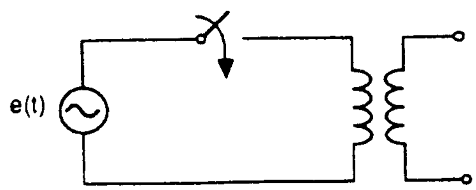
INRUSH CURRENTS

Transformer inrush currents can be divided into three categories: energization inrush, recovery inrush, and sympathetic inrush. The first, energization inrush, results from the reapplication of system voltage to a transformer which has been previously deenergized. The second, recovery inrush, occurs when transformer voltage is restored after having been reduced by a nearby short circuit on the system. The third, sympathetic inrush, can occur when two or more transformers are operated in parallel. Offsets in inrush currents can circulate in transformers already energized, which in turn causes a mild inrush.

Energization inrush is the most commonly investigated form of inrush, and can result in the largest current magnitudes. To gain an analytical understanding of inrush, we must first understand the relationship between the voltage applied to the transformer winding and the flux in the transformer's magnetic core. That relationship is:

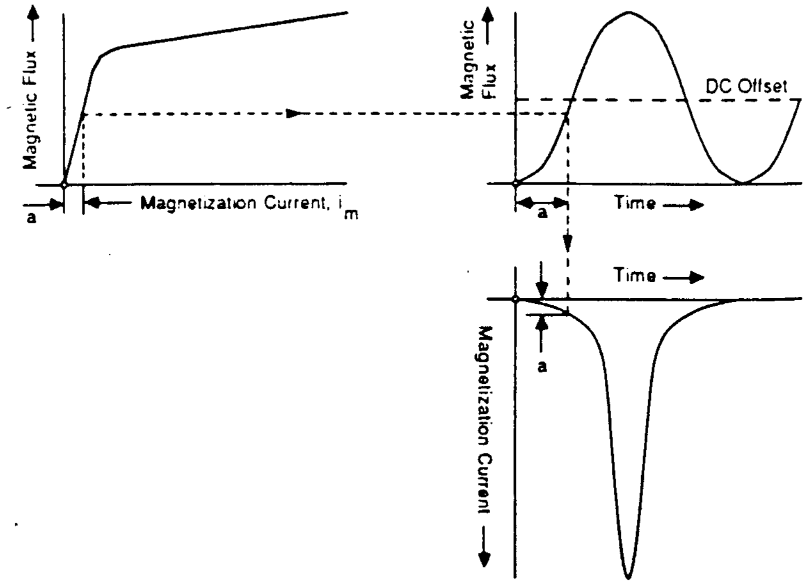
$$e(t) = \frac{d\,\lambda(t)}{dt} \qquad \text{or} \qquad \lambda(t) = \int e(t)dt + \lambda(0)$$



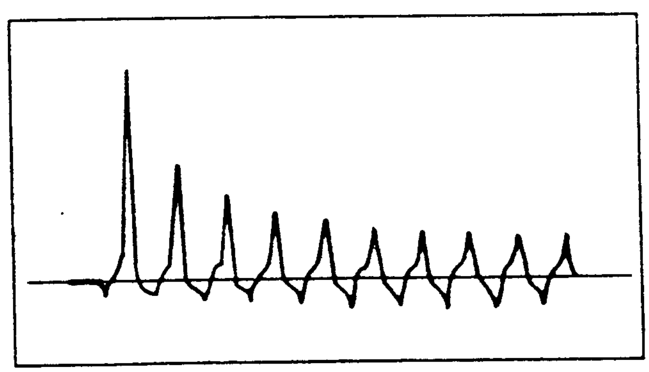
Suppose a voltage $e(t) = V_m \cos(wt + \phi)$ is applied to an unloaded transformer at some random value of ϕ. Since $e(t)$ is a sinusoid, the flux linked will also be a sinusoid, delayed by 90° or $\pi/2$ radians. Due to the integral relationship, $\lambda_m = V_m/w$. A dc offset will also appear, due to both $\lambda(0)$ and to ϕ.

$$\lambda(t) = \lambda_m \sin(wt + \phi) + \lambda(0) - \lambda_m \sin \phi$$

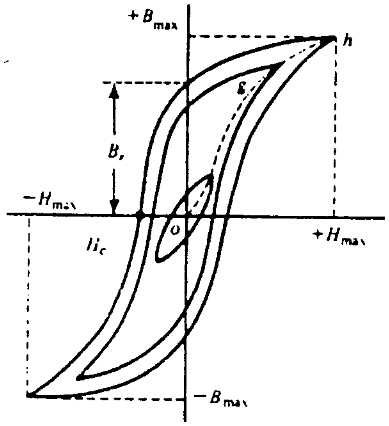
It is seen that the maximum possible value of λ upon energization is $2\lambda_m + \lambda(0)$. The relationship between λ and inrush current is given by the saturation characteristic of the transformer core's magnetization inductance L_m. Note that it is much easier to work in terms of λ the flux linked than with the flux ϕ, since working with ϕ requires knowledge of number of winding turns and cross-sectional core area. A graphical example showing the connection between the magnetization characteristic, flux-linked waveform, and magnetizing current is shown below.

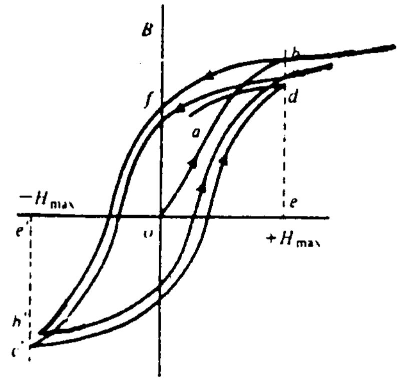


A waveform typical of inrush to a single phase transformer is shown below. Decay of inrush current depends on the series resistance of the transformer winding. In theoretical cases where the winding resistance is ignored, flux offset will never fall back to zero and inrush will persist. In a real transformer, winding resistance will damp out the inrush. It is difficult to consider the rate of decay using an L/R time constant, since the magnetization inductance involved is nonlinear. An approximation can be made by considering the time required for the inrush current to decay to 1/e of the maximum peak value. Time constants for inrush can range from a few cycles up to maybe one minute, depending on the transformer´s size and other design parameters.



It is also interesting to observe inrush by looking at the flux-current loop. (This characteristic is often referred to in error as a "hysteresis loop". Note that this loop is called the flux-current loop because it relates flux-linked to total exciting current. This means that the losses include eddy currents in addition to hysteresis.) The figures below show this effect. For normal steady-state operation (left), the positive and negative vertical extrema are equal for any given level of excitation and the core draws only the usual exciting current. During inrush, however, the range of flux-linked traversed during a cycle is shifted (right). As damping slowly removes the dc offset from the flux-linked, the flux-current loop becomes symmetric and the inrush current decays back to normal exciting current.





Inrush currents are of special concern to relay applications engineers. Protection must be able to tell the difference between a temporary inrush and an actual short circuit. Fuses must be selected so that the I^2t produced by inrush does not cause melting. Transformer differential relays usually contain a "harmonic restraint" that filters out second harmonics, which are one of the main frequency components of inrush current.

All transient simulations involving transformers (especially inrush and ferroresonance) are only as accurate as the parameters given to the model. In the case of a single phase transformer, the saturation characteristic can be measured without too much difficulty - either from RMS (effective) V-I excitation measurements or more exact measurement of flux-current waveforms can be used. Good approximations of the saturation characteristic can also be made from core dimensions and B-H characteristics, if that information is available from the manufacturer.

In the case of three phase transformers, however, it is very difficult to measure the saturation characteristic of each phase. Due to nonlinearities and magnetic coupling between phases, use of superposition is not possible. As a rule, each of the currents is non-sinusoidal, different in magnitude and distorted with different harmonics. Added confusion is caused by manufacturer's open-circuit test reports which give the <u>average</u> RMS line current flowing into the three phases. There is also a great problem in developing proper models. The model must be different for each type of core configuration and winding connection.

On the following pages is some additional information on inrush taken from Westinghouse's book <u>Applied Protective Relaying</u>.

II. MAGNETIZING INRUSH

When a transformer is first energized, a transient magnetizing or exciting current may flow. This inrush current, which appears as an internal fault to the differentially-connected relays, may reach instantaneous peaks of 8 to 30 times those for full-load.

The factors controlling the duration and magnitude of the magnetizing inrush are:

a. Size of the transformer bank

b. Size of the power system

c. Resistance in the power system from the source to the transformer bank

d. Type of iron used in the transformer core and its saturation density

e. Prior history, or residual flux level, of the bank

f. How the bank is energized.

II.A. Initial Inrush

When the excitation of a transformer bank is removed, the magnetizing current goes to zero. The flux, following the hysterisis loop, then falls to some residual value ϕ_R (Figure 8-1). If the transformer were reenergized at the instant the voltage wave form corresponds to the residual magnetic density within the core, there would be a smooth continuation of the previous operation with no magnetic transient (Figure 8-1). In practice, however, the instant when switching takes place cannot be controlled and a magnetizing transient is practically unavoidable.

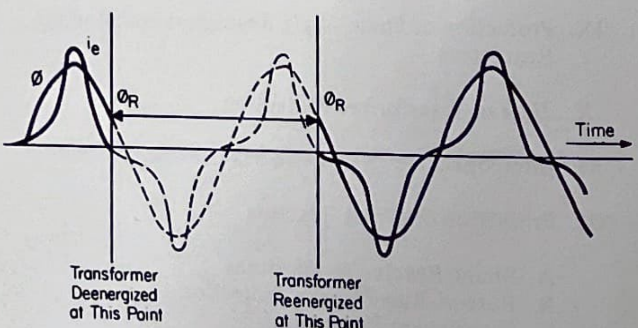


Figure 8-1: Magnetizing Current When Transformers Were Reenergized at That Instant of The Voltage Wave Form Corresponding to The Residual Magnetic Density Within The Core.

In Figure 8-2, it is assumed that the circuit is reenergized at the instant the flux would normally be at its negative maximum value ($-\phi_{max}$). At this point, the residual flux would have a positive value. Since magnetic flux can neither be created nor destroyed instantly, the flux wave, instead of starting at its normal value ($-\phi_{max}$) and rising along the dotted line, will start with the residual value (ϕ_R) and trace the curve ϕ_t.

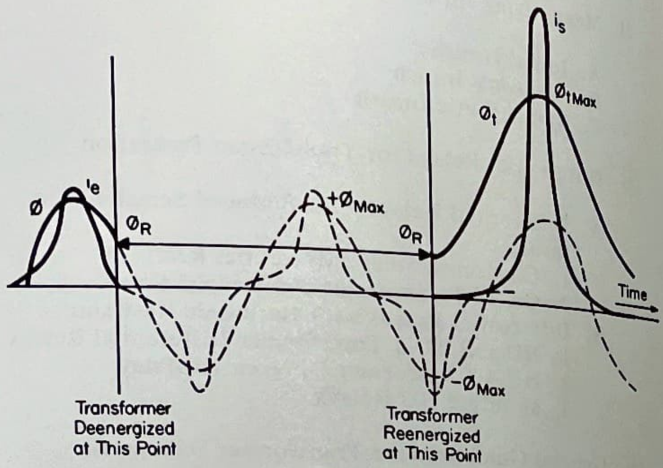


Figure 8-2: Magnetizing Current When Transformers Were Reenergized at The Instant When The Flux Would Normally be at its Maximum Value.

Curve ϕ_t is a displaced sinusoid, regardless of the magnetic circuit's saturation characteristics. Theoretically, the value of ϕ_{max} is $\pm(|\phi_R| + 2|\phi_{max}|)$. In transformers designed for some normal, economical saturation density,* ϕ_S, the crest of ϕ_t, will produce supersaturation in the magnetic circuit. The result will be a very large crest value in the magnetizing current (Figure 8-2).

The residual flux, ϕ_R, is the flux remaining in the core after the voltage is removed from the transformer bank. Since current continues to flow momentarily after the voltage is removed, the flux will decrease along the hysterisis loop to a value of ϕ_R where $i = 0$. Because the flux in each of the three phases is 120° apart, one phase will have a positive ϕ_R and the other two a negative ϕ_R—or vice versa. As a result,

*Saturation density is the projected saturation flux in per unit of rated voltage flux. In physical terms, saturation density is the per unit value of the flux density at which the iron core starts to saturate. Saturation density is a function of the transformer design parameters, such as KVA rating, loss, noise level, rated voltage, and so on. It is more easily determined, however, from the excitation curve.

the residual flux may either add to or subtract from the total flux, increasing or decreasing the inrush current.

A typical inrush current wave is shown in Figure 8-3. For the first few cycles, the inrush current decays rapidly. Then, however, the current subsides very slowly, sometimes taking many seconds if the resistance is low.

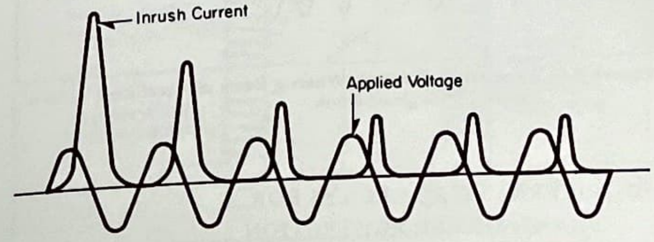


Figure 8-3: A Typical Magnetizing Inrush Current Wave.

The time constant of the circuit (L/R) is not, in fact, a constant: L varies as a result of transformer saturation. During the first few cycles, saturation is high and L is low. As the losses damp the circuit, the saturation drops and L increases. According to a 1951 AIEE report, time constants for inrush vary from 10 cycles for small units to as much as one minute for large units.

The resistance from the source to the bank determines the damping of the current wave. Banks near a generator will have a longer inrush because the resistance is very low. Likewise large transformer units tend to have a long inrush as they represent a large L relative to the system resistance. At remote substations, the inrush will not be nearly so severe, since the resistance in the connecting line will quickly damp the current.

In addition to the conditions which influence single-phase inrush, the wave shape of the inrush current into a delta winding is influenced by the number of cores affected and by the vector sum of the currents from the bank windings. First, more than one core may experience an inrush. Since the inrush current peaks in each of the cores will be out-of-phase by 60°, or a multiple of 60°, the normal shape of a single-phase inrush will be distorted. The net wave could, in fact, become oscillatory (Figure 8-4). Second, the shape of a polyphase or a single-phase inrush to a delta winding is affected by the nature of the line current itself, which is the vector sum of two currents from the bank windings. Assuming that only one core has saturated, the nature of the line current can result in either oscillatory waves or the distortion of the single-phase shape.

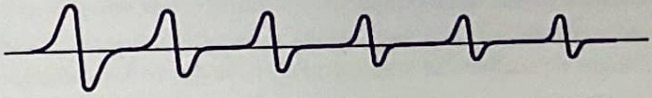


Figure 8-4: Typical Magnetizing Inrush Current Wave that can Exist in One of The Phases to a Delta Connection or in The Secondary of Delta Connected Current Transformers.

Where there is more than one delta winding on a transformer bank, the inrush will be influenced by the coupling between the different voltage windings. Depending on the core construction, three-phase transformer units may be subject to interphase coupling that could also affect the inrush current.

Similar wave shapes would be encountered when energizing the wye winding of a wye-delta bank, or when energizing an autotransformer. Here, the single-phase shape would be distorted as a result of the interphase coupling produced by the delta winding (or tertiary).

Maximum inrush will not, of course, occur on every energization. The probability of energizing at the worst condition is relatively low. Energizing at maximum voltage will not produce an inrush with no residual. In a three-phase bank, the inrush in each phase will vary appreciably.

The maximum inrush for a transformer bank can be calculated from the excitation curve if available, and Table 8-I shows a typical calculation of an inrush current.

From these calculated values it can be seen that:

a. The lower the value of the saturation density flux, ϕ_S, the higher the inrush peak value.

b. The maximum phase-current inrush occurs at the zero-degree closing angle (i.e., zero voltage).

c. The maximum line-current inrush occurs at ±30° closing angle.

Table 8-I

Typical Inrush Current Calculation

ϕ_S	Closing Angle	Peak Value of Inrush Current Wave (p.u.)					
		I_a	I_b	I_c	I_a-I_b	I_b-I_c	I_c-I_a
1.40	0°	5.60	-3.73	-3.73	8.33	-3.73	-8.33
1.40	30°	5.10	-1.87	-5.10	5.96	5.10	-9.20
1.15	0°	6.53	-4.67	-4.67	10.20	-4.67	-10.20
1.15	30°	6.03	-2.80	-6.03	7.83	6.03	-11.06

Because of the delta connection of transformer winding or current transformers, the maximum line-current inrush value should be considered when applying current to the differential relay.

II.B. Recovery Inrush

An inrush can also occur after a fault external to the bank is cleared and the voltage returns to normal (Figure 8-5). Since the transformer is partially energized, the recovery inrush is always less than the initial inrush.

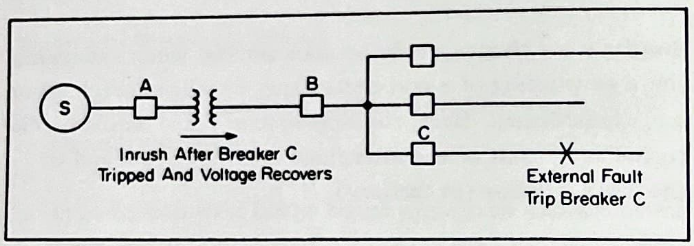


Figure 8-5: Recovery Inrush After an External Fault is Cleared.

II.C. Sympathetic Inrush

When a bank is paralleled with a second, energized bank, the energized bank can experience a sympathetic inrush. The offset inrush current of the bank being energized will find a parallel path in the energized bank. The d-c component may saturate the transformer iron, creating an apparent inrush. The magnitude of this inrush depends on the value of the transformer impedance relative to that of the rest of the system, which forms an additional parallel circuit. Again, the sympathetic inrush will always be less than the initial inrush.

As shown in Figure 8-6, the total current at breaker C is the sum of the initial inrush of bank A and the sympathetic inrush of bank B. Since this wave form looks like an offset fault current, it could cause misoperation if a common set of harmonic restraint differential relays were used for both banks.

Unit-type generator and transformer combinations have no initial inrush problem because the unit is brought up to full voltage gradually. Recovery and sympathetic inrush may be a problem, but, as indicated above, these conditions are less severe than initial inrush.

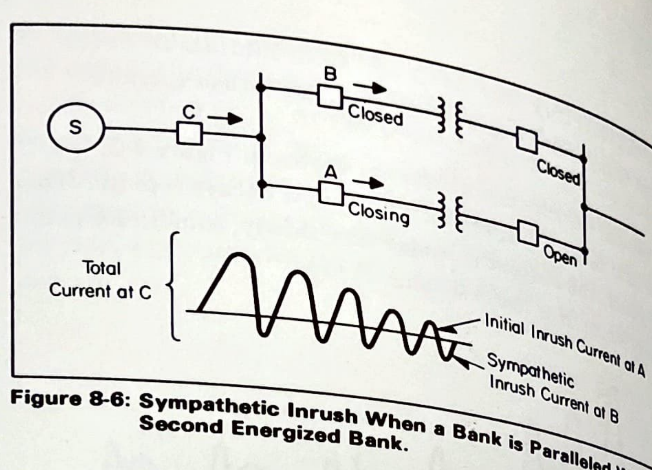


Figure 8-6: Sympathetic Inrush When a Bank is Paralleled With a Second Energized Bank.

III. DIFFERENTIAL RELAYS FOR TRANSFORMER PROTECTION

Since the differential relays see the inrush current as an internal fault, some method of distinguishing between fault and inrush current is necessary. Such methods include:

a. A differential relay with reduced sensitivity to the inrush wave (such units have a higher pickup for the offset wave, plus time delay to override the high initial peaks)

b. A harmonic restraint or a supervisory unit used in conjunction with the differential relay

c. Desensitization of the differential relay during bank energization.

III.A. Differential Relays with Reduced Sensitivity to Inrush

III.A.1. CA (87) Transformer Differential Relay

The CA transformer differential relay has reduced sensitivity to magnetizing inrush. There are many such relays in successful service.

The CA relay consists of a percentage differential unit and an indicating contactor switch. The percentage differential unit, an induction disc type, has an electromagnet with poles above and below the disc (Figure 8-7). There are two restraint coils on the lower left-hand pole; an operating coil is wound on the lower right-hand pole. Both the left- and right-hand poles have transformer winding, connected in parallel to supply current to the upper pole windings.