3-PHASE OPERATION OF CURRENT-LIMITING POWER FUSES

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Abstract

The breaking capacity of power fuses is usually verifed in single-phase tests but in service fuses are very often used in three-phase power systems. In the paper the relative severity of fuse testing is discussed, using computations based upon a relatively simple fuse model. The sequence of fuse operation in 3-phase systems is illustrated and the worst cases are highlighted. The maximum arc energy is shown to be dependent upon system neutral earthing, as well as the test voltage and closing angle. Normalised characteristics are presented showing the circuit severities in terms of arc energy, and the results are discussed in the light of fuse testing standards. The practice of using only two fuses in an unearthed 3-phase system is shown to produce exceptionally severe stresses on the fuses.

LIST OF SYMBOLS

- E = r.m.s line to neutral voltage
- e_a = $\sqrt{2}$ E sin (wt + θ)
- e_b = $\sqrt{2}$ E sin (wt + θ - 120°)
- e_c = $\sqrt{2}$ E sin (wt + θ - 240°)
- i_a = instantaneous current in phase 'a'
- i_b = instantaneous current in phase 'b'
- i_c = instantaneous current in phase 'c'
- I_o = half-cycle melting current
- L = source-circuit inductance
- R = source-circuit resistance
- v_o, r_o = constants in Hirose's fuse model
- vf_a = instantaneous voltage for fuse 'a'
- vf_b = instantaneous voltage for fuse 'b'
- vf_c = instantaneous voltage for fuse 'c'
- v_p = instantaneous voltage at fault point
- θ = circuit closing angle with respect to e_a
- w = supply angular frequency

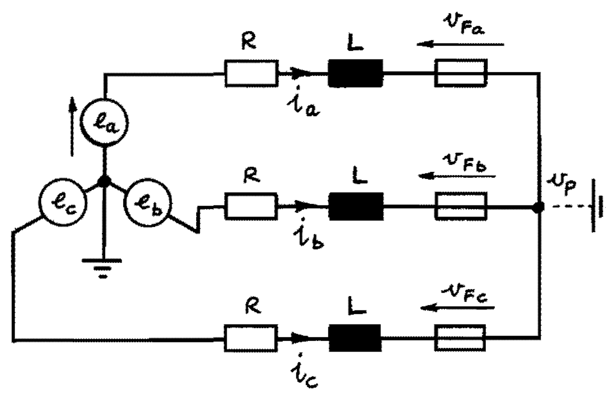

Fig.1 Circuit arrangement.

INTRODUCTION

Although the breaking-capacity of current-limiting fuses is normally verified in a single phase test circuit, in service fuses are very often used in 3-phase systems, in which the fuses may interact with one another in some way when interrupting a short-circuit fault current. There is some disagreement and confusion about the relative severity of the stresses imposed upon fuses in a 3-phase situation, compared to those produced in a single-phase test. For example the IEC high-voltage current-limiting fuse specification allows fusesto be tested at 87% of the intended 3-phase line voltage, whereas many users insist that the fuse should be tested at the full line voltage. For circuit breakers which clear at a current zero the first phase to clear has to do so against a source voltage of 1.5 times the line-to-neutral voltage, which is 0.866 times the line voltage. Gibson [1] has discussed this problem, pointing out that a current-limiting fuse operates in a manner which is fundamentally different from that of a circuit breaker, and that the correspondence between the 87% test for fuses and the 0.866 value used for circuit breakers is a coincidence.

In this paper this problem is discussed qualitatively by describing the sequence of fuse operation in 3-phase circuits, and quantitatively using Hirose's fuse model [2].

The results, which are illustrated with normalised arc-energy characteristics for a typical fuse, are only relevant to the testing of fuses when they operate in the current-limiting mode (I_1 and I_2 tests).

CIRCUIT MODELS

Fig.1 shows a typical 3-phase power system fitted with 3 fuses during the interruption of a 3-phase fault by the current-limiting action of the fuses. If the 3-phase fault involves earth and the supply neutral is earthed the circuit can be regarded as three single-phase circuits which operate independently of one another, and the fuses will be stressed at the same levels that would obtain in a single-phase test at the line-to-neutral voltage E. If however the fault does not involve earth the fuses will interact with one another. This situation will be referred to as the "unearthed" case, and it would also arise if the supply neutral is unearthed when the fault involves earth.

The general case can be treated by letting the voltage at the fault point be v_p. The circuit currents at any instant in time can then be found by solution of the three differential equations below:

$$\frac{di_a}{d_t} = \frac{e_a - Ri_a - vf_a - v_p}{L}$$

$$\frac{di_b}{d_t} = \frac{e_b - Ri_b - vf_b - v_p}{L} \qquad (1)$$

$$\frac{di_c}{d_t} = \frac{e_c - Ri_c - vf_c - v_p}{L}$$

The equations (1) may be solved by numerical integration. It is convenient to use normalised values for all the variables [3]. In this system all voltages are expressed as multiples of E while all currents are expressed as multiples of the one-half-cycle melting current. The fuse voltages were modelled as follows:

(i) Prearcing state

$$vf_i = 0$$

(ii) Arcing state

$$vf_i = v_0 + r_0 |i|$$

This is Hirose's model [2] which gives a more realistic voltage than the more commonly-used 'rectangular' arc voltage profile.

Solution of (1) also requires v_p to be computed at each time step. This can be done as follows:

(i) Earthed system

$$v_p = 0$$

(ii) Unearthed system

since $i_a + i_b + i_c = 0$ it follows that

$$\frac{di_a}{d_t} + \frac{di_b}{d_t} + \frac{di_c}{d_t} = 0 \qquad (2)$$

(a) All fuses intact

Using (1) and (2) we obtain for v_p

$$v_p = -\frac{1}{3}(vf_a + vf_b + vf_c)$$

(b) After 1st fuse has cleared

If, say, fuse 'a' clears first and thereafter present an infinite impedance, using (1) and (2) we obtain

$$v_p = \frac{1}{2}(e_b + e_c - vf_b - vf_c)$$

Cyclically similar expression may be derived for v_p if fuse 'b' or fuse 'c' clears first.

The solution procedure requires that after each time step the 'states' of all three fuses are checked to see whether a change of state has occurred. There are 3 possible states - (1) intact (the initial setting), (2) arcing, and (3) blown. Transition from state 1 to state 2 occurs if the integral of i^2 for that fuse exceeds the prearcing I^2t value (0.01 using normalised currents and a 10 ms half-cycle time). Transition from state 2 to state 3 occurs if the fuse is already in the arcing state and current was forced to pass through zero during the previous time-step. The appropriate value for v_p is used at each time step and the computation is terminated (i) when all fuses have blown if the system is earthed, or (ii) when any two fuses have blown if the system is unearthed.

The numerical integration procedure as well as giving the phase currents by solution of (1), is also used to calculate the i^2t integral for each fuse and the arc energy liberated in each fuse (the integral of $v_f.i.d_t$).

ADEQUACY OF FUSE MODEL

Use of complex dynamic fuse models such as that described previously [4] requires excessive computation for the present purpose, since hundreds of simulations are necessary to investigate the variation of arc energy with point-on-wave, prospective current, test voltage and circuit arrangement for all 3 phases. For this reason Hirose's simpler model was used.

It is required in this case that the model should adequately represent the way in which maximum arc energy varies with test voltage. Some test results have been published by Hirose [5]. Use of the dynamic fuse model for this purpose [6] shows that for a typical fuse arc energy increases with test voltage raised to the power 1.93. Similar results have been obtained with the simple Hirose model. Indexes of 1.7 - 1.9 were found for the values of v_0 and r_0 given below. These values are representative of those obtained from tests on a typical low-voltage fuse and a typical high-voltage fuse. [1]

	v_0	r_0
LV	0.60	0.70
HV	0.35	0.45

The lower values for the high-voltage fuses suggest that this type is more sensitive to increase in test voltage. This has been found to be the case.

In order to restrict the number of variables the power factor of the test circuit was set to 0.1 for all simulations.

TYPICAL WAVEFORMS

The precise sequence of fuse melting and of arc extinction for all 3 phases varies considerably with the test current, closing angle and test voltage relative to the fuse arc voltage. Some typical examples only are given here to illustrate the way in which the fuses can interact with one another when the system is not "fully" earthed.

Figs 2 and 3 show the sequence of fuse operation for earthed and unearthed systems at a current close to the critical current for phase 'a'. The circuit closing angle here was set at 0° which gives a high arc energy for the fuse in phase 'a'. The results shown here and in Figs 4 and 5 are for the typical high-voltage type.

Detailed analysis of Figs 2 and 3 reveal the following:

Fig 2 (Earthed)

At circuit closing phase 'b' voltage is near its negative maximum. The initial rate-of rise of current is therefore highest for fuse 'b' which melts first, followed by 'c' then 'a'. All fuses operate independently. Fuse 'c' clears first (minor loop) followed by 'b' then 'a'.

Fig.3 (Unearthed)

Until fuse 'b' melts the currents are the same as in the previous case. However when fuse 'b' melts it produces an arc voltage which acts in opposition to the source voltages in phases 'a' and 'c' and which thus delays the melting of fuses 'a' and 'c'. Fuse 'b' clears first, after which arcing continues in 'a' and 'c' in series against the line-to-line voltage, until eventual clearance by 'a' and 'c' simultaneously. Note that the duration of arcing in fuse 'a' is prolonged compared with Fig.2.

EFFECT OF OMITTING FUSE 'C'

In some systems with unearthed neutral it is practice to fit only 2 fuses, the third being replaced by a link. Since the phase-to-earth fault current is zero in these systems, high short-circuit currents only occur when more than one phase is involved, so the fault will always be detected by at least one of the two fuses. This circuit connection has also been occasionally used for fuse testing. [1]

However in this case very severe stresses can be imposed on the fuses as can be seen from Fig.4, which has been drawn for a closing angle of 0° for phase 'a' for ease of comparison with Figs.2 and 3. A closing angle of 0° is not the worst condition: if only two fuses are fitted the worst condition is near a closing angle of 90° for phase 'a', producing the maximum stress on fuse 'b'. (Since the circuit is not cyclically symmetric, random variation of closing angle produces a different range of stresses on the 2 fuses - this is quite different from Figs.2 and 3 where a random variation of closing angle in the range 0-60° produces an equal range of stresses upon the 3 fuses). The responses for a closing angle of 90° are shown in Fig.5.

Detailed analyses of Figs.4 and 5 reveal the following:

Fig.4 (Unearthed)
(2 fuses, $\theta=0°$)

Initially the situation develops as in Fig.3 but after fuse 'b' has cleared fuse 'a' is left alone to clear against the line-to-line voltage ($V_a - V_c$) with no assistance from an arc voltage in phase 'c', just as the phase 'c' voltage is approaching its maximum. Arcing is prolonged in phase 'a' at a high current level.

Fig.5 (Unearthed)
(2 fuses, $\theta=90°$)

In this case the phase 'a' voltage is at its maximum so fuse 'a' melts and clears first. The arc voltage of fuse 'a' forces the current in fuse 'b' from a negative minor loop to a positive value. The melting of fuse 'b' is thus accelerated and after 'a' has cleared fuse 'b' is left alone in circuit in the arcing state and early in the rising half-cycle of the phase 'b' voltage. Arcing is thus prolonged in phase 'b'.

ARC ENERGY CHARACTERISTICS

Fig.6 shows the variation of arc energy as a function of prospective current for various test circuit arrangements. In every case the values shown are the maximum possible i.e. the effect of the closing angle has been eliminated by plotting for every test current only the highest value of arc energy, (which occurs at different closing angles for different levels of current). The normalised arc energy is expressed as a multiple of the base value EI_0t_0.

The curves show the well-known maxima in arc energy but there are large differences between the values. The lowest energy is obtained for the "earthed" case, which corresponds to a single-phase test at the line-to-neutral voltage. The relative severities for various test arrangements are shown below.

Circuit	Maximum arc energy, p.u.		Relative severity	
	HV	LV	HV	LV
Single phase	1.96	1.38	1.0	1.0
3-phase unearthed	2.38	2.21	1.21	1.60
Single-phase at 87% of line voltage	4.26	2.80	2.17	2.03
Single-phase at 100% of line voltage	5.72	3.61	2.92	2.62
Unearthed with only 2 fuses. Fuse 'b' value.	6.10	3.95	3.11	2.86

The results above show that the arc energy for a 3-phase fault not involving earth may be 1.21-1.60 times the value obtained in a single phase test at the normal line-to-neutral voltage. However the arc energies obtained at 87% of the line voltage (i.e. 1.5 times the line-to neutral voltage) are significantly higher (2.03-2.17). This shows that the 87% test is more than adequate to verify the breaking capacity for the types of fault simulated. Tests at the full line voltage give an unrealistically high stress on the fuse. The only justification for testing at the full line voltage would be that it is desired to protect against a 'cross-country' fault e.g. where the load side of one fuse is shorted to the supply-side of a fuse in an adjacent phase, which results in the full line voltage appearing across the first fuse.

It is also clear from the results that the manner and sequence of the fuse operation in a 3-phase system is quite different from that obtained with zero-awaiting devices and therefore the 87% level which appears in the standard has no special significance.

The use of only 2 fuses in an unearthed 3-phase system means that both fuses will be subjected to exceptionally high arc energies, especially if the prospective current is high (see Fig.6). Furthermore, the computer simulations show that very high recovery voltages may appear across the first fuse to clear, increasing possible restriking problems.

UNBALANCED FAULTS

The above analyses have been restricted to 3-phase faults. Unbalanced faults will generally give stresses on current-limiting fuses which are no greater than those produced by 3-phase faults. The source power factor may be affected by the type of fault but it is unlikely to be lower than the values used in fuse testing. If the sequence impedances have the same X/R ratio the maximum possible arc energies for single and double line-to-earth faults will be the same as for the three-phase earthed case. For phase-to-phase faults the arc energy will be lower as two fuses will be acting in series against an effective source voltage of 1.732 times normal.

CONCLUSIONS

The transient variation of phase currents for fuses operating in a 3-phase system have been computed and the maximum stresses upon each of the fuses have been obtained by numerical integration.

For normal faults the stresses are slightly lower than those obtained in a single-phase test at 87% of the line voltage and very much lower than those in a test at the full line voltage, particularly for high-voltage fuses.

The practice which is sometimes adopted, of using only fuses in an unearthed 3-phase system is shown to produce very high stresses on the fuses, higher than those obtained in a single-phase test at the full line voltage.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Gibson J.W., Reply to discussions. Int. Conf. on Electric Fuses and their Applications. Liverpool Polytechnic, April 7-9 1976

[2] Hirose A : "Mathematical analysis of breaking performance of current-limiting fuses", ibid, pp182-191

[3] Wilkins R : "Generalised short-circuit characteristics for h.r.c. fuses", Proc IEE, 1975, vol 122, pp1289 - 1294

[4] Wilkins R : "A suite of interactive programs for fuse design and developement", Int. Conf. on Electric Fuses and their Applications, NTH, Trohdheim, 13-15 June 1984, pp227-235

[5] Hirose A : "Maximum arc energy of low-voltage fuses in terms of their voltage", 5th Int. Symp. on Switching Arc Phenomena, TU Lodz, 1985, pp341-345

[6] Wilkins R : Discussion contribution on reference [4], ibid, part II, pp126-127

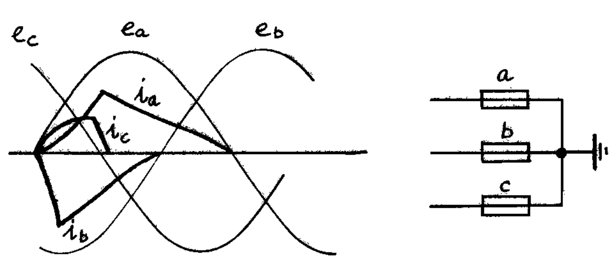

Fig.2 Fault current transients. (Earthed, θ = 0°)

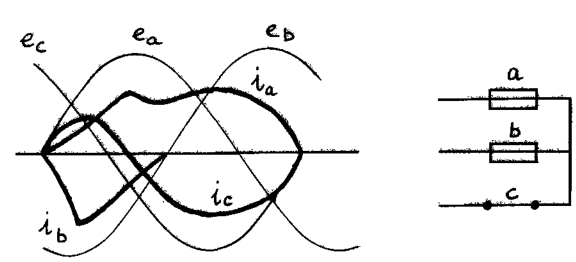

Fig.4 Fault current transients. (2 fuses, unearthed, θ = 0°)

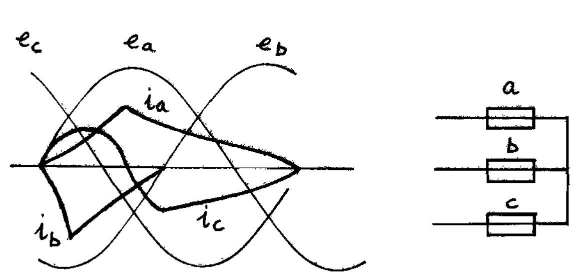

Fig.3 Fault current transients. (Unearthed, θ = 0°)

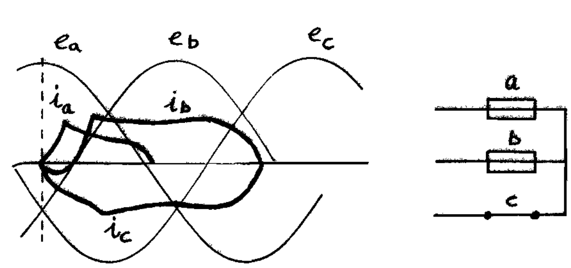

Fig.5 Fault current transients. (2 fuses, unearthed, θ = 90°)

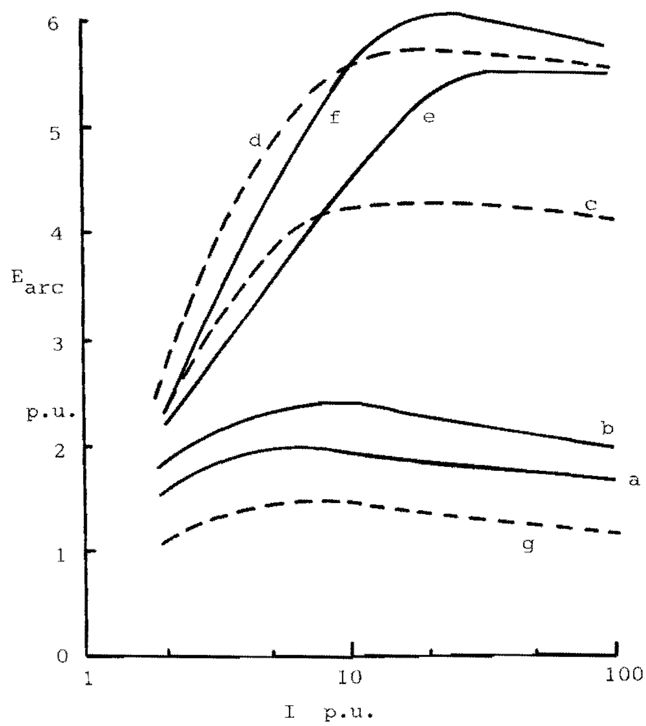

Fig.6 Arc energy characteristics for fuse HV.

a. Earthed
b. Unearthed
c. Earthed, 87% of line voltage
d. Earthed, 100% of line voltage
e. Unearthed, only 2 fuses, fuse 'a'
f. Unearthed, only 2 fuses, fuse 'b'
g. Phase-to-phase fault