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Prefluxing Technique to Mitigate Inrush Current of Three-Phase Power Transformer

Mr.Pradeep J.Kotak[1] Prof.Jaikaran Singh[2]

Abstract— At the time of transformer energization, a high current will be drawn by the transformer. This current is called transient inrush current and it may rise to ten times the nominal full load current of transformer during operation. Energization transient can produce mechanical stress in the transformer causes protection system mal-function. This current often affects the power system quality and may disrupt the operation of sensitive electrical loads such as computer and medical equipment connected to the system. Reduction and the way to control energization transient currents have become important concerns to the power industry. Conventionally, controlled switching or point on wave switching was the method being used to counter the problem, but this method requires the knowledge of residual fluxes of transformer before energization, which was quite tedious to get. Hence, this paper proposes a technique to mitigate inrush current in three phase transformers which involves injecting some amount of DC flux in the primary of transformer, the process known as prefluxing. After setting the initial fluxes of the transformer it is energized by conventional controlled switching. To verify the efficientness of the proposed prefluxing method to mitigate inrush current for power transformer, a MATLAB simulation model is designed and developed. The results are verified using the sample in which transformer is connect with a supply source, which have conformed the efficient inrush current control.

Index Terms— Controlled switching, Inrush current, MATLAB, Prefluxing, transformer, transient, point on wave switching.

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1 INTRODUCTION

Three-phase transformers are key components in power system network. Security and stability of transformers are both important and necessary to system operation. The large transient current of transformer due to flux saturation in the core, which is called inrush current, often causes the malfunction of the protective relaying system. This transient current affects costing time and money as the engineers have to examine closely the transformer and the protective system, to check for faults. The large transient current also causes serious electromagnetic stress impact and shortens the life of transformer. The overvoltage resulting from the inrush current causes serious damage to power apparatus. It is very important to solve the effect of inrush current[1].The uncontrolled energization of transformer produces high inrush currents, which can reduce the transformer's life due to the high mechanical stresses involved, and can also lead to the unexpected operation of protective relays and power quality reduction. This current depends upon various operating conditions, such as the magnitude of the voltage, the switching-on angle, the residual flux, the [I-φ] hysteresis-characteristics of the core, the resistance in the primary circuit, and many others which has been described in [8]. There are three negative side-effects of inrush currents:

1) The protective devices for overloads and internal faults may falsely operate and disconnect the transformer. There are examples of the available techniques for relays to distinguish between faults and inrush currents used to reduce the number of undesirable trips 2) The windings are exposed to mechanical stresses that can damage the transformer and and 3) Power-quality problems may arise: high resonant harmonic overvoltages and voltage sags[2].

In recent years, various protective systems for transformers, based on the differential relaying system, were developed. Various techniques based on complex circuits or microcomputers and proposed to distinguish inrush current from fault current. However, the transformer still must bear with large electromagnetic stress impact caused by the inrush current. Transformer is the most sensitive component in response of power system harmonics. As non-sinusoidal harmonics have been generated from many sources, harmonic flow through many transformers and causes the compound effect the power system. The main factors affecting the magnetizing inrush current are point- on- wave voltage at the instant of energization magnitude and polarity of remanent flux. In addition total resistance of the primary winding, power source inductance, air-core inductance between the energizing,the core geometry of transformer core and the maximum flux carrying capability of the core material is also affected inrush current[3][4]. This paper proposes a new technique to mitigate inrush current of three phase power transformer called prefluxing. In this method, some amount of DC flux is injected in primary of transformer before energization.

- *Mr.Pradeep kotak is currently pursuing masters degree program in electric power system inRGPV University Bhopal M.P. India, PH-07387987970. E-mail: pradeepkotak5@gmail.com*
- *Prof.Jaikaran singh is currently working as professor in SSSIST Sehore M.P. India, PH-01123456789. E-mail: jaikaransingh@gmail.com*

2. NATURE OF INRUSH TRANSIENT

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Caused by switching transient, out of phase synchronization of a generator, external faults and fault restoration.The energization of a transformer yield to the most severe case of inrush current and the flux in the core can reach a maximum therotical value of two to three times the rated value of peak flux.There is no direct evidence that the energization of a transformer can cause an immediate failure due to high inrush currents. However, insulation failures in power transformers which are frequently energized under no load condition support the suspicion that inrush currents have a hazardous effect. A more typical problem caused by the energization of transformers is due to harmonics interaction with other system components that develops into over-voltages and resonant phenomena. The study of the energization of a transformer installed in an industrial facility carried out in highlights problems due to harmonics, over-voltages and resonances. In [5] the authors show how the harmonic distortions caused by the switching of lightly loaded or unloaded transformers may be amplified during a power system restoration process, creating high harmonic overvoltages. In the energization of large size transformers in EHV substations with long transmission lines is discovered to cause significant temporary disturbances when harmonic resonances are reached. In particular, when there are transformers already connected to the bus, the disturbances caused by the energization of one more transformer have greater duration and intensity. In it is discussed how transformer inrush current can excite resonance frequencies in inter-connected offshore power systems [3].

3. MODELING OF INRUSH CURRENT IN TRANSFORMER

In [5] had done the modelling of transformer for his doctorate thesis. Firstly, he had done the magnetic modelling of core and then transformed it into electric modelling by using Maxwells equations. A MATLAB model has been prepared for simulation study. Three-phase power transformer having a rating of 250 MVA, 25 kV/400 kV, 50 Hz, connected to a supply source as shown in Fig. 1. A three phase 25 KV source connected with the transformer[6]. Current and flux measurement devices are connected. the results are shown in Section V.

The three-phase transformer which is used for simulation has

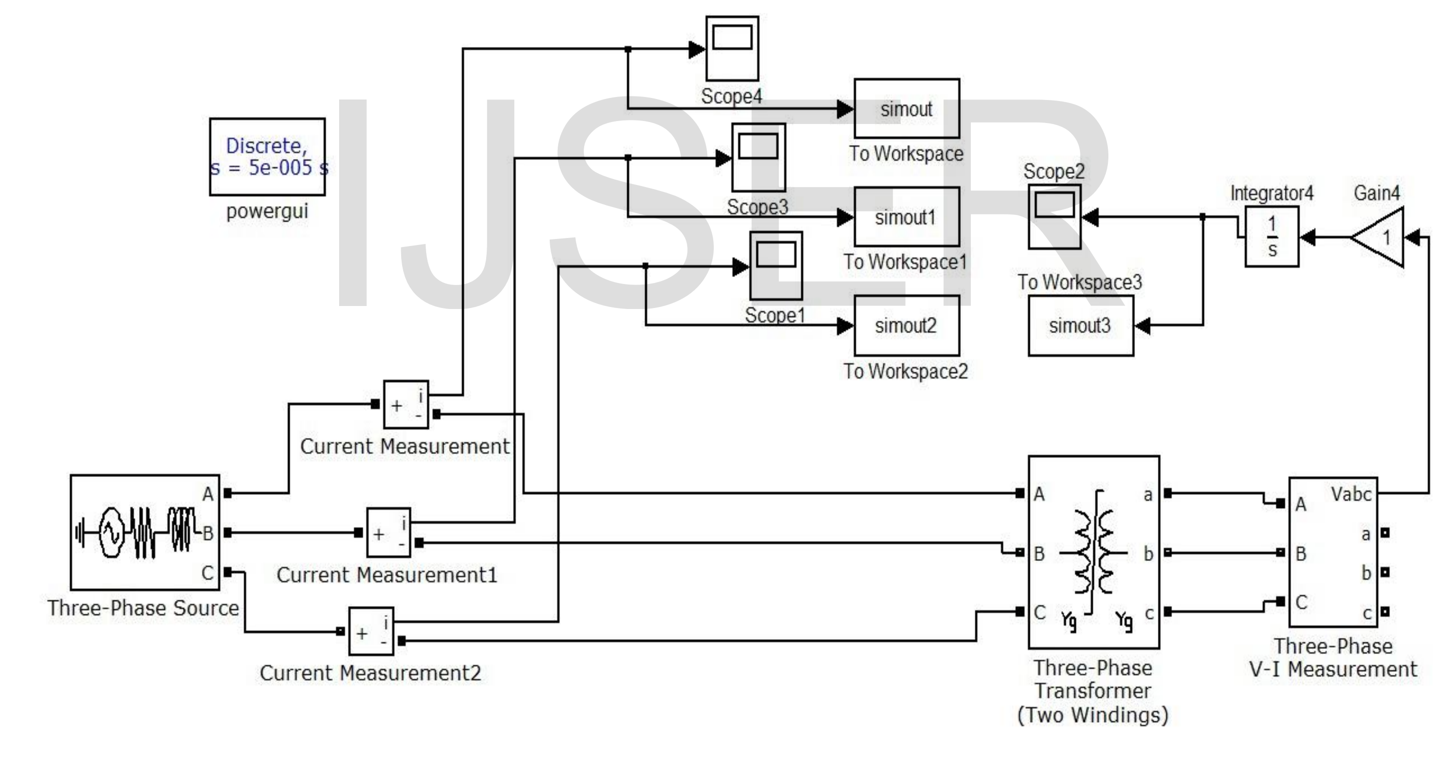

Fig. 1. MATLAB simulink model of inrush current in transformer

star winding in primary and secondary both. The core magnetization resistance of three phase transformer is 450 ohm and core magnetization inductance is 1.4325 H. The core is used with specified initial fluxes and saturated core. Some amount of flux provided in each phases to get the value of inrush current. When the transformer is energized, the flux of all three-phases will increase and reach till the maximum value of flux. After that maximum value, the flux will become saturated and draw more current from source, which may be 5 to 10 times greater than rated current. The main reason of saturation of flux is residual flux. Residual flux is nothing but it is some amount of flux which remain in the transformer core at the time of de- energization of transformer. Residual flux is depends on the rating of transformer and de-energization instant. It will have different values for different ratings of transformer [6].

4. PREFLUXING TECHNIQUE

As controlled switching had been the most popular technique to mitigate inrush current, the most important aspect in the method is knowledge of residual flux of a transformer. Many techniques had been suggested to obtain residual flux on the basis of the instant of transformer was previously turned off, but it is slightly tedious process. To make a user free from knowledge of residual flux the paper proposes a new technique to set the initial fluxes of transformer as per the desired values. This is called as prefluxing[7].

The innovation behind the prefluxing inrush current reduction strategy lies in the prefluxing device itself. The prefluxing device capacitor is charged to a user specified voltage and then discharged into the transformer when closing the isolator switch. It is necessary for the prefluxing device to set the residual flux of a transformer as high as possible to minimize the inrush current, but also to do so efficiently. The prefluxing reduction strategy is a two part process. First, the transformer's residual flux is set as close as possible to its maximum achievable residual flux when the transformer is de-energized. The second part of process controls the circuit breakers (CBs) to energize the transformer. There are three controlled strategies for switching control of circuit breakers, first is rapid closing, second is delayed closing and third is simultaneous closing. In rapid closing, closes one phase first and the remaining two phases within a quarter cycle. It requires knowledge of the residual flux in all three-phases, independent pole breaker control, and a model of the transformers transient performance. In delay closing, closes one phase first and the remaining two phases after 2-3 cycles. It requires knowledge of the residual flux in one phase only, independent pole breaker control, but does not require any transformer parametric data. In simultaneous closing, This closes all three phases together at an optimum point for the residual flux pattern. It does not require independent pole breaker control, but requires knowledge of the residual flux in all three phases and the the residual flux magnitudes in two phases are high and follow the most traditional residual flux pattern[3][4].These closings are chosen as part of an inrush current reduction strategy for the three phase transformer that enables the use of the three pole CBs. The prefluxing device shown in Fig.2, consists of a capacitor, a diode and a switch. A charging circuit (not shown) establishes the initial voltage across the capacitor. The device is used when the transformer is isolated from the power system and connects across one of the transformer winding (the primary winding). Ideally, the high voltage winding is

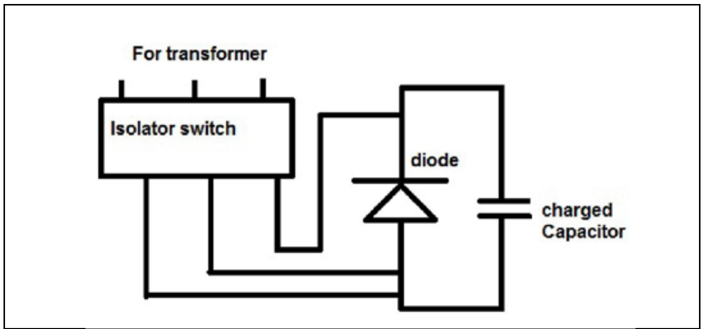

Fig. 2. Prefluxing device

used because of the reduced magnetizing current on this winding. Since the prefluxing device is applied only when the transformer is isolated and can operate at very low voltage, relatively inexpensive isolator switches can be used to connect the device to the transformer. The prefluxing device is sized to operate around the transformer's magnetizing current level, so the capacitor, diode and switch can be sized for a fraction of the transformer rated current[7].

5. MITIGATION OF INRUSH CURRENT IN TRANSFOMER USING PREFLUXING

The inrush current can be mitigate using prefluxing device as shown in Fig.2. As section III describes that mitigation of inrush current is two steps process.

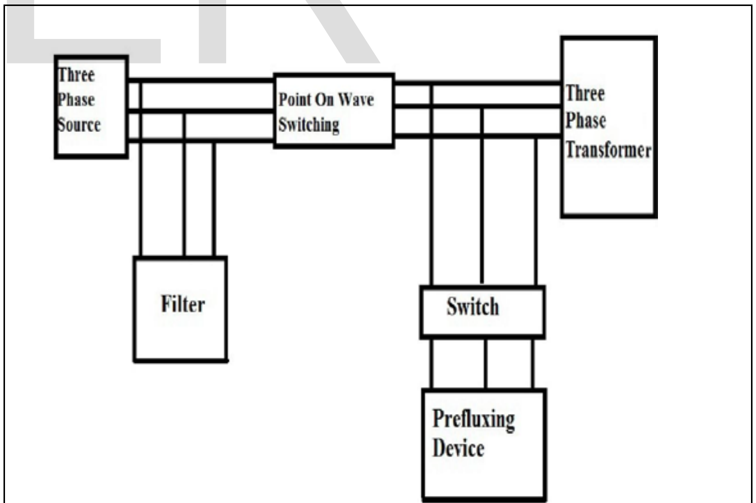

Fig. 3. Connection of prefluxing device in three phase transformer

A. Step I- Prefluxing Device

The prefluxing device which shown in Fig. 2 is connect in the primary winding of transformer. The device should connected to transformer only when transformer is isolated. It will feed some amount of DC flux before energization of transformer. When the transformer is energized, at the same instant, the prefluxing device will be separated by circuit breakers or isolated switches[7]. This prefluxing device sets a known residual flux in the primary of transformer. Then by point- on- wave switching, the transformer will be energize at according to the residual flux. The capacitor will be charged according to the maximum value on the transformer. It should be almost equal to the maximum value of flux. Fig. 5 shown the prefluxing device which is connected to primary of power transformer. This device inject DC flux till the phases of transformer energized. The simulation has been designed and developed in MATLAB and filters are also used to limit the harmonics.

B. Step II- Controlled Switching

The controlled switching has been used to mitigate inrush current after applying the prefluxing device. The switching will be controlled by circuit breakers. Three circuit breakers are connected to each phase of which are normally open type. When circuit breakers are open, it means transformer is isolated at that time and the prefluxing device connected to transformer[8]. As the circuit breakers goes close and connect the supply to transformer, that same instant the prefluxing device will disconnect through isolated switch. The controlled switching has been applied after the prefluxing. The controlled switching have three strategies which has been described in Section III. In this paper, simultaneous closing strategy has been used for controlled switching[3]. Fig. 4 shows the simultaneous closing in three phase transformer. An example to describe simultaneous closing. Fig. 4 shows basic concept of controlled switching. A three- phase ac voltage consisting of three voltage waves U, V, and W is shown in Figure 4a. Let us assume that the magnitudes of the residual magnetic fluxes, which depend on the phase angle at which the circuit breaker opened the circuit, are as shown in Figure 4b. In this example, the maximum residual magnetic flux is in magnetic phase U. The sum of the residual magnetic fluxes in the three iron cores in a three-phase transformer with delta windings is zero. Consequently, when the residual magnetic flux is a maximum in a certain core, the residual magnetic fluxes in the other two cores have the reverse polarity and smaller absolute values. The three sinusoidal voltage waves U, V, and W in Fig. 4b show the magnetic flux magnitudes that would be induced by the voltage waves, as functions of the phase angle at which the voltages are applied. Figure 4c shows the calculated inrush currents induced in each iron core as a function of phase angle. If the voltage U is applied at about -50°, when the magnitude of the magnetic flux that it induces is equal to that of the residual magnetic flux in core U, the inrush current denoted by U will be zero, and the two other inrush currents will be reduced to low levels because the difference in magnitude between the residual magnetic flux and the magnetic flux induced by the voltage application is small. In the phase-angle range shown by the arrow in Fig. 4c, the inrush currents can be reduced to a level less than half of their maxima.

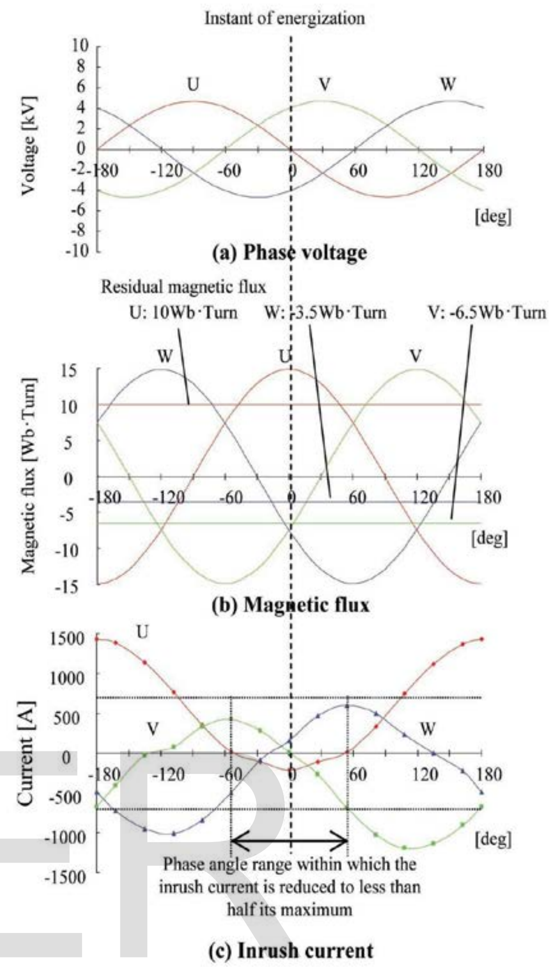

Fig. 4. Three-phase simultaneous closing controlled with phase voltage

6. SIMULATION RESULT

A. Inrush Current Without Using Prefluxing

The results of model which shows in Section III . The inrush current in each phases shown which is 7 times greater than rated current. Figs. 5, 6 and 7 shows the inrush current in phase A, B and C and Fig. 8 show the flux in primary.

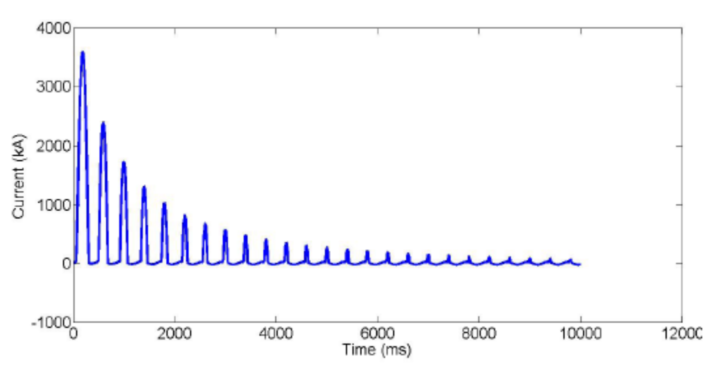

Fig. 5. Inrush current in phase A.

Fig. 5 shows the inrush current in phase A in power transformer without using any mitigation technique. The magnitude of current is 3500 kA and this goes in steady state condition in 5000 ms (5 s). This current is highest inrush current among the all phases.

Fig. 6 shows the inrush current in phase B without using mitigation technique in power transformer. The value of this inrush current is 2800 kA and it goes in steady state condition in 5500 ms(5.5 s). The magnitude of this current is less compare to phase A current.

Fig. 7 shows the inrush current in phase C without using mitigation technique in power transformer. The value of this inrush current is 550 kA and it goes in steady state condition in 7000 ms (7 s). This current lowest current compare to other two phase current.

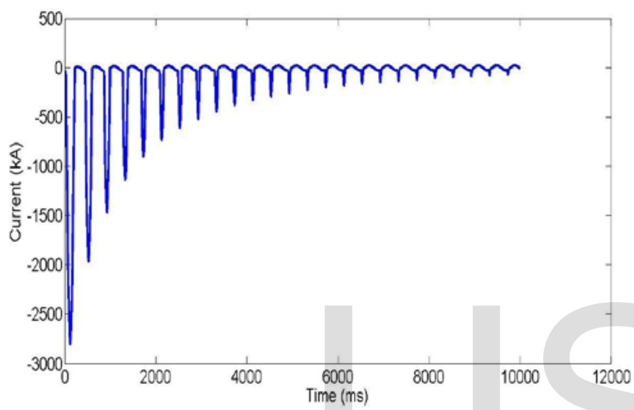

Fig. 6. Inrush current in phase B

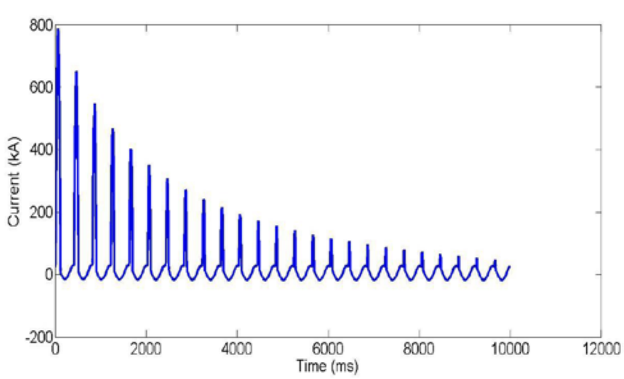

Fig. 7. Inrush current in phase C

Fig. 8 shows fluxes in each phase.The maximum flux in phase A is 1700 Wb, in phase B is 1800 Wb and in phase C is 1500 Wb.

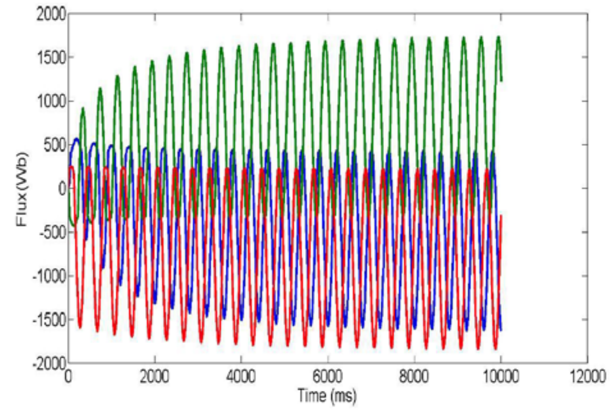

Fig. 8. Fluxes in all three phases.

B. Harmonic Analysis Without Filter

As section I describes that inrush current is harmonic rich current so results show that total harmonic distortion in each phases are much high. Harmonic analysis of inrush currents with residual flux in phase A, B and C is shown in Figs. 9, 10 and 11. Fig. 9 shows harmonic in phase A. Total harmonics distortion is 38.98 %. The DC component ni this phase is 8 % and second harmonics is 35 %. The fundamental component is 39 %.

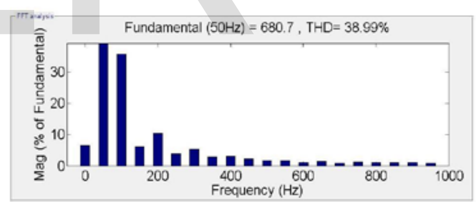

Fig. 9. Harmonics in phase A

Fig. 10 shows harmonic in phase B. Total harmonics distortion is 27.32 %. The DC component in this phase is 65 % which is large compare to phase A and second harmonic is 30 % which less than phase A. The fundamental component is 78 %. Fig. 11 shows harmonic in phase C. Highest total harmonic distortion generated in this phase. Total harmonics distortion is 103.70 %. The DC component in this phase is 45 % which is large compare to phase A but less compare to phase B. Second harmonic is 76 % which is highest amoung all three phases . The fundamental component is 80 %.

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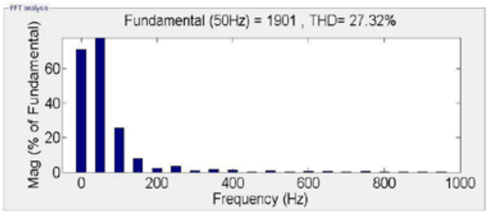

Fig. 10. Harmonics in phase B.

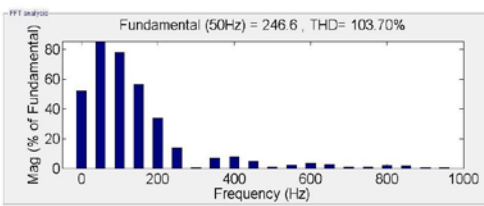

Fig. 11. Harmonics in phase C.

C. Mitigate Current With Prefluing

Now, prefluxing device connected in power transformer and inject some amount of DC flux in primary and remove at the same instant when transformer energized and get following results shown in Figs. 12, 13 and 14 and Fig. 15 shows fluxes of all three phases. Figure 12 shown the inrush current in phase A in power transformer with using preuxing.

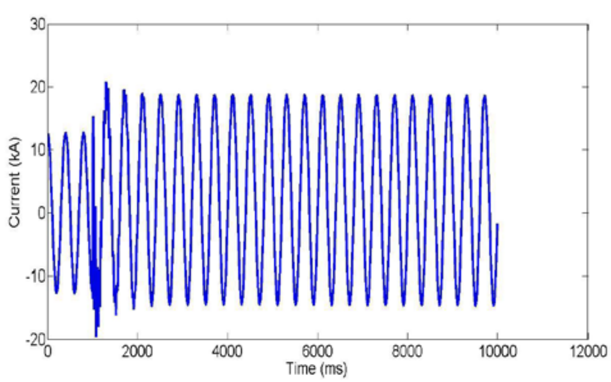

Fig. 12. Mitigate current in phase A.

The magnitude of current is 19 kA. If compare with Fig. 4, the inrush current is mitigate from 1300 kA to 19 kA. Fig. 13 shown the inrush current in phase B in power transformer with using preuxing .

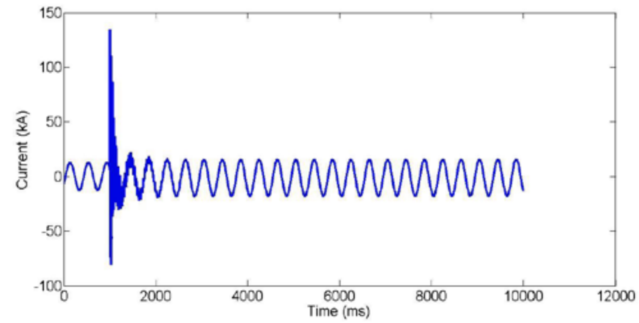

Fig. 13. Mitigate current in phase B.

The magnitude of current is 17 kA.Comparison with fig. 5, the inrush current is mitigate from 1300 kA to 17 kA. Fig. 14 shown the inrush current in phase C in power transformer with using preuxing.

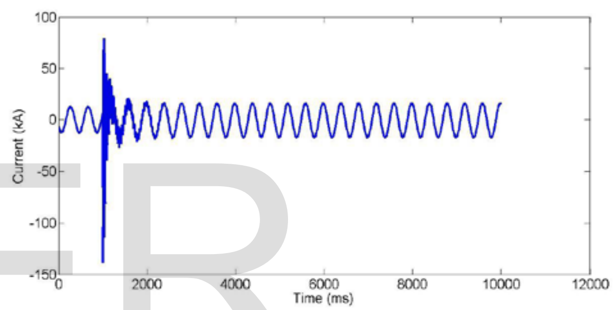

Fig. 14. Mitigate current in phase C.

The magnitude of current is 16 kA. Comparison with fig. 6, the inrush current is mitigate from 1300 kA to 16 kA.

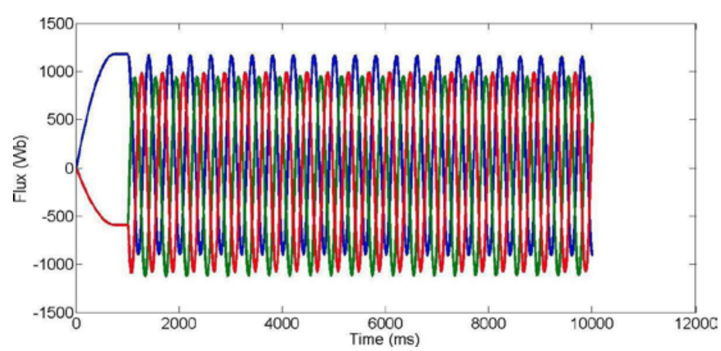

Fig. 15. Fluxes in all three phases

Fig. 15 shown the fluxes in each phase. The maximum flux in phase A is 1500 Wb, in phase B is 1700 Wb and in phase C is 1550 Wb.

D. Harmonic Analysis With Filter

As filter connect to transformer, harmonics will also go down which shown in Figs. 16, 17 and 18. Fig. 16 shows harmonic in phase A. Total harmonic distortion in phase A is 0.01 %.

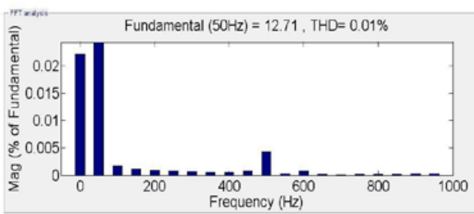

Fig. 16. Harmonic in phase A.

The magnitude of frequency in this phase is 0.025 % and DC component is 0.022 %. Fig. 17 shown harmonic in phase B. Total harmonic distortion in phase B is same as phase but the magnitude of frequency in this phase is 0.013 %.

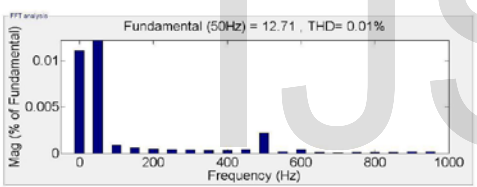

Fig. 17. Harmonic in phase B.

The DC component in this phase is 0.011 %. Fig. 18 shown harmonic in phase C. Total harmonic and DC component in phase C is same as phase B. DC harmonic and magnitude is less than compare to phase A.

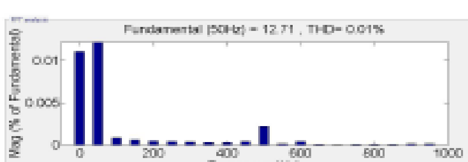

Fig. 18. Harmonic in phase A,B and C.

7. CONCLUSION

This paper presents inrush current reduction strategy which sets the residual flux of a three-phase transformer to a large magnitude and specific polarity in a method known as preflux-ing and then energized the transformer at a specified system voltage angle based on the flux polarity. This strategy has advantage over some of the presently suggested reduction strategies, including removing the need for residual flux measurement during transformer de-energization. The prefluxing device that sets the flux of the transformer is simple in form and the transformer is simple in form and flexible to apply to any range of transformer sizes. In addition, the device can operate at low-voltage levels, such as the substation AC or DC supply, regardless of the voltage rating of the transformer.

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