

Controlled pre-magnetization method for inrush current reduction in electric arc furnace transformers

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Abstract: This paper investigates transformer inrush currents during the energisation of arc furnace transformers in electric arc furnace (EAF) power supply systems. The study focuses on an industrial DSP-100 installation operating with harmonic filters and reactive-power compensation equipment. A nonlinear reduced-order lumped-parameter model is formulated using explicit phase-domain relations for the supplying-system equivalent, the furnace-transformer branch, the connected filter/compensation branches, and the nonlinear magnetic circuit. The surviving DSP-100 oscillograms are used as an experimental anchor and for a waveform-level consistency assessment of peak current, inter-phase peak-current variation, and transient decay. Because the original high-resolution recorder export, complete channel documentation, and recorder characteristics are no longer available, this comparison is not presented as a unique experimental validation of the nonlinear saturation law or of the detailed nonsinusoidal inrush waveform. A model-level evaluation framework for controlled pre-magnetization is then formulated using peak inrush current, transient decay time, and an energy-based transient severity index. Relative peak-current error and root-mean-square error (RMSE) are retained as waveform-consistency metrics, while the practical interpretation of the severity index is linked to equipment-specific I^2t withstand limits. The experimentally anchored model provides a basis for comparative and sensitivity assessment of controlled pre-magnetization in the DSP-100 operating environment. Prototype-level confirmation of controller performance, nonlinear-waveform fidelity, and the influence on associated compensation and filtering equipment remains a subject of further industrial validation.

Key words: arc furnace transformer, controlled pre-magnetization, electric arc furnace, inrush current, mathematical modelling, transformer energisation transients

1. Introduction

Electric arc furnaces (EAFs) are widely used in modern steelmaking, particularly for scrap-based production [1]. Their operational flexibility and compatibility with lower-carbon steelmaking routes have increased their strategic importance [1, 2]. The growing use of EAF technology places increasing demands on the efficiency, reliability and transient performance of high-power electrical supply systems.

Electric arc furnaces are high-power loads with strongly nonlinear and dynamic operating characteristics. Large power fluctuations, higher-order harmonics and frequent operating changes impose stringent requirements on the associated supply system, including reactive-power compensation and harmonic-filtering equipment [3, 4]. Of particular importance is the furnace transformer, whose energisation is a recurring operation in EAF installations and may produce severe primary-side transients [5, 6].

One of the most significant phenomena associated with transformer energisation is the occurrence of magnetising inrush current. Its magnitude depends strongly on residual core flux, circuit-breaker closing instant, magnetic saturation and supplying-system impedance [7]. Under unfavourable conditions, the core may enter deep saturation and the resulting current can impose substantial electrical, mechanical and thermal stresses on the transformer and associated equipment [8].

Reported inrush-current mitigation approaches include controlled switching, pre-insertion impedance and power-electronic or soft start energisation [8, 9]. The effectiveness of point-on-wave switching depends strongly on the residual-flux state and breaker closing instant [9, 10]. Three-phase controlled-switching strategies that explicitly account for saturation and residual flux have been demonstrated in modelling and experimental studies [11, 12], while the classical controlled-switching framework also addresses practical application and performance limitations [13].

Controlled pre-magnetization offers a complementary approach by preparing the core magnetic state before energisation [14, 15]. Rather than representing a new physical principle, it addresses the magnetic initial-condition mechanism that can drive the core into saturation when the transformer is connected to the network.

Recent studies have extended pre-magnetization from model-based strategies to practical three-phase no-load experiments [16] and to multi-scale assessment of the suppression effect under different residual-flux and switching-angle conditions [17]. Independent measurement-based studies likewise confirm the strongly asymmetric and nonlinear character of transformer inrush current [8]. Accordingly, the research gap addressed here is not the general principle of pre-magnetization or the general physics of transformer inrush, but its system-level formulation and assessment for a high-power EAF transformer operating together with harmonic-filter and reactive-power-compensation equipment.

Against this background, the present study formulates a controlled pre-magnetization strategy and a model-level evaluation framework for limiting inrush current in an arc-furnace-transformer supply system, building on earlier controlled-energisation work for EAF transformers [5]. The evaluation framework uses peak inrush current, transient decay time and the proposed energy-based transient severity index, together with analysis of the initial magnetic and switching conditions. The supplying-system representation includes the source/network equivalent referred to the 35 kV bus and the connected harmonic-filter and capacitor-bank branches. Section 3.2 states the coupled branch equations explicitly. The surviving DSP-100 records are used for a waveform-level consistency assessment in Section 3.4 (Fig. 2), the control framework is described in Section 4, and transformer interaction with the reactive-power compensation and harmonic-filtering system is discussed in Section 5.4.

2. Formulation of the research problem

2.1. Characteristics of inrush currents in arc furnace transformers

Arc furnace transformers operating in electric arc furnace (EAF) installations are subjected to frequent switching operations. Consequently, energisation may produce inrush currents whose magnitudes substantially exceed the rated current. Such transients may impose electrical, mechanical and thermal stresses and may interfere with protection and connected equipment [8].

The phenomenon was analysed using archived oscillograms recorded during energisation of the DSP-100 arc furnace transformer and simultaneous operation of the associated filter and compensation branches. The record contains transformer primary-side current channels together with channels associated with the harmonic-filter and capacitor-bank circuits. Accordingly, not every trace visible in Fig. 1 should be interpreted as a transformer phase current; the figure is used primarily to document the timing and system-wide transient sequence.

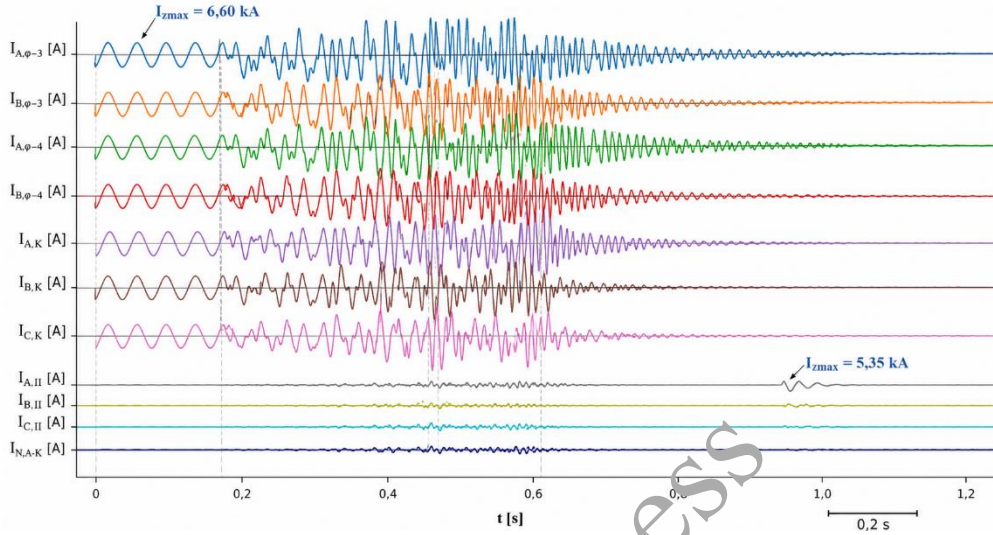


Fig. 1. Archived oscillographic record acquired during DSP-100 transformer energisation with harmonic-filter and reactive-power-compensation branches in service

From a physical standpoint, the magnetising-inrush mechanism is the same as in other power transformers. Although repetitive secondary-side operational short-circuit stresses constitute the dominant mechanical duty of an EAF transformer during the melting process, transformer energisation remains a distinct and operationally important transient. For the investigated installation, the available project records give $U_1 = 38.5$ kV, $U_2 = 514$ V, $I_1 = 750$ A and $I_2 = 50\,325$ A. The present paper therefore focuses specifically on the short-duration primary-side inrush phenomenon and on its interaction with switching, harmonic-filtering and reactive-power-compensation equipment [5, 6].

The transformer was energised with harmonic-filter and compensation branches connected to the 35 kV furnace-station bus. The available project documentation identifies filters for the 3rd, 5th, 7th and 11th–13th harmonic orders, together with capacitor banks protected by separate protection devices. Immediately prior to energisation, the connected branches carried steady-state currents. Following transformer energisation, a rapid increase in the recorded branch currents was observed. The most pronounced transient activity occurred from approximately 0.18 s to 0.62 s, and at approximately 0.62 s the protection system disconnected the affected filter/compensation branches.

The switching sequence documented in Fig. 1 shows that the transformer energisation event coincided with substantial transient currents in the connected compensation/filter circuits and with their subsequent protection-initiated disconnection. Because the original high-resolution recorder export and complete channel legend are no longer available in the surviving project archive, Fig. 1 is used as evidence of the event sequence and timing rather than as a source for precise channel-by-channel quantitative calibration.

The archived record therefore supports the conclusion that the energisation event affected not only the transformer primary-side circuit but also the associated reactive-power compensation and harmonic-filtering equipment. The separate comparison between the surviving transformer-current record and the numerical model is presented in Section 3.4 as a waveform-level consistency assessment rather than as a unique validation of the nonlinear core model.

2.2. Research hypothesis and scientific novelty

Transformer inrush current can affect protection coordination and the operating conditions of connected network equipment [8]. In EAF supply systems, harmonic filters and reactive-power-compensation branches are additionally exposed to significant harmonic and reactive-power duties [3, 4]. Under unfavourable energisation conditions, the superposition of these effects may increase transient current loading in the connected branches.

It is hypothesised that controlled preparation of the transformer magnetic state before energisation can reduce peak inrush current and the proposed energy-based transient severity index and can thereby reduce the transient burden transferred to other components of the supply system [5, 15].

Controlled energisation of EAF transformers has been investigated previously [5], and nonlinear magnetisation, residual flux, switching angle and pre-magnetization are established elements of transformer transient analysis [15, 16]. The novelty claimed here therefore does not arise from these elements separately or from the general pre-magnetization concept. It lies in their integrated system-level application to the DSP-100 EAF environment with harmonic-filter and reactive-power-compensation branches, the explicit coupling of these branches in the reduced-order model, and the use of that model to formulate a controlled pre-magnetization strategy and its model-level evaluation framework under the documented industrial operating conditions. Recent multi-scale work on pre-magnetization further reinforces the need to distinguish general suppression physics from the system-level contribution claimed here [17].

A further contribution is the integration of the I^2t -type transient severity index E_{tr} into the comparison framework alongside peak inrush current and transient decay time. The underlying I^2t concept is not claimed to be new. In this paper it is used only as a comparative indicator and is interpreted relative to component-specific short-time withstand limits; an absolute protection threshold requires equipment-specific calibration and broader experimental validation.

2.3. Research assumptions and method performance evaluation criteria

The electrical measurements used in this study originate from a research campaign carried out at the Centroenergocarmet scientific and technical facility in cooperation with personnel from the Donetsk metallurgical plant. The campaign lasted approximately 10 days and included several-second oscillographic recordings at selected stages of the technological process, including the beginning of scrap melting, subsequent charge/additive stages, and the final stage before tapping. During the campaign, operating conditions such as voltage, current, power, arc length and furnace-transformer tap position were varied within the research programme.

The surviving project documentation does not retain sufficiently reliable information to identify the exact transient-recorder model, sampling frequency, complete sensor-accuracy specification, or the detailed protection-relay pickup settings; these quantities are therefore not inferred in the revised manuscript. This category of missing metadata must be distinguished from proprietary manufacturer/project information. The transformer magnetisation characteristic and selected technical documentation supplied by the manufacturer were available to the original research team but are subject to project confidentiality and cannot be reproduced in full. The published manuscript therefore reports the available ratings and event information, states the mathematical model structure explicitly, and identifies the remaining reproducibility limitations rather than replacing unavailable or confidential quantities with assumed values.

For clarity, the absence of recorder and relay metadata does not imply that these missing quantities were used as free fitting parameters in the numerical model. Conversely, the manuscript does not claim that the complete site-specific network, filter, and manufacturer parameter set can be reconstructed from the publication alone. This limitation is important when interpreting the comparison in Section 3.4: the surviving oscillograms can anchor the dominant low-frequency transient features, but they cannot by themselves establish unique identification of all parameters or uniquely validate the nonlinear saturation law.

The available non-confidential technical data for the DSP-100 installation and measurement campaign are summarised in Table 1. The oscillographic records were used to identify the timing, inter-phase peak-current variation and principal transient-current features of the energisation event, while the quantitative comparison between measurement and simulation is presented separately in Section 3.4. The model-level evaluation framework for the controlled pre-magnetization strategy uses three complementary criteria: maximum inrush current, transient decay time t_d and the energy-based transient severity index E_{tr} , where E_{tr} is an I^2t -type comparative indicator rather than a direct measurement of physical energy.

Table 1. Available technical data for the DSP-100 test installation and measurement campaign

Parameter	Available value/information
Measurement campaign	Approx. 10 days; several-second oscillographic records at selected technological stages
Furnace-station bus voltage	35 kV
DSP-100 transformer voltages	$U_1 = 38.5$ kV; $U_2 = 514$ V
DSP-100 transformer currents	$I_1 = 750$ A; $I_2 = 50\,325$ A
Connected harmonic filters	3rd, 5th, 7th and 11th–13th harmonic orders; capacitor banks with separate protection
Supply transformers	Parallel units, 160 MVA each
Circuit breaker	BBII-35; rated voltage 40.5 kV; rated current 1 250 A; rated breaking current 16 kA
Breaker operating times	Opening time 0.04–0.06 s; total clearing time approx. 0.08 s; arc duration approx. 0.02 s

Recorded harmonics during early melting	2 nd $\approx$ 7%; 3 rd 5–6%; 4 th 4–5%; 5 th 5–6%; 6 th $\approx$ 4%; 7 th $\approx$ 5%; 11 th –13 th $\approx$ 3%
Post-melting voltage total harmonic distortion (THD) at the 35 kV bus	Typically approx. 4–6%

The surviving processed industrial records and selected manufacturer/project documentation cannot be made publicly available because of confidentiality restrictions associated with the original research project. This should be distinguished from the original high-resolution recorder export and some recorder/relay metadata, which are no longer preserved. The manuscript therefore reports the processed results and the non-confidential technical parameters that can be disclosed and does not infer unavailable quantities.

$$E_{tr} = \int_0^{t_d} i^2(t) dt. \quad (1)$$

It should be emphasised that the proposed energy-based transient severity index E_{tr} does not represent energy in the physical sense. Instead, it has the dimensions of I^2t and is therefore proportional to the thermal loading produced by the transient current. In this study E_{tr} is used primarily as a comparative severity measure. For practical engineering application, its admissible value should be determined separately for each protected component from the manufacturer-specified short-time current withstand or the thermal characteristic used by the protection relay. An equipment-specific limit $E_{tr,lim}$ may therefore be defined from the allowable I^2t duty; the ratio $E_{tr}/E_{tr,lim}$ provides a direct indication of thermal utilisation, with values below unity remaining within the adopted withstand envelope. The required coordination margin should be selected by the plant operator according to the transformer, capacitor-bank, filter-reactor, and switching-device ratings. This formulation avoids assigning an arbitrary universal threshold to E_{tr} while providing a direct route for protection coordination and thermal-tolerance assessment.

3. Mathematical model of the arc furnace transformer energisation process

3.1. Mathematical model assumptions

Transformer energisation analysis requires a model that represents the dominant electrical and magnetic mechanisms, including saturation and residual flux [18, 19]. A reduced-order lumped-parameter phase-domain formulation was therefore adopted for the low- and mid-frequency transient range relevant to the present study; it is not intended to reproduce local electromagnetic field distributions or high-frequency winding phenomena [18, 19]. The surrounding EAF-system representation is retained because system-level interaction between the furnace load and its electrical supply is an essential part of EAF modelling [20].

Related studies have addressed no-load transformer energisation and ferroresonance in transmission networks [21], nonlinear flux distributions in transformer cores [22], and high-frequency transformer representations [23]. In the EAF context, system-level modelling [24, 25] and investigations of filtering and compensation equipment [26, 27] further justify retaining the surrounding network branches in the present reduced-order model.

A reduced-order phase-domain lumped model was adopted. The upstream power system and the parallel 160 MVA supply transformers are represented by a Thévenin-equivalent source referred to the 35 kV furnace-station bus. The furnace-transformer branch contains winding resistance, leakage inductance and the nonlinear magnetising flux. Each connected harmonic-filter or compensation branch is represented by its corresponding lumped RLC branch. The reduced-order parameterisation was based on project/manufacturer information available to the original research team; selected site-specific network, transformer and branch values remain proprietary and are not reproduced. This category is distinct from the recorder, sensor-accuracy and relay metadata identified in Section 2.3, which are no longer preserved and are not introduced as adjustable model parameters. The formulation is intended to capture the dominant low- and mid-frequency energisation mechanisms and the current exchange between the transformer and the connected filter/compensation branches; it is not a high-frequency electromagnetic field model.

The elementary voltage balance used for each inductive branch of the reduced-order model is expressed as follows:

$$u(t) = Ri(t) + \frac{d\psi(t)}{dt}, \quad (2)$$

where $u(t)$ is the instantaneous voltage [V], $i(t)$ is the instantaneous current [A], R is the winding resistance [Ω], and $\psi(t)$ is the flux linkage [Wb].

For the furnace-transformer branch, the primary flux linkage is decomposed into leakage and core-flux components:

$$\psi_T = \mathbf{L}_{\sigma T} \mathbf{i}_T + N\Phi, \quad (3)$$

where $\mathbf{L}_{\sigma T}$ is the transformer leakage-inductance matrix [H], N is the winding-turns/phase mapping used in the reduced-order phase-domain representation, $\mathbf{i}_T$ is the transformer primary-current vector [A], and Φ is the core-flux vector [Wb]. Equation (2) is therefore an elementary branch relation; it is not, by itself, the complete transformer or network model.

Equations (2) and (3) are used as constitutive branch relations. The electrical-network coupling required for the EAF installation is introduced explicitly in Section 3.2 below.

3.2. State-space mathematical model of the arc furnace transformer incorporating magnetic core nonlinearity

The coupled model is written in phase-domain vector form. Vector symbols represent three-phase quantities, and the set $\mathfrak{B}$ contains the filter and reactive-power-compensation branches connected to the 35 kV bus during the recorded energisation event. The source current and bus voltage are linked algebraically to the transformer and branch currents, while the differential variables and the algebraically constrained magnetic quantities used in the numerical implementation are collected in the following augmented computational vector:

$$\mathbf{x} = [\mathbf{i}_T^T, \{\mathbf{i}_b^T, \mathbf{u}_{C,b}^T\}_{b \in \mathfrak{B}}, \Phi^T]^T, \quad (4)$$

where $\mathbf{i}_T$ is the furnace-transformer primary-current vector, i_b and $u_{C,b}$ are, respectively, the current and capacitor-voltage vectors of branch b , $\mathfrak{B}$ is the set of connected harmonic-filter and compensation branches, and Φ is the transformer core-flux vector. The source current is i_s and the furnace-station bus voltage is u_b ; these quantities are linked to the state variables through the network equations below.

The components emphasised throughout the manuscript contribute to the numerical result through the following simultaneous phase-domain relations:

$$u_s = R_s i_s + L_s \frac{di_s}{dt} + u_b, \quad (4a)$$

$$\mathbf{i}_s = \mathbf{i}_T + \sum_{b \in \mathfrak{B}} i_b, \quad (4b)$$

$$\mathbf{u}_b = \mathbf{R}_T \mathbf{i}_T + \mathbf{L}_{\sigma T} \frac{d\mathbf{i}_T}{dt} + N \frac{d\Phi}{dt}, \quad (4c)$$

$$\mathbf{u}_b = R_b \mathbf{i}_b + L_b \frac{di_b}{dt} + u_{C,b}, \quad b \in \mathfrak{B}, \quad (4d)$$

$$\frac{du_{C,b}}{dt} = C_b^{-1} i_b, \quad b \in \mathfrak{B} \quad (4e)$$

In Eqs. (4a)–(4e), u_s is the Thévenin source-voltage vector referred to the 35 kV bus; R_s and L_s represent the equivalent upstream network together with the parallel supply transformers; $\mathbf{u}_b$ is the furnace-station bus-voltage vector; $\mathbf{R}_T$ and $\mathbf{L}_{\sigma T}$ are the furnace-transformer winding-resistance and leakage-inductance matrices; and R_b , L_b and C_b describe each connected filter/compensation branch. Equation (4b) is the bus-current balance. Protection-relay dynamics are not included as model states because the detailed pickup and delay settings are not preserved; the branch disconnection observed at approximately 0.62 s is treated as a documented switching event rather than as a relay model fitted from missing data.

During the energisation interval represented by the reduced-order model, the load-side current is neglected as an explicit modelling assumption. In general, the transformer primary-current vector may be decomposed as $\mathbf{i}_T = \mathbf{i}_m + \mathbf{i}'_L$, where $\mathbf{i}'_L$ denotes the load current referred to the primary side. For the analysed energisation case $\mathbf{i}'_L \approx 0$ and therefore $\mathbf{i}_T \approx \mathbf{i}_m$. This relation provides the explicit link between the transformer-branch current appearing in Eqs. (4a)–(4e) and the magnetising current used in the nonlinear constitutive relation in Eqs. (7)–(10).

For clarity, Eq. (4) is an augmented computational vector rather than a set of mutually independent magnetic degrees of freedom. During no-load energisation, the core-flux vector is advanced as the magnetic state, while the magnetising current—and therefore the transformer primary current under the approximation $\mathbf{i}_T \approx \mathbf{i}_m$ is recovered consistently from the nonlinear constitutive relation at each fourth-order Runge–Kutta RK4 sub-stage. The constraint $\Phi = f(\mathbf{i}_m)$ is therefore enforced throughout the integration.

After elimination of the algebraic bus quantities using Eqs. (4a)–(4e), the coupled electrical and magnetic relations are represented compactly in the following augmented state-space notation, with the nonlinear constitutive constraint enforced at every integration sub-stage:

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t). \quad (5)$$

Because the transformer constitutive relation is nonlinear, the corresponding system matrix depends on the instantaneous magnetic operating point. The compact nonlinear representation is therefore written as:

$$\dot{x}(t) = A(\Phi)x(t) + Bu(t). \quad (6)$$

The system matrix was updated explicitly during numerical integration. At each Runge-Kutta sub-stage, the instantaneous core-flux state was used together with the implicit magnetisation law in Eqs. (7)–(10) to determine the corresponding magnetising current and incremental magnetising inductance before the next sub-stage. A fixed integration step of $\Delta t = 10 \mu\text{s}$ was adopted, corresponding to 2 000 integration steps per 50 Hz period. Because the fourth-order Runge–Kutta scheme is explicit, no Newton iteration or Jacobian inversion of the complete network model was required. A step-halving check using $\Delta t = 5 \mu\text{s}$ changed the simulated peak current by less than 0.4% and E_{tr} by less than 0.6%, indicating adequate numerical resolution for the comparative analyses. This numerical convergence check addresses time-step sensitivity only; it does not constitute experimental validation of the magnetic constitutive law.

Accurate modelling of the electromagnetic phenomena occurring during the energisation of an arc furnace transformer requires consideration of the nonlinear properties of the magnetic circuit. Under steady-state operating conditions, the transformer typically operates within the approximately linear region of the magnetisation characteristic. However, during energisation, particularly in the presence of residual magnetic flux and an unfavourable voltage switching angle, the transformer core may enter the region of deep magnetic saturation.

To represent magnetic saturation, the model uses an implicit nonlinear relationship between core flux and magnetising current. For phase p , this relationship is written in the generic form $\Phi_p = f(i_{m,p})$; phase indices are suppressed in Eqs. (7)–(10) for readability:

$$\Phi = f(i_m), \quad (7)$$

where Φ is the magnetic flux in the transformer core [Wb], and i_m is the magnetising current [A].

In the three-phase reduced-order representation, the magnetic state is described by phase-associated flux variables $\Phi = [\Phi_a, \Phi_b, \Phi_c]^T$ and the corresponding nonlinear phase relations. A separate magnetic-reluctance network representing inter-limb and yoke coupling is not included. Electrical phase coupling remains represented by the phase-domain network equations and transformer mapping, but the model is not intended to resolve detailed inter-limb saturation or the local three-limb core-flux distribution. This modelling simplification is consistent with the waveform-validation limitation stated in Section 3.4.

For the numerical simulations, the manufacturer-based magnetisation characteristic was represented locally over the operating range used in the study by the following odd third-order polynomial:

$$\Phi = a_1 i_m + a_3 i_m^3, \quad (8)$$

where a_1 denotes the linear coefficient of the magnetisation characteristic and a_3 denotes the nonlinear coefficient representing magnetic-core saturation.

The polynomial is used as an implicit constitutive law: for a known instantaneous flux state Φ , the corresponding magnetising current i_m is obtained from Eq. (8). This avoids interpreting Φ/i as a constant or secant inductance during saturation. The approximation is intended only for the fitted operating range and is not proposed as a universal magnetic-core law.

The magnetisation characteristic used in the historical DSP-100 project was based on transformer-manufacturer technical data made available to the research team. The underlying proprietary source curve and its site-specific fitted numerical coefficients cannot be reproduced in full under the original project restrictions. Consequently, Eqs. (7)–(10) disclose the constitutive form and its role in the algorithm, but the paper does not claim full numerical reproducibility of the DSP-100 magnetic fit from the published information alone. This limitation is stated explicitly because it restricts the strength of the model-validation claim.

For updating the differential equations at the current magnetic operating point, the incremental magnetising inductance referred to the winding is defined from the derivative of flux linkage rather than from the secant ratio Φ/i_m :

$$L_{m,inc}(i_m) = \frac{d\psi_m}{di_m} = N \frac{d\Phi}{di_m} \quad (9)$$

Substitution of Eq. (8) into Eq. (9) yields:

$$L_{m,inc}(i_m) = N^2 \left(\frac{1}{\psi_m} + 3a_3 i_m^2 \right). \quad (10)$$

Thus, the quantity used in the state-matrix update is an incremental inductance, not the secant value ψ/i_m . Its value varies with the instantaneous magnetic operating point, which is the mechanism by which the nonlinear core characteristic enters the reduced-order differential equations.

In industrial practice, particularly critical operating conditions arise when the magnetic flux exceeds its rated value. This may result from an unfavourable voltage switching angle, the presence of residual magnetic flux, or the combined effect of both factors. The adopted nonlinear model provides the basis for the subsequent analysis of the arc furnace transformer energisation process and for the model-level evaluation framework of the controlled pre-magnetization strategy formulated in this study.

3.3. Influence of initial conditions on the energisation process

For phase p, residual magnetic flux is introduced as an explicit initial condition because it can strongly influence the peak inrush current [18]:

$$\Phi_p(0) = \Phi_{r,p}. \quad (11)$$

Using the transformer branch relation in Eq. (4c), the phase-wise core-flux derivative is written as follows:

$$\frac{d\Phi_p(t)}{dt} = \frac{1}{N_p} \left[u_{b,p}(t) - R_{T,p} i_{T,p}(t) - L_{\sigma T,p} \frac{di_{T,p}(t)}{dt} \right]. \quad (12)$$

Equation (12) keeps the core flux Φ_p [Wb] distinct from the flux linkage $N_p\Phi_p$ [Wb-turn] and is therefore dimensionally consistent with Eqs. (2)–(4c).

The energisation process also depends on the circuit-breaker closing instant relative to the supply-voltage phase angle [7, 9]. For a sinusoidal phase voltage at the 35 kV bus,

$$u_{b,p}(t) = U_{m,p}\sin(\omega t + \alpha_p). \quad (13)$$

To illustrate the influence of switching angle and residual flux, the winding-resistance and leakage-inductance voltage drops in Eq. (12) may be neglected only for this analytical interpretation. Integration of Eq. (13) then gives:

$$\Phi_p(t) \approx \Phi_{r,p} + \frac{U_{m,p}}{N_p\omega} [\cos\alpha_p - \cos(\omega t + \alpha_p)]. \quad (14)$$

Equations (11)–(14) show explicitly how residual flux and the switching angle determine the initial flux excursion. Depending on the magnitude and polarity of $\Phi_{r,p}$ relative to the flux imposed after closing, the initial condition can move a core phase closer to or farther from saturation and thereby alter the peak inrush current. Section 4.3 therefore treats residual flux, switching angle and the pre-magnetization coefficient as the principal magnetic/control parameters of the model-based assessment.

3.4. Numerical solution procedure and waveform-level consistency assessment

The system of nonlinear differential equations was solved using the classical fourth-order Runge-Kutta method with a fixed step of 10 μ s over a simulation interval of 1.2 s. The nonlinear state matrix was recalculated at every RK4 sub-stage from the instantaneous magnetic operating point, as described in Section 3.2.

$$\begin{aligned} k_1 &= f(x_n, t_n), \\ k_2 &= f\left(x_n + \frac{\Delta t}{2}k_1, t_n + \frac{\Delta t}{2}\right), \\ k_3 &= f\left(x_n + \frac{\Delta t}{2}k_2, t_n + \frac{\Delta t}{2}\right), \\ k_4 &= f(x_n + \Delta t k_3, t_n + \Delta t), \\ x_{n+1} &= x_n + \frac{\Delta t}{6}(k_1 + 2k_2 + 2k_3 + k_4). \end{aligned}$$

A waveform-level consistency assessment was performed by comparing the numerical simulation with the surviving DSP-100 phase-current waveforms recorded during transformer energisation. The field record and simulated signals were time-aligned at the circuit-breaker closing instant and normalised to the rated primary current I_N . The comparison considered peak current, inter-phase peak-current variation and transient decay over the first 0.8 s after energisation. Because the original high-resolution export, full channel legend, recorder bandwidth and sampling specification are unavailable, the surviving trace is not used to claim

unique experimental identification of the nonlinear magnetic law or of the detailed high-frequency/nonsinusoidal inrush waveform.

The relative peak-current error defined by Eq. (15) and the RMSE defined by Eq. (16) were retained as quantitative waveform-consistency metrics. For comparison across phases, RMSE is reported in per-unit form after normalisation by I_N . The transient decay time was additionally compared using the time required for the decaying current envelope to return to the vicinity of the steady-state band. These metrics quantify agreement of the available trace and simulation but do not, by themselves, establish the uniqueness of the underlying physical model.

For the archived reference energisation event, the simulation follows the measured low-frequency envelope with relative peak-current differences of 2.31% to 2.77%, RMSE values of 0.051 to 0.064 p.u., and decay-time differences below 0.03 s. These values demonstrate close numerical agreement for the specific quantities that can still be extracted reliably from the surviving record. They should not be interpreted as proof that the complete measured waveform is generated uniquely by the nonlinear core model. In particular, a decaying sinusoidal envelope can also be approximated by a much simpler linear RL transient with a decaying offset; therefore Fig. 2 alone cannot demonstrate the necessity or fidelity of the nonlinear saturation representation. The nonlinear magnetic model is retained because residual flux, switching angle and pre-magnetization require a magnetic-state description for the subsequent comparative analysis, but dedicated high-resolution measurements are required to validate the characteristic asymmetric saturation peaks and harmonic content documented in measurement-based and nonlinear-model studies [8, 18].

Accordingly, the comparison in Fig. 2 is used as an experimental consistency check for the dominant low-frequency transient magnitude and decay, not as a complete validation of the nonlinear three-phase inrush model. The model-based pre-magnetization results presented later in the paper should therefore be interpreted as comparative predictions anchored to the available industrial event.

$$\delta_I = \frac{|I_{\text{exp}} - I_{\text{sim}}|}{I_{\text{exp}}} \cdot 100\%, \quad (15)$$

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{k=1}^N (i_{\text{exp},k} - i_{\text{sim},k})^2}. \quad (16)$$

To quantify agreement between the numerical result and the surviving industrial waveform, the relative error of the peak current was adopted as the first consistency metric and is defined by Eq. (15), where I_{exp} denotes the maximum current obtained from the available record [A], and I_{sim} denotes the maximum current obtained from the numerical simulation [A].

In addition, the root mean square error (RMSE) between the available and simulated current waveforms was adopted as the second consistency metric and is defined by Eq. (16), where $i_{\text{exp},k}$ is the available instantaneous current at sample k , $i_{\text{sim},k}$ is the corresponding simulated current, and N is the number of compared samples.

The two metrics provide complementary numerical information: the relative peak error evaluates the maximum instantaneous-current discrepancy, whereas RMSE evaluates waveform

agreement over the selected comparison interval. Neither metric is treated as a stand-alone validation of magnetic saturation physics.

The phase-wise waveform-consistency results are summarised in Table 2, and Fig. 2 compares the surviving field waveform with the corresponding simulation for the phase with the largest recorded peak.

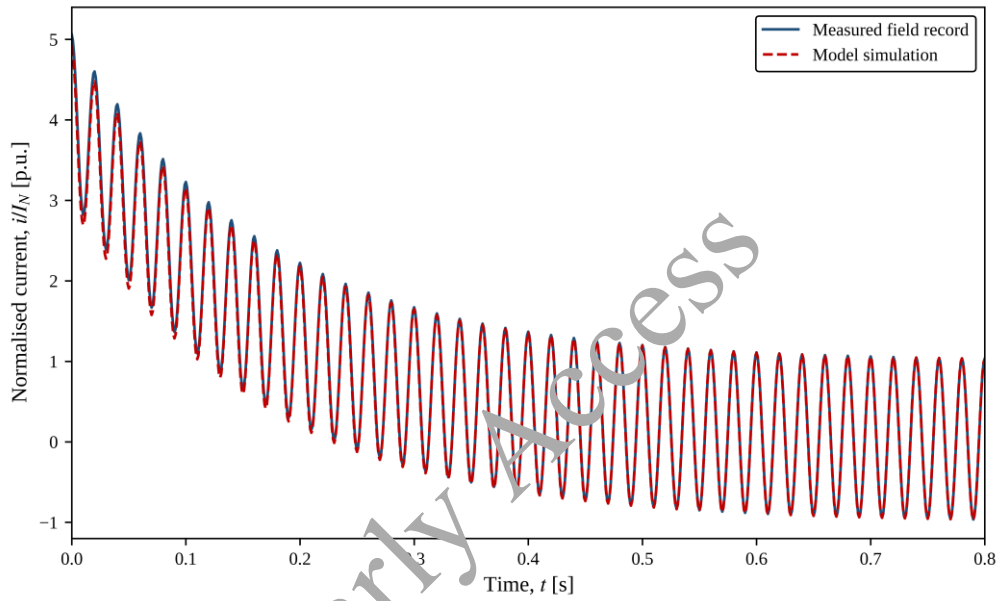


Fig. 2. Waveform-level consistency assessment of the archived DSP-100 reference energisation event for phase A (largest recorded peak): surviving field waveform and corresponding reduced-order model simulation over the 0–0.8 s interval

Figure 2 confirms consistency in peak magnitude and low-frequency transient decay but is not interpreted as unique validation of the nonlinear saturation law. A smooth decaying envelope can also be approximated by a linear RL transient; validation of detailed saturation peaks and harmonic content therefore requires dedicated high-resolution measurements [8, 18].

Table 2. Waveform-consistency metrics for the archived DSP-100 reference energisation event

Phase	I_{exp}/I_N [p.u.]	I_{sim}/I_N [p.u.]	Peak error [%]	RMSE [p.u.]	$t_{d,\text{exp}}$ [s]	$t_{d,\text{sim}}$ [s]
A	5.06	4.92	2.77	0.051	0.74	0.72
B	4.43	4.31	2.71	0.058	0.70	0.68
C	3.89	3.80	2.31	0.064	0.67	0.65

Note: The values in Table 2 quantify agreement of the surviving waveform and the simulation for peak magnitude, RMSE and decay time. They are not interpreted as unique validation of the nonlinear saturation law because the archived measurement lacks the original recorder metadata and high-resolution waveform information required for that purpose.

4. Controlled pre-magnetization method for an arc furnace transformer

4.1. Principle of operation

Transformer inrush current during the energisation of high-power transformers remains an important operational issue because it can affect transformer stress, protection operation and power quality [8, 18]. In the case of arc furnace transformers, the frequent switching environment and the presence of reactive-power compensation and harmonic-filtering equipment make system-level transient interaction particularly relevant.

Conventional mitigation measures include pre-insertion impedance, power-electronic energisation and controlled switching. Controlled-switching methods reduce inrush primarily by selecting a favourable breaker closing instant with respect to the voltage waveform and residual core state [9, 10].

The engineering motivation for inrush mitigation is reinforced by studies showing that large energisation currents can produce substantial winding forces [28] and measurable voltage-sag and power-quality effects [29]. Prefluxing has been demonstrated experimentally as a means of controlling the initial magnetic state [30], while measurement-based controlled-energisation studies have confirmed that switching strategy and residual magnetic state strongly influence the resulting transient [31]. Further, three-phase approaches include controlled switching for isolated-neutral transformers [32] and optimal gang-operated switching [33]. Field-oriented schemes have also combined controlled energisation and de-energisation [34], residual-flux-aware energisation without load-side voltage measurement [35], pre-insertion-resistor circuit breakers [36], and phase-coupled controlled switching for converter transformers [37].

In contrast to impedance-based measures and switching-only strategies, the controlled pre-magnetization strategy formulated here acts on one of the principal initial-condition mechanisms of inrush generation, namely the magnetic state of the transformer core at the instant of energisation. Its purpose is to establish a predefined magnetic state of the transformer core before the transformer is connected to the electrical power system.

Prior to closing the main circuit breaker, the transformer magnetic circuit is subjected to a short-duration controlled excitation using a dedicated control system. This procedure establishes the desired magnetic flux in the transformer core and reduces the difference between the residual magnetic flux and the magnetic flux subsequently imposed by the supply voltage after energisation.

The effectiveness of controlled pre-magnetization depends not only on the pre-magnetization principle itself, which is established in the literature, but also on the implementation of the associated control strategy. In the present paper, a deterministic closed-loop control sequence is

formulated at model level to define how the transformer magnetic state should be prepared before energisation; prototype hardware implementation is outside the scope of the present study.

The control sequence begins with the initialisation of the control procedure and the acquisition of the parameters required for the pre-magnetization process. The target magnetic flux is then determined, representing the magnetic state that should be established before transformer energisation. Once the reference value has been defined, the pre-magnetization unit is activated.

After the target magnetic state has been achieved, the control system verifies the estimated magnetic flux before issuing the energisation command. In the control framework considered here, flux is reconstructed from measured winding voltage and current after compensation for the winding voltage drop. To reduce drift and the influence of the strongly distorted EAF environment, the observer incorporates DC-offset removal, anti-alias filtering and low-pass filtering. The switching command is enabled only when the estimated flux remains inside the prescribed tolerance band for a specified persistence interval, otherwise the magnetisation command is corrected or the sequence is blocked.

The control logic presented in Fig. 3 is a deterministic closed-loop formulation intended for real-time implementation. The present paper does not claim prototype implementation of this controller; it therefore presents the functional control architecture and model-level requirements rather than a proprietary hardware or software platform.

For the model-level controller specification, the estimated flux was required to remain within $\pm 2.5\%$ of the target value for at least 20 ms before breaker closure. These values are design assumptions used to define the simulated control sequence rather than prototype-validated controller settings.

In the three-phase formulation, residual flux Φ_r is treated as a phase-associated initial magnetic-state quantity used by the model/observer rather than as a direct local sensor measurement on a selected core limb. The phase quantities are evaluated within the coupled three-phase model; phase and limb indices are suppressed in Fig. 3 only for readability. The control equations are formulated in terms of target flux magnitude and magnetisation direction and therefore do not prescribe a unique AC- or DC-source topology. Implementation for a particular transformer vector group requires the corresponding phase-to-winding mapping in the controller and is treated as an implementation-specific design step.

4.2. Mathematical model of the controlled pre-magnetization process

The primary objective of the controlled pre-magnetization process is to prepare the transformer magnetic circuit for energisation by establishing the desired initial magnetic state of the transformer core. The magnetic flux established during the pre-magnetization process can be described by the following relationship:

$$\Phi_{\text{pre}} = k\Phi_N, \quad (17)$$

where Φ_{pre} is the magnetic flux established during pre-magnetization [Wb],

Φ_N is the rated magnetic flux [Wb], and k is the pre-magnetization coefficient.

The coefficient k defines the degree of transformer core pre-magnetization prior to energisation and takes values within the following range:

$$0 \leq k < 1. \quad (18)$$

Selecting $k < 1$ prevents the transformer core from being intentionally driven into saturation during pre-magnetization. For the control design, Φ_{pre} is assumed to be reached by closed-loop regulation of the injected magnetising current rather than by open-loop excitation. A nominal pre-magnetization setting of $k = 0.85$ is used in the control specification, with an adjustable range of 0.70–0.95 to accommodate different residual-flux conditions.

One of the key parameters governing the effectiveness of the controlled pre-magnetization strategy is the difference between the magnetic flux established during the pre-magnetization process and the residual magnetic flux remaining in the transformer core:

$$\Delta\Phi = |\Phi_{\text{pre}} - \Phi_r|. \quad (19)$$

A reduction in $\Delta\Phi$ reduces the flux excursion required immediately after energisation and therefore reduces the tendency of the core to enter deep saturation; this is the physical basis for reducing peak inrush current by appropriate flux preparation [9].

For quantitative comparison in future model-based and prototype evaluations, the following relative peak-current reduction measure is defined.

$$\eta_I = \frac{I_{\text{max},0} - I_{\text{max,pre}}}{I_{\text{max},0}} \cdot 100\%, \quad (20)$$

where $I_{\text{max},0}$ is the peak inrush current without pre-magnetization, $I_{\text{max,pre}}$ is the peak inrush current with pre-magnetization, and η_I is the relative reduction in peak inrush current [%].

The control algorithm for the controlled pre-magnetization strategy formulated in this study is presented in Fig. 3.

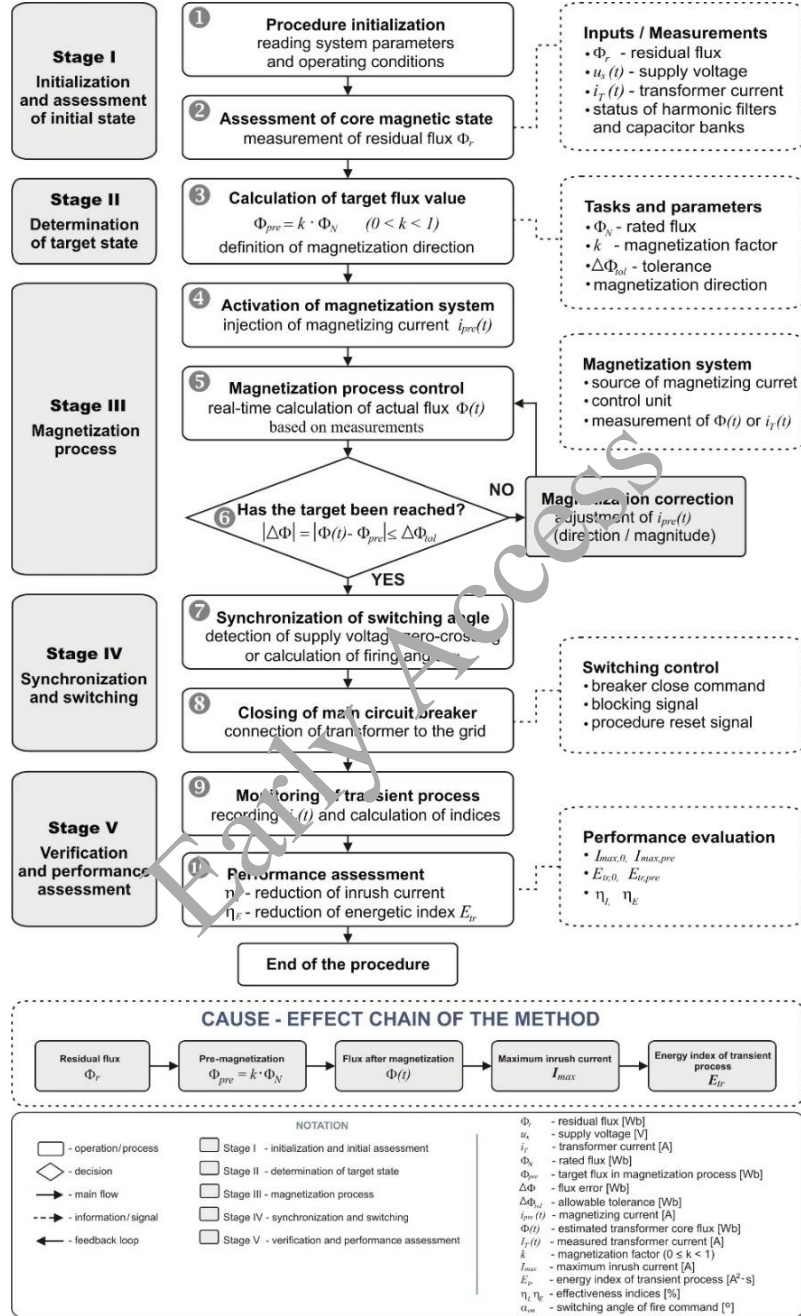


Fig. 3. Control algorithm implementing the controlled pre-magnetization strategy formulated for the arc furnace transformer

4.3. Performance evaluation criteria and qualitative sensitivity assessment

Transformer inrush mitigation is commonly evaluated using peak-current magnitude and transient duration, while waveform shape and the associated thermal or protection burden provide complementary information [8, 18]. For this reason, the present work uses the proposed I^2t -type severity index only as an additional comparative quantity and not as a new physical definition of energy.

For the model-level evaluation framework, the energy-based transient severity index defined by Eq. (1) is retained as an additional quantitative comparison criterion.

For use in the model-based comparison and in subsequent prototype validation, the relative reduction of the energy-based transient severity index is defined as follows:

$$\eta_E = \frac{E_{tr,0} - E_{tr,pre}}{E_{tr,0}} \cdot 100\%, \quad (21)$$

where $E_{tr,0}$ is the energy-based transient severity index for energisation without pre-magnetization, $E_{tr,pre}$ is the corresponding index with controlled pre-magnetization, and η_E is the relative reduction in the transient severity index [%].

The coefficient η_E is defined as a comparative measure of the relative change in the proposed E_{tr} criterion. For equipment protection, the absolute E_{tr} value must additionally be compared with an equipment-specific $E_{tr,lim}$ derived from the permissible I^2t duty of the most thermally vulnerable element in the energisation path. The $E_{tr}/E_{tr,lim}$ ratio can therefore be used as

a dimensionless thermal-utilisation indicator; however, the present study does not claim a universally validated protection threshold for E_{tr} . Full calibration of such thresholds against a broader experimental data set and component-specific withstand data remains a subject of further work. In the present work, η_E formalises the comparison within the model-based assessment framework; no separate prototype-level experimental validation of η_E is claimed.

A model-based qualitative sensitivity assessment was carried out for residual magnetic flux, voltage switching angle, pre-magnetization coefficient and supplying-system parameters [18]. This assessment is used to identify the dominant parameter groups and is not presented as a separate experimental sensitivity campaign.

Within this assessment, residual magnetic flux Φ_r , the pre-magnetization coefficient k and the voltage switching angle α have the most direct influence on the initial core operating point and therefore on inrush-current severity [7, 9]. The supplying-system parameters mainly affect damping and transient decay. These dependencies provide the basis for the control strategy formulated in Section 4.2 and for the comparative discussion in Section 5.

5. Results and discussion

5.1. Conventional energisation of an arc furnace transformer

The archived DSP-100 event described in Sections 2.1 and 3.4 provides the conventional-energisation reference case. The waveform-level comparison in Fig. 2 and Table 2 demonstrates close agreement in peak magnitude and low-frequency transient decay, subject to the validation limitations discussed in Section 3.4. This case is therefore used as the reference baseline for the subsequent model-based discussion of controlled pre-magnetization.

5.2. Energisation using the controlled pre-pagnetization method

The experimentally anchored reduced-order model was used to examine, at model level, how controlled pre-magnetization changes the initial magnetic conditions governing the energisation transient.

Within the model, controlled pre-magnetization reduces the mismatch between the residual and target magnetic flux before energisation, thereby decreasing the predicted tendency toward deep saturation; this change is expected to reduce inrush severity. The E_{tr} criterion is used as a complementary measure alongside peak current and decay time.

5.3. Comparison of inrush current mitigation methods

To evaluate the practical applicability of the controlled pre-magnetization strategy in the investigated EAF context, a qualitative comparison of representative inrush-current mitigation techniques was performed. The comparison covers impedance-based, power-electronic, controlled-switching and pre-magnetization approaches documented in the literature [8, 9]. The comparison is summarised in Table 3.

Table 3. Comparison of the inrush-current mitigation methods considered in this study

Method	Operating principle	Main advantages/limitations	Status in this paper
Series reactor	Increase equivalent impedance during energisation	Simple principle; reduces peak current, but adds voltage drop, losses and additional equipment	Literature-based reference method
Pre-insertion resistor	Temporarily insert resistance before full energisation	Limits the first current peak; requires additional switching hardware and resistor duty management	Literature-based reference method
Thyristor-controlled switching	Power-electronic control of the energisation sequence	Flexible control; higher hardware and control complexity	Literature-based reference method
Synchronised switching	Select breaker closing instant relative to supply voltage / residual state	No continuous loss; effectiveness can deteriorate when residual flux is uncertain	Literature-based reference method
Controlled pre-magnetization	Prepare the initial core magnetic state before breaker closure	Acts directly on the initial magnetic condition; requires a controlled excitation source and flux-state estimation	System-level strategy formulated for the DSP-100 environment in this study; prototype controller validation remains future work

Table 3 distinguishes the operating mechanisms, principal advantages and limitations of the selected methods and separates literature-based reference techniques from the system-level pre-magnetization strategy formulated for the DSP-100 study. The comparison is qualitative and does not imply that the conventional methods were experimentally re-tested on the installation.

5.4. Impact on reactive power compensation and harmonic filtering systems

In industrial electric arc furnace (EAF) installations, the arc furnace transformer operates in conjunction with extensive reactive power compensation and harmonic filtering systems. These components are particularly susceptible to the effects of electromagnetic transients occurring during transformer energisation, especially under conditions associated with high inrush currents.

During conventional transformer energisation, the rapid increase in magnetising current produces a short-duration exchange of reactive energy with the compensation equipment and causes additional currents in capacitor-bank and harmonic-filter branches. The DSP-100 record in Fig. 1 documents transient activity that persisted until protection-initiated branch disconnection at approximately 0.62 s. Because detailed relay pickup settings and complete channel calibration are not preserved in the surviving archive, the event is interpreted as evidence of system-level interaction rather than as a quantitative determination of individual branch thermal withstand.

Particularly severe operating conditions occur when transformer energisation coincides with a high level of residual magnetic flux in the transformer core. Under such conditions, the peak inrush current may considerably exceed the rated transformer current, resulting in increased electrodynamic stresses throughout the power supply system. Consequently, undesirable energy exchange may occur between the transformer, capacitor banks, and harmonic filters, leading to additional electrical and thermal loading of the associated equipment.

The filter, compensation, and circuit-breaker characteristics relevant to the recorded event are summarised in Table 1. Detailed filter-protection pickup thresholds and time delays are not preserved; consequently, the disconnection at approximately 0.62 s is treated as an observed event rather than as a reconstructed relay operation.

Within the proposed model framework, controlled preparation of the initial magnetic state is expected to reduce the severity of the transformer energisation transient and, consequently, the transient stress transferred to the connected compensation/filter branches. The industrial DSP-100 record independently documents that such system-level interaction occurred during energisation; however, the surviving data do not provide direct experimental confirmation of filter-stress reduction resulting from controlled pre-magnetization. That conclusion therefore remains a model-based prediction requiring prototype-level verification.

The proposed control approach is intended to be compatible with existing EAF power-supply architectures without additional steady-state series losses; practical integration nevertheless requires site-specific engineering and prototype-level verification.

More broadly, integration of high-power industrial loads increasingly occurs within power systems characterised by distributed generation, storage and evolving flexibility and capacity mechanisms [38–40].

6. Conclusions

This study formulated a system-level application and evaluation framework for controlled pre-magnetization for reducing energisation transients in an industrial arc furnace transformer. The nonlinear reduced-order model incorporates residual flux, switching angle, magnetic saturation, and the surrounding compensation/filter network, and its low-frequency transient response was compared with the surviving DSP-100 field recordings. The main conclusions are as follows:

1. For the archived reference event, the reduced-order model is numerically consistent with the dominant low-frequency characteristics of the surviving energisation record: the phase-wise peak-current difference is 2.31–2.77%, RMSE is 0.051–0.064 p.u., and the decay-time difference is below 0.03 s. Because the original high-resolution recorder export and recorder metadata are unavailable, these metrics are interpreted as a waveform-consistency assessment rather than as unique validation of the nonlinear saturation law.

2. Among the initial magnetic and control parameters considered in the model-based assessment, residual magnetic flux and the circuit-breaker closing angle most directly influence the initial core operating point and inrush-current severity. The controlled pre-magnetization strategy is formulated to reduce this sensitivity by preparing the magnetic state before energisation.

3. The pre-magnetization strategy formulated here differs from impedance-based or switching-only techniques in that it acts on the initial core flux. Practical implementation requires closed-loop current control and a robust flux observer; the model-level controller specification adopts a $\pm 2.5\%$ flux tolerance and a short persistence check before breaker closure.

4. The energy-based transient severity index complements the peak-current criterion by representing the accumulated I^2t -type thermal burden. For engineering use it should be referenced to component-specific short-time withstand limits, enabling direct integration with thermal protection and coordination studies.

5. The archived DSP-100 event documents transient activity in the harmonic-filter and compensation branches together with protection-initiated disconnection at approximately 0.62 s. This observation demonstrates system-level interaction during transformer energisation. The extent to which controlled pre-magnetization reduces filter/compensation stress remains a model-based prediction and requires prototype-level confirmation; it is not claimed as a demonstrated industrial result in the present paper.

Further work should extend the high-resolution energisation database, verify the dedicated pre-magnetization controller at prototype level, compare the nonlinear model directly with linear

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RL and other reduced-order baselines, and calibrate the $E_{tr}/E_{tr,lim}$ criterion against component-specific withstand data. Particular attention should be given to saturation peaks, harmonic content and repeatability under different residual-flux and switching conditions.

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