VOLTAGE RATING OF FUSES FOR THE PROTECTION OF REGENERATIVE DC DRIVES

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1 Introduction

Fuses protecting a 3-phase drive system such as that shown in **Fig.1** have to deal with a variety of different types of fault current from the a.c. side, and it is widely accepted that the a.c. voltage rating of the fuses must be at least equal to the a.c. line voltage to clear all possible a.c. faults adequately. However when the drive is regenerating (inverting) the situation is more complicated. Accidental triggering of a thyristor when regenerating can lead to a d.c. shoot-through (diametric) fault, in which fault current from the d.c. side has to be cleared by 2 fuses acting in series. A second type of fault (non-diametric fault) is due to commutation failure (Fig.1) and results in the fault current being driven round the fault loop by the a.c. and d.c. source voltages in series. This appears to be a very severe fault condition and it is often proposed that the fuses' a.c. voltage rating needs to be increased by adding a proportion of the d.c. side voltage to the a.c. line voltage. This leads typically to a required a.c. voltage rating of 1.8 times the a.c. line voltage [1, 2].

Application of this criterion to a 660V system would mean that the fuse would need to be rated to at least 1188V. However, in the authors' experience, the use of factors as high as 1.8 is unduly pessimistic. In this paper the severity of commutation failure is investigated in detail and rules are suggested for the selection of the required voltage rating.

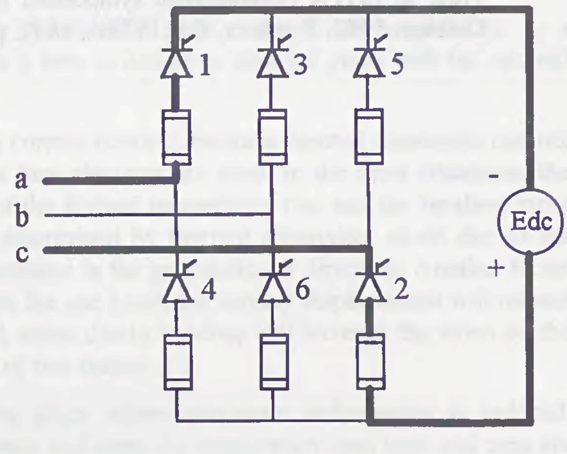

Fig.1 Commutation failure in regenerative mode.

2 Fault current following commutation failure

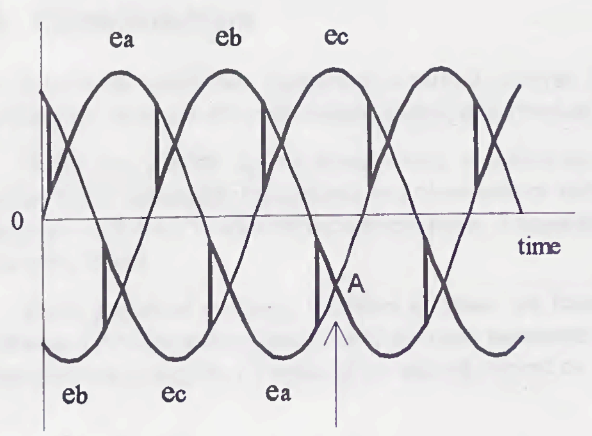

Fig.2 Output voltage waveforms in regenerative mode.

In the normal operation of the bridge in the regenerative mode the output voltages are as shown in **Fig.2**. If thyristors 1 and 2 are conducting, thyristor 3 should be turned on before the point A is reached and current will commutate from thyristor 1 to thyristor 3. If however thyristor 3 fails to turns on (due to a missing gate pulse or if there is insufficient time for overlap to be completed) thyristor 1 continues to conduct, the fault situation shown in Fig.1 develops, and control of the bridge is lost [3].

The equivalent circuit for this condition is shown in **Fig.3**. If we take $t = 0$ at the point A the a.c. voltages can be expressed as

$$e_a = \sqrt{2}\, E_{ph} \sin(\omega t - 30°) \quad ; \quad e_c = \sqrt{2}\, E_{ph} \sin(\omega t - 270°) \quad ; \quad \text{which gives}$$

$$e_{ac} = \sqrt{2}\, E_{LL} \sin(\omega t - 60°) \tag{1}$$

where $E_{LL} = \sqrt{3}\, E_{ph}$ and E_{ph} is the a.c. phase - to - neutral voltage.

In Fig.3 the source voltage acts clockwise around the loop, which has a loop resistance and inductance

$$R = 2R_{ac} + R_{dc} \quad ; \quad L = 2L_{ac} + L_{dc}$$

The solution for the prospective fault current is

$$i = \frac{\sqrt{2}E_{LL}}{Z}\left\{\sin(\omega t + \theta - \phi) - \sin(\theta - \phi)\,e^{-t/\tau}\right\} + \frac{E_{dc}}{R}\left\{1 - e^{-t/\tau}\right\} + I_0\,e^{-t/\tau} \qquad (2)$$

where

$Z = \sqrt{(R^2 + \omega^2 L^2)}$ — ω = angular frequency of a.c. supply

θ = angle of fault initiation after line voltage zero — τ = L/R = loop time constant (not the d.c time constant)

I_0 = initial value of current

Fig.4 shows a typical fault current wave and the corresponding voltage acting around the loop. Since the fault condition always begins at point A in Fig.2 the fault initiation angle θ is always -60° with respect to the a.c. line voltage *Eac*.

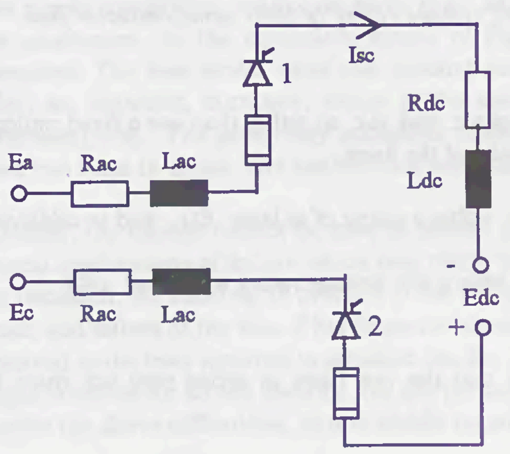

Fig.3 Equivalent circuit after commutation failure.

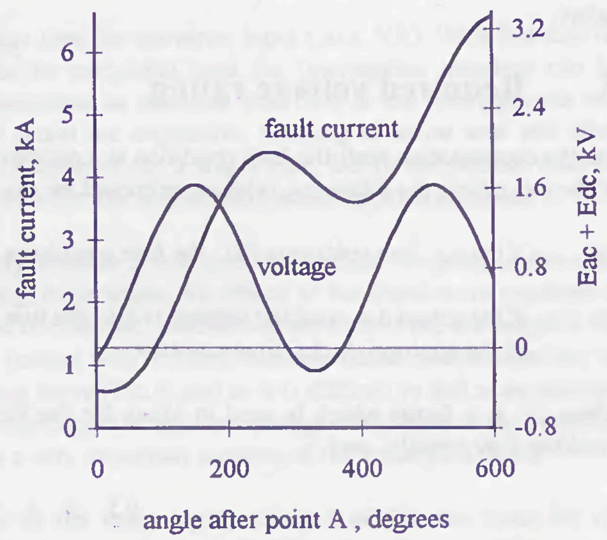

Fig.4 Source e.m.f. and fault current waveforms.

3 Fuse melting instant

The severity of the fault condition is affected by the point on the supply voltage wave at which the fuse melts, just as is the case for a simple a.c. fault. For the simple a.c. fault the so-called maximum arc energy condition requires a particular combination of the prospective current and the angle θ [4]. However, for the commutation fault, θ is fixed at -60° and the prospective current, as a multiple of the fuses' rated current, only varies within a limited range in practice. The parameter that has the greatest influence on the fuse melting instant is the d.c. time constant *Tdc (= Ldc/Rdc)* .

Fig.5 shows the angle after the a.c. line voltage zero at which melting occurs (arcing angle) as a function of the d.c. time constant for a typical modern 500V 200A semiconductor fuse. These results were obtained using the computer model of fuse operation which has been described previously [5, 6]. (The system data for Fig.5 is as given later in section 6.) In order to get a high arc energy the fuse must melt on the rising part of the supply voltage wave, just before the maximum. We define the range of arcing angle 60-90° after the a.c. voltage zero as "critical zone 1". To get melting within this zone we need a d.c. time constant of the order of 10-20 ms, as shown in Fig.5. If the d.c. time constant is

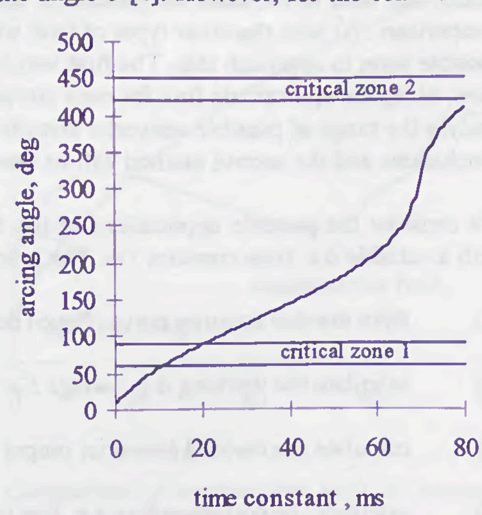

Fig.5 Variation of arcing angle with DC time constant for 200A semiconductor fuse.

higher than this melting occurs on the falling or negative part of the voltage wave (see Fig.4), and the potential severity of the fault condition reduces. The situation again becomes critical for d.c. time constants greater than 80ms, when melting may occur in the next positive half-cycle of voltage, with an arcing angle of 420-450°.

4 DC voltage rating

The voltage rating of a fuse for a simple d.c. fault falls as the d.c. time constant of the circuit increases. Fuse manufacturers normally allow for this by publishing a derating curve such as that shown in **Fig.6**. The curve is derived by testing the fuse to failure (under the maximum arc energy condition for each value of time constant) by increasing the test voltage, and then assigning a d.c. voltage rating well below the failure level, to ensure an acceptable factor of safety.

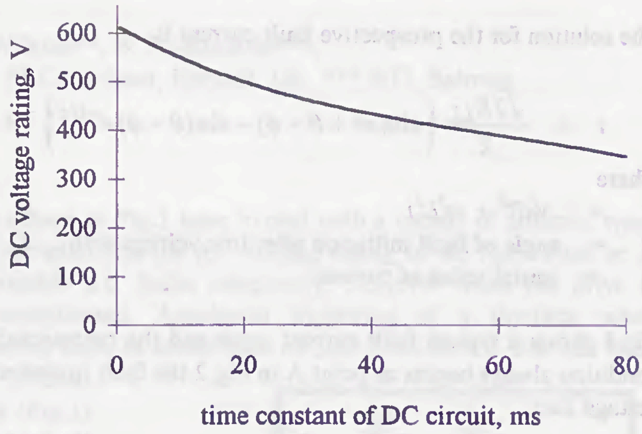

Fig.6 DC voltage rating of 500V semiconductor fuse.

5 Required voltage rating

For the commutation fault the fault condition is a combination of a.c. and d.c. so rather than use a fixed multiple of the a.c. rating, the following rules are proposed for the selection of the fuses :

(a) if the a.c. line voltage is E_{LL} the fuse must have an a.c. voltage rating of at least E_{LL}, and *in addition*

(b) if the actual d.c. working voltage is E_{dc}, the fuse must have a d.c. voltage rating of at least xE_{dc} at the appropriate d.c. time-constant

where x is a factor which is used to allow for the fact that that the two fuses in series may not share the breaking duty equally, and

$$0.5 \leq x \leq 1 \qquad (3)$$

$x = 0.5$ corresponds to the case where the two fuses share the duty equally, while for $x = 1$ no sharing between the fuses is assumed, i.e. each fuse would have to be rated for the full d.c. voltage.

6 Severity of commutation fault

Direct experimental work on a range of converters with various fuses was impractical, and so the computer model was used to simulate the process of interruption, and evaluate the severity of the commutation fault, by comparison ; (i) with the other types of fault which may occur and (ii) with the standard type tests. There are two possible ways to approach this. The first way is to analyse the faults for a full range of standard converter power sizes, using the appropriate fuse for each circuit [7]. The second approach is to consider one specific fuse, and to analyse the range of possible converter circuits in which it could be used. Both methods lead to the same general conclusions and the second method will be described here since it is simpler.

We consider the possible applications of the 500V 200A semiconductor fuse mentioned previously, in systems with a variable d.c. time constant T_{dc}. The procedure is as follows, for each value of T_{dc}.

(a) from the d.c. derating curve (Fig.6) determine the fuses' maximum d.c. working voltage, V_{fdc}

(b) calculate the working d.c. voltage $E_{dc} = V_{fdc} / x$

(c) calculate the no-load converter output $E_{d0} = E_{dc} / 0.95$

(d) calculate the corresponding a.c. line voltage $E_{LL} = E_{d0} / 1.35$

(e) if E_{LL} exceeds 500V, reset it to 500V and reduce the d.c. working voltage to $E_{dc} = 0.95 \times 1.35 \times 500$

Use of the 0.95 factor allows for the fact that the actual induced e.m.f. of the d.c. machine will be less than E_{d0} because of armature voltage drop in the d.c. machine and phase control of the converter. This is a pessimistic assumption - in practice lower values will normally apply. Use of the calculated a.c. line voltage will also be pessimistic, since the calculated value will not generally be a standard system voltage and the value which applies in practice will therefore be lower than the value given in (d) or (e) above.

The fuse current loading (*Irms*) was set at 80% of rating = 160A, and the remaining system parameters were set as follows :

d.c. side :	I_0	=	$I_{rms} / \sqrt{3}$
	R_{dc}	=	*5% on d.c. machine rating*
	L_{dc}	=	$T_{dc} R_{dc}$
a.c. side :	Z	=	*5% on supply transformer rating*
	p.f.	=	*0.15*
	f	=	*60 Hz*

(the supply transformer rating was taken to be 20% higher than the converter input r.m.s. VA). With this data all the parameters in the equivalent circuit of Fig.3 can be calculated, and the interruption transient can be computed. The fuse model takes into account such phenomena as transient heat flow in the fuse elements and filler, arc initiation, burnback, fusion of the sand and radial arc expansion, merging of series arcs and other processes [5, 6]. The previously published models were however for a single fuse, but in the present case we have two fuses in series. The method that was used to allow for this is described in the Appendix, section 9.

However, the models cannot be used to predict precisely whether a fuse will fail to clear. In practice there are several mechanisms of failure which may occur including, for example, the effects of the shock-wave produced at arc initiation; the build-up of pressure if the arcing time is extended; puncture of the ends if the arc length is too great; and failure of the tube if hot fulgurite comes into contact with it. More than one failure mechanism may be involved in the tests required to establish the d.c. derating curve (Fig.6) and so it is difficult to define an accurate single criterion for circuit severity. For the purposes of this paper the total arc energy was chosen as the criterion, despite the above difficulties, as it is widely regarded as a very important measure of the stress on a fuse.

For the above system data, the computed arc energy in the more highly stressed of the two fuses for the commutation fault is shown in **Fig.7**, as a function of the d.c. time constant. A value of x equal to 0.6 was used, which has been found in practice to be suitable for well-matched fuses. At first the arc energy increases with time constant and then a maximum is reached, corresponding to the start of arcing in the first critical zone of Fig.5. Thereafter the arc energy decreases as T_{dc} increases beyond about 20 ms. For high time constants the permissible d.c. working voltage is reduced because of the derating curve (Fig.6), and requirement (e) above, which produces a relatively low arc energy.

Also shown in Fig.7 are the computed maximum arc energies for the "type" test conditions on a single fuse (i) at the rated d.c. voltage given by Fig.6, and (ii) at 500V a.c. These represent levels of arc energy which the fuse is known to be able to withstand. (The a.c. test is represented by a horizontal bar since no d.c. time constant is defined for this condition and the operating time is less than 10 ms.)

Over most of the range of time constant the arc energy for the commutation fault is lower than is produced in the simple d.c. test. Bearing in mind that a significant safety factor is built into the withstand levels for the a.c. and d.c. "type" test voltages, and that pessimistic assumptions have been made in the computations for the commutation fault, it may be concluded from Fig.7 that this type of fault is not as severe as may be thought at first.

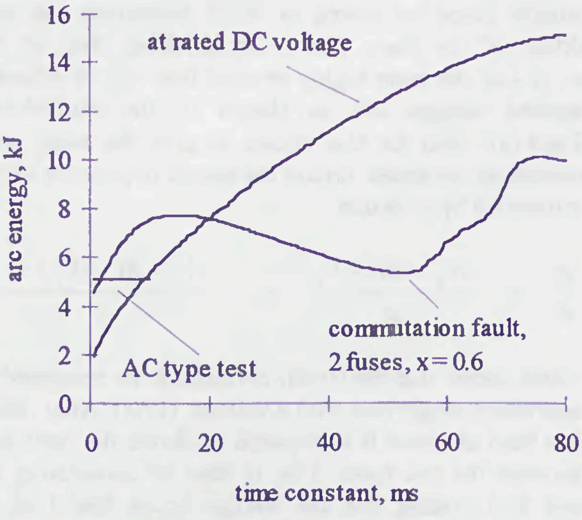

Fig.7 Comparison of commutation fault arc energy with arc energy in type tests.

7 Conclusions

Fuses protecting a regenerative d.c. drive system have to deal with simple a.c. and d.c. short-circuits and with commutation failure, which gives rises to a fault current containing both a.c. and d.c components. For the commutation fault a high arc energy can only be produced within a certain critical range of d.c. time constant. If the fuses are chosen with an a.c. voltage rating at least equal to the a.c. line voltage and a d.c. voltage rating (at the appropriate time-constant) at least equal to 0.6 times the d.c. working voltage then satisfactory protection can be obtained for all three types of short-circuit. This has been verified by computer modelling and by field experience. Variation of the parameters of the a.c. supply, such as impedance and power factor, within practical ranges, does not materially affect these conclusions.

8 References

[1] Howe, A.F. , Newbery, P.G., and Nurse, N.P.M. "DC fusing in semiconductor circuits", *IEEE Trans.*, 1986, **IA-22**, pp 483-488.

[2] Wright, A. and Newbery, P.G. "Electric fuses", (Peter Peregrinus 1982).

[3] Mohan, N., Undleland, T.M. and Robbins, W.P. "Power Electronic Converters and Design." (Wiley 1989).

[4] Toniolo, S.B. and Cantarella, G. "Conditions of maximum arc energy in operation of current-limiting fuses", *IEEE Trans.*, 1969, **PAS-88**, pp 94-99.

[5] Wilkins, R., Suuronen, D. and O'Shields, L. "Developments in the modelling of fuse breaking tests". *4th International Conference on Electric Fuses and their Applications*, Univ. of Nottingham, 23-25 Sept. 1991, pp 211-215.

[6] Wilkins, R. and Cline, H.C. "An advanced applications tool to enhance the fuse protection of power semiconductors". *Conference Record of the IEEE Industry Applications Society 28th Annual Meeting*, Toronto, Oct 2-8, 1993, pp 1226-1230.

[7] Al-Baharna, B, "Fuse protection of regenerative d.c. drives", M.Sc Dissertation, University of Manchester Institute of Science and Technology, October 1993.

9 Appendix

Consider two fuses in series of similar design with an applied voltage *Vs*. We assume that the arc voltage profiles are of similar shape but owing to slight differences the amplitudes differ. If the fuses share the breaking duty in the ratio $x : (1 - x)$, the more highly stressed fuse will be subjected to an applied voltage xVs as shown in the equivalent circuit **Fig.8** (a). But for this circuit to give the same prospective current as the actual circuit the source impedance must also be multiplied by x, so that

$$\frac{di}{dt} = \frac{xV_s - xRi - V_f}{xL} = \frac{V_s - Ri - (V_f / x)}{L} \quad (4)$$

which shows that the circuit current can be computed using an equivalent single fuse with a voltage (Vf/x). After the solution has been obtained it is required to divide the total arc energy between the two fuses. This is done by considering Figs 8(b) and 8(c). Noting that the voltage across fuse 1 in reality is equal to Vf, it is easily shown that the total computed arc energy of the equivalent fuse must be divided between the two fuses in the ratio $x : (1 - x)$.

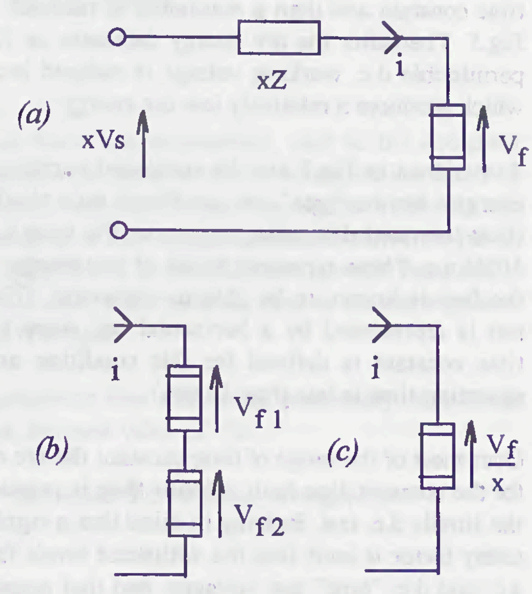

Fig.8 Equivalent circuits for two similar fuses in series with unequal sharing of the breaking duty.

MATERIALS AND MANUFACTURING METHODS