Modeling and Simulation of Single-Phase Transformer Inrush Current using Neural Network

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Abstract
Inrush current is a transient phenomenon which occurs during energization in transformer at no load. It depends on winding impedance, time constant of transformer circuit and core magnetization characteristics. Transient phenomenon of current represents non linear characteristics due to BH curve. Transformer circuit at no load is used to obtain various data. Data is obtained using semi – analytic solution approach. These data is used to develop neural network. Neural network shows exact modeling of inrush current.
Keywords: Inrush Current, ANN, Modeling.

1. Introduction
Inrush current is very important issue for transformer designer. It effects on relay coordination because of ten to twenty times (even more) of rated current during transient period. These abnormal behaviors of inrush current causes relay to operate. Second harmonic based relay discriminate this abnormality in power system [1]. Transient period of current (exponential decay) depends on circuit time constant. Transformer is R-L circuit with time constant of L to R. For large transformer resistance is very small, cause large transient period but for small transformer resistance is higher comparable, cause fast decay. Intensity of the inrush current depends on the instance of the sinusoidal voltage in which it is switched on as well as on characteristics of the ferromagnetic core such as its residual magnetism and its magnetization curve[2]. With the help of [2] inrush current data is obtained. In [3], an analytic formula is presented to calculate the peak inrush current of a nonlinear inductor with a series resistor. [4]In recent years, various protective systems for transformers, based on the differential relaying system, were developed. Various techniques based on complex circuits or microcomputers are proposed to distinguish inrush current from fault current. However, the transformer still must bear with large electromagnetic stress impact caused by the inrush current.

In this paper, first formulas that are used for calculation it, presented. Then a single-phase transformer is simulated in MATLAB. Simulation is performed to obtain various data. These data is utilized to train neural network.

2. Modeling of Inrush current
Inrush Current can be determined by following equations 1,2 and 3. Equivalent circuit of single phase transformer is shown by figure 1 [2].

$$Vm\ Sin(\omega t+\theta) = \left(r_p.i\right) + [(L]_p \frac{di}{dt}\Big) + \frac{d\lambda}{dt} \quad \text{.....(1)}$$

$$i = \left(\frac{1}{r_c}\frac{d\lambda}{dt}\right) + i_m \quad \text{.....(2)}$$

$$i_m = \alpha\ Sinh\,(\beta.\lambda) \quad \text{......(3)}$$

Where r_p , L_p, and r_c represents primary winding resistance, primary winding inductance, and core losses resistance respectively. i_m (eq 3) is showing magnetizing curve of core.

3. Neural Network
Neural Network consists of three layers namely input layer, hidden (Processing) layer(s), output layer. Input data fed to network through input layer, after that processing takes place. Output value comes out at output layer which compared with target value to find out error. Back propagation algorithm is used to minimize this error or reducing tolerance range. Neural Network has beauty to give accurate value depends on input value after well training of network as shown in figure 2[5].

3.1 ANN Modeling

The modeling of inrush current of transformer is accomplished by ANN network as shown in figure 3. This ANN Network is trained by providing practical data of time and flux linkage value with different time. These data have been obtained by conducting experiments, since these data have their own ranges. Therefore the data has been normalized at same scale for training the network. Trained Network represents modeling of inrush current. After training, output of network gives normalized values which will convert back to their original values to ensure practical behavior of inrush current.

4. Case Study

Some results are presented for a 120-VA, 60-Hz, (220/120)V transformer[2], obtained from (1) and (2), using a discrete time, with 83.33X 10^{-8} s. The equivalent circuit of this transformer is shown in Figure 1and its parameters, referred to the 220-V winding obtained experimentally, are r_p = 15.476Ω; L_p = 12 mH; r_c = 7260Ω For the transformer magnetization curve, as given in equation (3), the following parameters determined experimentally were used: α = 63.084mA; β = 2.43Wb^{-1} . Now, by considering the transformer parameters, the maximum initial flux-linkage value is 0.826-Wb coil, and the excitation angle corresponds to θ = 0 . Inrush current is obtained with the help of equation 1,2 and 3 using semi analytic solution approach as shown in figure 4.

5. ANN Model

Data of inrush current is utilized to train ANN as shown in figure 6. In figure 6 there is three neurons at input layer, they are i_m , λ_n and t_n . There is two hidden layer. After that one output neuron at output layer which is i_{inrush} . Error during training of ANN with respect to number of epochs is shown by figure 6. Mathematically, it can be defined by equation 4.

$$i_{inursh} = f_{ANN}(t_n, \lambda_n, i_m) \qquad \dots (4)$$

Where n is number of iteration, t is time, and λ is flux linkage. Accuracy of ANN Model for modeling inrush current is compared with data which is used to train ANN as shown in figure 4,5. Error with number of epochs during training ANN is shown in figure 7. Different Weight of neuron are shown by table 1,2, and table 3.

6. Conclusions

ANN Model has beauty to train network with data of non linearity which gives almost exact matching to target. Therefore ANN able to model inrush current wave as shown in figure 4, table 1 and predict inrush current value based on flux linkage, time and previous sample of current with average percentage error of 1.056. Magnetization curve of core with semi analytic solution approach and ANN based modeling is shown by figure 8,9 and figure 10(with zooming).

Table 1 : Weight between Input layer to Hidden Layer-1 (W_{I-H1})

W_{I-H1}	Input Neuron 1	Input Neuron 2	Input Neuron 3
Hidden Layer1-1	1.0847	-5.0678	3.5285
Hidden Layer1-2	-3.4451	-4.2004	1.1627
Hidden Layer1-3	-11.095	-3.3678	-0.42559
Hidden Layer1-4	-0.1392	-1.2362	0.0018401
Hidden Layer1-5	10.316	-1.4722	-2.9265
Hidden Layer1-6	-27.369	-3.2762	8.1826

Table 2: Weight between Hidden Layer-1 to Hidden Layer-2 (W_{H1-H2})

W_{H1-H2}	Hidden Layer1-1	Hidden Layer1-2	Hidden Layer1-3	Hidden Layer1-4	Hidden Layer1-5	Hidden Layer1-6
Hidden Layer2-1	0.11459	2.3128	0.07225	2.0329	0.084796	0.21367
Hidden Layer2-2	0.11139	1.3542	0.10149	-3.0301	-1.4033	0.16277
Hidden Layer2-3	0.34714	7.9291	28.492	5.0615	-7.3575	-40.717

Table 3: Weight between Hidden layer-2 to output layer (W_{H2-O})

W_{H2-O}	Hidden Layer2-1	Hidden Layer2-2	Hidden Layer2-3
Output Neuron	-9.8719	7.2919	2.219

Table 3: Bias Value of different neuron with different layer

Neuron of Hidden Layer-1	Bias Value
1	-1.8686
2	5.1622
3	6.3852
4	-1.3332
5	1.78
6	0.22031

Neuron of Hidden Layer-2	Bias Value
1	1.3763
2	-0.96866
3	-5.7563

Neuron of Output Layer	Bias Value
1	0.41341

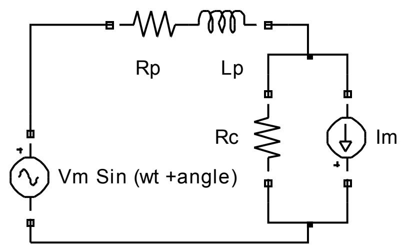

Figure 1: equivalent circuit of Single phase transformer

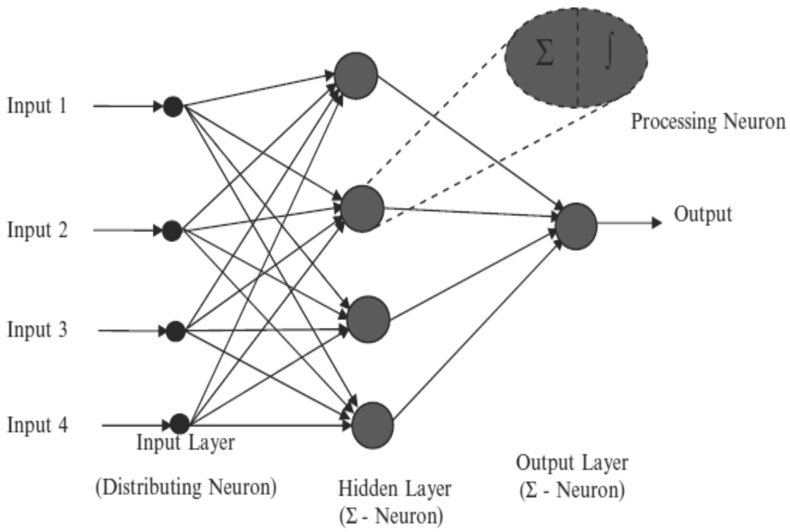

Figure 2: Neural network

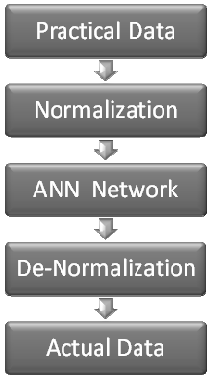

Figure 3: process flow of ANN Modeling

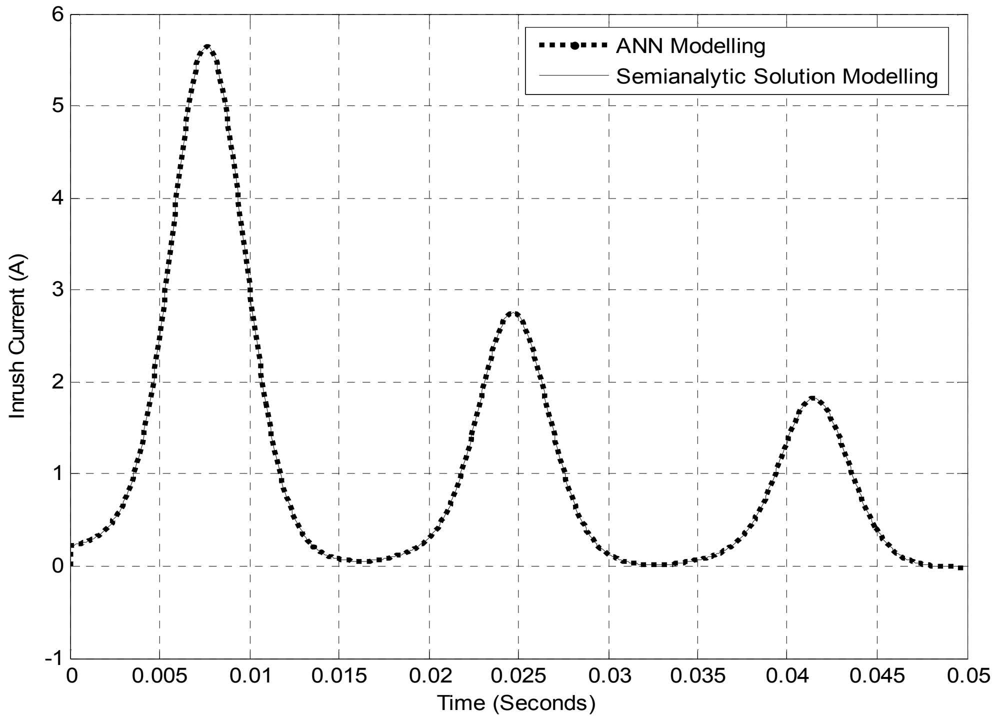

Figure 4: Inrush current with ANN Modeling (points) and semianalytic Solution (Line).

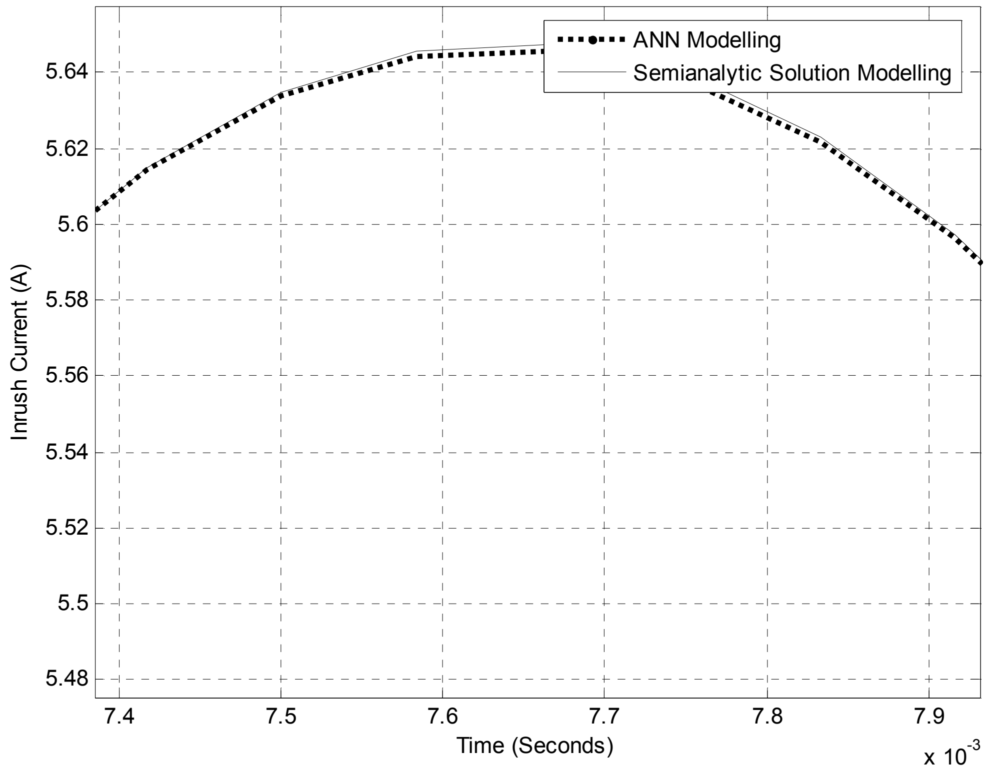

Figure 5: Zooming of first cycle of Inrush current

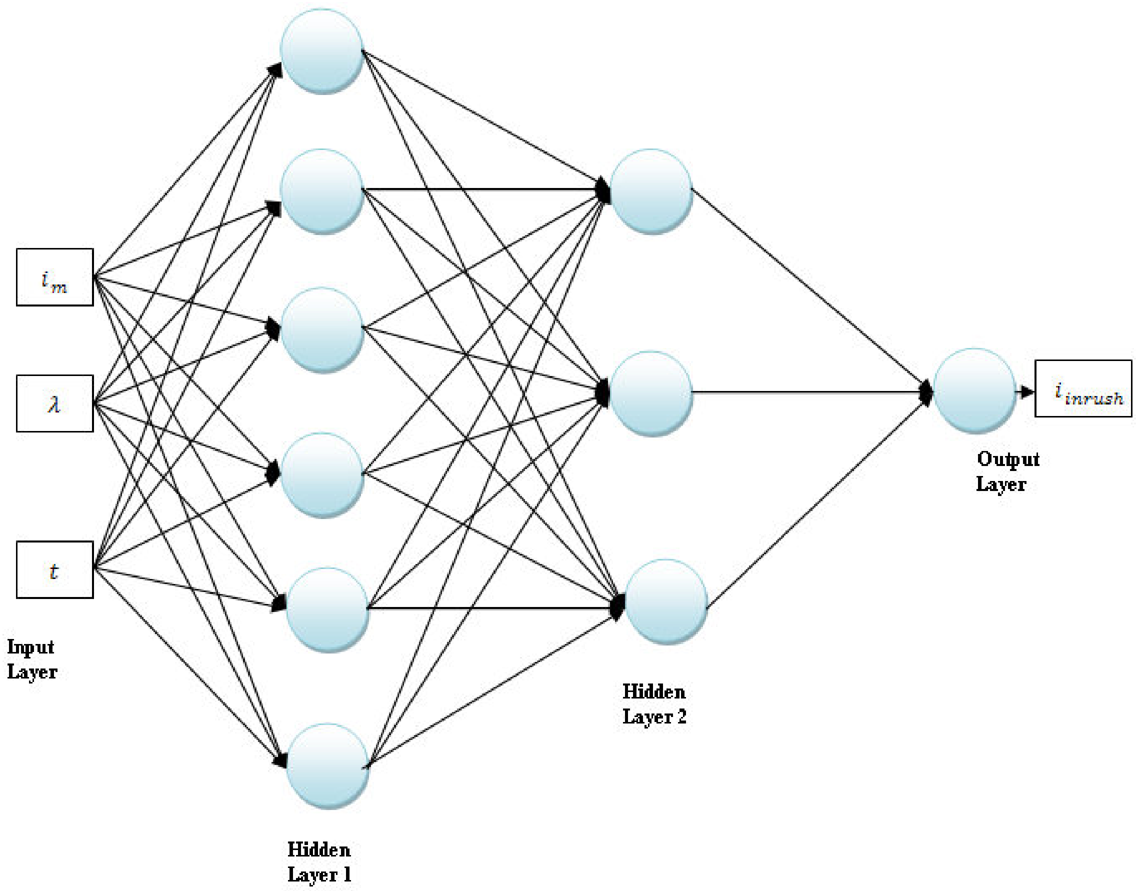

Figure 6: ANN for Inrush current Modeling

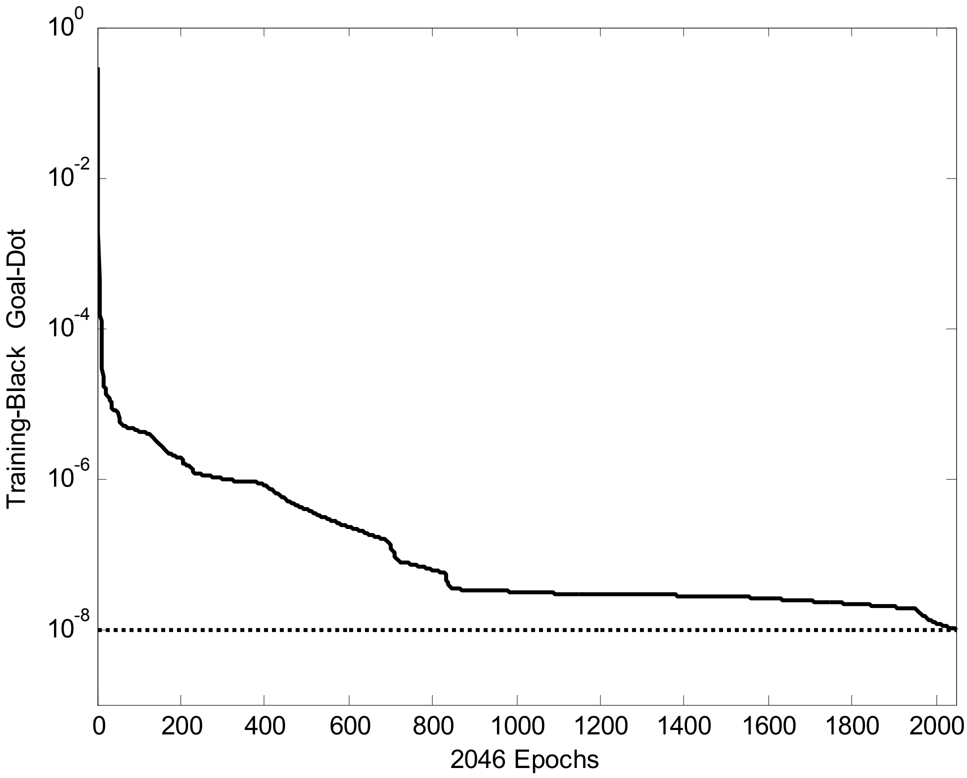

Figure 7: Error with epochs during training of ANN Modeling for inrush current

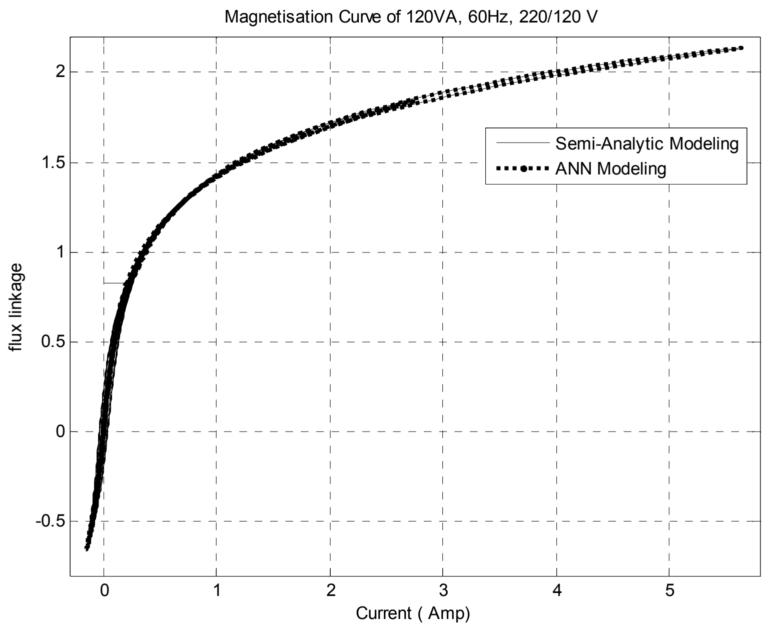

Figure 8 : Magnetization curve with ANN Modeling(dotted)

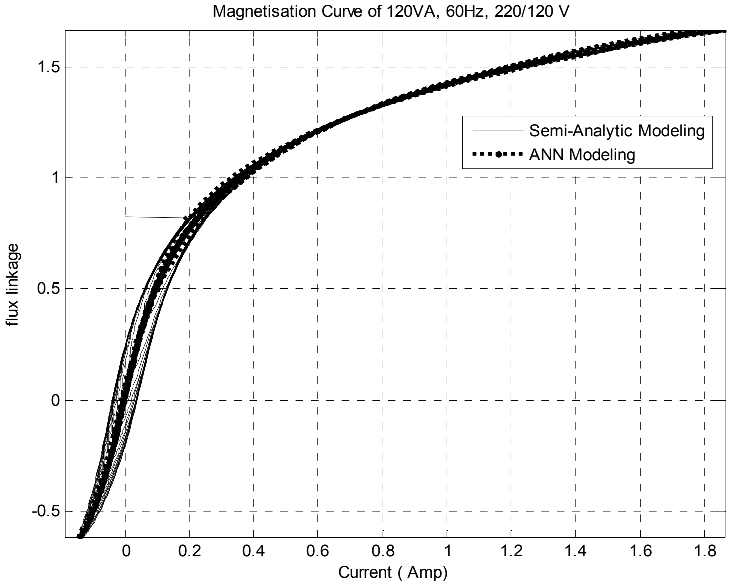

Figure 9 : Zooming of Magnetization curve

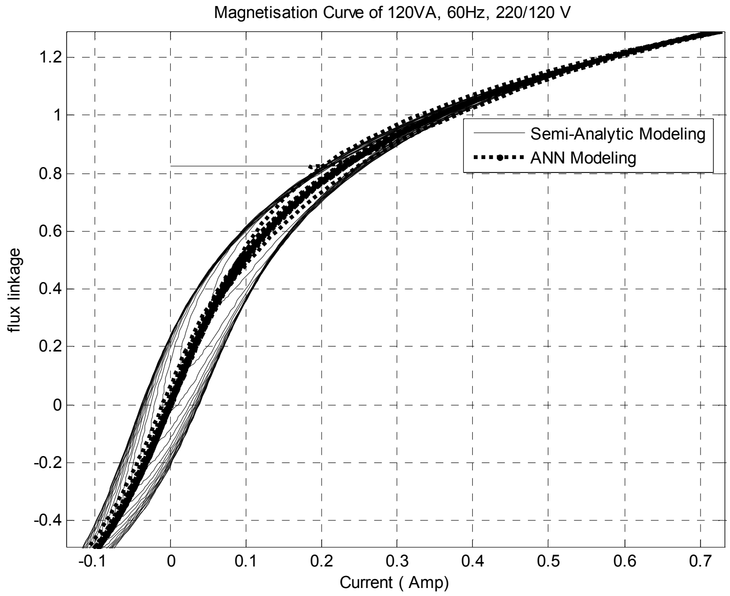

Figure 10 : Zooming of Magnetization curve with ANN Modeling(dotted)

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