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MITIGATION METHODS OF MAGNETIZING INRUSH TRANSIENT DURING ENERGIZATION OF LARGE POWER TRANSFORMER

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ABSTRACT

Energization of unloaded transformer results mainly in magnetizing inrush currents having a high magnitude with harmonic-rich currents, when transformer cores are driven into saturation during energization. The currents cause many undesirable effects on transformer attribute; large dynamic forces inside it, life-span reduction, insulation deterioration and mechanical fatigue in windings support, as well as, problems in protection system and finally reduced power quality of the system. A 230/66 kV Yn/Δ no-load transformer connected to a 230 KV power system was simulated using the PSCAD/EMTDC. The effect of pre–insertion resistors to suppress inrush transients was clearly demonstrated. Without controlled switching the energization may occur at any time on the voltage wave producing high current peak, when the transformer core is driven into saturation. Recent techniques have been presented to reduce inrush current phenomena and to minimize the residual flux during energization of large power transformer. Different mitigation methods were analyzed and evaluated by using Fast Fourier transform (FFT).

التيارات الدفعية العابرة تنتج بقيمة عالية وغنية بالتوافقيات عند شحن محولات القدرة، خاصة عندما يصل قلب المحول الي التشبع في بداية التشغيل، هذه التيارات تتسبب في تأثيرات غير مرغوب فيها علي المحول، تتمثل في تولد قوة ديناميكية داخلية، و قصر عمر المحول، و تدهور حالة العزل، و نشوء إجهادات علي حوامل الملفات، و كذلك مشاكل في أنظمة الوقاية، و أخيراً يؤدي لإضعاف جودة نقل الطاقة المطلوبة في الشبكة، و سيتم محاكاة شحن محول القدرة جهد 66/230 ك.ف متصل بمصدر جهده 230 ك.ف، بينما المحول غير متصل بأي أحمال، و يتم ذلك بإستخدام برنامج خاص للمحاكاة يدعي (PSCAD/EMTDC)، في هذه الدراسة سيتم إختزال هذه الموجات العابرة بإستخدام المقاومات المقحمه في النظام خلال فترة زمنية محددة ثم عزلها، وبدون التحكم في المفاتيح في اللحظة المناسبة لموجة الجهد المطبق، فإنه عند حدوث التشبع في قلب المحول ينتج تيارات ذات قمم عالية القيمة، التطبيقات الحديثة لإستراتجيات التحكم بالمفاتيح الكهربية سيتم عرضها و هي تختص بإختزال ظاهرة التيار الدفعي لتقليل تأثير الفيض المتبقي لحظة شحن محولات القدرة الكبيرة، و سيتم تحليل و تقييم الطرق المختلفة للإخماد بإستخدام نظرية تحليل فورير السريع (FFT) وذلك للمقارنة بين أداء الطرق المختلفة و تقييم قوة تأثيرها.

Keywords**:** Inrush current, Switching, Transient, Harmonics.

1. INTRODUCTION

The inrush current has a high magnitude. Its magnitude is ten times the full load current of the transformer, approach that of short circuit currents [1]-[2] and can cause mechanical stress of the transformer windings [3]-[4].

Uncontrolled energization of large power transformers may create a large dynamic flux and saturation in one or more cores of the transformer. The saturation results in high amplitude magnetizing inrush currents that are rich in harmonics and have a high direct current component [4]-[8]. The major sources of harmonics in inrush currents are nonlinearities of transformer core, saturation of current transformers, overexcitation of transformers, core residual magnetization, and switching instant. Some harmonic methods are used to analyze the inrush currents. Also; their effects in EHV system are proposed by [9]-[11]. This work aims to evaluate different mitigation methods for eliminating the inrush current of the 100 MVA, 230kV/66kV, Yn/Δ no-load transformer connected to a 230 kV power system. As apparent the residual flux can be influenced by means of controlled de-energization of the transformers. Thus, the inrush transient can be completely eliminated by controlling both opening and closing operations of breaker. Effect of pre–insertion resistors to suppress inrush transients was clearly demonstrated. Different mitigation methods were surveyed to evaluate the reduction of magnetizing inrush current by using Fast Fourier Transform (FFT).

2. INRUSH CURRENT TRANSIENTS SIMULATION

Transformer inrush currents are related to the high saturation of the iron-core during energization. The 'Knee' of the B-H curve has been assumed to be 125% of the nominal flux. When the power frequency voltage was applied to the primary of the transformer, the peak value of flux can reach two times normal maximum flux plus residual flux in the core. Therefore, transformer will be greatly saturated and draw a large amount of current. Since the current has short duration there are no adverse effects on the transformers, however, the protective devices for overloads may falsely operate and disconnect the transformer [4]-[8]. Further, the attenuation of inrush currents is due to losses, but losses have no clear relation with inrush current. The attenuation will be caused by the external resistive losses due to the harmonic. The iron and copper losses do not affect the rate of attenuation as presented in [9]-[10].

The transformer model adopted in this study was published in [12]. It is an equivalent electric and magnetic model. We have used PSCAD/EMTDC to evaluate the proposed scheme. For three–phase transformer consists of two windings; the case of 100 MVA, 230kV/66kV, Yn/Δ transformer units described in [12] is simulated. Transformer model and associated parameters details used in the simulations are illustrated in Fig 1.

The positive and zero sequence leakage impedances of three-phase transformer are dependent upon both core and winding configuration. The core has three-limbs; the zero sequence impedance has the same value of the positive sequence impedance. When transformer is subjected to zero sequence voltages, there will be no core path for zero sequence flux to flow. Consequently, the zero sequence flux passes through air, yoke and tank causing zero sequence impedance to be quite low. In the general transformer model, adding a delta winding approximates this effect as in [2], [13].

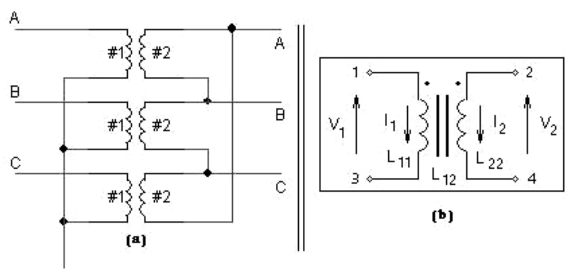

Fig. 1 PSCAD/EMTDC model (a) 3-phase, 2-winding transformer (b) classical modeling approach

2.1 Initial Conditions Associated With The Transformer

The conditions associated with the de-energizing of the transformer may not be known. It is useful to anticipate the worst energization. It is supposed that the residual fluxes inside the transformer follow a uniform distribution and may reach a value Φmax equal to 80% of the nominal flux [12], [14]. These assumptions are consecutive to the type of the magnetic core and the delta connection at the 66 kV secondary side. This was determined from the rated r.m.s. voltage Vr of the winding that is being referenced for remanence. Equation of the peak flux linkage referenced to winding at Vr was presented in [12].

To set desired residual flux in the un-energized transformer, the controlled current sources are used. In this case, the initial status of circuit breaker was being opened and the current sources in each phase adjusted to generate the required remanence. The current sources can be remained in the circuit at their remanence setting during the run, as they have no impact on the results. The residual flux in each leg was adjusted by setting the resulted flux linkages as in [12], [15].

2.2 Initial Conditions Associated With The Breaker

The closing instant of the pole A may occur at any time on the sinusoidal voltage according to a uniform distribution. The two other poles follow the pole A according to a Gaussian distribution characterized by its mean value Tav equal to zero and its standard deviations which is considered for this breaker to be equal to 20 ms [12]. In this simulation, initial state of breaker is opened, and then closed after 0.5 sec [13].

In practice, many factors prevent the complete mitigation of the inrush current. These factors are operating time of circuit breakers, pre-strike between the moving breaker contacts, and residual flux pattern which is not exactly known and dependent on operation of circuit breaker poles [7], [8].

3. ENERGIZATION OF 100 MVA UNLOAD TRANSFORMER

The three-phase model, a non-simultaneous switching of an unloaded 100 MVA, 230/66 kV and Yn/Δ transformer is simulated. The impact of the 230kV on the inrush transient during transformer energization, without residual flux, is illustrated in Fig. 2.

In general, rated current level of the transformer is 0.25 kA and short-circuit level of thevenin equivalent circuit of transformer is varying between 5kA and 40kA. Although the maximum inrush current reaches approximately 2.5kA, there is no severe overvoltage observed during the energization. Inrush wave will be slowly decayed over a period of 5 sec. Duration period which lies between (0.5-0.6) sec shall be studied.

By applying Fast Fourier Transform (FFT) for three phase magnetizing current to get magnitude contents up to third harmonics as a function of time are illustrated in Fig. 3 to Fig. 5.

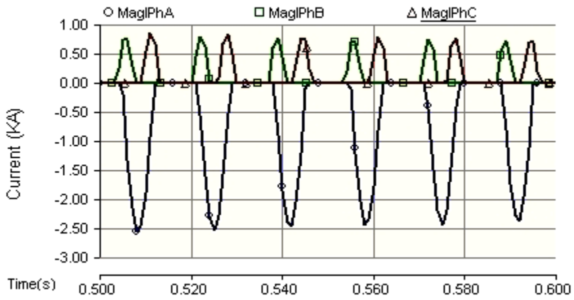

Fig. 2 Magnetizing Inrush current without residual flux

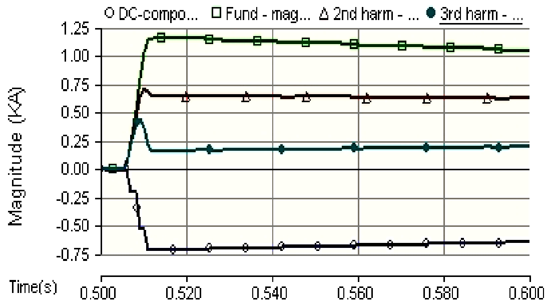

Fig. 3 FFT magnitudes for current in Ph (A).

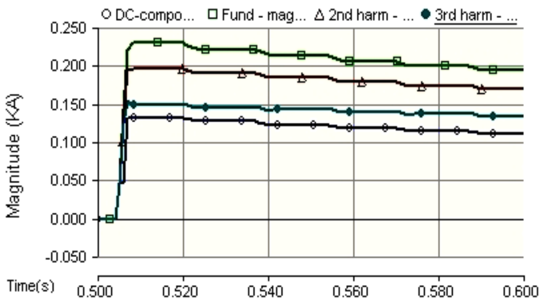

Fig. 4 FFT magnitudes for current in Ph (B).

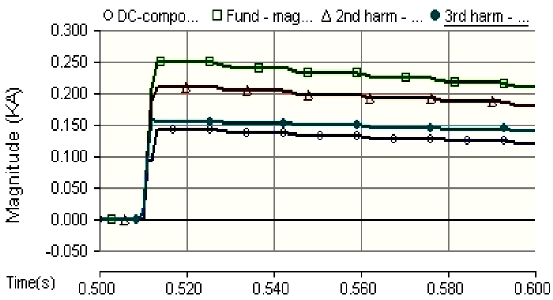

Fig. 5 FFT magnitudes for current in Ph (C).

When inrush current is simulated and FFT algorithm is applied, it can be found that the harmonic contents are rich in DC component, second and third harmonics. And the second harmonic value is larger than the DC component.

4. EFFECT OF PRE-INSERTION RESISTORS

The effect of pre-insertion resistors on 230kV circuit breakers to suppress these inrush transients has been investigated. Simulation results indicate that the pre-insertion resistor of 1800 Ω with a minimum insertion time of 10 ms would allow eliminating transient during the worst condition of energization "Fig. 6". The peak of inrush current reduces to rated current 0.25 kA.

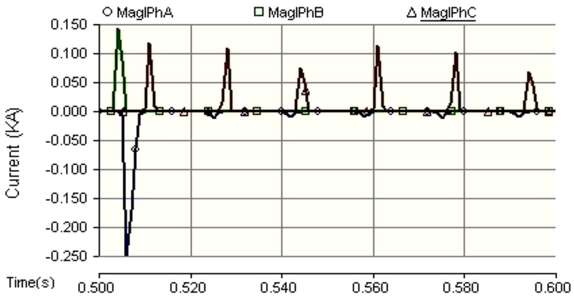

Fig. 6 Elimination of inrush current using pre-insertion resistor

By using Fast Fourier Transform (FFT) for three phase magnetizing current to get magnitude contents up to third harmonics as a function of time are illustrated in Fig.7 to Fig.9.

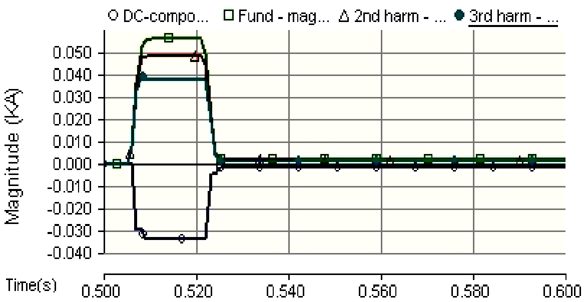

Fig. 7 FFT magnitudes for current in Ph (A).

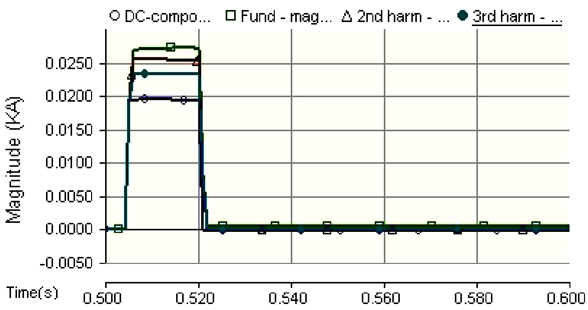

Fig. 8 FFT magnitudes for current in Ph (B).

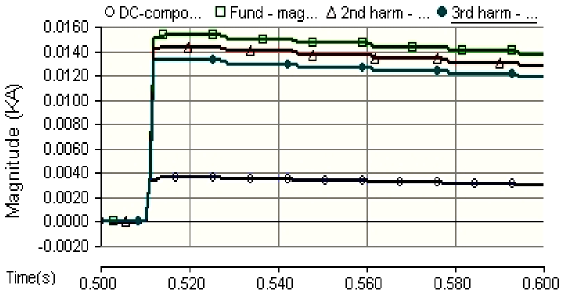

Fig. 9 FFT magnitudes for current in Ph (C).

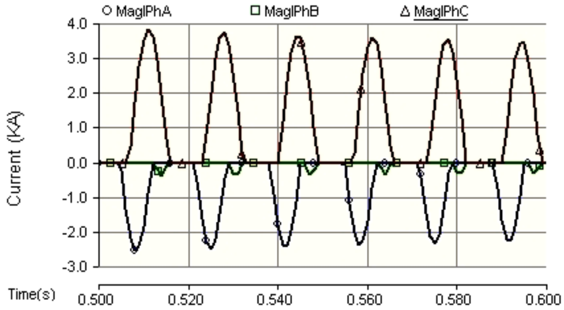

Fig. 10 Magnetizing inrush current with residual flux pattern

The harmonic contents are decreased in DC component, second and third harmonics.

5. ENERGIZATION OF 100 MVA UNLOAD TRANSFORMER WITH RESIDUAL FLUX PATTERN

The relationship between the residual flux and the moment of transformer de-energization has been established by [7]-[8]. At the instant of first pole, opening action will be shifted systematically by 1 ms. The current chopping characteristics of the breaker have been set according to the "chopping number" of the SF6 breaker. The residual flux can be managed effectively by means of controlling the breaker operations when disconnecting an unloaded transformer [8].

The switching instant is evaluated from the recorded voltage wave shape. Before each switching, the transformer is de-energized using a variable AC source to reduce the residual flux in core to zero. As often the case, detailed information about magnetization curve of transformer core is not readily available [14].

The residual flux is influenced by the transformer core material characteristics, core gap factor, winding capacitance, circuit breaker current chopping characteristics and other capacitances connected to the transformer. The residual fluxes still summed to zero and this effect has been observed that it causes formation of a residual fluxes pattern in three phase transformers [4]-[8], [16]-[18].

High level of saturation in the core of transformer was obtained, when the switch poles are being closed at instant of energization. The residual flux in the limb of phases a, b, and c is assumed to be 0%, 40% and -40% of the nominal flux, respectively. The results of the simulation are shown in "Fig. 10". It can be seen that from the current wave shapes, the limbs of the phase b and c are deeply saturated, producing inrush currents of high magnitude.

Inrush current recorded when the first phase of the main transformer has been energized close to zero voltage and the residual flux pattern is applied. The worst case appears when the maximal flux due to the two causes on the same limb. Because of the voltage drop on the external impedance, the de-energization due to off-peak switching will normally be well below its theoretical maximum, and the resultant d.c. de-magnetization will probably rarely exceed 1p.u. [10], [11]. This worst case scenario resulted in inrush current peak 2.5kA in phase (A) and 3.8kA in phase (B) for the 230 kV winding.

Analyzing by Fast Fourier Transform (FFT) for three phase magnetizing current to get magnitude contents up to third harmonics as a function of time are illustrated in Fig.11 to Fig.13.

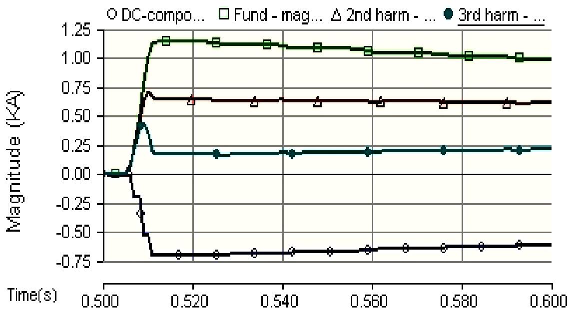

Fig. 11 FFT magnitudes for current in Ph (A).

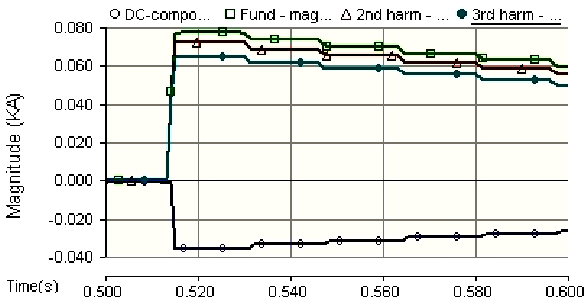

Fig. 12 FFT magnitudes for current in Ph (B).

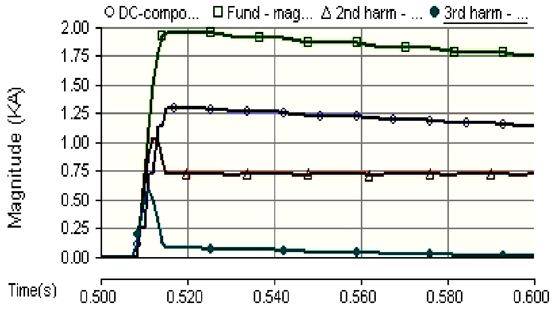

Fig. 13 FFT magnitudes for current in Ph (C).

It can be found that, the harmonic contents are rich in DC component, second and third harmonics in two phases (A & C). Further, the DC component, second and third harmonics have small value in phase (B).

6. TRANSFORMER CONTROLLED SWITCHING STRATEGIES

In order to obtain inrush current during free energization of large power transformer, the operating time of the circuit breaker poles must be controlled individually and contacts closing performed in a proper sequence. There is several control strategies published in the literature and realized in the practice [4]-[8]. Point-on-wave controlled transformer energization is probably the most widely controlled switching technology today [4]-[8].

Controlled closing is implemented with the closing time for each phase, when the instant of residual and prospective fluxes are equal. The closing time can easily be determined by using the expression as in [8].

6.1 Controlled Switching Without Residual Flux

Many of power transformers are however manufactured with at least one delta winding, which accomplish interaction between the phases. In presence of a delta winding the energization of the first phase at the Y side will change the static residual flux in the other phases. If the residual flux is zero in all phases, the peak of sinusoidal voltage makes the optimal instant to close the first phase at the HV side. After closing the first phase, a voltage is generated and a dynamic core flux appears in the other two phases of the delta winding. In this case, the optimal energization can be achieved by energization the first phase at 4.17 ms before the last two phases, when the prospective flux is equal to the dynamic core flux in each phase [7]-[8]. Reduction inrush current is illustrated in Fig.14.

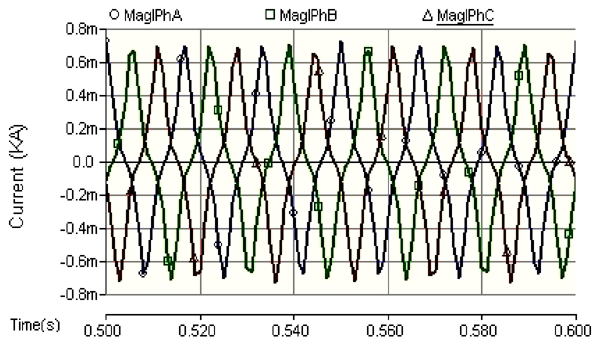

Fig. 14 Reduction of Inrush with no residual flux.

By using Fast Fourier Transform (FFT) for three phase magnetizing current to get magnitude contents up to third harmonics as a function of time are illustrated in Fig.15 to Fig.17.

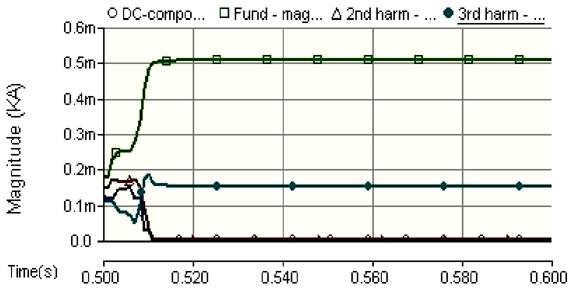

Fig. 15 FFT magnitudes for current in Ph (A).

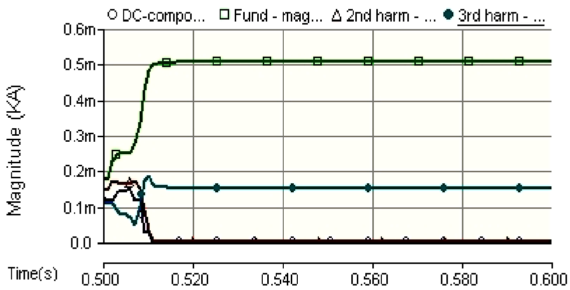

Fig. 16 FFT magnitudes for current in Ph (B).

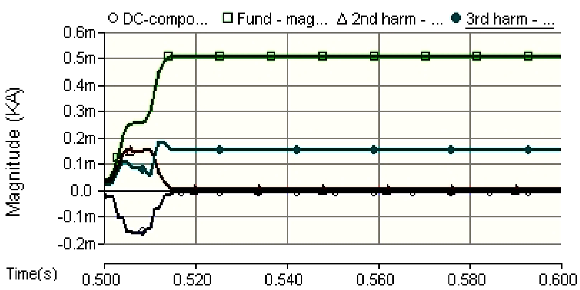

Fig. 17 FFT magnitudes for current in Ph (C).

The harmonic contents are decreased in DC component, second and third harmonics in all phases.

6.2 Controlled switching with residual flux

It is known that the sum of the residual flux must be zero for core-type (3-leg) transformers or for the transformer which has at least one delta winding. In this case under study two techniques are applied to reduce inrush magnetizing currents.

Rapid closing technique closes one phase first and closes the remaining two phases within a quarter cycle. If the residual flux pattern is known, the best strategy is to energize the first phase with the lowest residual flux. Depending on the polarity of the residual flux in the other two legs, the dynamic core fluxes and prospective fluxes will be equal in certain moments following closing of first pole. These instants offer an opportunity to energize the remaining phases without core saturation. Knowledge of the residual flux in all three phases, independent pole breaker control, and model of transformer transient performance are required [7]-[8].

The rapid closing technique provides significant reductions in peak inrush current for breaker closing deviations of 0.5 to 2.0 ms at the same condition of residual flux pattern. Magnetizing inrush currents are eliminated as observed in Fig. 18.

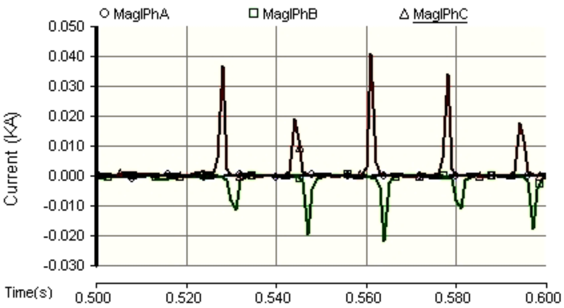

Fig. 18 Reduction of Inrush with residual flux by rapid closing strategy

By applying Fast Fourier Transform (FFT) for three phase magnetizing current to get magnitude contents up to third harmonics as a function of time are illustrated in Fig.19 to Fig.21.

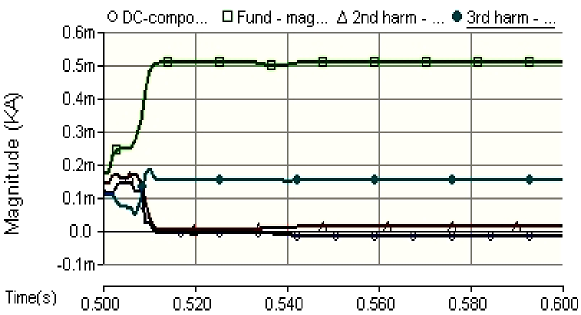

Fig. 19 FFT magnitudes for current in Ph (A).

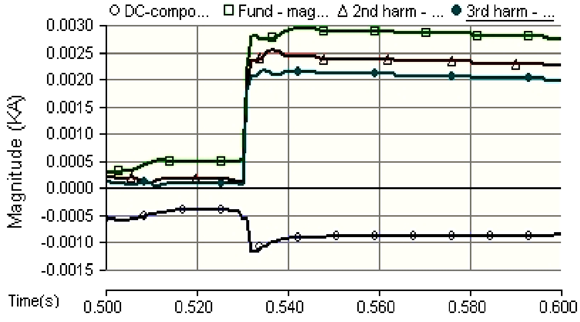

Fig. 20 FFT magnitudes for current in Ph (B).

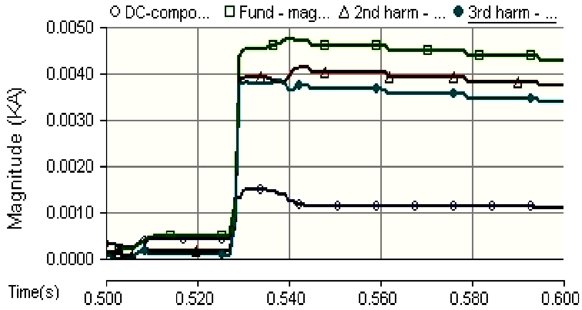

Fig. 21 FFT magnitudes for current in Ph (C).

The harmonic contents are decreased in DC component, second and third harmonics in all phases.

Delay closing technique closes one phase first and the remaining two phases after 2–3 cycles in simultaneous closing, all phases are closed at the same time. This means that if one phase is energized when the residual and prospective core fluxes are equal, and that the closing of the last two phases is delayed a few cycles, residual flux can be ignored on these two phases. This technique is limited to cases where the residual flux equals zero in one phase, and high in the other two which with opposite polarity. It requires knowledge of the residual flux in one phase only, and independent pole breaker control, but does not require any transformer parametric data [7]-[8].

The results of simulations for the delayed closing technique showing the influence of closing accuracy are illustrated in Fig.22.

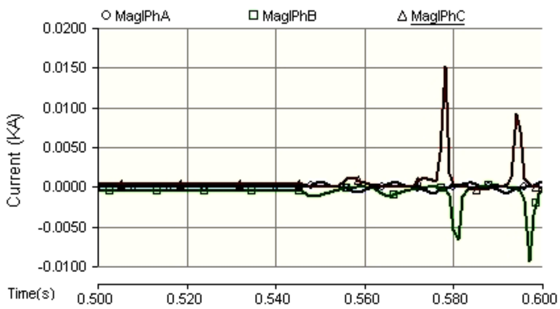

Fig. 22 Reduction of Inrush with residual flux by delay closing strategy.

Analyzing by Fast Fourier Transform (FFT) for three phase magnetizing current to get magnitude contents up to third harmonics as a function of time are illustrated in Fig.23 to Fig.25.

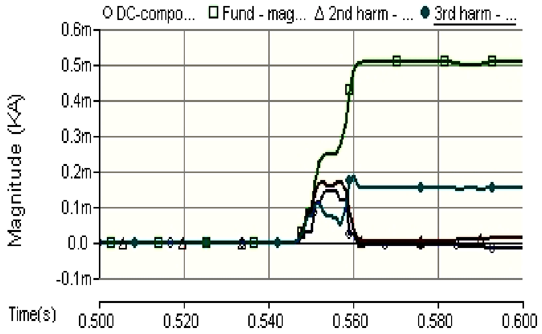

Fig. 23 FFT magnitudes for current in Ph (A).

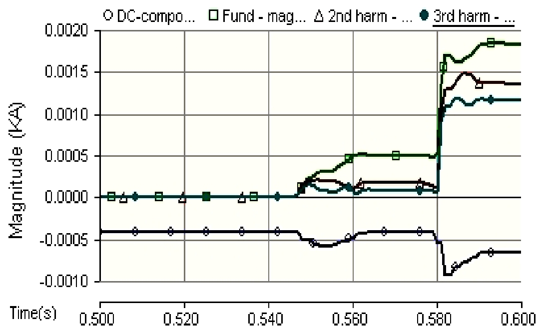

Fig. 24 FFT magnitudes for current in Ph (B).

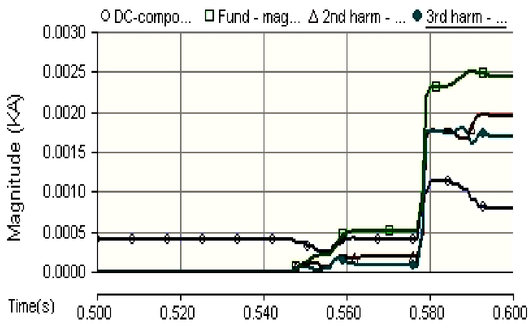

Fig. 25 FFT magnitudes for current in Ph (C).

The harmonic contents are decreased in DC component, second and third harmonics in all phases. These results indicate considerable improvements over the 2% value for the uncontrolled case of 2.5 kA. The inrush currents is reduced over 90%. For a circuit breaker with a statistical deviation of 1.0 ms, the resulting inrush currents range less than the rated current for this transformer model. The controlled closing of transformer became recently a practical method of reducing the magnitude of inrush current. It is much cheaper than the pre-insertion resistor technique but the scheme needs to determine the residual flux of transformer cores to work effectively

7. CONCLUSIONS

Precise investigation of inrush transients during the energization of large power transformer has been performed. The pre-insertion resistors of 1800 Ω during 10 ms on 230 kV circuit breakers would allow suppressing inrush transients during the energization of 230/66 kV transformer.

The transformer controlled switching using the measured residual flux is clearly demonstrated as economical and reliable alternative methods. Rapid and Delayed closing techniques have been proposed for controlled energization of three-phase transformers for independent pole breaker. Energization with low inrush current can be achieved even with circuit breakers which have a built-in time delay in the operating time of the opening/closing poles.

Finally, the inrush current amplitude can be easily kept below or in the range of the transformer nominal current making the stresses caused by the energization less or equal to that of the normal, steady-state operation. Fast Fourier transform also ensures that harmonics magnitudes have been decreased by using controlled switching methods so that relays can be set without harmonic restraint and keep protection system to sensitize during transformer energization to differentiate between fault and inrush phenomena. When proper controlled methods are being used and the differential relay became unblocked, any internal faults can be detected and cleared quickly during energization of transformer.

8. REFERENCES

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