Section 3.2a Transformer Energization

Section 3.2.1 Introduction

Transformer behavior under varying line conditions is described by the nonlinear characteristic of its magnetic core. This characteristic is a relation between the magnetic core flux and the transformer magnetizing current. Principal features of this relation are saturation and hysteresis.

Under normal steady state operating conditions, the transformer magnetic core operates in the high permeability region of its characteristic. As a result, most of the magnetic flux is in the core and only a small percentage, the leakage flux, is in the air. The core flux constitutes the principal linkage flux between the transformer windings. Under this condition, the transformer magnetizing current is a small percentage of the transformer rated current (typically 2% to 7%).

The linkage flux is related to the transformer excitation voltage according to Equation (3.2.1).

$$\Phi_m(t) = \Phi_o + \int_0^t V_m(t)\,\mathrm{d}t \qquad \textbf{(3.2.1)}$$

where Φm(t) is the linkage flux at time t, Vm(t) is the transformer excitation voltage, and Φo is the initial flux of the transformer. This variable can, in energization studies, represent the remanent core flux.

Assuming that the magnetic core permeability remains constant under normal steady state conditions, the magnetizing current can be found from the linkage flux using Equation (3.2.2).

$$I_m(t) = \frac{\Phi_m(t)}{L_m} \qquad \textbf{(3.2.2)}$$

where Im(t) is the transformer magnetizing current, and L describes the equivalent magnetizing inductance of the transformer.

Hysteresis of the flux, and hence the current in the magnetic core contributes to thermal losses in the transformer. These losses are proportional to the square of the magnitude of the transformer excitation voltage. Therefore, hysteresis losses can be accounted for using an equivalent resistor in the transformer equivalent circuit. Figure 3.2.1 shows a terminal equivalent of a single phase two-winding transformer.

With reference to this figure,

Ls1, Ls2 represent the leakage flux of primary and secondary windings respectively,
R1, R2 are the primary and secondary winding resistance respectively, and
Rc represents total core losses.

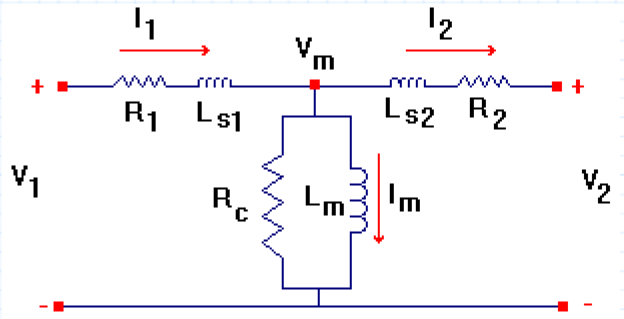

Fig. 3.2.1 Circuit representation of a single-phase transformer

The equivalent of Figure 3.2.1 is valid at normal steady state only, since it does not account for transformer saturation. The circuit parameters can be calculated from the no load (open-circuit) and short circuit tests or from the name plate data of the transformer (To learn more about the steady-state transformer representation, see **Section 1.4a**).

We will now develop a more detailed, non-linear model which will take into account various transformer saturation effects. First, the causes of saturation are discussed, then a model which predicts the magnitude of the saturation is developed. Finally, various compensation schemes are explored.

Section 3.2.2 Transformer Saturation

Transformer saturation is the magnetizing characteristic which most strongly influences the system voltage and current during abnormal conditions, such as **faults and switching**. Saturation occurs as the transformer linkage flux increases resulting in operation in the low permeability region of the core characteristic. In this condition, the core magnetic reluctance becomes comparable to the air reluctance. Thus, as the transformer operates deeper into its saturation region, an increasing portion of the magnetic flux passes through low reluctance paths. This condition increases the magnetizing current requirements to maintain the excitation voltage. Therefore, transformer saturation is followed by an increased magnetizing current with a non-sinusoidal wave-form. Depending on the conditions that cause saturation, the magnetizing current can appear as a combination of two independent forms: symmetric magnetizing current and inrush current.

Symmetric Magnetizing Current

Symmetric magnetizing current pre-supposes symmetric transformer saturation. Symmetric transformer saturation results from long sustained temporary overvoltages, which cause the linkage flux to exceed the saturation limits of the transformer. The main characteristics of the magnetizing current under symmetric transformer saturation are its periodicity, non-sinusoidal waveform, and symmetry about zero.

A qualitative analysis can be given with reference to Figure 3.2.2. For simplicity, we assume that the excitation voltage of the transformer is sinusoidal at the power frequency. This assumption is not realistic, and, therefore, more accurate modeling is necessary to solve a complete system.

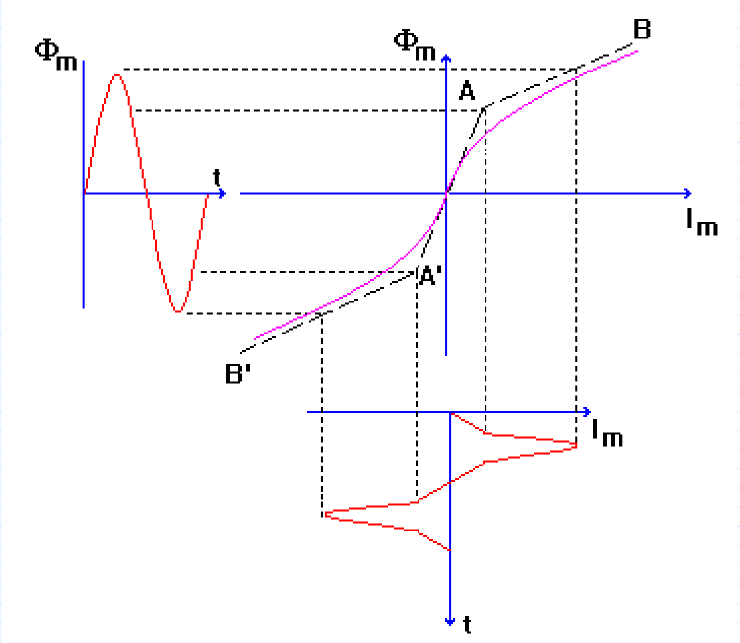

Fig. 3.2.2 A core characteristic, current vs. flux, showing conditions for symmetric saturation. The dashed line shows the approximate slopes and breakpoints in the core characteristic.

If the excitation voltage has been applied for a long time on the transformer, the transformer linkage flux will reach a sinusoidal steady state and it will be in quadrature with the excitation voltage. The flux amplitude, under this condition, is given by Equation (3.2.3).

$$\Phi_{m}\,,\max = \sqrt{2}\cdot\frac{V_m}{\omega}\,,\mathrm{rms} \qquad \mathbf{(3.2.3)}$$

With reference to Figure 3.2.2, as the flux waveform traverses the linear part of the core characteristic, an incremental flux change causes a proportional change in the magnetizing current according to Equation (3.2.2). In this region, therefore, the magnetizing current waveform will also be sinusoidal. Since the magnetizing inductance, approximately provided by the slope of segment **A'A** of the transformer characteristic, is large, the magnetizing current will be relatively small.

As the flux waveform enters the region **B'A'** or the region **AB**, the slope of the transformer characteristic decreases significantly, resulting in small values of the transformer incremental magnetizing reactance. This decrease implies that an incremental flux change will cause a proportionally larger change in the magnetizing current. Therefore, in the saturation region, the magnetizing current will increase sharply. The amplitude of the magnetizing current depends on the saturation depth and, therefore, on the amplitude of the temporary overvoltage. The symmetric magnetizing current is in quadrature with the excitation voltage. Thus, its sharp peaks are centered around the excitation voltage zero crossings.

The symmetric magnetizing current contains both the fundamental and all odd-order harmonics. The harmonics of the magnetizing current may interact with the system harmonic impedance on any side of the transformer. The result of this interaction is harmonic overvoltage in the system, which stresses the insulation of the equipment and the arrester energy dissipation capability. If the system impedance has a low order resonance near a characteristic harmonic of the magnetizing current, the system voltage harmonics will be amplified. Consequently, harmonics in the system voltage will tend to increase the linkage flux. This increase drives the transformer further into saturation increasing the amplitude of the magnetizing current harmonics, which increases the system voltage harmonics. This amplification effect can result in a form of resonance between the transformer core and system impedance known as **ferroresonance**.

Inrush Current

Inrush current is normally produced during transformer energization. It is produced by two flux sources: remanent flux, or flux trapped inside the transformer core, and the spike on the supply voltage waveform created during transformer switching.

Remanent flux is due to the core hysteresis and typically does not cause excessive inrush at transformer energization. We will therefore not consider hysteresis in the model, but be aware that it can add to the saturation effect.

Trapped flux can exist in the transformer as a result of a fault near the transformer terminals, and is a larger concern. In this case, the excitation voltage of the transformer is near zero and, according to Equation (3.2.1), the linkage flux does not change appreciably during the fault.

With reference to Figure 3.2.3, immediately prior to transformer energization (or fault clearing and breaker reclosure), the linkage flux equals the trapped (or remanent) flux of the core, Φo. Following breaker closing, the flux will change according to Equation (3.2.1). Assuming a sinusoidal excitation voltage, the resulting flux waveform will be an offset sinusoidal. Given unfavorable switching timing, the flux offset may drive the transformer into deep saturation, resulting in the magnetizing current shown in Figure 3.2.3.

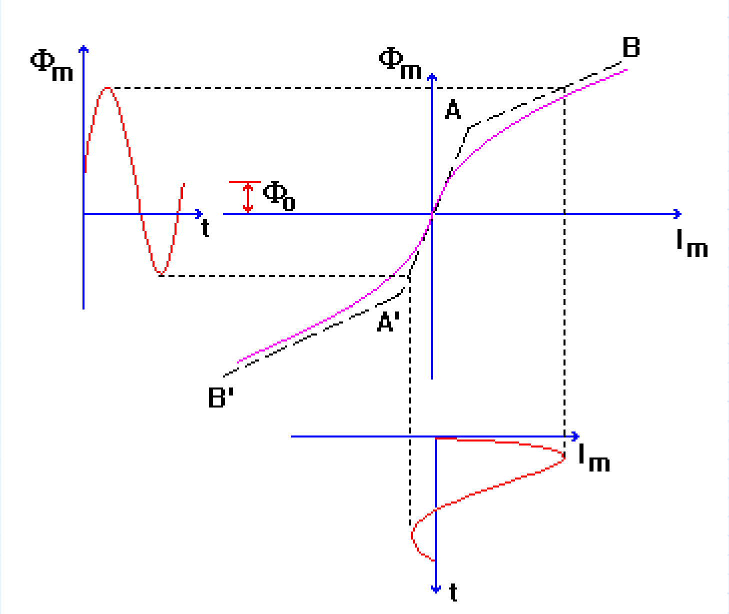

Fig. 3.2.3 Inrush current

Note that, if we were to include the remanent flux in our analysis, the core characteristic in Figure 3.2.3 would display hysteresis, and would further increase the inrush current by jumping onto a higher value of magnetizing current upon energization.

The dc offset of the inrush current decays slowly according to the system damping. It can typically take up to 10 seconds for its decay. After its decay, the inrush current takes the form of the symmetric magnetizing current. The harmonic content of the inrush initially consists of even order harmonics. As the inrush decays its harmonic content becomes equal to that of the symmetric inrush current.

The excessive initial value of the inrush current stresses the thermal limits of system equipment. In addition, this current interacts with the **system harmonic impedance**. The interaction is complex and it can only be analyzed using time-domain simulation because of the time varying harmonic content of the inrush current.

(To see an example of the time-domain simulation, see **Section 3.2b**.)

The most unfavorable conditions likely to produce the highest inrush current are the following: a spontaneous fault occurs during a system voltage zero crossing — this fault produces the highest trapped flux as the flux lags the voltage waveform by 90°. Then, during fault recovery, transformer re-energization also occurs during a voltage zero crossing. This condition will produce the maximum flux offset and, therefore, will result in the deepest saturation.