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The Role of Semiconductor Devices in High Power Circuit Breaker Applications

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Abstract: - The role of power semiconductor devices in high power circuit breaker applications are discussed. Different types of Conventional electromechanical Circuit Breakers (CCBs) are reviewed and summarised with the main associated problems highlighted. The use of solid-state devices as a replacement for CCBs is presented and their use in parallel with the CCBs to eliminate the arc is illustrated in a single- phase model Hybrid Circuit Breaker (HCB).

Key Words: - Power Devices, Thyristors, GTO, IGBT, Circuit Breakers, Hybrid Circuit Breaker

1 Introduction

The growing demand for electricity has resulted in a corresponding increase in power generated and transmitted. The increase in installed capacity may result in high fault currents. Circuit breakers were developed to protect circuits against faults. They are required to control electrical power networks by switching circuits ON, carrying load currents and switching circuits OFF, to isolate them with manual or automatic operation.

Conventional circuit breakers, CCBs (Air blast, Oil, Sulphur Hexafluride etc) have been used for a long time for interruption of fault currents. Because of the thermal and electrical stresses inherent in opening and closing of conventional circuit breakers, such breakers have traditionally been very large and expensive devices, requiring expensive maintenance after a number of switching operations. Arcing which occurs across the contacts during interruption of fault current can damage contact electrodes and restricting nozzles [1]. For this reason conventional circuit breakers require frequent inspection and expensive maintenance. The problem of arcing becomes very acute for breaker applications where high switching frequency is required such as conveyor drives, inching and reverse operations, industrial heaters, test beds etc.

In the last few decades a great progress has been achieved in the performance characteristics of conventional circuit breakers (CCBs) in respect of their voltage ratings, breaking capacities and speed of operation. In spite of that, the basic principle of conventional electromechanical circuit breaker technology has changed very little in more than 50 years. The main reason for its continuing popularity is its good reliability.

In this paper, different alternative solutions to the arcing problems encountered in circuit breakers are given by employing power semiconductor devices as the main breakers, or in conjunction with the CCBs forming Hybrid Circuit Breakers (HCBs).

2 Mechanical Circuit Breakers-Moving Contacts

2.1 Requirements

There are three basic requirements that a circuit breaker must meet:

2.1.1 It must conduct service load currents with minimal power loss.

2.1.2 It should be capable of fast transition to its blocking state without damaging itself in the process.

2.1.3 It must block any current from flowing when it is open, despite the high voltage across its terminals.

The conventional mechanical circuit breaker gives excellent results for the first and third of these requirements, but it could fail in the second due to transient conditions of the switching circuits.

2.2 Types of Traditional Circuit Breakers

2.2.1 Air-Break Circuit Breaker (CB): This type of breaker operation depends on the transfer of the arc to large splitter plates where the arc is extended in air until it collapses. The main problem with this CB is the huge size.

2.2.2 Air-Blast CB: It is constructed in such a manner that its contacts are of a fixed tubular construction with a moving rod pushed down through the middle to complete the contact. On opening, a blast of air is forced into the breaker to blow out the arc. An interlock is built into the system to ensure the breaker does not open when there is low air pressure. The main problem with this CB is the large size and possible mechanical failure.

2.2.3 Sulphur Hexafluoride (SF_6) CB: This type is similar in principle to the air-blast CB except that instead of compressed air, SF_6 gas is used. Because of the use of this gas a requirement is needed not to blow the gas out into the atmosphere but back into the system. This need for a gas tight construction, not only increases the difficulty of maintenance, but also increases the complexity and cost of the device.

2.2.4 Oil CB: The main contacts are immersed in oil to reduce the size and cool the arc. The main problem is the risk of explosion and fire.

2.2.5 Vacuum CB: The idea behind this type is that putting the contacts in vacuum, there is no ionisation gas to form arc plasma. The main problems are the production and maintenance of a high vacuum and the problem of contact bounce and welding together, as no oxide films forms in vacuum.

Looking at the various types of circuit breakers, the problems of arcing and maintenance immediately spring to mind. Also the size, cost and reliability are other important factors that need looking into. Engineers have speculated for many years about the possibility of replacing the existing conventional circuit breaker designs with new designs using semiconductor devices.

3 Solid-State Circuit Breakers

Over the last few years, power semiconductor devices have evolved to a point where a single device can carry few thousands of Amps and can block few thousands of Volts. The feasibility of using semiconductor devices for circuit breaker applications was examined by many workers [2, 3, 4]. Other applications for these devices in power electronic systems include Electric Traction Systems, High Voltage Direct Current Schemes (HVDC), Static VAR Compensators etc.

Semiconductors switching devices have many advantages which include fast switching operation (High frequency applications) and low maintenance. Due to the absence of moving parts there is no arcing, contact bounce or erosion. Recently, considerable progress has been made in the development of low power solid-state breakers for AC and DC applications [2, 3, 4]. The main disadvantage of the solid-state breaker is the high thermal losses generated by the continuous load current.

Electronic switching devices, such as thyristors and GTO's, always have a voltage drop across their terminals resulting in heating through the I^2R Loss. The amount of heat depends on the current. As the current increases, this drawback start to mount and large heat sink becomes a necessity. At very high currents, the electromechanical breaker remains firmly established, with no short-term likelihood that the solid-state breaker replacing it. But electronics still has a role to play and hybrid form of switch has emerged which marries the advantages of both, see Fig.1 and Fig.2.

4 Hybrid Circuit Breaker

In hybrid circuit breaker [5] the continuous current is handled by the conventional breaker, whereas the make and break processes are handled by power semiconductor devices (thyristors, IGBTs, etc…) connected in parallel with the breaker contacts. When switching on, the semiconductor devices are fired first, these carry the inrush current and prevent arcing. As soon as the main contacts close, the contact resistance is lower than the resistance of the semiconductors, and consequently the current will commutate to the contact path. The continuous current is now carried by the breaker with negligible losses.

On disconnection, the semiconductor devices are fired and the current will again pass through the semiconductors because the resistance of this current path is lower than the resistance of the arc path. Again the arc will almost be eliminated and the semiconductors will eventually block the voltage.

A single-phase hybrid model circuit breaker has been designed, constructed and demonstrated using thyristors [5].

Similar work with using Insulated Gate Bipolar Transistors (IGBTs) instead of thyristors in the Hybrid Circuit Breaker (HCB) has been done and results are presented in figures (3 – 9). The main power handling limitations here are the maximum current and voltage ratings of the devices in parallel with the conventional breaker.

Figures (1 and 2) shows the HCB circuit layout and block diagram of the whole system. Figures (3, 4, and 5) shows the CB feeding different type of loads without the parallel IGBT, and the effect of arcing is clearly evident on the voltage waveform. Figures (6, 7, and 8) shows the corresponding cases with IGBT in parallel with the CB. It can be clearly seen that the arc has been eliminated and no noise present on the voltage waveform.

5 High Power Hybrid Circuit Breaker

For these applications, devices need to be connected in series (for high voltage) and in parallel (for high current).

In series operation of power semiconductor devices the important issue is to maintain equal blocking voltage sharing among devices in the series string during the steady state as well as during the transient state. Since voltage unbalance is due to device parameter spread and gate drive delays, careful selection of devices which has low parameter spread and synchronising gate drive signals will minimise the problems associated with the series connection. In practical situations this is rather impossible and therefore different mitigation techniques have been developed for different power devices.

Successful paralleling of devices requires care and adequate de-rating due to variations in device characteristics and circuit layout. It cannot be assumed that parallel connection of N devices, each with current rating of R amps will have a combined current rating of NR amps.

Further details of problems encountered in series and parallel applications are given in references [6] and [7] respectively.

6 Conclusion

Arcing is one of the main problems with conventional circuit breakers. The main advantage of using semiconductor devices in circuit breaker applications is that the effect of arcing could be eliminated completely. This leads to other major improvements which include reduction of size and weight, improved speed of operation, reduction of pollution and improved efficiency. For high power HCB, several series/parallel combinations of power semiconductor devices will be needed in parallel with the CCB.

Safe disconnection of supply voltage requires the need of isolators as usual. The main disadvantage is the short circuit failure mode of IGBTs and thyristors. Therefore proper design and protection and inclusion of redundant devices will be essential.

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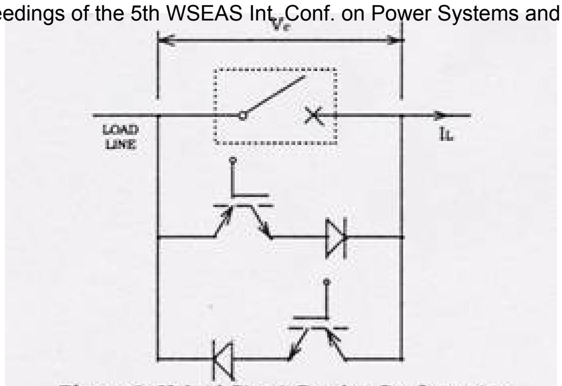

Figure 1: *Hybrid Circuit Breaker Configuration*

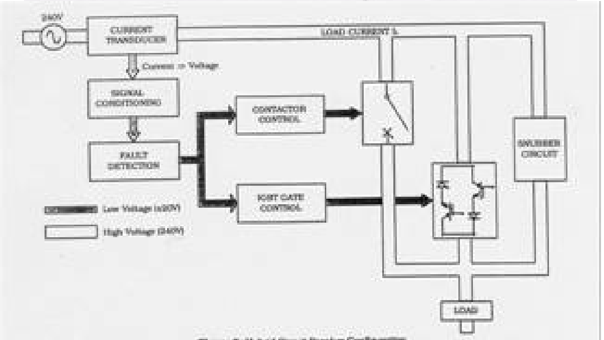

Figure 2: Hybrid Circuit Breaker Configuration

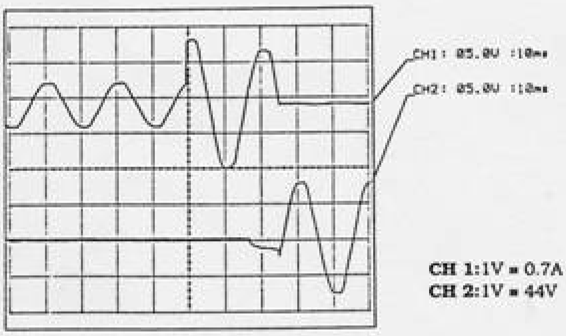

Figure 3: *Fault Interruption of Resistive Load without IGBT's*
Channel 1: Load Current IL
Channel 2: Voltage Across Circuit Breaker VC

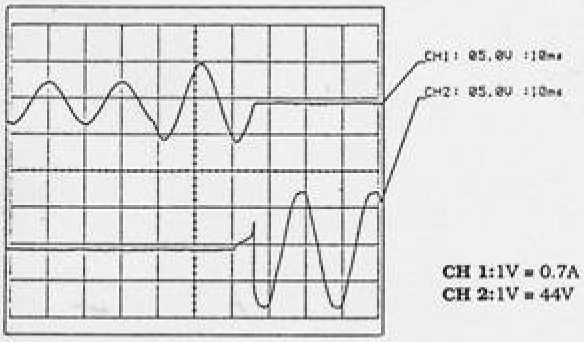

Figure 4: *Fault Interruption of Inductive Load without IGBT's*
Channel 1: Load Current IL
Channel 2: Voltage Across Circuit Breaker Vc

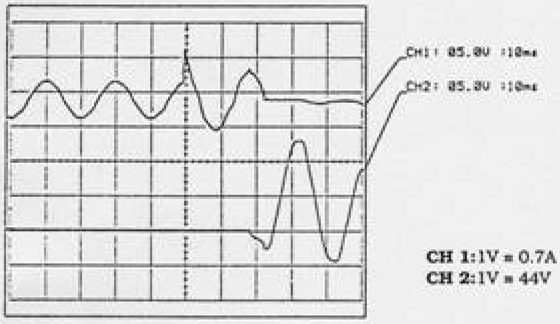

Figure 5: *Fault Interruption of Capacitive Load without IGBT's*
Channel 1: Load Current IL
Channel 2: Voltage Across Circuit Breaker Vc

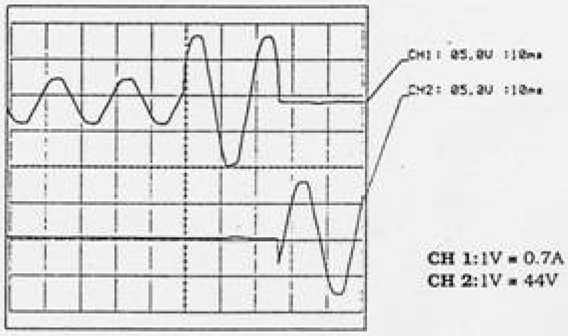

Figure 6: *Fault Interruption of Resistive Load with IGBT's*
Channel 1: Load Current IL
Channel 2: Voltage Across Circuit Breaker Vc

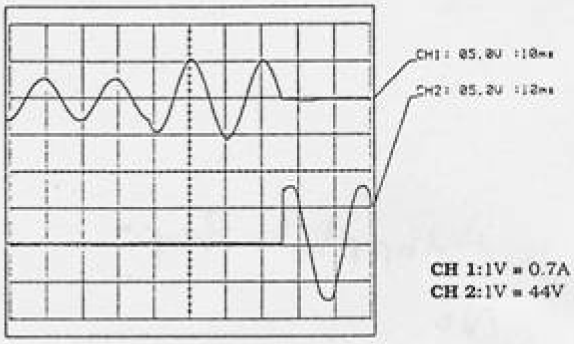

Figure 7: *Fault Interruption of Inductive Load with IGBT's*
Channel 1: Load Current IL
Channel 2: Voltage Across Circuit Breaker Vc

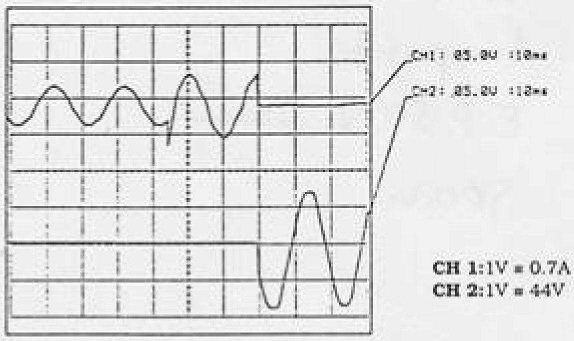

Figure 8: *Fault Interruption of Capacitive Load with IGBT's*
Channel 1: Load Current IL
Channel 2: Voltage Across Circuit Breaker Vc

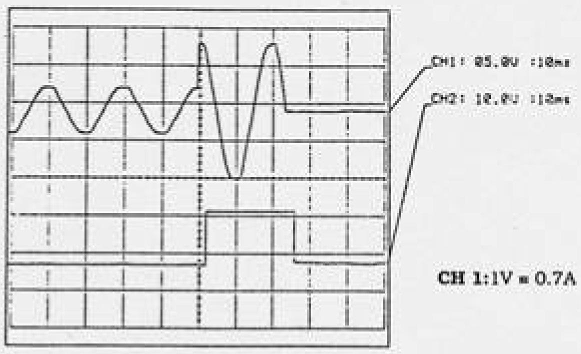

Figure 9: IGBT Gate Pulse on Fault Interruption
Channel 1: Load Current I_L
Channel 2: Gate-Emitter Voltage V_G