A SOLID STATE DC CIRCUIT BREAKER BASED ON THE GATE TURN OFF THYRISTOR (GTO)*

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Abstract - Design procedures for a d.c. circuit breaker based on the GTO are presented. Because d.c. circuits will contain some amount of inductance, a recovery voltage will appear during interruption due to inductor trapped energy. This voltage must be controlled in order to protect the GTO and other system components. In the circuit breaker designs presented here, the trapped energy is dissipated in a resistors bank or absorbed by a commutation capacitor. It is shown that circuit breaker performance can be improved by adding switched resistors to the breaker design. Optimization techniques are used to determine resistor sizes and switching times which reduce interruption time. A switched RC topology is introduced in which a series capacitor is included with the switched resistor bank to reduce the interruption time to near ideal. This paper presents design, analysis and experimental evaluation of a switched resistor and switched RC circuit breakers.

Introduction

An important component of the power supplies used in particle accelerator or fusion reactor applications is the d.c. interrupter. Since the electrical energy to control and accelerate a particle or initiate a fusion reaction cannot be supplied by the local power utility, the required energy must be built up in the energy storage components of a pulsed power supply. Because these supplies use direct current, an efficient and reliable d.c. interrupter is needed for pulse shaping and d.c. circuit protection. The most common switch used is the vacuum interrupter which is well researched and inexpensive due to its mechanical construction. However, the mechanical nature leads to a high maintenance rate and low reliability. Previous analysis has shown that the solid-state gate turn-off thyristor (GTO) should be more reliable and smaller than a mechanical switch due to a reduction in commutation energy storage requirements. [1]

The objective of this paper is to develop an understanding of d.c. interruption with inductive loads and study possible circuit breaker configurations based on the GTO thyristor. These designs should effect control over transient voltages in addition to current interruption. This is necessary when pulsed power circuits rely on inductors as an energy storage medium and voltage transients must be limited.

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Principles of DC Interruption

In a d.c. system a naturally occurring current zero is not available to produce interruption. Instead, a mechanical breaker will draw an electric arc with a characteristic voltage when the contacts are fully open. This arc voltage is determined by the breaker design and will be greater than the system voltage, as shown in Figure 1, thereby tending to drive the current to zero [2]. The time it takes to interrupt current in this manner depends on the amount of energy stored in the d.c. system. This can be troublesome since the stored energy is always at maximum when the contacts part and must be dissipated in the arc. One method which avoids this is to create an artificial current zero with a counterpulse circuit. This circuit provides a reverse pulse of current to turn the breaker off and the trapped system energy is absorbed by the commutation circuit.

With any method of interruption, the turn off time of the circuit breaker is dependent on the rate of energy extracted from the circuit. To achieve the maximum interruption power, the circuit breaker voltage must be kept as high as possible. One method to develop this power is to open the circuit breaker into a dump resistor. As current decays, larger resistors can be switched into the circuit in order to keep the recovery voltage at a maximum. Another design is a commutation circuit in which a capacitor is placed in series with the switched resistor bank.

DC Circuit Breaker Designs

The circuit breaker design which will yield the shortest interruption time can be obtained by holding a constant maximum voltage across the load inductance. Since the d.c. source is usually small compared to the maximum recovery voltage, the recovery voltage is approximately the voltage across the breaker when it opens. The resulting current can be described by

$$i(t) = -\frac{V_{max}}{L}t + I_0 \quad A. \tag{1}$$

If the breaker voltage is held constant at maximum, the decay of current will be constant and yield the shortest interruption time. Because the current is decaying linearly an expression for a time variable resistance which would result in shortest turn off times is

$$R(t) = \frac{V_{max}}{I_0 - \frac{V_{max}}{L}t} \quad \Omega \tag{2}$$

and a plot of this functions is shown in Figure 1 for I_0 = 15A, V_{max} = 200V, and L = 5mH.

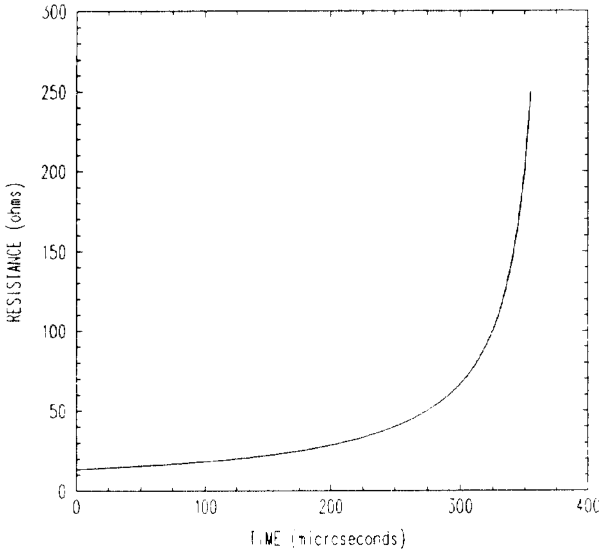


Figure 1 Time Variable Resistance Function

In application, since a continuous switching of an infinite number of resistors is not possible, it is desirable to know how well a set of switched resistors approximates this response. A breaker can be designed in which the recovery voltage can be adjusted by switching a second resistor into the circuit. The new value of resistance is calculated to bring the value of the dump resistor back to the optimum value on the curve in Fig.1 and is dependent on the switching time.

Calculating the optimum switching time is a four-dimensional problem where the turn off time, t_{off} is expressed as a function of the resistor switching time, t_1, and the two resistor values, R_0 and R_1. By writing expressions which identify the levels of current at each switching and taking the level of current at turn off to be 1% of the initial current, the turn off time can be expressed

$$t_{off}(t_1, R_0, R_1) = \frac{L}{R_1}\left[\frac{R_1 - R_0}{L}t_1 - \ln(.01)\right] \quad s. \qquad (3)$$

The turn-off level of 1% was taken as the level of current in which enough energy had been dissipated by the breaker to allow an isolation switch to open. The complexity of equation (3) can be reduced by considering that both R_0 and R_1 are sized to drive current down by imposing maximum voltage across the breaker at the time they are switched in. Since the initial current is known and maximum voltage has been defined, R_0 is found simply by

$$R_0 = \frac{V_{max}}{I_0} \quad \Omega \qquad (4)$$

and R_1 can be expressed as a function of t_1 by

$$R_1(t_1) = \frac{V_{max}}{I_0}\, e^{V_{max}/I_0 L)t_1} \quad \Omega. \qquad (5)$$

With these constraints, the equation predicting the turn off time becomes a function of the switching time only and can be expressed

$$t_{off}(t_1) = \left(1 - e^{\frac{V_{max}}{I_0 L}t_1}\right)t_1 - \frac{LI_0}{V_{max}}[\ln(.01)]\, e^{-(V_{max}/I_0 L)\,t_1} \quad s \qquad (6)$$

where, with the same initial conditions as Fig. 1, the minimum can be seen from the plot in Figure 2.

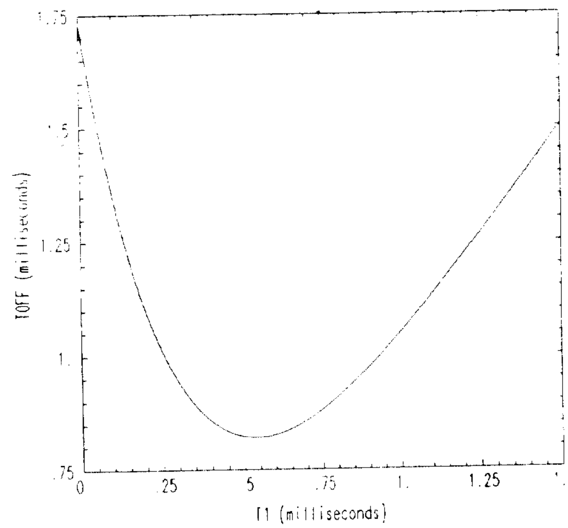


Figure 2 Two-Stage Resistive Breaker Optimization Curve

A circuit breaker configuration which combines the favorable features of the switched resistor bank and a commutation circuit is an RC design. The breaker capacitor will provide for fast commutation of load current and the switched resistor bank will allow control of the circuit breaker voltage, primarily during the initial current interruption. The RC combination can be tuned to provide nearly ideal turn off characteristics and analysis has shown that a series, switched RC design, tuned with the load inductance to exhibit an underdamped response, will yield the shortest turn off time.

The optimization of the switched RC circuit breaker is a complex numerical process. The solution chosen here involved computer simulation of various designs and choosing the design with the shortest interruption time. By simulation of possible designs, the non-optimal best RC configuration chosen was a series underdamped circuit because the recovery voltage of this circuit during current interruption is higher than in other configurations such as a parallel circuit.

Laboratory Tests of Solid-State DC Circuit Breakers

Based on the results of the analysis, a switched resistor circuit breaker and a switched RC breaker were built in the laboratory. The current supply for the test circuit, shown in Figure 3, consisted of a bank of precharged capacitors large enough so that it would not effect the response of the circuit breaker. The

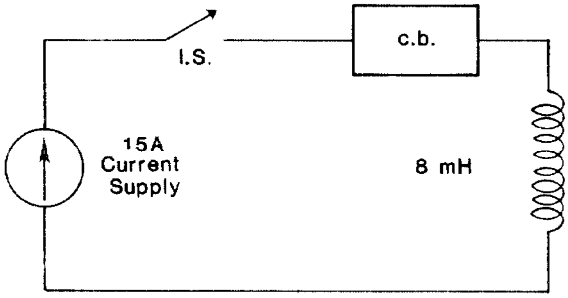


Figure 3 Experiment Test Circuit

isolation switch (IS) is used to decouple the test circuit from the charger. Because the load was assumed to be mostly inductive, an 8mH air core inductor design was wound in which the desired inductance is obtained with a minimum winding resistance [3]. Because the time constant of this coil is large, resonance with the current supply capacitor bank would be very slow and approximate a direct current.

The objective of the experiments was to verify the analytical procedures and compare the performance between circuit breaker designs. These objectives are achieved by using the analytical procedures determine the best design which could be built with readily available hardware, and simulating the circuit response with these values. For analysis, the initial conditions were taken to be an initial current of 15A with a maximum allowable recovery voltage of 200V.

Analysis of the two-state resistive breaker resulted in the optimum and actual circuit breaker configurations in Table 1. The two-stage breaker

Table 1 Two Stage Resistive Breaker Configurations

	R_0	R_1	t_1	t_{off}
OPTIMUM	13.33	55.68	835 us	1.28 ms
SIMULATED	11.54	50.00	845 us	1.32 ms

shown in Figure 4 was built, and placed in the test circuit, and the results are shown in Figure 5.

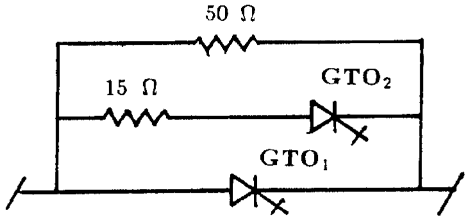
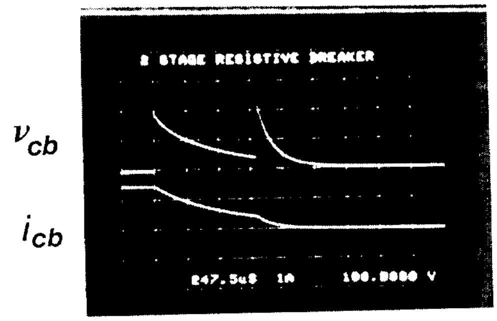


Figure 4 Experimental Two-Stage Breaker Design



V =100 V div, I=10 A div, t =250 μs/div.

Figure 5 Experimental Results of Two-Stage Resistive Breaker Test

The interruption time at 1% of initial current of the test breaker was measured to be 1.455 ms which compares favorable with the expected time of 1.32 ms. It is noted that the breaker voltage at the second switching reaches 250V which is due to an actual circuit resistance of 52.65 at this point. This implies that the test breaker should have interrupted current faster, but this is compromised by an early switching time of 810us and indicates that an optimum t_1 is dominant in providing the fastest current interruption.

The configuration in Table 2 was implemented as the best switched RC design found through analysis and simulations. The switched RC breaker design shown in Figure 6 was built and put in the test circuit.

Table 2 Switched RC Circuit Breaker Configuration

	R_0	R_1	C	t_1	t_{off}
SIMULATED	10.00	20.000	30.00 uf	485 us	615 us

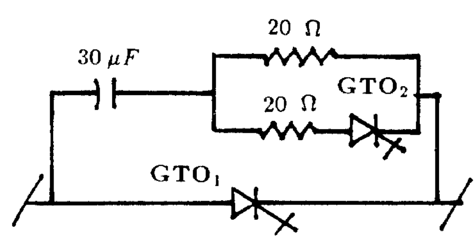
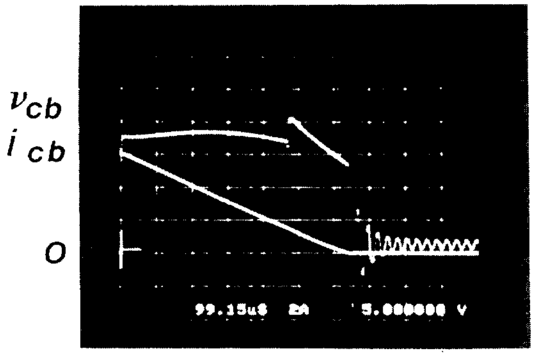


Figure 6 Switched RC Circuit Breaker Design

The experimental results in Figure 7 show that the switched RC breaker is much faster than the switched resistive breaker as expected and exhibits near ideal interruption characteristics. The test results



V = 50 V/div, I = 5 A/div, t = 100 μs/div

Figure 7 Experimental Results of Switched RC Breaker Test

end with an oscillation in the voltage waveform which is due to ringing of the load inductor with the stray capacitance of the SCR used as the isolation switch in the test circuit.

Conclusions

Two dc circuit breaker designs were studied in which the design objective was to make the circuit breaker as fast as possible while limiting the recovery voltage. It was shown that interruption times could be improved in designs which rely on dump resistors by adding switched resistors banks. This circuit breaker would be built from a bank of parallel resistors and at a calculated optimum time, resistors are switched out increasing the overall resistance. This would keep the voltage across the breaker high and reduce the time it takes to dissipate the energy stored in the power circuit. Better results are obtained by a switched RC circuit breaker in which a capacitor is used to speed up interruption times. The switched resistor bank in this circuit keeps the breaker voltage high during the interruption time and shorter interruption results can be obtained. Experimental tests of the two designs confirm the theoretical procedures and show that the switched RC design can reduce interruption time by approximately one-half.

References

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