

ANALITICAL ANALYSIS OF TRANSFORMER INRUSH CURRENT AND SOME NEW TECHNIQUES FOR ITS REDDUCTION

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Keywords: Inrush Current, Transformer, Analytical, Switching Time, EMTP, ATP

ABSTRACT

This paper presents some techniques for reduction of transformer inrush current. The equation of inrush current is obtained and then by using these methods, transformer inrush current is reduced, then after comparing the result of each method, the best choice is determined. Results which have been obtained from EMTP simulation confirm these subjects.

I. INTRODUCTION

Energization of unloaded transformers results magnetizing inrush current (IC) with high amplitude. These currents have many unfavorable effects, including operation failure of transformer differential protection, deterioration of the insulation and mechanical support structure of windings and reduced power quality of the system [1]. Without controlled switching the energization may occur at any time on the voltage wave producing high IC peak, when the transformer core is driven into saturation. Power transformers, as one of the vital components of electric power systems, require the protective relays with very high dependability, security, and speed of operation. But the magnetizing IC, which is often generated when the transformer is energized, can cause the false tripping of the differential relay therefore reduction of IC is necessary [2]. Some methods have been to reduce IC. Pre-insertion of series resistors and synchronous closing of circuit breakers are examples of the available mitigation techniques [3]. A neutral resistor based scheme for mitigating inrush currents was proposed in some papers [4-5].

II. TRANSFORMER MODEL

In this section, we describe transformer original model and equation for calculate maximal of IC. The transformer behavior during first phase energization can be modeled through the simplified equivalent electric circuit shown figure 1.

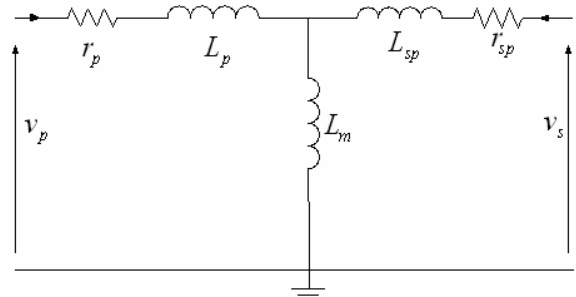


Figure 1. Transformer single phase model

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 1:

$$v_p = v_m \sin(\omega t + \theta_0) = i_\phi r_p + N_1 d\phi_L / dt \quad (1)$$

Where θ_0 is the phase of primary voltage at $t = 0$, i_ϕ is magnetize current, ϕ_L is core flux and N_1 is number of turn in primary side. Therefore we have:

$$v_m \sin(\omega t + \theta_0) = (N_1 \phi_L r_p / L_1) + N_1 d\phi_L / dt \quad (2)$$

where L_1 is primary inductance.

After solve Eqn.2 for ϕ_L :

$$\phi_L = (\phi_m \cos \theta_0 \pm \phi_r) e^{-\frac{r_p t}{L_1}} - \phi_m \cos(\omega t + \theta_0) \quad (3)$$

where ϕ_m is the max of ϕ_L and ϕ_r is residual flux.

At $\theta_0 = \pi/2$ in Eqn. 3 we have:

$$\phi_L = \pm \phi_r e^{-\frac{r_p t}{L_1}} + \phi_m \sin \omega t \quad (4)$$

In this case transient flux exists with ϕ_r magnitude and time constant equal $\tau=L_1/r_p$, the max of magnetizing current obtain as below:

$$i_{\phi_m} = \frac{2\phi_m + \phi_r - 2.22A_i}{\mu_0 A_t} \quad (5)$$

Where A_i is area of core, A_t is the area of the core with winding and μ_0 is air permeability. The primary transient current obtains from below when transformer is connected to load.

$$i_1(t) = \frac{1}{2} i_{\phi} e^{-\frac{r_p}{L_1}t} + I e^{-\frac{r_p}{L_{sp}}t} \quad (6)$$

Where I is the nominal current. Since $L_{sp} < L_1$, then transient current produced with load current is damped very fast, in this case IR is equal 4-6 pu. From the equation we see that the magnitude of the magnetizing IC is in the range of the short circuit current and may by occurs serve dynamical stress in the transformer windings [6]. The IC amplitude usually does not exceed the fault current withstand capability of the transformer, however the duration of these stresses are significantly longer than occurrence is more frequent than of the short circuit which is cleared by the relay protection within some tens of ms. 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 integral of the sinusoidal supply voltage. When energizing a transformer at zero crossing of the sinusoidal voltage the prospective magnetizing current and the flux have their maximal values, and delay by 90 electrical degrees. Transient flux starts from the residual flux and reaches its highest amplitude a half period later. At that point the flux saturates the core and a high amplitude IC current appears because the inductance of the magnetic core is very small in that region. In follow describe some methods to reduction IC.

III. METHODS OF REDUCTION OF IC

For analyze transformer inrush current suppose circuit shown in figure 2.

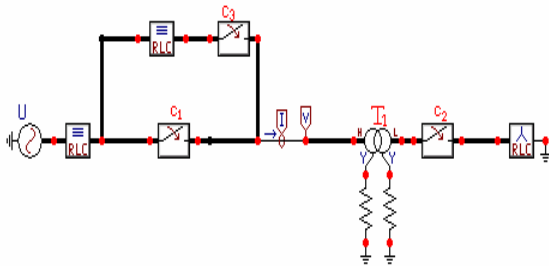


Figure 2. ATPDraw circuit for network

A. EFFECT OF CLEARING RESIDUAL FLUX

If transformer is energized without any methods for reduction IC in circuit which shown in figure 2 then IC will be as follow which shown in figure 3.

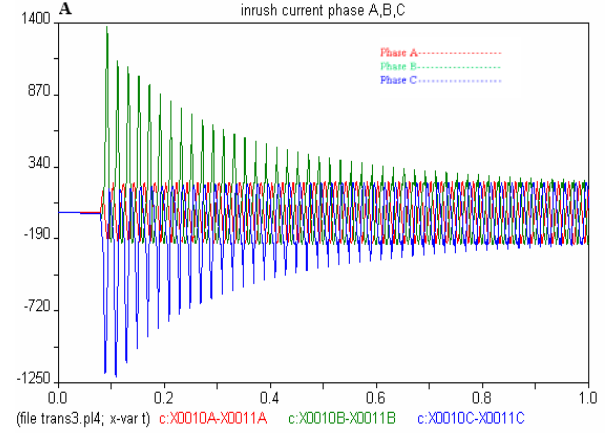


Figure 3. Inrush current without any control

According to the above described in part II, the magnitude of residual flux in the transformer is the main parameters to change magnitude of inrush current, when circuit breakers are opened transformer is isolated from network, residual flux remains in transformer and when transformer is energized IC will be increased. For clear this effect, capacitor are inserted in primary side of transformer, which reduce residual flux then IC are obtain in this case are shown in figure 4.

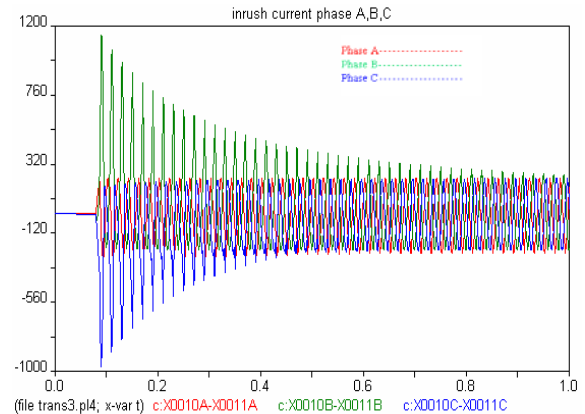


Figure 4. Inrush current with clearing residual flux

From the above figure, we can see that the IC is reduced.

B. EFFECT OF PRE-INSERTION RESISTOR

In order to reduce IC, in circuit that shown in figure 2 at first C_3 is closed, which series with resistor, after 10 ms the main switch (C_1) is closed and bypassed other switch and resistor. In this case IC is shown in figure 5.

From this, can see that the IC is effectively reduced, there for one of good methods to reduce inrush current is pre-insertion resistor.

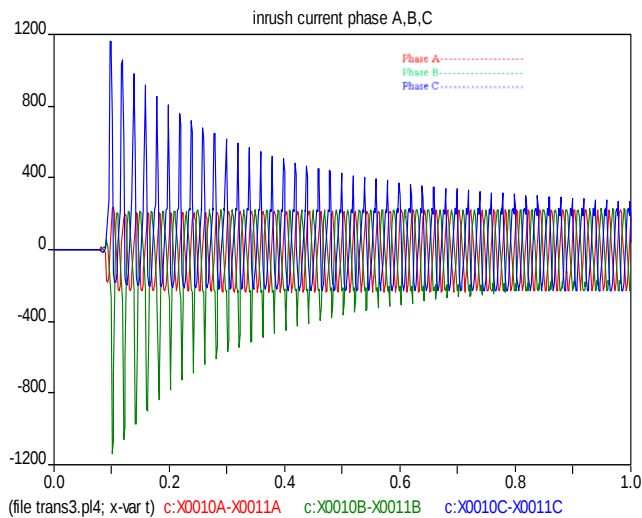


Figure 5. Inrush current with pre-insertion resistor

C.EFFECT PER-INSERTION RESISTOR & CLEARING RESIDUAL FLUX

In previous parts see that pre-insertion resistor and clearing residual flux are effective in reduction IC, there for in this part both method together used. The results from this simulation are shown in figure 6.

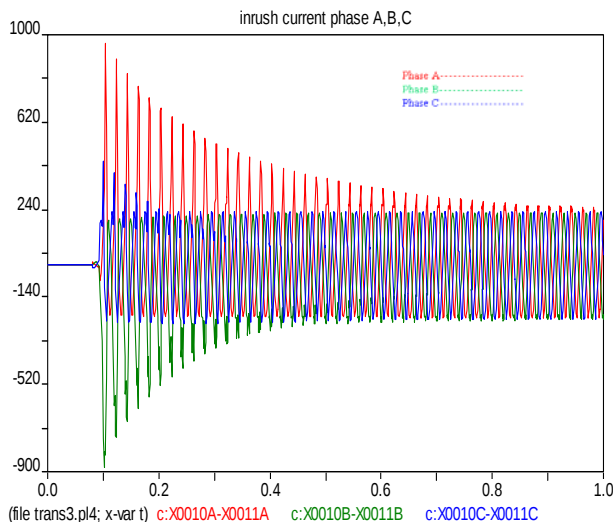


Figure 6. Inrush current with clearing residual flux & pre-insertion resistor

From figure 6, can see that apply both methods insertion pre-resistor and capacitor for clearing residual flux more effectively reduce IC.

D. EFFECT ENERGIZING OTHER LOADS

One of the methods that can reduce IC is energization another load simultaneous with transformer. For this goal, proposed another circuit which is shown in figure 7.

In this circuit auxiliary load is energized therefore, at first transformer inrush current is reduced.

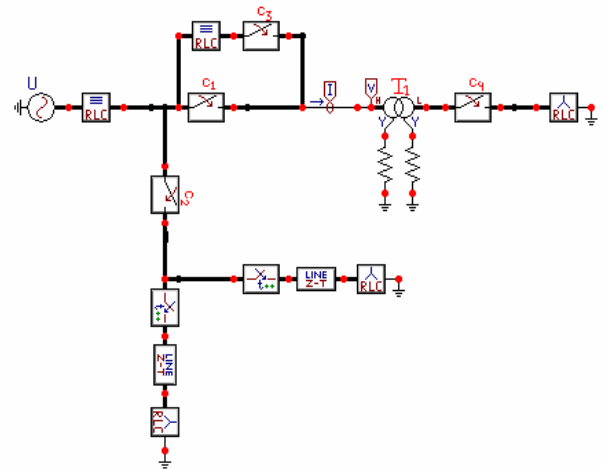


Figure 7. ATPDraw circuit for network with auxiliary load

When this load are disconnected another again inrush current are exist, which results of simulation are shown in figure 8.

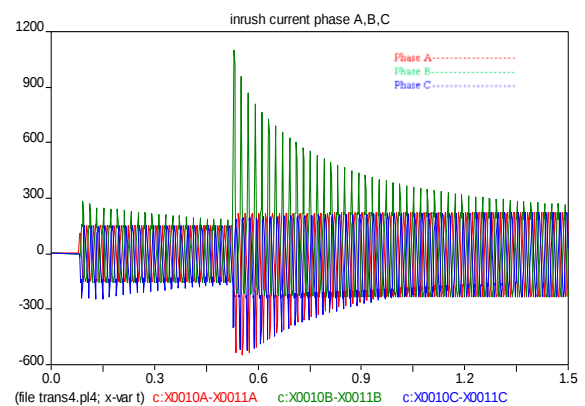


Figure 8. Inrush current when auxiliary load is used

E.EFFECT ENERGIZATION AUXILIARY LOAD & CLEARING RESIDUAL FLUX

In order to find best method to reduce the IC, in this part both methods energization auxiliary load and clearing residual flux are used, which results simulation are shown in figure 9.

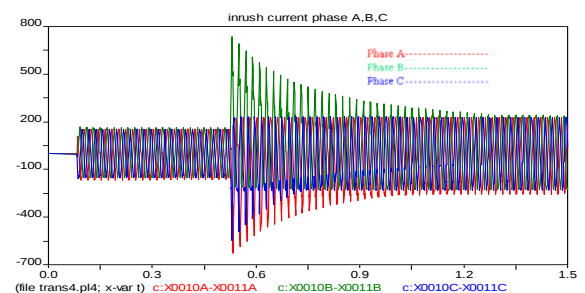


Figure 9. Transformer inrush current, when auxiliary load and clearing residual flux are used

From figure 9 can see that combination these two methods cause more reduction of IC.

F.EFFECT OF ENERGIZATION AUXILIARLY LOAD & CLEARING RESIDUAL FLUX& INSERTION PRE-RESISTOR

At following we use each three methods together to reduce IC. Results of this simulation are shown in figure 10.

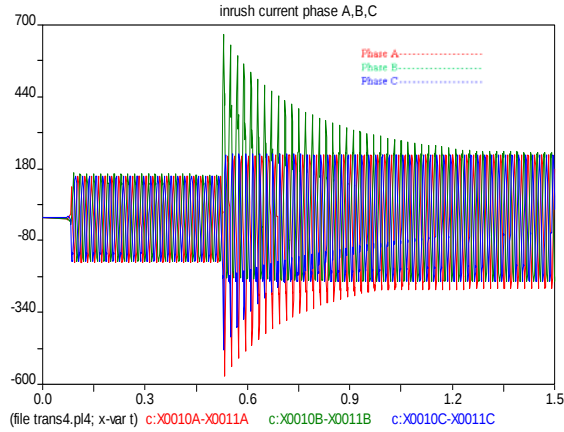


Figure 10. Inrush current, with each three methods
From the above figure, we can see that use these three method with together cause more reduce IC, but IC is great still therefore must be find solve to reduce more IC.

G. BEST TIME OF SWITCHING

In this part try to find best time of closing and opening the switches and this schedule is used in manner F. Best time of opening and closing are shown in table 1.

Table1. Best time of switching

Switch	TIME OF CLOSE	TIME OF OPEN
C1	0.0775 sec	-
C2	0.07 sec	0.52 sec
C3	0.071 sec	0.15 sec

With use above switching time in manner part F, inrush current will be reduced, results from simulation are shown in figure 11.

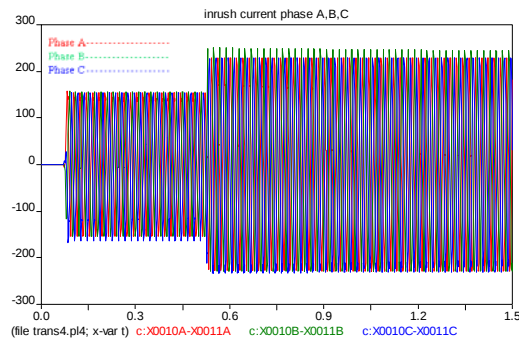


Figure 11. Inrush current when both, method is used in F part and best time of switching is used

From above can see that IC is eliminated. Therefore with combination this methods, we can find best case to reduce IC with lower cost.

H.ASYNCHRONOUS SWITCHING

In this part we use asynchronous method switching for switch C_1 without C_3 in circuit which is shown in figure 2. Best time of switching for C_1 is shown in table2, which at these moments supply voltage in each phase is maximum therefore residual flux is suitable.

Table 2. Best time of switching for C_1

Phase	A	B	C
Time of closing	0.08 sec	0.086 sec	0.083 sec

Using switching time table 2, inrush current is shown in figure 12.

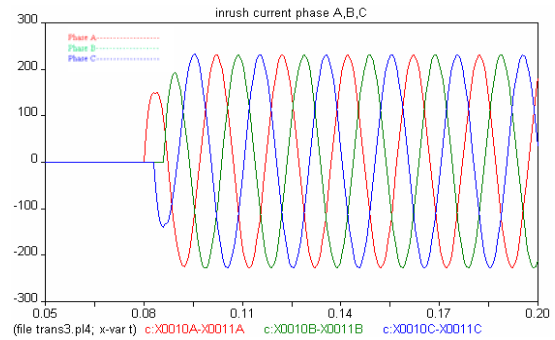


Figure 12. Transformer current when switching is asynchronous

Therefore with use asynchronous switching only, inrush current is eliminated. In following no load transformer IC is shown in figure 13, when transformer is energized without any control method. For comparison, when asynchronous switching method is used, the IC is shown in figure 14. Therefore IC is very small by using asynchronous method.

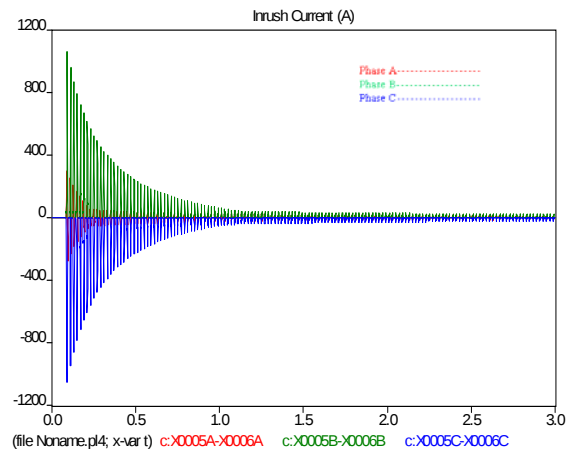


Figure 13. No load transformer IC without any control method

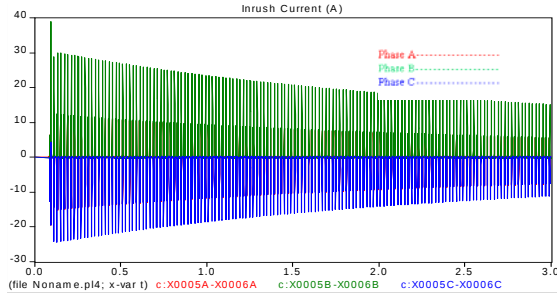


figure 14. No load transformer IC with asynchronous method

IV. CONCLUSION

The residual flux plays a significant role in the development of the magnetizing inrush current; it is observed that residual flux can be reduced by putting phase-to-ground capacitor at transformer terminals. It is also observed that pre-insertion resistor can reduce inrush current and the combination of all methods gives best results. Finally saw asynchronous switching can eliminate inrush current but the method is expensive because all circuit breakers must be exchanged. Numerical comparison results are shown in table 3. In table 3 it can be seen that the method G is the best because IC is almost eliminated. But in this situation trade off between cost of circuit breaker and cost of resistor and IC value is necessary. If loss of pre-insertion resistor and resonance invention probability has in mind, then asynchronous method is the best method.

APPENDIX

Transformer information:

$F=50$ Hz, $S=50$ MVA, $V_h=132$ kV, $V_l=11$ kV, $I_{base}=230$ A

Table 3. Comparison results of methods

Method	Positive max current (pu)	Negative min current (pu)
Normal	5.96	-5.24
A. With pre-resistor	5.05	-4.91
B. With capacitor	4.95	-4.2
C. Capacitor& pre-resistor	4.19	-3.82
D. Auxiliary load	4.78	-2.39
E. Auxiliary load & capacitor	3.2	-2.72
F. Auxiliary load & capacitor & pre-resistor	2.89	-2.48
G. Best time of switching	1.08	-1.01
H. Asynchronous	1	-1

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