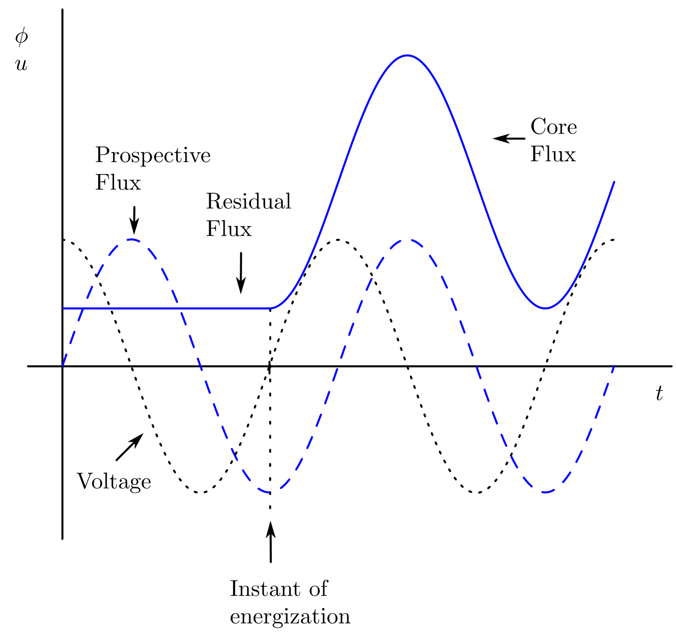

Fig. 1. Large flux asymmetry created by energization at zero crossing of voltage.

the flux is higher than twice the normal maximum (Fig. 1). The prospective flux is the steady-state flux if the supply source was already connected to the transformer.

Fig. 2 illustrates the influence of the maximum flux on the inrush current. Power transformers are designed to operate at a rated voltage and flux close to the saturation knee point (Fig. 2a). The core enters deep saturation as soon as the core flux exceeds the rated value, resulting in a large magnetizing current (Fig. 2b).

The basic principle for the elimination of the core flux asymmetry in single-phase transformers is shown in Fig. 3. The optimal instant for transformer energization is when prospective and residual fluxes are equal. This is equivalent to selecting the switching instant t_0 such that $\phi_r = \phi_o\sin(\omega t_0)$, in accordance with (2).

3. Proposed strategy

In this section, an optimal strategy for three-phase transformer energization using simultaneous closing is described. The method can be applied to three-phase transformers energized from any winding connection where the sum of the three winding fluxes is equal to zero, that is, for three-legged-core transformers or transformers with a delta connection in another winding. This is not the case for five-leg or shell-type core transformers without delta connected winding.

In order to describe the energization process more clearly, it is assumed that the residual fluxes are $\phi_{Ar} = R_1$, $\phi_{Br} = R_2$, $\phi_{Cr} = R_3$ with $|R_1|, |R_2| \geq |R_3|$, and $R_1 > 0$.

As already mentioned, in single-phase transformers, the inrush current can be eliminated by selecting the energization instant when the prospective flux is equal to the residual flux. However, except when the remanent fluxes have certain patterns, this condition cannot be fulfilled simultaneously in each of the three windings of a three-phase transformer.

Fig. 4 illustrates the residual fluxes (solid line) R_1, R_2 and R_3 and prospective fluxes (dashed lines) $\phi_{Ap}(t)$, $\phi_{Bp}(t)$ and $\phi_{Cp}(t)$, as well