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Review on Reduction of Magnetizing Inrush Current in Transformer

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Abstract: ***Transformer is considered as the most important apparatus as heart in electrical transmission and distribution system. When a transformer is first energized, a transient current many times larger than the rated transformer current can flow for a number of cycles. Inrush currents are of very high magnitude generated when transformer cores are driven into saturation during energisation. The worst inrush current happens to flow when the primary winding is supplied at an instant of voltage zero crossing. These currents have undesirable effects such as reduced power quality on the system, loss of life to the transformer itself. To mitigate this magnetizing inrush current, few of the methods are discussed as Controlled switching, sequential phase energization, Asymmetrical winding configuration.***

Keywords: Controlled switching, residual flux, transformer switching, sequential phase energization, Asymmetrical winding configuration, Inrush current, power quality.

1. Introduction

The essential components of power system are the Power transformer and knowledge of their performance is fundamental in determining system reliability. Though attention usually concentrates on overload and short circuit calculations, a potentially disruptive transient condition may occur when an unloaded transformer is connected to the power system. Under certain conditions, a transient in-rush current several times the rated value [1] may result in the mal-operation of overload/ fault relays with the consequent disconnection of the transformer from the power system. The phenomenon is usually observed when a lightly loaded transformer is connected to the supply. When transformer is first energized, a transient current up to 5 to 6 times the rated current flows for several cycles. The inrush current has various effects on the protective devices of the transformer, generally reducing the quality of the power system. The mechanical structures of the transformer may be destroyed due to increased magnetic forces caused by the inrush current. Worst case inrush happens when primary winding is connected at an instant around zero crossing of primary voltage. During such start, the core will be saturated. When a power transformer is switched on from primary side, keeping its secondary circuit open, it acts as a simple inductance. If the transformer is switched on at the instant of voltage zero, the flux wave is initiated from the same origin as voltage waveform, the value of flux at the end of first half cycle of the voltage waveform will be twice the maximum flux. The transformer core are generally saturated just above the maximum steady state value of flux. During switching on the transformer, the maximum value of flux will jump to double of its steady state maximum value. As, after steady state maximum value of flux, the core becomes saturated, the current required to produce rest of flux will be very high. So transformer primary will draw a very high peaky current from the source which is called magnetizing inrush current in transformer or simply inrush current in transformer. Although the magnitude of inrush current is so high but it generally does not create any permanent fault in transformer as it exists for very small time. But still inrush current in power transformer is a problem, because it interferes with the operation of circuits as they have been designed to function. Some effects of high inrush include nuisance fuse or breaker interruptions, as well as arcing and failure of primary circuit components, such as switches. High magnetizing inrush current in transformer also necessitate over-sizing of fuses or breakers. Another side effect of high inrush is the injection of noise and distortion back into the mains. The inrush current can be limited by additional control circuitry [2] and the interior improvement method. Controlled switching requires additional control circuitry. The method of controlling the switching-on angle never works in practice because of uncertainties such as parameters of the spring and the remnant flux in the circuit breaker, and the phase of the source that provides power to the circuit breaker coil, among others. The interior improvement method of air gap windings (AGW) is based on the use of a core with a DC source to introduce an air gap into the magnetic circuit during the switching-on period. The method worsens some of the characteristics in the magnetic circuit and its reduction of the inrush current is finite. To decrease the inrush current by asymmetrical winding configuration which differs from the traditional symmetrical winding structure in transformer design, the objective is procured by appropriate asymmetric winding configurations i.e. by changing the secondary winding coil distribution. This method can provide high inrush equivalent inductance and suitable leakage inductance for a transformer with changing the cross-sectional area of the primary winding. The inrush equivalent inductance can be increased by changing the distribution of the coil windings for reducing inrush current. But, the high inrush equivalent inductance must be appropriately designed according to the considerations of voltage regulation and the rating interrupting capacity of the circuit breaker. Several factors are considered in designing transformers, such as weight, output power, efficiency of power conversion, cost etc. [3-5]. Low voltage regulation, the match rating interrupting

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capacity of the and the restraint on the inrush current equally emphasized. The inrush current can be reduced by the larger inrush equivalent inductance.. So, if the cross sectional area of the primary winding is increased, then the inrush equivalent inductance gets increased. The asymmetric winding configuration can obtain this effect.

2. Transformer Magnetizing Inrush Current Reduction Problem

Transformer inrush currents are high-magnitude, harmonic-rich currents generated when transformer cores are driven into saturation during energization. These currents have undesirable effects including potential damage or loss of life to the transformer, protective relay disoperation, and reduced power quality on the system. So, the random power transformer energization can create large flux asymmetries and saturation of one or more winding cores of the transformer. This saturation results in high magnitude currents that are rich in harmonic content and have high direct current component. 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. The effects of these transients are normally mitigated by desensitizing protective relays or over sizing fuses [1]. Closing resistors have been used to reduce the magnitude of 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. Controlled transformer switching can potentially eliminate these transients if residual core and core flux transients are taken into account in the closing algorithm[2]. A number of factors can prevent achieving the goal of complete elimination of transformer inrush transients. These factors include: Deviation in circuit breaker mechanical closing time, effect of circuit breaker prestrike, errors in the measurement of residual flux, transformer core or winding configuration that prevent an optimal solution. The simultaneous closing strategy allows the use of a non-independent pole controllable breaker, but requires the residual flux pattern and residual flux magnitudes to be within certain limits. Further investigation is necessary to determine how to achieve this is a practical and economical manner. Representative examples to limit the inrush currents are the synchronous closing of circuit breakers and pre-insertion of series resistors [3].There are many references in the literature to this phenomenon, but few of them estimate the magnitude of inrush current. Although present regulations do not require the calculation of inrush current, its accurate determination is desirable to predict potential problems when switching on an unloaded transformer. The transient electromagnetic state of a transformer connected to the power supply depends on factors such as the instant of switching-on the supply voltage, the residual core flux and the ratio between the core magnetizing inductance L_o and the core loss resistance R_o [12]. Normally, a transformer is energized by connecting it directly to the network voltage. This direct switching-in may occasionally give rise to an annoying transient phenomenon associated with a current surge, similar to or above the rated current of the transformer that may cause the automatic protection to operate. Let R is the resistance of the winding. The absolute value of the voltage appearing across the resistance of the winding is low, yet it is important from the point of view of the phenomenon, for the attenuation of the inrush current is determined by this resistance, together with the core loss of the transformer and with the self-inductance of the winding. It is to be noted that the inrush current drops to a fraction of its initial value after a few tenths of a second, and its full decay occurs only after several seconds. The expected maximum inrush current, occurring when the transformer is switched-in at the most unfavorable instant, is an important characteristics of the no load performance of a transformer. In large transformers, where the attenuation effect of the winding and core is small, the maximum peak flux $Ø_m$ occurs at zero transition of voltage. From the point of view of inrush current, the most unfavorable conditions arise when switching-in takes place at zero voltage transition and at this instant the value of remnant flux is maximum and has the same sign as the tangent of the voltage curve at zero transition. Generally, the sign and the magnitude of the remnant flux cannot be influenced, since they are determined by the conditions prevailing at the instant of previous disconnection of the transformer. The most unfavorable conditions are: the flux starting from the remnant flux, has to change so as to make its derivative vary as the imposed network voltage variation as a function of time. This is only possible if the flux, and with it the exciting current, increases during the period of the first half cycle following the instant of switching-in. The maximum possible value $Ø_e$ of the flux is the sum of the change of flux $2Ø_m$ developing in steady state condition and of the remnant flux $Ø_r$:

$$Ø_e = 2Ø_m + Ø_r = A_i (B_r + 2B_m)$$

Where A_i is the cross sectional area of the core, B_r is the remnant induction pertaining to flux density B, and B is the peak value of flux density in the core in the steady-state condition. Transformer designers usually work with values of 1.5 T to 1.75 T selected for B, and the remnant flux density pertaining to this induction may reach values as high as 1.3 to 1.7 T. A switching-in operation occurring at an unfavorable instant, if coinciding with a remnant flux of similarly unfavorable magnitude and polarity, will cause magnetization of the core beyond the saturation limit, and will make a considerable proportion of the flux $Ø_e$ required for inducing a voltage maintaining equilibrium with the supply voltage appear in the air gap(of the cross sectional area A) between winding and core.

The maximum magnetizing inrush current is influenced by the cross sectional area between core and winding. Therefore, it is expedient, where and when possible, to switch in first the terminals belonging to the winding of larger diameter. Another way of reducing the magnetizing inrush current is to increase the resistance of switched-in circuit. For this purpose, special switchgear is required to bypass the inserted resistor after decay of the inrush phenomenon. The peak value of the magnetizing inrush current may exceed the rated current of the winding and may impose considerable electrodynamics stresses on the transformer, and cause the transformer protection to trip. This latter may jeopardize the transformation insulation,

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because the interruption of magnetizing current of such magnitudes may give rise to over voltages exceeding the switching surges normally occurring in network.

3. Techniques for Reduction of Transformer Magnetizing Inrush Current

3.1 By Controlled Switching

Random power transformer energisation can create large flux asymmetries and saturation of one or more winding cores of the transformer. This saturation results in high magnitude currents which have high harmonic content and also have high direct current component. With the result, protective relays and fuses may maloperate, there occurs mechanical damage to transformer windings from magnetic forces and generally this reduces power quality on the system. The closing resistors have been used to reduce the magnitude of inrush currents. Controlled closing or controlling the point on power frequency voltage wave where energisation occurs, has also been employed to reduce these inrush currents [1]. The power transformers are operated with peak core flux at the knee of transformer core's saturation characteristics. The sinusoidal core flux is the integral of applied voltage. When the transformer is de-energised, a permanent magnetization of the core remains due to hysteresis of magnetic material. This residual flux is influenced by the transformer core material characteristics, core gap factor, winding capacitance and other capacitances connected to the transformer. The core flux and therefore residual flux can be measured by integration of winding voltage. When the transformer is energised, the instantaneous magnitude of core flux at the instant of energisation is the residual flux. The amount of offset of the sinusoidal flux generated by the applied voltage is dependent upon the point of voltage wave where transformer is energised. The peak core flux Φ can therefore reach a value of $2\Phi_{normal} + \Phi_{residual.}$ For the most severe case, where energisation was at a voltage zero, the peak transient core flux is more than two times higher than peak normal core flux[2] . The core has been driven into saturation. This asymmetrical saturation results in the typical inrush current transient characterised by a high harmonic content and a direct current component. Although the closing resistors have been employed to reduce these transients, the only way these transients can be eliminated is to prevent the core saturation. This can be accomplished by controlling the instant of energisation.

Controlled switching of single phase transformers: In case of Controlled closing of capacitors, optimal energization point is at the instant when the source voltage is equal to the trapped charge voltage on the capacitor. For the case of controlled closing of transformers, the "trapped charge" has a parallel in the residual flux. So the basic principle to eliminate the core flux asymmetry, the "induced" flux (integral of applied voltage) at the instant of energization must equal the residual flux. There is of course no induced flux before energization, but the source voltage has the prospect to create an induced flux. If the source voltage is considered as a virtual flux source, then an optimal instant to energize transformer is when the prospective flux is equal to the residual flux. It provides the basic strategy for controlled closing on single phase transformers. In case of controlled switching in multiphase transformer with no residual flux, only transformers with single-phase cores and only grounded windings may be considered as three single phase transformers, but most transformers on power systems have interaction between the phases. In these other transformers, after one phase has been energised, the flux in the other cores or core legs is not a static residual flux, but a transient flux, in the following called "dynamic" core flux. Residual Flux: The residual core flux can assume values up to 85% of peak normal flux, although more typical magnitudes are in the range of 20 to 70%. In most three phase transformers, it is possible to use residual flux measurements and controlled closing to eliminate transformer inrush transients.

The residual flux can assume values up to 85% of peak normal flux, although more typical magnitudes are in the range of 20 to 70%. The residual flux in the cores of three phase transformers must inherently sum to zero, and typically forms a pattern with near zero residual flux in one phase and plus & minus some finite values in the other two phases [1]. To mitigate inrush current in transformers, three strategies are proposed for controlled energisation of multi-phase transformers. For all three strategies, closing each winding without core saturation or inrush transients. (a) Rapid Closing Strategy: This strategy closes one phase first and the remaining two phases within a quarter cycle. It requires the knowledge of the residual flux in all three phases, independent pole breaker control and a model of transformer transient performance. (b) Delayed Closing Strategy: This strategy closes one phase first and the remaining two phases after 2-3 cycles. It requires the knowledge of the residual flux in one phase only, independent pole breaker control but does not require any transformer parametric data. (c) Simultaneous Closing Strategy: This strategy closes all three phases together at an optimum point for the residual flux pattern. It does not require independent pole breaker control, but requires the knowledge of the residual flux in all three phases and that residual flux magnitudes in two phases are high and follow the most traditional residual flux pattern[1]. Each of these has advantages and disadvantages. Here is addressed the practical issues of application and expected performance in service. In practice, however, a number of factors can prevent achieving the goal of complete elimination. These factors include: Deviation in circuit breaker mechanical closing time, effect of circuit breaker prestrike, errors in measurement of residual flux, transformer core or winding configuration that prevent an optimal solution.

Deviation in mechanical closing times: All circuit breakers have some statistical deviation in their mechanical closing time from operation to operation. For a breaker designed for controlled closing, typical closing time deviations are less than ± 1 ms [2]. In selection of closing instant, it is important to consider these timing deviations and to understand the influence they have when considered together with flux transients and prestrike. Timing deviations caused by very long periods between operations (idle time) can be a potential difficulty in some circuit breaker design. Reduction of over 90% from the worst case inrush currents can be achieved with a circuit breaker of normal closing time

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performance. This can be accomplished by measuring the residual flux in transformer core, and using that information with the appropriate breaker closing control strategy. The phenomenon of core flux reduction can greatly simplify closing strategies, allowing the delayed strategy to be very effective. The delayed strategy can also provide a reduction of inrush transients when switching transformers with more than three core legs and no delta connected winding. However, complete elimination of inrush currents is not possible with these configuration.

3.2 Sequential Phase Energisation Technique

This is a simple and low cost method to reduce inrush currents caused by transformer energisation. The method uses a grounding resistor connected at a transformer neutral point. By energizing each phase of the transformer in sequence, the neutral resistor behaves as a series inserted resistor and thereby significantly reduces the energisation inrush current. This method is much less expensive, however, since there is only one resistor involved and the resistor carries only a small neutral current in steady-state.

Inrush currents from transformer and reactor energisation have always been a concern in power industry. Over the past several decades, a few methods have been proposed to limit the inrush current. Representative examples are the synchronous closing of circuit breakers and pre-insertion of series resistors.

In view of the fact that the inrush currents are always unbalanced among three phases, a neutral resistor could provide some damping to the currents. This is the basis of the proposed idea. The ideas is further improved by introducing delayed energisation of each phase of the transformer. This improvement has made the proposed scheme almost as effective as the pre-insertion resistor scheme.

It is well known that inrush currents are highly unbalanced among three phases. If a transformer is Y grounded at the energisation side, its neutral current will also contain the inrush current. One may therefore speculate that if a resistor is inserted into transformer neutral, it may reduce the magnitude of the inrush current in a way similar to that of the series-inserted resistor. This consideration formed the basic idea of the proposed scheme.

Simultaneous closing of all three-phase breakers did not produce sufficient reduction on the inrush currents. However, if one closes each phase of the breaker in sequence with some delays between them, the neutral resistance could behave as a series resistor and improve the results. This simple improvement has proven to be very effective. In fact, the idea of sequential energisation of three-phase equipment can lead to a new class of techniques to reduce switching transients.

3.3. Using Superconductor

An inrush current limiting element as a new application of high-temperature superconductor (HTS) IS proposed. : An inrush current limiting element is required to recover automatically to superconducting state without any current interruption after the current limiting operation. The limiting element proposed suppresses the inrush current using the flux flow resistance generated in HTS[3]. Since the flux-flow resistor is small as to be neglected when the instantaneous value of the current in HTS is below its critical current, the limiting element may satisfy the above requirement for inrush current limitation. It has been observed that the limiting element suppresses the magnetizing inrush current of a transformer and self-recovers to the superconducting state. The magnitude of the inrush current is several times as high as the normal load current in some cases. Since the inrush current is temporary, it is distinguished from a short circuit fault current flowing continuously and is not interrupted by circuit breaker. Hence electric power equipment must be manufactured robustly so that they are not damaged by mechanical and/or thermal stress caused by inrush currents. This means that equipments are forced to be made big, heavy and expensive [4].

3.4 Virtual Air Gap Technique

This technique is based on the use of virtual air gap which equivalent thickness varies in function of controllable parameters adapted to the configuration of magnetic circuit and the associated control system. This study aims to modify the reluctance of a magnetic circuit using auxiliary windings called AGW (Air Gap Windings). The AGW 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 [31]. Physically, the effects 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 (primary of a transformer..).

4. Modern Transformer Design by Using Asymmetrical Winding

The magnetizing transient inrush current occurs in an electric circuit when a transformer is switched on. The transient current often causes the inadvertent operation of circuit over-current protection systems. Moreover, the mechanical structures of the transformer may be destroyed due to the magnetic forces caused by the inrush current. During the period of transient inrush current, the transformer's core normally enters a state of saturation[6]. In this core-saturated state, the magnitude of permeability would be regarded as the absolute permeability, and then the magnitude of inductance is reduced. The current increases quickly due to the decrease in inductance. The steady state exciting current of a transformer is typically less than 1% of the rated current, but the inrush current may be as high as ten times the rated current or more. Many studies have discussed the phenomenon of inrush current in transformers. However, the problem of reducing inrush current is a top priority for the circuit's protection systems. The inrush current can be reduced by the method of controlled switching . This method requires additional control circuitry, and suffers from uncertainty factors in the switching-on angle, including the

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variables of spring and remnant flux in the circuit breaker, the phase of the source that provides power for the circuit breaker coil, and others. If semiconductor components are used as substitutes for circuit breakers, their on-state voltage or resistance result in very large power consumption. Therefore, this method is difficult for practical applications. During the switching-on period, a core with a DC source is used to introduce an air gap into the magnetic circuit. The method tends to worsen some of the characteristics in the magnetic circuit, and its reduction of the inrush current is finite. This study attempts to decrease the inrush current by asymmetrical winding. Differing from the traditional symmetric winding structure in transformer design, the objective is procured by changing the secondary winding coil distribution. This method can provide a high inrush equivalent inductance for reducing inrush current, and a suitable leakage inductance for voltage regulation and short-circuit current. In the modern Asymmetrical winding configuration technique, the same attention has been paid on the appropriate voltage regulation and short circuit current in the design of transformer. From the structural parameters of transformer, the leakage inductance and inrush equivalent inductance are to be analyzed which takes care of magnetizing inrush current in transformer before the transformer manufacturer under the corresponding leakage inductance value[6]. The magnetizing inrush is a transient and occurs primarily when a transformer is energized. The major source to reduce this inrush current is the inrush equivalent impedance during this period. If we are in a position to increase this inrush equivalent inductance, inrush current gets reduced to a considerable extent. So, the characteristics and the magnitude of inrush equivalent impedance must be understood. The impedance of the transformer is a combination of resistance and inductance. The magnitude of winding resistance is so small that it can be ignored in the discussion of restraining inrush current [6]. A larger value of impedance reduces the short circuit current, but increases the voltage regulation. Therefore, impedance of transformer ought to be controlled within an appropriate range. Different distribution transformers of the S-P-S and S-P-S-P structures can be used for demonstration purposes. Calculated values of leakage inductance will vary with the value of x in S-P-S structure and the values of x and y in the S-P-S-P structures. So, the asymmetric winding configuration affects the magnitude of leakage inductance A transformer requires an appropriate leakage inductance to match the rating interrupting capacity of the breaker and low voltage regulation. The per unit value of the equivalent impedance Z% and the voltage regulation e% are set in standards for impedance. Before performing the experimental switching-on, transformers should be demagnetized using a variable AC source to eliminate the residual flux in the core. The relationship between the maximum inrush current and inrush equivalent inductance, the increase in inrush equivalent inductance and the decrease in inrush current are all proportional to each other. Moreover, these relationships demonstrate that the main cause of the reduction in the inrush current is the increase in the inrush equivalent inductance, as implemented by the method of coil winding distribution. Using this method, restrained inrush current will be able to increase the rating of the capacity and voltage, because the size of the iron coil, size of the oil duct, thickness of the wire, thickness of paper insulation etc are all increased. So, this study presents a new viewpoint in the design for a transformer that involves a multilayer structure and an altered winding coil distribution to restrain the inrush current. The limited inrush current, satisfying the low voltage regulation and providing a suitable short-circuit impedance are equally emphasized. The inrush equivalent inductance and the leakage inductance are determined from the structural parameters of the transformer in asymmetrical winding configuration such that the various magnitudes of inrush currents can be estimated before the transformer manufacturing with the corresponding leakage inductance magnitude.

5. Conclusion

The phenomenon of core flux reduction can greatly simplify closing strategies, allowing the delayed strategy to be very effective. The delayed strategy can also provide a reduction of inrush transients when switching transformers with more than three core legs and no delta connected winding. However, complete elimination of inrush currents is not possible with theses configurations.

In Sequential phase energization technique, there is an optimal neutral resistor value for the proposed scheme. This value is a compromised value between the need to suppress the inrush currents when the first two phases are energized and need to suppress the current when the third phase is energized. It is not essential to use an exact optimal value. Resistances around the optimal value are almost equally effective. With the proposed resistance value(s), the neutral resistor based scheme can lead to 80% to 90% reduction on inrush current[3]. A small neutral resistor size of less than 10 times the transformer series saturation reactance can achieve 80 to 90% reduction in inrush current among three phases.

References

[1] J. Brunke, K. Frohlich, “Elimination of Transformer Inrush Currents by Controlled Switching-Part I: Theoretical considerations” IEEE Transactions on Power Delivery vol 16 no.2 April 2001.
[2] J. Brunke, and K. Frohlich, “Elimination of Transformer Inrush Currents by Controlled Switching-Part II: Application and performance considerations” IEEE Transactions on Power Delivery vol 16 no.2 April 2001.
[3] S. Abdulsalam, and W. Xu, “A Sequential phase Energisation technique for transformer inrush current reduction – Transient performance and Practical Considerations” IEEE Transactions on Power Delivery vol 22 no.1 January 2007.
[4] Y. Cui, G. Abdulsalam, S. Chen and W. Xu, “A Sequential phase Energisation technique for transformer inrush current reduction-Part I: Simulation and experimental results” IEEE Transactions on Power Delivery vol 20 no.2 April 2005.
[5] W. Xu, G. Abdulsalam, Y. Cui and X. Liu “A Sequential phase Energisation technique for transformer inrush current reduction-Part II:

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Theoretical analysis and design guide" IEEE Transactions on Power Delivery vol 20 no.2 April 2005.

[6] 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" IEE Proc.-Electr. Power Appl., Vol.152, No.3, May 2005.

[7] J. Faiz and S. Saffari, "Inrush Current Modeling in a Single-Phase Transformer", " IEEE Transactions on Magnetics , vol.46, No.2, February 2010.

[8] Y. Wang, S. Abdulsalam, and W. Xu, "Analytical Formula to Estimate the Maximum Inrush Current", IEEE Transactions on Power Delivery vol 23 no.2, April 2008.

[9] M. Vanti, S. Bertoli, S. Cabral, A. Gerent, "Semianalytic Solution for a simple Model of Inrush Currents in Transformers", IEEE Transactions on Magnetics , vol.44, No.6, June 2008.

[10] A. Rezaei-Zare, " An Accurate Current Transformer Model Based on Preisach Theory for the Analysis of Electromagnetic Transients", IEEE Transactions on Power Delivery vol 23 no.1, January 2008.

[11] J. Faiz and S. Saffari, "Inrush Current Modeling in a Single-Phase Transformer", IEEE Transactions on Magnetics , vol.46, No.2, February 2010.

[12] A. Abou-Safe, G. Kettleobrough, " Modelling and Calculating the In-Rush Currents in Power Transformers", Damascus Univ. Journal Vol. (21)-No. (1) 2005

[13] A. A. Adly, 2001, "Computation of Inrush Current Forces on Transformer Windings," IEEE Transactions on Magnetics, Vol. 37, No. 4, pp. 2855-2857.

[14] C. K., Llang, T. J., Chen, J. F., Chen, S. D. and Yang, W. H., 2004, "Novel Approach to Reducing the Inrush Current of a Power Transformer," IEE Proceedings on Electric Power Applications, Vol. 151, No. 3, pp. 289-295.

[15] Lin, C. E., Cheng, C. L., Huang, C. L. and Yeh, J. C., 1993a, "Investigation of Magnetizing Inrush Current in Transformers. I. Numerical Simulation," IEEE Transactions on Power Delivery, Vol. 8, No. 1, pp. 246-253.

[16] Lin, C. E., Cheng, C. L., Huang, C. L. and Yeh, J. C., 1993b, "Investigation of Magnetizing Inrush Current in Transformers. II. Harmonic Analysis," IEEE Transactions on Power Delivery, Vol. 8, No. 1, pp. 255-263.

[17] Mao, P. L. and Aggarwal, R. K., 2001, "A Novel Approach to the Classification of the Transient Phenomena in Power Transformers Using Combined Wavelet Transform and Neural Network," IEEE Transactions on Power Delivery, Vol. 16, No. 4, pp. 654-660.

[18] Molcrette, V., Kotny, J. L., Swan, J. P. and Brudny, J. F., 1998, "Reduction of Inrush Current in Single-Phase Transformer Using Virtual Air Gap Technique," IEEE Transactions on Magnetics, Vol. 34, No. 4, pp. 1192-1194.

[19] Rico, J. J., Acha, E. and Madrigal, M., 2001, "The Study of Inrush Current Phenomenon Using Delivery, Vol. 16, No. 2, pp. 231-237.

[20] Yabe, K., 1997, "Power Differential Method for Discrimination Between Fault and Magnetizing Inrush Current in Transformers," IEEE Transactions on Power Delivery, Vol. 12, No. 3, pp. 1109-1118.

[21] A. Abou-Safe, G. Kettleborough,"Modeling and Calculating the In-Rush Currents in Power Transformers" Damascus Univ. Journal Vol. (21)-No. (1)2005

[22] The J & P Transformer Book,Twelfth edition,"A PRACTICAL TECHNOLOGY OF THE POWER TRANSFORMER" Martin J. Heathcote, CEng, FIEE

[23] E. Cardelli, E. D. Torre, "Theoretical consideration of magnetic Hystersis and Transformer Inrush Current", IEEE Transactions on magnetics , vol.45, No.11, November 2009.

[24] Y. Wang, S. G. Abdulsalam, "Analytical formula to estimate maximum Inrush current", IEEE Transactions on Power Delivery, vol.23, No.2, April 2008.

[25] S. Chen, R. Lin, "Magnetizing Inrush Model of Transformers based on Structure Parameters", IEEE Transactions on Power Delivery, vol.20, No. 3, July 2005.

[26] N. Chiesa, H. Kristian, "Novel Approach for reducing transformer inrush current: Laboratory measurements, Analytical interpretation and simulation studies", IEEE Transactions on Power Delivery, vol.25, No. 4, October 2010.

[27] M. Nagpal, T. G. Martinich, "Assessing and limiting impact of transformer inrush current on power quality", IEEE Transactions on Power Delivery, vol.21, No. 2, April 2006.

[28] A. Gaudreau, P. Picher, "No-Load losses in transformer under over excitation/Inrush- Current conditions: Tests and a new model", IEEE Transactions on Power Delivery, vol.17, No. 4, October 2002.

[29] B. A. Mork, D. Ishchenko, F. Gonzalez and S. D. Cho, "Parameter estimation methods for five limb magnetic core model", IEEE Transactions on Power Delivery, vol.23, No. 4, October 2008.

[30] S. E. Zirka, Y. I. Moroz, A. J. Moses, "Static and Dynamic Hysteresis Models for studying Transformer Transients", IEEE Transactions on Power Delivery, vol.26, No. 4, October 2011.

[31] V. Molcrette, J. Kotny, j. Swan and J. Brudny, "Reduction of Inrush current in single phase transformer using virtual air gap technique", IEEE Transactions on Magnetics, vol.34, No. 4, July 1998.

[32] A. A. Adly, "Computation of Inrush Current Forces on transformer windings", IEEE Transactions on Magnetics, vol.37, No. 4, July 2001.

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