

# Thermal Stress and Power Quality Impacts during Transformer Energization

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**Abstract- — Transformer energization is commonly accompanied by severe inrush currents that may lead to protection maloperation, thermal stress, and power quality degradation. This paper presents a comprehensive comparative investigation of transformer inrush current mitigation using voltage ramping and closed-loop flux linkage control strategies. A nonlinear transformer model incorporating magnetic saturation and core losses is developed to evaluate peak inrush current, inrush ratio, thermal stress expressed through the  $i^2 t$  index, and control effort under multiple energization conditions. Simulation results demonstrate that the uncompensated case exhibits a peak inrush current of 83.37 A, corresponding to an inrush ratio of 16.47 and significant thermal stress. Voltage ramping effectively limits the peak inrush current to 7.15 A, achieving an inrush ratio of 1.41 and reducing the  $i^2 t$  energy by approximately 97%. The flux control strategy, while requiring higher injected voltage and control energy, maintains inrush currents below 16.3 A under ideal conditions and demonstrates strong robustness against residual flux and unfavorable switching angles, with peak inrush currents of 14.69 A and 7.94 A, respectively. Total harmonic distortion values approach 100% for all cases due to the non-periodic and transient nature of inrush current, indicating that THD is not a reliable metric during transformer energization. The results highlight the trade-off between mitigation effectiveness and control effort, and confirm the superior robustness of flux-based control under practical energization uncertainties.**

**Keywords:** Transformer inrush current, Series voltage compensation, Flux linkage control

## I. INTRODUCTION

The safe and reliable operation of power systems requires effective control of large power transformers during energization, as connecting an idle transformer to an AC source produces a transient surge known as inrush current that can reach 10–15 times the nominal full-load current and persist for several seconds [1]–[3]. This inrush current may cause voltage distortion, harmonic generation, mechanical stress on windings, and maloperation of protective relays, with its magnitude highly dependent on the switching instant, reaching a maximum when energization occurs near the voltage zero crossing. During energization, the secondary is typically open-circuited, making the primary behave predominantly as an inductive element; although inrush current does not cause permanent damage, it presents significant operational challenges, making mitigation essential. Transformer inrush currents are generally classified into energization inrush due to residual core flux, recovery inrush following supply restoration after disturbances, and sympathetic inrush in parallel transformer networks when energizing one unit induces transients in others [4].

## II. PROBLEM STATEMENT

High transformer inrush currents pose significant threats to system reliability and equipment lifespan. During transformer energization, large transient inrush currents can induce mechanical stress on the winding structure due to high electromagnetic forces, potentially accelerating insulation aging and reducing transformer life [5]. These inrush currents may also lead to maloperation or false tripping of protective relays, resulting in unnecessary service interruptions and reduced reliability [6]. From a power quality perspective, the substantial reactive power drawn during inrush events can cause voltage sags across the distribution network, adversely affecting sensitive loads and system performance [7].

The magnitude of transformer inrush current is strongly influenced by the instant of switching and the level of residual core flux present at the time of energization. The worst-case inrush condition occurs when the supply voltage is applied near its zero crossing while the residual flux approaches its maximum value ( $\Phi_r = \pm \Phi_{max}$ ), causing deep core saturation and a severe transient current surge [8].

### III. REVIEW OF MITIGATION TECHNIQUES

Transformer inrush current mitigation methods are classified as passive and active approaches: passive techniques such as pre-insertion resistors are simple but involve losses and limited control, whereas active methods regulate applied voltage or core flux during energization. Controlled (point-on-wave) switching minimizes flux offset but depends on accurate residual flux estimation and synchronization [8]; voltage ramping limits flux rate of change to reduce saturation [9]; and closed-loop flux linkage control injects a compensating series voltage to enforce symmetrical flux, providing superior suppression and reduced sensitivity to switching conditions [10], often implemented using dynamic voltage restorers (DVRs). The research work [11], Provides a comprehensive review of modeling techniques employed for simulating the frequency response of transformer windings. In this research work, a fuzzy logic-based method is proposed to control the energization instant of a no-load power transformer to reduce inrush current, which depends on residual flux, core saturation, transformer rating, and switching time; the technique detects the voltage waveform crest without using zero-crossing or PLL methods, and simulation as well as laboratory results demonstrate its effectiveness [12].

### IV. CONTRIBUTION OF THIS STUDY

This This paper presents a comparative analysis of voltage ramping and closed-loop flux linkage control, featuring a detailed nonlinear transformer model with saturation and core losses, quantitative evaluation of peak inrush and THD, and robustness assessment under worst-case residual flux and peak switching conditions, with the methodology illustrated in the figure below.

The proposed methodology evaluates transformer inrush current mitigation using time-domain simulation under worst-case energization conditions. Three strategies—uncompensated operation, voltage ramping, and flux-linkage-based control—are implemented and analyzed using a nonlinear transformer model. Key performance indices, including peak inrush current, steady-state RMS current, and inrush ratio, are computed. Steady-state harmonic performance is further assessed through FFT-based THD analysis to enable a comprehensive comparative evaluation.

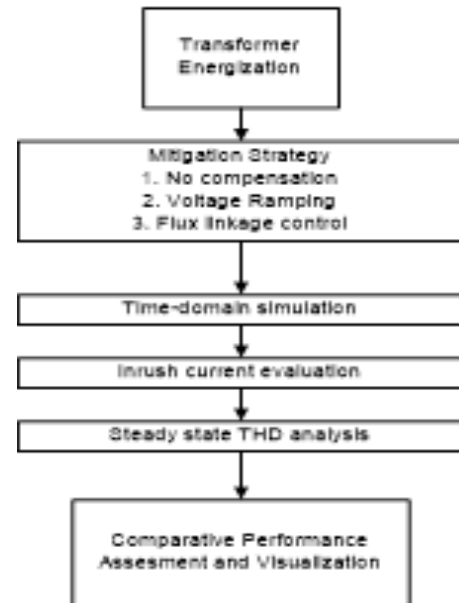


Figure 1 Proposed methodology for evaluation of inrush current mitigation

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#### Simulation Parameters

The mitigation strategies were evaluated in time-domain simulation using MATLAB for a nonlinear single-phase transformer model (including saturation and core losses) energized from a 50 Hz, 325 V source. Simulations (0.5 s, 10  $\mu$ s step) assessed voltage ramping and PI-based flux linkage control (limited injected voltage) under different residual flux and switching angles. Performance was compared using peak inrush current, RMS current, inrush ratio,  $i^2t$  index, injected voltage, control energy, and steady-state harmonic content (FFT), followed by model, control, results, and conclusion sections.

#### Transformer Model And Non-Linear Formulation

The dynamic behavior of the single-phase transformer primary winding is described by the fundamental voltage balance equation [9]:

$$V(t) = R_{primary}I(t) + \frac{d\phi(t)}{dt} \quad \dots(1)$$

where  $V(t)$  is the applied terminal voltage (source plus injection),  $R_{primary}$  is the primary winding resistance,  $I(t)$  is the total primary current, and  $\phi(t)$  is the flux linkage.

#### Current-Flux Linkage Relationship

The total primary current,  $I(t)$  is the sum of the non-linear magnetizing current  $I_{\mu}$  and the linear core loss current  $I_{coreloss}$

$$I(t) = I_{\mu}(\phi) + I_{coreloss}(V) \quad \dots(2)$$

**1. Non-linear Magnetizing Current ( $I_{\mu}$ ):** This current is modeled using an exponential function that captures the saturation characteristic of the core.

$$I_{\mu}(\phi) = I_{linear} + I_{saturation} \quad \dots(3)$$

$$I_{linear} = \frac{\phi}{L_{iron}} \quad \dots(4)$$

$$I_{saturation} = \begin{cases} \text{sign}(\phi) \cdot k \cdot (|\phi| - \phi_{knee})^P & \text{if } \phi > \phi_{knee} \\ 0 & \text{if } \phi \leq \phi_{knee} \end{cases} \quad (5)$$

Where  $L_{iron}$  is the linear inductance,  $\phi_{knee}$  is the saturation knee flux,  $k$  is the saturation gain and  $P$  is the saturation exponent.

**2. Core Loss Current ( $I_{coreloss}$ ):** To ensure a realistic steady-state Total Harmonic Distortion, a parallel core loss resistor ( $R_c$ ) is included:

$$I_{coreloss} \approx \frac{V_{applied}}{R_c} \quad \dots(6)$$

#### Dynamic Flux Calculation

The discrete-time flux evolution is calculated by integrating the voltage balance equation (1) using the Euler method (used in the simulation):

$$\phi[k] = \phi[k - 1] + (V[k] - R_{primary}I[k] - 1) \Delta t \quad \dots(7)$$

#### Control Strategies

This section details the two compensation methods used in our simulation.

#### Active Compensation Strategies

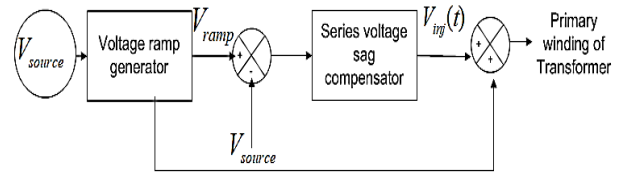
Both active compensation methods utilize an externally injected voltage  $V_{inj}$  via a power electronic converter to modify the terminal voltage  $V(t)$  applied to the transformer primary winding:

$$V(t) = V_{source}(t) + V_{inj}(t) \quad \dots(8)$$

The objective of  $V_{inj}(t)$  is to ensure the core flux  $\phi(t)$  avoids the saturation region during the energization transient.

#### Voltage Ramping Method

The Voltage Ramping method achieves mitigation by gradually increasing the applied voltage from zero to the full source voltage  $V_{source}$  over a defined ramp duration  $T_{ramp}$ . This slow increase ensures the integral of the voltage, and thus the flux, is applied symmetrically. This method is illustrated in the figure below.



**Figure 2** Block diagram of series voltage sag compensator employing voltage ramping for transformer inrush current mitigation

The required injection voltage  $V_{inj}(t)$  is designed to cancel the source voltage initially and then slowly phase it back in:

$$V_{ramp}(t) = \begin{cases} 0 & \text{for } 0 < t < T_{ramp} \\ V_{source}(t) & \text{for } t \geq T_{ramp} \end{cases} \quad \dots(9)$$

The compensation voltage  $V_{inj}(t)$  is therefore:

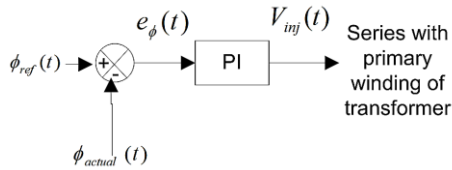
$$V_{inj}(t) = V_{ramp}(t) - V_{source}(t) \cdot \left(\frac{t}{T_{ramp}} - 1\right) \quad \dots(10)$$

This technique is simple and effective under ideal conditions but lacks the adaptability required for robustness against residual flux or switching angle errors.

#### Closed-Loop Flux Linkage Control

The Closed-Loop Flux Linkage Control employs a Proportional-Integral (PI) controller to actively regulate the

actual core flux  $\phi_{actual}(t)$  to a symmetrical reference flux  $\phi_{ref}(t)$  as shown in the figure below



**Figure 3** Closed loop flux linkage control method

The symmetrical flux reference is generated based on the ideal steady-state flux:

$$\phi_{ref}(t) = \phi_{max} \cdot \cos(\omega t + \theta) \quad \dots(11)$$

where  $\theta$  is the switching phase angle. The flux error  $e_{\phi}(t)$  is fed into the PI controller to calculate the required series compensation voltage  $V_{inj}(t)$ . The flux error is defined as the difference between the reference flux trajectory and the actual core flux, as given by

$$e_{\phi}(t) = \phi_{ref}(t) - \phi_{actual}(t) \quad \dots(12)$$

The PI controller generates the compensation voltage according to

$$V_{inj}(t) = K_P e_{\phi}(t) + K_I \int e_{\phi}(t) dt \quad \dots(13)$$

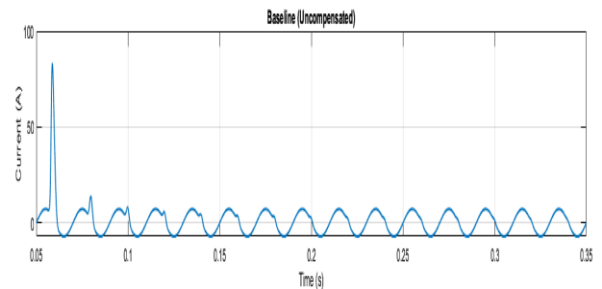
The gains ( $K_P$ ) and ( $K_I$ ) were tuned through systematic trial-and-error by first adjusting ( $K_P$ ) for fast response with minimal overshoot and then setting ( $K_I$ ) to eliminate steady-state error while ensuring stable operation. The closed-loop flux linkage control is inherently robust, as deviations from the reference flux due to residual flux, parameter uncertainties, or switching errors generate an error signal that drives a series voltage compensator to inject corrective voltage, restoring symmetrical flux and suppressing deep saturation and inrush current.

## V. SIMULATION RESULTS AND DISCUSSION

This section quantitatively compares uncompensated energization, voltage ramping, and closed-loop flux linkage control using a nonlinear saturated transformer model, evaluating peak inrush current, RMS current, inrush ratio,  $i^2t$  energy, and control effort, with results summarized in Table I.

### Uncompensated Transformer Energization

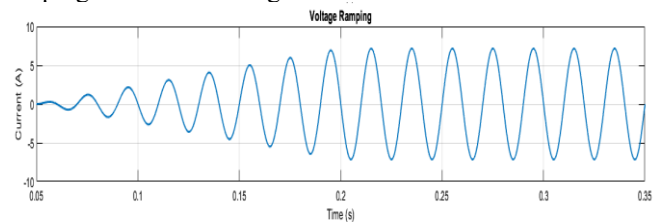
In the baseline case, transformer energization without any mitigation results in a severe inrush current with a peak magnitude of 83.37 A. The corresponding steady-state RMS current is 5.06 A, yielding an inrush ratio of 16.47. The associated thermal stress, quantified by the index  $i^2t$ , reaches 13.26  $A^2s$ , indicating a high risk of thermal and mechanical stress on the transformer windings. This behavior is attributed to core saturation caused by unfavorable flux conditions at the instant of energization. As expected, no control energy or injected voltage is required in this case.



**Figure 4** transformer current waveform under uncompensated energization

### Voltage Ramping–Based Mitigation

The voltage ramping strategy significantly suppresses the inrush current by gradually applying the source voltage during transformer energization. The peak inrush current is reduced to 7.15 A, corresponding to an inrush ratio of 1.41, which represents a reduction of approximately 91% compared to the uncompensated case. The  $i^2t$  thermal energy is reduced to 0.38  $A^2s$ , demonstrating a substantial mitigation of thermal stress. This improvement is achieved with a moderate injected voltage, exhibiting an RMS value of 159.42 V and a peak value of 314.24 V, and a total control energy requirement of 2.54 kJ. These results confirm the effectiveness of voltage ramping under ideal energization conditions.

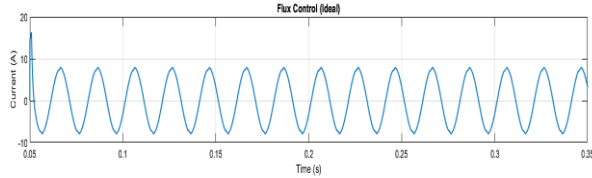


**Figure 5** Transformer current with voltage ramping method

### Closed-Loop Flux Linkage Control Using Series Voltage Injection

The closed-loop flux linkage control limits peak inrush to 16.30 A (inrush ratio 2.99,  $i^2t = 3.24 A^2s$ ) under ideal

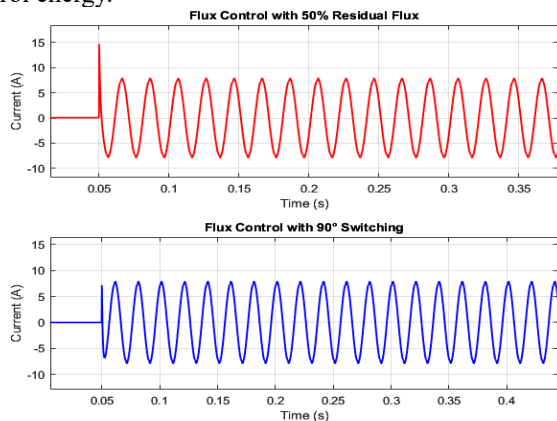
conditions, maintaining acceptable steady-state performance with higher control effort, requiring 471.08 V RMS injected voltage (650 V peak limit) and about 22.19 kJ control energy.



**Figure 6** Transformer current with flux linkage control method

### Robustness to Residual Flux and Switching Angle

To assess robustness under practical energization uncertainties, flux linkage control is evaluated in the presence of residual core flux and a 90-degree switching angle. With 50% residual flux, the peak inrush current is limited to 14.69 A, corresponding to an inrush ratio of 2.69 and an  $i^2 t$  value of 3.07  $A^2 s$ . Under a 90-degree switching condition, the peak inrush current is further reduced to 7.94 A, yielding an inrush ratio of 1.46. These results indicate that flux control maintains stable and bounded inrush current levels even under adverse initial conditions, albeit at the expense of increased control energy.



**Table 1** Performance evaluation of three energisation strategies

These results demonstrate that series voltage sag compensation techniques, particularly those based on closed-loop flux regulation, are highly effective for transformer inrush current mitigation. In addition to reducing mechanical stress and improving protection coordination, such methods also contribute to improved power quality by minimizing voltage disturbances during transformer energization.

### Thermal Stress Comparison

Thermal stress imposed on the transformer during energization is quantified using the inrush energy index  $i^2 t$ , which directly reflects copper loss accumulation and potential winding temperature rise. As observed in Table I, and shown in figure below the uncompensated energization produces a severe thermal burden with an  $i^2 t$  value of 13.26  $A^2 s$ , indicating a high risk of insulation degradation and accelerated aging.

**Figure 7** thermal stress comparisons

### Comparative analysis

Voltage ramping achieves better peak inrush reduction with lower control energy under ideal conditions, while flux linkage control offers greater robustness to residual flux and switching variations, highlighting the trade-off between effectiveness and control effort in selecting a suitable mitigation strategy.

**Table 2** Performance analysis across different strategies

Strategy	Peak inrush	Steady RMS (A)	Inrush ratio	Inrush energy
Baseline (uncompensated)	83.374	5.0626	16.469	13.262
Voltage ramping	7.1513	5.0567	1.4142	0.37946
Flux control (ideal)	16.301	5.4522	2.9898	3.2425
Flux control + Residual	14.687	5.4522	2.6938	3.07
Flux control + 90 deg	7.9441	5.4522	1.457	2.8968

### Conclusion

The study compares voltage ramping and closed-loop flux linkage control for transformer inrush mitigation: the uncompensated case shows severe inrush (83.37 A,  $i^2 t = 13.26 A^2 s$ ), voltage ramping achieves the greatest reduction (7.15 A, ~97% lower thermal stress), while flux linkage control, though requiring higher control effort, maintains peak currents below 15 A under residual flux and unfavorable switching, demonstrating superior robustness; high THD values reflect the transient nature of inrush, and overall results highlight the trade-off between mitigation effectiveness and control effort.

### Future scope

Future work should reduce control effort in flux linkage control using adaptive or data-driven methods, validate performance experimentally, extend analysis to three-phase

and network variations, and develop transient-specific energy and thermal metrics for reliability assessment.

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