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# Analysis of Hysteresis Loss Measurements for Single-Phase Transformers

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**Abstract.** Our study proposes a MATLAB simulation to analyze the hysteresis loss in single-phase transformers under a frequency of 50 Hz, calculating the variables and the relationship between the magnetic flux density ($B$) and the magnetic field intensity ($H$) in the theoretical equation to design used in numerous conditions, including consideration of parameter of the ferromagnetic silicon steel core material, sizes, power rated, and amplitude of alternating current (AC) sinusoid that affects the *B-H* curve, and saturations point in the time domain. Comparing the hysteresis loss characteristics between the model and empirical experiments and the experiment test results are given in this paper.

**Keywords.** hysteresis loss, MATLAB, transformer cores, single-phase transformers

## 1. Introduction

Single-phase transformers are commonly used to require high-efficiency applications suitable for substantial applications, for example, the communications industry, the electronics industry, small-scale industries, and railway systems. Generally, a single-phase electrical power system demand is moderate to convert the power rated and reduce the voltage from a power system requiring lower voltage use to electricity safely. Typically, the structure consists of two crucial parts: the magnetic core creates a magnetic field, a vital part of the operation transformers, created by silicon steel or other ferromagnetic materials with high electromagnetic properties [1], and the second part, windings are wrapped around the transformer core for an electrical current path in the circuit in conditions design. The transformer core structures designed efficiently will decrease energy loss in the transformer system, which increases the capability of heat dissipation from the transformer. However, improvements have limitations; power loss can arise from voltage conversion required in systems continuously, and changes in the properties of the transformer cores and magnetization under load conditions are complicated.

Supplying the AC will engender a loss in the system called transformer loss that can be divided into two main types: electrical loss, such as copper loss and resistance loss.

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Magnetic or iron loss from magnetism properties has changed to eddy current loss and hysteresis loss [1]. Decreasing hysteresis loss can be achieved by selecting appropriate transformer core materials with high permeability, silicon steel or super-alloy, as ferromagnetic materials. Also, frequency and current should be controlled for proper use with electrical loads. Using software simulations to design is essential to develop high-efficiency transformers and analyze the initial hysteresis loss before designing. Furthermore, improving the transformer design before empirical experiment production can be done using simulation software such as PSpice, SPICE, and LTspice [2] interrelated to electromagnetic circuits, which helps to work quickly, is friendly to use, is low cost, and is safe.

This paper analyzes hysteresis losses in the single-phase transformers using MATLAB simulation by considering essential variables, such as the size of the transformer cores, operating amplitude and frequency of the AC, and RC integrator circuit [3] design appropriately for improving use in power-rated, and other essential conditions. The evaluation of the hysteresis loss was designed from the empirical experiments to analyze the consistency of the *B-H* curve results and propose a limit of the model obtained from testing to design a transformer efficiently.

## 2. Equations

Hysteresis loss ($P_h$) occurs when the magnetic force changes in magnitude and direction in proportion to the amplitude and frequency of the AC source fed into the system, which incurs a reversal of the orientation molecules in the magnetic materials. The hysteresis loop area is essential to indicate the energy lost in one cycle of the AC change per unit volume [4] that can be found in the equation:

$$P_{\mathrm{h}}=K_{\mathrm{h}}fB_{\mathrm{m}}^{\mathrm{n}}V \tag{1}$$

where $P_h$ is proportional to the frequency value ($f$) of the AC voltage signals, the volume ($V$) of the transformer core materials, the operating maximum magnetic flux density ($B$m) of the transformer core materials, the value $K_h$ is a constant known as the Steinmetz's constant, and n is the Steinmetz exponent being 1.6 for $B$m < 1 T and 2 for $B$m > 1 T that depends on the core materials. There is also the equation of semiempirical Richter's [5] to compute the $B$m.

The AC is supplied to the magnetic circuit, and sinusoidal signals are distorted from their waveforms due to harmonic currents. They will occur in a nonlinear region when the inlet pressure rating increases [6]. The magnitude of magnetic field intensity ($H$) increases in the time-varying, using Ampere's law may be derived:

$$H(t)=\frac{N_1 I(t)}{l_{\mathrm{m}}} \tag{2}$$

where $N_1$ is the number of primary windings, $I(t)$ is the AC source in the time domain, and $l_m$ is the average length of the $l$-axis, respectively. The magnetic flux density ($B$) in the time-varying relatedness is used to approximate it mathematically using a simple RC integrated circuit. The connection between the resistor and capacitor is in series with the number of secondary windings ($N_2$) supplied. The resistance $R_2$ should be made large, and the capacitive reactance ($X$c) is kept small using a large capacitance ($C$). The $R_2$ sets the AC in the circuit and is proportional to the capacitor voltage ($v_C$) expressed by the equation:

$$v_C(\mathrm{t}) = \frac{1}{R_2 C} \int v_2(t)\, \mathrm{dt} \quad (3)$$

The $B$ in the time-varying was measured from the $v_C$, which is calculated from a relation electromotive force (EMF) with the rate of change of the flux linkage given by the equation:

$$B(t) = -\frac{R_2\, C v_C(t)}{N_2\, A} \quad (4)$$

where $A$ is the cross-section area. The AC and voltage signal is measured in the time domain to the $X$-$Y$ values of the electromagnetic circuit, representing the variables $H$ and $B$, respectively. The hysteresis loss estimate shows the relationship of the $B$-$H$ curve. Also, saturation points were observed in the transformer core materials, effects on the energy loss that accumulates heat from $B$m, and maximum magnetic field intensity ($H$m).

## 3. Experiments

Hysteresis loss analysis in single-phase transformers using MATLAB simulation, considering the designed hysteresis loss from the empirical experiment, and comparing obtained from the designed model is necessary to improve the test and evaluate the hysteresis loss to ensure data consistency. Then, assess risk and the possibility of using the model for experimental study transformer design. The simulation for determining the hysteresis loss of a single-phase transformer using MATLAB/Simulink [3] PS-Simulink converter block parameters to convert Simscape to Simulink output signal that measures the $B$-$H$ curve relationship as equations (2) and (4)—using a linear reluctance mode with hysteresis (Jiles and Atherton model; JA) [7]. There are general methods as follows:

- The transformer core designs (power rating, frequency rating, sizes, etc.) follow the usage requirements.
- Calculate the size of the transformer cores as theoretical principles and relevant equations.
- Consider parameter materials that impact the transformer's hysteresis loss, including the core transformer materials, windings, and insulating materials.
- Design using appropriate MATLAB software by creating numerous variables following correlation equation. Each transformer model template will be able to determine the size of the transformer core, RC integrator circuit, and other confederacy features quickly and safely.
- Evaluate the hysteresis loss of transformers designed and test the amplitude current rating to reach maximum saturation point values.
- Improve the model to be correct and precise.

After designing and testing the model to ensure it is correct as the theory and equations, tests will be performed on experimental study transformers to confirm the model results. Fig. 1 shows the empirical experiment's installation and *B*-*H* curve measurements. The circuit transformer tests start by connecting a resistor $R_1$ to the primary side of the transformer and using a high-impedance RC integrator circuit to connect it to the secondary side of the transformer [3, 8]. When supplying power according to the specified rating through an adjustable variable transformer, it supplies a variable AC voltage, a frequency of 50 Hz, and uses an oscilloscope in *X*-*Y* mode. The *X*-probe measures the current across $R_1$ for the *H* values, and the *Y*-probe measures the voltage across capacitors for the *B* values. Moreover, a flux meter measuring device was used to test saturation while distributing the AC as the test rating. Electrical transformers used for testing are a single phase 50 Hz.

The voltage ratio of transformers TN 1, TN 2, and TN 3 are 220 V to 220 V, 220 V to 110 V, and 220 V to 24 V, respectively. Different core sample sizes are represented in Table I. All variables are 10 Ω of $R_1$, RC integrator 10 kΩ of $R_2$, and 18 µF of C, respectively. Also, silicon steel of the transformer core, iron alloy steel, was used for all three samples. The methods are as follows:

- Producing the single-phase transformer systems corresponding with the simulation design. Consider essential parameters (the core lengths, the number of windings turns on each side, the core cross-sectional area, etc.) associated with the equations.
- Evaluate the hysteresis loss and calculate the amplitude current, voltage, and frequency affecting the *B*-*H* curve saturation point.
- Compare the values obtained from the designed model to ensure accurate and precise values and improve the test. Also, evaluate the capability to ensure consistent results again.
- Check several constants corresponding to the hysteresis loss between MATLAB and the empirical experiment.
- Assess risk and the possibility of using the model.
- Summary of results obtained from all comparison tests.

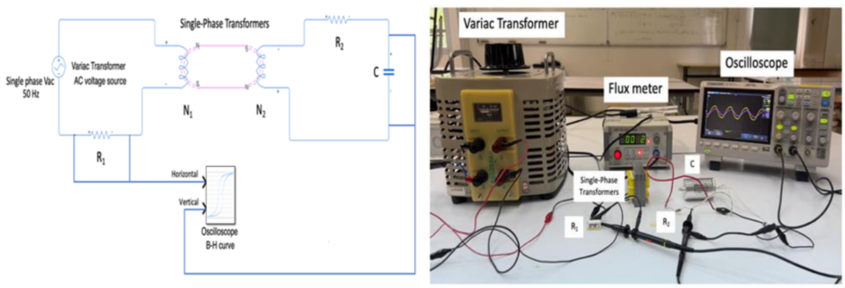



**Figure 1.** Installation scenario and the *B*-*H* curve measurement of the empirical experiments.

**Table 1.** Sample name and sizes of the transformer core materials.

| **Sample** | ***lm* [mm]** | ***A* [mm$^2$]** |
|---|---|---|
| TN 1 | 218 | 484 |
| TN 2 | 188 | 400 |
| TN 3 | 153 | 306 |

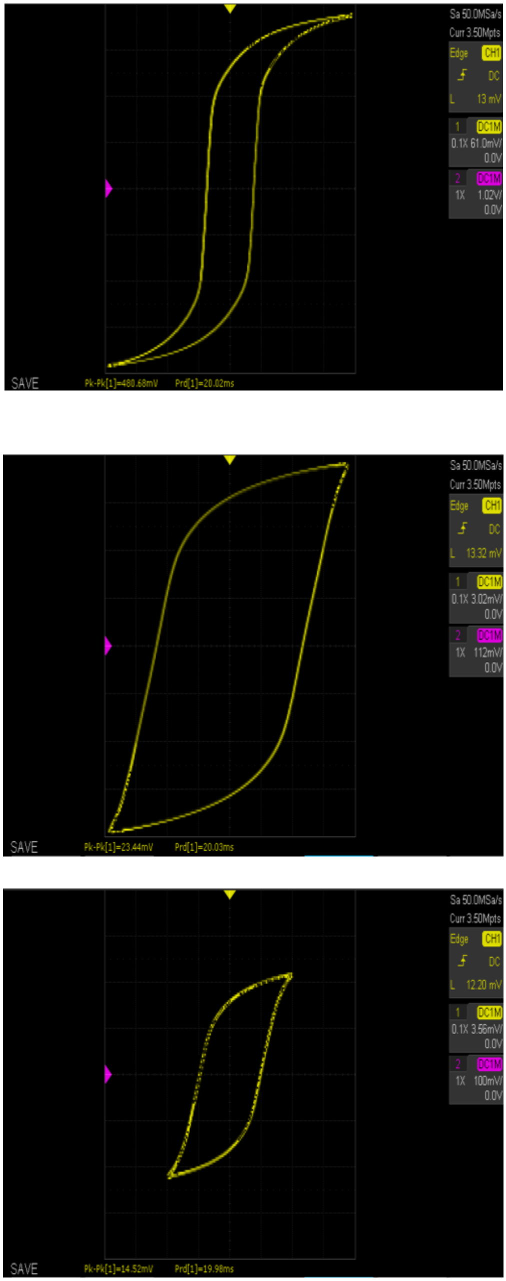
## 4. Results

The hysteresis loss in the transformer for TN 1, TN 2, and TN 3 samples were obtained to design from the MATLAB simulation to compare the values obtained by experimental study measurement; the results were obtained as follows:

In Fig. 2, all samples of the *B*-*H* curve are plotted by the *B* against the *H*. The calculations obtained by the proposed equation (4) represent the *B,* and equation (2) represents the *H*, respectively. Measuring the *X*-*Y* mode voltage signals while transformers were input to the AC source using an oscilloscope to analyze the empirical experiments with saturation points. The results show that when supplying the AC 150 V 50 Hz had a saturation point (*H*m, *B*m) of TN 1, TN 2, and TN 3 samples are (0.244,4.080), (0.011,0.426), and (0.007,0.200), respectively. In addition, using a magnetic flux meter that appeared in the magnetic flux path, the average outer surface area of the core of TN 1, TN 2, and TN 3 samples are 0.16 T, 0.03 T, and 0.01 T, respectively.

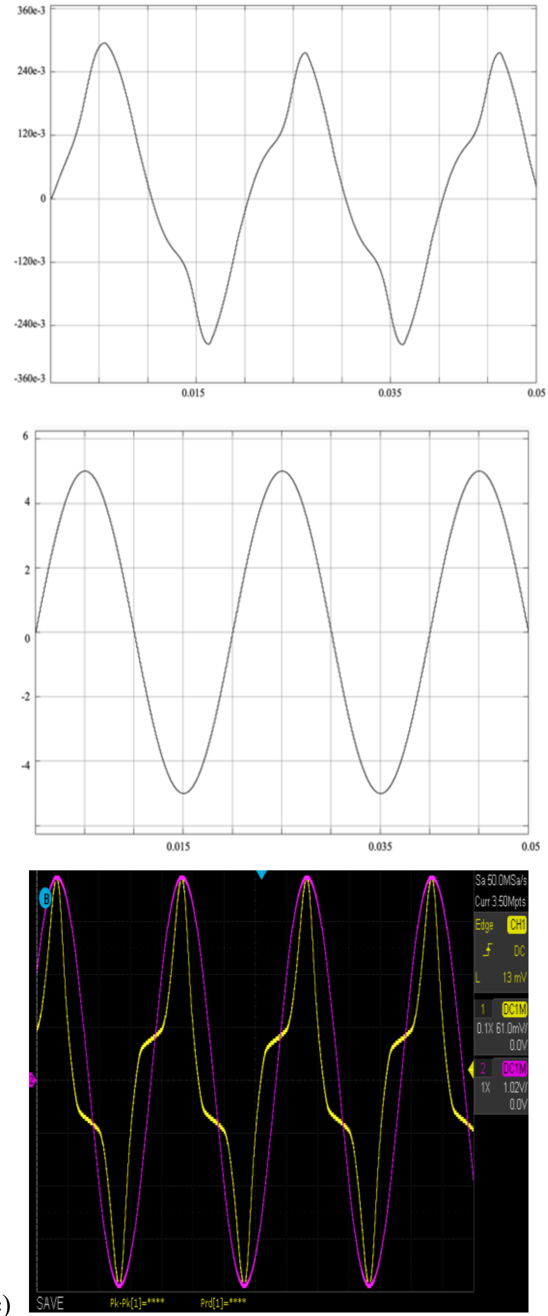
For the MATLAB simulation results, using the *X*-*Y* scope block parameter, the stop time value of all simulating samples is 0.5 seconds. The hysteresis loss obtained with saturation point values at the AC 150 V 50 Hz, TN 1, TN 2, and TN 3 samples are (0.256,4.284), (0.012,0.437), and (0.008,0.210), respectively. The empirical experiment and analysis results using simulations are consistent. The direction of the AC reversal affects the magnetic domains within the material, which are aligned with the external magnetic field acting on the magnetic circuits, thus making it possible to flip magnetic domains back and forth quickly [4]. As a result, the hysteresis loss of core material causes energy loss that accumulates heat from the saturation point from the amplitude and frequency of the AC supply, which continuously influences the electromagnetic circuit. Hence, power transformers should be designed so that the magnetic flux density is below the level that would incur saturation.

The results show the correlation of the amplitude and frequency AC source into the electromagnetic circuit system compared between the model and empirical experiment as shown in Fig. 3; the MATLAB simulation results (a) *H*-values, (b) *B*-values, and (c) Comparison *B*-*H* of empirical experiment measurement, in the time domain of TN 1 sample at the AC 150 V 50 Hz, respectively. The experiment's results found that the hysteresis loss depends on the rated amplitude and frequency of the transformer during operation [3]. The flux and magnetomotive force when the material is saturated in the *B*-*H* curve nonlinear region, the *H* signal in the time domain will be distorted from the original sinusoidal signal [9]. The amplitude AC voltage source indicates the energy lost in one cycle of current change per unit volume of the magnetic circuit. In the case of frequency, it affects the number of turns of the hysteresis loop when the current enters a specific period [3]. Also, both methods showed similar experimental results with a voltage of around 20 V to 150 V and a frequency of 50 Hz ratings. The limitations of the model require knowing the specific variables of the test material by using a mathematical equation to find the result to display the values before it can be taken into the process of converting the result into hysteresis loss, consisting of the value of the Steinmetz's constant (*K*h), the Steinmetz exponent ($n$), and the magnetic permeability ($\mu$) that will require finding references or empirical experiment measurements. These variables may affect the discrepancies in the MATLAB model analysis.




(a) (b) (c)

**Figure 2.** The hysteresis loss results of the empirical experiment at the AC 150 V 50 Hz, (a) TN 1 sample, (b) TN 2 sample, and (d) TN 3 sample, respectively.




(a)

(b)

(c)

**Figure 3.** The MATLAB simulation results (a) *H*-values, (b) *B*-values, and (c) Comparison *B*-*H* of the empirical experiment in the time domain of TN 1 sample at the AC 150 V 50 Hz, respectively.

## 5. Conclusions

The paper proposes explicating a hysteresis loss model for single-phase transformer design, including the proper design evaluation. The experiment sample selected silicon steel core materials of three samples with different power ratings at a frequency using a 50 Hz rating and comparing obtained from the designed model used to improve testing to ensure data consistency with empirical experiments to assess the risks and feasibility of using the simulation. The analysis of the hysteresis loss concerning the theoretical *B-H* curve equation shows the relationship between the permeability of the transformer steel core material.

The saturation flux density varies with the magnitude and frequency of the AC in the electromagnetic circuit, and the variables are related to the design. All test results demonstrate an accurate analysis of the results from the model compared with the values obtained from empirical experiments, presenting the model's advantages in solving math problems quickly, high efficiency, and low cost. Also, the design for use at power-rated and other operating frequencies to improve the accuracy of those tests must be repeated according to the guidelines presented to improve the model further. The consideration is that accumulated heat energy can cause long-term, time-varying damage to the transformer. Therefore, the parameters for choosing the appropriate ferromagnetic materials for the transformer core should be considered suitable as the power rate. The elements relevant to the core loss of the single-phase transformer should be considered for the effect in use.

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