MATHEMATICAL MODEL OF RCCB SENSITIVE TO PULSATING DIRECT CURRENTS

J. Kaser[1] and J. Valenta[1]

[1]Doctoral Degree Programme, Power Electronics and Energy, FEEC BUT, Brno University of Technology, Czech Republic

E-mail: xkaser00@vut.cz, valentaj@vutbr.cz

Abstract—This study is focused on a residual-current circuit breaker (RCCB) and its eventual operation malfunction due to direct current components. This problem is associated with magnetic phenomena inside its transformer core. These phenomena are described in detail in the magnetic equations used in a mathematical model created in Simulink. The model incorporates the comparison of individual transformer B/H loop and verifies its reaction to the various residual currents and the correct operation of residual current circuit breaker to achieve results.

Keywords— Residual-current circuit breaker, Mathematical model, Simulink program, Magnetic phenomena, Pulsating direct current

1. INTRODUCTION

The electrical protections ensure a fundamental safety in the power electrical engineering and installations and guarantees a fast interruption in a required time. It must fulfil the conditions of correct protection (selectivity, maximum line resistance, sensitivity, speed and next) against an overload, a short-circuit current and a thermal or force stress. Furthermore, a minimum risk to electrical shock is very important and essential. Therefore, it is necessary to detect and interrupt a direct and indirect contact in a few milliseconds. Basically, the residual-current device reacts on this fault. However, there are some problems with the tripping as shown reference 7. In this case, this protection may not detect a pulsating or a smooth direct current from the rectifiers (one way, six-pulse and next). The main issue is that the transformer core of device is saturated. Thus, it is useful to choose the correct type of residual-circuit breaker as described in chapter 2.

2. RESIDUAL-CURRENT DEVICE

According to refences 1, 2 and 3, the residual-current circuit breaker (RCCB) or residual-current device (RCD) is a protection to detect a leakage (residual) fault current and ensures safety against electrical shocks caused by the indirect and direct contacts in a grounded installation. As a result, the RCCB indicates all earth fault currents, including the earth short-circuit currents.

The RCCB disconnects the circuit whenever the current exceeds a rated residual sensitivity. This protection contains a sum current transformer that measures and compares the instantaneous vector values of currents passing through the working wires (L and N) for the closure of loop. As already mentioned, the RCCB is connected without earth wire (PE). In the normal conditions, the sum of the current vector values is zero. When an earth fault occurs and the rated residual current sensitivity is exceeded, this device interrupts a circuit. The induced secondary current creates the magnetic field of coil of the sensitive relay which effects against the magnetic field of permanent magnet. This magnet drops out and then disconnects the mechanical contacts.

The type of transformer core and its sensitivity are important for next results in chapters 4.

AC - Residual sinusoidal alternating current.
A - Residual sinusoidal alternating current, pulsating direct current and smooth current to 6 mA.
F - Same as type A but it utilizes for frequency up to 1 kHz.
B - Residual sinusoidal alternating current, pulsating direct current and smooth current over 10 mA.

3. MAGNETIC TERMS AND EQUATIONS

The model of transformer core of residual current device utilizes the magnetic phenomena and their basic equations to create the loops for complete closure. The necessary parameters are magnetic flux ϕ of core and magnetic flux linkage ψ, inductance L and mutual inductance M, magnetic flux density B and magnetizing field strength H to create B-H loop, magnetization current i0 to establish this magnetic flux ϕ. The basic magnetic explanation and the knowledge are obtained from references 4, 5 and 6.

In the ferromagnetic core, the magnetic flux ϕ is the product of the magnetic flux density B and the perpendicular area of core S that it penetrates. The magnetic flux is the measure of total number of induction lines passing through this area.

$$\Phi = B\,S\,cos\alpha = B\,S \tag{3.1}$$

The coil of transformer has several turns, so this flux is a magnetic flux linkage and is marked ψ. Furthermore, this flux ψ is expressed as the product of inductance L and the total current flowing I in the circuit.

$$\Psi = \Phi\,N = L\,I \tag{3.2}$$

The magnetic flux density B is expressed as the product of the magnetic field strength of core H, the vacuum permeability μ0 and material permeability μr (ferromagnetic materials). The permeability is the measure of magnetization that the material obtains in reaction to the magnetic field in the loop. The B-H loop determines the core type mainly according to remanence B_r.

$$B = \mu\,H = \mu_0\,\mu_r\,H \tag{3.3}$$

In the electromagnetism, an inductance L of coil is 1 H where induces a voltage 1 V if a current change itself 1 A per second. The inductance expresses dependence between the induced voltage and current change. In this equation, a core dimension as a length l and area S, permeability μ and the number of turns N are important for a whole expression.

$$L = \frac{N^2\,\mu_0\,\mu_r\,S}{l} \tag{3.4}$$

The mutual inductance M expresses the proportionality of induced voltage in the first coil that produces the magnetic field in the second coil.

$$M = \frac{N_1\,N_2\,\mu_0\,\mu_r\,S}{l} \tag{3.5}$$

4. MATHEMATICAL MODEL OF RCCB IN SIMULINK

The research has 2 parts. The first is a magnetic model and second is a fault current loop with the pulsating direct current 30 mA controlled by the thyristors in the 0°, 90° and 135°.

This magnetic model consists of the fundamental equations from chapter 3 to create the final loop of transformer core of RCD. The loop includes the magnetic flux linkage Ψ from equation 3.2. and the current carrying in the turns (i1 and i'2) and through the core (i0). The current of secondary turn i'2 transfer to the primary side to correct results. The mutual inductance M create the magnetic field from induced side as shown in 4.1. and a stray inductance is neglected due to toroid core.

$$\Psi = L\,i_1 + M\,i_2' \tag{4.1}$$

$$i_0 = i_1 - i_2' \tag{4.2}$$

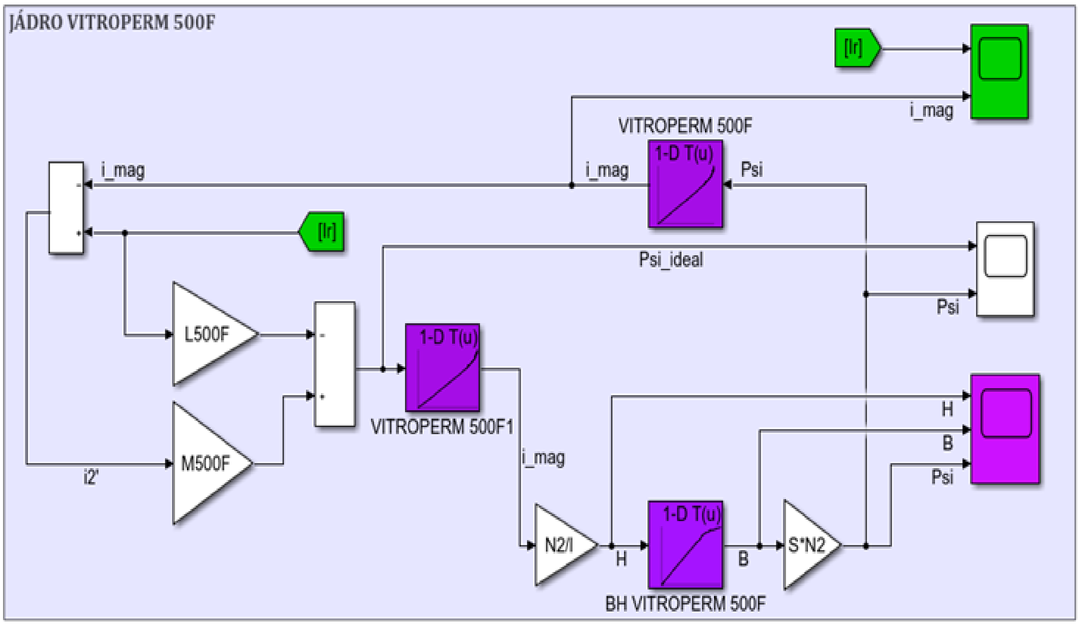
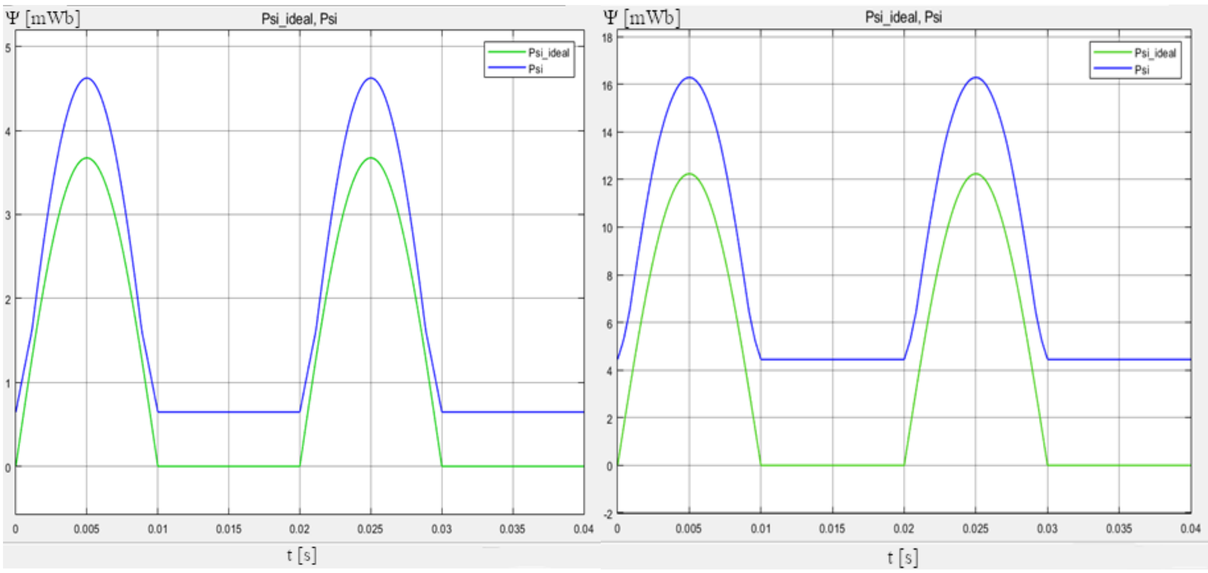


Figure 1: Transformer core of Vitroperm 500F

The research verifies three different materials for transformer core. Each material has a specific B-H loop with magnetic features. In the Figure 1 is Vitroperm 500F, other loops of the materials look like same. The green arrow (Ir) is the residual pulsating direct current. The purple squares show the B-H loop and Ψ-i0 characteristics of core. The results draw the comparison of magnetic flux linkage Ψ of all 3 materials and are measured by the oscilloscopes. The simulations are for pulsating direct current 30 mA controlled in 0° in the Figure 2 and even with smooth direct current 6 mA in Figure 3.



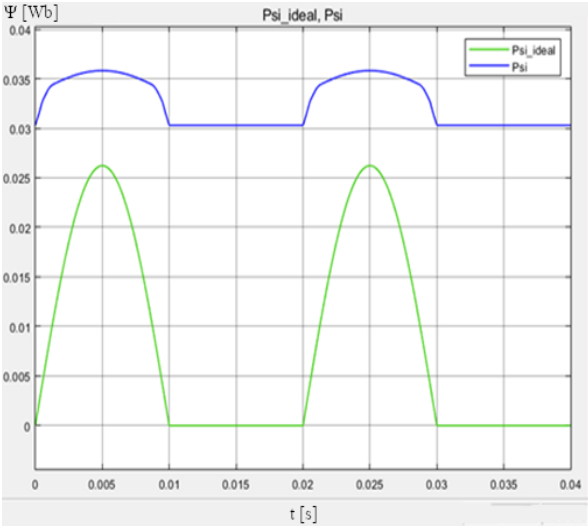


Figure 2: Simulation of magnetic flux Ψ a) Vitroperm 500F b) Vitroperm 800F c) Material C

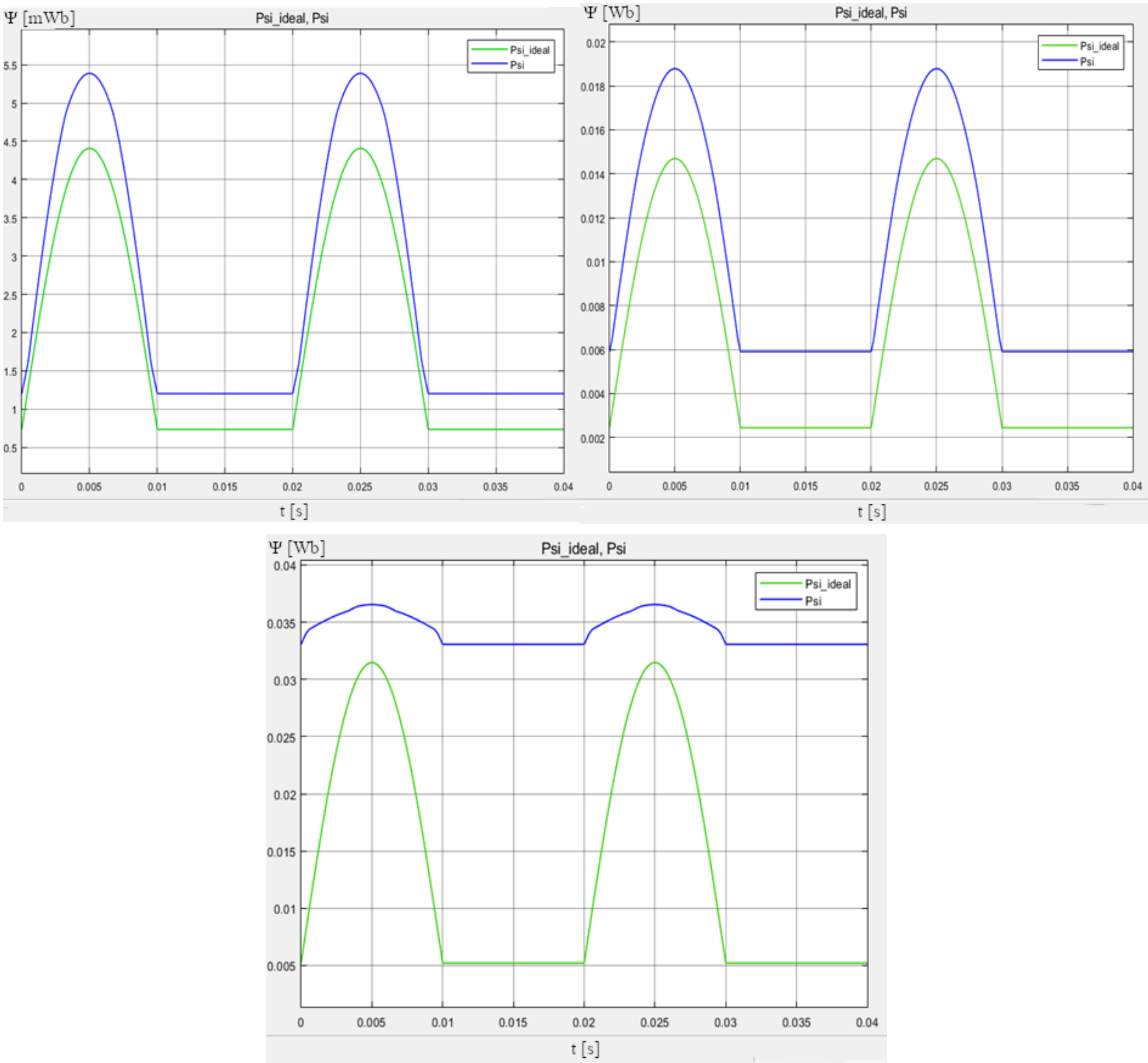


Figure 3. Simulation of magnetic flux Ψ with smooth direct current 6 mA a) Vitroperm 500F b) Vitroperm 800F c) Material C

5. RESULTS AND DISCUSSION

The residual-current circuit breaker is a fundamental protection, and correct type of core and its sensitive must fulfil the conditions. The residual pulsating direct current 30 mA flow through the mathematical model and the obtained results in figure 2a and 2b show the successful simulations of Vitroperm 500F and 800F due to the low remanence (B_r) their B-H loops. The remanence of Vitroperm 500F is the lowest of all materials (0,008 T), so the circuit have no significant saturation of core (each Psi blue course). The similar simulation has the Vitroperm 800F. The remanence is raised (0,055 T) but an overall course is not different from ideal as shown in figure 3b. It is only shifted along the y-axis, so the inductive voltage of secondary winding is high enough.
The third material C have the highest remanence (around 0,37 T) and the simulation is significant deformed as shown figure 3c (Psi blue course) and the saturation occurs. The magnetic flux density B comes up to 0,45 T that exceeds the linear values of B-H loop. The magnetic flux linkage is four times less than ideal and the induced voltage would not be sufficient. Therefore, this material utilizes only for type AC.
In the next analysis in Figure 3, the smooth direct current 6 mA raises a saturation probability. However, the Vitroperm 500F and 800F withstood these conditions and could handle even higher smooth direct current. So, these materials fulfil the standard conditions for type A. The material C is even more deformed (Figure 3c) and there is high permanent magnetic field.
In this research, the model of transformer core is simplified. The magnetic flux linkage must be derived for the correct form of induced voltage. However, this operation represents a high numerical error for the Simulink. So, a load is not in this model and the current transformer is short-circuited. The load and induced voltage would change slightly the secondary current i'_2 and magnetization current i_0. The next simplification is the neglect of stray inductance as shown in the equation 4.1 and winding resistance for its minimum value. On the secondary side is a toroid core (number of turns is 795), so the stray inductance would be minimum, too.
As shown in the figure 2, the residual pulsating direct current is controlled in 0°. However, the thyristors of fault loop can control current in 90° and 135° according to the norm and this loop even produce the smooth direct current to increase the saturation of core. The next courses as the magnetic flux density B and this controlling in the next steps are not contain in this article.

ACKNOWLEDGMENT

This research work has been carried out in the Centre for Research and Utilization of Renewable Energy (CVVOZE). Authors gratefully acknowledge financial support from the Ministry of Education, Youth and Sports under institutional support and BUT specific research program (project No. FEKT-S-20-6379).

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DOI: 10.1016/j.epsr.2013.07.020