

Inrush Current in Transformer And Its Mitigation

Roopal R Kapadia¹, Dr.R.M.Patel², Dr. J.J.Patel³

¹Research Scholar,Electrical Engineering, GTU, Ahmedabad, Gujarat, India

²Dept. of Electrical Engineering, MITR, Rajkot, Gujarat, India

³Dept. of Electrical Engineering, GCET, Vallabh Vidyanagar, Gujarat, India

Abstract

Power Transformer is most expensive apparatus of electrical power system. When Power transformer is energized from the de energized state, it experiences a large amount of current which is known as inrush current. Inrush current impacts on winding of transformer, causes of generation of harmonics and related Problems of power quality. Here, the effects of inrush current on power system and types of inrush current are elaborated. Also methods for the inrush current mitigation by suitable means are discussed.

Keywords: *Inrush current, Residual flux, switching angle, Energization inrush, sympathetic inrush, recovery inrush current.*

INTRODUCTION

Power Transformer is one of the most important and expensive device of power system network. Transformer is static equipment of power system network which transfer the electric energy from one circuit to another circuit without change in frequency. When transformer energized large amount of current is flow through the transformer primary winding called inrush Current [1]. Inrush current is 10 to 15 times than that of the rated current. In transformer inrush current remains high for several cycle but it is slowly decreases and after some cycle it is reach at rated value of current. Inrush current is either positive or negative direction due to its asymmetric properties. The inrush current has numerous effects such as voltage distortion, harmonics, mechanical stress and mal operation of protective relay. Maximum amount of inrush current is drawn by transformer when voltage is applied to the transformer while there will be an instant of crossing through zero in voltage waveform. Because, at the moment of transformer energization, secondary winding of transformer is open so primary act as simple inductance. If applied voltage of power transformer is at zero degree,the inrush current is maximum. Inrush current never generates any permanent fault in transformer but still that creates the major problems in power system. So focus on the minimization of this incipient current is essential in the power system Operation. Inrush current can be classified to three categories as follows.

1. Energization inrush: Energization inrush current is mainly produced due to multiple times energization of power transformer (Switching Phenomena), It results due to residual flux(Remanance) which always remains in core of transformer due to Ferro magnetic properties of the transformer core material [2].

2. Recovery inrush: This is type of inrush current is mainly generated when applied Voltage to the power transformer is becoming normal (restore) after being subjected to the some kind of system disturbances(Fault appearance) and upon its complete removal[2].

3. Sympathetic inrush: Such type of inrush current is mainly seen in Power System when numbers of transformers are connected parallel and another one is energized to connect across it. That newly energized transformer creates disturbance in the magnetic field of the remaining transformers of network [2].

II. Factors Affecting the Inrush Current

Some factors which are responsible for inrush current in transformer are:

Switching angle: Switching angle of voltage depends on instant of transform energization as per below equation of flux in transformer is given as below when the supply voltage to the transformer is [3].As we know that,

$$v = V_m \sin(\omega t + \alpha) \text{ ----- (1)}$$

$$v = n d\Phi/dt \text{ ----- (2)}$$

$$\Phi = \Phi_r + \Phi_m \cos(\alpha) - \Phi_m \cos(\omega t + \alpha) \text{ (3)}$$

Where α = Switching Instant.

From equation (3) derived values of flux for the various angle of switching instants are listed as follows:

Table I. Switching angle Vs. Flux Amount

Switching Instant	Flux Amount
$\alpha = 0^\circ$	$\Phi = 3\Phi_m$
$\alpha = 45^\circ$	$\Phi = 2.12\Phi_m$
$\alpha = 90^\circ$	$\Phi = 2\Phi_m$

It is obviously noted that inrush current depends on mainly two factors called residual flux and switching angle of supply voltage as shown. It is clearly seen that in equation 1, when switching instant of the voltage is zero ($\alpha = 0^\circ$) and $\phi_r = \phi_m$ then the amplitude of the flux is three times of the maximum flux (with $\omega = \omega t$) and realization of this situation ($\Phi = 3\Phi_m$), Primary winding of the transformer draws very huge amount of magnetizing current,

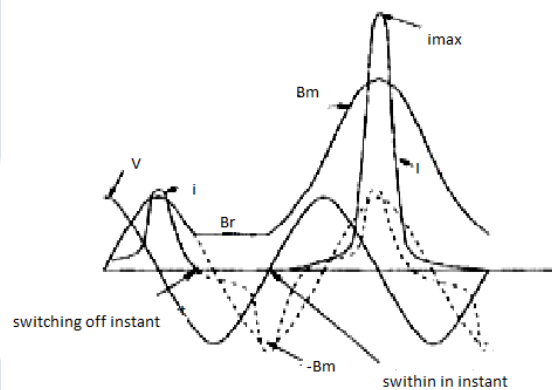


Fig. 1 Inrush Phenomena at voltage switching with zero angle

The inrush current can be spitted into two parts called decaying DC and Distorted AC components. The rate of the decay of this inrush current is usually very fast for the first few cycles and then progressively become slow

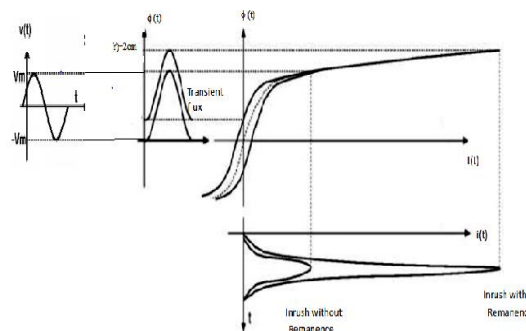


Fig. 2 Voltage, flux and current at instant of inrush phenomena with remanence

The typical wave shape of inrush current is as shown below:

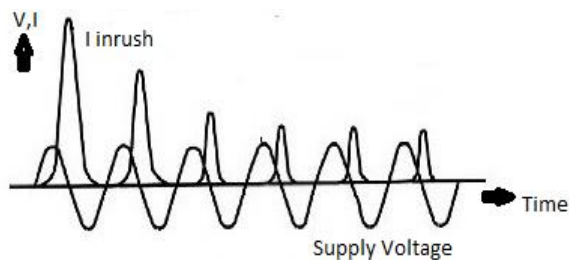
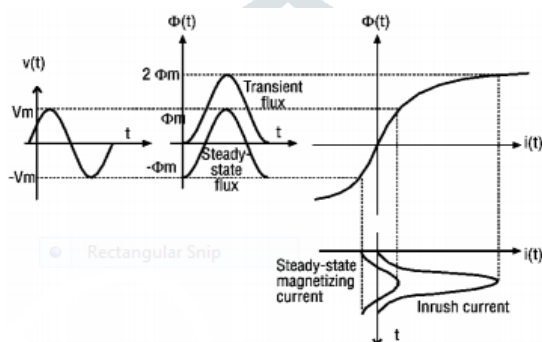


Fig.3 Typical Inrush Current Waveform

Residual flux density: Transformer is made using the ferromagnetic materials and due to its core hysteresis properties, little amount of flux remaining inside the core material after de energization which is known as “residual flux” and the property is called “retentivity” of that material.



Courtesy: (Gladstone 2004, p.14)

Fig. 4 Inrush Phenomena with switching with zero angle without remenece.

Inrush current is due to remanance, which again depends on the magnetic characteristics of material of the core. Peak value o residual flux is usually taken as about 85 to 90 percentage of its maximum i.e. the saturation value for different types of material respectively [1]. Table show the value of residual flux (in Wb) for different ratings of power transformer.

Table II. Transformer Residual flux for various ratings of Transformers.

Transformer (KVA)	300	80	50000
Residual Flux (Wb)	0.3	0.8	13.0

Value of residual flux in transformer can be obtained by de energization instant of transformer. Residual flux measurement is used for deciding the optimal instant of transformer energization for minimizing the inrush current in control switching techniques [4].

Series resistance: The resistance of line between transformer and sources is the prime parameter in case of inrush current. The damping effect offered by series resistance realized between the transformer and the source reduces initial inrush current maximally and also speed up its decay rate for inrush current. Transformer which is nearer to the source generally has higher inrush current than others because of the low resistance of line. [1].

Source impedance: The peak value of inrush current in the transformer can be determined by the source impedance in the power system. The maximum inrush can be transferred if when transformer primary winding impedance and source impedance is same or transformer impedance is lower than that of the source impedance. The transformer inrush current and impedance between the sources and the energized transformer creates temporary voltage sags for the little time duration.[5].

Inrush under load: The inrush current crest is affected little by power factor of load when the transformer is switched on load condition. When the transformer is switched on under heavy load

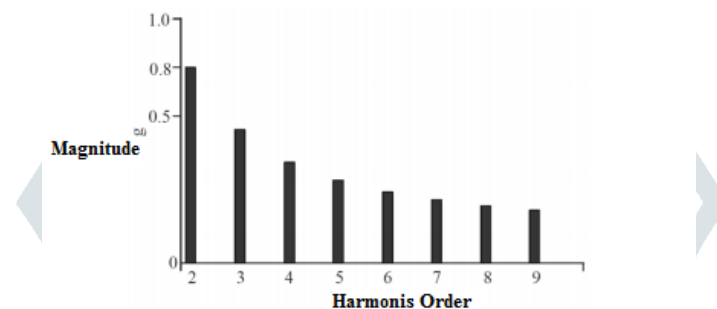
(while power factor close to unity), the peak value of inrush current is very less. As Power factor reduces, the inrush current peak is become higher [6].

Size of transformer: The value of inrush current is depends upon the size of Power transformer. The large Power transformer having high ratings more than 1000 KVA produces lower inrush current for longer time duration in terms of seconds while small rated power transformer of (less than1000 KVA) is generates higher inrush current for small time duration in terms of milliseconds [7].

III. Effects of inrush current

Voltage distortion: When transformer is energized, and if transformer impedance is smaller than the source impedance, voltage drop will occurs due to inrush current phenomena called voltage distortion. It may affect the industrial costumer using sensitive load and equipment used in medical field etc. [5].

Harmonics: In the transformer inrush current, second order harmonics are predominant due to its asymmetric properties of material. The key reason is that when inrush current start it pulsates in any of the positive or negative direction and instead of full wave that will become half wave where frequency is considered as 100 Hz.(i.e. for supply of 50Hz frequency)[6].



Harmonic Contents in INRUSH CURRENT : (Ashrami et al 2012, p.537)

Fig. 5 Harmonics contents in Inrush Current

Table III. Contents of Harmonics in transformer Inrush current.

Order of Harmonic	Amplitude (in%)
DC	50 to 70%
2 nd	63 to 80%
3 rd	30 to 50%
4 th	5 to 6%
5 th	4 to 5%
6 th	3 to 3.8%
7 th	2 to 2.5%

Stress on transformer winding: During inrush current phenomena in transformer, two types of main forces acting on the transformer winding as per the Flemings law.

1. Radial force: Radial force occurs during inrush current tries to increase the diameter of winding
2. Axial force: Axial force occurs during inrush current produces thrusts on the winding towards ground which changes the sizes and able to damage the transformer winding [9] [10].

Malfunction of protective relay: At the time of transformer energization, its draw inrush current at the amount of 10 to 15 times higher current than that of the rated current, so it makes the malfunctioning of relays, circuit breakers and send the signal to operates for tripping which is undesirable as this is temporary phenomena pertains not more than 2 to 3 cycles [11].

IV. Methods to mitigate the inrush current

Asymmetrical winding design: Such type of method used in designing transformer to minimize the inrush current by the use of asymmetrical winding. This method is totally different from old methods where equal stress occurred. The inrush current is reduced by increasing the inrush equivalent inductance by varying the proportion of internal coat to external coat in coil winding in transformer design. In transformer, the inrush equivalent inductance and leakage inductance were treated and analyzed as the essential parameters. [12].

By using series compensator: In this method we can use of an inverter-based series compensator which comprised of series transformer and single-phase inverter. Such strategy is easier to practice because in this no information of the transformer parameters, power-on angle of circuit breaker and measurement of residual flux are needed. In this method, the compensating current injection on the secondary winding of the transformer is done by the series compensator. The polarity of the compensating current applied by the series compensator is opposite than that of the inrush current generated by the power transformer [13]. Value of residual flux is shown below.

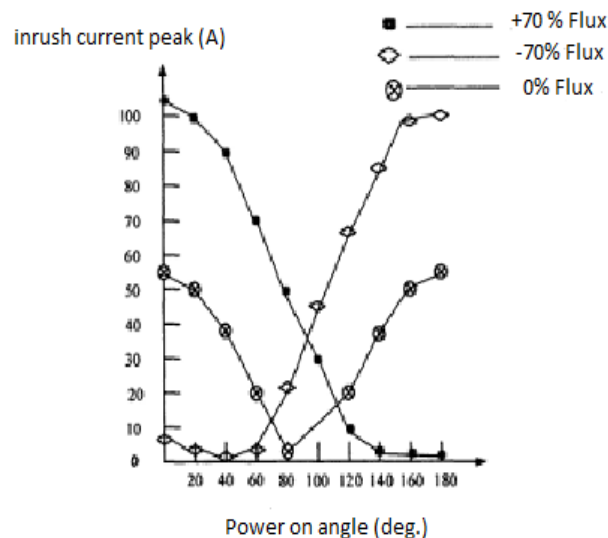


Fig. 6 Inrush current peak for various residual flux without series compensator [13]

Fig.5 and 6 show the residual flux in transformer primary winding without compensator and with compensator respectively.

Sequential phase energization method: In this type of method the energization of all three phases of transformer are done at proper instant by the use of suitable means. In this case energization of each phase of transformer is done in sequential way (at calculated desired) so as to reduce the inrush current. If say for 50 Hz frequency, the suitable instant of energization in the transformer can be calculated as mentioned. For 50 Hz power supply voltage we can say that there are 50 cycles in one second. so 20msec is the time lapsed for one cycle.

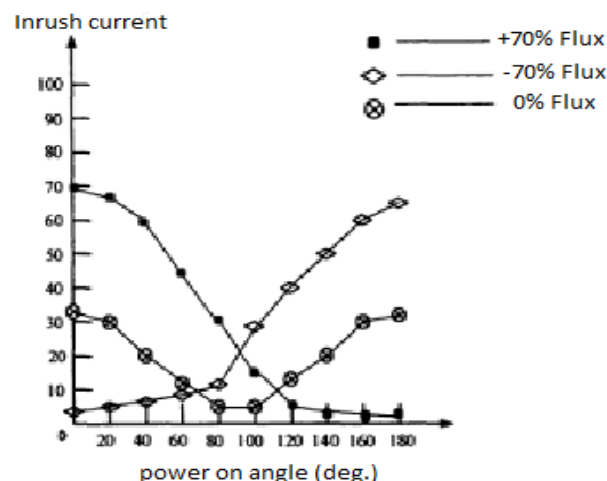


Fig. 7 Inrush current peak for various residual fluxes with series compensator [12]

By that, 10 msec. is needed to complete the half cycle (180° degree), 5 msec. is for quarter cycle (90° degree). In given transformer say the closing sequence of circuit breakers (of all 3 phases) is RYB, then the closing instant for the phase R voltage for the 90° is after 5 msec. assuming that we supply breaker of phase R will operated first as per the given sequence, Now the Next one breaker of phase Y is connected at 120° apart from phase R that means to have realization of $90^\circ + 120^\circ = 210^\circ$, equivalent time needed for lapse of an angle 0° to 210° is 11.666666 msec. similarly after energization of phase Y, phase B is energized at 120° from phase Y as equal to $210^\circ + 120^\circ = 330^\circ$ which in turn need the time delay duration for 0° to 330° as 18.333333 msec. [14] [15].

Controlled switching method: For the reducing the inrush current in Power transformers, Controlled switching method is used by suitable instant switching on techniques.

Basically the Inrush current will be minimal when the switching will be done for the applied voltage to the power transformer while the value of residual flux and the prospective /virtual flux of the core are being same.

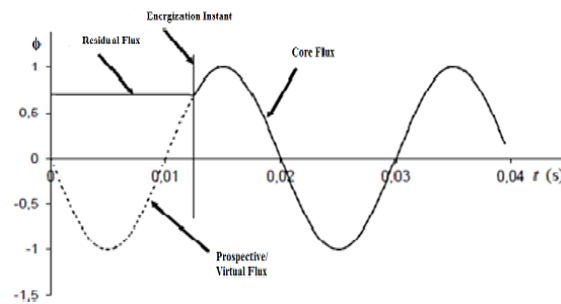


Fig. 8 Optimal controlled switching instant of transformer energization.

For controlled energization of multi-phase transformers usually three methods are proposed. In all these three methods, closing of each phase winding is done without core saturation or inrush transients.

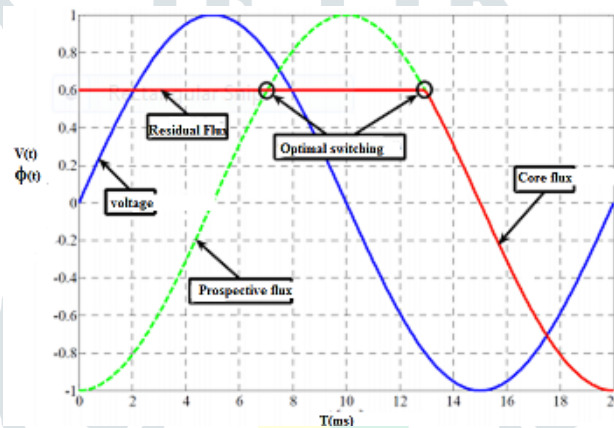


Fig. 9 Different possible Controlled Switching Instants

(1) Rapid Closing Strategy: In this method, first there will be closing of one phase and then the remaining both the phases are closed within quarter cycle. This needs the Information regarding following three:

- The residual flux for entire three phases.
- Breaker control of Independent pole.
- Model of transformer transient performance.

(2) Delayed Closing Strategy: In this method first closing of one phase and after the delay of more 2-3 cycles, the remaining two phases were being closed. This needs the Information regarding following things:

- The residual flux of any one phase.
- Independent pole breaker control

This method does not require any transformer parametric data or model of it for the transient phenomena.

(3) Simultaneous Closing Strategy: Such methods requires the closing of all three phases simultaneously at an optimal instant for the given residual flux pattern. The independent pole breaker control is not needed here but the residual flux information in all three phases is needed. The residual flux values in two phases are seems high and follow the most conventional residual flux pattern.

Every method has its own advantages and disadvantages. In actual scenario many factors can obstruct the goal achieving of total inrush current elimination. These factors include:

1. Irregularity in circuit breaker.
2. Time for mechanical closing.
3. Circuit breaker prestrike Effect.
4. Erroneous residual flux measurement.
5. Winding configuration or Transformer core which stop a best possible solution.
6. Irregularity in mechanical closing times: All circuit breakers have some statistical abnormality in their time of mechanical closing varying from operation to operation. For a breaker designed for controlled closing, approximate closing time deviations are less than ± 1 ms [16] [17].

Virtual air gap: This strategy depends upon the applications of virtual air gap which equivalent thickness differs in function of controllable constraints changed to the configuration of magnetic circuit and the related control system. The AGW (air gap width) current is either set to a specific value using an external source, or a current sensor, in the main magnetization winding of the magnetic circuit [18]. Physically, the effects are observed on the experimental system are very similar to those of devices with a real built-in-air-gap. The originality of the method is in the control of the air gap thickness by the AGW current. Using an AGW always requires a magnetic circuit which is magnetized through a main winding.

Pre fluxing method: In this method, the residual flux will be set to its maximum value and after that use of pre-fluxing device to remove the residual flux in the transformer. Pre-fluxing method is performed into two parts:

Step-1) when transformer is totally de-energized, residual flux is set to possible of its optimum value.

Step-2) In second phase controlling of the circuit breaker for the energization of the single phase transformer at any of one angle of 210° or positive residual flux, or 330° for negative residual flux. Use three pole circuit breaker is there for the three phase circuit breaker

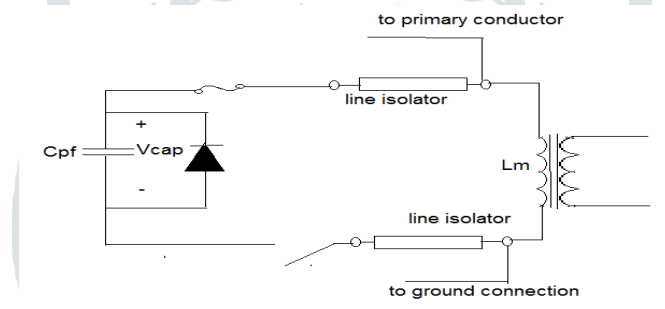


Fig. 10 Pre-fluxing device

The pre-fluxing device is shown in above figure. That is made of a diode, capacitor, a fuse, and a switch. Pre fluxing device is employed only when the transformer is isolated from power system and connected across one of the winding of transformer. Charging of the pre-fluxing device will be done before transformer energization. Charging circuit disconnected from the device when the charging is finished, and transformer is connected to pre fluxing device through isolator [19] [20] [21].

By using ultra low frequency power source: In this strategy, reduction of the flux in core by supplying voltage to the tertiary winding before the actual energization of transformer primary winding. Low voltages of power frequency and high frequency are applied to tertiary winding of transformer to minimize the inrush current of transformer. It is equivalent of injecting a very low voltage (power frequency signal) into the tertiary winding so as prevent the flux of core entering in the region of deep saturation [22]. The minimization of residual flux of transformer is done by the help of a low power ultra-low frequency voltage source. Here the source is connected between any two out of three terminals points of the head of the feeder line. De magnetizing device is contains of power electronic switch, low voltage constant DC source and simple controller [23].

Bidirectional impedance type transformer inrush current limiter: When a transformer is energized, the BITICL instantaneously and automatically connects into the circuit to prevent the inrush current without using any control circuit. After reducing the transformer inrush current, the BITICL is bypassed automatically and the transformer seems to connect directly to the source voltage. Thus, when the transformer is loaded, almost no deformation in the steady-state load voltage and current waveforms due to the voltage-compensation effect in the limiter [24].

V. Conclusion: Different method for reduce the inrush current in transformer; a most suitable method is pre- fluxing method. In pre fluxing method calculation of residual flux is not necessary. But in

controlled switching method it required the calculation of residual flux. Asymmetrical winding design is considered at designing of transformer. It's not useful for that transformer which already active in power system network. Pre fluxing device is used for those transformer which are executed in system.

REFERENCES

- [1] S.V.kulkarni, S.A.kharpade. *Transformer engineering:design and practice*, MARCEL DEKKER INC;2004.
- [2] Vaddeboina, V, Taylor, G & Proudfoot C:Switching large transformers on weak transmission networks – *A real time case study*, *Universities power engineering conference,47th international conference,IEEE, London*. September 2012; 4-7:1-6.
- [3] Y.G. paithankar and S.R. bhide. *fundamental of power system protection* PHI Pvt. Ltd.2011.
- [4] Blume, LF, Camilli, G, Farnham, SB & Peterson, HA: 'Transformer Magnetizing Inrush Currents and In-fluence on System Operation,' *AIEE Transactions*. 1994;Vol. 63, No. 6: pp. 366-375.
- [5] Goran Petrović, Tomislav Kilić, Stanko Milun :Remanent flux measurement and optimal energization instant determination of power transformer..*XVII IMEKO World Congress Metrology in the 3rd Millennium, Dubrovnik, Croatia*,June 22 –27, 2003.
- [6] Seo, HC & Kim, CH :The analysis of power quality effects from the transformer inrush current. *A case study of the Jeju power station, Korja*”, *Power and energy society general meeting-conversion and delivery of electrical energy in the 21st century 2008,IEEE, PA Pittsburgh*. , 2008: 20-24 July:pp. 1-6.
- [7] Lin, C.E., Cheng, C.L., Huang, C.L., and Yeh, J.C.: Investigation of magnetizing inrush current in transformers- Part I: *Numerical simulation.IEEE Transactions on Power Delivery*. January 1993;Vol. 8, No. 1:pp. 246–254.
- [8] Al-Khalifah A. K. and Al-Saadany E. F. :Investigation of magnetizing inrush current in a single-phase transformer. *IEEE Conference on Power Engineering*, July 26-28, 2006;pp. 165-171.
- [9] Neves, W, Fernandes, D, Baltar, F, Rosentino, A, Saraiva, E, Delaiba, A, Guimaraes, R, Lynce, M & de Oliveira, J 2011:A comparative investigation of electromechanical stress on transformers caused by inrush and short-circuited currents. *International conference on electrical power quality and utilisation EPQU, Libson*,October 2011;17-19.
- [10] Faiz, J., Ebrahimi, B.M., Abu-Elhaija, W.Computation of static and dynamic axial and radial forces on power transformer windings due to inrush and short circuit currents. *Applied Electrical Engineering and Computing Technologies (AEECT)Jordan*.2011.
- [11] Fahrudin Mekic, Ramsis Girgis, Zoran Gajic, Ed teNyenhuis.Power Transformer Characteristics and Their Effect on Protective Relays.*33rd Western Protective Relay Conference*. October 17-19, 2006.
- [12] J. Chhen, T. Liang, C. Cheng, S. Chen, R. Lin and W. Yang.Asymmetrical winding configuration to reduce inrush current with appropriate short-circuit current in transformer.*IEEE Proc.-Electr. Power Appl*. May 2005;Vol.152, No.3.
- [13] Juei - Lung Shyu," A Novel Control Strategy to Reduce Transformer Inrush Currents by Series Compensator ", *IEEE PEDS 2005*.
- [14] F. Ali Asghar and K. P. Basu.Reduction of three phase transformer magnetizing inrush current by use of point on wave switching .*IEEE Student Conference on Research and Development, Malaysia*. Nov. 16-18 2009;pp-368-370.
- [15] Hany A. Abdelsalam , Almoataz Y. Abdelaziz. A New Strategy for Selection of Switching Instant to Reduce Transformer Inrush Current in a Single-phase Grid-connected Photovoltaic System. *Electric Power Components and Systems Taylor & francis*, , 13 jun. 2015; vol.43:page 1297-1306.
- [16] J. Brunke, K. Frohlich. Elimination of Transformer Inrush Currents by Controlled Switching- Part I: Theoretical considerations. *IEEE Transactions on Power Delivery*. April 2001; vol 16 no.2.

- [17] J. Brunke, and K. Frohlich. Elimination of Transformer Inrush Currents by Controlled Switching Part II: Application and performance considerations. *IEEE Transactions on Power Delivery*. April 2001; vol 16 no.2.
- [18] V. Molcrette , J. L. Kotony, J. P. Swan and J. F. Brudny.Reduction of inrush current insingle-phase transformer using virtual air gap technique. *IEEE Trans.Magn.*. 1998. vol. 34:pp.1192 - 1194,.
- [19] D.I.Taylor, N.Fischer, J. D. Law, and B. K. Johnson.Using Lab-VIEW to measure transformer residual flux for inrush current reduction.*The North Amer. Power Symp., Starkville, MS.* Oct. 4–6, 2009.
- [20] Douglas I. Taylor, Joseph D. Law, Brian K. Johnson, and Normann Fischer. Single phase transformer inrush current reduction using prefluxing. *IEEE Transactions On Power Delivery*. January 2012;Vol. 27, No. 1.
- [21] Douglas I. Taylor.System apparatus, and method for reducing inrush current in a three phase transformer.*United states patent, patent no. US 8,878,391 B2.*date: Nov, 4, 2014.
- [22] V. Oiring de Castro Cesar, L-L. Rouve, J-L. Coulomb, F-X. Zgainski, O. Chadebec, and B. Caillault.Elimination of inrush current using a new prefluxing method. Application to a single-phase transformer.*IEEE*. 2014.
- [23] B. Kovan, F. de Leon, D. Czarkowski, Z. Zabar, and L. Birenbaum. Mitigation of inrush currents in network transformers by reducing the residual flux with an ultra-low-frequency power source. *IEEE Trans. Power Del.* , Jul. 2011; vol. 26, no. 3: pp. 1563–1570.
- [24] D. P. Balachandran, K. R. Sreerama and V. P. Shimnamol. Transformer Inrush Current Redution by Power Frequency Low Voltage Signal Injection to the Tertiary Winding. *IEEE conf Powertech ‘07*. 2007; pp.1953 -1958.
- [25] Hsu-Ting Tsenga, Jiann-Fuh Chenb .Bidirectional impedance-type transformer inrush current limiter.*ELSEVIER*.November 2013;Volu me 104: pp. 193-206.

