Transient Simulation of a Transformer Core Demagnetization Scheme

A. Mukherjee, S. C. Mukhopadhyay, M. Iwahara, and S. Yamada

Laboratory of Magnetic Field Control and Applications, Faculty of Engineering, Kanazawa University,
Kodatsuno 2-40-20, Kanazawa 920-8667

Switching a transformer primary with a perfectly demagnetized core brings down the possibility of high inrush current. This paper gives a method for transient solution of a scheme which can demagnetize the core after the primary of the transformer is switched off. A transient hysteresis model has been utilized to properly deal with the residual magnetism which has to decay for demagnetization. The method is expected to help the design of such a scheme by quick calculation of the transient current and voltages in the circuit.

Key words: electromagnetic transient, hysteresis model, Runge-Kutta method, rational function

1. Introduction

When a transformer primary winding is connected to its supply, an inrush current may flow several times of the normal value. This causes severe mechanical stresses and dictates that fuses and control gears must be of a higher rating than would be required in absence of such inrush current.

The magnitude of the effect depends on the residual core magnetization which may approximate to peak normal induction in either direction. The worst case occurs when switching is at an instant of zero voltage and residual magnetism is at a maximum in the direction opposite to that which would exist under steady state conditions.

However, if the state of core magnetization at the moment of switching is already that of the steady conditions at the particular part of the cycle, no inrush current will occur. Even if the residual magnetism can be brought to zero before switching, possibility of an extremely large inrush current can definitely be brought down to a large extent. Thus R. J. Newmann suggested use of a scheme¹⁾ with additional magnetizing windings to bring down the residual magnetism to zero.

To get an exact design by the use of the proposed method, it is required to calculate precisely the demagnetization process taking into account the hysteresis of the core. This paper presents a comprehensive analysis of the phenomena behind the demagnetization, using a hysteresis model with appropriate numerical method.

If hysteresis effect is to be introduced in any non-linear circuit analysis, hysteresis models for random variation of H should be proposed. The value of B depends not only on the value of H but also on the history of H prior to arriving at this value. In this

paper, the model presented by Talukdar and Bailey²⁾ has been followed. The hysteresis model represents the nonlinear function relating B to H in the core. It traces the B/H excursion by defining the gap between the curve to be traced and the biggest possible (parent) loop as a linear function of the induction B .

The parent hysteresis loop is represented by means of second order rational fractions whose coefficients are related to material constants, depending on the material under investigation. Such functions³⁾ were successfully proposed by Rivas *et al.* To judge the accuracy of this rational fraction technique, they numerically tested many experimentally obtained hysteresis loops. The agreement were better than 1 percent.

The algorithm developed for calculating the transient response will help design the additional magnetizing winding by determining both the transient current through and voltage impressed across each of them at consecutive instants after disconnecting the primary.

2. Representation of Hysteresis Loop by Rational Fractions

Figure 1 shows a typical nonlinear behavior of a $B-H$ loop, where f_1 and f_2 are the descending and ascending curves, respectively. From these curves, auxiliary curves W_1 and W_2 are obtained so that,

$$W_1 = \frac{1}{2} (f_1 + f_2)$$

and

$$W_2 = \frac{1}{2} (f_1 - f_2) \quad (1)$$

Making pertinent assumptions about the symmetry of auxiliary curves and supposing a second degree approximation we have,³⁾

$$W_1 = \mu_0 \left[H + \frac{a_1 H + a_2 H|H|}{1 + b_1 |H| + b_2 H^2} \right] \quad (2)$$

Fig. 1 $B-H$ loop with auxiliary curves.

$$W_2 = \mu_0 \left[\frac{c_1(H_m - |H|) + c_2(H_m^2 - H^2)}{1 + b_1|H| + b_2H^2} \right] \quad (3)$$

Where a_1 , a_2 , b_1 , b_2 , c_1 , and c_2 are coefficients of the rational functions. The term H_m correspond to the maximum field strength and $|H|$ is the absolute value of magnetic field strength. Estimating a safely large H_m which will never be exceeded during the transient, the coefficients can be determined to obtain the function for parent loop curves f_1 and f_2 .

3. Functional Simulation of Transient B - H Excursion

The shape of the B - H curves are determined by both the geometry of the flux path and the magnetic properties of the material in it. For most materials, including laminated transformer steel, it is safe to assume that as long as the flux penetration level remains constant, the B - H trajectory being followed at any time t is uniquely determined by the last point at which the flux density derivative dB/dt changed sign. Henceforth we will refer to such points as "turnaround" points. In all cases, the B - H curves can be separated into two families—one for increasing values of flux (upgoing) and the other for decreasing values (downgoing).

Figure 2 shows a parent or biggest possible hysteresis loop to be represented by rational fractions and another member of the family of upgoing B - H curves within the loop. Let the gap between the two upgoing curves be d_T at the turn-around point X which correspond to flux density B_T . Studying several families of upgoing and downgoing curves, to assume that the gap d corresponding to any flux density value B on the inner curve, is a linear function of B , is not only mathematically convenient but also yields B - H curves close enough to actual ones.

Thus

$$\frac{d}{d_T} = \frac{B_{\max} - B}{B_{\max} - B_T}$$

and hence,

$$B_P = B - d_T \frac{B_{\max} - B}{B_{\max} - B_T} \quad (4)$$

where $d = B - B_P$ and B_P is the flux density on the parent curve for the same H that produces B on the inner curve to be traced. Obviously, the equation to trace a curve inside the loop for decreasing flux densities is

Fig. 2 The parent loop and an upgoing B - H curve.

$$B_P = B - d_T \frac{B - B_{\min}}{B_T - B_{\min}} \quad (5)$$

As for the slope of the B - H curve to be traced, if the flux has to change in the positive direction along the upgoing B - H curve, since,

$$\frac{B - f_2(H)}{d_T} = \frac{B_{\max} - B}{B_{\max} - B_T} \quad (6)$$

where H is the solution field intensity, differentiating Eq. (6) with respect to H and then simplifying,

$$\frac{dB}{dH} = \frac{B_{\max} - B_T}{B_{\max} - B_T + d_T} \frac{df_2}{dH} \quad (7)$$

where

$$\frac{df_2}{dH} = \frac{dW_1}{dH} - \frac{dW_2}{dH}$$

Obviously, for the flux to change in the negative direction along a downgoing B - H curve

$$\frac{dB}{dH} = \frac{B_T - B_{\min}}{B_T - B_{\min} + d_T} \frac{df_1}{dH} \quad (8)$$

4. Solution for the Demagnetization Scheme

If the residual core magnetization can be brought to zero after switching off the primary and before the next switching, possibility of a large inrush current can be reduced to a large extent. It is possible to approach this condition by use of additional windings as arranged in Fig. 3.

When the main contact is opened, nearly all the supply voltage appears across the new windings, one of which continues the magnetization of its limb in the same direction as hitherto. The other reverses the flux in its limb; hence a flux path is established around the peripheral path, which does not give any appreciable induction in the central limb, so that the limb becomes demagnetized.

In the circuit of Fig. 4 representing the scheme of magnetizing windings,

E_0 is the supply voltage to the primary which falls across the magnetizing windings when primary is switched off,

i the current in the magnetizing windings which are in series,

Z_{th} the Thevenin source impedance comprizing resist-

Fig. 3 The proposed scheme.

Fig. 4 The schematic circuit for analysis.

ance and leakage reactance of magnetizing windings also,

e' and e'' voltages across the magnetising windings, B' and B'' are flux densities in the two side limbs of the three limb core setting and l is the length between points P & Q along an additional arm. Evidently,⁴⁾

$$E_0 - Z_{th} \cdot i = e' + e'' = NA \left(\frac{dB'}{di} + \frac{dB''}{di} \right) \cdot \frac{di}{dt}$$

or

$$\frac{di}{dt} = \frac{E_0 - Z_{th} \cdot i}{\frac{N^2 A}{l} \left(\frac{dB'}{dH} + \frac{dB''}{dH} \right)} \quad (9)$$

Since, total m.m.f. $2Ni = H \cdot 2l$ and A is the area of the core provided to the peripheral magnetic path.

Starting initially from the state of normal induction in the central limb, which is shared equally by the outer ones, once dB/dH is calculated on the basis of B_T and d_T of the previous time step as per Eqs. (7) or (8), Eq. (9) is solved for successive close time steps at a gap of, say, Δt second by a 4th order Runge-Kutta method⁵⁾ to obtain the solution of the current i . Once current i in the magnetizing winding is obtained,

$$H = N \cdot i / l$$

B_P (on the parent loop) for each limb can be calculated using Eqs. (1), (2), and (3). Then applying either of Eqs. (4) and (5) B' and B'' can be determined.

We know that the voltage across any of the magnetizing windings is

$$e = NA \frac{dB}{dt}$$

or

$$\int e dt = NA \int dB$$

Using trapezoidal rule of integration and indicating the time instant within parenthesis,

$$e(t) = -e(t - \Delta t) + \frac{2NA}{\Delta t} [B(t) - B(t - \Delta t)] \quad (10)$$

All the above quantities thus obtained are used as previous instant quantity for the next time step solution.

4.1 Criteria for selection of upgoing or downgoing $B-H$ curve

To decide whether the solution should be attempted on an upgoing $B-H$ curve or a decreasing one, the following technique is employed.

$$E = E_0 - Z_{th} \cdot i = e' + e''$$

If the current and hence the flux densities remain unchanged over successive time steps, i.e., $B(t) = B(t - \Delta t)$ then from Eq. (10) we get $E(t) = e'(t) + e''(t)$

$$= -[e'(t - \Delta t) + e''(t - \Delta t)] = -E(t - \Delta t) \quad (11)$$

Also,

$$E(t) = E_0(t) - Z_{th} \cdot i(t) \quad (12)$$

Now, if $E(t)$ obtained from Eq. (12) is greater than that obtained from Eq. (11), the current and hence flux densities have to increase. On the other hand selection of downgoing $B-H$ curve is warranted if Eq. (12) yields lesser $E(t)$ than yielded by Eq. (11).

5. A Case Study

Figure 5 shows the hysteresis loop from saturation to saturation for the core material of the transformer and the auxiliary limbs. The coefficients of the rational functions to represent the loop are: $a_1 = 13826.95$, $a_2 = 573.7998$, $b_1 = 4.179791 \times 10^{-2}$, $b_2 = 3.7676 \times 10^{-4}$, $c_1 = -21631.08$, and $c_2 = 22.20541$.

The dimensions of the auxiliary limbs as provided to the 250 kVA transformer are:

length l as defined in Fig. 4 = 5.0 m

cross sectional area $A = 0.09 \text{ m}^2$

number of turns in each of the magnetizing windings $N = 350$

For a supply voltage equal to the phase to ground voltage in a line of 33 kV nominal voltage, impressed across the magnetizing windings, the transient current drawn by the magnetizing windings is given in Fig. 6.

Figure 7 shows the decay of residual flux density in the transformer core and Fig. 8 gives the waveforms of fluxes in the three limbs.

Figure 9 gives the transient voltages developed across the two magnetizing windings just after dis-

Fig. 5 The hysteresis loop of the core.

Fig. 6 Transient current in the magnetizing winding.

Fig. 7 Decay of residual flux density.

connecting the primary off the supply.

The basic design requirements for such a demagnetizing scheme are:

(a) The cross-sectional areas and lengths of the auxiliary limbs should be identical and the cross-sectional area of the auxiliary limb should not be less than at least half of that of the central limb.

(b) The number of turns of the auxiliary or demagnetizing winding is a compromise between two effects.

If the number of turns is too small, the inductance of the windings being too small will draw high current through themselves which is not desirable in all the cases.

Also, if the number of turns is too large, the current being too small, the magnetization of the auxiliary limbs will not be enough to bring about a quick demagnetization.

6. Conclusion

One of the limitations of the approach has been neglecting the secondary winding current during demagnetization. A loaded or short circuited secondary would have had current induced in it in such a direc-

Fig. 8 Waveform of the flux in the limbs.

Fig. 9 Voltages e' and e'' across auxiliary windings after switching.

tion that decrement of the residual flux would have been opposed and hence slowed down. Thus this paper presents an open secondary scheme. However, if simultaneous opening of both primary and secondary can be ensured, fastest decay of the residual flux can be achieved.

A slight voltage drop in the primary winding that occurs when supply voltage is impressed upon the auxiliary magnetizing windings, has been ignored. The design should be such that this drop should be minimal for quick demagnetization of the central limb.

References

- 1) R. J. Newman: *Proc. IEEE*, **111**, 2096 (1964).
- 2) S. N. Talukdar and J. R. Bailey: *IEEE Trans. Power App. & Sys.*, **PAS-95**, 1429 (1976).
- 3) J. Rivas, J. M. Zamarro, and E. Martin: *IEEE Trans. Magn.*, **17**, 1498 (1981).
- 4) A. Mukherjee and P. K. Mukherjee: *Indian J. Technol.*, **31**, 615 (1993).
- 5) M. L. James, G. M. Smith, and J. C. Wolford: *Applied Numerical Methods for Digital Computation* (Harper & Row, Publishers, 2nd, 1977).

Received Oct. 27, 1997; Accepted Feb. 2, 1998