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EVALUATION OF THE GTO FOR 270 MVA INTERRUPTER APPLICATIONS[†]

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Abstract : The fundamental problem of interrupting a direct current is producing a current zero which will allow for the elimination of current flow. Historically, external circuits have been used to extinguish a plasma (arc) conducting medium by counterpulsing the arc current to zero. Preliminary results show that solid-state dc interrupters utilizing gate turn-off thyristors can provide for reduced capacitive energy storage requirements over vacuum interrupters and SCRs in creating a current zero. Additionally, the hardware required in the gate circuit of the GTO is significantly reduced over the counterpulse circuits in vacuum interrupters and SCRs by taking advantage of the turn-off gain available in the GTO. Interrupters designed around the GTO can have applications in the power conditioning and protection circuits of particle accelerators and fusion reactors.

Introduction

The most common method of interrupting direct current in fusion research and particle accelerator applications is to create an artificial current zero by applying a counterpulse through the interrupting element. However, an alternative has been made available by the development of the gate turn-off thryristor (GTO). Like the silicon controlled rectifier (SCR), the GTO can be turned on by a current pulse to the gate; however, unlike the SCR, the GTO may also be turned off by a negative gate pulse.

This paper will investigate the energy storage and commutation circuit requirements for interruption of direct current in three different breaker schemes using a vacuum interrupter, SCRs, and GTOs. The complexity of the associated circuitry will be compared and research areas will be proposed.

Breaker Switching Elements

Traditionally, the vacuum interrupter has been the switching element used to interrupt large direct currents. Vacuum interrupters are inexpensive and readily available with large VA ratings. Vacuum interrupter technology is well developed and further research into its use in dc applications has resulted in large current capacities and enhanced reliability. Early counterpulse techniques and application of an axial magnetic field to destabilize the arc are two such examples.[1] While the vacuum interrupter provides large ratings with a single device, its duty cycle is restricted by associated mechanical hardware and by physical limitations such as contact erosion. Therefore, it requires maintenance and has a limited lifetime. Also, this is a device originally designed for ac switching and a significant amount of external circuitry is required for its use in dc interruption.

The attention given to solid state devices for use in interrupting high direct currents has centered around the SCR.[2] At turn-on, the SCR is capable of withstanding large di/dt and once conducting has good surge current capabilities and low on-state voltage. For use in fusion reactors and particle accelerators, the SCR has shown promise because it has a longer lifetime, and requires less maintenance than a vacuum interrupter and since a solid-state interrupter is not hampered by the limitations of mechanical actuators, the switching frequency can be much greater if needed. However, because individual SCR device ratings are comparatively small, their use can become expensive in large VA breaker applications.

One of the more recent advances in power semiconductor technology has been the development of the GTO. The GTO is structured similar to the SCR except the gate is designed so that enough charge can be extracted to bring the GTO out of conduction and turn the device off. The GTO possesses characteristics which favor its application in a current interrupter, for instance, the GTO can handle surge currents more than 10 times its current rating and has high power gain which reduces the requirements of the control circuits. As a member of the thyristor family, the GTO is not only characterized by its ability to begin conduction on command but also it possesses a low on-state voltage drop which is necessary to keep conduction losses low.

Turn-on of the GTO is initiated by a positive gate current pulse in the same manner as an SCR as shown in Fig. 1.

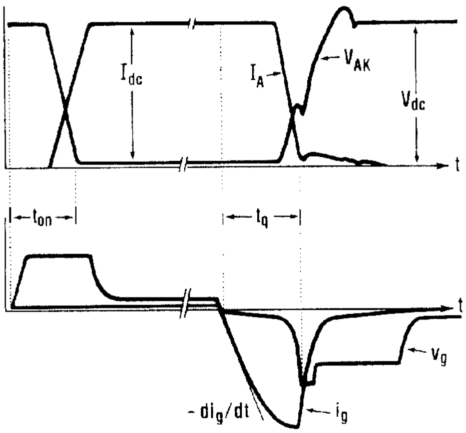

Figure 1: *Switching Characteristics of the GTO*

Given a sufficient turn-on pulse: the GTO will allow a very fast rate of rise of anode current (450 A/μs) and turns on quickly. Application of a negative gate voltage is used to draw current out of the gate and turn the GTO off (Fig. 1). Since the GTO is turned off by removal of sufficient charge, the rate at which the device ceases to conduct is directly proportional to the $-di_g/dt$. A small "tail current" flows from anode to gate after the anode current has fallen to nearly zero. This current is partially attributed to avalanche breakdown in the gate-cathode junction caused by reverse voltage imposed by the gate circuit inductance after the GTO has turned-off. This tail current appreciably increases switching losses and should be minimized.[3]

Commutation Energy Comparison

In commutating direct current in a switching element, most of the energy required in commutation is spent ensuring

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that turn off is complete by providing ample time for the elimination of excess carriers so that restrike does not occur. The commutation energy must be stored, usually in capacitors, so that it may be used as desired or needed. This capacitive commutation circuit contributes significantly to breaker complexity. A good measure of the relative complexity of the commutation circuit is to compare the capacitive energy storage requirement for the various alternative switching elements. This analysis compares the energy storage necessary to interrupt 2000 A using a vacuum interrupter, an SCR, and a GTO as the switching element. The operational capacitor voltage was assumed to be the voltage rating of the device being studied.

The circuit in Fig. 2(a) is used to determine the turn-off energy requirement for the GTO. The response of this circuit is shown in Fig. 2(b). It is assumed that when the GTO comes out of conduction, it turns-off instantly because the resulting avalanche breakdown does not affect load current. The largest GTO presently available is a Hitachi Model No. GFP2000B25 which has a voltage rating of 2.5 kV and a current rating of 800 A_{RMS}. The maximum controllable current specification, or peak current which can successfully be interrupted, is 2000 A for this device.[14]

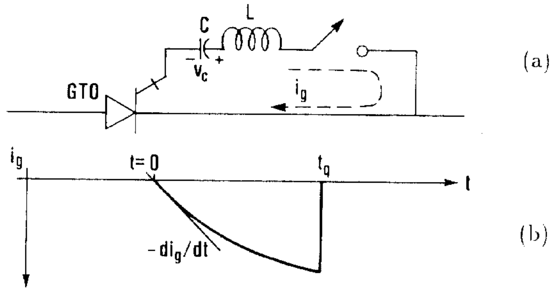

Figure 2: *GTO Turn-off*

From the response of the gate circuit as shown in Fig. 2(b), the gate current can be described as

$$i_g(t) = v_c(C/L)^{1/2}\sin(LC)^{-1/2}\,t;$$

where i_g is the gate current, v_c is the gate capacitor voltage, C is the gate capacitor, and L is the gate inductor. In the gate circuit, the conditions for turn-off are a maximum $-di_g/dt$ of 16A/μs which allows for a specified turn-off time of 35 μs. The turn-off gate charge is specified as 10 mC. The equations which describe the turn-off response are

$$di_g/dt|_{t=0} = V_{co}/L = 16 \times 10^6 \text{ A/s},$$

$$\int_0^{t_q} i_g dt = CV_{co}[1 - \cos((LC)^{-1/2}35 \times 10^{-6})] = 10^{-2}\text{C},$$

where V_{co} is the initial gate capacitor voltage and t_q is the GTO turn-off time. If the initial gate capacitor voltage is chosen to be 16V, which is the rated reverse gate voltage, the element values of inductance and capacitance can be determined as

$$L = 1\mu\text{ H} \quad \text{and} \quad C = 667\mu\text{ F}$$

From this the capacitive energy storage requirement will be

$$E_c = \tfrac{1}{2}(667 \times 10^{-6})(16)^2$$
$$E_c = 85 \times 10^{-3}\text{J}$$

The circuit in Fig. 3(a) is used to analyze the energy requirements to counterpulse a vacuum interrupter. The waveforms in Fig. 3(b) show the ideal commutation capacitor voltage and current if it is assumed that the current rises instantaneously. This assumption is made since the actual fall time of current, 1-3 μs, is much smaller than a deionization margin of the interrupter, t_q, of 20 μs. Since no manufacturer's data is available on the dc properties of vacuum interrupters, these data have been obtained by experimental methods.[5] This assumption is further enhanced if the saturable reactor, L_s, is assumed to be ideal with an inductance of 0 when saturated and ∞ inductance when in the active region. The vacuum interrupter studied is a Westinghouse Model No. WL23332 which has a voltage rating of 15.5 kV and a current rating of 600 A_{RMS}. The interrupting capacity of this vacuum bottle is 2000 A.

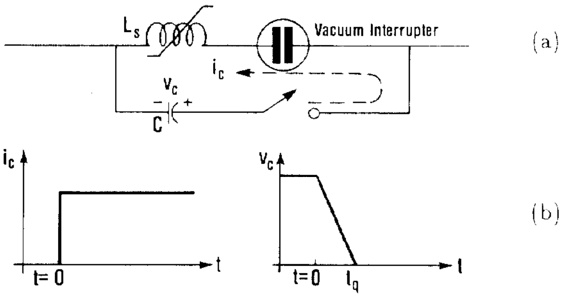

Figure 3: *Vacuum Interrupter Commutation*

With i_c being the commutation capacitor current, v_c the commutation capacitor voltage, C the commutation capacitor, an initial voltage, V_{co}, equal to rated interrupter voltage and a constant load current, the commutation capacitor can be sized

$$i_c(t) = C dv_c/dt = C\, V_{co}/t_q$$
$$2000A = C\ 15.5 \times 10^3/20 \times 10^{-6}$$
$$C = 2.5\mu\text{ F}$$

The total energy for turn-off would necessarily include the energy required for the opening actuator of the interrupter. It was taken that a 500 μF capacitor charged to 1000 V would be used to part the interrupter contacts. The total turn-off energy can be found

$$E_c = \tfrac{1}{2}[(2.5 \times 10^{-6})(15.5 \times 10^3)^2 + (500 \times 10^{-6})(1000)^2]$$
$$E_c = 310 + 250\text{ J}$$

Any energy dissipated in keeping the contacts open is not included because turn-off has already occurred.

The circuit in Fig. 4(a) shows the SCR as the switching element of a dc breaker. The commutation circuit is similar to the circuit chosen to counterpulse the vacuum interrupter except that the saturable reactor is removed and an inductor, L, is included. Figure 4(b) shows the voltage and current waveforms of the commutation capacitor when the fall time of the interrupted current is much smaller than the turn-off time of the SCR. Because the switching frequency is of no concern here, a General Electric phase control SCR Model No. C784 is chosen for the analysis. This SCR has a voltage rating of 4300 V, a current rating of 2120 A_{RMS}, a one cycle surge capacity of 25 kA, and a specified turn-off time of 200 μs.

In an analysis similar to the vacuum interrupter: sizing of the commutation capacitor is based on the assumption that the capacitor will be precharged to the voltage rating of the SCR. For this circuit: the commutation capacitor will be

$$C = 2000/21.5 \times 10^{-6}$$
$$C = 93\mu F$$

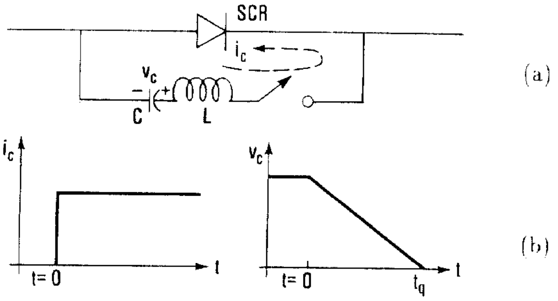

Figure 4: *SCR Commutation*

The total energy storage requirement will be

$$E_c = \tfrac{1}{2}(93 \times 10^{-6})(4300)^2$$
$$E_c = 860 \text{ J}$$

The foregoing three case studies show that for the given conditions of 2000 A_{dc} and rated switch data, the GTO requires far less capacitive energy to interrupt the direct current. Furthermore, the turn-off circuitry for the GTO is at the electronic voltage level and can fit on a small circuit board whereas the large counterpulse circuitry for the SCR and vacuum interrupter is on the high power side of the circuit.

It is apparent that it is the gain provided by the gate of the GTO which allows for the greatly reduced turn-off circuitry. This can be physically realized because the energy to turn-off the GTO is only required to be sufficient enough to extract a charge necessary to bring the device out of conduction. Whereas the counterpulse circuit is required to store more energy because it must not only produce a current zero very quickly, it must also hold a reverse bias across the switching element long enough for the device to regain forward blocking capabilities.

270 MVA Interrupters

Even though the GTO is easier to turn-off, its device rating is small when compared to vacuum interrupters available for applications in nuclear experiments. In order to use the GTO in these applications, several devices must be combined and it is desirable to know how this will affect the advantage of using a GTO. For this study, the GTO will be compared against a 270 MVA vacuum interrupter which is a size more commonly used.

The vacuum interrupter to be compared is a Westinghouse Model No. WL34121 which has a voltage rating of 15 kV and an interrupting capacity of 18 kA. The continuous current rating for this interrupter is 2000 A_{RMS}. For the commutation circuit and waveform of Fig. 3(a) and (b), the capacitor can be sized

$$C = 18 \times 10^3/750 \times 10^{-6}$$
$$C = 24\mu F$$

and the stored energy required for interruption is

$$E = \tfrac{1}{2}(24 \times 10^{-6})(15 \times 10^3)^2 + (500 \times 10^{-6})(1000)^2$$
$$E_c = 2700 + 250 \text{ J}$$

In order to utilize the SCR described earlier as a switching element for nuclear experiments, many of the devices must be used in combination. To meet the voltage requirements, the module must consist of 4 of these SCRs in series. Only one branch will be needed for this SCR module to have the same continuous and surge current capacity as the vacuum interrupter. In this case, the commutation capacitor must be

$$C = 18 \times 10^3/75 \times 10^{6}$$
$$C = 240\mu F$$

The energy storage requirement is therefore

$$E = \tfrac{1}{2}(240 \times 10^{-6})(15 \times 10^3)^2$$
$$E_c = 27 \text{ KJ}$$

Nine branches of six series Hitachi GTOs would be needed for a module the size of the Westinghouse vacuum interrupter. This would result in a stored energy requirement of 5 Joules needed to interrupt current in a 270 MVA module if a separate gate circuit is supplied for each GTO.

Even though it is seen that the GTO is much easier to switch off and the associated hardware is simpler, the application of the GTO to a large VA interruper is not very well researched. The use of GTOs in series and parallel constructions would require voltage and current equalizing circuits. These circuits can be designed to work equally well on turn-off as well as turn-on. Furthermore, gate circuit complexity of the multi-GTO module can be simplified.

Conclusions

The stored energy requirements and commutation circuit complexity of breakers based on the GTO are greatly reduced, as opposed to force commutated SCRs or vacuum interrupters. A dc interrupter based on any one of these switching elements will probably have additional components, not considered in this paper, which depend on the power circuit. Although the ratings of available GTOs are improving rapidly, their use in the large VA switching requirements of particle accelerators and other nuclear experiments demands that several of the devices be connected in series and parallel constructions to provide the capacity available from a vacuum interrupter. The design and operation of these circuits are currently a topic of research at Texas A&M. University.

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