Elimination of Transformer Inrush Currents by Controlled Switching

Part II - Application and Performance Considerations

John H. Brunke, Fellow, IEEE
Bonneville Power Administration
Vancouver, Washington, USA

Klaus J. Fröhlich, Senior Member, IEEE
Swiss Federal Institute of Technology
Zürich, Switzerland

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 practical considerations of core flux transients, performance of control strategies, and the application of circuit breakers to control transformer inrush transients.

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

I. Introduction

This paper is the second part of a two-part paper on the topic of controlled energization of transformers to reduce inrush currents. The first part [1] presented theoretical considerations of core flux transients and the basic principles.

Three strategies were introduced for controlled energization of typical three-phase transformers. Each of these has advantages and disadvantages. The strategies are the "rapid closing strategy," "delayed closing strategy," and the "simultaneous closing strategy." These strategies will be investigated along with a strategy for single-phase transformers. In addition, using residual flux to determine the correct closing instant will be discussed. This second part addresses the practical issues of application and expected performance in service.

II. Practical Considerations

In theory, transformer inrush transients can be eliminated using controlled energization. In practice, however, a number of factors can prevent achieving the goal of complete elimination. These factors include:

- Deviations in circuit breaker mechanical closing time.
- Effects of circuit breaker prestrike.
- Errors in the measurement of residual flux.
- Transformer core or winding configurations that prevent an optimal solution.

Deviations in Mechanical Closing Times

It is well known that all circuit breakers have some statistical deviation in their mechanical closing time from operation to operation. For a breaker designed for controlled closing, typical closing time deviations are less than +/- 1 ms [2]. In the selection of the closing instant it is important to consider these timing deviations and to understand the influence they have when considered together with flux transients and prestrike [3]. For the performance studies included here, the 3-sigma timing deviation of the circuit breaker will be assumed to be from +/- 0.5 to +/- 2.0 milliseconds. Timing deviations caused by very long periods between operations (idle time) can be a potential difficulty in some circuit breaker designs, they were not considered in this study.

Flux Considerations

As described in Part I [1], the relative slopes of the plots of prospective and dynamic core flux can create a preferred optimal closing instant. Figure 1 illustrates this for the case of a transformer with single-phase cores and a delta-connected winding switched from a ground wye winding. Assuming a typical residual flux pattern as shown in Figure 1, one phase is energized near its optimal instant, where the residual and prospective fluxes are equal. The vertical lines at "A" and "B" show two possible optimal closing instants for the remaining two phases. Closing time errors will produce higher magnitude inrush transients at point "B", because the difference between the dynamic and prospective flux is greater for any closing time error than for point "A."

Influence of Prestriking

Prestrike is the dielectric breakdown of the closing contact gap in a circuit breaker before metal-to-metal contact. Therefore the timing of transformer energization also depends upon the circuit breaker's prestrike characteristics and the voltage across the contacts as it closes. The effect of both prestrike and mechanical timing deviation is shown in Figure 2.
With the same mechanical closing time deviation, closing on the rising voltage wave (A) produces a significantly better overall timing accuracy than closing on the falling voltage (B).

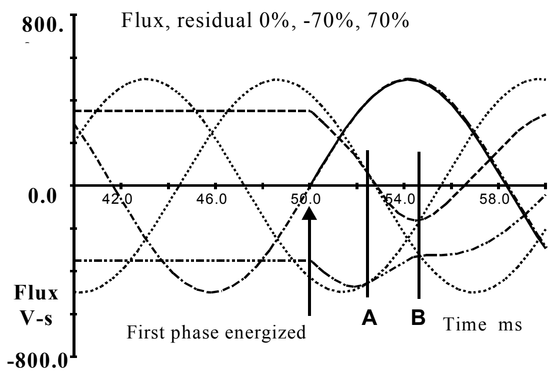

Figure 1. After the first phase is energized near its optimal point, the dynamic and prospective fluxes of the other two phases make point "A" the preferred optimal closing time.

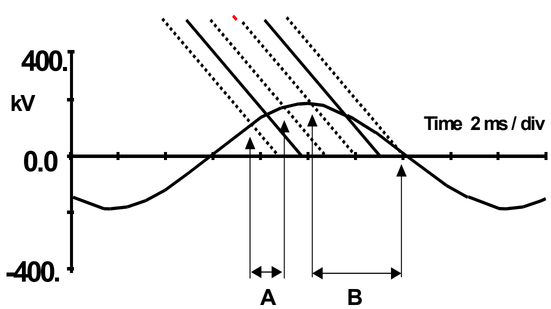

Figure 2. The combined effects of mechanical timing deviation and prestrike.

III. Statistical Performance

When the effects of transient flux, prestrike, and mechanical deviation are considered together, the expected real performance of controlled closing using the three closing strategies [1] can be studied. Using the ElectroMagnetic Transients Program (EMTP) [4], numerous series of statistical studies were performed. The mechanical closing time was programmed to follow a Gaussian distribution. Prestrike was included in the model with a typical closing dielectric characteristic for a 242 kV SF_6 single chamber circuit breaker of 100 kV/ms. The transformer characteristics initially studied were from a 230/115 kV autotransformer with three single-phase cores and a delta-connected 13.8 kV tertiary. The transformer was switched from the 230 kV winding.

Case 1: Wye-Connected Windings with Single-Phase Cores (Three Single-Phase Transformers)

Table 1 gives the results of the initial benchmark studies for transformer energization using random breaker closing (uncontrolled). The highest phase current is reported in three phase studies.

Table 1. Peak Inrush Currents for Benchmark Case Using Random Closing.

Case	Mean (A)	2% Current Level (A)
3 Phase, Zero Residual on all Phases	1540	1700
3 Phase, 70% Residual on all Phases	2680	3000
1 Phase, 70% Residual on all Phases	1303	3000

Note: 2% Current Level - The peak inrush current that is exceeded in only 2% of the closing cases.

Controlled closing was implemented with the closing time for each phase set for the instant the residual and prospective fluxes are equal. The closing time can easily be determined using the expression:

$$t_0 = (\arccos(-\Phi_R / \Phi_N)) / \omega \qquad (1)$$

Where the residual core flux is Φ_R and peak normal core flux is Φ_N. The power radian frequency is ω.

Table 2 shows the results of statistical simulations using controlled closing on the transformer described above for the case of residual flux equal to zero.

Table 2. Performance Improvement Using Controlled Closing - No Residual Flux

3 σ Closing (ms)	2% Current Level (A)	Reduction From Random (%)
0.5	125	92.7
1.0	420	75.3
1.5	800	53.0
2.0	1300	23.5

Notes: 3σ Closing - Breaker statistical closing deviation among the three phases.

Reduction from Random - The percent of reduction from the case with no controlled closing.
The resulting peak inrush current levels using four different mechanical timing deviations for the circuit breaker are provided.

Table 3 shows the results of a series of statistical simulations performed using the Case 1 transformer for a condition of 70% residual core flux on all phases. The results with 70% residual flux differ from the zero residual performance of Table 2 because the prestrike voltages and therefore the effects of mechanical time deviation are different. Closing with a higher residual flux has an improved statistical performance. Significant reductions are achieved for all residual flux conditions using controlled energization.

Table 3. Performance Improvement Using Controlled Closing - 70% Residual Flux

3 σ Closing (ms)	2% Current Level (A)	Reduction From Random (%)
0.5	62	98.0
1.0	140	95.3
1.5	350	88.3
2.0	620	79.3

Case 2: Rapid Closing - Strategy Single-Phase Transformers with a Delta-Connected Winding

Using the model transformer with a delta-connected tertiary, statistical studies were again performed. The first studies were for random closing as a benchmark for performance improvements. The results are shown in Table 4.

Table 4. Peak Inrush Currents for Case 2 Transformer Using Random Closing.

Case	Mean (A)	2% Current Level (A)
3 Phase, Zero Residual on all Phases	1021	1380
3 Phase, 0, 70, -70% Residual	1267	2280
3 Phase, 0, 35, -35 % Residual	1076	1775

Studies were then conducted for the rapid closing strategy using various residual flux levels and closing sequences. Prestrike was included in the model. The results are shown in Table 5 and Table 6. Table 5 shows the results for a residual flux pattern of 0, -70%, 70% or peak normal, with the phase with zero residual closed first.

Table 6 shows the results for a residual flux pattern of 70%, 0%, and -70% of peak normal flux. The phase with a residual of 70% peak normal flux is closed first. Closing this phase first provides better prestrike conditions than closing a phase with zero residual flux first. In addition, the closing performance of the first phase to close has a strong influence on the performance of the second and third phases to close with the rapid closing strategy.

Table 5. Performance Improvement Using Rapid Closing Strategy, 0, - 70, 70% Residual Flux (first phase to close has zero residual flux)

3 σ Closing (ms)	2% Current Level (A)	Reduction From Random (%)
0.5	125	94.5
1.0	292	87.2
1.5	452	80.2
2.0	600	73.7

The rapid closing strategy provides significant reductions in peak inrush current for breaker statistical closing deviations of 0.5 to 2.0 ms. This strategy requires a complete knowledge of the transient phenomena associated with this particular transformer. The most accurate method is to perform model studies or field measurements, and place the results in a look-up table. An approximate functional relationship could also be developed and incorporated into the controlled closing device.

Table 6. Performance Improvement Using Rapid Closing Strategy, 70, 0, -70% Residual Flux (first phase to close has 70% residual flux)

3 σ Closing (ms)	2% Current Level (A)	Reduction From Random (%)
0.5	45	98.0
1.0	125	94.5
1.5	192	91.6
2.0	320	86.0

Case 3: Delayed Closing - Strategy Single-Phase Transformers with a Delta-Connected Winding

Additional statistical studies were performed using the delayed closing strategy on the transformer model of Case 2. This strategy is easier to implement because it requires very little information on the characteristics of the transformer. Also the timing accuracy for closing the first phase does not affect the optimal instant for energizing the second and third phases due to core flux equalization. An example of core flux equalization is shown in Figure 3. The first phase is energized at point "A" near the optimal point for its zero residual flux condition. The high residual fluxes in the other phases rapidly dissipate within a cycle. This provides for optimal closing times for the last two phases shown as "B" in Figure 3.

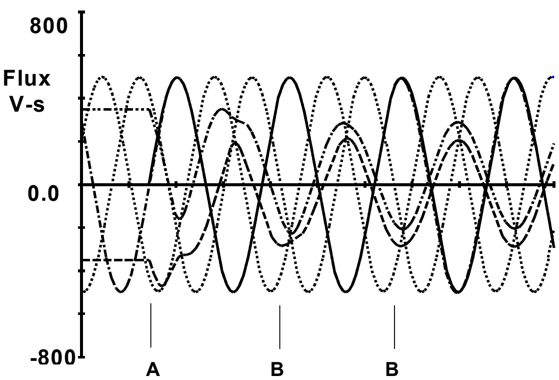

Figure 3. Core flux equalization. Prospective and dynamic core fluxes with one phase optimally closed at "a."

The results of simulations for the delayed closing strategy showing the influence of closing accuracy are shown in Figure 4. Performance improves by closing on a phase with a high residual flux first and, like the other strategies, by using a breaker with a small closing time deviation. As predicted, core flux equalization eliminated the effects of residual flux polarity and magnitude for the last two phases to close. These results represent considerable improvements over the 2% value for the uncontrolled case of 2280 amperes. The inrush currents are reduced by as much as 97%. For a circuit breaker with a statistical deviation of 1.0 ms, the resulting inrush currents range from 170 to 362 amperes, a reduction of from 93 to 85% over the uncontrolled case.

Case 4: Simultaneous Closing Strategy - Single-Phase Transformers with a Delta-Connected Winding

The final closing strategy to be discussed is the simultaneous closing strategy where all three phases are closed together. Its effective application is limited to cases in which the residual flux levels are high and follow the 0, -r, +r pattern

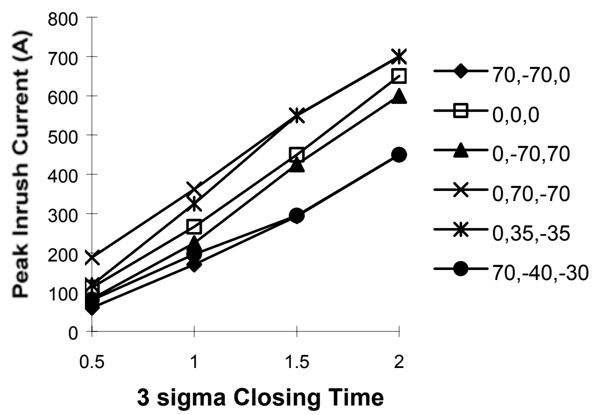

Figure 4. Peak Inrush Current (2% Level) vs. Breaker Closing Time Deviation for Various Combinations of Residual Flux.

Figure 5 illustrates the theory of this closing strategy, where the three phases are mechanically closed simultaneously. The upper traces show the residual, prospective and dynamic core fluxes and the lower traces show the cross-interrupter and prestrike voltages. The first phase prestrikes and is energized at point "A". The dotted line indicates the voltage withstand of the closing interrupter gap. As seen the second and third phase prestrike occurs at a slightly later time "B" and the result is a nearly optimal close.

IV. Other Core and Winding Configurations

In addition to the core and winding configuration used for the above examples (single-phase autotransformer with a delta-connected tertiary), other core and winding configurations can also be switched using these strategies.

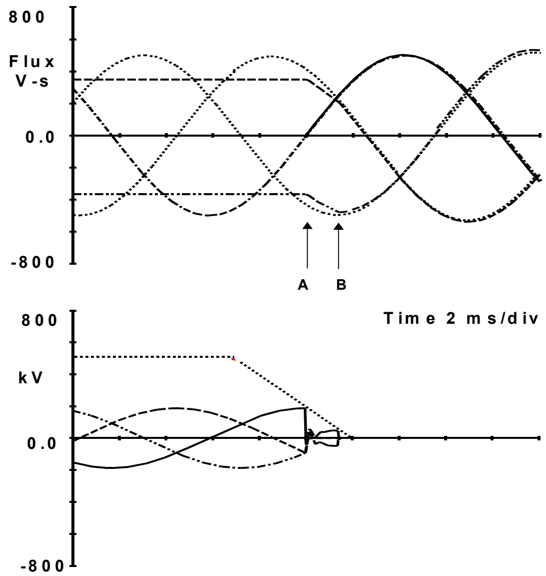

Figure 5. The flux plot (upper) and the cross-interrupter prestrike voltage plot (lower) for a simultaneous closing strategy

All transformers with three legged cores or a delta-connected winding can be switched from a grounded wye, ungrounded wye, or delta winding [5]. Changes in timing are required when switching from an ungrounded winding. For example, when switching from a delta-connected winding the first core leg is energized when the first two phases are energized, and the other two core legs are connected at reduced voltage as before. The last two core legs are energized when the last phase is energized. Optimal conditions still exist for elimination of inrush current [5].

Transformers that have four or five-legged cores, or shell form cores, and no delta-connected winding, do not have fluxes which sum to zero in the core legs with windings. Therefore as core fluxes in these winding legs do not sum to zero, there is no optimal closing instant for the last two phases to be energized. However, the first phase can still be closed optimally, and an approximate solution can be achieved using the delayed closing strategy. This is shown in Figure 6.

V. Laboratory Tests and Implementation

Implementation of these closing strategies first requires the measurement of the residual core flux, which can be accomplished by integrating the winding voltage (Faradays Law). This was demonstrated using both test instruments [5] and with an automated PC-based controller [6].

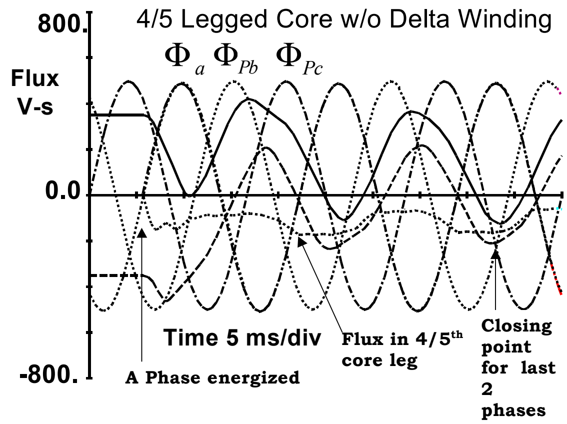

Figure 6. Prospective and dynamic core fluxes for a transformer with a four or five-legged core and no delta-connected winding.

In the selection of closing strategy a number of factors must be considered. Use of the rapid closing strategy requires a more detailed knowledge of the core characteristics for an exact solution, or a generalized approximation may be developed. To generalize this approach a survey of transformer transient characteristics to determine general applicability is required. The delayed closing strategy provides a more generalized approach. The simultaneous strategy is limited to situations with high residual core fluxes and a 0, -r, +r flux pattern. It may be possible that a passive circuit be constructed to generate this residual flux condition, but this was not investigated further.

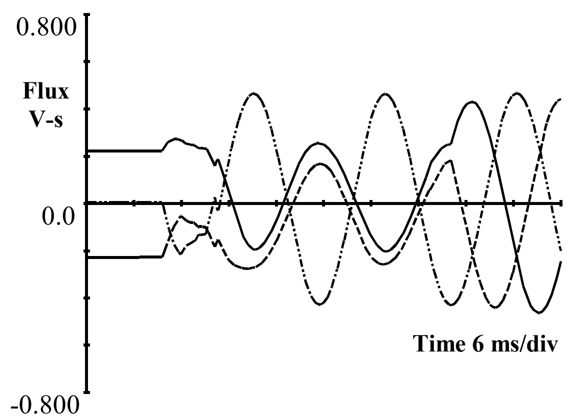

Figure 7. The core flux during a delayed strategy closing of the laboratory test transformer.

A prototype PC-based controller was constructed to demonstrate the feasibility of these closing strategies and the automated measurement of residual flux [6]. The control system was developed with commercial graphical software programming package and used to switch a 30 kVA, grounded-wye/delta transformer with a three-legged core. A typical laboratory test result of the core flux during a delayed strategy closing is shown in Figure 7. It should be noted that there is no flux asymmetry produced. The peak potential inrush current of over 400 A was reduced to less than 10 A. Laboratory test results were consistency with the computer model.

VI. Conclusions

As computer modeling and laboratory tests prove, transformer inrush transients can be greatly reduced or eliminated in most transformers. Reductions of over 90% from worst case inrush currents can be achieved with a circuit breaker of normal closing time performance. This can be accomplished by measuring the residual flux in a transformer core, and using that information with the appropriate breaker closing control strategy.

The phenomena of core flux reduction can greatly simplify closing strategies, allowing the delayed strategy to be very effective. The delayed strategy can also provide a reduction of inrush transients when switching transformers with more than three core legs and no delta-connected winding. However, complete elimination of inrush currents is not possible with these configurations.

The simultaneous closing strategy allows the use of a non-independent pole controllable breaker, but requires the residual flux pattern and residual flux magnitudes to be within certain limits.

Further investigation is necessary to determine how to achieve this is a practical and economical manner.

VII. References

[1] Brunke, John H., Fröhlich, Klaus J. "Elimination of Transformer Inrush Currents by Controlled Switching, Part I".

[2] Carvalho, A.C., Hofbauer, W. Högg, P., Fröhlich, K., "Controlled Switching as a Reliable Mean to Reduce Stresses Imposed to the Circuit Breaker and to the Network," *CIGRE Study Committee 13 Colloquium Florianopolis Brazil, pp. 1-7, Sept 1995.*

[3] CIGRE Working Group 13.07, "Controlled switching of HVAC circuit-breakers, Guide for application lines, reactors, capacitors, transformers," *Electra No. 183, April 1999, pp. 43-73.*

[4] EMTP, "Electro-magnetic Transient Program, Rule Book," *Bonneville Power Administration, Revised, Portland, Oregon*, *pp. 227-339, Sept. 1980*

[5] Brunke, J.H., "Elimination of Transient Inrush Currents When Energizing Unloaded Power Transformers," *Doctoral Dissertation No. 12791, ETH Zurich 1998.*

[6] Krüsi, Urs, Moser, Simon, "Implementation of Closing Algorithms to reduce Inrush Current Transients of unloaded Transformers," *Diploma Thesis, ETH Zürich, November 1998 - March 1999.*

John H. Brunke received his Bachelor of Science and Master of Science degrees from Portland State University in Portland, Oregon, and the degree of Doctor of Technical Science from the Swiss Federal Institute of Technology, Zürich, Switzerland. He is a past chairman of the IEEE Switchgear Committee, a past United States Representative to CIGRE Study Committee 13 (Switching Equipment). He is presently the Chairman of CIGRE Study Committee 13. Since 1975 the Bonneville Power Administration has employed him in various positions involved with the testing and application of high voltage equipment. He presently heads up the high voltage equipment engineering group. Dr. Brunke is a Fellow of the IEEE and a Distinguished Member of CIGRE. He is a registered professional engineer in the State of Oregon.

Klaus Fröhlich was born in 1945 in Salzburg, Austria. He received a Master of Electrical Engineering and a Ph.D. in Technical Science from the Vienna University of Technology, Austria. After 11 years in Switchgear and High Voltage Technology with BBC (later ABB) in Switzerland he became a full professor at the Vienna University of Technology in 1990. Since 1997 he has been a full professor of High Voltage Technology at the Swiss Federal Institute of Technology Zurich, Switzerland. Klaus Fröhlich is a senior member of IEEE, a member of CIGRE Study Committee 13, and the convenor of CIGRE Working Group 13.07 (Controlled Switching).