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Power Transformer Inrush Current Minimization During Energization using ANFIS based Peak Voltage Tracking Approach

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ABSTRACT- Energizing the power transformer at no load causes inrush current flow. The value of this current depends on main three factors, the residual and saturation flux of the transformer core, the rating of the transformer, and the switching instant. Inrush current may decrease the life of the transformer and causes mall function of the protective relays. Many efforts were done for limiting the inrush current using a current limiter or improve the core material to reduce residual flux. Other treating is to control energizing instance. This paper focused on controlling the instant of the transformer energization switch using fuzzy logic inference system. A new technique depends on adaptive seeking the crest of the voltage waveform. By this method there is no need to zero-crossing technique or phase looked loop. At this point, the flux of the core reaches the minimum value. Simulation and laboratory results show the success of this technique in reducing the inrush current. This technique gives the freedom to the operational engineering for energizing the power transformer at any time.

Keywords: Inrush current; Energizing transformer; Switching control.

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1. INTRODUCTION

An inrush current can be created at any mutual coupling device having magnetic core when this device supplied by energy source at no load. Inrush current founded in power transformer, coupling or injection transformer and induction motor. The value of inrush current may be high depending on the transformer rating, the supply voltage, and the transformer energization instant. Inrush current, also known as transformer magnetizing current, is a high magnitude current that flows into an energized transformer. This phenomenon can cause damage to the transformer and disrupt the power system, also it causes operation of protective relays. Therefore, it is important to minimize inrush current in power transformers. There are various efforts for reducing inrush current, including voltage compensation type inrush current limiter [1] using a storable reactor [2] depends on box dimension [3] employing reference modifier to the outer loop or the voltage loop to limit transformers inrush currents [4] installing a transformer differential protection system [5] applying grid-connected photovoltaic system [6] using bidirectional impedance-type inrush current limiter [7]. To reduce inrush current the authors in [8] employed a diode bridge while the others based on refluxing and controlled switching [9]. Some authors based on transformer configuration to restrain inrush current [10] other authors applying a modified transient current limiter [11]. The method for reducing the residual flux with an ultra-low-frequency power source is adopted in [12] another approach designs an asymmetrical winding configuration to reduce inrush current with appropriate short-circuit current in transformer [13]. Authors in [14] using controlled switching while the others inserting a grounding resistor connected at the transformer neutral and delayed energization of each phase of the transformer [15]. Authors in [16] design saturated amorphous alloy core-based inrush current limiter (ICL) to limit the inrush current. Other methods for mitigating the impact of inrush current using voltage sag compensator [17], while the others proposed the use of TCSC for mitigate the effect of inrush current [18]. Other researchers have developed models and simulations to understand the underlying causes of inrush current and to predict its behaviour in different electrical systems [19]. In other hand, some researchers have investigated a range of techniques for protecting against the effects of inrush current, including the use of resistors, inductors, and surge protection devices. Zero-mode inrush current characteristics and zero-sequence protection countermeasure under sympathetic interaction [20]. Eventually, researchers have explored alternative design approaches for minimizing inrush current, such as the use of soft starters and active inrush current limiting circuits. The main solution for inrush current problem is illustrated in *figure 1*. Minimizing inrush current in electrical systems may achieved using soft starters to gradually increase the voltage applied to an electrical device, which can reduce the inrush current, using of active inrush current limiting circuits that can detect the inrush current and limit it to a safe level by using control algorithms, by adding a resistor in series with the device, the inrush current can be reduced, use of inductors can be limit the inrush current by providing a high impedance to the initial current surge, use of surge protection devices such as metal oxide visitors (MOVs), limit the inrush current by diverting it to ground. It is important to carefully consider the trade-offs of each approach and to select the most appropriate solution for a given application. Some researchers are developing active inrush current limiting circuits that use control algorithms and high-speed switching devices to detect and limit the inrush current in power transformers. These circuits have the potential to significantly reduce the inrush current and improve the reliability of power transformers. By limiting the maximum voltage applied to the transformer, the inrush current can be reduced. There are several ways to control the maximum voltage applied to the transformer at the instant of energization. The researchers in [21] proposed a soft starter that can be used to gradually increase the voltage applied to the transformer, which can reduce the inrush current. [22] Coupled directly a voltage source inverter (VSI) to the transformer to reduce the peak value of inrush current. This effectively "chops" the voltage applied to the transformer, allowing the inrush current to be controlled and minimized. [23] Use of a pulse width modulation (PWM) control scheme that can be used to rapidly switch the voltage applied to the transformer on and off, with the duty cycle of the switching signal used to control the average voltage applied to the transformer. This can also be used to effectively control the inrush current. It is important to carefully select and implement the appropriate control strategy to ensure reliable and efficient operation of the transformer.

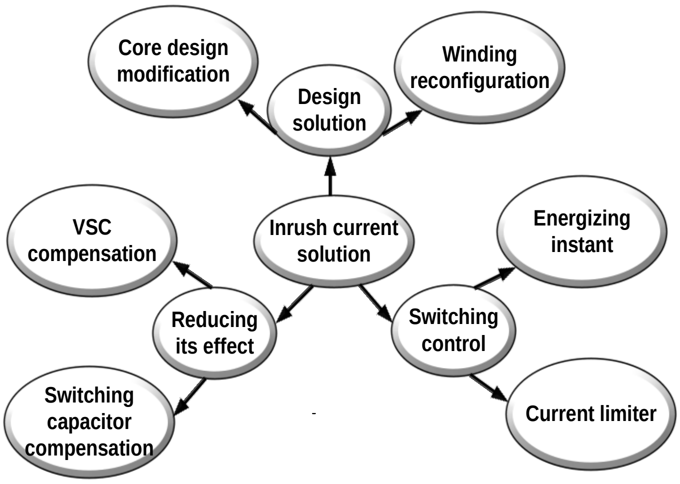


Figure 1. Inrush current solution methods

2. PEAK VOLTAGE SEEKING

This approach using controller switch that immune energizing transformer at any time except near the peak value. This is done adaptively using neuro-fuzzy inference system as described in the next section. By this method, there is no need to use a precise and complex zero crossing technique. Power transformer is energized only at 90 degrees or near it, depends on the required precision, when the core flux reaches its minimum value as shown in *figure 2*. Program code were used for processor type Arduino. In other hand, the processor receives the information of the voltage signal due to CT then control the power switch. Repetitive switching the transformer remains the trigger time around the crest of the applied voltage. Any trigger degree can be easily achieved by the program. The proposed circuit is shown in *figure 3*.

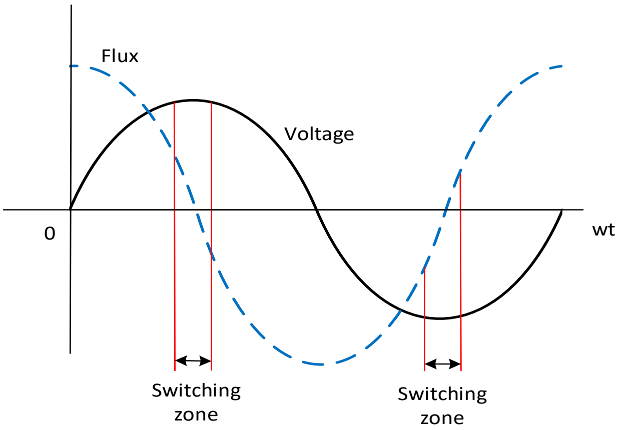


Figure 2. Voltage crest seeking for switching margin

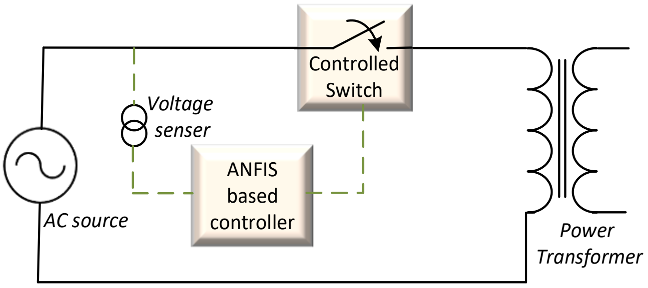


Figure 3. Proposed circuit for controlled switch

Applying Kirchhoff voltage law of the transformer circuit, shown in *figure 4*, as

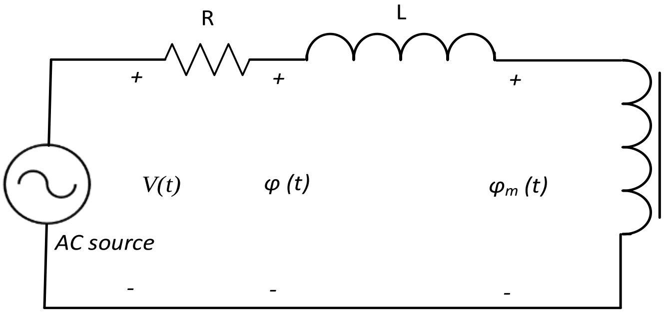


Figure 4. Transformer equivalent circuit

$$v(t) = V_m \sin(\omega t + \alpha) \quad (1)$$

$$\varphi(t) = \int_0^t [v(t) - ri(t)]dt + \varphi_r \quad (2)$$

Substituting *equation 1* into *equation 2*

$$\left(\frac{V_m}{\omega}\right)\cos(\omega t+\alpha)+\left(\frac{V_m}{\omega}\right)cos\alpha+\varphi_r-\int_0^t ri\,dt \qquad (3)$$

The transformer flux-current relation represented by the circuit shown in *figure 5 [24]:*

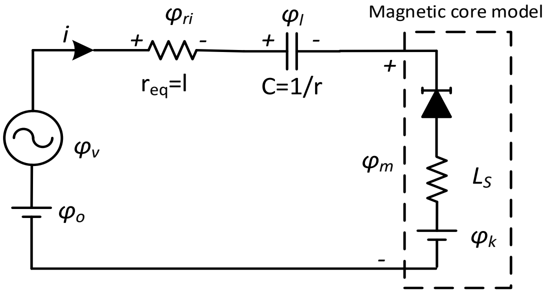


Figure 5. Transformer $\boldsymbol{\varphi - i}$ equivalent circuit [24]

In this equivalent circuit, the AC flux developed by ac grid voltage is represented by an AC flux source φ_v. The DC flux φ_o is represented by a DC flux source in series with φ_v. According to *figure 4*, φ_o consists of φ_{vo} due to the switching-on and the residual flux φ_r. As seen in *figure 5*, φ_r is positive, so, the φ–i core equivalent circuit for positive saturation region, circuit enclosed by rectangle crossed line, is employed as a core model. MATLAB equivalent circuit is shown in *appendix A*.

Where:
φ_v AC flux, pu
φ_{vo} Switching flux, pu
φ_r core residual DC linkage flux, pu
φ_o DC flux (φ_o= φ_{vo}+ φ_r), pu
$v(t)$ Applied voltage as function of time, pu
R Core loss resistance, pu
V_m maximum applied voltage, pu
ω angular frequency, rad/s
α switching angle, degree
r_{eq} total resistance of the transformer and its system, pu
φ_m transformer core linkage flux, pu
φ_1 steady-state linkage flux magnitude
λ_v sinusoidal steady-state linkage flux, pu
φ_{ri} lost linkage flux due to voltage drop on the resistance
C_{eq} equivalent capacitor in φ–i circuit, pu
l transformer and system leakage inductance, pu
r_{eq} equivalent resistor of φ–i circuit, pu
L_s incremental inductance of the core in saturation regions

This formula takes into account the resistance and reactance of the transformer's magnetic circuit, which determines the impedance of the transformer and therefore the inrush current. It's important to note that the inrush current of a transformer is highly dependent on its design and operating conditions, and can vary significantly depending on factors such as the transformer's size, voltage rating, and type of core material. As such, it is important to use accurate values for the transformer's equivalent circuit parameters when calculating the inrush current.

3. ANFIS CONTROLLER DESIGN

As mansion to prevent heavy inrush current the proposed method is to switching on the transformer at the peak voltage with tolerance of 20% this means the amplitude of waveform in *+ve* or *–ve* half wave as shown in *figure 6*. Neuro-fuzzy controllers are appropriate for approximate or uncertain reasoning, that especially for the system modelling mathematically is difficult to solve. Controllers based Fuzzy logic one of an important part in many practical models in applications.

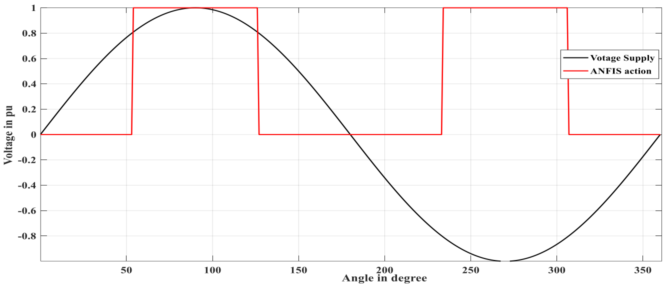


Figure 6. ANFIS action versus voltage supply

The Artificial Neural Network denote ANN that will be utilized in this paper for tuning the membership functions MF of Takagi Sugino-Fuzzy controller like PI. The TS –fuzzy has a highly efficiency especially in non-linearity for gain that variable. It makes wide range variations in the gain of controller. The chosen of the elements may lead to an unitability or adequate in response. A better response of controller accomplished by employ Neuro-Fuzzy for adapting the functions of Fuzzy controller elements and also associated rules by utilize ANN learning algorithm. After it add fuzzy specific approach using the adaptive capabilities of learning of ANN, this type of system can be trained without a big amount of knowledge or expert commonly required for the standard type of fuzzy controller [25]. The result is reducing the rule base. The elements of the membership functions for input and also the output are to be specified through the training period. The designed Fuzzy system composite of 5-layers; every layer has, either, variable node that have elements to be tuned through process of training and fixed nodes that have no elements need to tuned. The output of the 5-layers in which simulate the fuzzy design procedure is given referring to [26] for more details. The learning algorithm objective is to set the elements of the input / output MF so that the output of ANFIS beter in matching the data of training. A strategy of hybrid learning type Gradient Descent GD and Least Squared Estimation LSE is utilized for identifying the network elements [27]. GD procedure updates the antecedent MF elements. In this work paper, the input universe of discourse is split into 5-trapezoidal MF with overlapping of 50%, so that, for 2-inputs, 25-control rule resultant linear in functions require to be evaluated. For tuning the TS 25-rules utilizing ANFIS, two vectors' data are generated. The input data is a column matrix of the phase voltage and flux with output control signal. *Figure 7* shows the validation surface of designed fuzzy based ANN system.

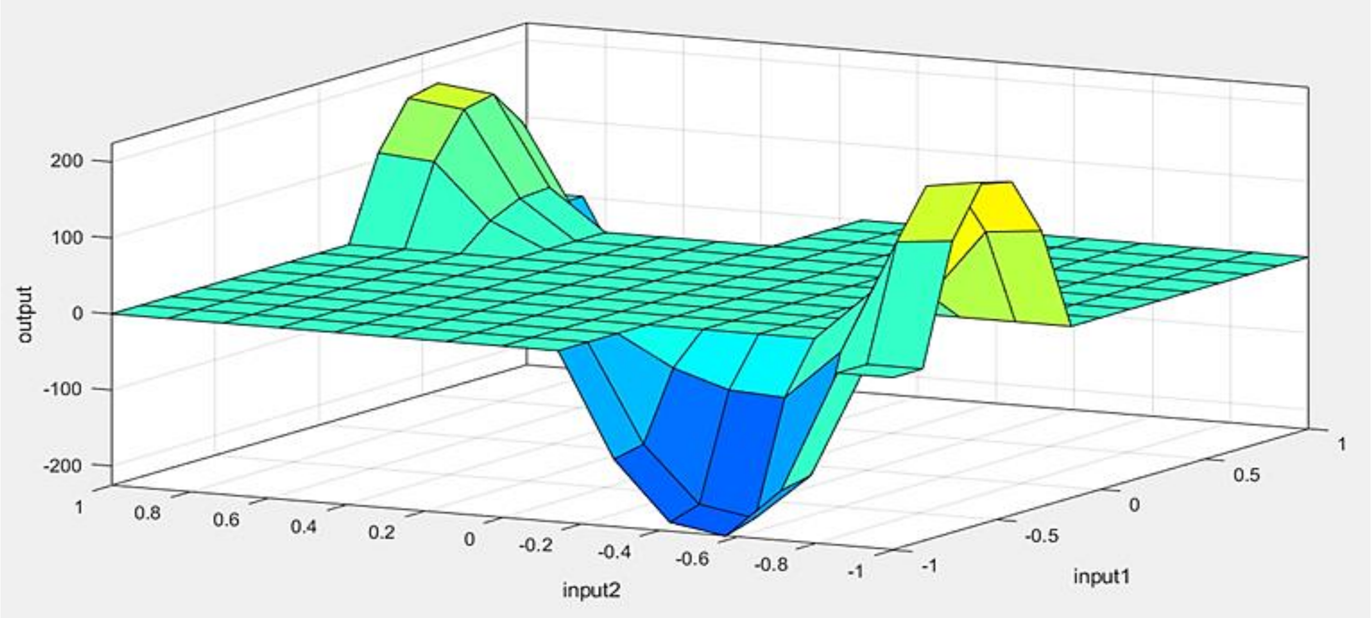


Figure 7. Validation surface of ANFIS

4. LAB TEST AND MATLAB SIMULATION

Figure 8 shows the MATLAB simulation circuit. Inrush current produced during energize unloaded saturable transformer. Firstly, the control circuit is bypassed and the four switching instant degrees are selected and compared with laboratory test. The saturable transformer MATLAB equivalent circuit is illustrated in Appendix A. *Figures 9*, *10*, *11*, *12* represent experimental and simulation transformer inrush current with applied voltage at trigging angles 0, 45, 135 and 90 degrees respectively. It’s shown that inrush current reduced as trigger time approaches the peak value. Minimum inrush current obtained at 0 degrees as depicted in *figure 12*.

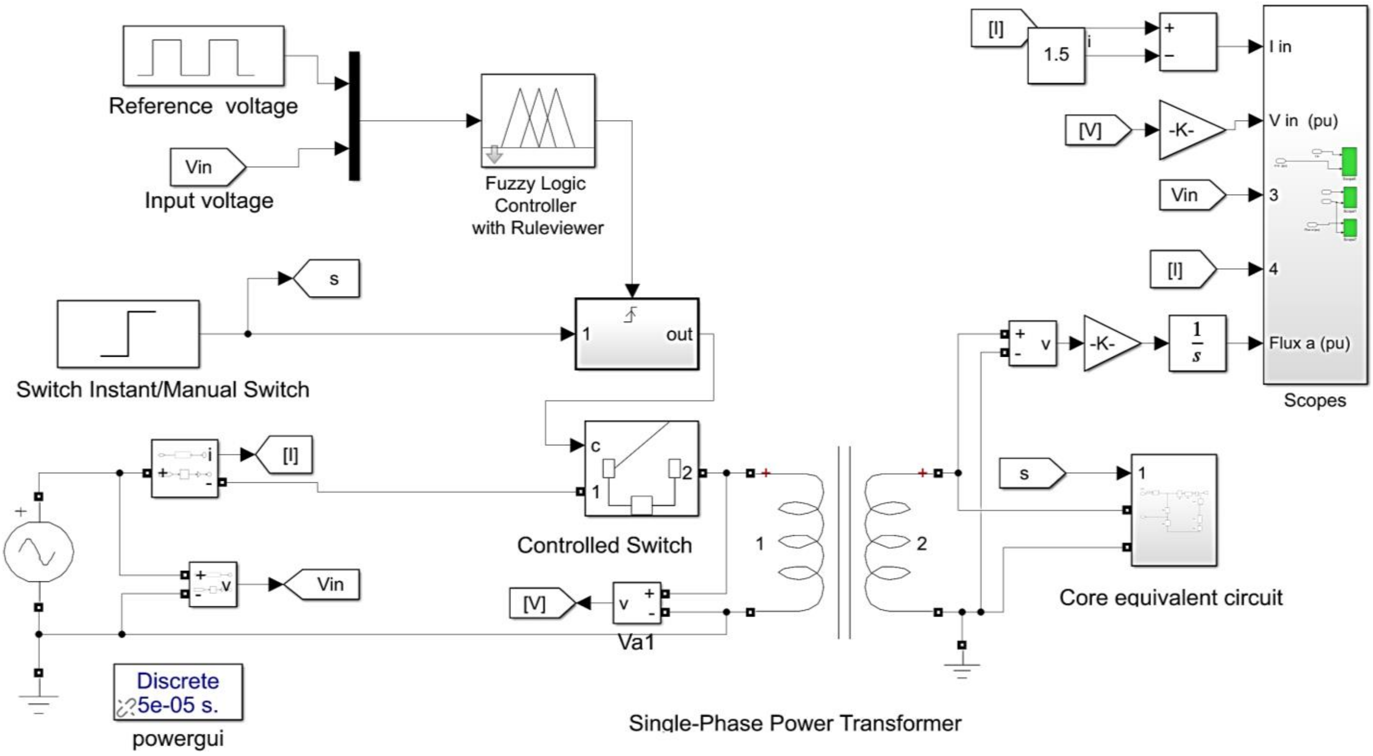
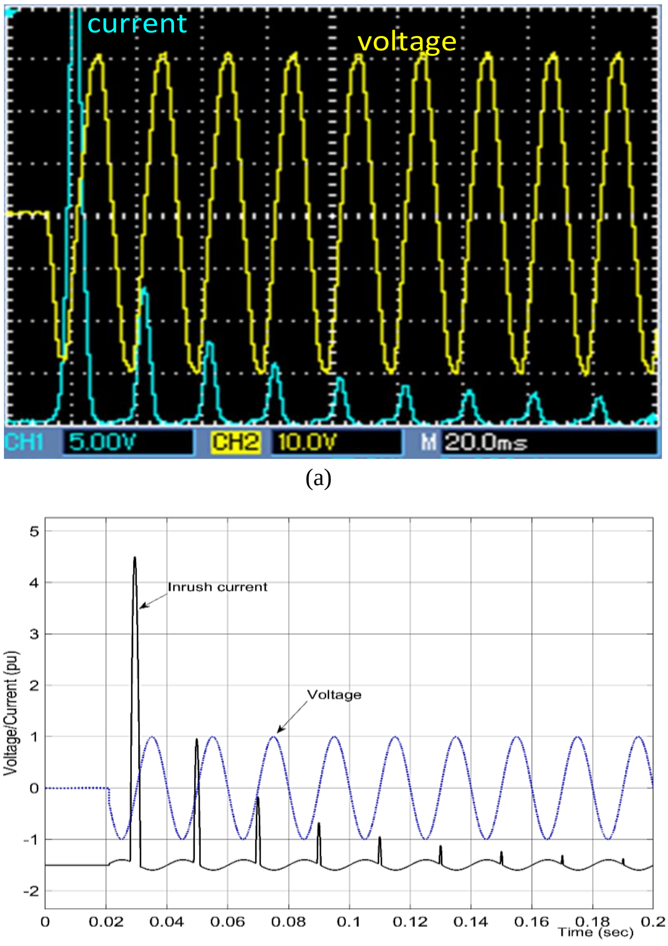


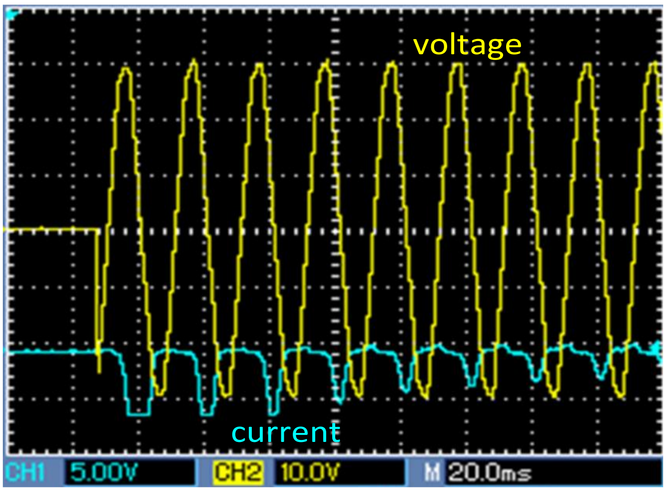
Figure 8. Switching control for inrush current using MATLAB/Simulink

The experimental circuit tested and the power switch set to trigger at peak voltage only. When control circuit activated, many repetitive re-energizing the transformer shows no inrush current produced. The controller let the energization done just at peak voltage between 0.9 pu up to 1 pu *i.e.* at minimum core flux.

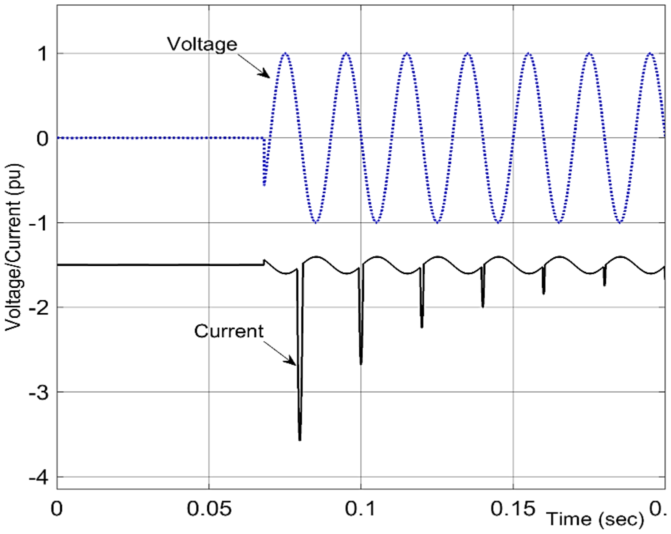


(b)

Figure 9. Switching angle α=180o or 0o (a) Lab test (b) simulation result

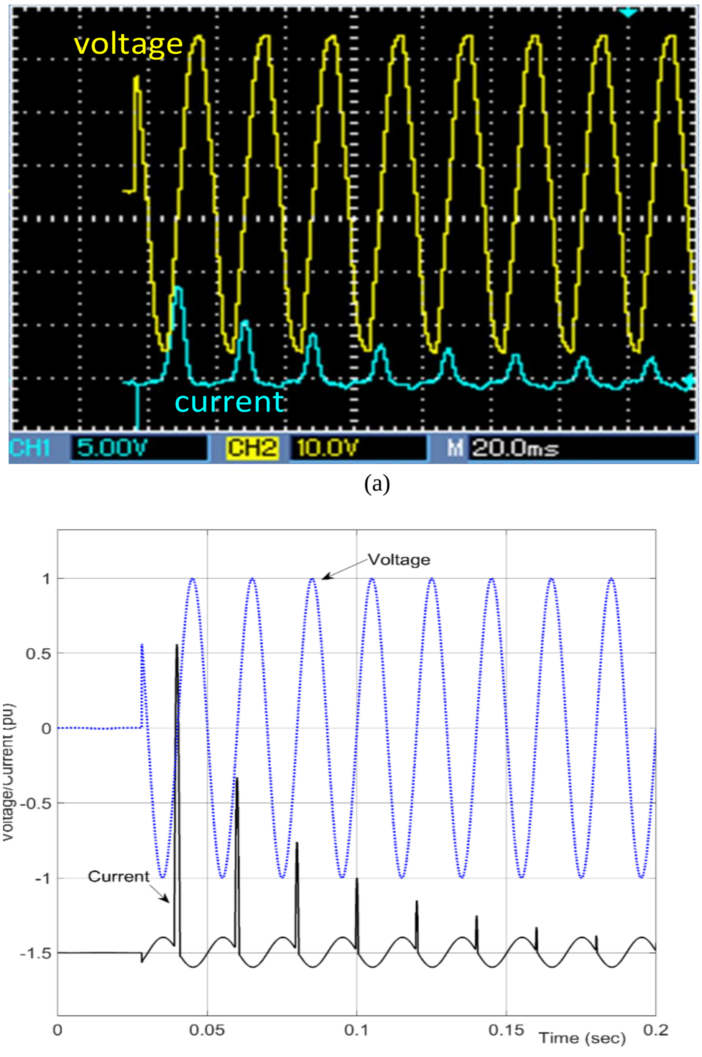


(a)



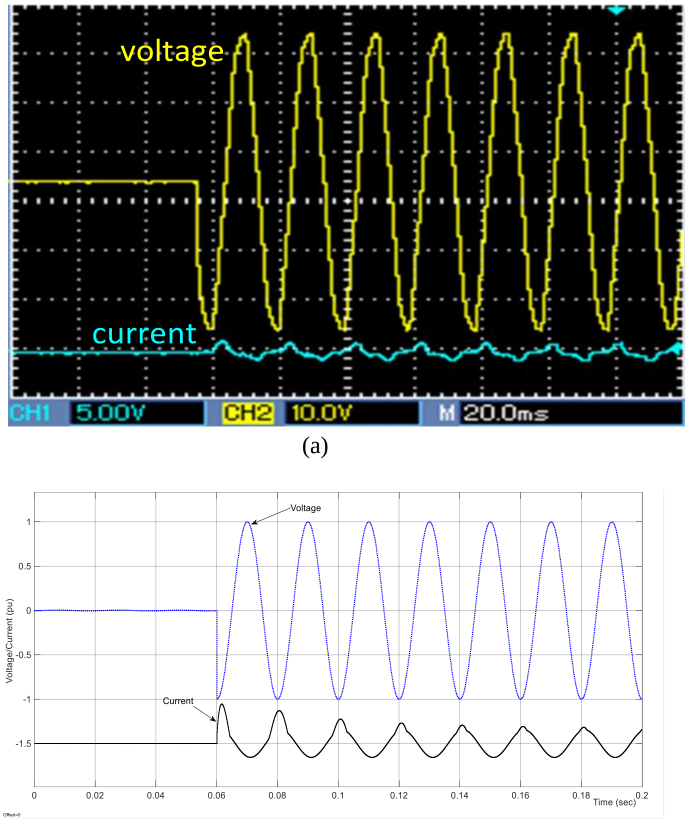
(b)

Figure 10. Switching angle α=45o+180o (a) Lab test (b) simulation result



(b)

Figure 11. Switching angle α=135o (a) Lab test (b) simulation result



(a)

(b)

Figure 12. Switching angle α=270o or 90o (a) Lab test (b) simulation result

5. CONCLUSION

Energizing transformer near crest voltage gives minimum inrush current and reduces its peak value from 4.5 pu to 0.1 pu. This done adaptively based on neuro-fuzzy inference controller system. Theoretical simulation is verified with experimental tests and shows the semi-identical results. The use of a switching controller is an effective method for minimizing inrush current of power transformers. The controller method based on the narrow range around the peak voltage using ANFIS system. By carefully controlling the switching device, the magnitude of the inrush current can be reduced, protecting the system and its components from damage and ensuring reliable operation. ANFIS based switching controller technique has several advantages, including fast response time, high accuracy, and adapting any change in the system conditions. This approach gives operational engineering the freedom during reenergizing power transformers. The validity of the minimum inrush current pattern scheme is only verified for an unloaded 1.1kVA prototype transformer. Further investigations are necessary to determine the general applicability of this approach.

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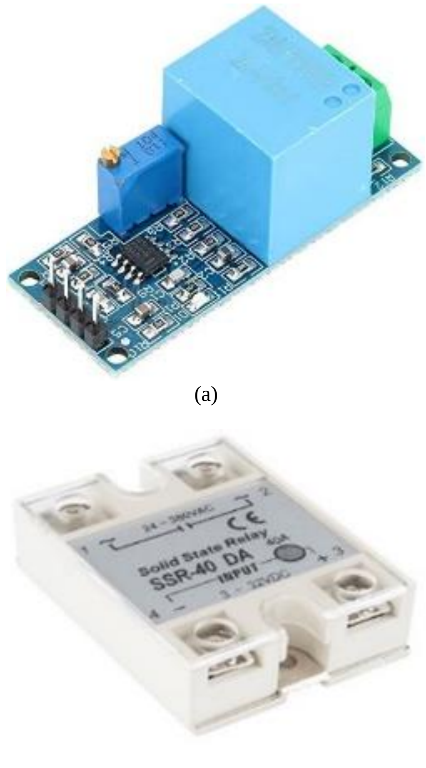
Appendix A: Switch control circuit and core equivalent circuit

This circuit consists of an Arduino Mega 2560 used for detecting the peak value of source voltage measured by a voltage sensor (ZMPT101B) *(fig. A1 (a))* and give a signal to a random solid-state relay *(fig. A1 (b))* then the transformer can turn on at the peak value of the source voltage (*i.e.* at 90 degrees). A detailed controller switch is shown in Figure A2. The MATLAB/Simulink saturable core equivalent circuit is shown in *figure A3*. A 1.1KVA transformer under test with detailed instruments are shown in *figure A4*. The Arduino based controller circuit is shown in *figure A5*.



(a)

(b)

Figure A1. (a) ZMPT101B AC Voltage Sensor, (b) Solid State Relay

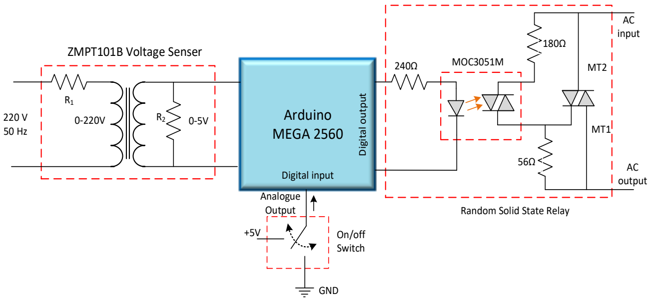


Figure A2. Detailed proposed circuit for instant energization control

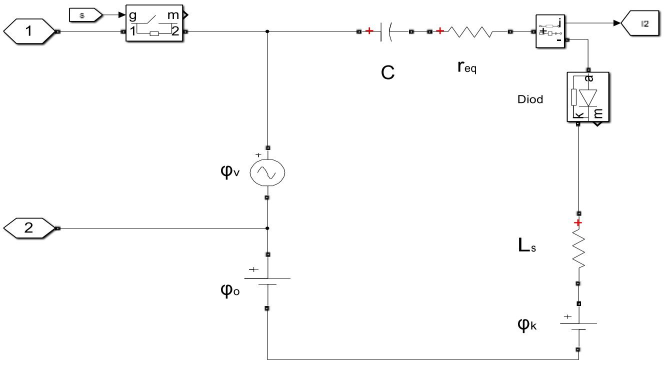


Figure A3. The saturable core equivalent circuit

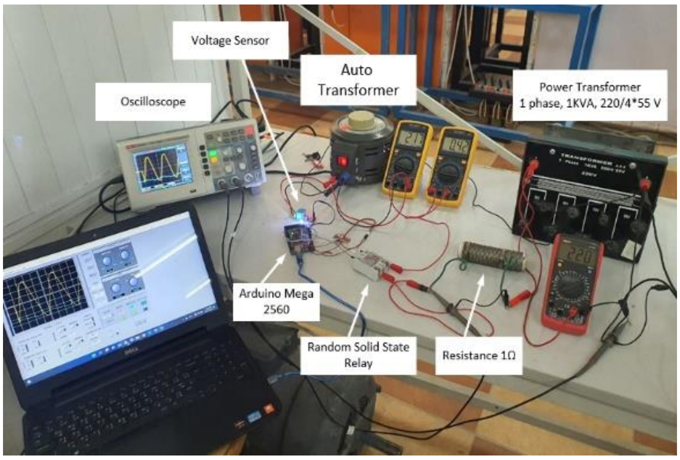


Figure A4. Lab prototype transformer under test

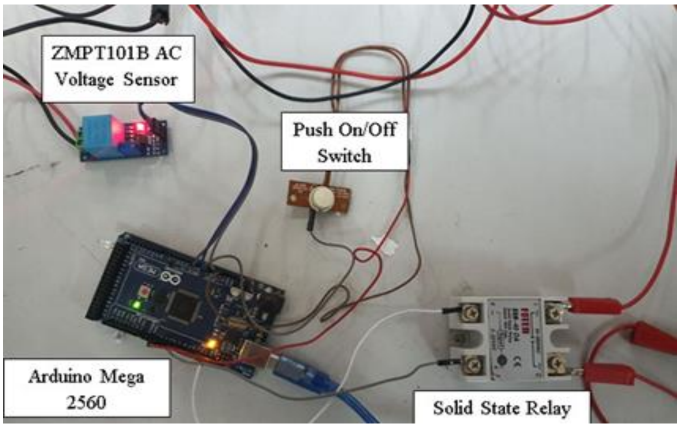


Figure A5. Lab controller switch

Appendix B: Transformer parameters and dimensions

Table B1 illustrate the data obtained from testing a 1-kVA, 220/110-V, step-down transformer:

Table B1. This is a table. Tables should be placed in the main text near to the first time they are cited.

Test	Voltage V	Current A
Open circuit	110	0.94
Short circuit	45	4.9

Since the open-circuit test must be conducted at the rated terminal voltage, the above data indicate that it is performed on the low-voltage side. Transformer parameters referred to the low-voltage side are indicated in table B2 as

Table B2. Transformer parameters referred to low voltage side

Leakage reactance Ω	**Winding resistance Ω**	**Magnetizing impedance Ω**
0.96	0.59	0.94+j134.14

A transformer core consists of 86 laminations of 0.5mm thickness and has the dimensions shown in *figure B1*.

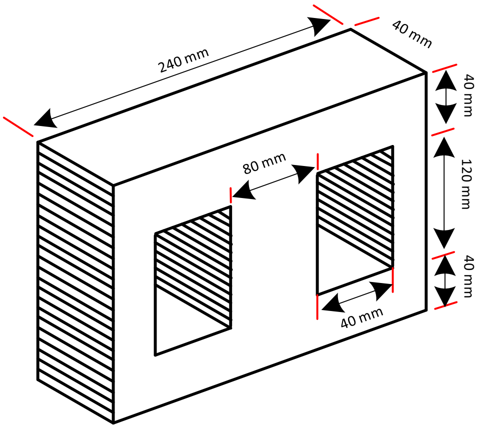


Figure B1. Core dimensions

REFERENCES

[1] H. T. Tseng J. F. Chen, Voltage compensation-type inrush current limiter for reducing power transformer inrush current, IET Electr. Power Appl., 2012, Vol. 6, Iss. 2, pp. 101–110. DOI: 10.1049/iet-epa.2011.0151.

[2] C.K. Cheng, T.J. Liang, J.F. Chen, S.D. Chen and W.H. Yang, Novel approach to reducing the inrush current of a power transformer, IEE Proc.-Electr. Power Appl., May 2004, Vol. 151, No. 3. DOI: 10.1080/02533839.2005.9671051.

[3] MaofaGong, RanZheng, LinyuanHou, Jingyu Wei, NaWu, A Method for Identification of Transformer Inrush Current Based on Box Dimension, Hindawi, Mathematical Problems in Engineering, 2017, Article ID 2095896, 6 pages. DOI: 10.1155/2017/2095896.

[4] M. Shahparastici, K. Kauhaniemi, P. Lauttams, S. Strandberg, J. Strandberg, Inrush Current Management During Medium Voltage Microgrid Black Start with Battery Energy Storage System, IEEE Transactions on Power Delivery, 2011, vol. 26, pp. 2349-2357. DOI: 10.1109/ACCESS.2022.3167701.

[5] Mohammed Yahya Suliman and Mahmood T. Alkhayyat, Discrimination Between Inrush and Internal Fault Currents in Protection Based Power Transformer using DWT, International Journal on Electrical Engineering and Informatics, March 2021, Volume 13, Number 1, DOI: 10.15676/ijeei.2021.13.1.1

[6] Abdelsalam A. Ahmed, Hany A. Abdelsalam, Mitigation of transformer-energizing inrush current using grid-connected photovoltaic system, International Journal of Electrical Power & Energy Systems, 2011, vol. 26, pp. 929-937. DOI: 10.1016/j.ijepes.2016.01.005.

[7] Hsu-Ting Tsenga, Jiann-Fuh Chen, Bidirectional impedance-type transformer inrush current limiter, Electric Power Systems Research, 2013, vol. 104, pp 193–206. DOI: 10.1016/j.epsr.2013.06.007.

[8] Seyed Majid Madani, Mehrdad Rostami, Gevork B. Gharehpetian Amirkabir, Inrush current limiting of transformer primary winding with grounded or non-grounded Y-connection using diode bridges, Canadian Journal of Electrical and Computer Engineering, summer 2017, vol. 40, no. 3. DOI:10.1109/CJECE.2017.2705278.

[9] Yuanlin Pan, Xianggen Yin, Zhe Zhang, Binyan Liu, Maolin Wang, Xin Yin, Three-Phase Transformer Inrush Current Reduction Strategy Based on Prefluxing and Controlled Switching, IEEE publisher, 2021, vol 21, pp 38961 – 38978. DOI: 10.1109/ACCESS.2021.3062143

[10] J.-F. Chen, T.-J. Liang, C.-K. Cheng, S.-D. Chen, R.-L. Lin and W.-H. Yang, Asymmetrical winding configuration to reduce inrush current with appropriate short-circuit current in transformer, 2005, IEE Proc.-Electr. Power Appl., Vol. 152, No. 3, pp 605-611.

[11] Morteza Ganji, Mehdi Bigdeli, Davood Azizian, A modifed transient Current limiter to mitigate energization inrush current in wind turbine transformers, Journal of Control, Automation and Electrical Systems, Springer, 2020. DOI:1007/s40313-020-00630-8.

[12] J. Kim and H. Lee, Mitigation of Inrush Currents in Network Transformers by Reducing the Residual Flux With an Ultra-Low-Frequency Power Source, IEEE Transactions on Power Delivery, July 2011, vol. 26, no. 3. DOI: 10.1109/TPWRD.2010.2102778.

[13] J.F. Chen, T.J. Liang, C.-K. Cheng, S.D. Chen, R.L. Lin, W.H. Yang, Asymmetrical winding configuration to reduce inrush current with appropriate short-circuit current in transformer, IEE Proceeding of Electric Power Application, May 2005, vol. 152, no. 3. DOI: 10.1049/ip-epa:20040985

[14] Joydeep Mitra, Xufeng Xu, and Mohammed Benidris, Reduction of Three-Phase Transformer Inrush Currents Using Controlled Switching, IEEE transaction on industry applications, Jan/Feb 2020, vol. 56. no. 1, PP. 890–897. DOI:10.1109/TIA.2019.2955627.

[15] Liana Cipcigan, Wilsun Xu, and Venkata Dinavahi, A New Technique to Mitigate Inrush Current Caused by Transformer Energization, IEEE Power Engineering Society Summer Meeting, 2002, DOI: 10.1109/PESS.2002.1043303.

[16] Md. Minarul Islam, Kashem M. Muttaqi, Danny Sutanto, A Saturated Amorphous Alloy Core-Based Inrush Current Limiter to Eliminate Inrush Currents and Restrain Harmonics during Transformer Energization, IEEE Transactions on Industry Applications, Nov. 2021, vol. 57, Issue: 6. DOI:10.1109/TIA.2021.3114665.

[17] Diksha Ahire, Shridhar Khule, Design of Voltage Sag Compensator with Transformer Inrush Current Mitigation Technique, IEEE International Conference on Automatic Control and Dynamic Optimization Techniques (ICACDOT), 2016, DOI:10.1109/ICACDOT.2016.7877644.

[18] Mojtaba Khederzadeh, Mitigation of the impact of transformer inrush current on voltage sag by TCSC, Electric Power Systems Research, 2010, 80, pp 1049–1055. DOI:10.1016/j.epsr.2010.01.011

[19] Md Maidul Islam, et al, A review of modelling techniques of power transformers for digital real-time simulation, IET, John Wiley & Sons, 2023, DOI: 10.1049/tje2.12221.

[20] Yuanlin Pan, Xianggen Yin, Xin Yin, Jinmu Lai, Cheng Xu, Ke Han, Zero-Mode Inrush Current Characteristics and Zero-Sequence Protection Countermeasure Under Sympathetic Interaction, IEEE Transactions on Power Delivery, October 2022, vol.37, Issue: 5,. DOI:10.1109/TPWRD.2021.3134825.

[21] Chunyan Li, Yi Yang , Wenyan Li, and Haixiao Li, A Soft-Start-Based Method for Active Suppression of Magnetizing Inrush Current in Transformers, Electronics, 2023. DOI:10.3390/electronics12143114

[22] Rickard Ekström, Senad Apelfröjd, and Mats Leijon, Transformer Magnetizing Inrush Currents Using a Directly Coupled Voltage-Source Inverter, Electronics, 2013, Volume 2013 ,Article ID 361643, 8pages DOI: 10.1155/2013/361643

[23] Abbas Ketabi, Ali Reza Hadidi Zavareh, New method for inrush current mitigation using series voltage-source PWM converter for three phase transformer, IEEE 2nd Power Electronics, Drive Systems and Technologies Conference, 2011, pp 501-506. DOI: 10.1109/PEDSTC.2011.5742470

[24] Arash Moradi, Seyed M Madani, Technique for inrush current modelling of power transformers based on core saturation analysis, IET Generation, Transmission & Distribution, 2018, vol. 12 Iss. 10, pp. 2317-2324. DOI:10.1049/iet-gtd.2017.1272.

[25] Alkhayyat, M.T., Suliman, M.Y., Neuro Fuzzy based SSSC for Active and Reactive Power Control in AC Lines with Reduced Oscillation, Przeglad Elektrotechniczny, 2021, Volume 97, Issue 3, Pages 75-79. DOI: 10.15199/48.2021.03.14

[26] Alkhayyat, M.T., Suliman, M.Y., Adaptive Neuro-Fuzzy Controller Based STATCOM for Reactive Power Compensator in Distribution Grid, , Przeglad Elektrotechniczny, 2022, Volume 98, Issue 4, Pages 107-112. DOI:10.15199/48.2022.04.23

[27] H. Khorashadi Zadeh, Fuzzy-Neuro Approach to Investigating Transformer Inrush Current, IEEE/PES Transmission and Distribution Conference and Exhibition, 2006. DOI: 10.1109/TDC.2006.1668699.