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Eliminating Inrush Current in Three-Phase Transformer using Artificial Neural Network

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Abstract
Transformers are important parts of an electrical power system. When a power transformer is connected to the grid, usually inrush current increases substantially with a high value of harmonic components with duration up to many cycles. This paper describes a technique to accurately predict the inrush current and third harmonic of three phase transformer. Where work was done on a three-phase Delta-Star (11/0.4 kv) transformer in the distribution network. The factors affecting the inrush current (Magnetizing resistance, switching angle and residual flux) were studied. A shallow artificial neural network (ANN) was created. The input parameters of the artificial neural network were the magnetization resistance Rm, the initial flux of phase A and the switching angle θ to predicts the output as maximum phase current and the maximum of third harmonic. The number of neurons has been changed to verify the best performance value. The best validation performance was at epoch 71 with a value of 5.3641e-05. A good prediction results were obtained using this ANN. The simulation of the inrush current was done using the MATLAB Simulink

Keywords: Three-phase transformer; Artificial neural network; Inrush current

الخلاصة : المحولات هي أجزاء مهمة من نظام الطاقة الكهربائية. عندما يتم توصيل محول الطاقة بالشبكة، عادةً ما يزداد تيار التدفق بشكل كبير مع ارتفاع قيمة المكونات التوافقية بمدة تصل إلى العديد من الدورات. يصف هذا البحث تقنية للتنبؤ بدقة بتيار الاندفاع والتوافقي الثالث لمحول ثلاثي الطور.حيث كان العمل على محولة ثلاثية الاطوار ذات الربط دلتا الى ستار (kv 11/0.4) على شبكة التوزيع . العوامل التي تؤثر على تيار الاندفاع (مقاومة المغنطة وزاوية الطور او التشغيل كذلك الفيض المتبقي داخل القلب الحديدي للمحولة) تم دراستهم. تم إنشاء شبكة عصبية ضحلة حيث كانت معلمات الإدخال للشبكة العصبية الاصطناعية هي مقاومة المغنطة Rm، والفيض المتبقي داخل قلب المحولة للطور A وزاوية التبديل φ والمخرج لها هو اعلى قيمة لتيار الاندفاع واعلى قيمة لتوافقي الثالث . تم تغيير عدد الخلايا العصبية لمعرفة أفضل قيمة للأداء. كان أفضل أداء للتحقق من الصحة في الدورة 71 بقيمة 5.3641e-05 . تم الحصول على نتائج تنبؤ جيدة باستخدام ANN. تمت محاكاة تيار الاندفاع باستخدام برنامج MATLAB Simulink

1. INTRODUCTION

Transformers are essential components of the transmission and distribution network. They also play an important role in maintaining the quality of service of an electrical energy system. The energization of the transformer gives a dangerous inrush condition and the flux in the core can reach a maximum theoretical value of two to three times the rated flux [1]. The resulting core flux, upon energization, will be generally asymmetrical with the degree of asymmetry depending on the point on the power frequency voltage wave at which the energization takes place and, on the core residual flux. This potentially asymmetric flux waveform can have peak values which can easily saturate the core. This causes high magnitude currents to flow in the winding whose peak values can exceed 10 times the transformer's rated current and persist for several seconds [2]. Furthermore, the resulting current is asymmetrical leading to the presence of higher order harmonics. These energization currents are known as Transformer Transient inrush currents, also commonly referred to as simply Inrush Currents (IC). The phenomenon manifests itself to both single-phase and to three-phase transformers. Random power transformer energization can create large flux asymmetries and saturation of one or more winding cores of the transformer. These currents can cause false operation of protective relays and fuses, mechanical damage to the transformer windings from magnetic forces, and generally reduce power quality on the system [3] . The effects of these transients are normally mitigated by de-sensitizing protective relays or over sizing fuses [4]. Closing resistors have been used to reduce the magnitude of the inrush currents. Controlled closing, or controlling the point on the power frequency voltage wave where energization occurs, has also been employed to reduce these inrush transients. Also, a transformer being energized may draw a large transient current from the grid supply, resulting in a temporary voltage dip at the point of connection (POC) where customers are connected [5]. The voltage dip is dependent upon the magnitude of the transformer inrush current. The inrush current has a large DC component and with long duration, and it has many harmonics. Its large peak values at the beginning approximately 8 to 30 times the normal current value of a transformer [6]. This condition causes an imbalance in the differential relays current loop which will occur with a trip fault.

There is a study conducted on energized industrial transformers showing the problems caused by harmonics [7] , overvoltage's and resonances. In [8] the authors have created a MATLAB-Simulink model to simulate the effect of several parameters on the three-phase transformer inrush current. An ANFIS (adaptive neuro-fuzzy inference system) model has been created to predict the maximum value of the inrush current as well as the maximum value of the second harmonic. Puneet Kumar Singh and D K Chaturvedi [9] have studied several factors that affecting the single-phase inrush current such as inductance and resistance of the primary winding, the switching angle, the voltage source frequency…etc. The ANN (Artificial neural network) was used to predict the peak value of the inrush current. The average error of the predicted peak of the inrush current was -0.00168, which is unacceptable value according to the authors. Prachi Gondane etal [10] have used wavelet transform to interpolate the output inrush current. The parameters of interpolation have been used to train an artificial neural network to predict the three cases of the output current (Fault-0, Inrush-1, Normal-2). Shahinul Islam and Monirul Kabir [11] have trained an ANN (artificial neural network) to discriminate between fault current and inrush current. Their method called discrimination of inrush and fault currents in three-phase power transformer (DSIF). They used feedforward neural network with backpropagation algorithm.

In this paper, the impacts of magnetizing inrush current on power transformers were discussed. Many influences on the inrush current have been studied, such as switching angle, magnetization resistance, and initial residual fluxes, to minimize the inrush current. The study is limited to the inrush current generated when energizing a no-load transformer. Neural network for three-phase transformer system is used and predict its behavior using as input the switching angle θ, Magnetization resistance Rm (pu) and the residual flux to predicts the output as maximum phase current and the maximum of third harmonic. in comparison to the closest reference to the current work [9].

2. INRUSH CURRENT

Inrush current is the maximum instantaneous input current given by an electrical device when it is switched on. This current arises due to high starting current. To charge the capacitor, inductor and transformer, high current is produced at the time of switch on. Its value depends on the core material, residual flux and instant of energization. In power transformer, inrush current other than energization also takes after the clearance of external fault until voltage recovery. Inrush current also contains even and odd harmonics. It also has DC offset. Inrush current can be high as 20 times the normal current value it can only last for about 10ms. It requires about 30 to 40 cycl.

3. LITREATURE REVIEW

Study of the inrush current is very important especially the power transformer is very expensive. For this reason, it requires an effective implementation of a continuous monitoring and protection. External malfunctions as well as internal malfunctions of power transformers may cause serious damage as well as instability of the power system. Therefore, many research papers discussed this phenomenon and the different ways to measure the output inrush current. Among these papers:

M. S. Islam et al. (2019) [11] have trained an ANN (artificial neural network) to discriminate between fault current and inrush current. Their method called discrimination of inrush and fault currents in three-phase power transformer. They used feedforward neural network with backpropagation algorithm. The input layer consists of 28 neurons (features) and the output layer consist of 13 neurons. The best mean square error (MSE) values for training, testing and validations were: 1.12e-2, 1.64e-2 and 1.42e-2 respectively, which are close to zero.

M. Ganji et al. (2019) [12] In This study a modified transient current limiter (MTCL) for reducing transformer inrush current. The MTCL is based on a standard transient current limiter (TCL), with its design adjusted to avoid the TCL's operational drawbacks. Under normal operating conditions, the suggested MTCL reduces power losses and voltage/current transient harmonic distortion (THD). It requires just one limiting reactor instead of two, resulting in cost savings. With the help of PSCAD/EMTDC modeling, it's able to verify ability to limit the inrush current. Simulation and experiment proved that the MTCL suppresses transformer inrush current. Additionally, the capability of the MTCL to reduce the inrush current of the transformer was compared with that of the traditional TCL.

H. Septiawan et al. (2019) [13] in their work showed that the switching angle is one of the main parameters that determines the inrush current of the transformer. A pre-energize circuit is used to insert DC flux to the transformer. Three tests were performed with different ignition angles of 0, 60, and 90 degrees. The switching angle of 0-degree will give large inrush current of value about 32.69A while a switching angle of 90 degrees gives small inrush current.

A. H. Fajariawan et al. (2020) [14] In this research, the author proposes a strategy that makes use of contemporary controlled switching in order to decrease the inrush current. In order to determine the time (t) at which circuit breakers are switching, switching control is utilized. The switching of capacitor banks results in a low amount of inrush current. As a result of the fact that the level of inrush current is lower than the limits of the power breaker rating, it does not result interruption of the power breaker and it also does not produce an overcurrent in the system. If the circuit breaker does not trip when there is a strong inrush current in a short period, it might be harmful for the electrical system equipment.

P. Pachore et al. (2020) [15] This research suggests employing gang operated circuit breakers in a controlled switching strategy to reduce the inrush currents for a three-phase transformer. The optimum values for controlled opening and closure are determined by minimizing the flux error function, which is computed using the transformer's residual and prospective fluxes. The closing delay is quantified at each switching operation and subsequently modified to ensure precise closure.

Y. PAN et al. (2021) [16] This research presents an inrush current reduction approach based on prefluxing and controlled switching technologies. An equivalent magnetic circuit model for large-capacity transformers gives an analytical estimate of the magnetic flux when performing the technique. On the basis of the analysis, the design technique of the control parameters, which include the prefluxing current and the ideal closure angle of each phase power supply, is provided. A comprehensive analysis is conducted on the impact of various factors, including the residual flux, the dispersion of the circuit breaker, and the deviation of the prefluxing time, on the reduction effect of the strategy. In result, the accuracy and superiority of the approach is demonstrated for an exact simulation of the inrush current.

T. B. Doan and C. P. Do et al. (2021) [17] have simulated 250kVA, 1500kVA and 2200kVA three phase transformers using Ansys Maxwell 3D software. The inrush currents, the winding voltages, and the flux density were studied. The highest inrush current was reached at the time of 10msec. The maximum inrush current was about ten times higher than the rated current. The core of the transformer was saturated at flux density B>2.4T. A steady state was reached after 800msec and the flux density was about 1.2T to 1.8T.

A. Yahiou et al. (2022) [18] The author present control technique by take into account the value of residual flux that is produced when the transformer is de-energized, in addition to the phase shifting that occurs between the three phases. An experimental was developed to collecting data of system by employing a dSPACE 1104 card to measure inrush current. The experimental setup also included the testing and application of a method that was designed to manage the circuit breaker in order to energize a three-phase transformer without the appearance of inrush current. It also calculates the instant of circuit breaker closure for one phase and subsequently for the other two phases with regard to the first phase.

The previous researchers mentioned worked on several methods in order to reduce or prevent the occurrence of transformer inrush currents. Where the researcher [9] worked to create a neural network in order to predict the inrush current based on the number of iterations, time, magnetic flux, as well as the magnetization current as inputs to the neural network. In our research will initiate feed forward artificial neural network to predict the maximum inrush current and maximum third harmonic with switching angle, residual flux and magnetizing resistance as input parameters of ANN.

4. THREE PHASE TRANSFORMER SIMULATION MODEL

The transformer used during this simulation is three phase delta-star transformer 11kV-400V rms phase to phase input voltage and output voltage respectively. Frequency and nominal power are 50Hz and 400kVA. The implementation of the project is done with the use of MATLAB/Simulink. Figure (1) shows the power system used in MATLAB/Simulink.

Table (1) characteristics of three-phase transformer

Nominal Power and frequency	Sn= 400 KVA, f= 50 Hz		
Primary Winding Parameters	V1= 11 kv	R1= 0.002	L1= 0.08
Secondary Winding Parameters	V2= 400 v	R2= 0.001	L2= 0.1
Core loss resistance	Rm= (0.5, 2, 5) p.u		

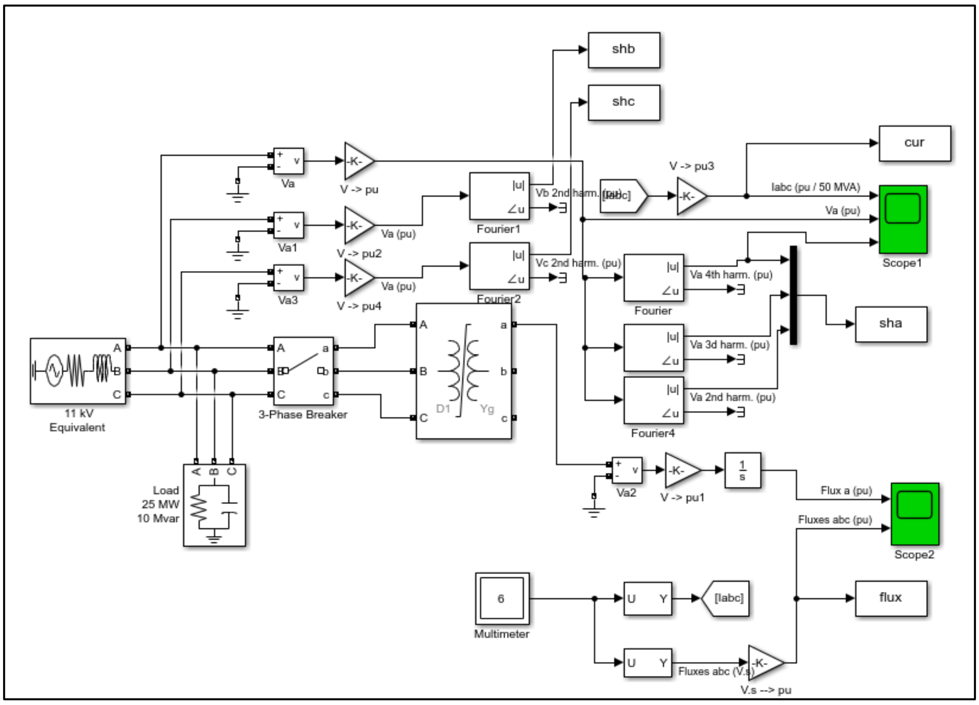


Fig. 1. Simulink Model for evaluating the three-phase transformer inrush current.

The Simulink model contains blocks as follow: -

1) **Three-phase source:** The Three-Phase Source block implements a balanced three-phase voltage source with an internal R-L impedance.

2) **The Three-Phase Parallel RLC Load block:** implements a three-phase balanced load as a parallel combination of RLC elements

3) **Three-phase transformer:** This block implements a three-phase transformer using three single-phase transformers

4) **Fourier:** The Fourier block performs a Fourier analysis of the input signal over a running window of one cycle of the fundamental frequency of the signal

5) **Voltage measurement:** The Voltage Measurement block measures the instantaneous voltage between two electric nodes

6) **Gain:** The Gain block multiplies the input by a constant value (gain). The input and the gain can each be a scalar, vector, or matrix.

7) **Multimeter:** This block measures the voltages and currents specified in the Measurements parameter of Simscape Electrical Specialized Power Systems blocks in your model.

8) **Selector:** The Selector block generates as output selected or reordered elements of an input vector, matrix, or multidimensional signal.

9) **To workspace:** The to Workspace block logs the data connected to its input port to a workspace from a Simulink® model.

10) **Terminator:** Use the Terminator block to cap blocks whose output ports do not connect to other blocks

11) **Goto and From blocks:** A Goto block can pass its input signal to more than one From block, although a From block can receive a signal from only one Goto block

12) **Scope:** Display signals generated during simulation.

The breaker is connected with the three-phase voltage source. Voltage Measurements blocks were used directly after the three-phase voltage source with gain blocks to convert the voltage to per-unit (pu). Three residual fluxes (0.8, -0.4, 0.4) p.u has been identified for phases A, B and C. The option (Fluxes and magnetization currents) is checked in the transformer component, to enable the measurement of the winding voltages, the magnetization currents and fluxes with the aid of Multimeter block. The simulation is started, and waveforms of voltage, current, and flux are observed on Scope1 and Scope2 respectively. After the circuit breaker is closed, it will be observed inrush currents and overvoltage in the transformer as shown in figure (2).

5. INRUSH CURRENT FOR THREE-PHASE TRANSFORMER

As shown in figure (2) the variation of Inrush phase current with time for phase angle θ=0°, magnetization resistance Rm=5 pu and the initial flux is 0.8 pu. The current decreases gradually with time for all phases until it reach stability within a very short period of time. Current represented when the circuit is closed between the source and the transformer coil at 0.1sec. Phase A records the highest current value of about 5.22 p.u as presented in figure (2).

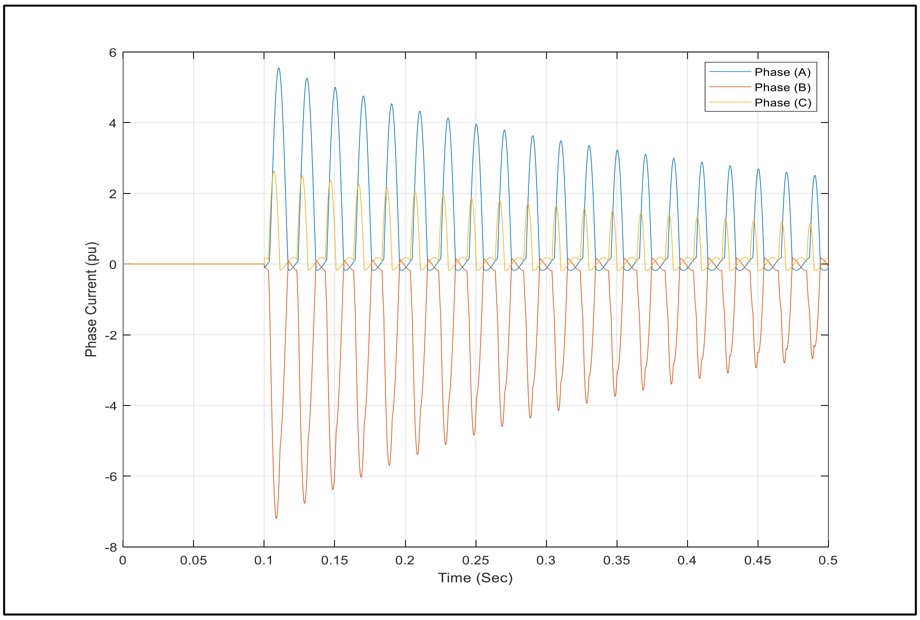


Fig. 2. Variation of Inrush phase current with time.

Figure (3) shows the flux generated by the three phases A, B, and C of the transformer itself. The highest flux value appears in phase A, reaching 3.2 p.u at the shutdown time of 0.1 second. With a prior residual flux before closing the circuit, which leads to increase the prospective flux of the applied voltage.

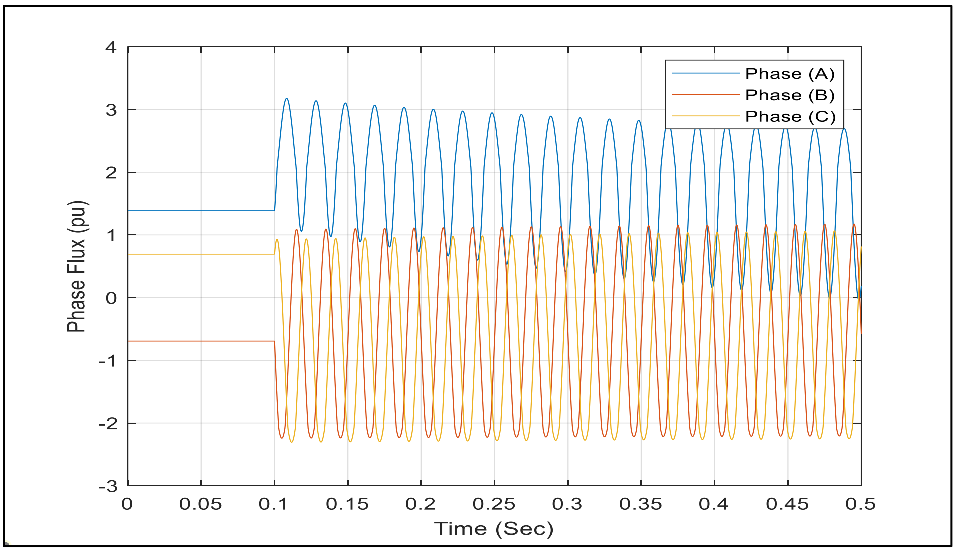


Fig. 3. Variation of phase flux with time

6. THE STUDY OF INRUSH CURRENT FOR DIFFERENT PARAMETERS

The simulation model for three phase transformer carried out according to the following cases: -

Case 1: inrush current and third harmonic with different switching angles (0º,45º,90º)

The inrush current of the three-phase transformer for phase A is studied by changing the operating angle of the electrical power supply. Through it, the effect of changing the phase angle and the extent of its effect on the inrush current when starting and feeding the transformer is studied. It can be notice the affect of the inrush current when changing the phase angle, including 0º, 45º, and 90º as shown in figure (4). It is clear from the figure that when the operating angle of the transformer increases, the inrush current decreases gradually, up to an angle of 90º, where at this angle it appears less peak current. The dc offset decreases at angle 90º and the wave appears balanced between the positive and negative parts. The highest peak of the current is at angle 0º, where it reaches 5.6 p.u.

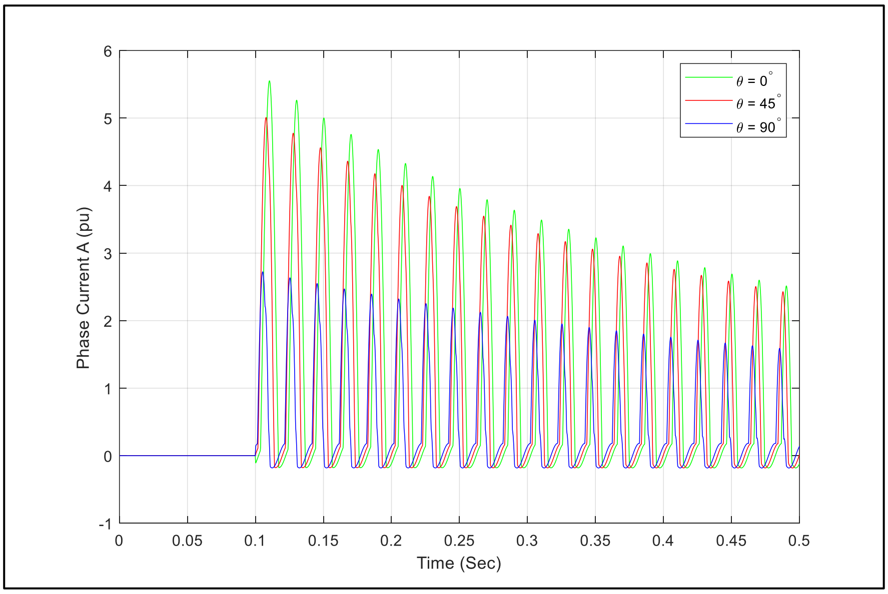


Fig. 4. Variation of inrush current of phase (A) with different switching angle with time.

The effect of phase angle on the third harmonic of phase A is shown in figure (5). At time 0.1 second, the graph indicates that operating at a phase angle of 0º makes the harmonic at its highest value, and the harmonic decreases with an increase in the operating angle at 45º, and decreases more at an angle of 90

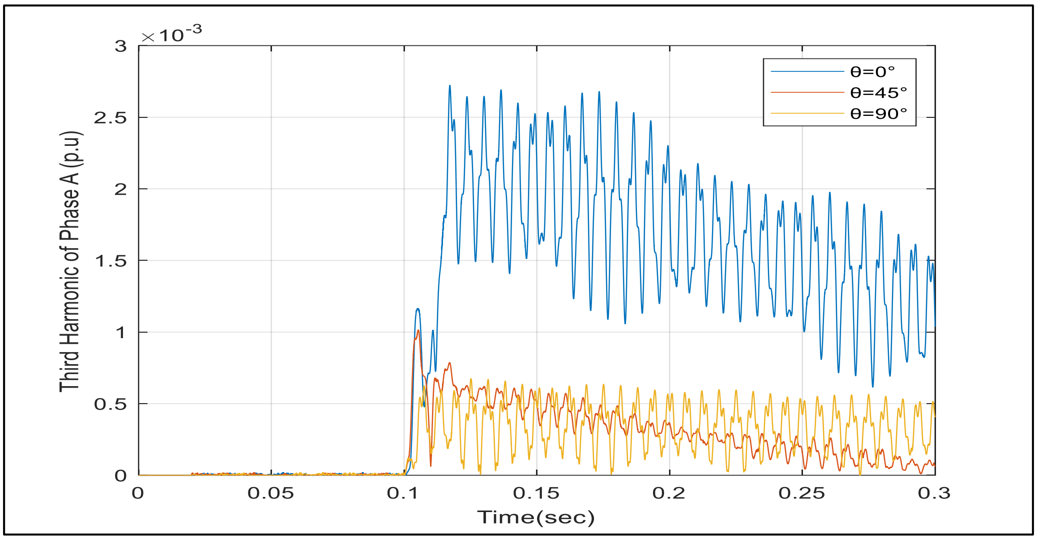


Fig. 5. Variation of third harmonic of phase (A) current with time at different switching angle.

Case 2: inrush current and third harmonic with different magnetizing resistance (0.5, 2, 5) p.u

The decrease in the inrush current is not affected by the phase angle only but also it changes by the resistance of the magnetic core as shown in figure (6).

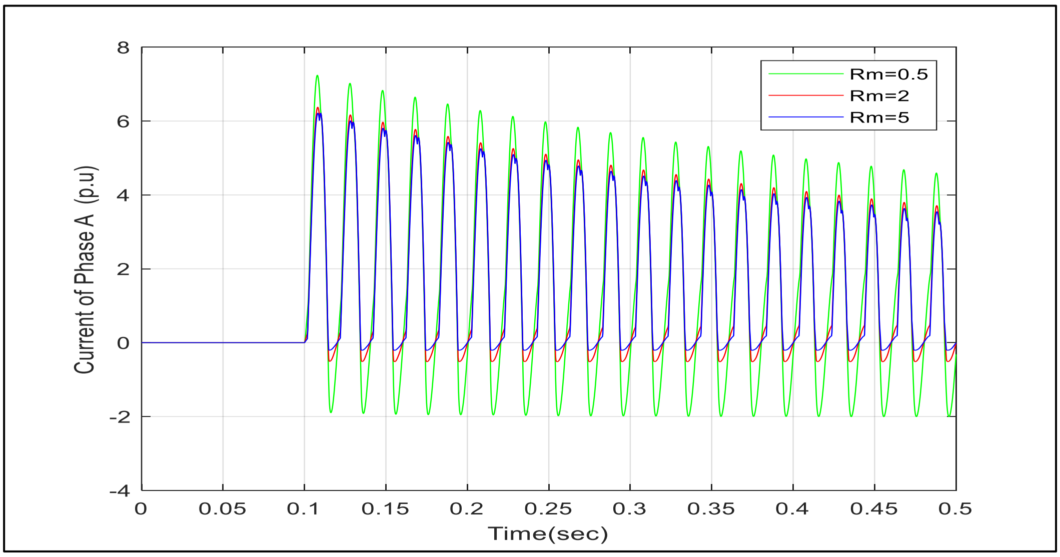


Fig. 6. Variation of inrush current of phase (A) with time at different Magnetization resistance Rm for phase angle θ=0°

The effect of magnetization resistance plays a role in changing the proportion of the voltage harmonic. The following figure shows the effect of changing the magnetization resistance of the transformer core and its major role with the increase and decrease of the third harmonic of phase A. Figure (7) shows that when the magnetization resistance increases, the third harmonic increases significantly. At 5 p.u resistor, the highest value appears for the third harmonic, and the lowest value appears at 0.5 p.u.

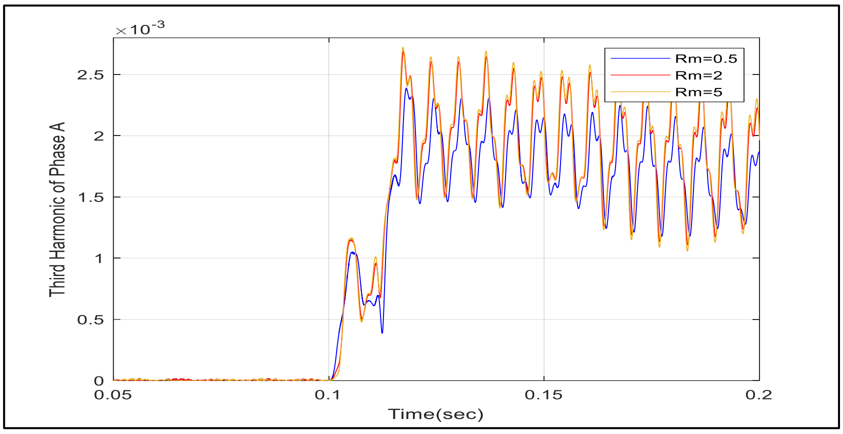


Fig. 7. Variation of Third harmonic of phase (A) current with time at different magnetization resistance Rm for phase angle θ=0°.

Case 3: Magnetizing current with residual flux in the transformer core

The effect of the residual flux inside the transformer core on the inrush current has been studied. Figure (8) shows the relationship between the three parameters with the peak of the inrush current. The parameters are magnetic resistance and the angle of operation that were mentioned previously with residual flux for each curve. It is clear from the figure that when the residual flux inside the transformer core increases, it leads to an increase in the peak inrush current and vice versa.

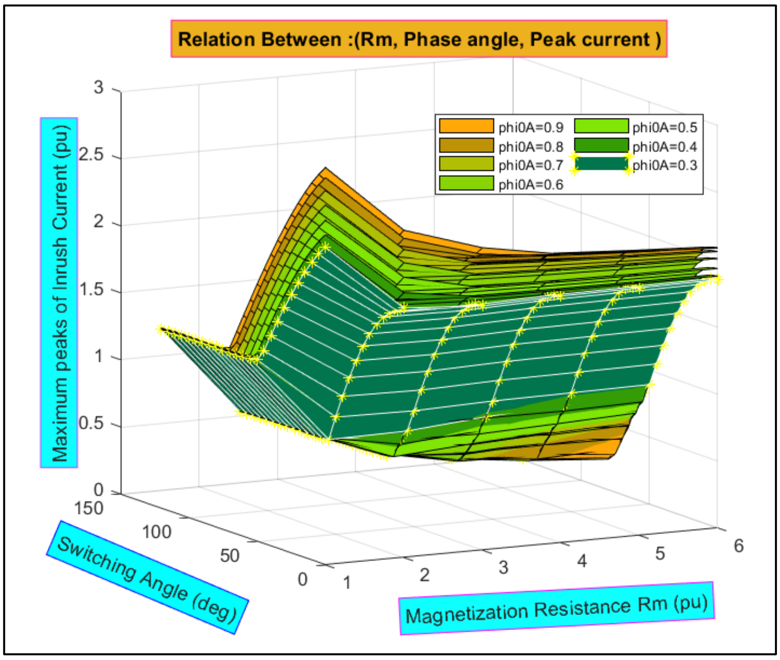


Fig. 8. Plot of the maximum inrush currents with switching angle at different Initial flux and Magnetization Resistances Rm.

7. NEURAL NETWORK FOR THE INRUSH CURRENT PREDUCTION

After simulation of three phase transformer in Simulink model a neural network was designed in prediction mode. In this research, the magnetization resistance Rm (pu), the initial flux of phase A (pu) and the switching angle θ (deg) have been selected as input and the output will be the maximum inrush current of phase A and the maximum third harmonic current of phase A. first stage the data of the work must be split into three groups as training, validation, and test sets. The data was split with percentage amount of:

- 70% for training.

- 15% to validate the network that is generalized and to stop training before overfitting.
- 15% To test the network in general and independently.

After splitting process of all data; the construct of artificial neural network begins. The network that is used in our study is two-layer feedforward network with a sigmoid transfer function in the hidden layer and a linear transfer function in the output layer. There are 3 input features with 592 observations (rows) in this neural network which represent [Rm, θ, φ_{0A}] and two outputs features with 592 observations (rows) represent maximum inrush current of phase A and the maximum third harmonic current of phase A. There will be 10 neurons in the hidden layer. Those neurons will give the new features and then those new features are used to predict the output of the model. The Layer size value defined by the number of hidden neurons, is equal to 10. it can be seen the network architecture in figure (9).

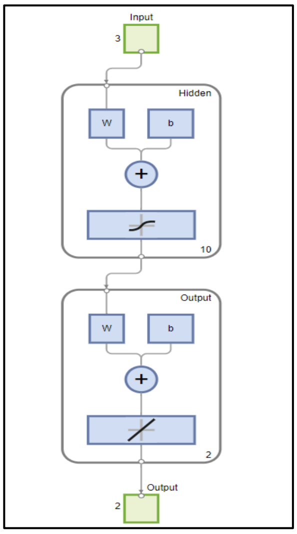
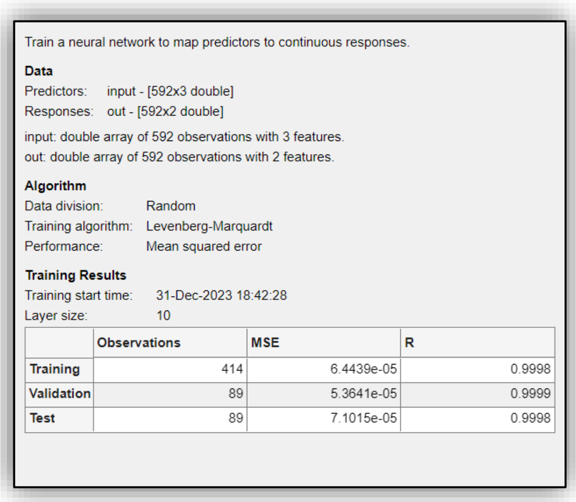


Fig. 9. Artificial Neural Network Diagram

A common method was used for optimizing neural network weights is the Leven-Burg Marquardt algorithm. To change the network's weights over and over again in a way that tries to lower the total error or loss of the network's estimated. The neural network was trained with Levenberg-Marquardt (trainlm) which is recommended for most problems as shown in figure (10). Learning is stopped when the validation error becomes minimum, or the fixed number of iterations reaches the maximum.


Train a neural network to map predictors to continuous responses.

Data
Predictors: input - [592x3 double]
Responses: out - [592x2 double]

input: double array of 592 observations with 3 features.
out: double array of 592 observations with 2 features.

Algorithm
Data division: Random
Training algorithm: Levenberg-Marquardt
Performance: Mean squared error

Training Results
Training start time: 31-Dec-2023 18:42:28
Layer size: 10

	Observations	MSE	R
Training	414	6.4439e-05	0.9998
Validation	89	5.3641e-05	0.9999
Test	89	7.1015e-05	0.9998

Fig. 10. Training algorithm and results

As shown in Figure (11) A plot of training errors, validation errors, and test errors appears that the best validation performance (lowest loss function) was reached at epoch 71, with a value of 5.3641e-05. This performance was achieved at the lowest possible loss. In most cases, validation performance is utilized to evaluate the efficiency of the model while it is being trained. It also examines how effectively the model handles the data that it has not before seen. So, a lower validation performance means the model is better because it can handle data it hasn't seen before.

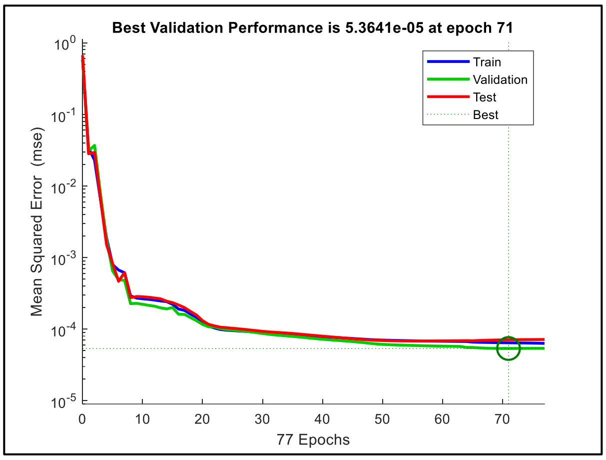


Fig. 11. The mean square error (MSE) as a function of the number of iterations

8. TEST THE ARTIFICIAL NEURAL NETWORK

After the network has trained, it can be used to compute the network outputs and compare between the target and predicted outputs of neural network as test for the network as shown in table (2). Therefore, the trained network is going to be like a function that can take any value of [Rm, θ, φ_{0A}] as input and maximum current with maximum third harmonics as output. Table (2) in appendix shows the effectiveness of the artificial neural network in extracting results with high performance by comparing the results of Simulink and the results predicted by the artificial neural network. The lower the error rate between the two results, the greater the performance and effectiveness of the neural network used

9. RESULTS AND DISCUSSION

By comparing the results of simulation model with different works that referee to them in the literature review show there is no much difference between these results. When the operating angle of the transformer increases, the inrush current decreases gradually, up to an angle of 90º, where at this angle it appears less peak current. In figure (4) The dc offset decreases at angle 90º and the wave appears balanced between the positive and negative parts. The highest peak of the current is at angle 0º, where it reaches 5.6 p.u. In figure (5) at time 0.1 second, the graph indicates that operating at a phase angle of 0º makes the harmonic at its highest value, and the harmonic decreases with an increase in the operating angle at 45º, and decreases more at an angle of 90. Figure (8) shows the relationship between the three parameters with the peak of the inrush current. The parameters are magnetic resistance and the angle of operation that were mentioned previously with residual flux for each curve in figure (8). It is clear from the figure that when the residual flux inside the transformer core increases, it leads to an increase in the peak inrush current and vice versa. The decrease in the inrush current is not limited to the phase angle only but also changes by the resistance of the magnetic core. When the magnetization resistance increases, the third harmonic increases significantly and the inrush current peaks will decrease.

10. CONCLUSION

In this paper an inrush current reduction used in real-time simulation. Calculated the optimal switching angle at which the circuit breaker receives the order to switch on a no-load transformer without the appearance of inrush current taking into account the residual flux. the impacts of magnetizing inrush current on power transformers is discussed. Many influences on the inrush current have been studied, such as switching angle, magnetization resistance, and initial residual fluxes, to minimize the inrush current. The study is limited to the inrush current generated when energizing a no-load transformer. The artificial neural network model is used for the inrush current prediction. using as input the switching angle θ, Magnetization resistance Rm (pu) and the residual flux to predicts the output as maximum phase current and the maximum of third harmonic. The database was divided into three parts: learning phase, testing phase and validation phase. The prediction of outputs is not obtained by linearization, but from the recursive and successive use of a non-linear model, allowing for gentle controls and better. The validation is carried out by comparison with Simulink/MATLAB results, where the developed model gives results in very good agreement with the simulation model. The ANN model is proved to be reliable and fast predictor of the inrush current.

11. APPENDIX

A- Table (2) Comparison between results of ANN and Simulink

inputs			Simulation Results		ANN predicted Results	
Rm (p.u)	Phi0A	Theta (degree)	MAX current A	Max 3rd harmonic A	Max current A	max 3rd harmonic A
1	0.6	0	1.61285	0.10709	1.62821	0.11487
1	0.6	5	1.57368	0.11271	1.58416	0.1124
1	0.6	10	1.5281	0.11792	1.53654	0.10992
1	0.6	15	1.47629	0.12275	1.48435	0.1074
1	0.6	20	1.41861	0.12728	1.4267	0.10487
1	0.6	25	1.35599	0.13159	1.36301	0.10238
1	0.6	30	1.28983	0.13567	1.29325	0.10007
1	0.6	35	1.21954	0.13791	1.21816	0.09815
1	0.6	40	1.14327	0.13486	1.13957	0.09698
1	0.6	45	1.06063	0.12618	1.06042	0.09697
1	0.6	50	0.98701	0.11299	0.98464	0.09859
1	0.6	55	0.91759	0.10532	0.91662	0.10227
1	0.6	60	0.8658	0.10689	0.86036	0.10823
1	0.6	65	0.79831	0.10779	0.81862	0.11633
1	0.6	70	0.78672	0.12255	0.7921	0.12603
1	0.6	75	0.78665	0.14038	0.77933	0.13639
1	0.6	80	0.78663	0.15099	0.77704	0.14625
1	0.6	85	0.78663	0.15435	0.7811	0.15448
1	0.6	90	0.78663	0.15675	0.7875	0.1602
1	0.6	95	0.78663	0.15816	0.79314	0.16298
1	0.6	100	0.78663	0.15858	0.79618	0.16282
1	0.6	105	0.78663	0.15799	0.79591	0.16009
1	0.6	110	0.78663	0.15641	0.79249	0.15538
1	0.6	115	0.78663	0.15386	0.78657	0.14935
1	0.6	120	0.78663	0.15038	0.77896	0.14263
1	0.6	125	0.78455	0.14602	0.77044	0.13575
1	0.6	130	0.77271	0.13777	0.76163	0.1291
1	0.6	135	0.76133	0.12975	0.75301	0.12302
1	0.6	140	0.75088	0.12311	0.74485	0.11781
1	0.6	145	0.74132	0.11599	0.73735	0.11392

12. REFERENCES

1. Chiesa, N. and H.K. Høidalen, *Novel approach for reducing transformer inrush currents: Laboratory measurements, analytical interpretation and simulation studies.* IEEE Transactions on Power Delivery, 2010. **25**(4): p. 2609-2616.
2. Mitra, J., X. Xu, and M. Benidris, *Reduction of three-phase transformer inrush currents using controlled switching.* IEEE Transactions on Industry Applications, 2019. **56**(1): p. 890-897.
3. Yazdani-Asrami, M., et al., *A novel intelligent protection system for power transformers considering possible electrical faults, inrush current, CT saturation and over-excitation.* International Journal of Electrical Power & Energy Systems, 2015. **64**: p. 1129-1140.
4. Yadav, A., et al., *Reduction of Inrush current in Three Phase Power Transformers using SSSC Device.* 2017.
5. Ekwue, A. and B. Rawn, *Investigations into the transformer inrush current problem.* Nigerian Journal of Technology, 2018. **37**(4): p. 1058-1064.
6. Elsayed Atwa, O.S., in *Practical Power System and Protective Relays Commissioning*. 2019, Academic Press. p. 189-280.
7. Witte, J., F. DeCesaro, and S. Mendis, *Damaging long-term overvoltages on industrial capacitor banks due to transformer energization inrush currents.* IEEE Transactions on Industry Applications, 1994. **30**(4): p. 1107-1115.
8. Metwally, H.M.B. and A.M.A. Mostafa, *Modeling and Analysis of Transformer Inrush current using ANFIS.* International Journal of Engineering Research and Applications, 2017. **7**(11): p. 61-68.
9. Singh, P.K. and D. Chaturvedi, *Neural network based modeling and simulation of transformer inrush current.* International Journal of Intelligent Systems and Applications, 2012. **4**(5): p. 1.
10. Gondane, P., et al. *Detection of Inrush Current through Wavelet Transform & Artificial Neural Network*. in *2018 National Power Engineering Conference (NPEC)*. 2018. IEEE.
11. Islam, M.S. and M.M. Kabir. *ANN Based discrimination of inrush and fault currents in three phase power transformer using statistical approaches*. in *2019 4th International Conference on Electrical Information and Communication Technology (EICT)*. 2019. IEEE.
12. Ganji, M., M. Bigdeli, and D. Azizian, *Mitigation Transformer inrush current using modified transient current limiter.* International Journal of Engineering, 2019. **32**(5): p. 701-709.
13. Septiawan, H., I.M.Y. Negara, and F.A. Pamuji, *Pre-energize Analysis on 3 Phase Transformer by Considering Each Phase Flux.* JAREE (Journal on Advanced Research in Electrical Engineering), 2019. **3**(2).
14. Fajariawan, A.H., et al. *A new switching control approach to reduce capacitor bank inrush current*. in *AIP Conference Proceedings*. 2020. AIP Publishing.
15. Pachore, P., et al., *Flux error function based controlled switching method for minimizing inrush current in 3-phase transformer.* IEEE Transactions on Power Delivery, 2020. **36**(2): p. 870-879.
16. Pan, Y., et al., *Three-phase transformer inrush current reduction strategy based on prefluxing and controlled switching.* IEEE Access, 2021. **9**: p. 38961-38978.
17. Doan, T.B. and C.P. Do. *Calculation of the Magnetic Field and Inrush Current in a Three-phase Transformer*. in *2020 Applying New Technology in Green Buildings (ATiGB)*. 2021. IEEE.
18. Yahiou, A., H. Mellah, and A. Bayadi, *Inrush current reduction by a point-on-wave energization strategy and sequential phase shifting in three-phase transformer.* International Journal of Engineering, 2022. **35**(12): p. 2321-2328.