AN ANALYSIS OF COORDINATION OF LOW-VOLTAGE CIRCUIT-BREAKERS AND H.B.C. FUSES

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Abstract: Problem of proper coordination of the downstream h.b.c. fuses with the upstream circuit breakers (CB) classically has been solved by a comparison of t-I characteristics of both protective devices. More recently also a co-ordination of both apparatus, in the short-circuit region, an the base of a comparison of current impulse characteristics has been suggested. The impulse withstand of CB should be compared with the let-through impulse of the fuse. The paper demonstrates the results of experiments and simulations of the impulse coordination, but taking into account detailed processes in the tripping mechanism of the CB at the short-circuit current. The results show clear that the discrimination can not be always achieved in the short-circuit current region on the base of comparison of CB current impulse withstand and fuse's let-through one. Responsible for that misleading co-ordination is the dynamics of the fuse and the CB operation. Results of the simulations of the dynamics of electromagnetic tripping mechanism and the experiments show a satisfactory agreement.

I. INTRODUCTION

In respect of overcurrent protection there are under considerations two configurations of the overcurrent apparatus coordination (Fig. 1): "CB-fuses" and "fuses-CB".

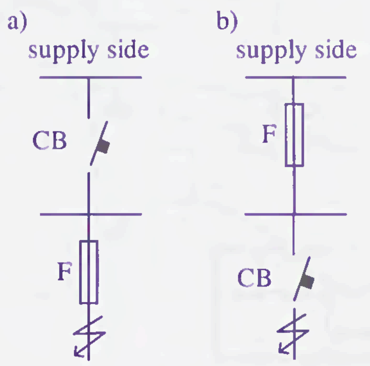


Fig. 1 Configurations of overcurrent coordination of apparatus
a - "CB-fuses (F)", b - "fuses (F)-CB"

Usually shall be achieved a discrimination of apparatus operation in the whole overcurrent region, if both shown in Fig. 1 devices are installed in two different stages of the energy distribution. The configuration "fuses-CB" (Fig. 1b) in respect of discrimination demonstrates less complicated case than "CB-fuses" one. In former case it is enough simply to compare t-I characteristics in the overload region and I^2t let-through characteristic of CB with pre-arcing I^2t characteristic of fuses in short-circuit region. Hence this configuration will not be under considerations.

On the other hand, in the case "CB-fuses", if one makes a coordination according to the existing classical rules (Fig. 2), one can get, in some cases, a not desirable operation of CB.

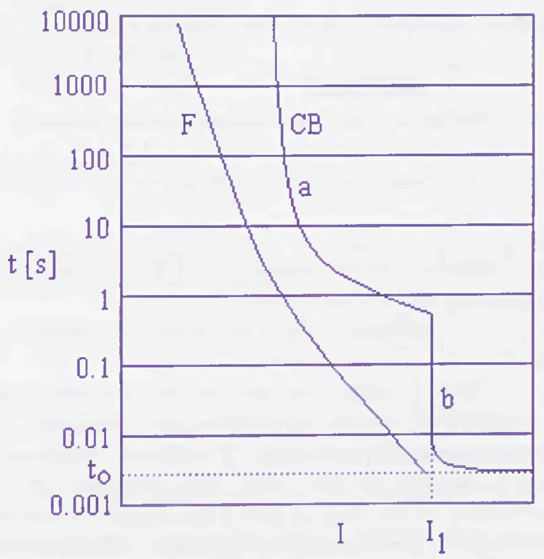


Fig. 2 t-I characteristics approach [1] to ensure a proper discrimination of operation of combinations "CB-fuses" (Fig. 1a)
F - largest times of fuse operation, CB - shortest permissible time to activate CB to get switch off position, a - overload region usually provided by thermal release, b - short-circuit region usually realised by instantaneous tripping device, I_1 - adjustable lowest current setting of instantaneous tripping, t_0 - time of CB operation normally given in catalogue

The t-I characteristic approach shall take into account the disadvantageous manufacturing tolerances, point on wave of the fault initiation and environmental influences. Also an effect of the ageing of both apparatus shall be considered, by introducing e.g. a safety margin, say 1.5 of the time scale. Aforementioned not desirable operation pertains to the short-circuit region, i.e. above the current I_1, and will be examined in the paper. Such an operation is manifested by switching off not only of the fuse but also of the CB in a defined short-circuit current region. Below and above this region the discrimination can be maintained. Responsible for such a behaviour is the dynamics of electromagnetic tripping device. That is why the authors of the publications [2, 3] suggest making an *impulse approach*, considering impulse characteristics of CB and fuse (Fig. 3).

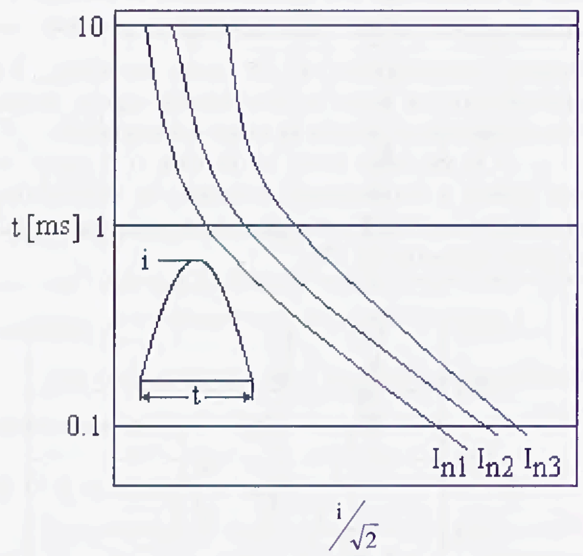


Fig. 3 Impulse characteristics of CB discriminative operation in short-circuit region

I_{n1}, I_{n2}, I_{n3} - different values of current I_1 marked in Fig. 2

Now to make sure that the discrimination will be achieved it is necessary to compare the characteristics given in Fig. 3 with the let-through current impulse of the fuse. This impulse can be determined on the base of fuse's maximum let-through current for a given prospective current. Moreover the fuse's let-through current shall resemble sine wave impulse because only for such an impulse shape the comparison is rational. Mentioned impulse parameters, i.e. the amplitude and half cycle sine wave can be evaluated on the base of known cut-off fuse's characteristic. It should be, in doing this, assumed that the pre- and arcing-times of the fuse operation are equal.

Mentioned impulse approach, however, much better then t-I characteristic one, still is a global one and not takes into considerations several details responsible for the discrimination process. This statement is a reason why a closer look into the problem is desired. The results of experiments and simulations on "CB-fuses" discriminative operation in the short-circuit region is given in this paper.

II. EXPERIMENTAL INVESTIGATIOS OF DYNAMICS OF CB ELECTROMAGNETIC TRIPPING DEVICE

The dynamics of "CB-fuses" discrimination was investigated at the beginning by an experiment (Fig. 4). Point on wave control *9* assured the switching on the circuit in a defined phase instant. A digital oscilloscope recorded, stored and processed all data on circuit current and anchor move. The current limiting fuse *4* was rechargeable.

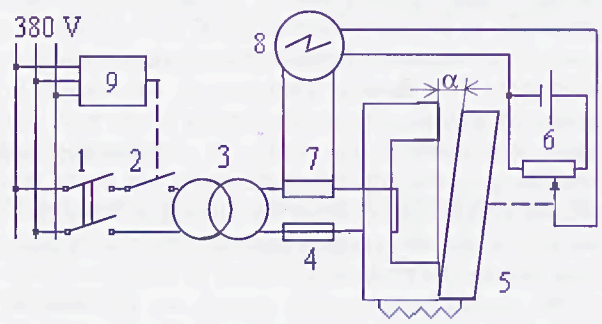


Fig. 4 Scheme used in experimental investigations of "CB-fuses" dynamics

1 - main circuit-breaker, 2 - point on wave controlled making switch, 3 - transformer, 4 - fuse F in combination shown in Fig. 1a, 5 - CB's electromagnet in combination given in Fig. 1a, 6 - gauge to sense movement of anchor 5, 7 - shunt, 8 - digital oscilloscope, 9 - point on wave control, α - angle defining anchor position

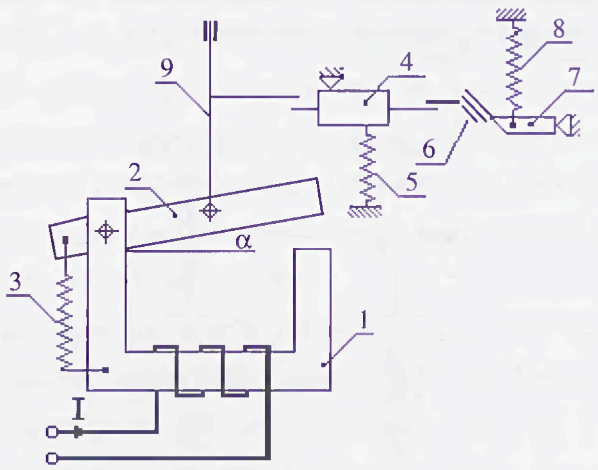


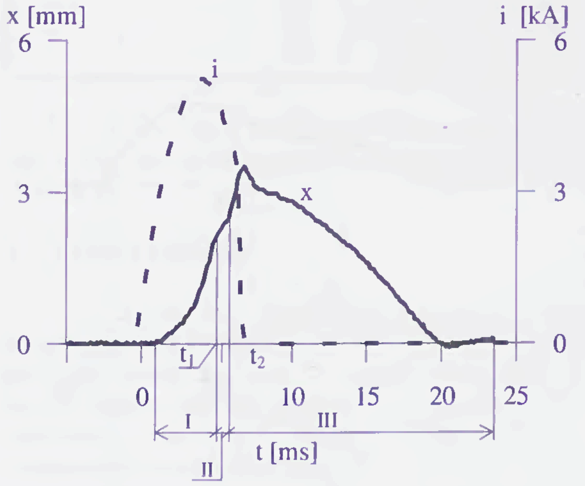
Fig. 5 Scheme of kinematics of investigated electromagnetic tripping

1 - core, 2 - anchor, 3 - anchor spring, 4 - latch lever, 5 - lever spring, 6 - rotating part of latch, 7 - lever, 8 - spring of latch, 9 - pulling member, α - angle defining anchor position

Its fuse-elements were made from a Cu-wire of different diameters with notches. The diameter, and dimensions and number of notches were selected to control the pre-arcing time and I^2t and the shape of let-through current decaying to zero, by given prospective current. In turn as CB a moulded case circuit-breaker 200 A rated current, 660 V was chosen. Its thermo-bimetal-electromagnetic release equipped within mechanical latch structure (Fig. 5) was extracted from the circuit-breaker and installed in the circuitry as in Fig. 4.

If a short-circuit appears the anchor *2* is pulled down to the core *1*. As a result is transmitted a mechanical impulse throughout interlink lever *4* to the latch parts which finally make free move of the lever *7* causing CB opening.

a)



b)

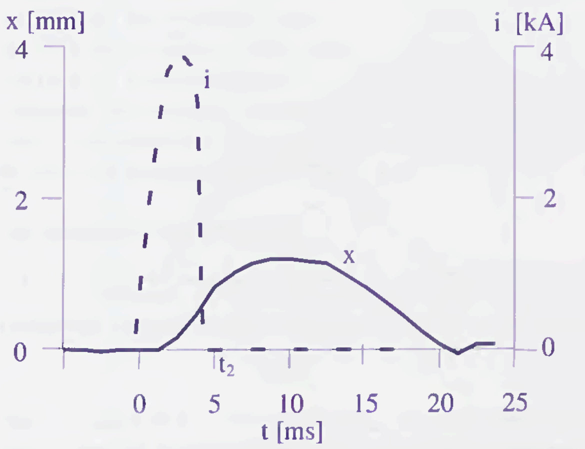


Fig. 6 Typical records of current i and anchor displacement x
a - fuse interrupts and CB opens, b - fuse interrupts and CB not opens, t_1 - latch first contact instant with lever *4* (Fig. 5), t_2 - forced current zero

Two series of the measurements were made: first at the prospective current 3.75 kA (RMS) at source voltage 17.5 V and 5.5 kA (RMS) at source voltage 35 V. The records show two basic regularities of the CB behaviour (Fig. 6).

In the case Fig. 6a one can recognise three characteristic phases of the anchor movement. Phase I characterizes by movement of anchor alone. In the instant t_1 anchor meets a mechanical resistance of the lever *4* (Fig. 5). Due to this it is recognisable diminishing of the move velocity. Since then the anchor and lever *4* in the phase II are moving together. If the anchor velocity in the instant t_1 is large enough some bounce is possible. During the phase II in a some instant appears the tripping itself, of course, if the rotating latch part *6* reaches a defined position in relation to the latch lever *7*. Next phase III means return move of the anchor and associated parts to the initial position because the electric power supply due to fuse operation become zero in the instant t_2.

In the case Fig. 6b the electromagnet powering stops in the instant t_2. Beyond this point the anchor still shows free movement ahead due to stored kinetic energy in the instant t_2. But this energy is too small to get tripping. After reaching a maximal displacement in direction of the core the anchor gets back to the initial position as a result of action of the springs *3* and *5*.

III. SIMULATION OF ELECTROMAGNETIC DYNAMICS

The dynamics of anchor describes the relation

$$J(\alpha)\frac{d^2\alpha}{dt^2} = M_{el}(i,\alpha) - M_{sp}(\alpha) \qquad (1)$$

In which: $J(\alpha)$ - momentum of inertia of the tripping mechanism, defined as follows:

$$J(\alpha) = \begin{cases} J_1 & ;\alpha > \alpha_z \\ J_1 + J_2 & ;\alpha \le \alpha_z \end{cases}; \qquad (2)$$

where:
J_1 - momentum of inertia of the anchor, J_2 - momentum of inertia of the lever, α_z - angle of the anchor position in which starts movement of the anchor, $M_{el}(i,\alpha)$ - electromagnetic momentum of the electromagnet related to the circuit current and the anchor position α (Fig. 5), $M_{sp}(\alpha)$ - momentum of the springs *3* and *5* (Fig. 5) is defined as follows

$$M_{sp}(\alpha) = \begin{cases} k_1 r_{11} r_{12}\alpha & ;\alpha > \alpha_z \\ k_1 r_{11} r_{12}\alpha + k_2 r_{21} r_{22}\alpha & ;\alpha \le \alpha_z \end{cases}; \qquad (3)$$

where:
k_1, k_2 - constants of the springs *3* and *5*; r_{11}, r_{12}, r_{21}, r_{22} - radii of fasten of the springs and joints of the drive

Start of the anchor movement is possible above a certain threshold current value. The angle of the anchor displacement can vary in the limits $0<\alpha<\alpha_o$, where α_o - initial angle of the anchor position.

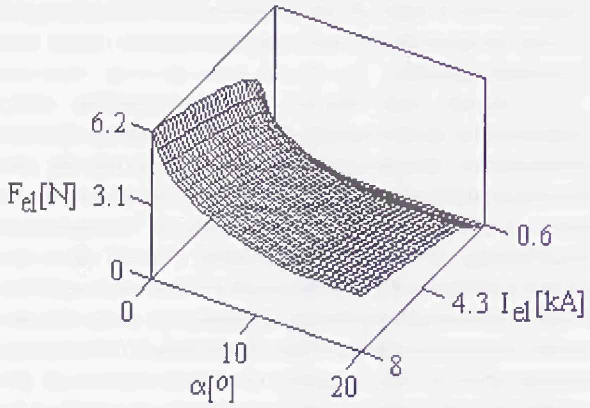


Fig. 7 Exemplary results of simulation by means of FLUX2D programme of pulling force of anchor
F_{el} - pulling force, I_{el} - maximum let-through current, α - angle describing position of anchor

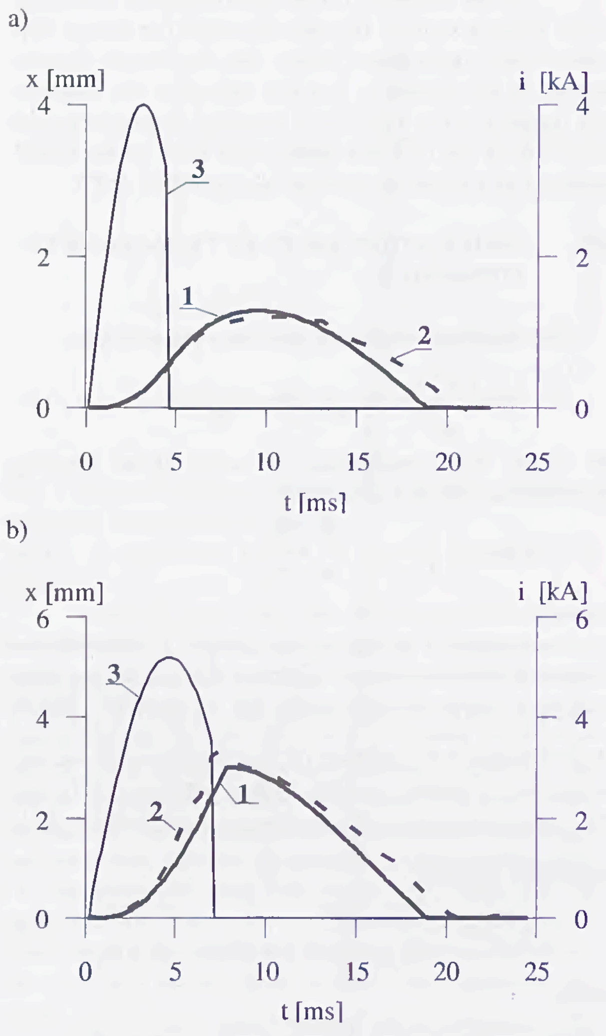


Fig. 8 Experimental (2) and simulation (1) profiles of anchor displacement x for assumed current impulse i (3)
a - tripping of CB not occurs, b - tripping of CB has take place

The electromagnetic momentum $M_{el}(i,\alpha)$ is determined by the magnetic flux distribution. This distribution and hence the pulling forces for a given angle α and current i were calculated by means of the 2-D finite-element programme FLUX2D [4] (Fig. 7). In turn, to calculate according the relation (1) the dynamics of anchor displacement, associated members including, was used programme MATHCAD. The results of simulations and from experiments are in a good agreement (Fig. 8). The calculations, among others, reveal that it is possible that the discrimination can has place in a strictly defined short-circuit current region only. At the currents above this region the discrimination is not fulfilled (Fig. 9, Table 1). The reason is an interaction of the anchor inertia and the parameters of the current impulse.

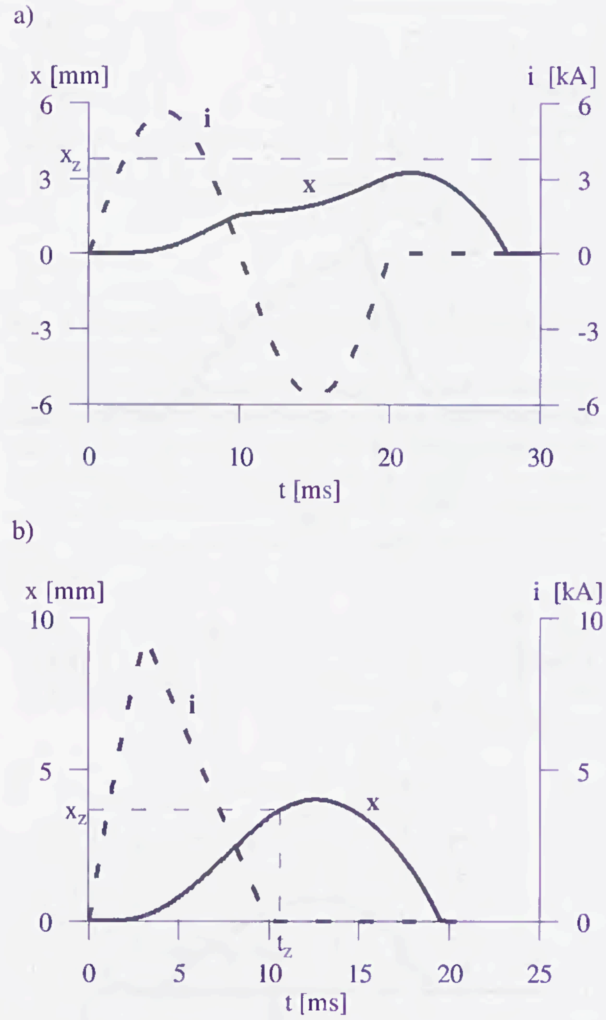


Fig. 9 Results of simulation of "CB-fuses" configuration in respect of discrimination of operation of a moulded - case circuit-breaker 400 A, and a fuse of rated current 200 A
a - prospective current 4 kA (RMS), discrimination is fulfilled; b - prospective current 8 kA (RMS), lack of discrimination; x - anchor displacement, x_z - dimention at which static tripping appears

Table 1. Results of simulation of discrimination of a moulded-case circuit-breaker and a fuse

CB rated current	Set of electro-magnet	Fuse's rated current	Test current	Trip-ping
A	kA	A	kA	yes/no
200	2	100	I_{sp}<22	no
400	4	160	I_{sp}<22	no
	4	200	I_{sp}<7.4	no
	4	200	7.4<I_{sp}<8.5	yes
	4	200	I_{sp} >8.5	no
630	6.3	250	I_{sp}<22	no
	6.3	315	I_{sp} <9.9	no
	6.3	315	9.9< I_{sp} <22	yes
	6.3	315	I_{sp} >22	no

At the end it is worth to demonstrate (Fig. 10) that in the case *a* the current lasts much longer than in the case *b*

I. CONCLUSIONS

Carried out experiments and simulations concerning discrimination "CB-fuses" combination gave the results that are in a good agreement. The results suggest that the discrimination coordination of "CB-fuses" based on simple comparison of t-I characteristics can lead to a misleading CB operation in the short-circuit current region. Also the approach based on a comparison of sine half wave impulses can give the misleading results. Simulation, namely, shows that sometimes the discrimination can be ensured within a defined short-circuit region. Above this region there can be lack of discrimination. To avoid in practice such a situation the impulse withstand characteristic of CB shall be established by the experiments in a careful way to discover mentioned region.

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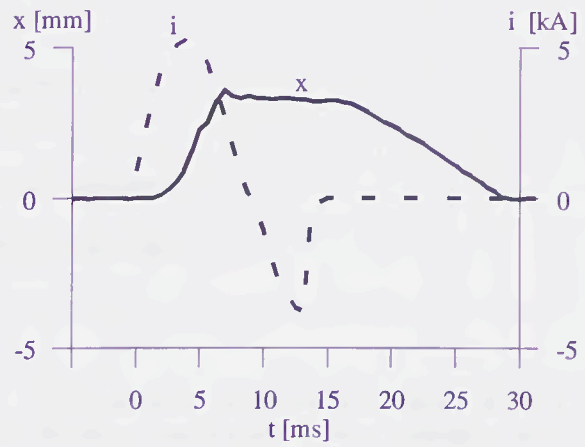
a)



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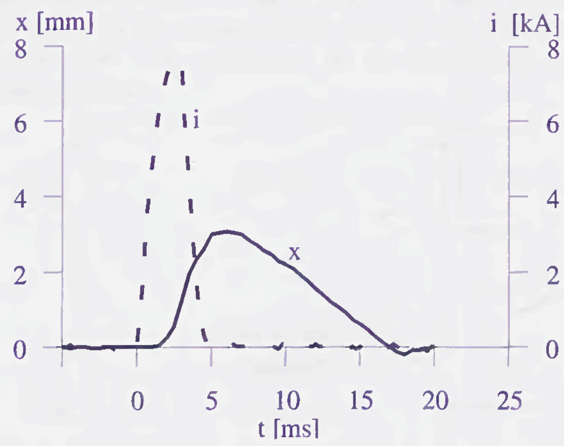

Fig. 10 Tripping behaviour
a - at smaller current than in case b

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