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Study on Power Transformer Inrush Current

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Abstract: *Transformers are the key components for electrical energy transfer in a power system. Stability and security of transformer protection are important to system operation, which otherwise may lead to defeating transformer protection. Inrush Current in transformer often gets less importance compared to other faults/effects. It may occur whenever the transformer is energised. Though the magnitude of inrush current may be less compared to short circuit current, the frequency and duration of inrush current is more frequent, leading to more adverse effects compared to other faults. This paper contains the basic principles, fundamental theory of inrush current and its effects. The various mitigation techniques for addressing the above problem are also discussed.*

Keywords: *Flux, Inrush Currents, Switching angle, Transformers*

I. Introduction

Transformers belong to a class of vital and expensive components in a power system. The large power transformers are considered to be important and very expensive asset of electrical power system. They are the static and passive devices for transforming voltage and current. The knowledge of their performance is fundamental in determining system reliability and longevity. They are energised using circuit breakers.

In a practical power system, when a transformer is switched on to the line by switching of these circuit breakers, it produces high current in the transformer and cause the circuit breaker to trip or it can blow off the fuse. Another major circumstance were the same situation can arise is when the transformer is on no load with its secondary open. The basic reason for the above mentioned problem is the heavy magnetising current drawn by the transformer. The value of the current may reach a level exceeding the full load current. This current is known as the Inrush Current. Inrush Current is a form of over current that occurs during energisation of a transformer and is a large transient current which is caused by part cycle saturation of the magnetic core of the transformer. For power transformers, the magnitude of inrush current is initially 6 – 10 times the rated load current. It slowly decreases by the effect of oscillation damping due to winding and magnetising resistance of the transformer as well as the impedance of the system it is connected to, until it reach the normal current value [1]. The excitation characteristics of the transformer core are expressed by the non – linear relationship between the flux and the magnetising current. In the steady state the transformers are designed to operate below the knee point of their saturation curve. However, when transformers are energised, due to the effect of inrush current, the flux increases to a high value in the saturation region such that the magnetising current increases drastically [2]. The transformer inrush current is considered to be a critical problem in the practical power systems. Due to its high current it can cause effects like insulation failure, mechanical stress on the transformer windings [2], introduction of power quality issues [3], and can also affect the sensitive protection devices [4]. Many researchers have worked and analysed the different ways to calculate and mitigate this inrush current. The various factors affecting the magnitude of inrush current is [3]:

- The value of residual flux in the transformer core.
- The non – linear magnetising characteristics of the transformer core.
- The phase of the supplying source voltage at the instant of energising the transformer.
- The impendence and short circuit power of the supplying source.

As the power grid is moving towards accommodating more distributed generations, the need to study about the causes and effects of t\inrush current is evident.

II. Inrush Currents

Inrush Current, Input Surge Current or Switch – On Surge Current is the maximum, instantaneous input current drawn by an electrical device when it is first turned on. It can last for few cycles of the input waveform. When electrical power transformer runs normally, the flux developed in the core is quadrature with the applied voltage. Inrush current occurs in a transformer whenever the residual flux does not match the instantaneous value of the steady – state flux [5].

For explaining the cause of inrush current in transformers primary winding when connected to an AC voltage source, we consider the equation (1);

$$v = \frac{d\emptyset}{dt} \qquad (1)$$

where Ø and v are the instantaneous flux in transformer core and voltage drop across the primary winding respectively.

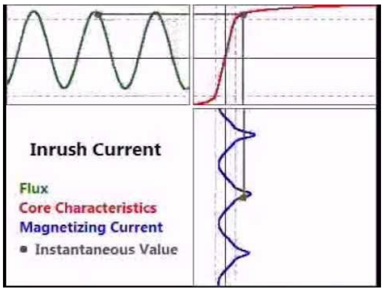

Figure 1: Generation of Inrush Current in a Transformer [5]

From equation (1), we can understand that the voltage cross the transformer primary is proportional to the rate of change of flux in the transformer core. The flux because of the non – linear characteristics of the magnetising curve causes the saturation of the transformer core. The flux waveform can be treated as the integral of the voltage waveform. In a continuously operating transformer, these two waveforms are 90° shifted. When voltage is at zero, the flux waveform will be at its negative peak. This is not the case during energisation of the transformer. At this time, the flux will start from zero.

The figure (1) shows the generation of inrush current in a transformer. As we can see, in certain cases the flux exceeds the knee point resulting in large magnetising current which can be even 10 times as that of the rated current in the transformer.

According to Faraday's law of Electromagnetic Induction, the voltage induced across the winding is given by:

$$e = \frac{d\emptyset}{dt} \qquad (2)$$

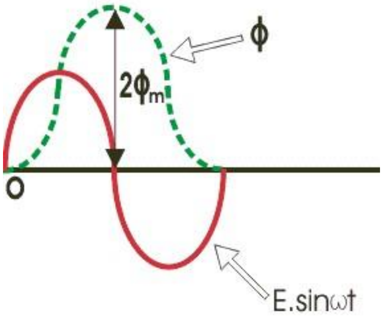

Figure 2: Voltage - Flux Graph

Where Ø is the flux in the core. Hence the flux is the integral of the voltage. If the transformer is switched on at the instant of voltage zero, the flux is initiated from the same origin as that of the voltage. Therefore, the value of the flux at the end of the first cycle will be:

$$\begin{aligned} \emptyset' &= \frac{E}{\omega}\int_{0}^{\Pi} \omega \sin \omega t . dt \\ &= \emptyset \int_{0}^{\Pi} \sin \omega t \, d(\omega t) \\ &= 2\emptyset_{m} \end{aligned}$$

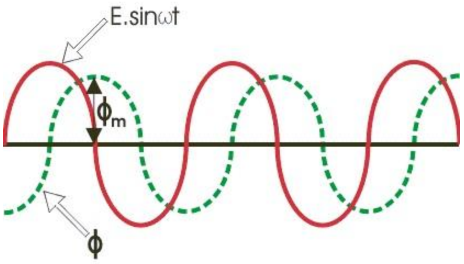

Figure 3: Voltage - Flux Graph

Where $\emptyset_m$ is the maximum value of the steady – state flux. The transformer core generally gets saturated above the maximum steady – state value of flux. During switching on of the transformer, the maximum value of flux will increase to double the steady state maximum value. As the core becomes saturated, the current required to produce rest of the flux will be very high. So the transformer primary will draw very high peak current [5].

III. Factors affecting Inrush Current

The inrush current phenomenon occurs due to temporary over fluxing of the transformer core. This may depend upon [6]:

- Switching instant on the voltage waveform at which the transformer is energised.
- The magnitude and polarity of the residual flux present in the transformer during re – energisation.
- Rating of the transformer.
- Total resistance of the primary winding.

3.1. Starting Phase angle of Voltage

The starting phase angle of voltage depends on when the transformer is switched on. The equation of flux can also be expressed as:

$$\emptyset = \emptyset_{max}\sin(\omega t + \alpha) + \emptyset_{residual} + \emptyset_{max}\sin\alpha \qquad (3)$$

Where

$$\alpha = \Theta - \frac{\Pi}{2} \qquad (4)$$

From equation (3), it is clear that Ø depends upon the residual flux and the switching angle. When the residual flux in the transformer is zero and the switching angle of voltage has 90°, then the flux will be:

$$\begin{aligned} \emptyset &= \emptyset_{max}\sin(\omega t + 0) + 0 + \emptyset_{max}\sin 0 \\ \emptyset &= \emptyset_{max}\sin(\omega t) \qquad (5) \\ \emptyset &= \emptyset_{max} \end{aligned}$$

If the transformer is switched on when switching angle of voltage is zero degree, then the flux will be:

$$\begin{aligned} \emptyset &= \emptyset_{max}\sin\left(\omega t + \frac{\Pi}{2}\right) + 0 + \emptyset_{max}\sin\frac{\Pi}{2} \\ \emptyset &= \emptyset_{max}\cos(\omega t) + \emptyset_{max} \qquad (6) \\ \emptyset &= 2\,\emptyset_{max} \end{aligned}$$

Therefore, when the voltage switching is 90°, the flux produced is the minimum and hence the current drawn will be minimum.

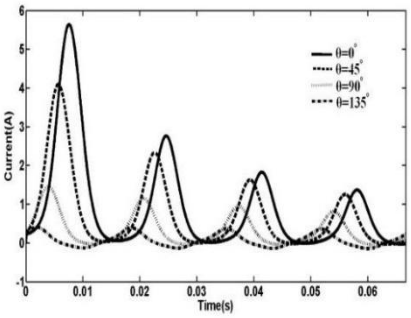

Figure 4: Effect of switching angle variation on amplitude of inrush current

3.2. Residual Flux in the core

The practical transformers are made up of ferro – magnetic materials and therefore will have the effect of hysteresis. From the figure (5) and figure (6), we can draw the optimum closing time with no inrush current is when the residual flux is zero and the switching angle of voltage is 90°.

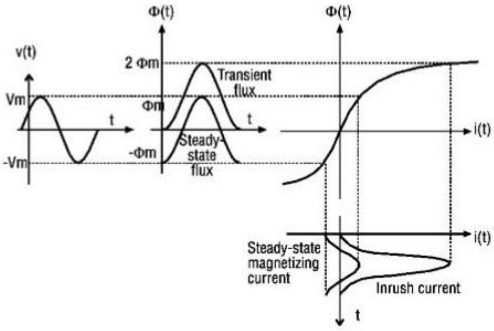

Figure 5: Inrush current for twice flux

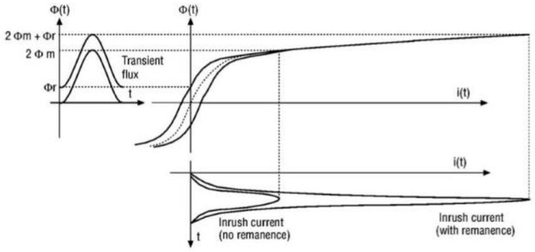

Figure 6: inrush current for twice plus residual flux

3.3. Source Resistance

Figure (7) shows the resistance on the amplitude of inrush current. As the source resistance increases, the amplitude of inrush current decreases and also leads to faster decay of amplitude in inrush current [6].

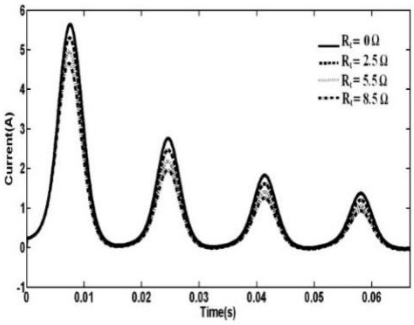

Figure 7: Effect of source resistance on the amplitude of inrush current

IV. Inrush Current Mitigation Techniques

4.1. Neutral Earthing Resistors

Optimal neutral resistor on the transformer can significantly reduce the inrush current magnitude and duration. The neutral earthing resistor limits the current going through the neutral which in turn controls the inrush of current during the first and second phase energisation.

4.2. Pre – Insertion of resistors

Resistors are typically inserted into the capacitor – energising circuit for 10 – 15msec prior to the closing of the main contacts, through the closing of an additional set of contacts. Synchronisation between the resistor and the main contact is required and is usually achieved by connecting the resistor contact rod directly to the main contact control rod. Once the switching has been achieved, the resistor is then switched off from the circuit.

4.3. Controlled Switching

The high inrush current can lead to the mal – operation of relays and other protecting devices. With this result, there are chances of high mechanical stress on to the transformer winding due to the magnetic forces and can result in power quality issues. The use of resistors can only reduce the magnitude of inrush currents, whereas the use of controlled switching technology can limit the inrush current to greater extend. This strategy is also known as Point – On Wave Controlled Switching [9].

In this method, simply the transformer will be energised phase by phase at the corresponding voltage peak (switching angle of voltage will be Π/2). This strategy of switching seems to be accurate and reliable. However, the drawback of such a mechanism is the cost involved in the implementation of the technique. The practical power system employs the use of gang operated circuit breakers. When using the point – on wave switching strategy, the circuit breakers are needed to be replaced with single pole circuit breakers. The figure (8), shows the block diagram of this strategy.

This paves the way for the three pole switching strategy. This is done by using a gang operated circuit breaker, a control circuit to monitor the voltage waveform and send a closing signal to main pole at the zero crossing of the voltage waveform. The other poles are mechanically linked to the main pole and are staggered by 120° apart so that all poles are closed at the zero crossing of the voltage waveform.

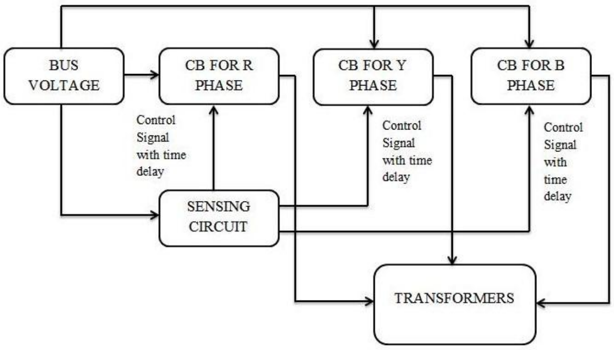

Figure 8: Block diagram for point - on wave controlled switching

V. Conclusion

When a transformer is energised from a standard power source it draws high charging current which can be as high as 10 times the rate current. This high current can lead to deterioration of the transformers life. The various factors affecting this inrush current are studied in this paper. Various mitigation techniques based on this study are also dealt with. Of those strategies, the controlled 0switching technique is found to be more accurate and reliable.

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