BACK-UP PROTECTION OF VACUUM CONTACTORS

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ABSTRACT
Fuses are suitable for preventing excessive damage to the contactor under short-circuit conditions. Relatively high interrupling capability of vacuum contactor allows to create fuse-contactor combination having an operating characteristic like that of a circuit-breaker. The combination may be assembled on the basis of the coordination principles given in this paper. Defined also was a new parameter: contactor withstand on cut-off current pulses, which allows to estimate a breaking capacity of the combination. These coordination principles were confirmed in 1000V a.c. combination interrupling tests. In take-over current region the breaking task is shared between contactor and fuses, resulting the interruption of a two-phase fault by the contactor. It may to lead to revision of coordination principles.

INTRODUCTION

In the last decade vacuum contactors have been succesfully replacing conventional air-break ones, mainly in 1000V and 6000V a.c. motor circuits. However, these contactors exhibit the ability to perform very well under normal operating conditions and higher, than air-break ones, capacity for withstanding the fault currents, their application in industrial installations at fault level above abt. 10kA is restricted. To extend application of vacuum contactors, special H.R.C. back-up fuses are used to protect them against high-level faults. Placed ahead of a contactor or a panel of contactors, the fuses should be coordinated with the contactors to act only on those faults that exceed withstand or interrupting rating of the contactor.

The fuse - vacuum contactor combinations are intended to be applied as an operating as well as protecting devices simultaneously. These combinations find their application specially in underground installations 1000/1140V and 6000 V in mining industry.

In the paper the problems of creating of the fuse-vacuum contactor combination is discussed and some experimental results are given.

COORDINATION CRITERIA AND SELECTION OF COMBINATION ELEMENTS

The time current characteristics of realy-operated fuse-contactor combinations are presented in Figs.1a/ and b/.

The Fig. 1a/ presents the characteristic of the combination in which opening of the contactor can be initiated by an overload /inverse time/ relay. In Fig. 1b/ opening of the contactor can be initiated by the overload or short-circuit /instantaneous/ relay. The basic difference between these both characteristics are the current ranges at which the contactor operates alone, preventing fuse to melt.The upper limit of this range depends on breaking capability of the contactor. For this reason in the first combination /Fig. 1a/ are as a rule used air-break contactors and in the second /Fig. 1b/ vacuum ones. It is commonly known that breaking capability of vacuum contactors is several times higher than of the air-break ones. This ability of the vacuum contactors allows to create a combination of which performaces and characteristic are the same as those of a fuse-circuit-breaker combination /Fig. 1b/. As a back-up protection of vacuum contactors are applied "aM" fuse-links /up to 1000 V a.c./ [1] or h.v. fuses for motor applications [2] which are generally used to provide short-circuit protection only-in current region above interrupting capacity of the contactor conjuncted with. The contactor is designed to interrupt overload currents up to its breaking current. The short-circuit current in practice have less likelihood to occur in case of fault. The above mentioned combination may be of interest from economical point o view since it allows taking better advantage of the vacuum contactor interrupting performances.

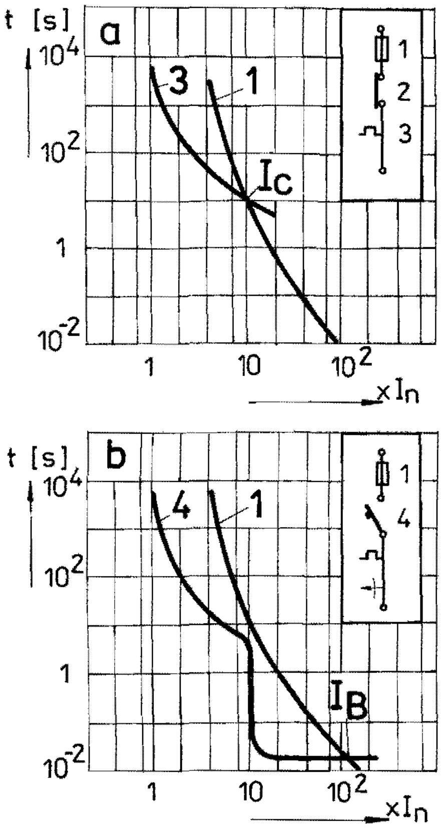

Fig.1. Time-current characteristic of fuse - vacuum contactor combinations

a/ contactor with an inverse time relay only
b/ contactor with inverse time and instaneous relays
1 - fuse; 2 - vacuum contactor; 3 - inverse time /overload/ relay; 4 - vacuum contactor/or c.b./ with overload and short-circuit relay; I_B, I_c- take-over currents; I_n - contactor continuous current /overload relay current setting/.

In Fig.2 are presented time-current zones of a fuse - vacuum contactor /overload and short-circuit - operated/ combination.

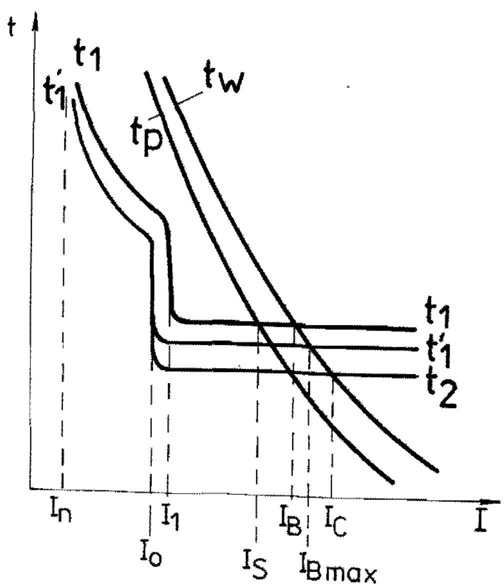

Fig.2. Time-current zones of a fuse-vacuum contactor combination type Fig.1b
t_1,t_1' - maximum and minimum operating times of contactor-relay assembly; t_2-contactor minimum pre-arcing time; t_w-maximum operating time of a fuse; t_p-minimum pre-arcing time of a fuse; I_n-current setting of an overload relay;I_0-I_1 - current setting zone of a short-circuit relay; I_B-take-over current; I_C-current limit above which a fuse is entrusted with the task of current interrupting.

At currents up to and not exceeding I_S/selectivity current [3] / the contactor operates alone preventing the fuse-link to melt. A take-over current value I_B is determined after I.EC Publ.for c.b combinations [3] . In some standards e.g. Polish Standard the take-over current is defined in point I_{Bmax} /Fig.2 /. Taking into account the width allowed by the fuse standard zone, if the take-over current is defined in point I_{Bmax}, one cannot to create the combination [4,5] . Note that value I_B in Fig.2 is equal to the I_{Smax}, for which the ordinate is upper limit of a pre-arcing time t_{pmax} /not shown in

Fig.2/. For longer times, about 40-80 ms , the pre-arcing time is nearly equal to the operating time value $/t_{pmax} = t_w/$. Within the current range $I_S - I_C$ the breaking task may be shared between relay-operated contactor and fuse, or one of these apparatuses may be entrusted alone with the task of interrupting the fault current only. Closer to the current I_S more probable is operation of the contactor alone but closer to the I_C more probable is breaking by the fuse only. The I_B current value should be lower than interrupting capacity of the contactor. The I_{Bmax} value is concerned with the operating time zone of relay-contactor assembly; the width of this zone depends on quolity of both aparatuses. The best practice is when components of the combination can be assemblied togather by one manufacturer which is able to guarantee that the combination will operate satisfactorily. Nevertheless, in some cases as a rule in Polish practice/ the combination components may be grouped togather by system desinger or user who must change the fuse to another one, or to one made by other manufacturer.
For this purpose the following data are needed:

a/ relay-vacuum contactor assembly:
- breaking current I_w
- peak withstand current /without fuse/ i_{sz}
- pulse withstand current /with fuse/ i_p
- maximum time-current characteristic $t_1 = f/I/$

b/ fuse data
- time-current zone $t_p - t_w = f/I/$
- cut-off current characteristic $i_o = f/I/$

The value i_{sz} is given by the contactor manufacturer as an electrodynamic withstand. When the contactor is used with fuse, the contactor withstand value varies greatly. After authors' investigations the pulse withstand value of Polish SV type vacuum contactors i_p is 1.5 - 2 times higher than peak one i_{sz}. Similar value is also given by Saputo [6] .
The combination coordination principles can be described by means of the following relations:

/1/ $$\bigwedge_{I \leqslant I_S} \; /t_1 < t_p/$$

/2/ $$\bigwedge_{I_B \leqslant I_w} ; \; \bigvee_{I = I_B} \; /t_1 = t_w/$$

/3/ $$\bigwedge_{I > I_B} \; /t_1 > t_w/$$

/4/ $$\bigwedge_{t_w \geqslant 10ms} \; /i_{sz} \geqslant i_u/$$

/5/ $$\bigwedge_{t_w < 10ms} \; /i_p \geqslant i_o/$$

where: i_u - peak short-circuit current
i_o - cut-off current of a fuse-link
for other symbols - see Fig.1.

When the value i_p for a contactor is not given in the relation /5/ one substitutes instead of i_p the i_{sz} current value. In such case the breaking capacity of combination will be lower /Fig.3/
The relation /1/ evaluates a minimum rated current of the fuse-link, and the relations /2/-/5/ the maximum rating of the fuse-link. The intention of designer is to select the fuse-link rated with so great current as it is possible.
Breaking capacity of combination may be found from characteristics shown in Fig.3. In this Figure are assemblied time - and cut-off current charakteristics. Having time-current characteristic and contactor breaking capacity the breaking capacity of

combination I_{wz} may be estimated and inverserly: if the I_{wz} value has been fixed, the main gates for time - current characteristic, needed by fuse-links designer, may be estimated from Fig.3.

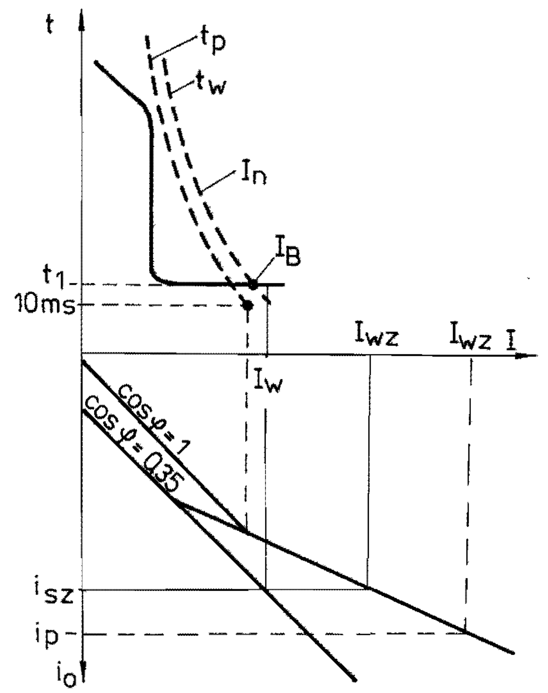

Fig.3. Evaluation of a combination breaking capacity from a fuse and centactor characteristics

for t_1, t_p, t_w and I_B - see Fig.2;
I_n - t-I zone and cut-off characteristic of the I_n-rated fuse; i_{sz}, i_p peak and pulse withstand currents of a contactor;
I_w -contactor short-circuit breaking capacity; I_{wz}-combination short-circuit breaking capacity.

BACK - UP FUSES

In the Gdańsk Branch of Electrotechnical Institute new low power-loss fuse-links for back-up protection of vacuum contactors 1000 V and 6000 V a.c. have been designed.

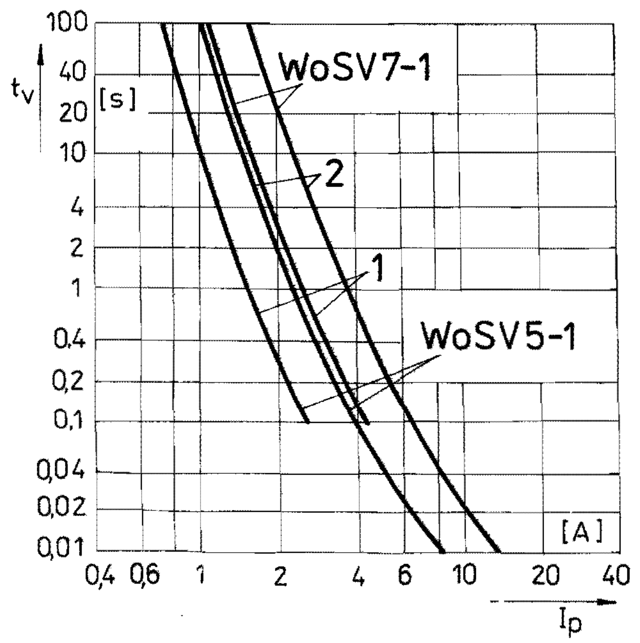

Fig.4. Time-current zones of aM fuses for back-up protection of 1000V a.c. vacuum contactors types SV5 and SV7

The 1000/1140V "aM" category fuse-links /Fig.4/ type WoSV5-1: rated 125, 160 and 200A, type WoSV7-1: rated 200, 250 and 315 A, are capable of interrupting fault currents up to 50kA. The power-losses of these fuse-links are very low i.e.: below 23W for 200A fuse-links and 41W for 315A fuse-links. A maximum temperature-rise on fuse terminals is not higher than 40K. This is particularly important for coal-mine switch-gears in which the fuse-contactor combinations are in special explosion-proof casings. Environment temperature inside of the casing is often above $50^{0}C$. The new fuse-links have substantially high current - limiting ability /Fig.5/ and resistance to pulse overloads i.e.:

a/ Copper strip fuse elements -
   - 50 pulses with test current $k_1.I_n/4I_n/$, pulse duration 15s, interval between pulses 450s; /after new VDE [7] /

b/ silver strip fuse elements - 80 pulses with current value and duration same as a/, interval between pulses 90s.

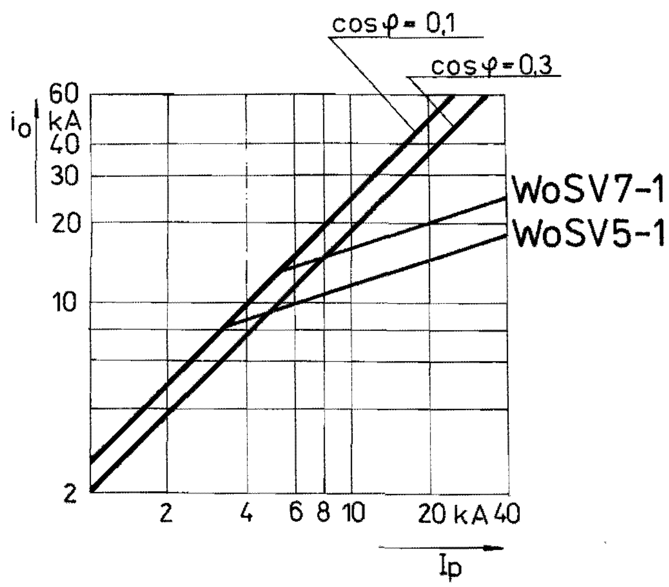

Fig.5. Cut-off current characteristic of 100V a.c. back-up fuses for SV5 and SV7 types contactors

The copper fuse - elements fulfil the requirements for "aM" fuses of normal execution, the silver ones fulfil more severe requirements for mining execution.
New designed h.v.-fuse-links type WoHSV7-1 for motor circuits /partial range/ /Fig.6/, rated 160, 200, 225 and 250A fulfil requirements of IEC Publ. 644 [2] .

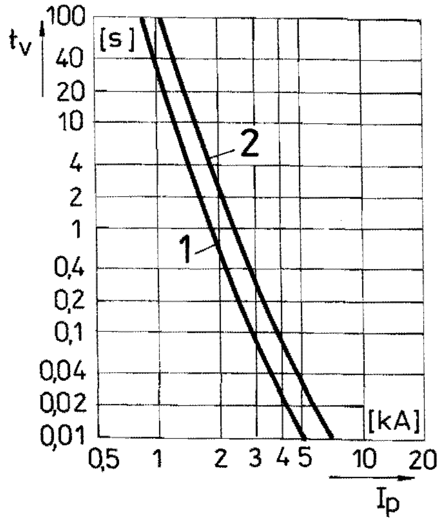

Fig.6. Time-current zone of partial range fuses for back-up protection of 6000V a.c. vacuum contactors type HSV7.

The fuse-elements of these fuses may be of silver or copper strips. Coefficient K, estimated after IEC Publ 644 [2] , specifies overload curve. After this curve, the fuse-link when submitted to overload cyclic pulses should not operate. The K value for copper strip-elements is 0,62, and for the silver ones: 0,66.

The WoHSV7-1 type fuse-links are destinated for industrial and coal-mine power systems with fault power up to 400 MVA. Current - limiting properties of these fuse-links are shown in Fig.7.

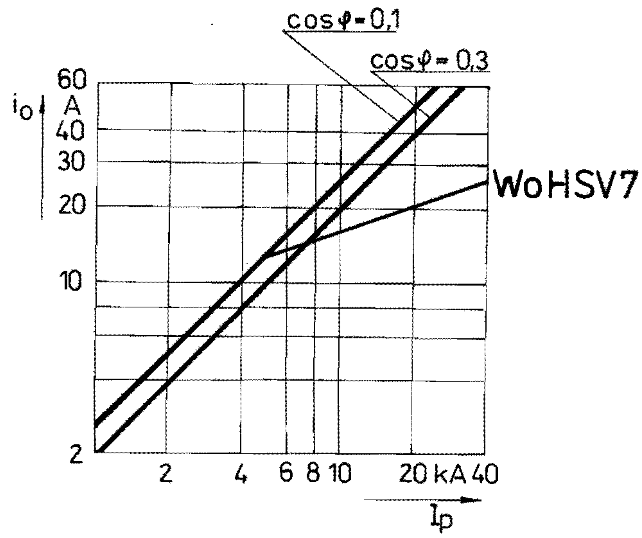

Fig.7. Cut-off current characteristic of 6000V a.c. back-up fuses for HSV7 type contactors.

/Their maximum interrupting capability, up to now has not been verified/. The power losses of these fuse-links are relatively low, i.e.: 100 W for 160A and 150 W for 225A fuse-links; temperature rises on terminals - 20K and 28K respectively.

FUSE AND VACUUM CONTACTOR COORDINTATION IN FAULT CONDITIONS

In order to verify the coordination principles /relation 1-5/ short-circuit tests of 1000V a.c. combinations have been carried out. These tests contained also verification of short-circuit withstands /without and with fuse/ of vacuum contactors [6] . A current flowing through the closed contacts of contactor causes an electrodynamic force to act in the opposite direction to the mechanical force to maintain contacts. This leads to sepation of contactor contacts and can develop substantial arcing and heat which cause contacts welding. The electrodynamic force acting between contacts is proportional to the square of the current; the energy converted to heat in the vicinity of the separated contacts, when arcing, is proportional to the time duration. For this reason the value of I^2t was taken as a characteristic parameter of contacts welding phenomena.
The Table 1 presents withstands of vacuum contactors types SV5 and SV7.

Table 1. Results of short-circuit withstand tests of vacuum contactors

Type	Rated current, I_n	Breaking capacity, I_w	Power factor, $\cos\varphi$	el.dynamic withstand without fuse, i_{sz}	el.dynamic withstand with fuse, i_p	Let-through Joule's integral, I^2t_w
-	A	kA r.m.s.	-	kA peak	kA peak	x $10^5 A^2s$
SV5	100	2,5	0,35	9	15	15
SV7	250	4,0	0,35	12	43	40

Taking into account the i_p current values given in the Table 1, from the Fig.5, the short - circuit breaking capacity of the combination I_{wz} / see relation /5/ and Fig.2/ may be estimated as follows:
SV5 combination: abt. 24kA r.m.s.
SV7 combination: above 60kA r.m.s.
The present fault current level in Polish coal-mine 1000V power systems is not higher

than 11kA, for this reason the combinations as above were verified with the test current up to 15kA only.
The short-circuit tests in take-over current region $I_S - I_C$, Fig.2, have shown that the performences of the contactor are much better than could be expected on the basis of Fig.2. The characteristic in Fig.2 is for single-phase symmetrical current [4,5] .
In a three-phase fault circuit, at least in the two-phases asymmetrical current is flowing. Hence the operating Joule's integral of the fuse in these two phases differs from the one where symmetrical current occurs. This why in a three-phase circuit the shorter operating time, than in time-current characteristic, may be expected.
Maximum and minimum possible relative r.m.s. values of asymmetrical current I_z/I versus time are presented in Fig.8:

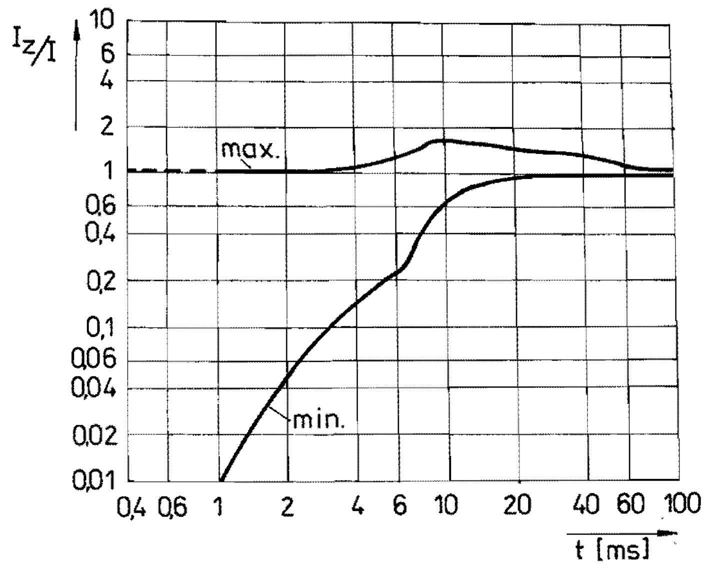

Fig.8. Maximum and minimum possible r.m.s.,values of asymmetrical current I_z/I in three-phase circuit.
t - time measured from a fault instant

$$/6/ \quad I_z/I = \sqrt{\int i_a^2\, dt / \int i_s^2 dt}$$

where: I_z - r.m.s. asymmetrical current
I - r.m.s. symmetrical current
i_a - instantaneous asymmetrical current
i_s - instantaneous symmetrical current

From Fig.8 the possible values of take-over current can be obtained i.e.:
For contactor operating time $t_1 = 40$ms the take-over current may be within limits /1-1,5/ I_B; for $t_1 = 1$ms the take-over current may be /0,01-1/I_B.
When $I_z > I$, in one of the phases the fuse operates as the first, then the three-phase fault inverts into a two-phase fault. The latter may be easily interrupted by a contactor-two contacts operate in series. This explains that if even the coordination criterion /2/ is not fulfiled, i.e. $I_B > I_w$, the contactor is able to interrupt the take-over current satisfactorily. It leads to the conclusion that in the relation /2/, instead of the breaking capacity value I_w, e.g after [3] , other value may be used, estimated in two-phase interrupting tests, as this is recommended by Polish Standard [8].

CONCLUSIONS

- The fuse-vacuum contactor combinations may be used in power circuits at fault power of 400 MVA /1000 volts/ and 250MVA /6000 volts/, respectively. The majority of faults may be interrupted by contactor, what is very important for a continuity of service
- The combination above may be applied as an operating and short-circuit protective device, and in this case no additional circuit-breaker is needed.

- On the basis of the given coordination principles the breaking-capacity of the combination can be evaluated by the designer. The additional contactor parameter has been introduced: the contactor withstant for cut-off current pulse.
- The tests and analysis of fuse-contactor coordination method in region of take-over current, shows that the breaking current value, which is compared with the take-over current , may be verified /higher/ on the basis of the contactor two-phase interrupting tests. It leads to a higher coordinated fuse rating.

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Session IX

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