Mitigation of Inrush Current For Single Phase Transformer by Control Switching Method

Amit Kumar Singh.
PG Scholars, Power system département
Sardar Vallabh Bhai Patel Institute of Technology Vasad

Prof. Sanjay Patel
Asst. Professor in Electrical department
Sardar Vallabh Bhai Patel Institute of Technology Vasad

ABSTRACT
Paper present Inrush phenomena in single phase transformer the magnitude of inrush current reach as high as six to ten times the rated magnetizing current which may cause transformer core saturation. The inrush current is modeled in MATLAB simulink for single phase saturable transformer under different conditions and also the best switching (control switching) moment is found for mitigation of Inrush current by giving delay and advance in the reclosing of breaker.

I-INTRODUCTION
Inrush current is also called as transient current which may occur when transformer is energized or switching of the heavy lighting and highly inductive load. The magnitude of inrush current is depends residual flux, angle of voltage during energization of transformer, source strength and leakage impedance. The large Inrush current causes serious electromagnetic stress on system and shortens the life of transformer, undesired operation of protective equipment. In recent years, various protective systems for transformers, based on the differential relaying system, were developed. Various techniques like pre-insertion of resistor, point on wave, series compensation based, Auxiliary loading. It is necessary with the help of complex circuits or microcomputers and proposed to distinguish inrush current from fault current. The transformer these days are designed to bear with large electromagnetic stress impact caused by the inrush current. Inrush current may arise power quality problem i.e. voltage sag, harmonic .The main factors affecting the magnetizing inrush current are angle of voltage at the instant of energization, magnitude and polarity of residual magnetism, source strength. But inrush current also depend flux carrying capability of transformer core material. In addition total resistance of the primary winding, air-core inductance, the core geometry of transformer core and the maximum flux carrying capability of the core material is also affected inrush current. The inrush current can be reduced or mitigated by various methods best amongst them is control switching.

II- INRUSH CURRENT IN TRANSFORMER
When an electrical power transformer is switch on from primary side, with keeping its secondary circuit open, it acts as a simple inductance. When transformer runs normally, the flux produced in the core is in quadrature with applied voltage as shown in the figure below. That means the flux wave will reach its maximum value at 1/4 cycle or π/2 angle after reaching maximum value of voltage wave. Hence as per the waves shown in the figure 1, 2 & 3, at the instant when, the voltage is zero; the corresponding steady state value of flux should be negative maximum. But practically it is not possible to have flux at the instant of switching on the supply of transformer. This is because, there will be no flux linked to the core prior to switch on the supply. The steady state value of flux will only reach after a finite time, depending upon how fast the circuit can take energy.
This is because the rate of energy transfer to a circuit cannot be infinity. So the flux in the core also will start from its zero value at the time of switching on the transformer. According to Faraday’s law of electromagnetic induction the voltage induced across the winding is is given as $e = \frac{d\varphi}{dt}$. $\varphi$ is the flux in the core. Hence the flux will be integral of the voltage wave.

\[ \varphi = E \int \sin(\omega t) \, dt \]

If the transformer is switched on at the instant of voltage zero, the flux wave is initiated from the same origin as voltage waveform, the value of flux at the end of first half cycle of the voltage waveform will be,

\[ \varphi' = E/\omega \int_0^\pi \omega \sin(\omega t) \, dt = \varphi m \int_0^\pi \sin(\omega t) \, d\omega t; \varphi m' = 2\varphi m \]

III-MATHEMATICAL MODEL FOR TRANSFORMER

In this section, we describe transformer original model and equation for calculate maximum value of Inrush Current. The transformer behavior during phase energization can be modeled through the simplified equivalent electric circuit of transformer shown figure .4

\[ \text{Figure 1 Voltage Flux wave form} \]

\[ \text{Figure 2 Voltage Flux waveform initial switching} \]

\[ \text{Figure 3 Inrush current as propionate to B/H} \]

\[ \text{Figure 4 Equivalent Circuit of transformer} \]
As shown in figure 1, \( r_p \) and \( L_p \) present primary resistance and leakage reactance. \( L_m \) represents the nonlinear inductance of the iron core as function of the magnetizing current. Secondary side resistance \( r_{sp} \) and leakage reactance \( L_{sp} \) as referred to primary side are also shown. \( v_p \) and \( v_s \) represent the primary and secondary phase to ground terminal voltage respectively. From the figure 4:

\[
V_p = V_m \sin(\omega t + \theta) = i_p r_p + N_1 \frac{d\phi_1}{dt}
\]

Where \( \theta_0 \) is the phase of primary voltage at \( t = 0 \), \( i_p \) is magnetize current, \( \phi_1 \) is core flux and \( N_1 \) is number of turn in primary side. Therefore we have:

\[
V_m \sin(\omega t + \theta) = (N_1 \phi_1/L_1) + N_1 \frac{\phi_1}{dt}
\]

where \( L_1 \) is primary inductance. After solve Eqn.2 for \( \phi_1 \):

\[
\phi_1 = (\phi_0 \cos \theta \mp \phi_0) e^{-\frac{t}{r_p}} - \phi_0 \cos(\omega t + \theta)
\]

Where \( \phi_0 \) is maximum flux and \( \phi_0 \) is residual flux. At \( \theta = \pi/2 \) in Eqn. 3 we will get:

\[
\phi_1 = \phi_0 e^{-\frac{t}{r_p}} + \phi_0 \sin(\omega t)
\]

In this case transient flux exists with \( \phi_0 \) magnitude and time constant equal \( \tau = L_1/r_p \), the max of magnetizing current obtains as below:

\[
i_{\phi_0 m} = (2\phi_0 + \phi_0 - 2.22 A_i)/\mu_0 A_i
\]

Where \( A_i \) is area of core, \( A_t \) is the area of the core with winding and \( \mu_0 \) is air permeability.

From equation (5) it is clear that \( i_{\phi_0 m} \) is directly proportional to the value of flux corresponds to the value of the magnetizing inrush current of B/H value which can minimize adjusting the value of phase angle of voltage at the time of switching.

IV-SIMULATION WORK AND RESULTS

1. SIMULINK model description

One phase of a three-phase transformer is connected on 11 kV, 14 MVA network. The transformer is rated at 11 kV /433 V, 10 MVA. The flux-current saturation characteristic of the transformer is modeled with the hysteresis as shown in Figure 5.

In order to illustrate remnant flux and inrush current at transformer energization, the circuit breaker which is initially closed is first opened at \( t = 6 \) cycles (0.12 s), then it is reclosed at \( t = 9 \) cycles (0.18 s) for seeing the value of Inrush without controlled switching as shown in the figure 6.

Figure 5 Model for single phase saturable Transformer 10 MVA 11kv/433V 50 Hz
The initial flux $\phi_0$ in the transformer is set at zero and source phase angle is adjusted at 90 degrees so that flux remains symmetrical around zero when simulation is started. A Multimeter block and a Scope block are used to monitor waveforms of flux, magnetization current (not including the eddy currents), excitation current (including eddy current modeled by $R_m$), voltages and current flowing into primary winding. A X-Y Graph block is used to monitor the transformer operating point moving on the flux-current characteristic.

2. Inrush current without best switching moment
The simulation result output shows the high amount of inrush current generated due to saturation of transformer core modeled at transformer energization, the circuit breaker which is initially closed is first opened at $t = 6$ cycles (0.12 s), then it is reclosed at $t = 9$ cycles (0.18 s) for seeing the value of Inrush without controlled switching as shown in the figure 6.

![Figure 6 Magnetizing Inrush Current at 9 cycle ($t=0.180$ s)](image)

3. Switching at 9.75 cycle (0.195 sec) high inrush current through breaker
After adjusting the switching time to 9.75 cycle ($t=0.195$ s) for switching moment found from continuous iteration we observes that result that the magnetizing inrush is very as observed in the breaker current found to be very large the wave form for same is shown in Figure 7 bellow.

![Figure 7 Inrush Current through Breaker at 9.75 cycle ($t=0.195$ s)](image)

4. Mitigation of Inrush current by best switching moment.
After adjusting the switching time to 9.25 cycle ($t=0.185$ s) for the best switching moment found from continuous iteration we observes that result that the magnetizing inrush is mitigated to very large extent the wave form for same is shown in Figure 8 bellow.
Flux $\Phi$ (pu)

I_{mag} \& I_{exc} \quad \text{Breaker Current}

**Figure 8 Mitigation of Inrush Current at 9.25 cycle (t=0.185 s)**

**V-CONCLUSION**

Inrush current is directly proportional to the value of magnetizing flux and the flux is lagging at the angle 90° with the supplied voltage at the time of energizing the transformer the value of Inrush current can goes as high as six to 10 time the magnetizing current. Due to saturation of the core of transformer in positive region we see the high inrush current value.

By best switching time (delay or advance of reclosing time of breaker) we can mitigate the Inrush current to very large extent, also the best switching moment (Controlled switching) method is very effective and economically viable method of mitigating the Inrush current value of inrush current can be reduced to as low as 1.1 time of nominal value from six to 10 times.

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