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EXPERIMENTAL VALIDATION OF A SIMPLIFIED MMODEL OF A CURRENT TRANSFORMER

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Abstract Modeling of current transformers (CTs) is essential for assessing their transient performance, as the nonlinear magnetizing characteristic of the iron core can lead to severe secondary current waveform distortion. Such effects are particularly critical for the measurement accuracy of protection relays, whose reliable and fast operation depends on the faithful reproduction of the secondary current. This paper presents the experimental validation of a simplified dynamic CT model that includes only the nonlinear (anhysteretic) magnetizing characteristic, while neglecting the winding resistance and leakage inductance. The magnetizing characteristic was measured using a commercial CT analyzer. To align the measured and simulated secondary currents, an optimization procedure was used to determine the initial value of the remanent magnetic flux. The optimization was applied to a transient condition, in which a primary current contains an aperiodic component, typical for power system faults. The simulated secondary current was then compared to the measured current using the range-normalized Root-Mean Square Error (NRMSE) method. After optimization, an NRMSE value ranging from 2% to 5% was achieved for the CT under consideration across six validation scenarios.

Keywords

validation,
current transformer,
model,
magnetizing
characteristic,
saturation,
NRMSE

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1 Introduction

Current transformers (CTs) are essential components in power-system measurement and protection, where accurate reproduction of the primary current is required for reliable operation. During fault conditions and certain transients, a high current magnitude and the presence of an aperiodic (DC) component may drive the iron core into saturation, causing substantial distortion of the secondary current waveform. Such distortion is known to degrade the performance of protection relays and may lead to delayed or incorrect tripping (Whang et al.; 2017, Wiszniewski et al., 2008). Different CT iron-core saturation detection and compensation methods have been developed, because this can have a major impact on power system operation stability and reliability (Naseri et al., 2019; Yang et al., 2022).

Therefore, CT models are indispensable for analyzing CT behavior during such transient events. Several modeling approaches exist, ranging from detailed electromagnetic models that include magnetic hysteresis and winding impedance, to simplified models that include only a nonlinear magnetizing characteristic (Afonso et al., 2020a), and some in between (Guo et al., 2017). While detailed models offer higher accuracy, they require more extensive parameter identification and can be computationally more demanding. Simplified models, in contrast, preserve only the dominant nonlinear magnetizing characteristic, while neglecting winding resistance and leakage inductance (Zhang et al., 2013). There are many different approaches to modeling the nonlinear magnetizing characteristic, which remain very challenging to describe accurately (Zhang et al., 2013; Ayyadurai et al., 2014). These simplified models provide a good compromise between accuracy and time-consuming parameter estimation, and are used widely in protection studies, where the key requirement is reproducing the onset and severity of iron core saturation (Yin et al., 2016; Afonso et al., 2020a).

Despite the practicality, all CT models should be validated experimentally, to ensure accurate reproduction of the real transformer's behavior under the most relevant conditions. The CT saturation depends strongly on the true magnetizing characteristic, residual flux, and the waveform of the driving current (Yin et al., 2016; Afonso et al., 2020b). Consequently, experimental validation is necessary to confirm that a simplified model provides sufficient accuracy for the desired case studies. This paper, therefore, focuses on the experimental validation of a simplified CT model

based solely on the measured nonlinear magnetizing characteristic, using a commercially available CT analyzer to speed up model parameter estimation and increase model usability.

2 Simplified model of a current transformer

The simplified model of the CT in this paper aims to reproduce only the dominant nonlinear behavior of the iron core, while avoiding the complexity associated with full electromagnetic representations (Zhang et al., 2013). The balance of magnetomotive force (MMF) produced by the primary and secondary windings can be described as:

$$\theta = N_1 i_1 - N_2 i_2 \quad (1)$$

where N_1 and N_2 denote the primary and secondary winding turns, while i_1 and i_2 denote the primary and secondary winding currents. The resulting net MMF drives the magnetic flux according to the static nonlinear magnetizing characteristic:

$$\phi = f(\theta) \quad (2)$$

which is introduced in the model as a look-up table instead of the more commonly used parametric hysteresis models (Zhang et al., 2013; Ayyadurai et al., 2014).

The time variation of magnetic flux induces a voltage in the secondary winding according to:

$$e_2 = -N_2 \frac{d\phi}{dt} = i_2 R_2 \quad (3)$$

which drives the secondary current over the secondary resistance (R_2), which consists of secondary winding resistance and burden resistance. The MATLAB/Simulink model presented in Figure 1 was built based on equations (1), (2), and (3).

In steady-state and non-saturated operation of the CT, the induced voltage (e_2) is sufficiently large to drive a secondary current i_2 that generates the secondary ampere-turns ($N_2 i_2$), which balance out the primary ampere-turns ($N_1 i_1$) almost exactly,

according to equation (1). As a result, the net MMF (θ) remains small, and the iron core operates in the linear region of its magnetizing characteristic.

However, when the magnetic flux exceeds the linear region, i.e., enters the saturation region, the incremental permeability of the iron core decreases rapidly, and the magnetic flux no longer follows the primary excitation proportionally. This loss of proportionality, reflected in amplitude reduction and waveform distortion, marks the onset of current-transformer saturation, which can occur during transient conditions, or when the burden resistance or current exceeds the rated values.

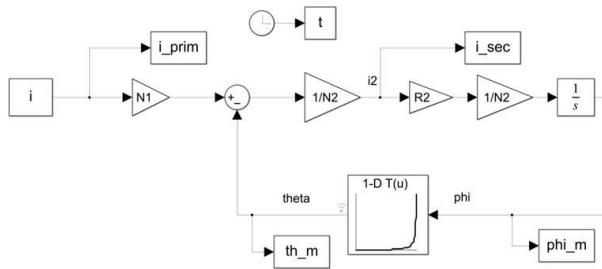


Figure 1: Simplified model of a current transformer in Matlab Simulink

Source: own.

3 Determining the parameters of the current transformer model

A measurement-class CT, the Circutor TA 210, was used to validate the simplified CT model experimentally. The rated values and parameters of the simplified CT model are presented in Table 1. The secondary resistance (R_2) was obtained by measuring only the secondary winding resistance with the GW INSTEK GOM-802 Ohmmeter.

Table 1: Rated values and parameters of current transformer TA 210

	Value	Unit	Description
I_1	10	A	Primary rated current (RMS)
I_2	5	A	Secondary rated current (RMS)
S_r	15	VA	Rated apparent power
N_1	40		Primary winding turns
N_2	80		Secondary winding turns
R_2	99,3	mΩ	Secondary (winding) resistance

Source: own.

The secondary winding terminals were shorted out with a very short wire, and no additional burden was used in the following experiment. The magnetizing characteristic $\phi(\theta)$ was determined using the Omicron CT Analyzer, which measures the induced voltage and magnetizing current according to four different Standards: IEC 61869-2, 60044-1, 60044-6, and IEEE C57.13. Each of these Standards defines the magnetizing characteristic using different calculations of the measured induced voltage (E) and the magnetizing current (I_m). The magnetizing characteristic $\phi(\theta)$ presented in Figure 1 can be, according to the IEEE C57.13 Standard, obtained by the calculation of MMF using equation (4) and magnetic flux using equation (5). In Figure 2, the magnetic flux saturation level is indicated for illustrative purposes as ϕ_{sat} at the value of 0.35 mVs.

$$\hat{\theta} = \sqrt{2} \cdot I_m \cdot N_2 \quad (4)$$

$$\hat{\phi} = \frac{\sqrt{2} \cdot E}{2\pi \cdot f \cdot N_2} \quad (5)$$

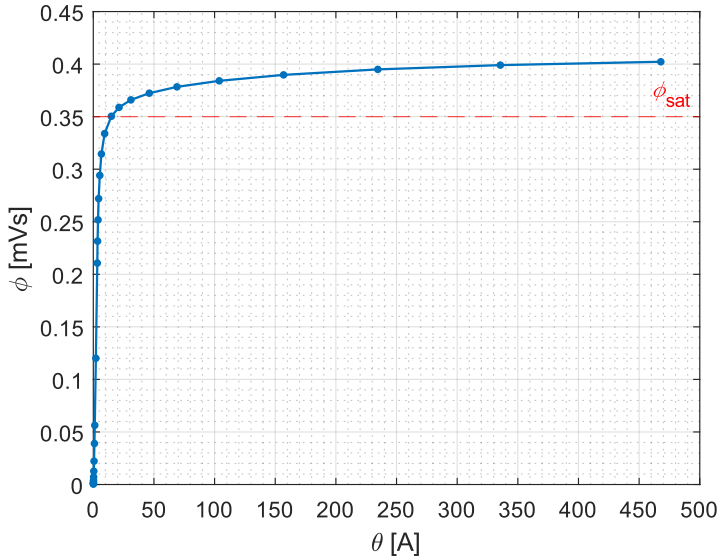


Figure 2: Magnetizing characteristic

Source: own.

4 The experimental validation of the current transformer model

The proposed simplified CT model was validated experimentally, with the CT primary winding supplied using the Omicron CMC 256-6 test and calibration device (Figure 3). The secondary winding terminals were shorted with a very short wire, allowing measurement of the secondary current while adding the least burden to the secondary resistance. The primary and secondary currents (i_1 and i_2) were measured using a LEM IT 60-S current transducer with a 60 A DC current range and the Dewesoft Sirius data acquisition system with a sampling rate of 20 kHz.

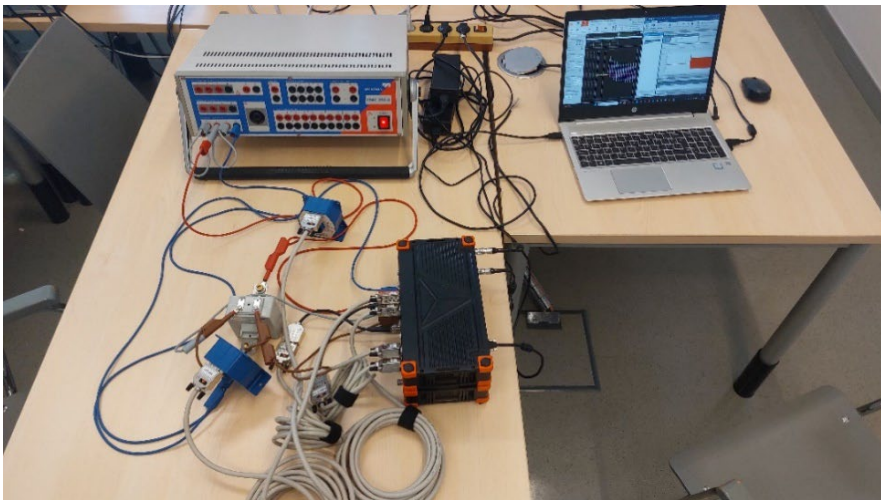


Figure 3: Experimental setup with an Omicron CMC 256-6 power supply, LEM IT 60-S current transducer, and Dewesoft Sirius data acquisition system

Source: own.

The primary winding of the CT was supplied with the primary current, (i_1), which consisted of two time sequences that represent the typical transient behavior of the power line's fault current. The first sequence, denoted with $i_{1,1}$ in equation (6), represents normal operating conditions with a constant current $I_{1,1}$ of 2 A, the angular frequency ω of $2\pi 50$ rad/s, and a fault inception angle φ equal to 90 degrees. The second sequence, denoted with $i_{1,2}$ in equation (7), represents the short-circuit current with a steady-state value $I_{1,2}$ of 10 A and contains an aperiodic component, which represents the short-circuit conditions. The angular frequency and inception angle remained unchanged, while $\delta = (\varphi - \tan^{-1}(\omega\tau))$. The time constant of the

decay τ was set to a value that caused saturation of the CT iron core without exceeding the measured range of the magnetizing characteristic shown in Figure 2. The decay time constant τ value of 60 ms was found by trial and error. Note that each sequence was simulated for a time period of 5 seconds.

$$i_{1,1} = \sqrt{2} \cdot I_{1,1} \sin(\omega t + \varphi); \quad t \in [t_o, t_1] \quad (6)$$

$$i_{1,2} = \sqrt{2} \cdot I_{1,2} \left(\sin(\omega t + \varphi) - \sin(\delta) e^{-\frac{t}{\tau}} \right); \quad t \in [t_1, t_2] \quad (7)$$

The described primary current (i_1) drives the magnetic flux of the CT into the nonlinear region of the magnetizing characteristic, which causes the increase of magnetizing current (i_m) and the distortion of the secondary current (i_2). Figure 4 shows all the described currents, where the secondary current is reduced to the primary side using the current ratio K_I , as given by:

$$i'_2 = K_I \cdot i_2 = \frac{I_1}{I_2} \cdot i_2 = \frac{N_2}{N_1} \cdot i_2 \quad (8)$$

An additional comparison was performed using the normalized peak-to-peak Root Mean Square Error (NRMSE) metric, which is calculated over a sliding time window of one fundamental period with N samples using equation (9). The $I_{1\max}$ and $I_{1\min}$ are the maximum and minimum values of the primary current (i_1), respectively, also calculated over a sliding window of N samples.

$$\text{NRMSE}_1 = \frac{\text{RMSE}_1}{I_{1\max} - I_{1\min}} = \frac{\sqrt{\frac{1}{N} \sum_{j=1}^N (i'_2(j) - i_1(j))^2}}{I_{1\max} - I_{1\min}} \quad (9)$$

The applied NRMSE provides a scale-invariant measure of the secondary current waveform distortion. The maximum value of NRMSE_1 obtained in this comparison was 18.9%, which occurred in the 4th period after the aperiodic component was applied to the primary current (Figure 4). This indicates the severe saturation of the iron core, because the secondary current no longer reproduces the primary current waveform accurately.

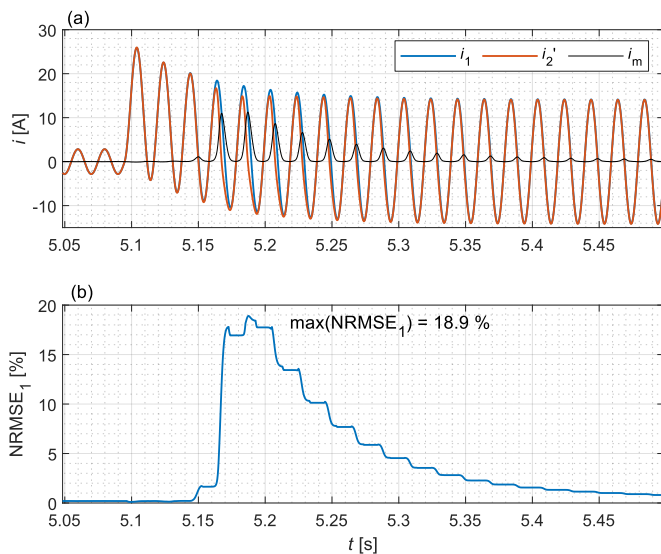


Figure 4: Measured primary, secondary, and magnetizing current of current transformer (a) and NRMSE of secondary current (b)

Source: own.

The above-described experiment was also used to validate the simplified model of the CT, by comparing the measured secondary current, denoted as i_{2m}' , with the simulated one, denoted as i_{2s}' , in Figure 5. This comparison uses the same NRMSE metric described in (9), where i_2' was replaced by i_{2m}' and i_1 was replaced by i_{2s}' . The newly calculated NRMSE is denoted with NRMSE₂.

Figure 5 shows all the currents, where the simulated secondary current was obtained using a demagnetized iron core in a CT model. This assumption (demagnetized iron core) was incorrect, and produced a large difference between the measured i_{2m}' and simulated secondary current i_{2s}' , exceeding 4.53 A, resulting in an NRMSE₂ for the simulated secondary current exceeding 14.63%. This large difference between the simulated and measured secondary current appeared only in the 4th period after the application of the aperiodic component. During the observed period, waveform distortion occurred only in the measured secondary current, indicating iron-core saturation, whereas, in the simulated secondary current, it was not observed, and the model showed that the magnetic flux was barely saturated (Figure 5). Furthermore,

the waveform distortion (iron-core saturation) in the simulated and measured secondary currents occurred at different times.

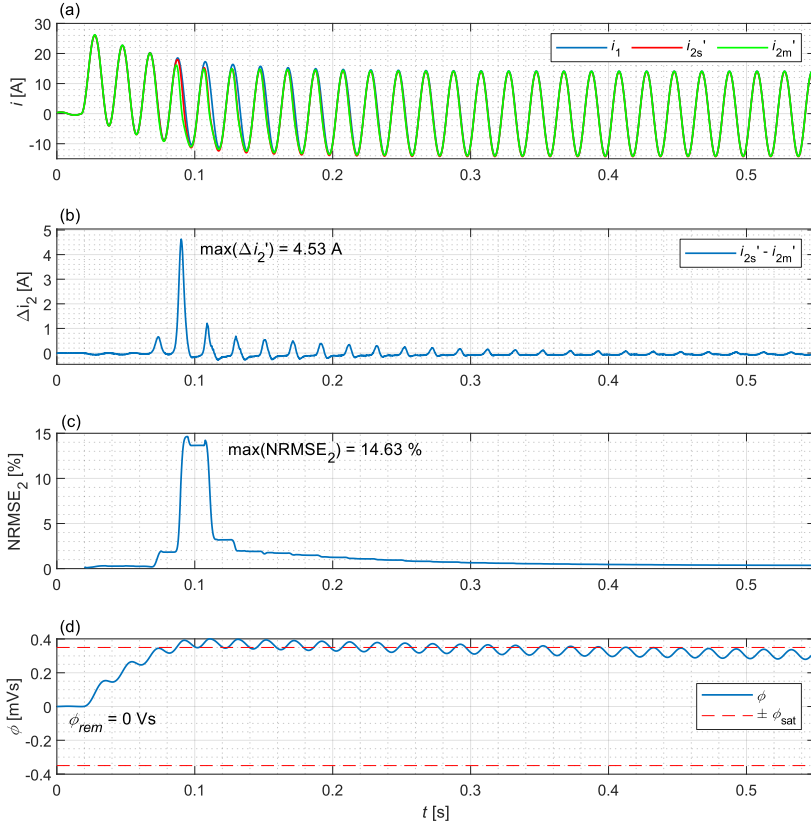


Figure 5: Simulated and measured primary and secondary currents of current transformer (a), difference between the simulated and measured secondary current (b), NRMSE (c), and magnetic flux without the remanent magnetic flux (d)

Source: own.

To match the measured and simulated secondary currents, an optimization procedure was employed to determine the remanent magnetic flux (initial value). The objective function was defined as the minimization of the RMSE between the measured and the simulated secondary current waveforms. In this case, the RMSE in (10) was calculated over the entire timeframe shown in Figure 5, which is 0.55 s long. This timeframe defines the total number of samples N used in the RMSE calculation.

$$RMSE = \sqrt{\frac{1}{N} \sum_{j=1}^N (i'_{2m,j} - i'_{2s,j})^2} \quad (10)$$

The optimization problem was solved using the "fminsearch" function from the Matlab Optimization Toolbox, where the only decision variable was the remanent magnetic flux denoted as ϕ_{rem} , while all the other model parameters were kept constant. The variable tolerance was set to 10^{-7} , since the remanent magnetic flux is in the range of μ Vs.

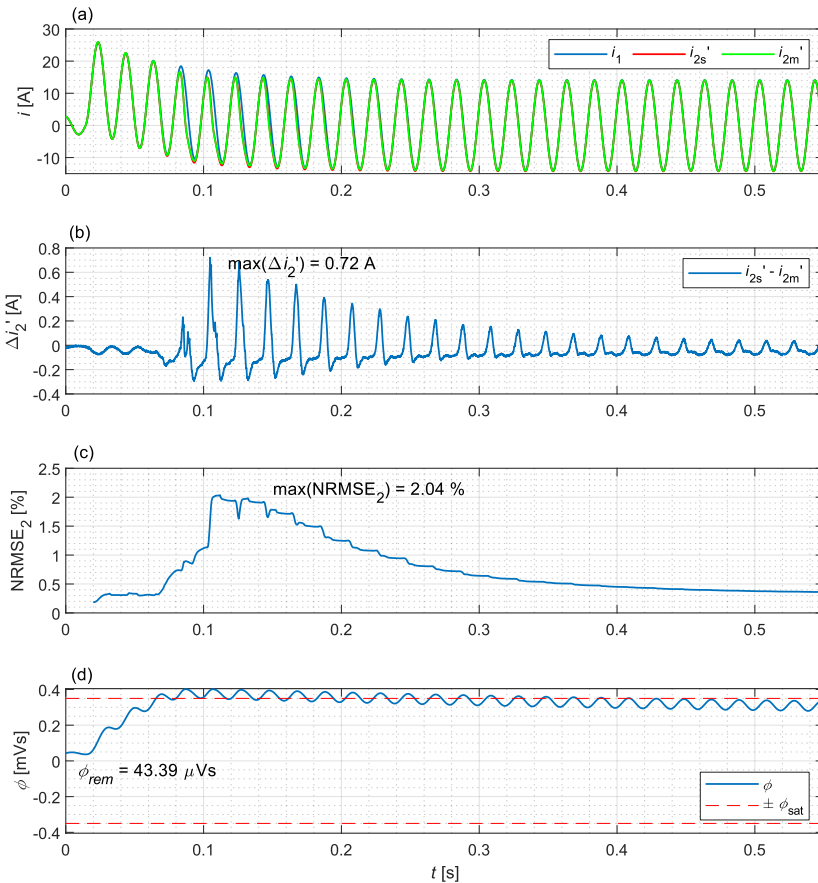


Figure 6: Measured and simulated primary and secondary currents of the current transformer (a), difference between the simulated and measured secondary current (b), NRMSE (c), and magnetic flux with remanent magnetic flux (d)

Source: own.

By applying the described optimization procedure, a remanent magnetic flux value of $43.39 \mu\text{Vs}$ was obtained for the discussed case. It must be emphasized that the actual value may differ, as it was not measured. Furthermore, the determined remanent magnetic flux value may not reflect the iron core's physical state accurately, but it can help address model simplifications, such as the omission of hysteresis and other nonlinear phenomena. However, the obtained remanent magnetic flux reduced the maximum NRMSE_2 of the newly simulated secondary current to only 2.04%. The maximum NRMSE_2 was again observed during the period with the most severe saturation, when the difference between the secondary and primary currents was greatest (Figure 6).

This low NRMSE_2 value confirms that the simplified model, based solely on the nonlinear magnetization characteristic, can capture the essential iron-core saturation dynamics with sufficient accuracy. Note that the NRMSE_2 exceeded 1.5% for only approximately 4 fundamental periods.

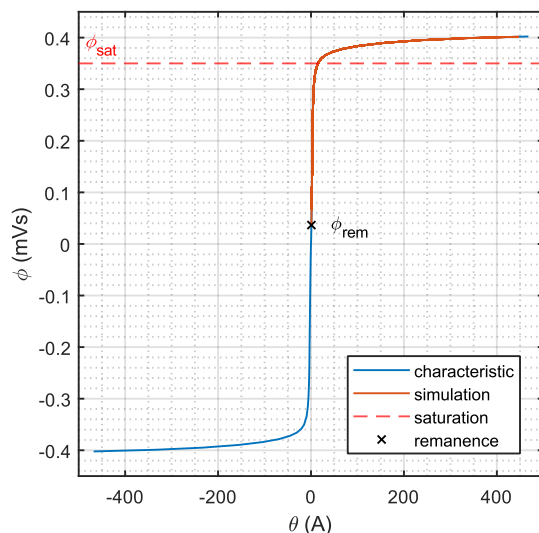


Figure 7: Measured magnetizing characteristic with simulated magnetic flux and magnetic flux saturation level

Source: own.

Figure 7 shows the measured magnetizing characteristic and the simulated magnetic flux, with a remanent magnetic flux of $43.39 \mu\text{Vs}$. The maximum value of magnetic flux in this simulation was $401.7 \mu\text{Vs}$, which is within the range of the measured

magnetizing characteristic, which as 402.2 μVs . Thus, it eliminates the need for extrapolation, which can introduce additional extrapolation errors to the results.

Table 2: NRMSE values at different remanent flux values and primary current parameters

	τ [ms]	$I_{1,1}$ [A]	$I_{1,2}$ [A]	ϕ_{rem} [μVs]	ϕ_{max} [μVs]	NRMSE ₁ [%]	NRMSE ₂ [%]
1	60	2.0	10	43.39	401.7	18.9	2.04
2	55	0.367	10	51.06	401.8	18.2	1.76
3	90	1.5	9	28.81	403.8	25.5	2.0
4	90	1.5	9	269.4	410.2	40.3	3.63
5	130	1.5	9	28.14	408.1	35.1	2.63
6	130	1.5	9	270.1	411.3	44.8	4.52

Source: own

Additional experiments were performed with different remanent magnetic flux ϕ_{rem} values and different primary current i_1 parameters, such as decay time constant τ , pre-fault current amplitude $I_{1,1}$, and short-circuit current amplitude $I_{1,2}$. For each experiment, the NRMSE₁ and NRMSE₂ were calculated, with NRMSE₂ computed from the remanent magnetic flux obtained by the optimization algorithm.

In the first two tests presented in Table 2 the magnetic flux remained within the measured range, resulting in an NRMSE₂ of approximately 2%, despite the relatively high saturation levels, which led to an NRMSE₁ of up to 19%. In the subsequent four tests, the decay time constant was increased to 90 ms and 130 ms, heightening the severity of the saturation further. It is important to note that the distinction between tests Nos. 3 and 4 lies in the degree of demagnetization prior to testing. The same distinction applies to tests Nos. 5 and 6. In tests Nos. 4 and 6, the optimization method yielded a remanent magnetic flux linkage value of around 270 μVs , which is approximately 75% of the saturation level indicated at 350 μVs . In these two tests, the saturation was at its highest, with the NRMSE₁ exceeding 40%. However, the NRMSE₂ remained below 5%, even in these cases, where the magnetizing characteristics were extrapolated using linear extrapolation.

5 Conclusion

This paper presents a simplified nonlinear model of a CT intended for analyzing saturation effects during transient conditions. The model incorporates only the nonlinear magnetizing characteristic of the iron core, which captures the dominant magnetic behavior responsible for iron core saturation. Experimental validation

using a primary current with an aperiodic component showed that the transformer operated in a state of severe saturation, as confirmed by a high NRMSE_1 of 18.9% between the measured primary current and the secondary current referred to the primary side. Despite this pronounced saturation, the comparison between the measured and simulated secondary currents yielded an NRMSE_2 of about 2% when the magnetic flux remained within the range of the measured magnetizing characteristic. In the tests where the magnetic flux exceeded the range of the measured magnetizing characteristic, the NRMSE_2 increased with the severity of iron core saturation, but remained below 5% in all the tests.

These experiments demonstrate that the simplified model reproduces the essential features of the saturation effect successfully. These results indicate that the model is sufficiently accurate for practical studies of CT transient performance, including scenarios that may lead to non-selective or misoperation of the protection relays. The described approach, therefore, provides a useful basis for further investigations, such as extending the model to include hysteresis, or analyzing the impact of burden variations, or introducing more complex excitation waveforms. Further investigations should include measurements of the remanent magnetic flux and analysis of the different types of current transformers, e.g., protection classes TPX, TPY, and TPZ.

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Povzetek s slovenskem jeziku

Eksperimentalna validacija poenostavljenega modela tokovnega transformatorja. Modeliranje tokovnih transformatorjev (TT) je ključnega pomena za ocenjevanje njihovega odziva med prehodnimi pojavi, saj lahko nelinearna magnetilna karakteristika železnega jedra povzroči izrazito popačenje sekundarne tokovne oblike. Takšni pojavi so še posebej kritični za merilno natančnost zaščitnih relejev, katerih zanesljivo in hitro delovanje je odvisno od verodostojne reprodukcije sekundarnega toka. V članku je predstavljena eksperimentalna validacija poenostavljenega dinamičnega modela TT, ki vključuje le nelinearno magnetilno karakteristiko brez upoštevanja histereze, upornost primarnega navitja in razpisna induktivnost pa sta zanemarejeni. Magnetilna karakteristika je bila izmerjena s komercialnim analizatorjem TT. Za uskladitev izmerjenih in simuliranih sekundarnih tokov je bil uporabljen optimizacijski postopek za določitev začetne vrednosti preostalega magnetnega pretoka. Optimizacija je bila izvedena za prehodno stanje, pri katerem primarni tok vsebuje aperioidično komponento, značilno za okvare v elektroenergetskem sistemu. Simulirani sekundarni tok je bil nato primerjan z izmerjenim tokom z uporabo metode korena povprečne kvadratne napake, normirane z razponom vrednosti (angl. NRMSE). Po izvedeni optimizaciji je bila za obravnavani TT v šestih validacijskih scenarijih dosežena vrednost NRMSE med 2% in 5%.

Ključne besede: validacija, tokovni transformator, model, magnetilna karakteristika, nasičenje, NRMSE