The Influence of Tap Position on the Magnitude of Transformer Inrush Current

H. S. Bronzeado
Companhia Hidro Elétrica do São Francisco - CHESF
Divisão de Estudos da Operação Elétrica - DOEL
50761-901, Recife/PE, Brazil
hebron@chesf.gov.br or bronzeado@ieee.org

J. C. de Oliveira
Universidade Federal de Uberlândia - UFU
Departamento de Engenharia Elétrica - DEE
38 400-902, Uberlândia/MG, Brazil
jcoliveira@ufu.br

Abstract - **The magnitude of the inrush current in a transformer being energized through windings with Load Tap Changer (LTC) can be significantly reduced if the tap is conveniently positioned to allows a much higher number of turns to be excited. This fact should be used by electric utilities as an operational procedure as it will reduce the disturbances caused by transformer inrush transients. This paper presents an analysis of this procedure, supported by theoretical and practical simulation results. It is also shown the importance of considering the saturation characteristic of the transformers already connected to the system as the sympathetic interaction between transformers (transferred saturation) may occur, affecting the magnitude and duration of the inrush current. The simulations were performed using the Alternative Transient Program (ATP).**

Keywords - Transformer Inrush, Transformer Saturation, Transferred Saturation, Sympathetic Interaction, Load Tap Changer, EMTP/ATP.

I. Introduction

The transient phenomenon that occurs when a transformer is energized has been with us since the transformer was invented. Since then, much research has been carried out in order to explain the nature of the transformer inrush current and to derive its mathematical formulations [1 - 3]. This current, which is characterized as being almost entirely unidirectional, rises abruptly to its maximum value in the first half-cycle after the transformer being energized and thenceforth decays until the normal steady-state magnetizing conditions in the transformer are reached. It often exceeds in magnitude the normal operating current and may last tens of seconds and even several minutes.

Under most practical system condition, the transformer inrush transient is of little consequence. However, in some cases a combination of circumstances may be obtained which result in this inrush being of such consequence as to impair momentarily the proper operation of the system [1]. If, for example, the harmonics of the inrush current coincide with resonance points in the system, harmonic voltages and currents of high magnitude will build up, which may cause the operation of equipment protection such as surge arrests and/or over-current relays of capacitor banks [4, 5].

It is evident that most of the disturbances caused by the transformer energizing can be mitigated if the magnitude of the transformer inrush current is reduced. A conventional method to do that has been the use of large pre-insertion resistors in the transformers breakers. Also, in the last few years, as stable breaker types and suitable synchronizing relays have become available, controlled switching has been pointed out as a modern solution to attenuate inrush currents. However, these solutions often involve further cost, as they normally require an exchange in the already installed circuit breakers and/or modification of the substation layouts.

Fortunately, transformer inrush currents can also be reduced, **at absolutely no additional cost**, if the tap in the LTC of the transformer being energized is conveniently positioned. This paper will analyze the influence of the tap position on the magnitude of the transformer inrush current. Also, it will be shown the occurrence of the phenomenon of sympathetic interaction between transformers, which normally appears when the transformer is energized onto a system to which there are other transformers already connected [6, 7].

II. Transformer Inrush Current

It is very well known from the general theory that when the voltage is applied onto the terminals of a transformer, the magnetic flux generated within the winding will be determined by the residual flux added to the volt-second area swept by the applied voltage wave between the instant t_0 of switching and the time t under consideration, i. e.:

$$\varphi_s = \varphi_{res} + \frac{1}{N_s}\int_{t_0}^{t} v_s \, dt \tag{1}$$

where φ_{res} is the residual flux in the limb wound by the winding, v_s is the applied voltage and N_s is the winding number of turns.

Assuming that the voltage v_s is sinusoidal, i. e:

$$v_s = V_{ms} sin \ \ wt \tag{2}$$

Then,

$$\varphi_s = \varphi_{res} + \varphi_{ms}(\cos wt_0 - \cos wt) \tag{3}$$

where

$$\varphi_{ms} = \frac{V_{ms}}{N_s w} \qquad (4)$$

If it is assumed that φ_{res} is positive and the transformer is being energized at $wt_0 = 0$, i.e., at the instant at which the voltage wave cross zero going positive, the maximum peak value of φ_s is:

$$\varphi_{s\ peak} = \varphi_{res} + 2\varphi_{ms} \qquad (5)$$

From equation (5), it is evident that the residual flux is one of the parameters that exercise a great influence on the magnitude of the inrush current. However, it is probably the parameter about whose magnitude least is known. Theoretical and experimental studies on three-phase three-limb transformers have indicated that residual flux between 0.7 pu and 1.0 pu is expected in two of the limbs of the transformer core (with opposite sign), and a very low value in the third one [8].

The maximum peak value of the magnetizing inrush current may be given by:

$$i_{s\ peak} = \frac{R}{N_s}(\varphi_{s\ peak} - \varphi_{sat}) \qquad (6)$$

where φ_{sat} is the flux saturation level in the transformer core (specified by the transformer designer as being usually around 1.2 pu to 1.3 pu) and R is the reluctance of the air space related to the magnetic path of the flux that exceeds φ_{sat}.

Combining (4), (5) and (6), and taking I_r, φ_{mr} and v_r as reference values, the following expression for the maximum peak of the inrush current in pu may be obtained by:

$$I_{V,N} = \frac{i_{s\ peak}}{I_r} = \frac{1}{N}\left(2\frac{V}{N} - \phi_o\right) \qquad (7)$$

where

$$N = \frac{N_s}{N_r} \qquad (8)$$

$$V = \frac{V_{ms}}{V_{mr}} \qquad (9)$$

$$\phi_o = \frac{(\varphi_{sat} - \varphi_{res})}{\varphi_{mr}} \qquad (10)$$

$$I_r = \frac{\varphi_{mr} R}{N_r} \qquad (11)$$

$$\varphi_{mr} = \frac{V_{mr}}{N_r w} \qquad (12)$$

$$v_r = V_{mr} \sin wt \qquad (13)$$

The values of V, N and ϕ_o are given in pu.

III. Tap Position Affecting Transformer Inrush Current [7]

The effect of the tap position on the magnitude of the transformer inrush current may be better visualized if the maximum peak of the current given by (7) is compared with the maximum peak of a reference inrush current. This reference current may be the inrush current in a transformer being connected to a bus-bar where the voltage is 1.0 pu (V=1.0), with the tap positioned at 1.0 pu (N=1.0)). In this case, assuming that the difference between φ_{sat} and φ_{res} is 0.4 pu (ϕ_o = 0.4), then:

$$\frac{I_{V,N}}{I_{1,1}} = \frac{1.25}{N}\left(\frac{V}{N} - 0.2\right) \qquad (14)$$

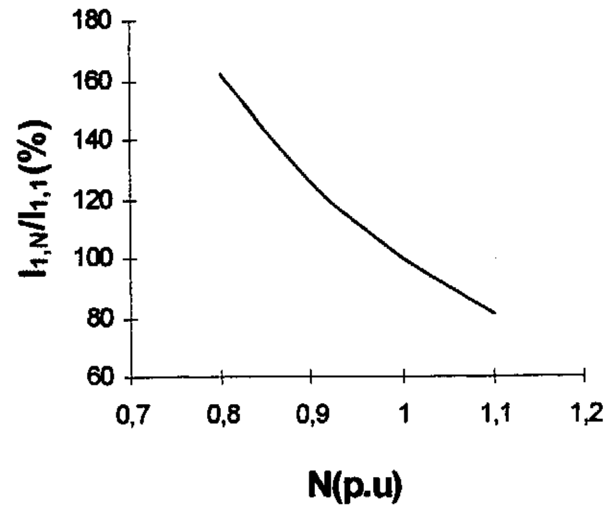


Fig. 1. Normalized transformer inrush current versus the tap position (V=1.0 pu)

Fig. 1 shows a curve derived from (14) calculated to V=1.0 pu as a function of N. As can be seen in this figure, when a transformer is energized with the tap positioned at a much higher number of turns, the maximum peak of the transformer inrush current is significantly reduced. A comparison between the values for N=0.9 pu and N=1.1 pu shows that the peaks of the inrush current was reduced in almost 50%.

It is evident that, from the point of view of the system operation, the most favorable condition to energize a transformer is positioning the tap to give the highest number of turns to be excited. This operational procedure, therefore, should be taken into consideration by the electric utilities, mainly if their transmission systems are predominantly radials, with long transmission lines, which are much more susceptible to develop the phenomenon of sympathetic interaction [7].

It is important to say that this proposed procedure is only feasible if the LTC is in the winding through which the transformer is being energized. Also, its implementation may introduce some delay in the system operation as it is necessary additional steps to position conveniently the LTC.

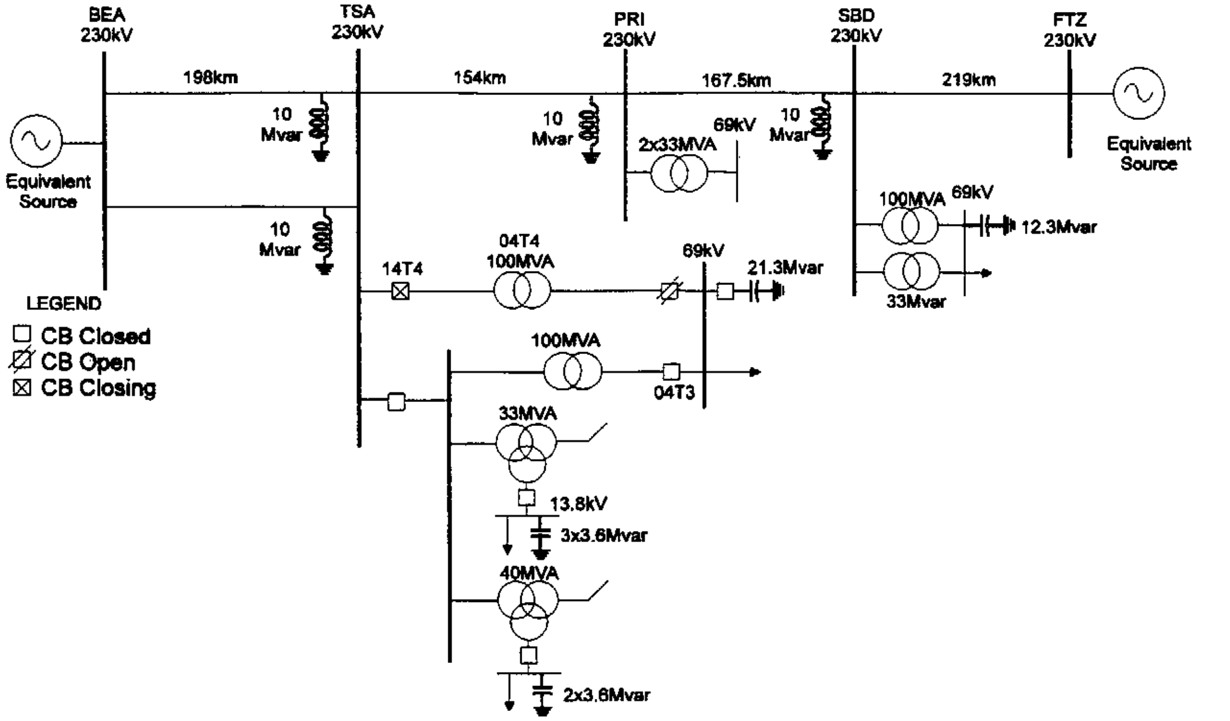
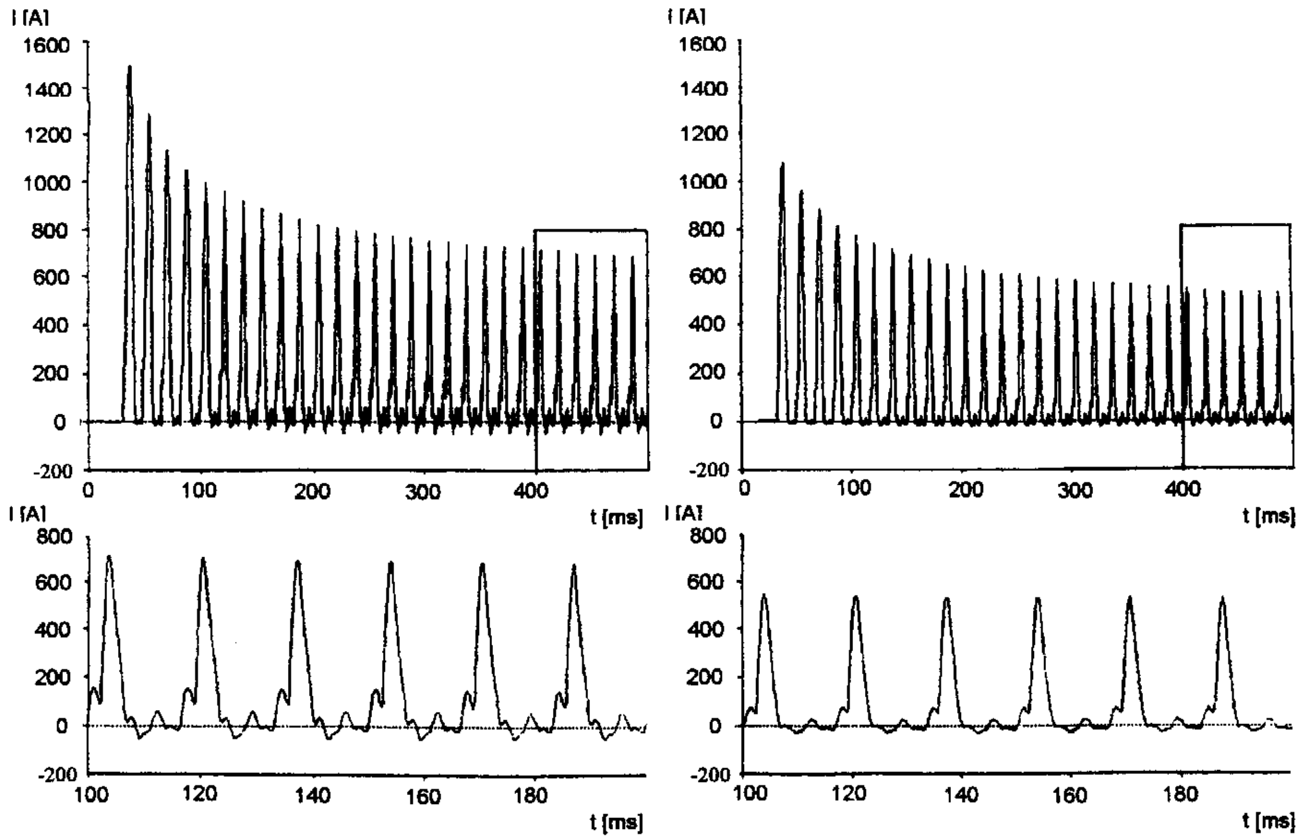


Fig. 2. Power system used to investigate the influence of tap position on the magnitude of the inrush current



a) Transformer 04T4 with tap at 0.9 u (207kV)

b) Transformer 04T4 with tap at 1.1 pu (253kV)

Fig. 3. Inrush current in the transformer 04T4.

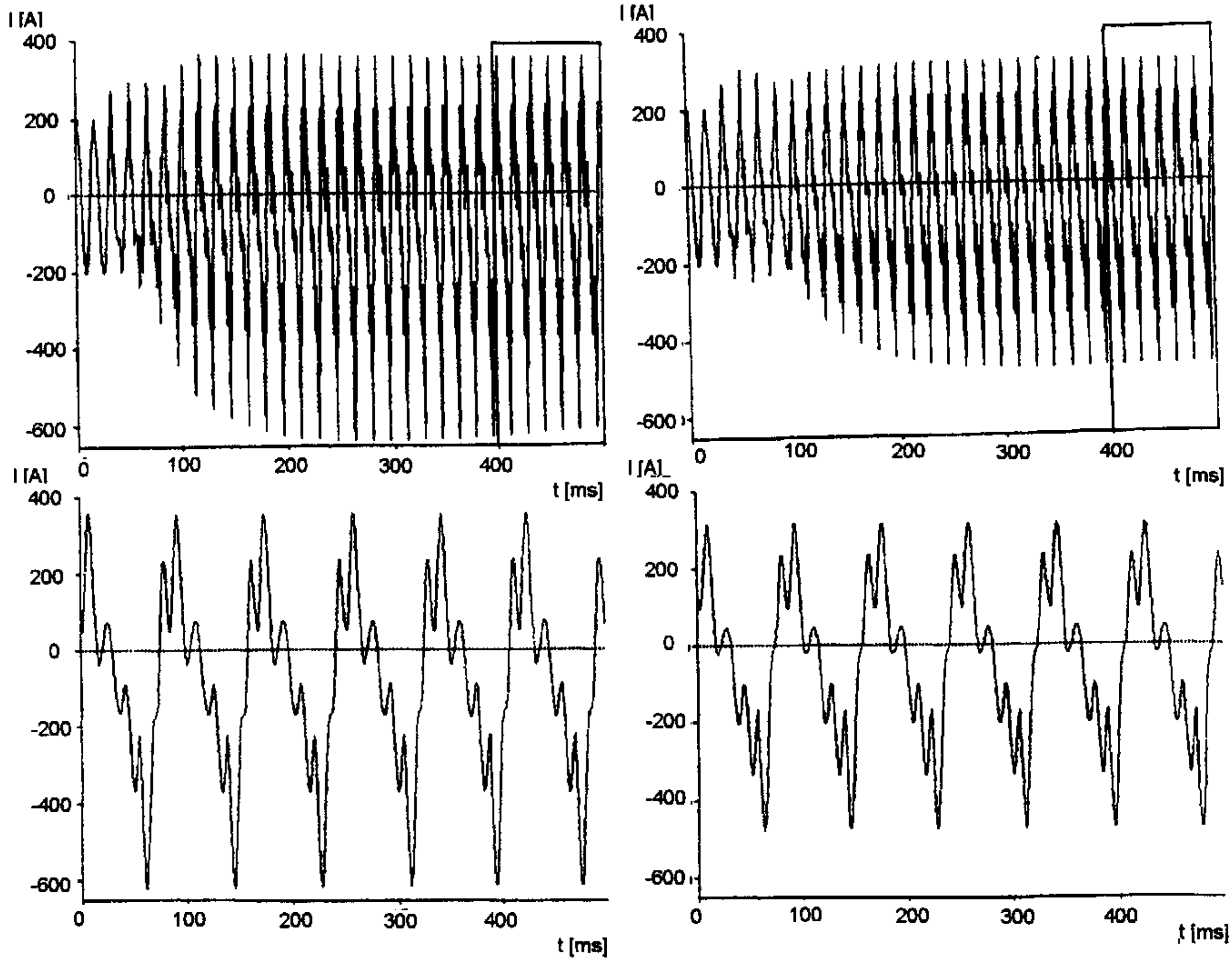
IV. CASE STUDY

The power system showed in Fig. 2 was used to investigate quantitatively the influence of tap position on the magnitude of the inrush current. The Alternative Transient Program (ATP) was used to perform the simulations which consisted in switching the transformer 04T4, of 100MVA, 230kV/69kV, by closing the circuit breaker 14T4. The closing instants was selected to give the highest magnitude of the inrush current in phase a, with the voltage in the bus-bar being 1.0 pu and the residual flux in the transformer being zero.

Fig. 3 shows the inrush current in the transformer 04T4 when it is energized with the tap positioned at 0.9 pu and 1.1 pu. The transformers were modeled as a bank consisting of three single-phase transformers with the non-linear magnetizing inductance connected phase-to-ground on the high voltage windings (SATURABLE TRANSFORMER model).

As the saturation curve of a transformer is normally supplied as a rms-voltage versus rms-current curve, it is necessary to convert this curve into a corresponding instantaneous flux-current curve in order to run a transient simulation. This conversion is performed using the support routine SATURATION in the ATP. This routine uses a method based on the assumption that the influence of the transformer losses (iron and copper) on the saturation curve can be ignored.

It is important to emphasize here that the transformer saturation curves are usually measured with the tap in the LTC positioned at 1.0 pu, i.e., with the tap at a position where the number of excited turns corresponds to its designed rated voltage. It is evident then, that if the tap is at a position that there is no correspondence between the number of turns and the applied voltage, the flux-current saturation curve will be quite different from that calculated with the tap positioned at 1.0 pu. Thus, a new saturation curve should be obtained by running again the subroutine SATURATION. This is done by changing the values of the reference voltage to that corresponding to the rated voltage of the required tap. In other words, if the transformer is to be energized with the tap at 1.1 pu, the flux-current curve that should be used in the transformer model must be generated with the reference voltage set up to 1.1 times the rated voltage in the which the actual curve was measured.



a) Transformer 04T4 with tap positioned at 0.9 pu

b) Transformer 04T4 with tap positioned at 1.1 pu

Figure 4 - Current in the transformer 04T3.

From the simulation results shown in Fig. 3, it can be seen that the peaks of the inrush current decrease when the number of excited turns increases (LTC at a higher position). Also, it can be observed that the inrush current decays relatively slowly. This indicates the occurrence of sympathetic interaction between the incoming transformer 04T4 and the transformers already in operation.

The current in the already connected transformer 04T3 (100MVA, 230kV/69kV), which is a combination of the load current and the sympathetic magnetizing current in the transformer 04T3, is shown in Fig. 4. This current, which presents a high distortion level with a low degree of damping, was pointed out as being the main reason for the trip out of the capacitor bank of 21.3 Mvar connected to the 69kV load bus-bar.

V. Conclusions

It has been shown that the tap position of the Load Tap Changer (LTC) affects significantly the magnitude of the transformer inrush current. Analytical and simulation results indicate that the peaks of the inrush current can be greatly reduced if the tap of the LTC is positioned in a manner to allow a much higher number of turns to be excited. This will reduce considerably the disturbances on power systems caused by the inrush current and, therefore, should be considered by the utilities as an operational procedure to energize transformers.

It has also been shown the importance of taking into account the saturation characteristic of the transformers already connected to the system when transformer inrush transients are to be accurately investigated. This changes dramatically the duration and magnitude of the transformer inrush current as the phenomenon of sympathetic interaction between transformers may occur.

VI. References

[1] BLUME L. F., CAMILLI G., FARNHAM S. B. and PETERSON H. A., "Transformer Magnetizing Inrush Currents and Its Influence on System Operation", *AIEE Trans.*, **Vol. 63**, pp. 366-375, 1944.

[2] SONNEMAN W. K., WAGNER C. L. and ROCKFELLER G. D., "Magnetizing Inrush Phenomena in Transformer Banks", *AIEE Trans.*, Vol. 77, pp. 884-892, Oct. 1958.

[3] YACAMINI R. and ABU-NASSER A., "Numerical Calculation of Inrush Current in Single-Phase Transformer", *IEE Proc.*, **Vol. 128**, No. 6, pp. 327-334, Nov. 1981.

[4] BRONZEADO H. S., BROGAN P. and YACAMINI R., "Harmonic Analysis of Transient Currents During Sympathetic Interaction", *1996 IEEE PES Winter Meeting*, paper 96 WM 288-1 PWRS, Baltimore, USA, Jan. 1996.

[5] BRONZEADO H. S. CORREIA LIMA M. and YACAMINI R., "Transformer Inrush Mitigation Using the Load Tap Changer (LTC)", *V Symposium of Specialist in Electric Operational and Expansion Planning - SEPOPE*, **Vol. III**, paper SP-64, pp. 859-864, Recife, Brazil, May 1996

[6] BRONZEADO H. S., "Transformer Interaction Caused by Inrush Current", MSc Thesis University of Aberdeen (Scotland), 1993.

[7] BRONZEADO H. S. and YACAMINI R., "Phenomenon of Sympathetic Interaction Between Transformers Caused by Inrush Current", *IEE Proc. - Science, Measurements and Technologies*, **Vol. 142**, No. 4, July 1995.

[8] HOLMGREM B., JENKINS R. S. and RIUBRUGENT J., "Transformer Inrush Current", *International Conference on Large High Voltage Electric Systems of CIGRE*, Paper 12-03, Session 1968.