

A COMPUTER SIMULATION OF TRANSFORMER MAGNETIZING CURRENT INTERRUPTION BY A VACUUM CIRCUIT BREAKER

Alexey M.Chaly, Alevtina T.Chalaya

Tavrida Electric Ltd, Marshala Biryuzova Street, 1 123294, Moscow, Russia

ABSTRACT

A computer program has been elaborated to calculate switching overvoltages during transformer interruption of a magnetizing current by a vacuum circuit breaker (VCB). This program uses the Monte Carlo simulation technique and takes into account a three-phase switching phenomena in an isolated neutral electric circuit.

The distinguishing feature of this program is the application of a current chopping model, based on the experimentally determined average arc lifetime vs current dependency. This model considers both the current's amplitude and shape. Some generalized dependencies, like maximum overvoltages on the circuit and VCB parameters, are also incorporated. Classification of switching regimes was carried out with respect to different switching behaviour and the VCB's effect on the reduction of maximum overvoltages.

1. INTRODUCTION

The problem of interruption of unloaded transformers by VCB was first studied by Lee & Greenwood more than 30 years ago [1]. Since then, many investigations have focused their attention on it [2-5]. It became clear during such investigations that the interruption of an unloaded transformer by a VCB is a complex phenomena, which consist of several current choppings and reignitions. These reignitions usually limit maximum overvoltages far below the values calculated using the simple model:

$$U_m = i_c \sqrt{\frac{L}{C}} \quad (1)$$

where i_c - current chopping, U_m - overvoltage peak, L, C - transformer inductance and capacitance.

While investigating this problem, it was shown that transformer core losses and magnetizing curve non-linearity also substantially contribute to limitation of maximum overvoltages [4]. In the 1980's, a Monte Carlo simulation technique was effectively applied to switching overvoltage simulations during the interruption of inductive load by a VCB [6-8]. This approach permitted consideration of the statistical properties of the VCB, and thus more realistically derived statistical values for the overvoltages.

However in this paper, current chopping is presented as a statistical value independent of current. Strictly speaking, this is not true [9]. Such an approach probably applies during a computer analysis of motor and reactor interruption, where the currents value is much higher than VCB current chopping. However it hardly applies during analysis of an unloaded transformer interruption, because current chopping and magnetizing current are basically on the same order of magnitude. Moreover, transformer magnetizing current is strongly nonlinear. This is why consideration of current chopping vs interrupting current dependency which is used for example in [9], in our opinion does not use the correct representation of VCB current chopping when considering the interruption of magnetizing current.

To achieve a better representation of current chopping, we have used an approach first proposed by Kesaev [10] and then further developed in other papers [11,12]. The demanding task of computer simulation required some new features to be added to this approach.

The papers mentioned above deal primarily with a simulation program that uses a linear load model. Again, this approach is not consistent with an analysis of unloaded transformer interruption. The aim of the present work is to develop a simulation program that uses realistic models for current chopping and also for unloaded transformers. This program is further applied during analysis of the influence of a VCB

and circuit parameters on the switching overvoltages.

2. EQUIVALENT CIRCUIT

The Equivalent circuit as used in the computer program is presented in Fig. 1.

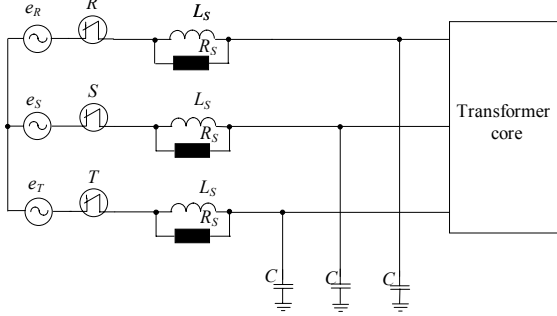


Fig. 1: Equivalent circuit.

The designations in Fig. 1 are as follows: e_R, e_S, e_T - symmetrical system voltages; C - equivalent capacitance of the transformer and connected cable; R_S - artificial resistor taking into account high frequency (HF) damping; R, S, T - VCB poles. Source side neutral is considered to be isolated for analysis of the HF currents to represent the worst case with respect to virtual current chopping (VCC) appearance.

Transformer core was represented with respect to actual steel non-linearity, frequency dependant damping and mutual phase inductance. The model used is similar to that described in [13].

3. REPRESENTATION OF THE VACUUM CIRCUIT BREAKER

A VCB is presented by three statistical values: current chopping, Dielectric strength rise, and HF current interrupting capability.

The VCB is treated as an ideal two-positioned switch. In the closed position (corresponding to the arcing) its resistance is considered to be zero. In open position (corresponding to the voltage recovery) its resistance is equal to infinity. Switching from the closed to open position and vice versa is determined by statistical conditions checked during every step of the computer program. These conditions are discussed bellow.

3.1 Current chopping

It is known that probability of the small AC current to be chopped within a time interval can be expressed as follows [12]:

$$P(t_0 < t_a < t) = 1 - \exp\left(-\int_{t_0}^t \frac{d\tau}{\bar{t}_a(i(\tau))}\right) \quad (2)$$

where t_a - arcing time, t_0 - moment of arc ignition, i - current, \bar{t}_a - average arc life time current i .

Let's assume that with any program, time step $t_{j+1} - t_j$ current may be expressed as a linear function of time:

$$i(t) = i_j + \frac{i_{j+1} - i_j}{\Delta t} (t - t_j) \quad (3)$$

where i_j, i_{j+1} - current values at the beginning and at the end of the j -th time step respectively: $\Delta t = t_{j+1} - t_j$.

Let's further assume the following dependency of the average DC arc lifetime on the current [11]:

$$\bar{t}_a = Bi^A \quad (4)$$

where A, B - constants. Then integrating (2) for the j -time step taking into account.

Eq. (3), (4) we obtain the following formula:

$$\Delta P_j = 1 - \exp\left(-\Delta t \frac{i_{j+1}^{(1-A)} - i_j^{(1-A)}}{B(1-A)(i_{j+1} - i_j)}\right) \quad (5)$$

where ΔP_j - conditioning chopping probabilities for j -th time step.

Eq.(2) follows from the fact that current chopping probability at any time interval is not affected by the previous arcing history. Taking this independence into account once more we get the following recurrent formula:

$$P_{j+1} = P_j + \Delta P_j(1 - P_j) \quad (6)$$

where P_j, P_{j+1} - chopping probabilities for time intervals $t_0 - t_j$ and $t_j - t_{j+1}$ respectively.

With Eq. (5) & (6), statistical conditions for current chopping may be express as follows:

$$P_j \geq P \quad (7)$$

where P is a rectangular distributed stochastic value. Condition (7) is checked by the computer program at each time interval until it satisfied the certain time step. It happens inevitably because with i approaching zero grows to unit.

This model described allows to take into account both current amplitude and form. It is especially useful for currents compatible in value with natural current chopping. For an unloaded transformer simulation, this is just the case.

3.2 Dielectric strength rise

A rise in dielectric strength (k-factor) [14], is a result of multiplication of the vacuum gap's dielectric strength E on the contact velocity.

E is a statistical value that depends on the contact material and contact shape. Weibull distribution is often used to express statistical properties of the dielectric strength E for a vacuum gap [15]. EV also obeys Weibull distribution. In this paper, it is expressed in the following form:

$$P(EV) = 1 - \exp\left(-\left(1.125\left(\frac{EV}{\overline{EV}} - 0.2\right)\right)^m\right) \quad (8)$$

where \overline{EV} - EV average, m - parameter responsible for EV scattering.

3.3 High frequency current interrupting capability

HF current interrupting capability is expressed in terms of «interruptible rate of current

decrease» di/dt obeying the same distribution as the dielectric strength rise:

$$P\left(\frac{di}{dt}\right) = 1 - \exp\left(-\left(1.125\left(\frac{\frac{di}{dt}}{\overline{\frac{di}{dt}}} - 0.2\right)\right)^n\right) \quad (9)$$

where $\overline{\frac{di}{dt}}$ - average $\frac{di}{dt}$; n - parameter responsible for $\frac{di}{dt}$ scattering.

This criteria is criticised by some papers [16] as being affected by the circuit parameters. Sample computer runs proved however, that maximum overvoltages at unloaded transformer interruption are not very sensitive to the HF interrupting capability. We believe that this allows the simplified criteria to be applied in the case under analysis.

4. CALCULATION PROCEDURE

The calculation procedure used in this text is analogous to that described in [6]. Four rectangularity distributed stochastic values are generated to determine contact separation time, current chopping, dielectric strength rise, and the HF current interrupting capability. Every computer run generally consists of repeated chopping reignitions and HF current clearings. This sequence of events continues until the VCB withstands recovery voltage. A computer then stores and registers all values for maximum overvoltages, number of breakdowns, and VCC. After fulfilling the assigned number of computer runs, a distribution function for maximum overvoltages is plotted «maximum maximoro», and the average number of breakdowns and percentage of VCC are also determined.

5. VERIFICATION OF THE COMPUTER PROGRAM

This computer program has been verified by comparing the measurements fulfilled by 6 power transformers. The transformer power scattered from 100 to 4200 kW. Rated voltages were 0.4 and 6 kV. Maximum overvoltages were

calculated with a margin of error from 2 to 16 % for the different transformers.

6. RESULTS OF THE COMPUTER SIMULATION

With the aid of the program discussed above, an analysis was performed to understand the dependency of maximum overvoltages on a main circuit's parameters - the transformer magnetizing current and equivalent circuit capacitance. The input parameters for the program were set up as follows:

Circuit parameters:

Rated voltage: $U = 6 \div 10$ kV;

Transformer winding connection: Δ , Y;

HF current damping factor: $a_{hf} = 0.8$;

Ultra HF voltage overshoot factor: $a_{uhf} = 1.8$;

Cable surge resistance: $Z = 30$ Ohm;

Busbars inductance: $L_b = 15$ μ H;

L_s in Fig. 1 has been determined as follows:

$$L_s = L_b + \frac{Z^2}{C} \quad (10)$$

VCB parameters:

The current corresponding to 5 ms DC arc stability: $I_5 = 5$ A;

Power factor in «average DC and life time - current» dependency: $B = 10$;

Average dielectric strength rise: $\overline{EV} = 50$ kV/ms;

Average interruptable: $\overline{di/dt} = 100$ A/ μ s;

Parameters of the Weibull distributions for EV and di/dt are $m=n=4$.

In Fig. 2 dependence of maximum overvoltages (99 % probability) on the transformer magnetizing current with Δ winding connections are presented for different circuit equivalent capacitance's (solid lines).

Dotted lines represent maximum overvoltages resulting from current chopping during

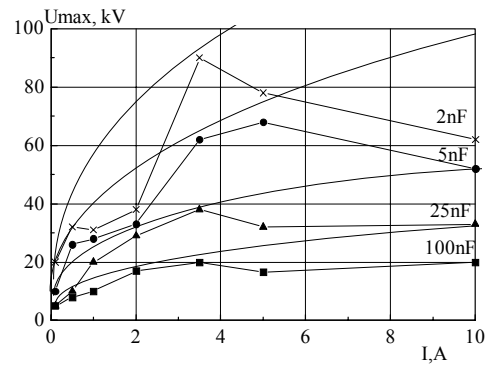


Fig. 2: Maximum overvoltages vs magnetizing current

transformer magnetizing current in one pole, while the two other poles are still arcing. They are calculated with the aid of a transformer model.

This value is named «predicted maximum» and note that it represents the worst (and generally unrealistic) case when the limiting effect of the VCB is *not* considered.

7. DISCUSSION

As seen in Fig. 2, maximum overvoltages are often much lower than «predicted maximum». To make the effect of a VCB more clear, let's call the ratio of the maximum calculated overvoltages to the predicted maximum as a reduction factor and then plot its dependency on the rated magnetizing current (Fig. 3).

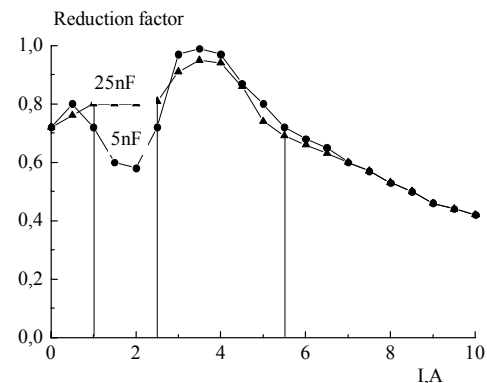


Fig. 3: Reduction factor vs magnetizing current

Looking at Fig. 3 one can distinguish four different Zones (Table 1).

Table 1

	Current range	Reduction factor	Switching behaviour
Zone I	$0 \div 4\overline{EVC}$	$0.72 \div 0.8$	Current is chopped immediately after contact separation. Breakdowns are absent or occasional (No limiting effect, no VCC).
Zone II	$4\overline{EVC} \div 0.5I_5$	$0.45 \div 0.72$	Current is chopped immediately after contact separation followed by a set of breakdowns limiting maximum overvoltages (No VCC).
Zone III	$(0.5 \div 1.1)I_5$	$0.72 \div 1.0$	Current may be chopped at maximum after several ms of arcing. Limiting effects are not perceivable. VCC are possible.
Zone IV	$> 1.1I_5$	< 0.72	Current can be chopped at maximum. Choppings usually occur before natural current zero. VCC are possible.

As it is clear from this table, for these Zones reduction factor and switching behaviour are different.

Reduction of maximum phase-to-ground overvoltages in Zone I is determined by immediate three phase chopping. With this, as it follows from calculations based on the transformer model maximum overvoltages are equal to 0.72 of the U_{pm} .

In Zone II maximum overvoltages are suppressed below 0.72 because of the multiple reignitions of the VCB - the process described for example in [2].

In Zone III the limiting effect of the VCB is not perceivable. This happens because of the increased arc stability that may lead to 1-2 ms of previous arcing before current chopping is at a maximum. For the considered conditions ($\overline{EV} = 50$ kV/ms), for example, it is clear that an average dielectric strength after 1 ms of arcing will be $50 \div 100$ kV - quite sufficient to withstand (and not to limit) high overvoltage.

In Zone IV maximum overvoltages are limited below $0.72 U_{pm}$ because the current cannot be chopped in maximum because of the high arc stability. It is interesting to notice that Zone II will not exist if $4\overline{EVC} > I_5$. Look for example at the dependency of the reduction factor on the magnetizing current for $C = 25$ nF (Fig. 3).

It must also be mentioned that because of the statistical nature of the VCB parameters, borders between the Zones in Table 1 cannot be strictly determined, and are presented mostly for physical guidance.

8. CONCLUSIONS

1. Interruptions of unloaded transformers by VCBs are a complex switching phenomena including several sequences of choppings, reignitions, and clearings of the HF current.

2. The main VCB parameters that determine switching behaviour for an unloaded transformer's interruption are current chopping and dielectric strength rise. HF interrupting capability is only of minor importance.

3. Dielectric strength and current chopping do not always cause a reduction in maximum overvoltages when compared with the predicted maximum. Reduction coefficients as well as behaviour of the switching phenomena depend upon the integration of the circuit and VCB parameters.

4. Four different Zones are identified and each characterised by different switching behaviour, reduction coefficients, and influence of VCB on maximum overvoltages.

9. ACKNOWLEDGEMENTS

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