REDUCTION OF TRANSFORMER INRUSH CURRENT BY CONTROLLED SWITCHING METHOD

Abhilash.G.R
Vocational Teacher ECT,
Ksmvhss Edavattom, Kollam

Smitha K.S
Assistant Professor
College of Engineering
Trivandrum

Abstract -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 misoperation and reduced power quality on the system. Controlled transformer switching can potentially reduce these transients if residual core and core flux transients are taken into account in the closing algorithm. This paper explores the theoretical consideration of core flux transients. Based on these studies algorithms were developed which allow controlled energisation of most transformers with reduced inrush current.

Key words :

inrush current (280), residual flux (200), core flux (106), transformer core (60), power transformer (60), applied voltage (50), dynamic core flux (47), transient inrush current (47), transformer inrush current (47), core saturation (40), flux showing worst energization (40), transient inrush (40), simulated output (40), voltage peak (40), asymmetric flux (40), phase transformer (40)

1. INTRODUCTION

Uncontrolled energization of large power transformers may result in large dynamic flux and drive the transformer core into saturation. Operating the magnetizing branch in that highly nonlinear region may produce high amplitude magnetizing inrush current that are rich in harmonics and have a high direct current component, as well.

The effect of inrush current is more when the transformer is energized under no load or light load conditions. Their magnitude may some times reach up to 10-20 times the rated current. They are normally short in duration, usually of the order of milliseconds. In

The amplitude of the magnetizing current depends mainly on two factors: the residual flux in the magnetic core and the transient flux produced by the time-integral of the sinusoidal supply voltage.

Energizing a transformer at zero crossing of the sinusoidal voltage the prospective magnetizing flux and current will have their peak values with 90 electrical degrees delay. To satisfy the principle of the flux steadiness, it is necessary to build an equalizing flux with the same magnitude, but opposite polarity to the prospective flux. This way the transient flux follows the residual flux and reaches its highest amplitude 180 electrical degrees later. At that point the core is fully saturated and a high amplitude inrush current appears because the instantaneous inductance of the core is very low (equal to the air-core inductance of the winding) in that region.

The phenomenon of magnetizing inrush current has always been a concern in the power industry. The magnetizing inrush current, which occurs at the time of energization of a transformer, is due to the temporary over fluxing in the transformer core. Its magnitude mainly depends on switching parameters such as the resistance of the primary winding, the point-on-voltage wave (switching angle), and the remnant flux density of the transformer at the instant of energization.

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inrush currents are highly unbalanced among the three phases.

2. INRUSHCURRENT DEFINITION

When a transformer is switched on to a line at times circuit breaker trips , or a fuse blows. This happens even if the transformer is on no load, ie its secondary is opened. This is due to the heavy current drawn by the transformer

Inrush current is described as the magnitude of instantaneous current drawn by the line frequency power transformer at the time when the core is energized. Random power transformer energization can create large flux asymmetries. That is if the transformer is switched on when the ac voltage waveform is going through its zero value then the current drawn by the transformer will be very high value .ie the transformer is switched on at the instant of zero value of voltage waveform, the total transformer will becomes two times the maximum flux.

3. FORMATION OF ASYMMETRIC FLUX DURING ENERGISATION

When a transformer is energized the instantaneous magnitude of core flux at the instant of energisation is the residual flux. The amount of offset of sinusoidal flux generated by the applied voltage is dependent on the point of voltage wave where the transformer is energized.

Normally power transformers are operated with the peak core flux at the ‘knee’ of the transformer core saturation characteristics. The sinusoidal core flux is the integral of applied voltage.

Now considering a continuously operating transformer. Here the relation between voltage current and flux will be

$$e = \frac{d\phi}{dt}$$

Voltage applied is rate of change of flux, ie flux can be expressed as the integral of applied voltage $\phi = \int e\, dt$

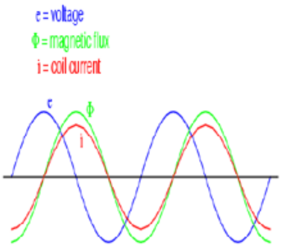

Fig. 1 **Relation between voltage and flux - continuously-operating Transformer**

If the transformer is energized at voltage peak, then the voltage, current and flux will be as shown in Fig. 2

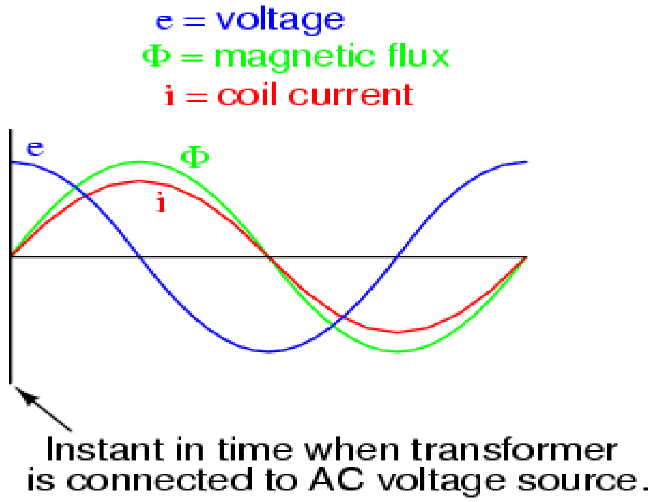

Fig. 2 Relation between voltage and flux – Transformer energized at
voltage peak

If the transformer is energized at the instant when the instantaneous value of voltage waveform is zero, then as the flux is the integral of applied voltage, flux cannot instantaneously rise to its peak value, it starts from zero and reaches 1pu after ¼ cycle of voltage and continues to increase until it becomes 2pu at ½ cycle after switching. This effect is called doubling effect. This is the cause of asymmetric flux.

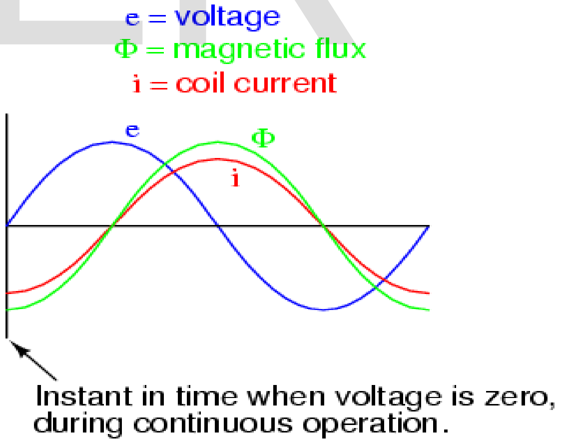

Fig. 3 Relation between voltage and flux – Transformer energized at
voltage zero

The normal flux leads the transformer to operate in linear region ,where the magnetizing current will be in the rated value. But flux asymmetry leads the transformer to operate in saturation region and a high inrush current is produced during energization.

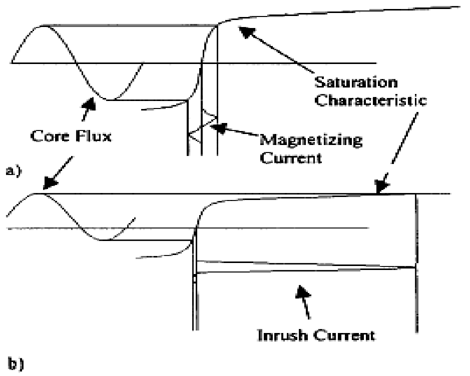

Fig. 4 a) Symmetrical Flux b) Asymmetrical flux

The most commonly used transformer core model utilizes a resister to represent loses, connected in parallel with an inductor that represents magnetizing current. If the flux is symmetrical the magnetizing current produced will be small, compared to that of large current produced at the time of asymmetric flux.

4. RELATION BETWEEN RESIDUAL FLUX AND INRUSH CURRENT

4.1 Residual flux

Looking at a single-phase transformer and neglecting leakage and other magnetic air fluxes as well as the coil resistance, the magnetic core flux Φ_{core} is related to the coil voltage u_{coil} by Equation (1).

$$u_{coil}(t) = N_{coil} \frac{d\Phi_{core}(t)}{dt} \quad (1)$$

When de-energising the transformer out of no-load steady-state, the current will be interrupted at time t_{open} and the residual flux Φ_{Res} is calculated using Equation (1)

$$\Phi_{Res} = \frac{1}{N_{coil}} \int^{t\,open} u_{coil}(t)dt \quad (2)$$

With

$$u_{coil}(t) = U_0 \sin(\omega_0 t) \quad (3)$$

and assuming steady-state, Equation (2) becomes

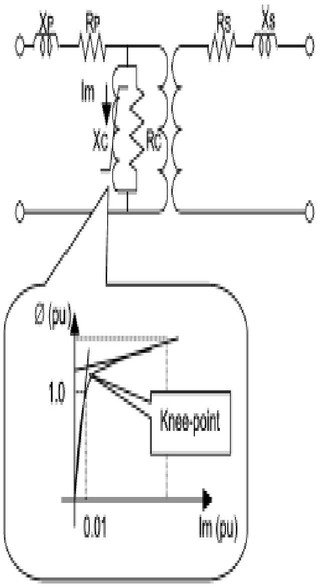

Fig. 5 Asymmetric flux the point of operation is above the ‘knee point’.

Then it is clear from Fig. 5 that during asymmetric flux the point of operation is above the

$$\Phi_{Res} = -\Phi_0 \cos(\omega_0 t_{open}) \quad (4)$$

Because the magnetising current of transformers is often smaller than the chopping current of the circuit breaker, the current will be interrupted prior to its natural zero crossing and the opening time t_{open} of Equation (4) can take any value. As a consequence of this, the residual flux can reach any value between -1 p.u. and 1 p.u.. Because no magnetising curve is able to exceed the maximum magnetising characteristic given by the properties of the core material, the residual flux margin will shrink to the range between the two points of the maximal residual flux $\pm\Phi_{Res,max}$ (Fig. 6). In real substations the maximal accessible residual flux is further reduced to a value of approximately 0.9 p.u. due to transients during de-energisation as seen in Figure 6.

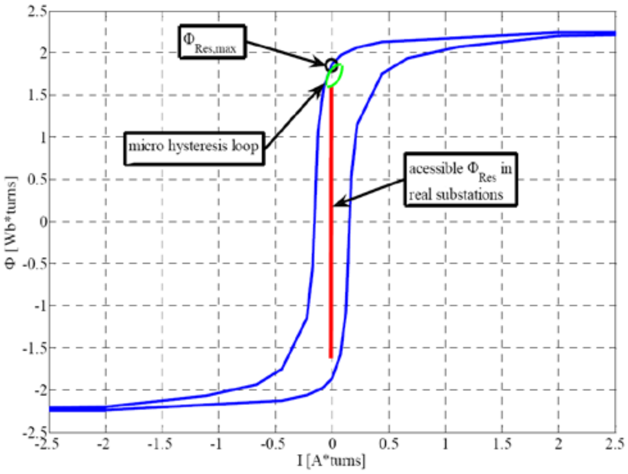

Fig. 6 Maximum magnetising characteristic and range of accessible residual fluxes

4.2 Formation of inrush current

If a transformer is energised at a random instant, it is possible that no transient inrush current will occur; but mostly transient inrush currents will arise. This happens because transient inrush currents depend not only on the instant of energisation, but also on the residual flux of the previous de-energisation.

Using equations (1) and (3), the magnetic flux during the first period of energisation can be calculated analytically neglecting damping effects (core losses, winding resistance)

$$\Phi_{core}(t) = \frac{1}{N_{coil}}\int_{t_{close}}^{t} u_{coil}(t)dt + \Phi_{Res}$$
$$= -\Phi_0 \cos(\omega_0 t) + \underbrace{\Phi_0 \cos(\omega_0 t_{close}) + \Phi_{Res}}_{\Phi_{offset}}$$

(5)

Later the influence of damping becomes more significant and decreases Φ_{offset} towards zero. When Φ_{offset} reaches zero, the transient phenomenon has finished and the steady-state magnetising current will flow. Looking at Equation (5), it is easy to see that an energisation at the positive voltage zero crossing with a residual flux of 0.9 p.u. respectively at the negative voltage zero crossing with a residual flux of -0.9 p.u. will result in the highest value of Φoffset. A value of 2.9 p.u. respectively -2.9 p.u. is reached which is far above the saturation point of the maximum magnetising characteristic. Thus, the transformer core is driven into saturation and can be considered as an air-core inductance that leads to high inrush currents (Figure 7).

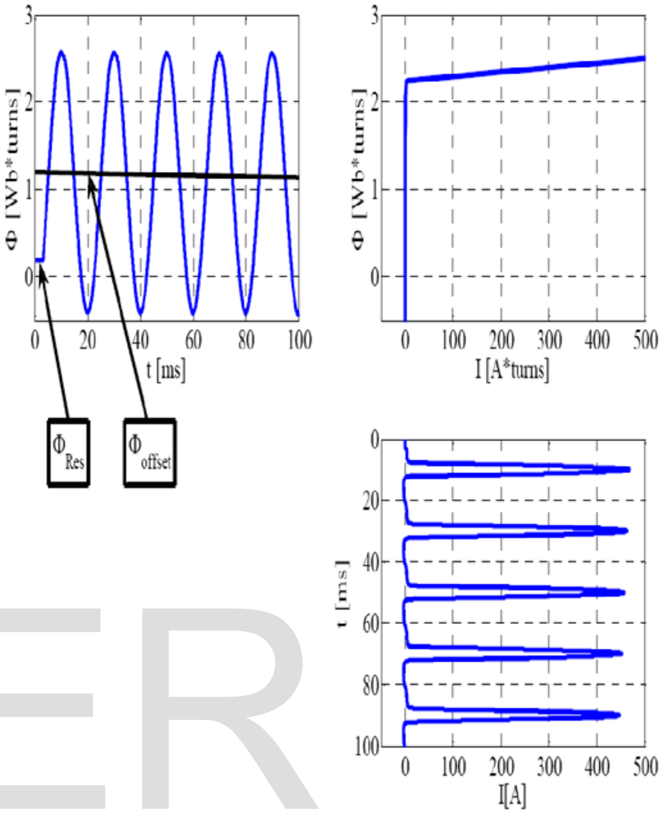

Fig. 7 Magnetic flux Φ and inrush current I

5. METHODS TO REDUCE TRANSIENT INRUSH CURRENTS

The phenomenon of transient transformer inrush currents was first published by Fleming in 1892. Anyhow, up to 1988 the only method to reduce inrush currents was the installation of pre-insertion resistors. This is however not the best solution because on the one hand they must be included in the circuit breaker design and need a lot of maintenance and on the other hand they just reduce the inrush currents but do not affect the cause of the phenomenon.

Introduction of an air gap to the magnetic circuits, which can lower the permeability and round out the shape of hysterical loop. But producing gapped cores is expensive and labour intensive. Gapped cores lose many of the benefits of standard or toroidal cores increasing loss and increase existing current after enersization. Ultimately lose gapping causes the transformer to fire, lower efficiency larger size, more weight and greater cost.

Another simple way to reduce inrush current is to insert a resistance in series with the transformer at the beginning of switching and cut it off after a short time to allow normal operation or to use a NTC items for which will provide high resistance during energization and low resistance after a time delay and does not affect normal operation. But any of these external components for inrush control also may add series impedance to the primary circuit which leads to lowering the efficiency of transformer. The external component connected step can some time may be ineffective under conditions of low line or momentary power outages.

The Sequential Phase Energization Method makes use of the imbalance characteristics of the inrush current. If a transformer is Y grounded at the energization side, its neutral current will also contain the inrush current. Therefore if a resistor is inserted into the transformer neutral, it may reduce the magnitude of the inrush current in a way similar to that of the series-inserted resistor. Since the inrush current is unbalanced among three phases, the grounding resistor connected at the transformer neutral will carry the current and contribute to the damping of the transients. The resistor can also reduce the voltage imposed on the transformer core reducing the core saturation.

With the strategy called “point-on-wave controlled switching” the transformer is energised phase by phase at the corresponding voltage peak. Assuming zero residual flux in the transformer core, the moment of energisation is optimal and no transient inrush current will arise. Even though valuable improvements in the reduction of transient inrush currents can be achieved with this quite simple algorithm, there exists one drawback: The assumption of zero residual flux is solely true, if the transformer will be de-energised under no-load and if there is no current chopping as well as the transformer has no magnetic coupling between the phases.

Subsequent studies improved the concept of Moraw et al. so that the drawback could be removed. Finally a much more flexible method called “controlled switching taking into account the residual flux” was presented by Brunke and Fröhlich. Today, this is the most promising approach because it can be used in every switching case and for any core and winding-configuration of power transformers. If the residual flux is known exactly, the transient inrush current will be eliminated completely. Despite these results, the algorithm is hardly deployed in substations.

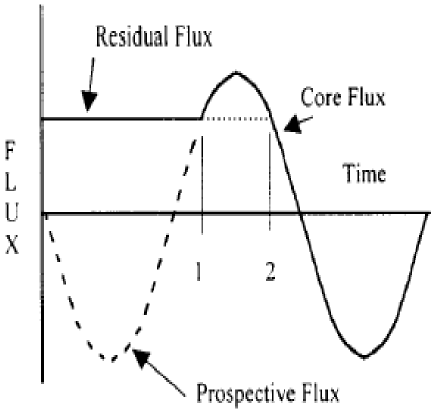

Fig. 8 Optimal energization of a single phase transformer is shown. Optimal energization points exist at times (1) and alternate optimal time (2)

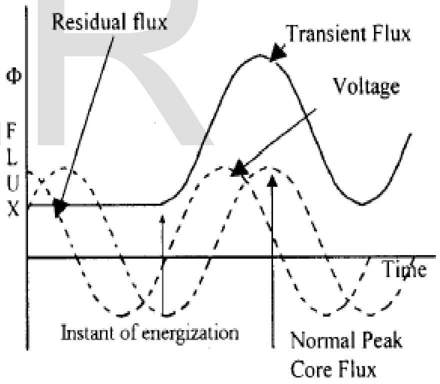

Fig. 9 Core flux showing worst energization case for this residual condition

When a transformer is energized the instantaneous magnitude of core flux at the instant of energization is the residual flux. The amount of offset of the sinusoidal flux generated by the applied voltage is dependent upon the point of the voltage wave where the transformer is energized. This is illustrated in Figure 9. The peak core flux Φ can therefore reach a value of $2\Phi_{normal} + \Phi_{residual}$. Fig. 9. Core flux showing worst energization case for this residual condition. For the most severe case shown in Figure 9, where energization was at a voltage zero, the peak transient core flux is more than two times higher than the peak normal core flux. The core has been driven far into saturation. This asymmetrical saturation results in the typical inrush current transient characterized by a high harmonic content and a direct current component.

Although 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 energization.

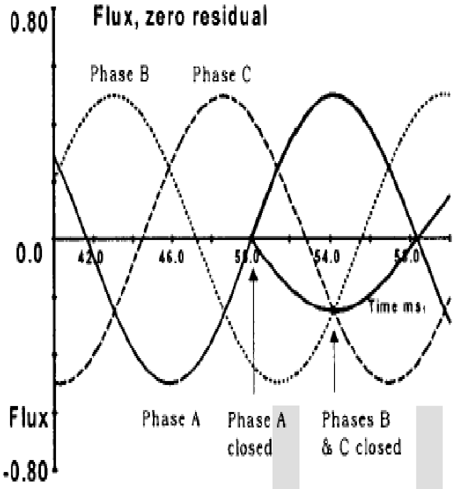

Fig. 10 3-Phase Switching Strategy

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 interactions between the phases. In these other transformers, after one phase has been energized, 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. Figure 4 shows an example of a transformer with three separate cores connected by a delta winding. First, assuming that the residual flux is zero in all three phases, then the optimal instant for the first phase to close is when the prospective flux is equal to zero. This instant is at a voltage peak. After the first phase closes, a voltage is generated in each of the other two phases of the delta winding. These voltages are each one half the magnitude and 180 degrees out of phase of the voltage of the fully energized phase. The flux created in the cores of the other two phases is dynamic core flux.

6. SIMULATION RESULTS

1. Simulation has been done in SIMULINK for a 3-phase 250 MVA, 400/110kV transformer which produces inrush current in simultaneous closing. The simulated output is shown in Fig. 13.

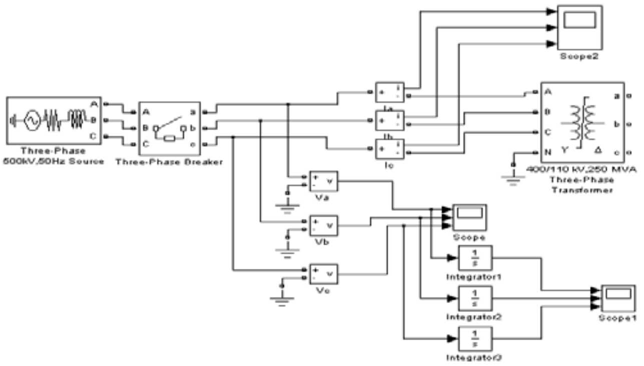

Fig.11. Simultaneous closing of a 3-phase transformer

2. Simulation has been done for 3-phases of a transformer with neutral resistor. The simulated outputs are shown in Figs. 14 and 15.

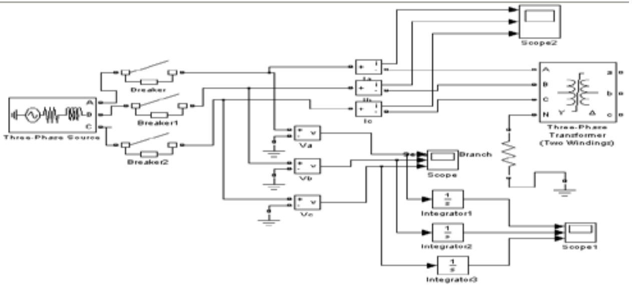

Fig. 12 Reduced inrush current by connecting neutral resistor

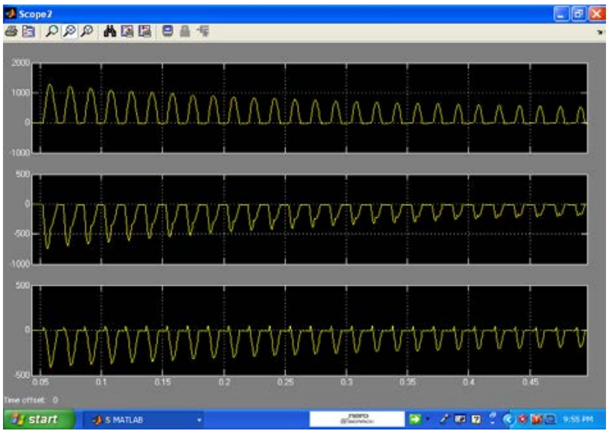

Fig. 13 Simulated output producing inrush current

Fig. 14 Simulated output of sequential switching

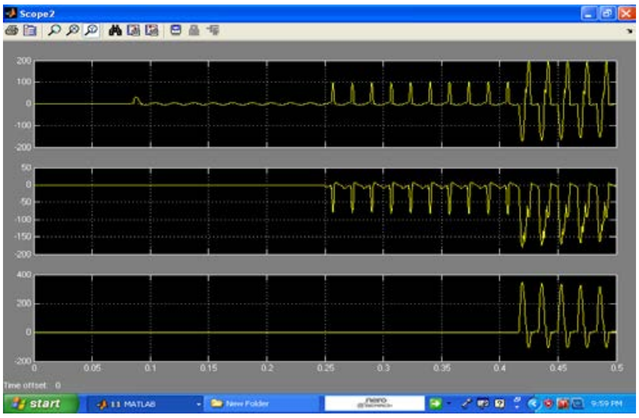

Fig. 15 Reduced inrush current by connecting neutral resistor

7. CONCLUSION

- Closing each winding, when the prospective and dynamic core fluxes are equal, results in an optimal energization, without core saturation or inrush currents.
- Harmonics are greatly reduced.Voltage sag is reduced which would otherwise badly affect the power system esp., thyristor controlled machinery.
- Stability of the power system is improved.By finding out the instant at which the residual flux and witching method is to be done.

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