EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 442

MODELING AND COMPUTER SIMULATION OF THE PULSED POWERING OF MECHANICAL D.C. CIRCUIT BREAKERS FOR THE CERN/LHC SUPERCONDUCTING MAGNET ENERGY EXTRACTION SYSTEM

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Presented at the 6th International Computational Accelerator Physics Conference
11-14 September 2000, Darmstadt, Germany

Administrative Secretariat
LHC Division
CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 16 November 2000

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I. Introduction

The world's largest hadron collider, the LHC, is under construction at CERN, the European Organization for Nuclear Research. The collider's magnetic system will be about 27 km long and will be based mainly on superconducting magnets, cooled to 1.9 K by superfluid helium. The maximal operating d.c. current of its main dipoles and quadrupoles will reach 13 kA. The total stored energy in the 1232 dipoles exceeds 11 GJ at Imax. For the purpose of limiting the voltage to ground of the magnet chain during energy extraction as well as for operational convenience, the ring is divided into 8 sectors, each having independent power circuits [1]. This topology will distribute the energy recuperation systems around the collider ring.

All the power systems are designed so that if a resistive transition ("quench") occurs in an individual magnet of the chain, the energy stored in the complete circuit will be extracted to the ballast load (dump resistor), the other power systems being unaffected. Beside the ballast load resistor, an energy extraction facility comprises, among other components, a system of switches (composed of mechanical circuit breakers), connected in parallel with the extraction resistor. In the normal operating mode of powering the magnet chain the breakers are closed, shunting the resistor. In case of a quench in one or more magnets of the chain, the breakers will open within some milliseconds and connect the ballast load resistor to the circuit, herewith allowing an exponential decay of the current.

A 13 kA extraction switch is composed of a parallel connection of four breaker assemblies, each assembly consisting of two series-connected units. Breakers of type VAB-49 from Company UETM («Uralelectro-tyazhmash»), Ekaterinburg, Russia [2] have been chosen. The power contacts of this breaker are designed for operation with continuous direct currents of up to 4.5 kA. One understands that the faster the breakers operate, the shorter is the period of overload for the 'slowest' of them and the more reliable and durable are these devices. Calculations and tests, made at UETM, have shown the complexity in optimization of the parameters of this strongly non-linear device. It seems quite natural to resort to computer simulation of the driver. Definition of the various components of the driver system, the possibility of verifying the composed or selected models and elaboration of adequate representations of the processes involved are the mandatory requirements for such a simulation, which is the essence of this work. The goal is to formulate recommendations on selection of the parameters for the electromagnetic driver of the VAB-49 breaker as well as for the controls electronics to be built at CERN [3].

II. Breaker operation.

A simplified sketch of the breaker is represented at **Fig.1**. Breaker consists of the main contacts operating with 4.5 kA DC/AC current, auxiliary power contacts and electromagnetic driver. Connection of the contacts group with the driver is realized by dielectric rods and the system of springs. The electromagnetic driver has a four-rod core with three air gaps of variable value. The core is made from the transformer steel. Rods have parts with different cross-sections.

In the initial state, i.e. when both the control coils of the electromagnet are de-energized, the movable parts of its core (yokes) are in the released state and the mechanical springs hold the mechanism in a position, where both the main and auxiliary power contacts are opened.

To close the contacts of the breaker's power circuit, a current of 11 to 22 A is applied to the central (holding) control coil. The magnetic field generated by this current, will overcome the spring force and pulls both the left and the right yokes to the main core.

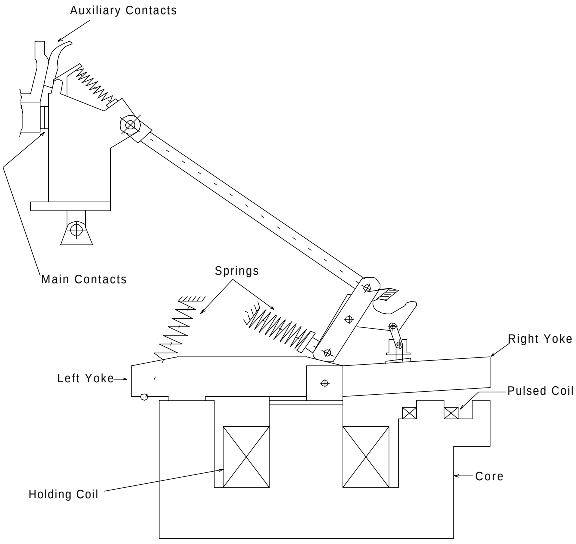

Fig.1. Simplified mechanical and magnetic system of the breaker.

This process leads to setting the breaker to the ‘stand-by’ state, in which the gap between the main contacts is reduced to 5 mm. Additional block-contacts on the driving circuit will indicate that the ‘stand-by’ position has been reached, allowing the activation of the next step in the closing procedure: the reduction of the current in the main coil. The current starts decaying down to 0.5 A with a time constant of about 20 ms. This current is enough to hold the left yoke pulled, but it is absolutely insufficient for holding the right yoke. It means that at some moment after the start of the current fall the right yoke will be released and the spring-level mechanism will set it in the ‘ON’ state. In such a condition (the left yoke is pulled to the core, the right one is released), the breaker is ready for passing a current through the power contacts. The auxiliary power contacts are also closed, but they are shunted by the main contacts with a lower resistance and hence are not under the current load.

The power contacts may be opened in two ways, i.e. by two control channels. The first method is the standard procedure, in which the control circuit will initiate the de-excitation of the central (holding) coil. The coil current will start decaying and the force, pulling the left yoke to the core, weakens. The spring force will lead to an opening of the magnetic circuit and an activation of the mechanical system, which is connected to the power contacts, resulting in an opening of the breaker. Due to the large number of turns of the main coil, its time constant is noticeably large and, consequently, the breaker operates rather slowly (the slow-opening control channel).

The second method of opening is the pulsed mode. In this case, a current pulse of several hundreds of amperes and several milliseconds long is applied to the pulsed coil, placed on the right limb of the magnetic core. Herewith, a large magnetic flux appears in this right limb, pulling the right yoke towards the core, - a comparatively fast action. As this takes place, the existing magnetic flux in the left limb (generated by the holding coil, which is still not de-energized) is compensated (opposite flux directions) and the left yoke is released from the core under the influence of the spring force. Both these processes lead to a fast operation of the breaker.

Thus basing on the Breaker construction and on the main working principles we can formulate the next base problems, which we faced:

1) the magnetic circuit consists of the parts with different cross-sections, which are deeply saturated;
2) the magnetic circuit has a gap, the value of which is changed with time, it means that the forces affecting the yoke are also changed;
3) it is necessary to link the electrical control circuits with electrical representation of the magnetic circuits.

III. Grounds for choosing the equivalent circuit

A. Equivalent circuit of the electromagnetic driver.

To create the equivalent circuit for the electromagnetic driver, we will make some simplifying assumptions.

Firstly, we will assume that there is no leakage flux in the magnetic system, i.e. there is no magnetic field outside the magnetic circuit.

Secondly, we neglect the hysteresis effects and the losses in the core iron.

Thirdly, the boundaries of the core parts with different cross-sections were selected comparatively arbitrarily, basing on common sense.

We believe that these limitations will to some extent change the quantitative relations in the processes being simulated but will not significantly influence the qualitative simulation of electromagnetic driver.

As it is known one can write Kirchhoff’s law for magnetic circuits as well as for electrical ones. In particular, for a closed circuit containing air gaps and/or subcircuits with different μ and/or subcircuits with different cross-section of the core, the equation equivalent to Kirchhoff’s law can be written as follows [4]:

$$I\cdot w=E_m=\bullet\ \cdot\Sigma(R_{mi})$$

where $\Sigma(R_{mi})$ is the impedance of the magnetic circuit (the sum of impedances of the sub circuits), E_m – magnetomotive force (MMF) and • – magnetic flux. Reasoning in the same way, one can apply the second Kirchhoff law to a magnetic circuit: the sum of fluxes in a node equals zero. In accordance with the principles of equivalence between electrical and magnetic circuits, the electromagnetic driver's magnetic circuit can be represented with the equivalent electrical circuit shown in **Fig.2.** The circuit consists of three loops: the first one includes resistors R1, Rx1, R6, R7, and source Iw1; the second loop includes resistors R2, Rx2, R5, R6, and sources Iw1 and Iw2; the last one includes resistors Rx2, R3, Rx3, R4, and source Iw2. In this case

$$R_{mi}=l_i/(\mu_r(B)_i\cdot\mu. \cdot S_i),$$

where

l_i – the length of the magnetic path of the corresponding section of the circuit (if the core cross-section is the same all over this sub circuit),

$\mu_r(B)_i$ - the relative magnetic permeability of the steel in the i-th section of the core,

$\mu.$ – magnetic permeability of vacuum,

S_i – the area of the cross-section of the i-th section of the core.

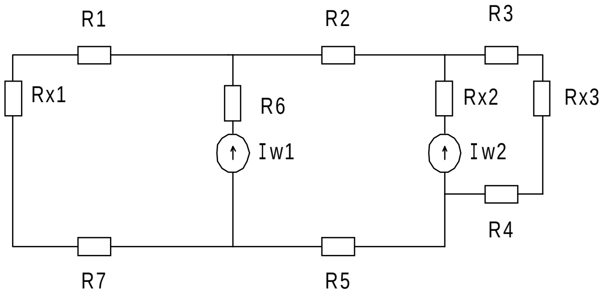

Fig.2. Equivalent electrical circuit of the magnetic system of the electromagnetic driver.

The roles of the MMFs is played here by two sources: Iw1 - the holding coil, and Iw2 - the pulsed coil. The turns are determined by the coil design, the currents are set by the control circuits. The magnetic resistances Rx1, Rx2 and Rx3 correspond to the air gaps, with variable value when the yoke moves. The other magnetic resistances correspond to different sections of the steel, with different cross-section, length and of non-linear characteristics.

B. Taking into account saturation of the core.

Evaluations of the magnetic circuit of the electromagnetic driver show, that at different stages of the driver operation (i.e. at different moments) the MMFs reach such values, that some sections of the magnetic steel core operates in the non-linear area of B(H) characteristics. The levels of non-linearity differs in different sections.

To take into account the non-linearity and/or saturation of the magnetic circuit, the equivalent circuit resistances R_i are made piecewise linear and consist of several, series-connected resistors, with differential resistance value Rinew = Rio + δRi, when the current through the resistor reaches a certain «critical» value. In our equivalent circuit the nonlinear resistor consists of six series-connected resistors. Thus, the volt-ampere characteristic of each of the resistors is a piecewise linear approximation of the B(H) curve of the core material, with a scaling taking into account the length and cross-section of the section being approximated.

In our approximation the resistance of the various sections are calculated under the condition, that the magnetic flux has the same value all over the section, i.e. there is no leakage flux (no tangential components of the magnetic flux).

C. Variable controlled resistor

As it can be seen from **Fig.1.,** the magnetic system of the electromagnetic driver has three air gaps between the mobile yoke and electromagnet's core. During the switching process, the gap values change under the influence of the magnetic- and spring tension forces. An equivalent representation of such gap shall comprise a gap resistance which is variable and controllable.

We have developed two different variants of the variable controlled resistor:

1) on the base of pulse-wide modulation (PWM);
2) on the base of analog multiplier.

The circuit of the first resistor is represented on the **Fig.3a.** It is easy to show that with the averaging time much more than PWM period:

$$<R>=[\frac{1}{R_1}+\frac{\tau}{T}(\frac{1}{R_2}-\frac{1}{R_1})]^{-1}$$

To get sufficient accuracy it is necessary to reduce the step size in the calculations. This, however, leads to an enormous increasing of the calculation time.

The circuit of the second resistor is represented on the **Fig.3b.**

The circuit consists of a signal multiplier with zero output resistance and gain factor **'k'**, a reference resistor and a scale amplifier with a gain factor **'a'**, from which the output signal is applied to one of the inputs of the signal multiplier.

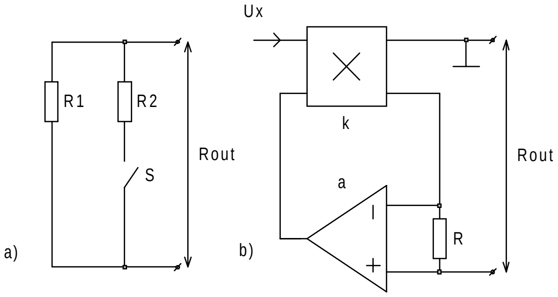

Fig.3. Circuit of the variable controlled resistor.

It can be easily shown that the output resistance of the circuit, presented as U_{out}/I_{out}, equals

$$R_{out} = R\cdot(U_x\cdot k\cdot a + 1).$$

This variant of the resistor presentation is fast and simple, but it should be kept in mind that the model must be grounded, since it is supposed that one terminal of such a resistor is grounded via the virtual power circuit of the operational amplifier. But in our equivalent circuit it is possible to reorganize the grounds so that we can use this variant of the variable controlled resistor.

D. Magnetic forces affecting the yoke.

The force F_m affecting the ferromagnetic core (in our case the electromagnet's yoke) placed in the magnetic field:

$$F_m = dW/dx = \bullet^2/(2\cdot\mu_o\cdot S)$$

Hence, in our equivalent circuit, having measured the magnetic flux with help of a small resistor R, series-connected with the variable resistor of the gap, one can calculate also the magnetic force affecting the yoke. Taking into account the small rotation angle of the yoke and small yoke displacement, relative to the core cross dimensions, we will consider that the yoke surface, forming the air gap, moves in parallel to the opposite surface of the core and the flux of magnetic induction is uniform inside the gap. Then the resulting force may be treated as applied to one point, relatively to which the gap value is determined. We will regard it as coinciding with the core center.

E. The spring elasticity forces affecting the yoke.

Taking into account the mechanical diagram of the electromagnet **(Fig.1.),** we will find the spring elasticity force F_{el} affecting the yoke:

$$F_{el} = k\cdot x$$

where:

k – the elasticity coefficient of the spring [N/m].

x – the yoke displacement (variation of the gap value),

F. Yoke movement equivalent circuit.

Since the movable yoke is rotating around one, fixed stationary point, the resulting force, transferred to the center of the core's cross-section, equals (the gravitational force being neglected):

$$F_\Sigma = F_m - F_{el}$$

With well-defined boundary conditions the yoke motion law is written as follows:

$$x = 1/m \cdot \iint F_\Sigma \, dt$$

where m is equivalent mass of the yoke.

Initial motion and final conditions.

Initial conditions, corresponding to the extreme positions of the yoke, shall be taken into account during the calculation of the yoke motion:

For the right yoke:

1) the origin of coordinates for the yoke displacement (x=0) is set for the «closed» position of the breaker's power contacts, i.e. for a maximal air gap of the right yoke;
2) having reached the stopper (x=0) or the core (x=max), the yoke is forced to stop, i.e. dx/dt=0 ;

For the left yoke:

1) the origin of coordinates for the yoke displacement (x=0) is set for the «closed» position of the breaker's power contacts, i.e. for a zero air gap of left yoke;
2) having reached the stopper (x=max) or the core (x=0), the yoke is forced to stop, i.e. dx/dt=0 ;

The equivalent circuit presented in **Fig.4.** may be realized.

Here r=1 is the instrumental resistor, across which the voltage drop is measured by amplifier OP1, with output voltage equal to the magnetic flux in the circuit. Further, squaring this output voltage by multiplier "X" and multiplying result by a corresponding coefficient, we obtain the magnetic force. The elasticity force is formed by summing on OP9 the voltage of source U1 (the initial spring tightness) and the voltage at the OP8 output, equal to the yoke displacement value multiplied by the spring elasticity factor (the variable component). At the OP2 output we obtain the resulting force, which is integrated by first integrator (OP3), which output means velocity, and by second integrator (OP4), which output means displacement. The time constant of the integrators is taken from the following considerations:

$$x = \iint F_\Sigma \, dt/m = F_\Sigma/(RC)^2 p^2$$

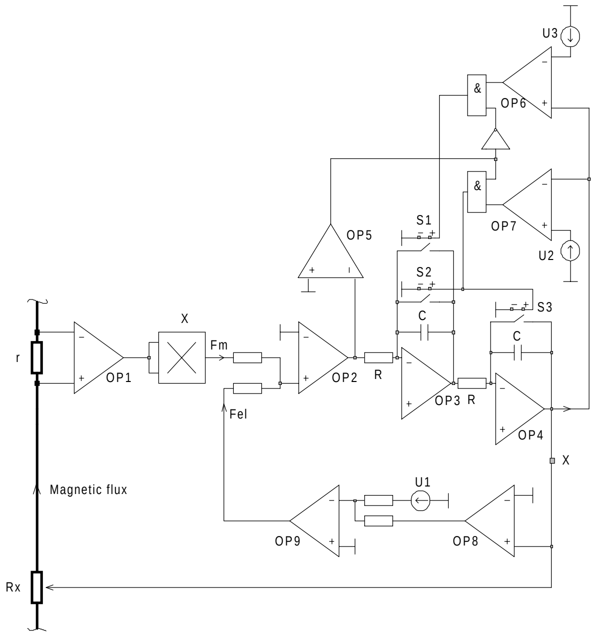

Fig.4. Yoke movement equivalent circuit representation.

hence

$$(RC)^2 = m.$$

The initial conditions are provided by introduction of a logic circuit, working in accordance with the following rules:

For the right yoke

1) $x = 0$ – capacitor of second integrator is short-circuited by voltage-controlled switch S3. This corresponds to the initial condition that the right yoke is «pulled away». This may be observed, as mentioned above, both in the «closed» state and in the «open» state of the breaker.
2) $dx/dt = 0$ – $F\Sigma > 0$, $x = max$ or $F\Sigma < 0$, $x = 0$ – the capacitor of first integrator is short-circuited by voltage-controlled switches S1 or S2. This corresponds to yoke’s reaching the extreme positions, i.e. yoke’s stopping.

For the left yoke

1) $x = max$ – the capacitor of the second integrator is charged up to its maximum voltage, corresponding to the initial condition, where the left yoke is «pulled away» and the breaker is in the «open» state.
2) $dx/dt = 0$ – $F\Sigma > 0$, $x = 0$ or $F\Sigma < 0$, $x = max$ – the capacitor of the first integrator is short-circuited by voltage-controlled switches S1 or S2. This corresponds to yoke reaching the extreme positions, i.e. yoke’s stopping.

Conditions 2) are verified by comparing the yoke coordinate with the reference voltage of sources U2 or U3 by comparators OP6 and OP7. Sign of the force is checked by comparator OP5. After that the signs are summed up by element «&».

At the output of the second integrator we obtain the yoke displacement, the value of which is plotted as well as used for forming the control voltage for variable resistor R_x.

Also the effect of the yoke repulsion was checked. This was allowed in the initial conditions calculations by using the additional switches in the first integrator's feedback circuit. These switches commute the capacitors to the opposite polarity, which means that the yoke velocity changes sign. Also if with yoke's reaching the stopper we will provide a particular capacitor's discharging adding the resistor with switch we could allow the energy dissipation with inelastic impact of the yoke with stopper. However, after checking this circumstance with left and right yokes it became clear, that we could neglect the effect.

G. Circuits inductance, self-inductance.

In the above-described approach to build the equivalent circuit of the magnetic system, the circuits are completely independent of the electric controls system. The resistance-equivalent circuit does not reflect the ability of the inductance to store energy by its magnetic field. Matching such circuit with the electric scheme, one has to introduce elements, which would adequately reflect its inertia reaction to the attempts to change the energy stored in the magnetic field of the circuit to be simulated. This reaction is named the self-inductance EMF, opposing any change of the magnetic flux through the circuit. The self-inductance EMF is aimed against the flux change:

$$U = - d(w\cdot\bullet)/dt = -w\cdot d(L\cdot I)/dt$$

The energy accumulated by the magnetic field is equal to:

$$W=L\cdot I^2/2=\bullet^2/2L$$

where:

I – the current in the coil,

W – the magnetic field energy accumulated in the system,

L – the inductance,

w – the coil turns number.

From the above-listed relations as well as from the Kirchhoff’s law for a magnetic circuit it is seen that with reference to our circuit the equivalent inductance of the circuit with magnetic resistance R_m and coil number of turns «w» is:

$$L = w^2/R_m$$

Introduction of a fixed element L in the circuit is, therefore, not descibing reality. The equivalent inductance must change when the circuit magnetic resistance changes. In addition, the transient appearing when L changes shall be taken into account in the circuit.

Taking the above-mentioned facts into account, the circuit design, presented in **Fig.5**, was used for matching the equivalent of the magnetic circuit with that of the electrical control.

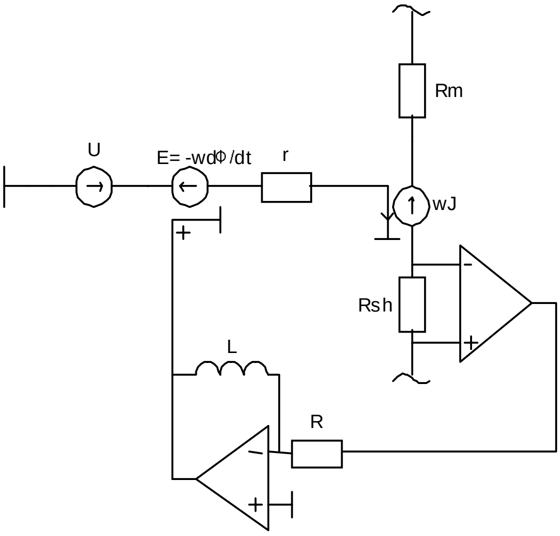

Fig. 5. Circuit Diagram of matching the electrical and magnetic equivalent circuits.

The circuit includes:

1) the magnetic part, consisting of magnetic resistor R_m, instrumental resistor R_{sh} = 1 and magnetomotive force wI. The MMF is represented by the current-controlled voltage source with a gain equal to the number of turns of the coil, in resistance units.
2) the electrical control circuit, consisting of voltage source U and resistor r,
3) the circuit of feedback loop by the derivative of the magnetic flux. The feedback loop consists of the differential amplifier OP1 with instrumental resistor R_{sh}; a differentiator based on an operational amplifier OP2 and elements L and R, as well as a voltage-controlled voltage source E with a gain equal to the number of turns in the coil.

Thus the inductance influence is taken into account by introduction into the circuit of the local feedback loop by the magnetic flux derivative, the feedback causing anti-EMF E = -w·d• /dt. Here the conception of ‘virtual’ inductance can be introduced. It is determined by the above formulae and is equal to $L_v = w^2/R$ (as in the real circuit). In this case, the requirement of uniformity of the magnetic flux is provided automatically. This can be verified by a ‘measurement’ of the current in the coil due to a change of inductance: when inductance increase N times, current in the coil decrease N times. This checked was made on the various simple models.

IV. Complete Model equivalent circuit.

When the all sub-models were checked we design the complete model equivalent circuit, that includes approximately 120 different elements, such as resistors, capacitors, amplifiers, switches and logic microcircuits. The complete model was developed by the CAD program “NL” [5], which algorithm is based on the reverse Euler Method.

The simplified block-scheme of the electromagnetic driver is represented at the **Fig.6.** Here R1, R2, R3, R4, R5 are piecewise-linear resistors, Rx1, Rx2, Rx3 are variable controlled resistors, L1, L2 are "virtual" variable inductances, r1, r2, r3 are measurements resistors, U1 is a holding coil’s voltage source, S1 is a voltage controlled switch for the holding coil, S2 is a block-contact, C is a capacitor, charged from the voltage source U2, S3 is a voltage controlled switch for the pulsed coil, r4 is a holding coil own resistance, r5 is a shunt resistor, r6 is a pulsed coil own resistance.

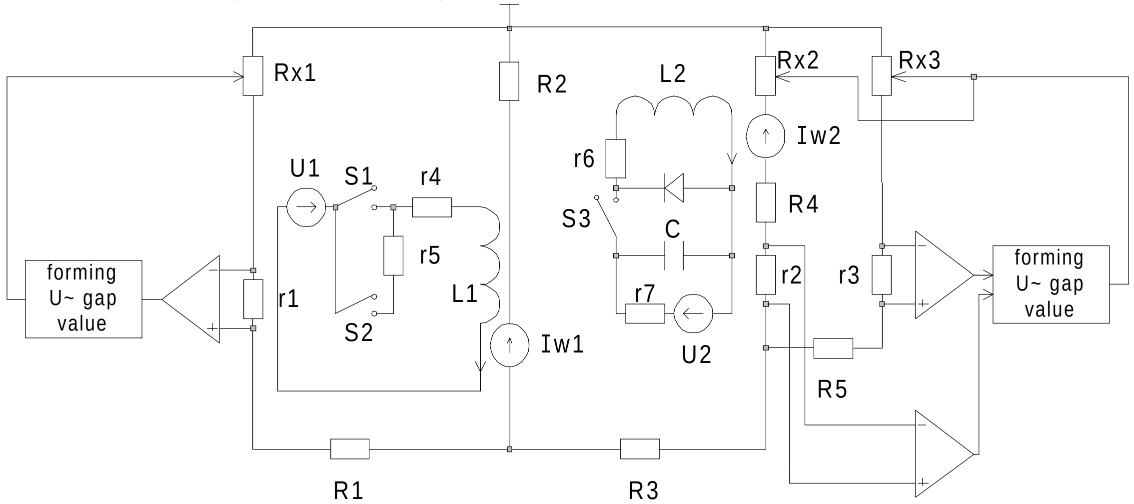

Fig.6. The simplified block-scheme of the electromagnetic driver.

For understanding the model operation, **Fig.7** presents a simplified view of the time diagrams. We will take the «Open» mode of the Breaker as the initial state. In this case, both of the yokes are released from the core and the holding coil and pulsed coil are in the de-energized state.

Switching ON of the breaker.

Let at moment t_1 a switch S1 be closed and a voltage of 110V from source U be applied to the holding coil. The current I of the holding coil starts increasing. When $I_{\text{holding coil}}$ equals I1 (moment t_2), both the yokes start to move towards core. At moment t_3 both the yokes are pulled to the core, the main contacts of breaker go to the ‘stand-by’ state, making the block contact S2 to be activated. As this takes place, current in the holding coil starts decaying with a time constant of about 20 ms, to attain a value of 0.5 A. When $I_{\text{holding coil}}$= I2 (moment t_4), the right yoke starts movement away from the core and reaches the extreme (open) position at moment t_5 (the left yoke staying in the pulled state). The breaker is now ready for operation - its main contacts are closed (ON).

Switching OFF of the breaker.

Let at moment t_6 (maybe triggered by an external interlock) switch S3 be closed and capacitor C starts discharging into the pulsed coil. The current in the pulsed coil, $I_{\text{pulse coil}}$, starts rising and the right yoke begins the movement towards the core, opening the main contacts. At moment t_8 the right yoke is pulled to the core and the main contacts are open. The breaker changed to the OFF (‘Open’) state. The operation time interval of the breaker under the pulsed coil control is made up as $\bullet\, t = t_8 - t_6$. Simultaneously with the processes occurring in the right yoke, a part of the magnetic flux, originating from the pulse, penetrates through the left core and left yoke. This flux is subtracted from the flux created by the holding coil and the resulting flux attains such a low value that the magnetic force holding the left yoke becomes less than the spring forces, pulling it away from the core. Therefore, the left yoke also starts moving and in approximately 10 - 15 ms reaches the extreme (open) position. The last one leads to the main contacts "Off" mode fixation.

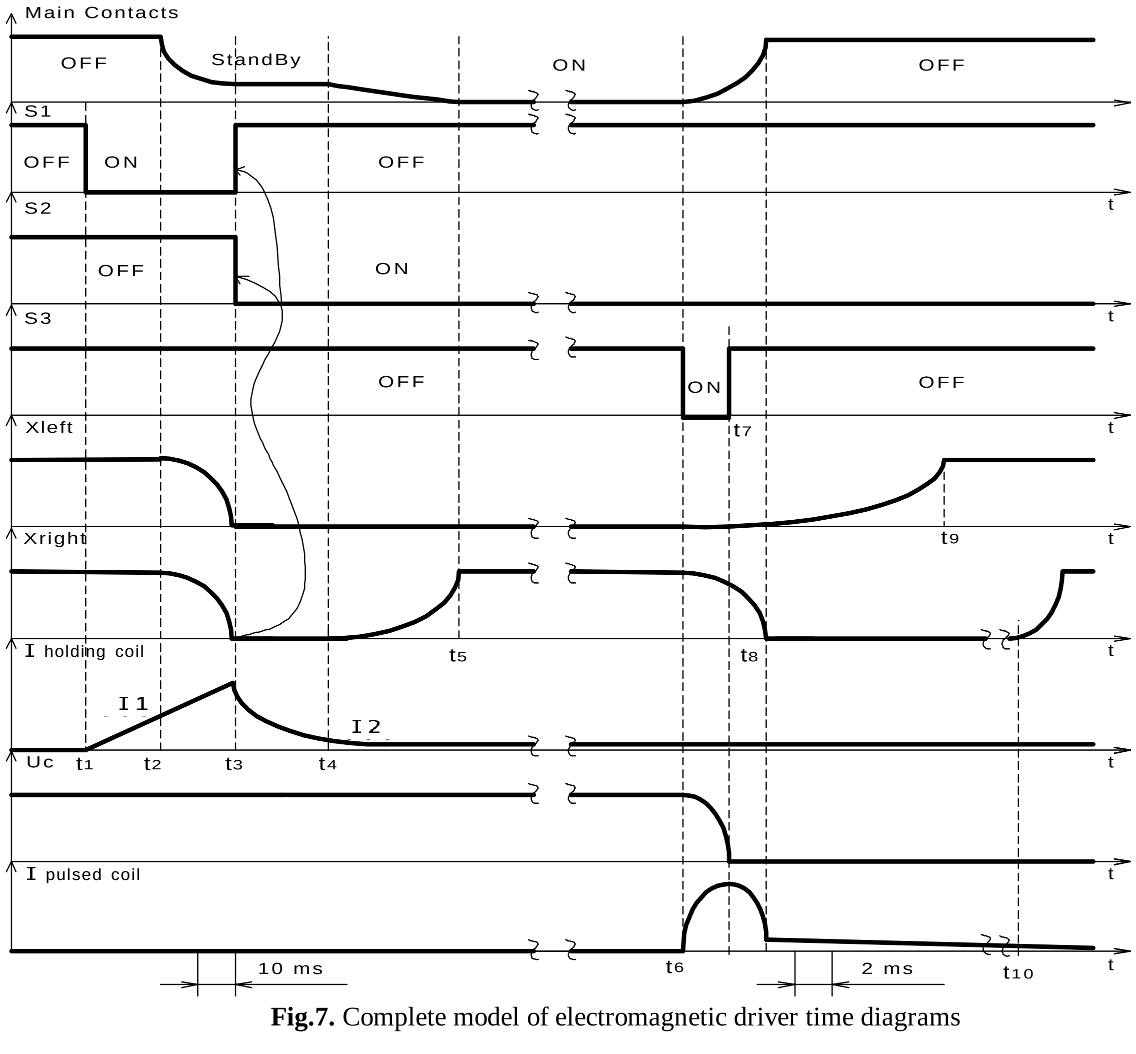

Fig.7. Complete model of electromagnetic driver time diagrams

When the capacitor discharge pulse is extinguished at moment t_7, the capacitor is disconnected by S3 and the current of the pulsed coil decays through the reverse diode. Initially a time constant is small, but then due to rapid inductance increasing a time constant increases up to 50 ms**.** During the decay the current in the pulsed coil will attain a level, where it can no longer hold the right yoke and it returns to the initial (open) state at moment t_{10}. But the breaker will still be in the OFF state, because the left yoke prevents a repeated closing of the breaker.

The principal goals of further modeling are:

- to optimize the control circuits for both the holding and the pulsed coils in such a way that the OFF-operation time of the breaker (• t) is being minimized, and
- to provide a reliable opening of the breaker, satisfying of the condition (t_9 - t_6)< (t_{10} - t_6)

V. Modeling results.

Modeling was performed with both the closing process (the ON process) and the opening process by operation of the holding coil and of the pulsed coil (fast-OFF process).

Investigations were conducted on the reliability of the closing and opening processes and the dependence of the current values in the holding and pulsed coils on the operation time of the left and right yokes was determined

In the course of simulation of the transients processes in the driver's electromagnetic system the following parameters were being modeled and recorded:

1) the magnetic fluxes in all the circuits;
2) the coordinate of the left and right yokes,
3) the velocity of movement of the left and right yokes;
4) the resulting forces affecting the yoke;
5) the currents in the holding and pulsed coils;
6) the voltages across the coils.

Considering all these processes in details for the pulsed coil (fast)OFF operation:

Typical diagrams of modeling of this process are presented in **Fig.8** and **Fig.9.**

Capacitor start discharging into the pulsed coil at t = 350 ms and the current in the coil starts increasing. The resulting force affecting the *right yoke* changes its sign and the yoke starts being pulled. When the current reaches its maximum value it immediately begins a sharp decay because of the rapid increase in the circuit inductance due to the reduction of the gap size. At the moment t ≈ 354 ms (• t = 4 ms) the yoke reaches the core, its speed becomes zero, the gap resistance gets close to zero and the inductance then remains relatively constant. The current in the pulsed coil starts falling with a large time-constant (which increases in time because of the slow growth of the inductance due to decrease in saturation). At the moment of maximum current the magnetic fluxes in the right limb attains their maximum value.

During all this process the magnetic flux in the *left core* is minimum, since a part of the flux from the right core penetrates to the left core, thus compensating the flux holding the left yoke. The magnetic force affecting the left yoke is decreasing. When the spring force starts dominating over the magnetic force, the yoke starts to break away from the core. However, with the further current decrease in the coil, the fluxes in the right limb diminish and therefore those in the left limb increase. If the current in the pulsed coil is large enough, the yoke keeps moving, but with smaller speed. Since the gap enlarges, the magnetic resistance of the left limb increases and the magnetic flux here starts weakening, causing an increase of the resulting force, moving the yoke away. The left yoke reaches its extreme position (open state), staying there until the next switch-on procedure. In such a way the breaker has changed to the open (OFF) state, approximately in 4 milliseconds (this is determined only by the time of movement of the right yoke). Removed from the core, the left yoke does not allow the breaker to get re-closed when the magnetic fluxes are reduced, making the right yoke return to the open state.

If the left limb flux component, originating from the pulsed coil current, is not large enough, the resulting force affecting the left yoke can change its sign, making the left yoke start being pulled again and return to the initial (pulled) state. Evidently, such a situation would be inadmissible.

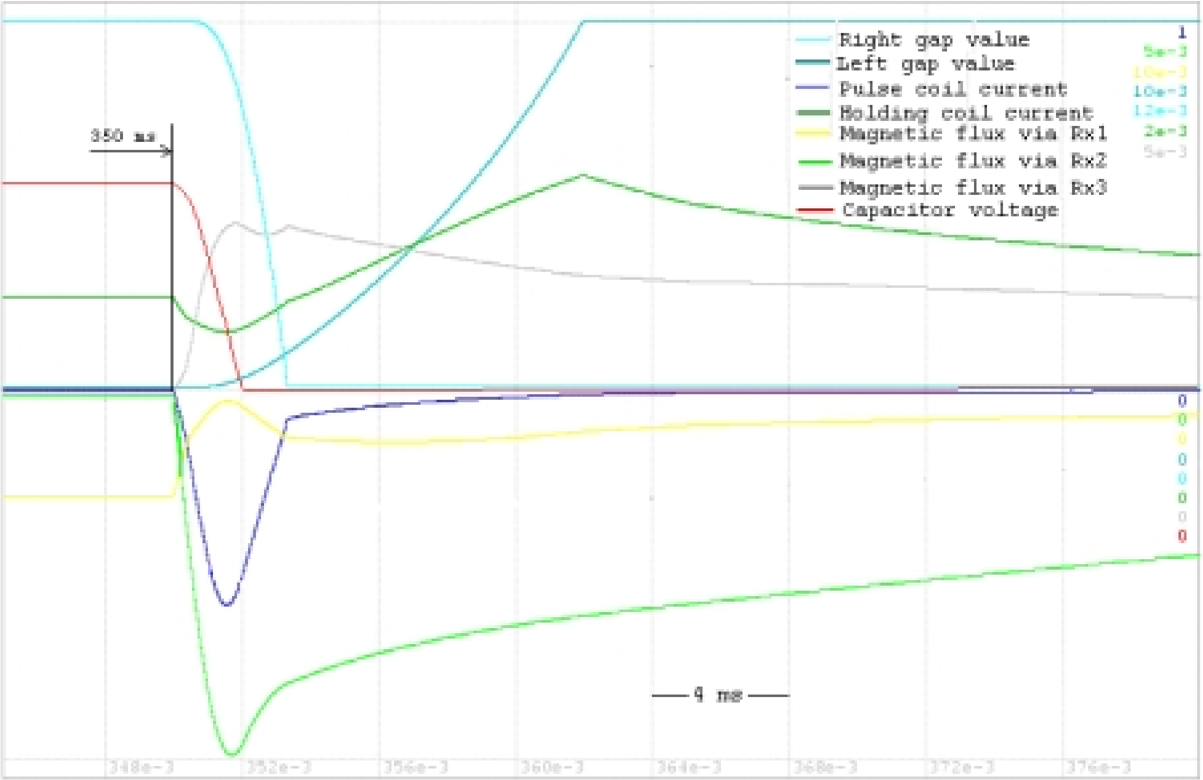

Fig.8. Pulsed coil "OFF-operation". Gaps, currents,
forces and velocities.

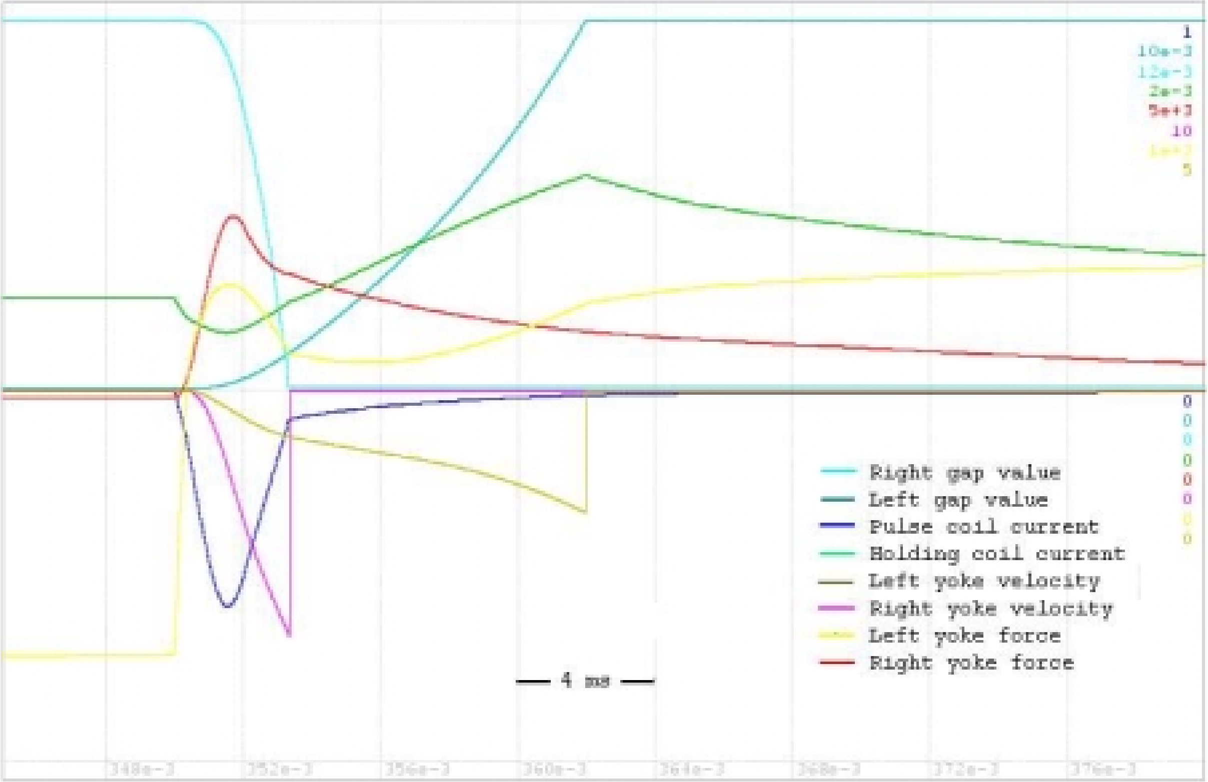

Fig.9. Pulsed coil "OFF-operation". Gaps, currents and magnetic fluxes.

VI. Conclusions:

The breaker opening time is determined by the current in the pulsed coil (i.e. capacitor voltage) and its duration, i.e. by the coil parameters, the capacitor charging voltage and the capacitance. During the pulse the left yoke must be moved away from the core and arrive the extreme position. This is determined by the current value in the pulsed coil but equally by the value of the holding coil current, generating the holding magnetic flux in the left core.

To find the optimum operation of the breaker, we had simulated the switching ON/OFF processes for holding currents of 0.4 A to 0.6 A with a 0.05 A interval. In each case the simulation were conducted for the capacitor voltage range of U_{min}, at which the left yoke is not moved away completely (the U_{min} value is different for each value of the holding current) up to 280 V. **Fig.9** presents a family of curves, which characterize the dependence of the capacitor voltage on the switching OFF time of the left yoke for the indicated values of the holding current (we define the switching OFF time as the time interval necessary for the yoke to move from one fixed position to the other). The lower curve presents the time in which the right yoke is being pulled as a function of the capacitor voltage. This dependence is closely the same for all the holding current values.

It appears that the optimum operation regime of the breaker's electromagnetic driver is:

$$I_{holding}=0.5A,\ U. \ =170\ V$$

In this case the time of the driver operation is 3.3 milliseconds and the switching OFF time for the left yoke is completely in 12 milliseconds. If the mains voltage changes within +10% to –20% (the usual variation) the operating point moves along the dotted curve.

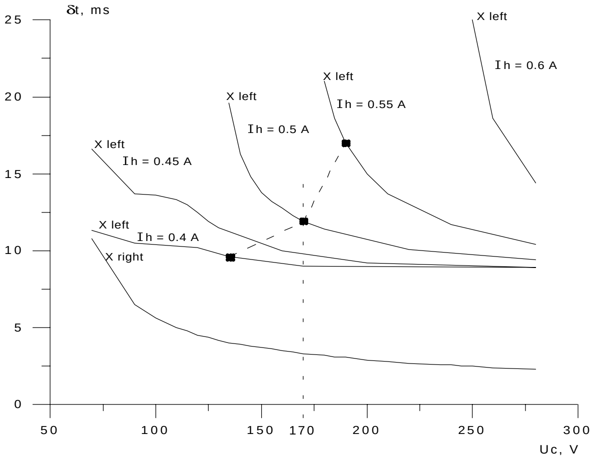

Fig.10. Pulsed coil "OFF-operation". Gaps switching family dependence on capacitor voltage and holding current. Optimal working point (w.p.) is recommended like I_{hld}=0.5 A, U_c=170 V.

Acknowledgements

The authors would like to thank Dr. M. Tiunov (BINP) for the consultations related to the magnetic calculations and Dr. A. Smirnov for the assistance with the support software. This work was supported by BINP (Novosibirsk) and LHC/ICP at CERN (Geneva).

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