Influence of excess eddy current core losses of saturable reactor on the process of semiconductor valve turn-on

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Abstract. In this article the transient process was analyzed when the semiconductor valve turn-on with a new modernized equipment of the Vyborg HVDC scheme. It was found that transient processes occur at high frequencies of about 50-60 kHz. During high-frequency transients when the valve turn-on current can reach zero and negative values. This oscillation can lead to premature valve turn-off and even to its destruction, depending on the switching conditions. The paper deals with issue of damping of the turn-on high-frequency current oscillation witch can be achieved by effective eddy-current resistance due to excess eddy current magnetic core losses of the saturable reactors. Calculation energy losses in thin structures of laminated magnetic core of the saturable reactor were carried out using obtained data of transient process and Comsol Multiphysics modeling. This gave a numerical estimate of the effect of these losses on the transient process. In terms of obtaining data modificated equivalent electrical circuit was proposed. This modification allows to estimate the influence of excess eddy current core losses of saturable reactor on the semiconductor valve turn-on.

1. Introduction

December 2018 marks the 37th anniversary of commissioning of the first converter unit of Vyborg converter substation which provides asynchronous connection between power networks of Russia and Finland. The new high-voltage valve (HVV) is developed as part of reconstruction of Vyborg converter substation and in order to increase the energy efficiency of the electrical equipment [2, 3, 4]. The objective of developing new valve is to replace the Vyborg substation equipment, which has exhausted its service life, and to create a reliable prototype for future HVDC transmissions [5].

2. High-frequency transients at the valve turn-on

The discharge of capacitor in the damping RC circuit increases the initial commutation current of the valve [6]. This capacitor, together with equipment self-capacitance and inductances of busbars and current-limiting nonlinear reactors, can cause high-frequency (orders of 10⁴-10⁵ Hz) oscillatory processes after thyristor turn-on [7]. The peak-to-peak value of the current oscillation (the change between peak (highest amplitude value) and trough (lowest amplitude value)) is determined by the damping coefficient, which is associated with the effective resistance to eddy currents of the reactor core. If the damping coefficient is too small, the current value immediately after turn-on on can reach large negative values t the lower point of the curve, and this can lead to the extinction of the thyristor or even its destruction depending on the switching conditions [8].
To assess the nature of the mentioned transient process, the rectifier bridge circuit is used (Figure 1), its equivalent circuit is shown in Figure 2 at the time of valve 3 commutation. Until the time of firing valve 3, the current flows through the valves 1 and 2. The voltage on each phase capacitance $C_A$, $C_B$, $C_C$ coincides with the corresponding phase EMF at the converter input, the voltage on the capacitance of the poles $C_{P1}$ and $C_{P2}$ is equal to the voltage at phase A and C, respectively.

Let’s calculate the considered voltages on the capacitances at the time of valve 3 commutation. The single-bridge converter operates in a rectifier mode with a firing angle $\alpha = 85^\circ$. The maximum line voltage is 100 kV. At the time of valve 3 commutation we have the following voltages on the capacitances: $C_{D3} = -9.962 \cdot 10^4$ V, $C_{D4} = C_{D5} = -5.736 \cdot 10^4$ V, $C_{D6} = -4.226 \cdot 10^4$ V, $C_{P1} = C_A = 5.233 \cdot 10^4$ V, $C_B = -4.729 \cdot 10^4$ V, $C_{P2} = C_C = -5.032 \cdot 10^4$ V.

Capacities $C_{P1}$ and $C_{P2}$ imitate the capacities of the pole inputs to the valve hall and the self-capacities of the equipment connected to one poles. The values of the capacities are approximately 10 nF [9]. The capacitances $C_1$, $C_2$ and $C_3$ imitate the distribution ground capacitances of the secondary windings of the transformer, the capacity of the transformer output and the capacity of the phase input to the valve hall. These capacities are approximately 10 nF. The parameters of the damping circuit are 1152 Ohms and 0.03125 uF. Since preliminary calculations showed that the currents do not reach the saturation currents of the nonlinear reactor, the inductance of the equivalent circuit was assumed to be equal to the linear inductance of the high-voltage valve reactors - 2.4 mH.

When making up the equivalent circuit, the assumption was made. Since the transient occurs at frequencies near several tens of kilohertz, the inductances of transformers and smoothing reactors represent a big resistance, and it can be assumed that the circuit is opened in these places. The Matlab Simulink simulation result of the equivalent circuit is shown in Figure 3.
Figure 3. Current when the valve turned-on.

As can be seen from the Figure 3, the transition process takes place at frequencies near 50-60 kHz, which generally justifies the assumptions made above. This result will be used to estimate the losses in the steel of the nonlinear reactor magnetic core.

3. Saturable reactor core losses

Traditionally, the total losses contain two components: losses that are proportional to the frequency and that are proportional to the square of the frequency with the constant shape of the curve and the amplitude of induction [10]:

\[ p = p_H + p_E = af + bf^2 \]  

(1)

However, the difference between the result obtained by the equation (1) and those obtained by real experiments \( p_{\text{real}} \) can be quite huge [11]. This difference causes the excess of eddy current losses (2):

\[ p_{\text{ext}} = p_{\text{real}} - (p_H + p_E) \]  

(2)

These losses are due to the non-uniform profiles of magnetic flux density [12]. This phenomenon is caused by the delayed domain motion responding to the excitation magnetic strength as it diffuses into the lamination.

The aim of the study is to determine the losses values using Comsol Multiphysics computer modeling. The modeling results will be used to estimate the influence of excess eddy current losses in the high-frequencies transient process. The specific losses will be calculated in one sheet of the core of the saturable reactor. The geometry is shown in Figure 4. The governing equations of the electromagnetic field in laminations are Ampere-Maxwell’s Equations (3):

\[
\begin{align*}
\nabla \times H &= J \\
B &= \nabla \times A \\
J &= \sigma \cdot E + \sigma v \times B + J_e \\
E &= -\frac{\partial A}{\partial t}
\end{align*}
\]  

(3)

Hysteresis loss is mainly determined by the area of the hysteresis loop [13]. At the studied frequencies these losses are relatively small and we neglect them.
Investigated saturated reactor is shown in Figure 4. Geometric parameters of the model in Comsol (Figure 5): thickness of steel sheet – Y·2 = 0.032 mm; magnetic package width – X·2 = 0.4 m. Magnetic material – 5BDSR [14] (Russian equivalent of FINEMET). Conductivity \( \sigma \) and density \( \rho \) 5BDSR – 6.25 S/m and 7600 kg/m\(^3\) respectively. To simulate the nonlinear behavior of the material, the Jiles-Atherton hysteresis model was used [15]. The Jiles-Atherton model parameters for material 5BDSR were taken from [16]. The sheet is affected by the magnetic field of the current calculated in the previous section (Figure 3).

An example of simulation results is shown in Figure 6 and Figure 7. In Figure 6 and Figure 7 shows the distribution of the magnetic field and current density in a thin sheet respectively.

Having the data of the current density distribution in a thin sheet using equation (4) we calculate the energy released for the transient process.

\[
Q_e = \frac{1}{\rho} \int dvdt \frac{\vec{J} \cdot \vec{E}}{\sigma}
\]

For 100 ms it was \( 5.836 \cdot 10^{-3} \) J/kg. Saturable reactor steel weight – 52 kg. The number of reactors in the valve is 8. Total energy loss in steel per valve \( 5.836 \cdot 10^{-3} \cdot 52 \cdot 8 = 2.334 \) J. Next we investigate how these losses affect the high-frequency process of the semiconductor valve turn-on.

4. Modification of equivalent electrical circuit in terms of excess eddy current losses

The modification of equivalent electrical circuit was made to assess the influence of excess eddy current core losses of saturable reactor on the semiconductor valve turn-on.
The resistor was connected in parallel with the inductance of the saturable reactor in the equivalent circuit (Figure 8). In a high-frequency transient the reactor resistance becomes comparable to the resistor resistance, thereby dissipating some of the energy on it. After the attenuation of the high-frequency component this resistor will no longer have an effect.

The resistance value \( R_{ex} \) is chosen so that the same amount of energy (according of the equation (5)) is dissipated in it (2.334 J) (Figure 9).

\[
Q = \int_0^T P(t)dt = \int_0^T IUdt
\]  

(5)

The simulation showed that for the saturable reactor under study \( R_{ex} = 18710 \) Ohm. In figure 10 are showed the process of semiconductor valve turn-on in terms of excess eddy current core losses of saturable reactor.

A losses of steel as shown by the result may have some influence on the transient process. This phenomenon requires further study and data acquisition on real samples.

5. Conclusions
In this paper a method for taking into account losses in non-linear reactor steel magnetic core caused by excessive eddy current losses is proposed. The main point of the technique is to modify the equivalent circuits for transient at valve turn-on calculations by adding additional resistances that simulate high-frequency component energy dissipation. The technique also includes a proposal for the method of calculating the losses.
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