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GAS BREAKERS FOR TOKAMAK OHMIC-HEATING DUTY*

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Summary

The current interrupting capacity of air blast and SF_6 breakers is reviewed for application in tokamak ohmic-heating circuits. Particular attention is paid to generator breakers for their large current interrupting capacity and suitability for ohmic-heating circuits.

Introduction

Switching operations for large tokamaks include plasma initiation in the ohmic-heating system, ohmic-heating current reversal, ohmic-heating coil crowbar, vertical field coil crowbar, and protection of the poloidal and toroidal field coils. A set of typical parameters for switching functions is given in Table I.

For reliability, thyristors, are probably the best state-of-the-art devices available. To interrupt large currents and to withstand high voltages requires using many SCR's in series-parallel arrays. Air blast, oil, and SF_6, and vacuum interrupters to interrupt large currents cost small fraction of the equivalent solid state breakers; however, their reliability is less or inadequately proven for particular dc operations. The saving to be made justifies considerable development and testing effort. Further, some maintenance cost might be acceptable to avoid the expensive solid state switches.

TABLE I

TOKAMAK EPR SWITCHING FUNCTIONS

	Max. Current kA	Max. Voltage kV	Action	Type Switch
Plasma initiation	450* total	50-95	O	solid state, air blast, SF_6, vacuum
	50/circuit	25		interrupters, oil
OH reversal	450* total	25	O-C	solid state, air blast, SF_6, vacuum
	50/circuit			interrupters, oil
OH crowbar	450* total	50	C	ignitrons, spark gaps
	50/circuit			
VF crowbar	500	1	C	ignitrons, spark gaps
Poloidal protect	500	0.2	C	gas gap, explosive
TF protect	21	<10	O	air blast, SF_6, oil, vacuum interrupters
	21	< 2	C	spark gap, vacuum interrupters

*The 450 kA value comes from the GA design study;[1] however, other studies place the upper limit at 200 kA.

Gas Breakers

An advantage of air blast, SF_6, and oil immersed breakers is the low cost per ampere of interrupting current. This is partially offset by higher maintenance and short life as compared with solid state switches.

The airblast breaker described in Table II has been tested[4] at the KEMA test facility. The breaker was considered for the ohmic-heating circuits of the Joint European Torus (JET) and Doublet III. Precise opening times and carefully made mechanical linkages will minimize contact erosion. Dry air at 80 bar is required to operate the breaker.

TABLE II

AIRBLAST BREAKER TESTED FOR OHMIC-HEATING DUTY

Type		ac Duty[2,3]	dc Duty[4]
Recovery voltage	kV	17	> 24
Continuous current rating	kA		
1 to 3 s current rating	kA	>100	>100
Closing current	kA	270	380
Interrupting current (symmetrical)	kA	80	125 (73 test)

All ac voltages and ac currents are given as rms values. The crest values of interrupting currents are approximately $1.8\sqrt{2}$ times the symmetrical rms current value.

The table shows typical interrupting currents. The recurring voltages are higher for some cases not shown in the table for somewhat reduced interrupting currents.

Cold arc phenomena dominate in mechanical breakers at arc voltages <10···30 V and currents <1···5 A because these small values are sufficient for arc heating. The resulting cold arc erosion is often referred to as "bridge point erosion." It causes some metal transfer between the parting electrodes because of local metal melting. Quantitatively, bridge point erosion depends on the electrode materials and is independent of the medium. Oil, air, SF_6, and vacuum breakers show, therefore, similar amounts of erosion for a given current under cold arcing conditions.

If the cold arcing limits are exceeded, then phenomena similar to cold arcing will still prevail in vacuum breakers whereas hot arcs will have to be interrupted in the other types of mechanical breakers.[5] A hot arc is one in which ions and neutrals are heated by the electrons to nearly the electron temperature, i.e., 0.1 to a few eV. Hot arc erosion is an order of magnitude greater than that caused by quasi cold arcing in vacuum breakers interrupting the same current with sufficiently large electrodes. The amount of erosion per unit current decreases with increasing contact area more strongly in vacuum breakers than in gas or oil breakers. Contact areas and electrode masses are, therefore, larger for vacuum breakers than for the other types of mechanical breakers for the same interrupting current rating.

One might draw the premature conclusion that vacuum breakers are constructed with comparatively large electrodes and exhibit small contact erosion as compared to airblast breakers in interrupting significant currents. The former deduction is true whereas the latter is not a meaningful one because airblast and SF_6 breakers can be designed for much higher relative contact speed. This speed allows synchronous operation in which the contacts start to part very closely to a zero-current occurrence. In the dc application the contacts start to depart at the instant the saturable reactor transits out of the saturation domain and thus holds the current at nearly zero level at which the contact erosion is very small. A vacuum breaker in usual operation, on the other hand, would require contact separation to begin earlier when the current has still nearly maximum amplitude.

For practical dc applications, contact erosion in synchronous breakers of the airblast or SF_6 types is probably roughly the same as in vacuum breakers, thus implying a contact life of perhaps 10^4 current interruptions.[6] In the case of vacuum breakers this is synonymous with the life expectancy of the breaker unit, whereas, in gas breakers, the contacts can be replaced easily. An additional important advantage of gas breakers is seen in the fact that the largest interrupting current ratings of airblast and SF_6 breakers are significantly higher than those of vacuum breakers. The art of operating vacuum breakers in parallel has just recently evolved. The minimum arcing time of the AEG airblast breaker[6] is 90•••500 μs.

Compact designs of SF_6 breakers for high voltage are available. The operating pressure of these breakers is in the range of 4 to 6 bar as compared to 50 to 100 bar for airblast breakers. The cost of an SF_6 breaker is less than that for a comparable airblast breaker. The interrupting current of existing SF_6 breakers is limited to values of approximately 80 to 100 kA (ac symmetrical).

Generator Breakers

The most economical method of frequently interrupting high currents appears to be found in the utilization of generator breakers. These are airblast breakers specially designed to be integrated with the three phase ∿ 36-kV output buses of large station generators. An advantage is the relatively large arc drop resulting from airblast cooling. The 60-Hz short circuit current may not have any zero-crossings if the circuit's L/R ratio is large. This ratio is significantly reduced by the airblast circuit breaker's arc drop with the beneficial result that current-zeros will occur after no more than 10 to 20 cycles.

In the case of current interruption for tokamak ohmic heating, we found that the energy fed into the arc is 3 to 10 J per switch opening. This would cause such small contact erosion that some contacts are estimated to be able to last for 10^4 operations.

Generator Breaker Interaction With Its Counterpulse Circuit

The reflexive effects of the arc resistance on the breaker voltage and current were studied by modeling the counterpulse circuit with a circuit code for the airblast breaker tested at KEMA. The principal parameters of the model circuit were those reported by Dokopoulos and Kriechbaum.[4]

The breaker currents are shown for both cases in Fig. 1. Curve 1 is for constant arc resistance of $10^{-8}\Omega$, and curve 2 is for the changing arc resistance reported by Thuries (1973). It can be seen that the time during which the breaker current is held near zero by the counterpulse circuit is lengthened by approximately 20% as a result of the arc resistance. The breaker current during the time interval $0.14 < t < 0.33$ or 0.35 ms varies between the limits $-5 < I < 1000$ A for case 1 and $9 < I < 1000$ A for case 2. The fact that the current in case 2 is never brought to exactly zero is not significant because a small increase in initial voltage on the counterpulse bank will cause two zero-crossings of the breaker current. The current rise shown in Fig. 1 for times $t > 0.35$ ms will obviously not occur if the arc is cleared as expected.

Another significant point to be made concerns the ohmic energy going into the arc which integrates to 3.4 J at t = 0.2 ms and 10-9 J at t = 0.34 ms. This corresponds to an average power dissipation of 54 kW. These small numbers are responsible for the modest contact erosion observed.

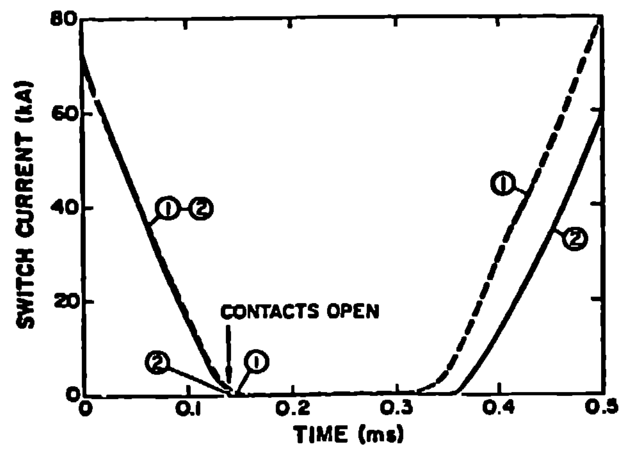

Fig. 1. Switch current versus time.

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