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Assessment of Inrush Current for Power Transformers by Three-Dimensional Representation

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Abstract: For power transformers, the magnitude of the first peak of inrush current is ten times more than the rated load current. The main feature of this current is its high amplitude and second harmonic content. An uncontrolled inrush current may lead to the inadvertent operation of the circuit over-current protection systems. Furthermore, the magnetic stress produced by the inrush current may destroy mechanical structure and windings of transformers. In addition, this current has undesirable effects on electricity quality, extra loss, and reduction of useful life of transformer. In this paper, the peak value of inrush current in three-phase power transformer with Y-Y connection has been calculated and shown with a three-dimensional representation and its harmonic spectrum has been evaluated. It should be mentioned that, this phenomenon occurs because in four-wire Y-Y connection three-phase power transformers, the probability of saturation in phases is lower in contrast with other possible connection of three-phase transformers.

Key words: Hysteresis flux, inrush current, power transformer, switching angle

INTRODUCTION

Inrush current is one of the power system transients that may occur when a transformer is switched on, when the transformer is not loaded. This current consists of high amplitude, large DC component and also has many harmonics when core is saturated. It is one of the main problems in both power system and distribution network. It not only may result in inadvertent operation of the protective relays, but also causes a voltage dip in the power system or distribution network.

The peak value of inrush current may exceed eight to ten times more than rated current. This value depends on various factors such as, the B-H characteristics of the iron core, the peak value of voltage and in particular its phase angle at the instant of switching, the resistance of the primary winding of transformer, the internal impedance of the power supply, the magnitude and particularly, the polarity of the residual or remnant magnetic flux density in the core of transformer at the instant of switching (Feyzi and Sharifian, 2006).

This current will cause fault in operation of protection relays and fuses, mechanical damage for windings caused by magnetic forces and power quality problems in power systems and also, in distribution networks. However, the problem of detecting inrush current is a major subject for the circuit protection systems. From a power quality point of view, the magnetizing inrush current can be considered as a distorted waveform with two kinds of disturbances (Nagpal *et al*., 2006; Anderson, 1989; ANSI/IEEE C37.91, 1985):

- Unbalance
- Harmonics

The duration and amplitude of the inrush current is a function of two sets of parameters. The first one considers parameters which belong to the transformer and the second includes parameters from the power system. Among other parameters, the following parameters should be considered:

- Nominal power of the transformer
- Material used to build the core of the transformer
- Residual flux just before the connection of the power transformer
- Short circuit power at the common coupling point (PCC)
- Distance between the bus of the substation and the power transformer

Points 1, 2 and 3 are specifically related to the transformer, while 4 and 5 are defined by the power system which the power transformer is connected to it (Anderson, 1989; ANSI/IEEE C37.91, 1985).

Many researchers have studied the inrush current phenomenon from different points of views such as definition, simulation, reduction, suppression and experiment, as follow:

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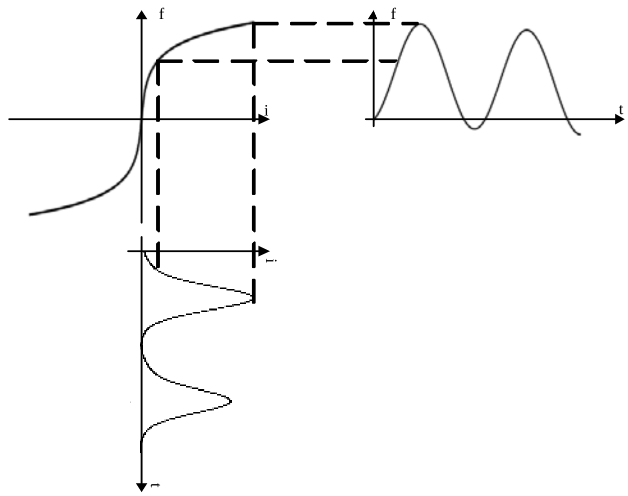

Fig. 1: Generation of inrush current in a power transformer

The AGW method is an interior improvement method for reduction of transformer's inrush current (Molcrette *et al*., 1998). This method tends to some of the characteristics in the magnetic circuit become worse, and its reduction of the inrush current is so limited.

The inrush current can be reduced or eliminated using controlled switching method (Brunke and Frohlich, 2001a, b). This method requires additional control circuits and as a result, increases cost of control, and suffers from uncertainty factors in the switching on-angle. Therefore, controlled switching method is difficult for practical applications.

Some researches compute inrush current or its forces by using Finite Element Method (FEM). Results of these researches have much coordination with experiments. Richard and Szylowicz (1994) carried out a set of simulations and compared corresponding results from an analytical method using a permeance model with results of a two-dimensional (2D) and a three-dimensional (3D) finite element model (Richard and Szylowicz, 1994; Adly, 2001; Faiz *et al*., 2008).

In a recent study, has been shown that the inrush current can be reduced considering design aspects, by increasing the distance between the primary winding and core. This, in fact increases the radius of the primary coil and results in the increase of the resistance and the leakage reactance of the winding. But in that paper, they ignored the primary winding resistance and also assuming an extremely saturation in the core area, and neglected the influence of iron core (Chen *et al*., 2005). Although this may be acceptable in some parts of the core, but it cannot be accurate enough for entire core region. Moreover, it cannot be valid after a few cycles when the saturation level is damped down with time.

According to applied forces to windings due to inrush current in many cases are bigger than forces due to short circuit (Faiz *et al*., 2008) and also inrush current has more iteration and duration in comparison with short circuit current, therefore its harmful effect is more severe than short circuit state. So to prevent inrush current harmful effect should use methods to discriminate and eliminate it. In (Youssef, 2003; Mao and Aggarwal, 2001; Faiz and Lotfi-Fard, 2006), has been presented two methods to discriminate between inrush current and short circuit based on wavelet transform.

To adjusting effect of transient inrush currents and decreasing their amplitude, sensitivity reduction of protection relays and makes the resistance series with primary winding or controlled switching respectively are used (Girgis and teNyenhuis, 2007; Wang *et al*., 2008).

Figure 1 shows the generation of inrush current in a transformer. As seen from the figure, exceeding flux from the knee point of saturation or magnetization curve, results in large magnetizing current that in some circumstances can be ten times of the rated current in a power transformer.

During the period of transient inrush current, the transformer core enters into state of saturation normally. In this core-saturated state, the magnitude of permeability would be regarded as the absolute permeability, and then the magnitude of inductance is reduced. The current would be increased quickly due to the decrease in inductance. The exciting current of steady state of a transformer is typically less than one percent of the rated current, but the inrush current may be as high as ten times to the rated current or more.

In this study, the peak value of inrush current in the three-phase power transformer with Y-Y connection for four-wire system has been investigated in MATLAB/SIMULINK. Then, results have been used for statistical discussions.

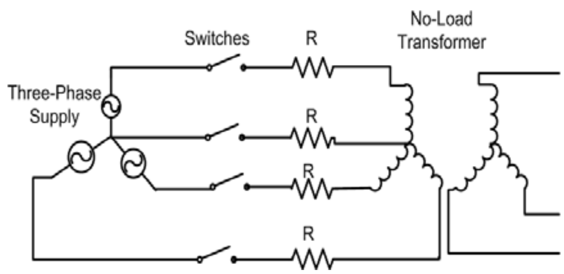

Fig. 2: Three-phase model of transformer with Y-Y connection

MATERIALS AND METHODS

To evaluate transient core flux in transformers, the theoretical method is needed. Transient modeling of transformer is so complicated. General model for all frequencies and modeling of all features of transformer has not presented until now. The required model for studying transient flux in the core, must be consisted of flux-current relation and also, hysteresis flux modeling. Usually, for modeling of transformer core, parallel structure of resistance and reactance are used. These elements show loss and magnetizing current of the transformer core, respectively. Three-phase model of transformer with Y-Y connection has been presented in Fig. 2.

It should be mentioned that, in this circuit, the secondary side of transformer is open and in order to simplicity, the transformer primary leakage inductance can be merged into the magnetizing inductor or be omitted since it is much smaller than the magnetizing inductance. Flux-current curve is a piece-wise linear curve for nonlinear inductor.

The typical amount of hysteresis or residual flux in the core of transformer is about 20 to 70% of the normal flux peak, but sometimes its amount is becoming more than 85% of the normal flux peak. Also, in steady-state, the summation of hysteresis flux in three-phase transformers core is equal to zero.

Switching angle is the source voltage angle in transformer energizing instant that typically for phase A, this angle known as θ.

To evaluate the peak value of inrush current in three-phase power transformer with Y-Y connection four-wire systems MATLAB/SIMULINK software has been used. The used parameters in simulation have been tabulated in Table 1 and the time interval of simulation is equal to one cycle. To consider step changing of switching angles and hysteresis flux in simulation a program has been written in MATLAB/M-file and also, this program has been shown in appendix.

In this study, supposed that hysteresis flux in phase A, has changed from -1 per-unit to +1 per-unit with eighteen steps and with supposing that hysteresis fluxes of other phases are remain; from balanced three-phase state, the flux of other phases follow these equations:

Table 1: The used parameters for simulation

Specifications	Values
Primary rated voltage	25 kV
Rated frequency	50 Hz
Winding inductance	750 H
Equivalent winding resistance	4.76 Ω
Winding inductance after saturation state	890 mH
Rated current	100 A

$$\lambda_{ob} = \lambda_n \times \sin(\sin^{-1}\left(\frac{\lambda_{oa}}{\lambda_n}\right) - 120) \qquad (1)$$

$$\lambda_{oc} = \lambda_n \times \sin(\sin^{-1}\left(\frac{\lambda_{oa}}{\lambda_n}\right) + 120) \qquad (2)$$

$$\lambda_n = \frac{V_m}{\omega} \qquad (3)$$

In above equations, λ_n is peak flux in steady-state condition. Peak value of inrush current in four-wire system can be calculated as follow:

$$i_{\max} = \left[\frac{\lambda_o - \lambda_s}{\lambda_n} + \cos\theta + 1\right] \times I_{ss} \qquad (4)$$

$$I_{ss} = \frac{V_m}{\sqrt{R^2 + (\omega L_s)^2}} \qquad (5)$$

In above equations, λ_o, λ_s and λ_n are hysteresis or remnant flux, knee point flux of $\lambda 1 - i$ curve and peak value of rated flux, respectively. Also, θ is Switching angle and L_s and I_{SS} are winding inductance after saturation, and amplitude steady-state current of saturated single phase transformer, respectively.

It should be mentioned that, in simulation the value of λ_s is equal to 1.2 λ_n. To apply these equations in estimating the peak value of inrush current for three-phase transformer with four-wire Y-Y connection, for each phase we should use specific λ_o and θ.

SIMULATION RESULTS AND STATISTIC DISCUSSION

The peak value of inrush current in first cycle for four-wire system and different phases-A, B and C has been shown in Fig. 3, 4 and 5, respectively using 3D representation in MATLAB/SIMULINK.

By comparison between simulation results that illustrated in above figures and because in some points in four-wire system this phase is not become saturated, it should be noted that the peak of inrush current in different phases in many points are low.

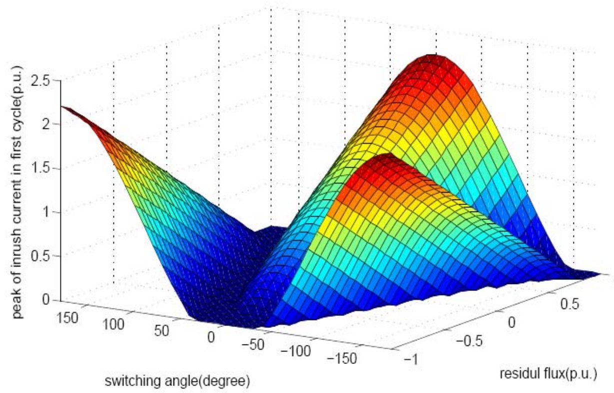

Fig. 3: The 3D representation of peak value of inrush current in first cycle for phase A

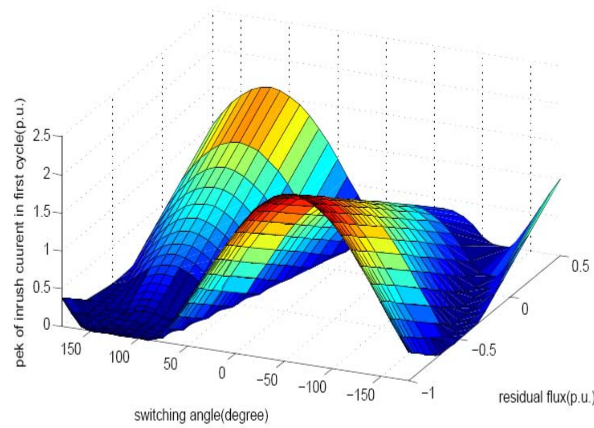

Fig. 4: The 3D representation of peak value of inrush current in first cycle for phase B

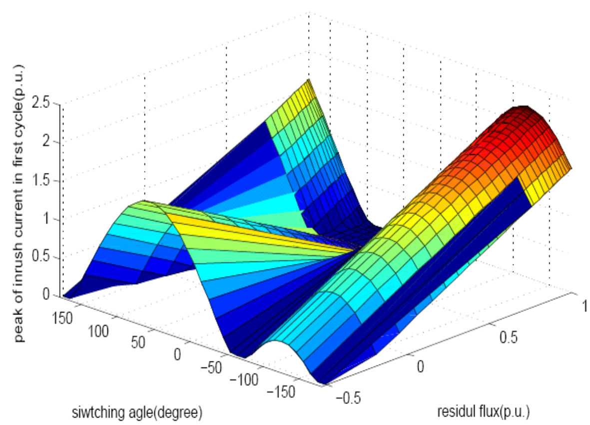

Fig. 5: The 3D representation of peak value of inrush current in first cycle for phase C

According to the switching angle that has been changed from -180 degree to +180 degree with ten degrees steps and hysteresis flux that has been changed from -1 per unit to +1 per unit with eighteen steps, obtained results for four-wire system will consist of 1369 different states.

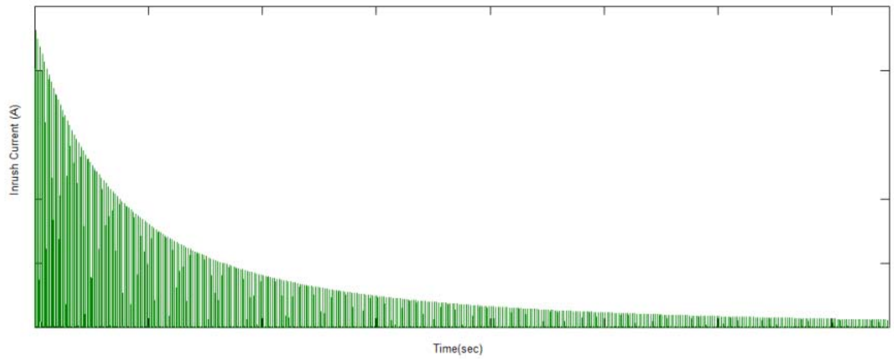

Fig. 6: A typical inrush current for studied transformer in 2D representation

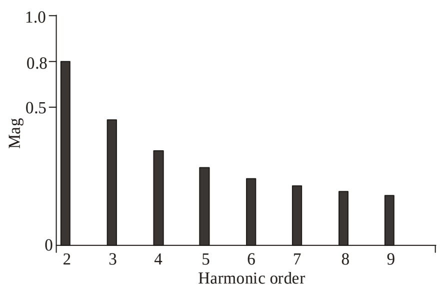

Fig. 7: The harmonic spectrum of Fig. 6

A Typical Inrush Current and its harmonic spectrum for studied transformer have been shown in Fig. 6 and 7 as a 2D representation. It could be seen that the 2nd harmonic content is the important order of harmonic and it is the main difference between inrush and fault current in power transformers.

CONCLUSION

In this study, the peak value of inrush current in the four-wire three-phase transformer with Y-Y connection has been investigated based on simulation in MATLAB/SIMULINK software package. Also, the harmonic spectrum of inrush current for four-wire system has been shown. According to three-dimensional (3D) and two-dimensional (2D) curves obtained from simulation and information acquired from statistical evaluation, this result show that four-wire system from a probability point of lower inrush current peak than three-wire system in same condition.

Appendix: One of the programs has been written in MATLAB/M-file for one phase is as follow:

```
clc
lamda = -112.5395;
lamdab = 56.26975;
lamdac = -56.46795;
for j = 1:1:37
teta = -180;
c(j) = (1/112.5395)*lamdac;
b(j) = (1/112.5395)*lamdab;
for I = 1:1:37
    sim threephase.mdl;
    ia(i,j) = max(i_a);
    ib(i,j) = max(i_b);
    ic(i,j) = max(i_c);
    teta = teta+10;
end
lamda = lamda+(112.5395/18);
fi = asin(lamda/112.5395);
lamdab = 112.5395*sin(fi-2*pi/3)
lamdac = 112.5395*sin(fi+2*pi/3);
end
x = -180:10:180;
lamda = -112.5395:(112.5395/18):112.5395;
surf (lamda,x,ia)
```

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