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Transformer inrush current mitigation using controlled switching and magnetic flux shunts

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Abstract: The inrush current is a transient current that results from a sudden change in the exciting voltage across a transformer's windings. It may cause inadvertent operation of the protective relay system and necessitate strengthening of the transformer's mechanical structure. Many methods were reported in the literatures for reduction and mitigation of transformer inrush currents. This paper represents a study of techniques that have been proposed for transformer inrush current mitigation. A new, simple and low cost technique to reduce inrush currents caused by transformer energization is presented here. In this method, a controlled switching approach with a grounding resistor connected to transformer neutral point and a magnetic flux shunt is used. By energizing each phase of the transformer in sequence, the neutral resistor behaves as a series-inserted resistor and thereby significantly reduces the inrush currents. The dimensions of the magnetic flux shunts are chosen such that the inrush current amplitude is further reduced. The proposed method has been tested by computer simulation using 2-D FEM (two-dimensional finite element method) by Maxwell software. The obtained results show that the proposed method is efficient in reduction of transformer inrush current and is much less expensive since there is only one resistor involved and the resistor carries only a small neutral current in steady-state.

Keywords: Transformer, Inrush Current Mitigation, FEM, Modeling, Magnetic Flux Shunts

1. Introduction

Transformers are one of the most important components in power systems. Security and stability of transformers are both important and necessary to system operation. The steady-state magnetizing currents of transformer may be one to five percent of the rated current, but anytime the excitation voltage applied to a transformer is changed, a magnetizing inrush current flows whose first peak may reach several times as large as the rated current. Although magnetizing inrush is typically considered to occur when a de-energized transformer is energized, magnetizing inrush can also flow after system voltage dips and during post fault voltage recovery. Such inrush currents may last from tens of milliseconds to tens of seconds before the steady-state condition is reached. The decay time of the inrush current is dependent on the time constant of the system.

The inrush current is asymmetric and unbalanced among the phases and may place a heavy stress on the network and the transformer itself. The mechanical forces within the transformer windings can have similar increases in amplitudes as those in short circuits but with longer duration time [1-3].

The inrush current of transformers often causes the inadvertent operation of the circuit's over-current and differential protection systems [4], [5].

The transformer inrush currents can have large magnitudes and rich harmonics, which can result in power system problems such as damage and decreased life expectancy of the transformer due to switching overvoltage [6]. The overvoltage resulting from the inrush current could happen and cause serious damage to power apparatus [7-8].

Considering these issues, it is important to suppress the inrush current in transformers. A method that uses a grounding resistor connected to a transformer neutral point to reduce inrush currents caused by transformer energization is proposed in [9]. By energizing each phase of the transformer in sequence, the neutral resistor behaves as a series-inserted resistor and thereby significantly reduces the energization inrush currents.

The inrush current is mitigated using appropriate asymmetric winding configurations in transformer design that differ from traditional symmetric winding structure, can provide the high inrush equivalent inductance and suitable leakage inductance for a transformer with changing the cross-sectional area of the primary winding [10].

In [11], the superconducting fault current limiter (SFCL) is applied to reduce the inrush current. The large current-limiting resistance (CLR) of the SFCL can help reduce the inrush current and the large CLR causes a significant voltage drop in the SFCL. The optimal insertion resistance of the SFCL to reduce the inrush current is decided and the effectiveness of the suggested scheme is demonstrated using the EMTP software.

In [12] a simplified approach to minimize the inrush current is achieved via a systematic switching study of the energization of a distribution transformer. A method for the visualization of the inrush current's first peak is also proposed and a mitigation scheme based on a consistent condition of minimum inrush current as a function of the switching in and out times as well as practical implementation issues and benefits of this method is investigated.

An approach for reducing the inrush current of a power transformer based on increasing the inrush equivalent inductance by changing the distribution of the winding coils with only a slight change in the design is presented in [13]. Moreover, the inrush equivalent inductance is analyzed with respect to the structural parameters of the transformer.

It was shown that a small neutral resistor size of less than ten times the transformer series saturation reactance can achieve 80–90% reduction in inrush currents among the three phases [14]. It was also found that the first phase energization leads to the highest inrush current among the three phases and, as a result, the resistor can be sized according to its effect on the first phase energization. The rise of neutral voltage is addressed as the main limitation of the proposed scheme and the use of surge arrester is proposed to overcome the limitation.

The optimum instant for unloaded transformer energizing with residual flux taken into account is when the prospective and residual flux is equal. Simulations and experimental results confirmed the capability of controlled switching to eliminate inrush transients on unloaded transformers without cores saturation [15].

Energization of the transformer from the delta side of a delta-star transformer does not allow the control of neutral resistor at the time of switching the supply for reducing the inrush current. The simulation studies on the inrush current produced by the delta side energization of delta-star transformer with additional resistors connected in series with the line are reported in [16]. Optimum resistance value is decided to get a quick decay of inrush current, low voltage drop and losses before it is shorted. Three resistors in series with 3 phases need a circuit breaker having 6 contacts. But controlled switching of one winding with resistor switching of only one line also reduces inrush current and needs a circuit breaker having 4 contacts.

When voltage sags happen, the transformers, which are often installed in front of critical loads for electrical isolation, are exposed to the disfigured voltages and a dc offset will occur in its flux linkage. When the compensator restores the load voltage, the flux linkage will be driven to the level of magnetic saturation and severe inrush current occurs. In [17] the inrush issue of loaded transformers under the operation of the sag compensator is presented and an inrush current mitigation technique based on the flux linkage close-loop control has been proposed for the sag compensator system.

The point on wave control is designed to energize the transformer at the optimal point on the voltage waveform, and its intention is to reduce transformer transient inrush at the time of energization. Closing at peak voltage by point on wave will minimize the transient flux generated by the transformer, and results in inrush current reduction to a lower value from its initial value. Ref [18] discusses the simulations and the experimental results on a three-phase transformer for reduction of inrush currents using the point on wave control.

A method that is independent of the winding connection and also usable in different magnetic core topologies is presented for inrush current elimination by forced magnetization [19]. Direct current magnetizing and simultaneous switching of all phases are used. The requirements of the synchronous switch closing time scatter were determined in dependence on the transformer working flux. The major advantage of this method is the fact that there are no problems with the first switch on after installation or service intervention.

From the sequential energizing scheme performance, the neutral resistor size plays the significant role in the scheme effectiveness. Through simulation, it was found that a few ohms neutral grounding resistor can effectively achieve inrush currents reduction. If the neutral resistor is directly selected to minimize the peak of the actual inrush current, a much lower resistor value could be found. Ref [20] presents an analytical method to select optimal neutral grounding resistor for mitigation of inrush current. In this method nonlinearity and core loss of the transformer is modeled and an analytical relationship between the peak of the inrush current and the size of the resistor is derived.

A methodology for the mitigation of large inrush currents taken by numerous transformers when a long feeder is energized is proposed in [21]. Time-domain simulations are used to prove that a small-power device can substantially reduce the residual flux of all transformers simultaneously. The device consists of a low-voltage dc source, a suitable power-electronic switching unit, and a simple controller.

The main objective of this paper is to propose a method for inrush current mitigation using combination of two methods. One of them is using a magnetic flux shunt in the design process that changes the inrush equivalent inductance via changing the flux distribution over the transformer windings. Another method is using an optimal neutral resistor with sequential switching [14, 20].

2. Transformer Inrush Phenomenon

The most severe case of magnetizing inrush current results from transformer energization. In this case there is a very large change in excitation voltage applied to the core. For three phase transformers, each phase will experience different peak values of inrush current due to the impact of the voltage angle at time of switching.

The value of the transformer inrush current is a function of various factors, such as the switching angle of the terminal voltage, the remanent flux of the core, the transformer design, the power system impedance, and others. Holcomb [28] proposes an improved analytical equation for the inrush current:

$$i(t) = \frac{\sqrt{2}U}{\sqrt{R_W^2 + \omega^2 . L_{\text{air-core}}^2}} . \left(\sin(\omega t - \phi) - e^{-\frac{R_W}{L_{\text{air-core}}}(t - t_s)} \sin(\omega t_s - \phi) \right) \quad (1)$$

$$\phi = \tan^{-1} \frac{\omega . L_{\text{air-core}}}{R_W} \quad (2)$$

Where U is the applied voltage; R_W is the winding resistance; $L_{\text{air-core}}$ is the air-core inductance of winding; and t_s is the time when the core begins to saturate $(B(t) > Bs)$. It is assumed that the inrush current is different from zero only between t_s and t_0, where t_0 is the time when the inrush current reaches zero at each cycle. The air-core inductance $L_{\text{air-core}}$ of a winding can be calculated as:

$$L_{\text{air-core}} = \mu_0 . N_{HW}^2 . \frac{A_{HW}}{h_{\text{eq-HV}}} \quad (3)$$

Where, $h_{\text{eq-HV}}$ being the equivalent height of the winding including fringing effects. The equivalent height is obtained by dividing the winding height by the Rogowski factor K_R (< 1.0) [22]. This factor is usually determined empirically and is a function of the height, mean diameter, and radial width of a winding.

3. Inrush Current Mitigation

The main factors affecting the inrush current are identified in [24] and are:

Point on wave voltage at the instant of energization,

Magnitude and polarity of remanent flux,

Total resistance of the primary winding,

Power source inductance,

Air-core inductance between the energizing winding and the core,

Geometry of the transformer core,

The maximum flux-carrying capability of the core material.

Heretofore, based on these affecting factors, many approaches have been proposed to lessen the phenomenon of the magnetizing inrush current; these are listed as follows:

DC reactor-type inrush current limiter [25],

Superconducting inrush current limiter [11],

Controlling the energizing angle or point-on-wave controlled closing [15,18, 26],

Sequential phase energization with or without neutral resistor [14,20],

Virtual air gap and increasing the inrush equivalent inductance [13],

Core forced magnetization and simultaneous closing [19],

Asymmetric winding configuration [10],

Reducing the Residual Flux With an Ultra - Low- Frequency Power Source [21],

Using voltage compensation-type inrush current limiter [17],

3.1. The Proposed Method for Inrush Mitigation

The proposed method for mitigation of inrush current is a combination of two approaches: One of them is using a magnetic flux shunt that changes the inrush equivalent inductance via changing the flux distribution over the transformer windings and the other approach is using an optimal neutral resistor with sequential switching.

The influence of arrangement, dimensions, and magnetic permeability of the magnetic flux shunts on the flux distribution and leakage reactance of the power transformers is studied in [27]. It can be deduced from the mentioned reference that the leakage reactance of transformer is directly proportional with the distance of shunt from yoke, length and the magnetic permeability of the shunt and is inversely proportional with the shunt thickness. Thus, it is possible to select the geometrical parameters and magnetic permeability of the magnetic shunt and its position in the transformer window in order to achieve highest leakage inductance for inrush current reduction.

3.1.1. Transformer Model

The transformer that was considered in this study is a 200MVA, (20/0.4) KV, primary winding star-connected and the secondary winding zigzag-connected with neutral grounded (Yzn5) three-phase core-type distribution transformer whose HV winding has 2166 turns with the nominal current of 5.77 A and its LV winding has 50 turns and the nominal current 289 A. In order to analyze the inrush current mitigation technique, this transformer is modeled in Maxwell software (see Fig.1).

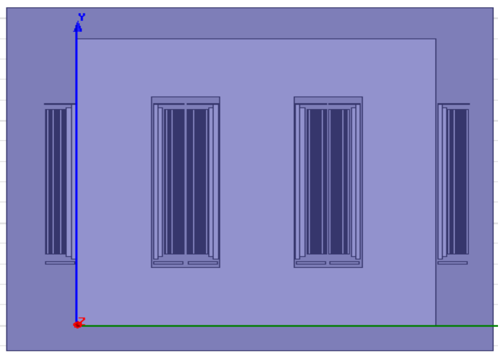

Figure 1. *The transformer model used in Maxwell software. The magnetic shunts can be seen in the top and bottom of windings.*

3.1.2. Transformer Inrush Current Analysis

After the transformer was modeled, the Dirichlet boundary conditions were applied to the boundary surrounding the transformer. Then, the material of the model components was assigned. The given model was discretized and then, the transient analysis was used for transformer inrush evaluation. Using the Ansoft Maxwell circuit editor, the relation between the finite element model and the circuit model of the transformer is established. The circuit model of the transformer is shown in Fig.2. In this model, by insertion of a neutral resistance in the transformer's primary winding, the effects of this resistance on the inrush current was investigated.

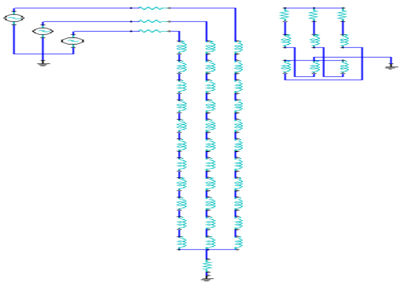

Figure 2. *The transformer circuit model in the Ansoft Maxwell circuit editor.*

3.1.2.1. Case A

In this condition, no magnetic flux shunt was used, and no controlled switching method was applied. The transformer was energized using voltage sources with phase angles of 0, 120 and 240 degrees for A, B and C phases, respectively. The value of neutral resistor was changed from zero to 300 ohms and the first peak of transformer inrush currents was determined, as shown in Table 1. As shown in this table, the use of neutral resistor has no significant positive effect in the inrush current reduction, since, by increasing the value of neutral resistor, the first peak amplitude of phase A and phase C was reduced a little, but the first peak amplitude of phase B was increased. The maximum value of first peak of inrush current happens in phase C and its value is about 150.88 A. The inrush current waveforms for case A.5 were shown in Fig.3.

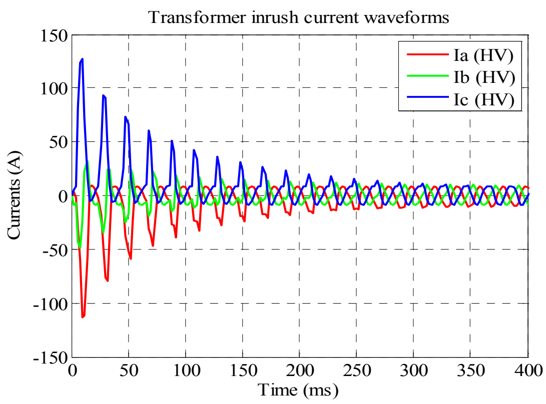

Figure 3. *The transformer inrush current waveforms for case A.5.*

Table 1. *Variation of first peak amplitude of inrush currents versus neutral resistor value for Case A.*

Case	First peak amplitude of inrush current			Neutral
	Phase A	Phase B	Phase C	resistor
A.1	-125.1715	-31.6844	150.8839	0
A.2	-120.7032	-40.1938	133.7328	15
A.3	-116.3249	-44.6002	128.1399	30
A.4	-113.3239	-47.2491	126.8263	50
A.5	-112.9477	-48.3432	127.2646	65
A.6	-112.6208	-49.0844	127.6326	80
A.7	-112.2689	-49.7659	128.0230	100
A.8	-111.6778	-50.7357	128.6690	150
A.9	-111.3229	-51.2463	129.0591	200
A.10	-111.0869	-51.5635	129.3156	250
A.11	-110.9195	-51.7785	129.4972	300

3.1.2.2. Case B

In this condition, no magnetic flux shunt was used, but controlled switching approach was applied. The transformer is energized with phase angle of 90 degrees for phase A. phase B is energized with a delay of a ¼ period than phase A and phase C is energized with a delay of a ¼ period than phase B. The value of neutral resistor was changed from zero to 300 ohms and the first peak of transformer inrush currents was determined, (see Table 2). As shown in this table, the use of neutral resistor has a significant positive effect in the inrush current reduction. By increasing the value of neutral resistor to 300 ohm, the first peak amplitude of all phases was reduced to about 80% of its value for case B.1 with no neutral resistor.

The maximum value of first peak of inrush current happens in phase C and is about 113.62 A. This value is less than that of case A due to this fact that switching was applied in the maximum values of phase voltages. Also, it can be seen that increasing the neutral resistor value from 65 ohm to 300 ohm resulted in inrush current reduction only by extent of about 5 A. Thus this value can be considered as an appropriate neutral resistor for this purpose. The inrush current waveforms for case B.7 are shown in Fig.4.

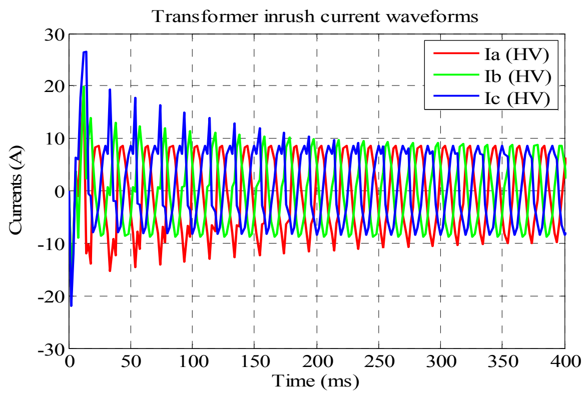

Figure 4. *The transformer inrush current waveforms for case B.7*

Table 2. *Variation of first peak amplitude of inrush currents versus neutral resistor value for Case B.*

Case	First peak amplitude of inrush current			Neutral resistor
	Phase A	Phase B	Phase C	
B.1	84.8555	85.7080	113.6190	0
B.2	63.0847	63.9121	80.9182	10
B.3	45.8576	46.6805	58.4904	20
B.4	35.5251	36.3465	45.2608	30
B.5	28.8136	29.6338	36.9264	40
B.6	24.0831	24.9018	31.4292	50
B.7	19.0386	19.8536	26.6072	65
B.8	15.5787	16.3913	24.9099	80
B.9	-15.5919	14.0046	23.5466	100
B.10	-15.7156	14.0506	22.5519	125
B.11	-15.8029	14.0858	21.9476	150
B.12	-15.8764	14.1119	21.5508	175
B.13	-16.0921	14.1323	21.2741	200
B.14	-16.3684	14.1615	20.9198	250
B.15	-16.5345	14.1807	20.7070	300

3.1.2.3. Case C

In this condition, magnetic flux shunt was used in the transformer model, but no controlled switching method was applied. The optimal dimensions of magnetic flux shunt are determined based on the approach that described in [27]. The transformer was energized using voltage sources with phase angles of 0, 120 and 240 degrees for A, B and C phases, respectively. The value of neutral resistor was changed from zero to 300 ohms and the first peak of transformer inrush currents was determined, as shown in Table 3. In comparison with case A, it can be seen that the use of magnetic shunts resulted in reduction of inrush current by about 8 A. This is due to the increase of equivalent inductance of windings due to the use of magnetic shunts. The use of magnetic shunts also can improve leakage flux pattern in the transformer window and thus can be used for reduction of axial forces acting upon the transformer yokes. In this case, use of a neutral resistor of the value of 50 ohms has the best effectiveness. The maximum value of first peak of inrush current happens in phase C and its value is about 142.83 A. The inrush current waveforms for case C.5 are shown in Fig.5.

Table 3. *Variation of first peak amplitude of inrush currents versus neutral resistor value for Case C.*

Case	First peak amplitude of inrush current			Neutral resistor
	Phase A	Phase B	Phase C	
C.1	-119.7738	-29.3955	142.8327	0
C.2	-115.3123	-35.9599	125.5639	15
C.3	-110.8043	-39.9900	119.8264	30
C.4	-108.0723	-42.7048	118.5793	50
C.5	-107.6854	-43.8330	119.0094	65
C.6	-107.3514	-44.5987	119.3811	80
C.7	-106.3811	45.3023	119.7761	100
C.8	-106.3775	-46.3047	120.4393	150
C.9	-106.0070	-46.8353	120.8387	200
C.10	-105.7615	-47.1632	121.1033	250
C.11	-105.5868	-47.3863	121.2908	300

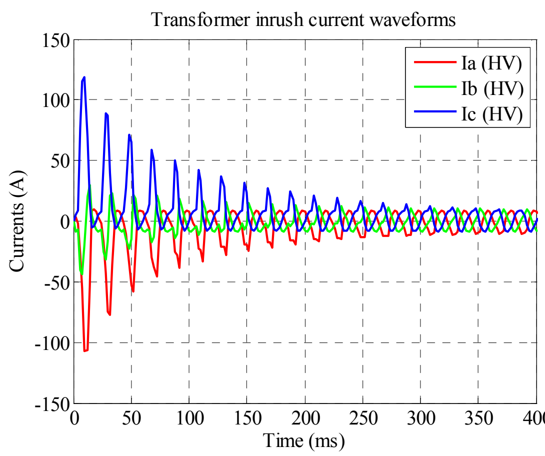

Figure 5. *The transformer inrush current waveforms for case C.5.*

3.1.2.4. Case D

In this condition, using of the magnetic flux shunts and the controlled switching approach was used simultaneously. Similar to case B, The transformer is energized with phase angle of 90 degrees for phase A. phase B is energized with a delay of a ¼ period than phase A and phase C is energized with a delay of a ¼ period than phase B. The magnetic flux shunts was inserted in the transformer model. The value of neutral resistor was changed from zero to 300 ohms and the first peak of transformer inrush currents was determined.

As shown in Table 4, the simultaneously use of magnetic shunts and controlled switching with neutral resistor has a significant positive effect in the inrush current reduction. By comparison of case B.1 and case D.1, it can be seen that the first peak amplitude of all phases was reduced to about 30%. The results obtained for case D.7 using is shown in Fig.6.

Table 4. *Variation of first peak amplitude of inrush currents versus neutral resistor value for Case D.*

Case	First peak amplitude of inrush current			Neutral
	Phase A	Phase B	Phase C	resistor
D.1	61.7643	62.5792	80.4427	0
D.2	61.7647	62.5797	80.4436	10
D.3	45.1004	45.9140	58.6028	20
D.4	35.0132	35.8268	45.4907	30
D.5	28.4419	29.2568	37.1444	40
D.6	23.7973	24.6102	31.6201	50
D.7	18.8220	19.6323	26.5066	65
D.8	15.3989	16.2074	23.8318	80
D.9	-15.0806	13.6140	22.4310	100
D.10	-15.2075	13.6641	21.4116	125
D.11	-15.2976	13.7018	20.7899	150
D.12	-15.3650	13.7302	20.3812	175
D.13	-15.4538	13.7521	20.0959	200
D.14	-15.7362	13.7833	19.7305	250
D.15	-15.9059	13.8047	19.5106	300

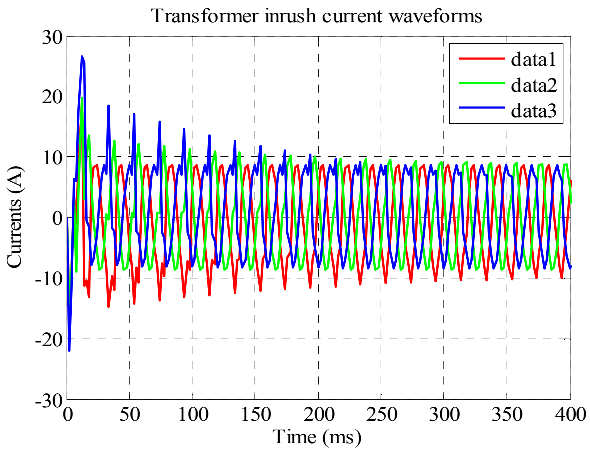

Figure 6. *The transformer inrush current waveforms for case D.7.*

3.1.3. Impact of the Neutral Resistance Value on the First Peak of Transformer Inrush Current

Considering that the first peak of inrush current in all of four cases occurs in Phase C, Phase C was selected for this study. For each of cases, the first peak amplitude of inrush current for a range of neutral resistor from 0 to 300 ohms were plotted (Figure 7). As shown in this figure, for cases A and C that the controlled switching method was not used, the maximum values for first peak of inrush current were occurred (150.8839 A for case A and 142.8327 A for case C, both for zero neutral resistor). Due to the use of magnetic flux shuns in case C, the values of first peak of inrush current for all values of neutral resistor is lower in comparison with case A. Also, for these two cases, it can be seen that the optimal value for neutral resistor is 50 ohms that resulted in the minimum value of first peak of inrush current (126.8263 A for case A and 118.5793 for case C). As shown in Figure 7, for cases B and D that the controlled switching method was used, the first peak amplitude of inrush current was reduced significantly (113.6190 A for case B and 80.4436 A for case D, both for zero neutral resistor). Lower value for case D is due to the use of magnetic flux shunt. It also can be seen that for the neutral resistor of 65 Ohm, the first peak amplitude of inrush current is reduced to an appropriate extent (about 26 A) and increasing the neutral resistor from 65 ohm to 300 ohm resulted in only to a slight reduction of about 6 A. Thus, we can say that the optimum value of neutral resistor for each case can be considered between 60% to 80% of short-circuit impedance at the HV side. The short-circuit impedance of this transformer at HV side is equal to 80.6 ohms.

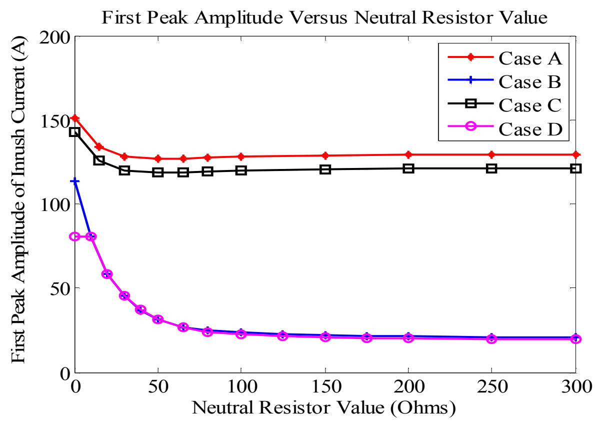

Figure 7. *The first peak amplitude of inrush current versus neutral resistor value for all four cases.*

4. Conclusion

In this paper, a relatively comprehensive study was done about the transformer inrush current phenomena and the factors that affect the amplitude of this transient current. A technique based on the use of magnetic flux shunts and the sequential switching with neutral resistor was proposed. The analysis was done for a range of neutral resistors in order to select optimal neutral grounding resistor for transformer inrush current mitigation. In this method, complete transformer model, including core loss and nonlinearity core specification, has been used. It was shown that high reduction in inrush currents among the three phases can be achieved by using this proposed approach.

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References

[1] Neves W., Fernandes Jr. D., Baltar F. J. A., A Comparative Investigation of Electromechanical Stresses on Transformers Caused by Inrush and Short-Circuit Currents, International Conference on Electrical Power Quality and Utilisation (EPQU), 17-19 Oct. 2011.

[2] Adly, A.A, Computation of Inrush Current Forces on Transformer Windings, IEEE Transaction on Magnetics, VOL. 37, NO. 4, pp. 2855-2858, JULY 2001.

[3] Hongkui Li, Yan Li, Xi Sun, Dongxu Li, Youteng Jing, Analysis of Three-Phase Power Transformer Windings Forces Caused by Magnetic Inrush and Short-Circuit Currents, Proceedings of 2009 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices, Chengdu, pp.233-236, China, September 25-27, 2009.

[4] Suhag P. Patel, P.E., Fundamentals of Transformer Inrush, 64th Annual Conference for Protective Relay Engineers, 11-14 April 2011. PP. 290-300.

[5] Li-Cheng Wu, Chih-Wen Liu, Shih-En Chien, Ching-Shan Chen, The Effect of Inrush Current on Transformer Protection, 38th North American Power Symposium, 2006, PP. 449-456.

[6] Kyeon Hur, Surya Santoso, Analysis and Modeling of Dynamic Overvoltage Phenomena due to Transformer Energizing, IEEE Power Engineering Society General Meeting, 12-16 June 2005, PP. 1126-1130.

[7] Mukesh Nagpal, Terrence G. Martinich, Ali Moshref, Kip Morison, and P. Kundur, Assessing and Limiting Impact of Transformer Inrush Current on Power Quality, IEEE Transaction on Power Delivery, Vol. 21, No. 2, pp. 890-896, APRIL 2006.

[8] Mojtaba Khederzadeh, Power Quality Enhancement by TCSC Application to Mitigate the Impact of Transformer Inrush Current, Transmission and Distribution Conference and Exposition, 2008. PP. 1-5.

[9] Y. Cui, G. Abdulsalam, S. Chen, and W. Xu, A sequential phase energization technique for transformer inrush current reduction-Part I: Simulation and experimental results, IEEE Transaction on Power Delivery, vol. 20, no. 2, pp. 943–949, Apr. 2005.

[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, IEE Proceedings -Electric Power Applications, May 2005, PP. 605-611.

[11] Hun-Chul Seo, Chul-Hwan Kim, Sang-Bong Rhee, Jae-Chul Kim, and Ok-Bae HyunV, Superconducting Fault Current Limiter Application for Reduction of the Transformer Inrush Current: A Decision Scheme of the Optimal Insertion Resistance, IEEE Transaction on Applied Superconductivity, Vol. 20, No. 4, PP. 2255-2263, AUGUST 2010.

[12] Nicola Chiesa and Hans Kristian Hoidalen, Novel Approach for Reducing Transformer Inrush Currents: Laboratory Measurements, Analytical Interpretation and Simulation Studies, IEEE Transaction on Power Delivery, Vol. 25, No. 4, pp. 2609-2616, OCTOBER 2010.

[13] 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, Proc. Inst. Elect. Eng., Elect. Power Appl., vol. 151, no. 3, PP. 289–295, May 2004.

[14] Sami G. Abdulsalam, and Wilsun Xu, A Sequential Phase Energization Method for Transformer Inrush Current Reduction-Transient Performance and Practical Considerations, IEEE Transaction on Power Delivery, Vol. 22, No. 1, PP. 208-216, JANUARY 2007.

[15] Duan xiongying, Huangzhihui, Liao minfu and Zou jiyan, Controlled Vacuum Circuit Breaker for Transformer Inrush Current Minimization, XXIII-rd International Symposium On Discharges and Electrical Insulation in Vacuum , Bucharest, 2008.

[16] K. P. Basu and Ali Asghar, Reduction of Magnetizing Inrush Current in a Delta Connected Transformer, 2nd IEEE International Conference on Power and Energy, PP. 35-38, December 1-3, 2008, Johor Baharu, Malaysia.

[17] Yu-Hsing Chen, Chang-Yi Lin, Jhao-Ming Chen, and Po-Tai Cheng, An Inrush Mitigation Technique of Load Transformers for the Series Voltage Sag Compensator, IEEE Transaction on Power Electronics, Vol. 25, No. 8, PP. 2211-2221, AUGUST 2010.

[18] F. Fard Ali Asghar, and K. P. Basu, Reduction of three-phase transformer magnetizing inrush current by use of point on wave switching, proceedings of 2009 IEEE Student Conference On Research and Development, PP. 368-370, 16-18 Nov. 2009, Malaysia.

[19] Miroslav Novak, Elimination of three-phase transformer inrush current through core forced magnetization and simultaneous closing, International Conference on Applied Electronics (AE), 2009, PP. 1-4.

[20] Gholamabas M.H. Hajivar, S.S. Mortazavi, Mohsen Saniei, The Neutral Grounding Resistor Sizing Using an Analytical Method Based on Nonlinear Transformer Model for Inrush Current Mitigation, UPEC2010, 31st Aug - 3rd Sept 2010.

[21] Baris Kovan, Francisco de León, Dariusz Czarkowski, Zivan Zabar, and Leo Birenbaum, Mitigation of Inrush Currents in Network Transformers by Reducing the Residual Flux With an Ultra-Low-Frequency Power Source , IEEE Transaction on Power Delivery, Vol. 26, No. 3, pp. 1563-1570, JULY 2011.

[22] S. V. Kulkarni and S. A. Khaparde, Transformer engineering: design and practice, ser. Power engineering. New York, N.Y.: Marcel Dekker, Inc., 2004, 476 pages.

[23] Ramsis girgis, Inrush current turorial session, IEEE standards transformer committee, Orlando, Florida, 2001.

[24] P. C. Y. Ling and A. Basak, Investigation of magnetizing inrush current in a single-phase transformer, IEEE Transaction on Magnetics, vol. 24, no. 6, PP. 3217–3222, Nov. 1988.

[25] M. Tarafdar Hagh and M. Abapour, DC reactor type transformer inrush current limiter, IET, Electric Power Application, 2007, Vol. 1, Issue. 5, PP. 808–814.

[26] Gaowa Wuyun, dichen Liu, and Po Li, Calculation of Residual Flux Based on Preisach Model and Entering Phase control of transformer to eliminate Inrush Current, the 4th Asia-Pacific Conference on Environmental Electromagnetics, 1-4 Aug. 2006, pp.396-401.

[27] S. Jamali Arand, K. Abbaszadeh, The Study of Magnetic Flux Shunts Effects on the Leakage Reactance of Transformers via FEM, Majlesi Journal of Electrical Engineering, Vol. 4, No. 3, pp. 47-52, September 2010.

[28] J. F. Holcomb, Distribution transformer magnetizing inrush current, Transactions of the American Institute of Electrical Engineers, Part III (Power Apparatus and Systems), vol. 80, no. 57, pp. 697–702, Dec. 1961.