

Elimination of Transformer Inrush Currents by Controlled Switching

Part I - Theoretical Considerations

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Abstract: Transformer inrush currents are high-magnitude, harmonic-rich currents generated when transformer cores are driven into saturation during energization. These currents have undesirable effects, including potential damage or loss-of-life to the transformer, protective relay misoperation, and reduced power quality on the system. Controlled transformer switching can potentially eliminate these transients if residual core and core flux transients are taken into account in the closing algorithm. This paper explores the theoretical considerations of core flux transients. Based on these studies algorithms were developed which allow controlled energization of most transformers without inrush current.

Keywords: Inrush current, controlled switching, residual flux, transformer switching.

I. Introduction

Random power transformer energization can create large flux asymmetries and saturation of one or more winding cores of the transformer. This saturation results in high magnitude currents that are rich in harmonic content and have a high direct current component. These currents can cause false operation of protective relays and fuses, mechanical damage to the transformer windings from magnetic forces, and generally reduce power quality on the system.

The effects of these transients are normally mitigated by de-sensitizing protective relays or over sizing fuses. Closing resistors have been used to reduce the magnitude of the inrush currents. Controlled closing, or controlling the point on the power frequency voltage wave where energization occurs, has also been employed to reduce these inrush transients [1].

Although reductions in inrush current magnitudes have been achieved with controlled closing, the present state of the art does not incorporate residual flux in the control algorithms, which results in non-optimal energization [1].

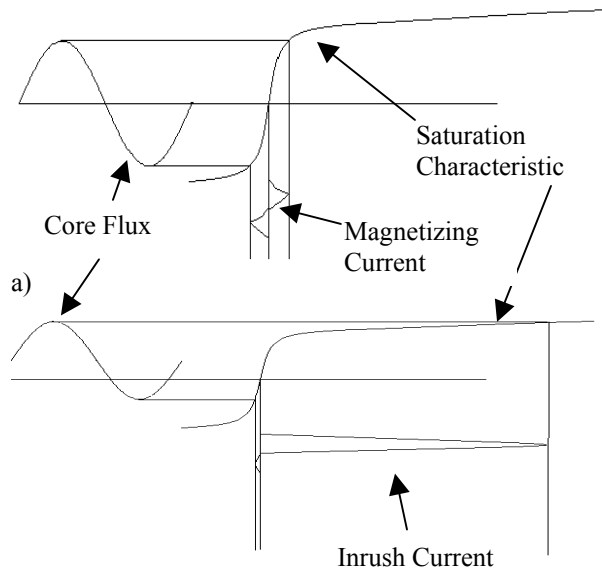
This paper will show that the effects of residual flux can be specifically included in determining an optimal closing instant. This optimal closing can theoretically result in the complete elimination of inrush transients in many transformer core and winding configurations. Part I of this paper presents strategies for controlled energization of large power transformers based on theoretical considerations. Part II discusses practical aspects of controlled transformer energization, including the limitations of typical circuit breakers.

II. Inrush Transients

Power transformers are operated with the peak core flux at the “knee” of the transformer core's saturation characteristic. A typical core saturation characteristic is illustrated in Figure 1, where, as well known, the sinusoidal core flux is the integral of the applied voltage.

The curve shown is a flux/current curve, and the slope at any point is proportional to the winding inductance. With only a modest flux increase beyond saturation, or a symmetry shift of the flux, very high magnitude current pulses will result as the slope, and therefore the inductance, is very small in that region of the curve (see Figure 1b).

When a transformer is de-energized, a permanent magnetization of the core remains due to hysteresis of the magnetic material. This “residual flux” is influenced by the transformer core material characteristics, core gap factor, winding capacitance, circuit breaker current chopping characteristics and other capacitances connected to the transformer. The core flux and therefore residual flux can be measured by integration of the winding voltage.



b)
Figure 1. The flux/current (saturation) characteristic determines the magnitude of the magnetizing and inrush current for a) symmetrical and b) unsymmetrical core fluxes. Note: a) and b) have different scale factors)

When a transformer is energized the instantaneous magnitude of core flux at the instant of energization is the residual flux. The amount of offset of the sinusoidal flux generated by the applied voltage is dependent upon the point of the voltage wave where the transformer is energized. This is illustrated in Figure 2. The peak core flux Φ can therefore reach a value of $2\Phi_{normal} + \Phi_{residual}$.

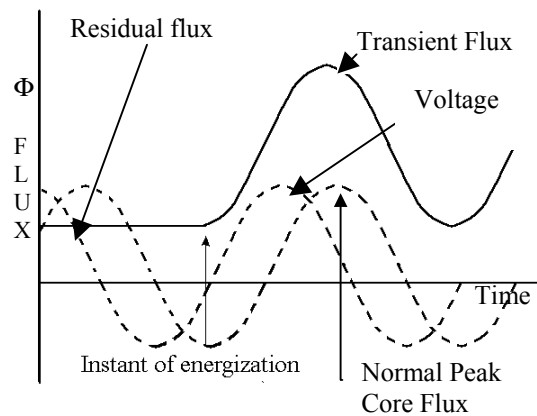


Figure 2. Core flux showing worst energization case for this residual condition.

For the most severe case shown in Figure 2, where energization was at a voltage zero, the peak transient

core flux is more than two times higher than the peak normal core flux. The core has been driven far into saturation. This asymmetrical saturation results in the typical inrush current transient characterized by a high harmonic content and a direct current component.

Although closing resistors have been employed to reduce these transients, the only way these transients can be eliminated is to prevent the core saturation. This can be accomplished by controlling the instant of energization [2].

III. Transformer Modeling

In order to investigate core flux transient phenomena in transformers with various core and winding configurations a theoretical model was required. Transformer modeling, especially of transient phenomena, is a complicated proposition. A universal model good for all frequencies and modeling all characteristics of the transformer is not available. In addition, the significant differences in parameters among various transformers make a detailed knowledge of the transformer parameters and characteristics a requirement. The requirements for the model to study core flux transients primarily include a correct core flux/current relationship and the ability to model residual core flux.

The most commonly used transformer core model utilizes a resistor, to represent losses, connected in parallel with an inductor that represents the magnetizing current [3]. Such a model does not allow for residual flux. Other methods using a current generator to represent residual flux function in a single-phase model but are not applicable in three-phase transformer models as they yield an effective short circuit.

In order to accurately model the core, the “type 96 hysteretic inductor” of the Electromagnetic Transient Program (EMTP) [3] was used. This model follows a hysteresis characteristic to represent the core. In order to gather the necessary data to accurately model the transformer, the Bonneville Power Administration (BPA) performed a field test. Comparison of simulations and the field test data verified the model performance. The model obviously has limitations, such as modeling the core characteristic only at one frequency, but this restraint is considered acceptable for this analysis.

IV. Controlled Switching of Single-Phase Transformers

In the case of controlled closing of capacitors, optimal energization point is at the instant when the

source voltage is equal to the trapped charge voltage on the capacitor. For the case of controlled closing of transformers, the “trapped charge” has a parallel in the residual flux. So the basic principle to eliminate the core flux asymmetry, the “induced” flux (integral of the applied voltage) at the instant of energization must equal the residual flux [2]. There is of course no induced flux before energization, but the source voltage has the prospect to create an induced flux. If the source voltage is considered as a virtual flux source, then the optimal instant to energize a transformer is when the “prospective” flux is equal to the residual flux. This principle is shown in Figure 3. It provides the basic strategy for controlled closing on single phase transformers.

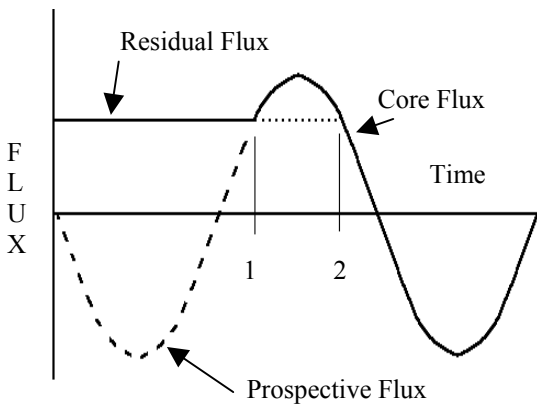


Figure 3. Optimal energization of a single-phase transformer is shown. Optimal energization points exist at times (1) and alternate optimal time (2).

V. Controlled Switching in Multiphase Transformers with No Residual Flux

Only transformers with single-phase cores and only grounded windings may be considered as three single-phase transformers, but most transformers on power systems have interactions between the phases. In these other transformers, after one phase has been energized, the flux in the other cores or core legs is not a static residual flux, but a transient flux, in the following called “dynamic” core flux. Figure 4 shows an example of a transformer with three separate cores connected by a delta winding.

First, assuming that the residual flux is zero in all three phases, then the optimal instant for the first phase to close is when the prospective flux is equal to zero. This instant is at a voltage peak. After the first phase closes, a voltage is generated in each of the other two phases of the delta winding. These voltages are each one half the magnitude and 180 degrees out of phase of the voltage of the fully

energized phase. The flux created in the cores of the other two phases is dynamic core flux.

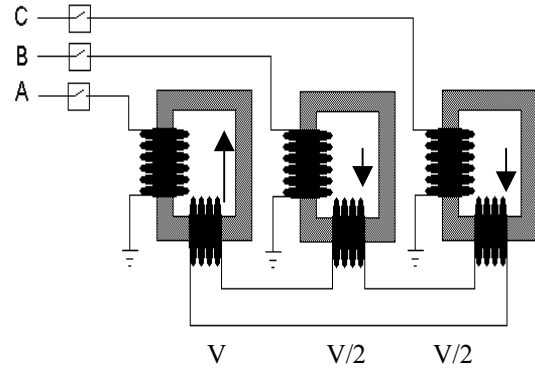


Figure 4. A multiphase transformer with single-phase cores and a delta-connected winding demonstrating the interaction of voltage and fluxes. The arrows show the phase relationship between the core fluxes.

The core fluxes in all three phases therefore have the same magnitude and phase relationships to each other as the winding voltages. The dynamic core fluxes are also 180 degrees out of phase and at one-half the magnitude as the flux in the fully energized phase. In these cases optimal energization can be achieved by energizing the last two phases one-quarter cycle after the first phase, when the prospective flux and the dynamic core flux in each phase is equal [1]. Figure 5 shows this situation.

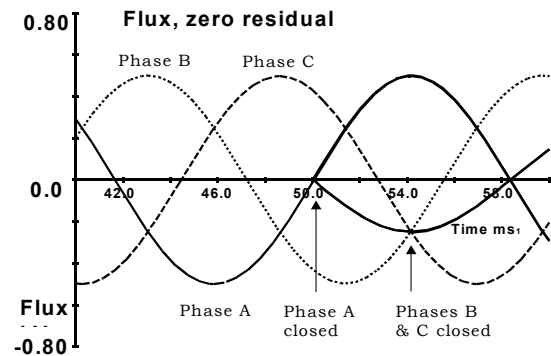


Figure 5. Energization of a three-phase transformer without residual flux. Prospective and dynamic core fluxes for each phase are shown.

The optimal energization for a transformer with a three-phase core will be the same. In that situation the flux generated by the energized phase will directly create dynamic fluxes in the other two phases. These dynamic fluxes will have the same characteristics as those induced by the delta windings (see Figure 4) described above.

VI. Residual Flux

Residual core flux can assume values up to 85% of peak normal flux, although more typical magnitudes are in the range of 20 to 70%[4]. It can be shown that the residual flux in cores of three-phase transformers must inherently sum to zero, and typically forms a pattern with near zero residual flux in one phase and plus and minus some finite value in the other two phases. This has been observed in the literature and demonstrated in field tests [2].

VII. Controlled Switching in Three-Phase Transformers with Residual Flux

First, for illustration, it is assumed that a typical residual flux pattern is formed in a transformer of the configuration shown in Figure 4, and the phase with zero residual (“A”) is energized at the optimal point on wave (peak voltage and therefore zero prospective flux). The resulting dynamic core flux in the other phases will not be divided evenly. The dynamic fluxes in Figure 6 start at their respective residual flux levels and move around their hysteresis loop in the same direction. One phase (“C”) will reach the “knee” of the saturation characteristic while the other phase (“B”) is still in the linear portion. As the slopes of the characteristics are significantly different at this point, the inductances of the two windings are

also significantly different. Therefore the voltage on the windings is not divided evenly, i.e. the winding with the largest inductance will have the highest voltage. This higher voltage will create a higher flux level, increasing the B-phase flux towards the magnitude of the C-phase flux. The result is that the flux in B and C phases rapidly equalizes and eliminates the effect of their residual flux. This phenomenon is referred to as “core flux equalization.”

As already mentioned, in most three-phase transformers, the flux in the main core legs sum to zero [5]. This is true for transformers with a three-legged core or a delta winding. It is not the case for transformers without a delta-connected winding that are single phase or have five-legged or shell-form cores. If one phase of a transformer which is configured such that fluxes sum to zero is energized such that its core leg does not go into saturation, the flux in that phase is equal to its prospective flux at every instant. Since the prospective fluxes and the core fluxes must sum to zero, the induced dynamic core fluxes must equal their prospective fluxes two times per cycle [2]. This is illustrated in Figure 7, where A-phase with zero residual flux is closed at point “A” and immediately induces dynamic fluxes in phase B and C.

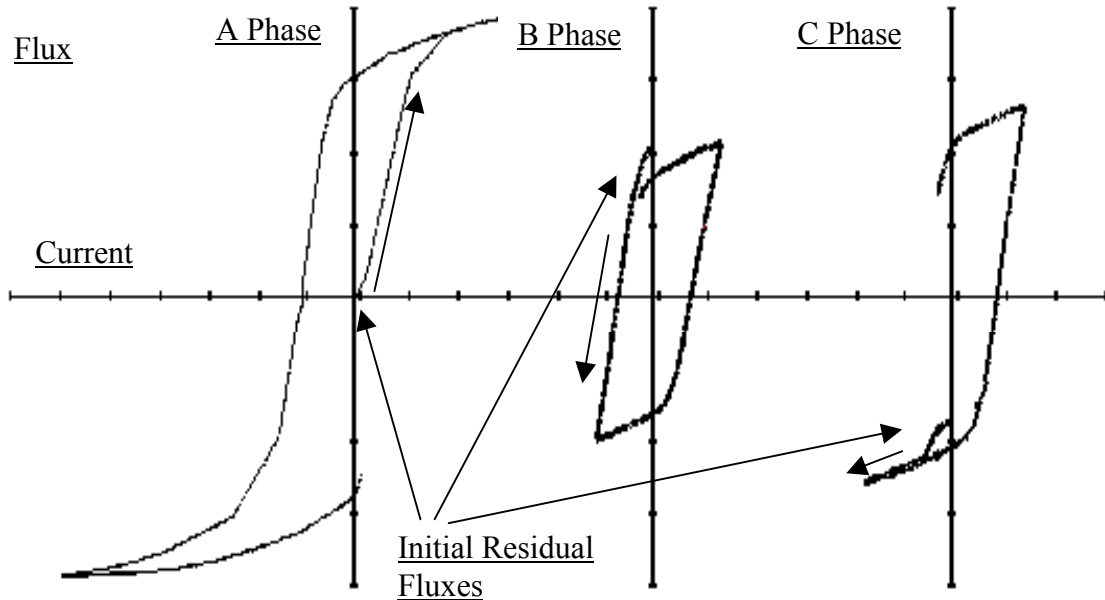


Figure 6. Flux-current core characteristic showing how the effective inductance of the B and C phase windings depend upon the residual flux and the trajectory around the hysteresis loop. After phase A is energized, the dynamic flux in the other two phases results in an inductance difference causing rapid core flux equalization.

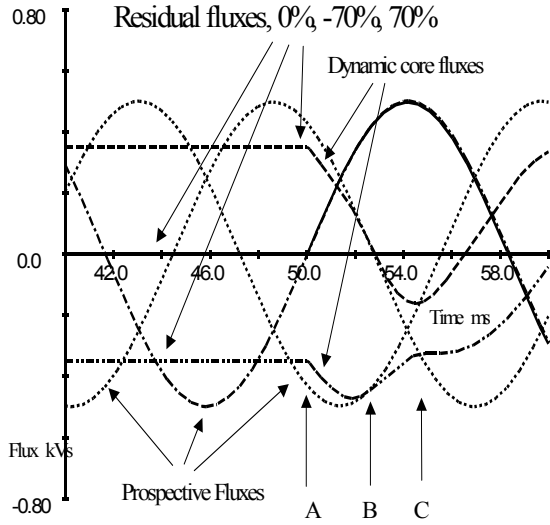


Figure 7. Prospective and dynamic core flux for a three-phase transformer with residual flux.

Depending upon the polarities of the residual flux in the two legs, the dynamic core flux and prospective fluxes will be equal either at the point marked “B” or “C” in Figure 7. These points offer the opportunity to energize the other two phases without saturation of the core. This closing strategy is called “rapid closing.” The point marked “B” obviously is more tolerant to closing timing error than point “C”, since the slopes of the prospective and dynamic fluxes are nearly equal for a period of approximately a millisecond, which is not the case at point “C”.

Another interesting closing opportunity can also be observed in Figure 7. At point “A”, where the first phase is closed, the dynamic and prospective fluxes of the other two phases are nearly equal and therefore optimal for this residual flux pattern. If the residual fluxes were slightly higher on these two phases, point “A” would be optimal for a simultaneous closing of all three phases. This offers some unique opportunities for lower voltage systems, where independent-pole-control circuit breakers are uncommon. This is called the “simultaneous” closing strategy.

As previously mentioned, after one phase is energized, the residual flux in the other phases is rapidly eliminated by “core flux equalization.” This means that if one phase is energized when the residual and prospective core fluxes are equal, and that the closing of the last two phases is delayed a few cycles, residual flux can be ignored on these two phases. This is referred to as the “delayed closing

strategy.” This strategy is demonstrated in the test energization of a laboratory transformer in Figure 8.

VII. Conclusions

In most three-phase transformers it is possible to use residual flux measurements and controlled closing to eliminate transformer inrush transients. Three strategies have been proposed for controlled energization of multi-phases transformers.

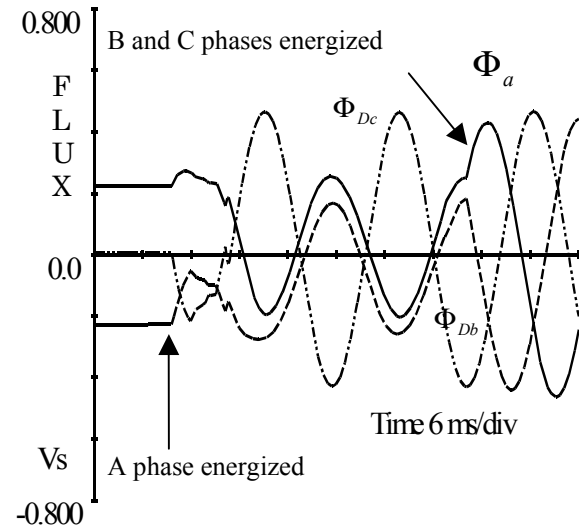


Figure 8. Laboratory test showing delayed closing strategy on a transformer with a three-legged core and a delta-connected winding.

For all three strategies, closing each winding when the prospective and dynamic core fluxes are equal results in an optimal energization, without core saturation or inrush transients.

Rapid Closing Strategy

This strategy closes one phase first and the remaining two phases within a quarter cycle. It requires knowledge of the residual flux in all three phases, independent pole breaker control, and a model of the transformers transient performance (no studies were run to compare transient performance of different transformer designs to determine error from assuming a standard model).

Delayed Closing Strategy

This strategy closes one phase first and the remaining two phases after 2-3 cycles. It requires knowledge of the residual flux in one phase only, independent pole breaker control, but does not require any transformer parametric data.

Simultaneous Closing Strategy

This strategy closes all three phases together at an optimum point for the residual flux pattern. It does not require independent pole breaker control, but requires knowledge of the residual flux in all three phases and that the residual flux magnitudes in two phases are high and follow the most traditional residual flux pattern.

Part II of this paper will further investigate the selection of the appropriate strategy and discuss practical aspects such as breaker closing errors.

VIII. References

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