A simple and accurate non-linear transformer model including hysteresis implemented in Matlab/Simulink

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A SIMPLE AND ACCURATE NON-LINEAR TRANSFORMER MODEL INCLUDING HYSTERESIS IMPLEMENTED IN MATLAB/SIMULINK

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ABSTRACT
A non-linear simulation model of a single-phase silicon steel core transformer is developed, with the purpose of simulating the instant voltages and currents. The goal of this paper is to present and then verify the model and showing how to extract the non-linear model parameters. Laboratory experiments are carried out to obtain the transformer model parameters. Comparison of the simulated and measured voltages and currents show close agreement. In the next verification step is the transformer core changed, and it is investigated if the developed transformer model is able of predicting the voltages and currents. It is shown by comparison of measurement and simulation results that the simulation model predicts the behaviour of the real transformer accurately. The transformer model is considered accurate enough to be useful for loss prediction.

KEY WORDS
Modelling, simulation and transformer

1. INTRODUCTION

Models describing magnetic core saturation have been presented using simple lumped circuits [1] and more physical orientated models [2,3] and variations in-between like the ones described in [3-8]. This paper present a lumped circuit model suitable for implementation in software packages as Simulink, parameters are found using Matlab programming.

2. TRANSFORMER MODEL FORMULATION

Implementing the mathematical model equations have been made considerable easy during the last ten years, due to the development of user-friendly programmes. Still one must consider the model complexity and use a model implementation, which do not increase simulation time to an unnecessary extent. The electrical equivalent circuit model of the transformer is shown Figure 1. The model is non-linear since L_M and R_M are functions of B(t). Modelling the inductor $L_M(B)$ in Simulink it is possible to use equation (1),(2) and (3) obtained from Figure 1, 2 and 3 and this was also done, but the implementation of L_M is simpler using equation (4) and (5), in the rest of the paper is equation (4) and (5) used as inductor model. Modelling R_M it is worth noticing that it is made dependent of B in order to model the hysteresis losses. The resistor $R_M(B)$ models core losses as function of B(t) and here the frequency and core-temperature is assumed constant. In the next section the unknown parameters of equation (4) and (5) and Figure 1 is determined by experimental obtained results.

$$u_M = \frac{dL_M i_{LM}}{dt} = L_M \frac{i_{LM}}{dt} + i_{LM} \frac{dL_M}{dt} \quad (1)$$

$$L_M = \frac{{n_p}^2}{\Re_M} \quad (2)$$

$$\Re_M = \frac{l_c}{A_c \mu_r (B) \mu_o} \quad (3)$$

$$u_M = \frac{1}{N_p A_c} \frac{dB}{dt} \quad (4)$$

$$i_{LM} = \frac{H_{LM}(B) l_c}{n_p} \quad (5)$$

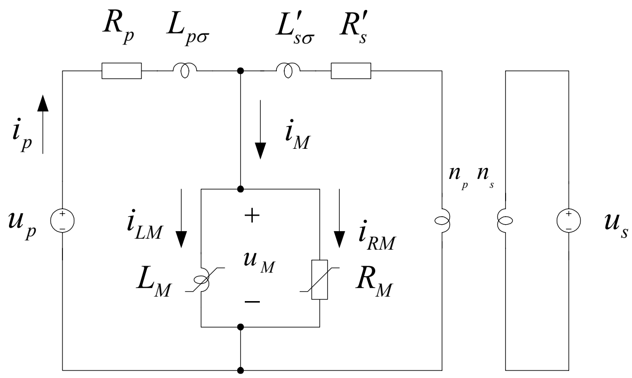

Figure 1 Electrical equivalent circuit model

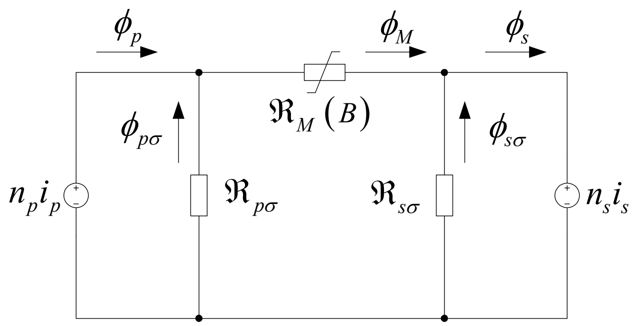

Figure 2 Magnetic equivalent circuit model

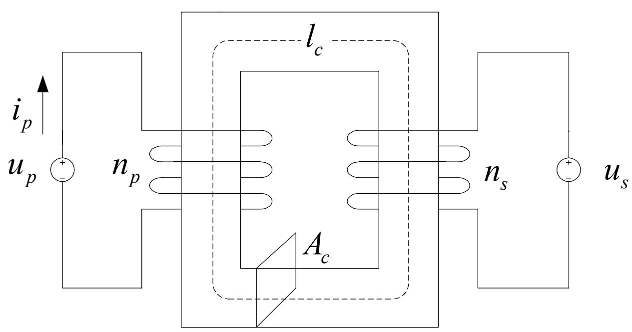

Figure 3 Sketch of transformer

3. TRANSFORMER MODEL PARAMETER DETERMINATION

By conventional measuring methods are the following parameters obtained:

The transformer parameters are:

l_c = 0.48 [m] : magnetic mean length
A_c = 0.00156 [m^2] : cross section area
n_p,n_s = 500,500 : winding turns

The electrical equivalent circuit parameters are:

$L_{p\sigma}$ = 55.4 [mH] : primary leakage inductance
$L_{s\sigma}'$ = 55.4 [mH] : secondary leakage inductance
R_p,R_s' = 2.6 [Ω] : primary and secondary winding resistance @25°C

Now the BH_M curve is obtained by first doing a no-load measurement of primary voltage u_p and current i_p. The primary voltage is a sinusoidal line voltage with the frequency of 50 [Hz]. Then the magnetizing voltage u_M is found and from this B is calculated using:

$$B = \frac{1}{A_c N_p} \int u_M \, dt \qquad (6)$$

approximately 40 fundamental periods were measured with a sample rate of 10 [kS/s]. The four of the thirteen measured BH_M curves are shown in Figure 4. It is noticed that the magnetic field strength H_M is calculated using the current i_M that is identical with current i_p, at no-load. What is needed here is a separation of the i_M into i_{LM} and i_{RM} - see Figure 1. First thing is to make a guess at some value of R_M say R_M =1800 [Ω]. A current will now flow though R_M and this current is subtracted from i_M (i_p) giving the current though i_{LM}. The field strength calculated using i_{LM} is named H_{LM}. In Figure 5 is the original BH_M curve and the BH_{LM} plotted. On the BH_{LM} curve there is an intersection two times and one of the times is marked with two lines giving the coordinate point values Brm and Hrm. At this coordinate point (Hrm,Brm) the hystresis area is zero and therefore the losses are zero, meaning that the value of R_M is modelling the real loss at that point. Using this idea, is the value of R_M changed and a curve of R_M as function of B is obtained, the R_M(B) curve is shown in Figure 6. The whole process may take 10-15 minutes. When R_M(B) is calculated the curve modelling saturation is found as being the curve which is left when the losses are pulled out of the BH_M curve. This is shown in Figure 7 and this loss less curve is the desired BH_{LM} curve used to model the saturation of the magnetic core. The BH_{LM} curve is stored as two vectors B and H_{LM}, which can be read by the Simulink simulation programme. The transformer parameters are now identified and in the next section are shown how simulation and measurement of current i_p, i_M agrees.

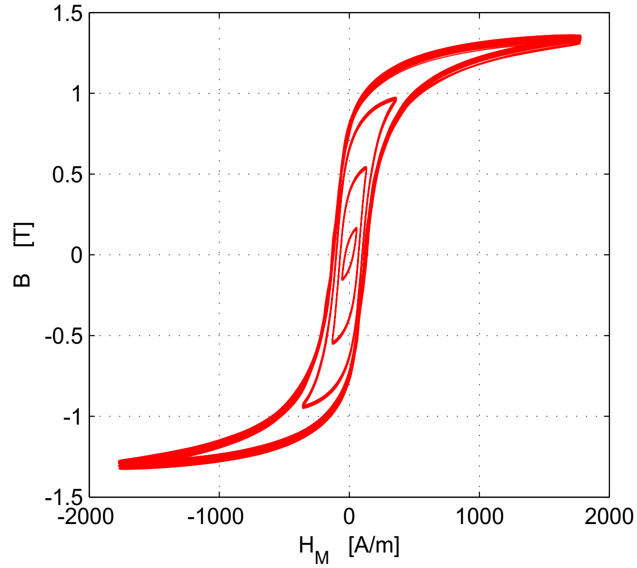

Figure 4 Measured BH_M curve's

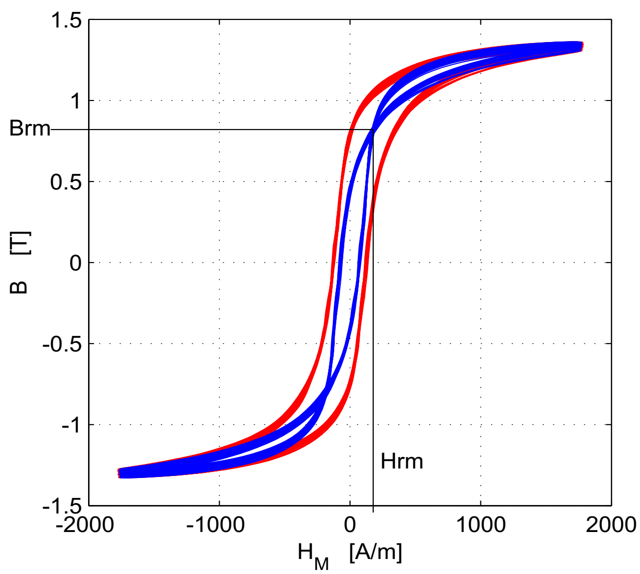

Figure 5 Illustrating method of separating i_M into i_{RM} and i_{LM}

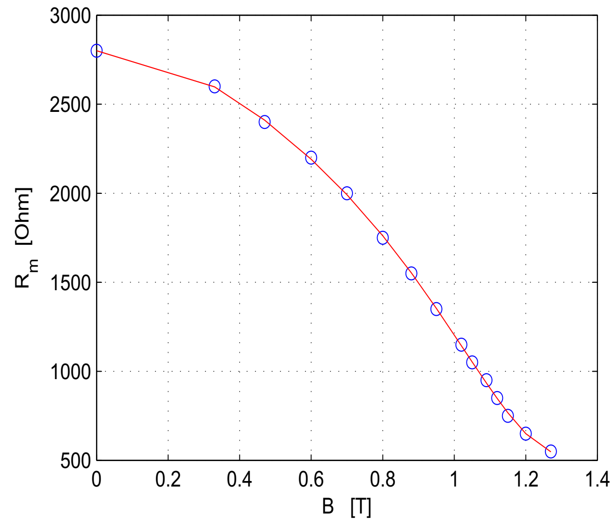

Figure 6 Identified iron loss represented by R_M.

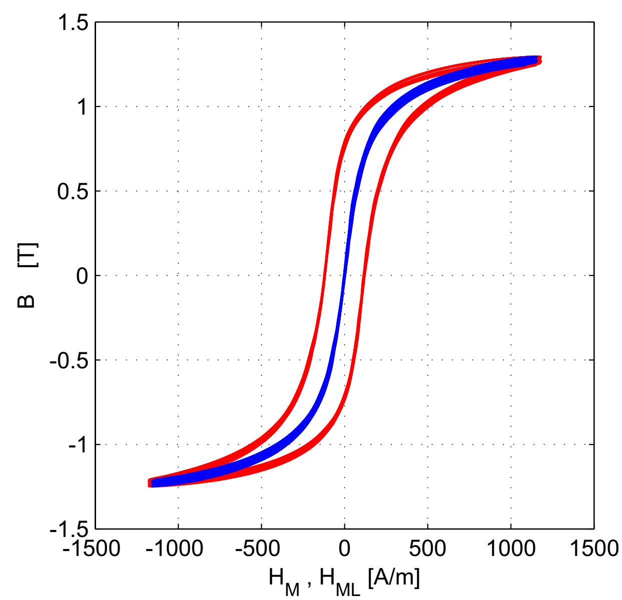

Figure 7 The BH curve with zero area is the desired BH_{ML} curve used to model the core saturation

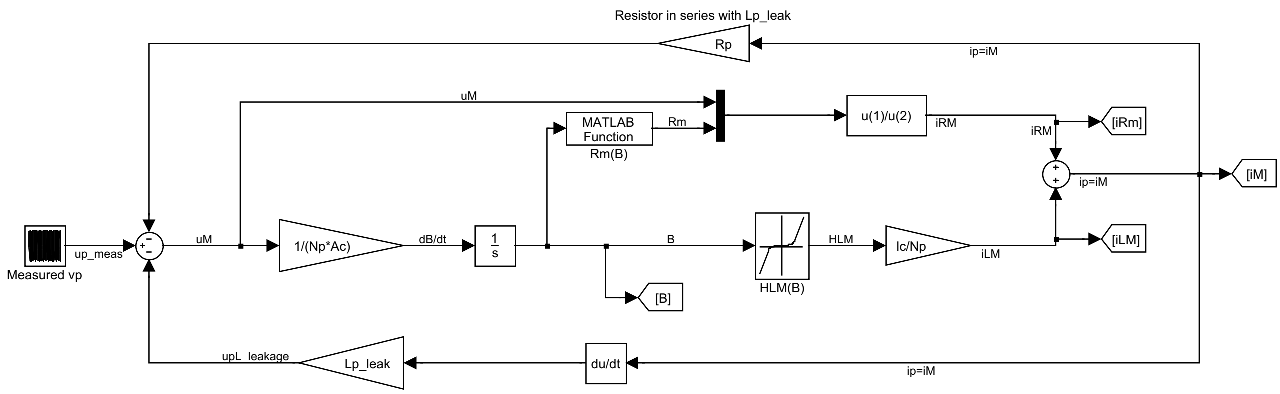

Figure 8 Simulink model of transformer at no load

4. SIMULATION OF THE TRANSFORMER

The Simulink programme is very simple as shown Figure 8. In Figure 9 is the simulated and measured values of i_M (i_p) shown, and they agrees well. The transformer primary voltage u_p is also shown.

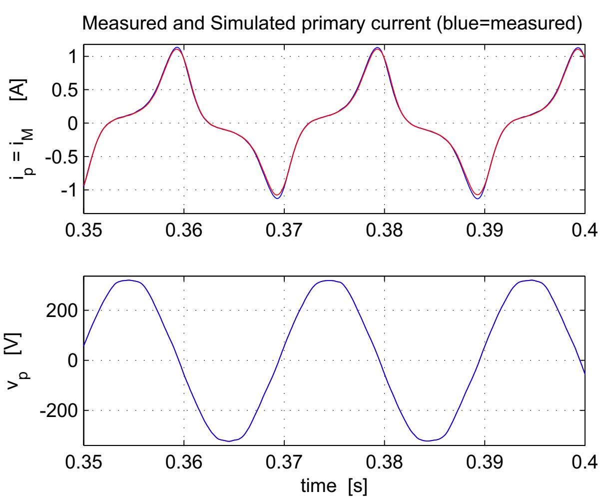

Figure 9 No-load measurement and simulation results

5. PREDICTING THE VOLTAGE AND CURRENT OF A TRANSFORMER WITH INCREASED MAGNETIC MEAN LENGTH.

The magnetic core geometry is changed; two U cores, similar to the one used in section 4, are connected with their two leg's facing each other. The magnetic average length is thereby increased from l_c = 0.48 [m] to l_c = 0.66 [m]. Again thirteen no-load measurements are carried out, this time the simulation is carried out using the parameters found in section 3 only changing l_c to 0.66 [m]. The simulated i_p (i_M) and the measured i_p (i_M) are shown in Figure 10 and the currents agree very well. The applied u_p and the u_p used in the simulation is also shown in Figure 10.

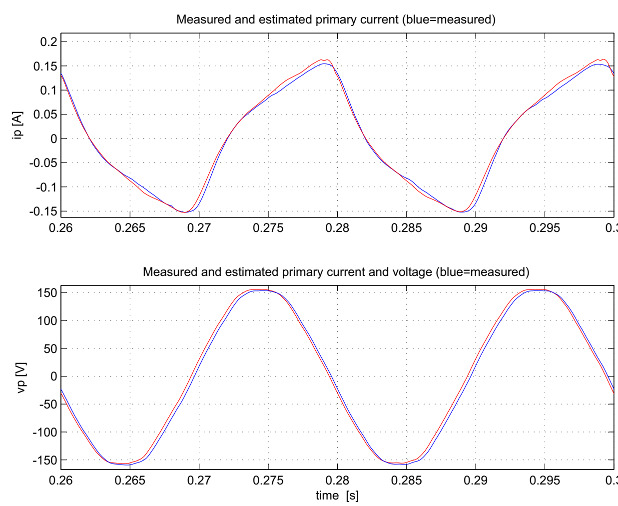

Figure 10 Verifying the simulation model.

6. DISCUSSION

The measured results do not show the inrush currents since only the steady-state behaviour was of interest in this work. The simulation time of the model was 40 seconds real time simulating 0.8 second on a 1.6 GHz Centrino lab top. The model is verified by comparison of simulated and measured currents. The inrush currents are present during simulation and therefore the simulation will simulate for 0.8 second to ensure steady state operation. The weak point of the presented model is a limitation of the validity, it is not expected that the model will represent minor loops accurately, since it involves a more complex primary voltage with several harmonics, but an extension of the model is under way. So the next step of work is to investigate how well the model work is the supplied voltage is no longer sinusoidal.

7. CONCLUSION

A simple and accurate model of the transformer including the non-linear core hysteresis phenomena has been presented. The key to the obtained good accuracy is given by using the method of separating the hysteresis curve into a loss resistor dependent on the flux density, B, and a saturation curve (BH_{LM} curve). The model has so far been tested at 13 different amplitudes of sinusoidal input voltages at two different core geometries, in total 26 tests, where the simulated and measured transformer voltage and currents agrees very well. The transformer model is considered accurate enough to be useful for loss prediction.

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