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Z SOURCE DC CIRCUIT BREAKER

Shubham Gayakwad[1], Aniket Bagal[2], Amol Dimble[3], Ganesh Khochare[4], Prof. S.D. Babar[5]

BE, Student Department of Electrical Engineering, Navsahyadri Education Society's group of institution Faculty Engineering, Naigaon, Pune[1,2,3,4]

Assistant professor, Department of Electrical Engineering, Navsahyadri Education Society's group of institution Faculty Engineering, Naigaon, Pune[5]

Abstract: A Z-Source series circuit breaker topology, which allows bi-directional power flow, and has the ability to autonomously disconnect DC faults is introduced. This topology allows current flow in the forward and reverse directions through the use of a diode bridge. The diode bridge allows response to faults on either the source or load side with only a single controlled switch. No additional passive components are required when compared with the unidirectional series Z- Source circuit breaker topology. Analysis is performed to find the fault conditions that cause the bi-directional circuit breaker to trip when operating in a single load power system. Then, using the hardware simulation platform, operation of the bi-directional circuit breaker is evaluated for both source and load side faults. To experimentally validate the findings, an experimental prototype has been implemented. This prototype is used to confirm the circuit breaker's function in both the forward and reverse directions in addition to its response to source side faults.

Keywords: *DC circuit, SCR , DC*

I INTRODUCTION

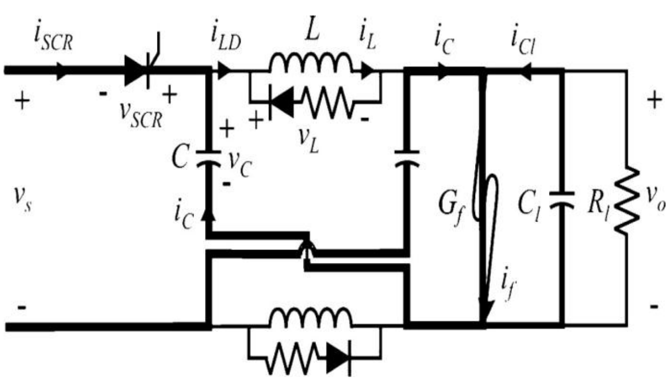
Inadequate protection options for direct current circuits restricts growth in the DC distribution field. Interruption of current flow in DC circuits is more difficult than in AC circuits due to the absence of a natural current zero crossing. Conventionally, DC circuit protection is implemented by: 1) Single blow fuses which require replacement following each fault 2) Use of over-sized and overrated AC circuit breakers to draw and extinguish an arc on one or both poles of the DC circuit which is often cost prohibitive 3) Solid State circuit breakers which result in substantial on-state power consumption by the semiconductors 4) Hybrid DC circuit breakers that combine a mechanical switch and solid state switches to reduce power consumption, but can be quite complex The Z-Source circuit breaker is proposed to force a DC current zero crossing with an impedance network to cause current fluctuation and isolation from the voltage source with a power thyristor. However, recent developments in fast mechanical switches facilitate opportunity for replacement of the solid-state switch. Mechanical switches can be robust, do not require cooling, and do not consume significant power in the circuit. Therefore, replacement of the solid state thyristor with a fast-mechanical switch reduces losses within the Z-Source DC circuit breaker RECENTLY, there has been a trend towards using direct current (DC) in power systems. Applications being investigated are: electric ships [1], high-voltage DC (HVDC) networks [2], micro-grids [3], [4], datacenters [5], battery energy storage [6], and wind farms [7]. However, viability of applications that use medium voltage DC (MVDC) is limited by current DC circuit breaker technology. Protection of low-voltage DC (LVDC) systems is commonly achieved using arc-based circuit breakers (ACBs). However, DC systems lack a natural zero-current crossing, which in- creases the difficulty of extinguishing the arc generated when the ACB opens [8]. Thus, as voltage and fault current in- crease, the size and cost of such ACBs become prohibitive. Thus, medium-voltage DC (MVDC) systems require a novel solution. Power electronic circuit breakers (PECBs) are an alternative to ACBs, which use semiconductors rather than mechanical switches. The series and parallel connection of semiconductor devices provides scalability. This allows PECBs to operate in MVDC systems, which operate at higher voltage and fault current levels than are feasible for ACBs [9]. Additionally, PECBs can limit fault currents, due to their high operating speed [10]–[12]. Although PECBs provide these advantages, they require additional sensing and control circuitry, have power loss in the semiconductor junctions, lack galvanic isolation, and have low fault current capability. Thus, there has been significant research effort to address these issues. In order to increase the efficiency of PECBs, use of custom silicon [13] or wide band-gap semiconductors [14]–[17] has been investigated. However, currently the availability of these semiconductor devices is limited, particularly at high. Background of

1.1 Fast Mechanical Switches and SCR

Advances in fast mechanical switches make way for the ability to achieve millisecond-switching times while providing negligible on-state resistance, effectively eliminating on-state power consumption. This is an incredible improvement from conventional electromechanical circuit breakers that operate on the order of 40-80 milliseconds to the SCR switch time scale of 1-2 milliseconds.

1.2 CIRCUIT BREAKER DESIGN

To ensure that resonant Z-Source circuit breakers could be replicated in the mechanically switched world, first a prior art Z-Source circuit breaker was analyzed to replicate circuit dynamics. Following development of the timing sequence and system dynamics, the thyristor in the traditional Z-source breaker was replaced with a SCR. Also, an additional source inductor was placed in series to gain necessary time interval between current zero crossing in the event of a fault and to replicate realistic circuit characteristics. The energy storage components (inductors and capacitors) used in a z-source circuit breaker dictate the system dynamics .They lead to the resonant current ripple during fault conditions which provides the zero crossing that is necessary for isolation. The system was implemented in simulation, analytical assessment and finally in test bench prototype testing as described throughout this section.



A traditional solid-state dc circuit breaker uses an auxiliary SCR in series with passive resonant elements in order to reverse bias the main switch . This auxiliary SCR must be actively gated when a fault is detected and must reverse bias the main switch before the fault current exceeds the turn-off capability of the main switch. Another SCR is used to reset the capacitor for the next turn-off cycle. Hence, with the traditional circuit, detection and timing are critical. However, the novel z-source dc breaker has unique features when compared to the traditional method. Namely, they are as follows.

1) Fast operation since the z-source dc breaker operates with natural commutation. The fault is first cleared by the operation of the z-source circuit and then the control is applied.

2) The control circuit is simplified. Instead of requiring a circuit to detect a fault, the control circuit only needs to detect that the SCR has commutated off or that the current has dropped below a certain level.

3) The source and SCR will not experience the fault path current.

4) Cascaded breaker coordination is inherently automatic .If two z-source breakers, each supplying a load, are connected in series, only the one closest to the fault will switch OFF.

5) Fault current may be limited by the impedance of the z-source breaker, making the system more fault tolerant.

6) The z-source circuit can be modified with bidirectional devices (or possibly integrated gate-commutated thyristors) and crowbar circuitry for bidirectional power flow and controlled switching.

7) The z-source breaker can be combined with power electronic converters to build fault handling into the converter. The following sections introduce the new z-source breaker and detail its operation and analysis.

II Z-SOURCE DC CIRCUIT BREAKER AND OPERATION

This research begins with the introduction of a novel dc circuit breaker, which is shown in Fig. 1. Therein, the z-source breaker consists of an SCR, a crossed *LC* connection, diodes, and resistors as indicated in the dashed box. The system load is represented by the *RC* circuit consisting of *Rl* and *Cl* . A fault is depicted by the conductance *Gf* .The z-source *LC* connection was initially suggested as a novel type of inverter input circuit [7]. Since its introduction, the z-source inverter has been modeled and analyzed extensively for a number of applications [8]–[20]. One of the unique features of a z-source inverter is that it can operate in boost mode, as well as the standard buck mode. The boost comes about because the z-source allows another state wherein the inverter can short circuit its dc bus. Herein, this feature is adopted for fault handling in MVDC power systems. When the fault occurs in this system, there is no direct short of the capacitor voltages, because of the inductors in the z-source circuit.

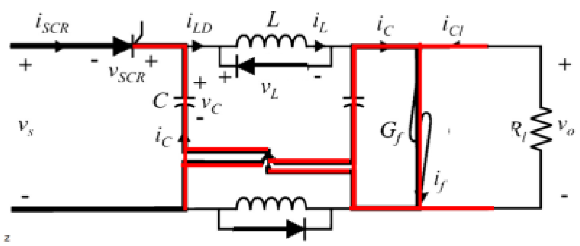
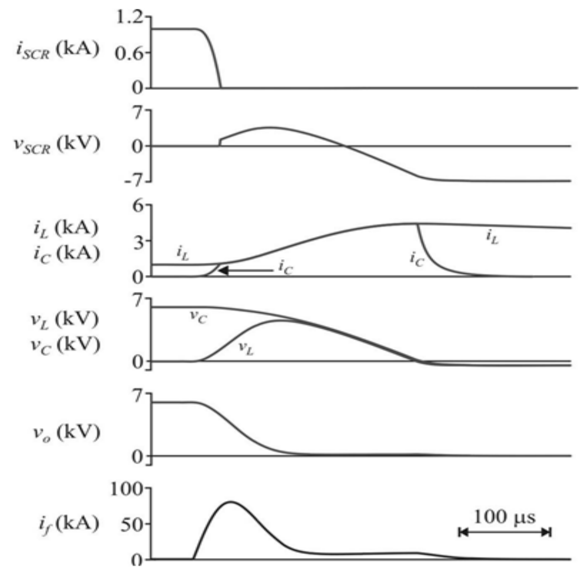


Fig Conduction Path of Transient Fault Current

The breaker components act together to quickly mitigate faults in a dc system. When a fault occurs at the output of a z- source breaker, current sources into the fault from the downstream system capacitance Cl as well as from the z-source capacitances as shown by the fault conduction path in Fig. 2. The full set of waveforms during the fault are shown in Fig. 3. In this system, the source voltage vs is set to 6 kV and the load is set for 6MW (Rl = 6Ω). The system is operating in the steady state and the fault conductance is ramped from 0 to 50 S. The operation of the z-source circuit can be understood by considering the current path shown in Fig. 2. A portion of the fault current will come from the z-source breaker capacitances. In the transient state, the inductor keeps the current iL constant as seen in Fig.

3. The conduction path is then through the z-source capacitors and back to the source as shown in Fig. 2. Therefore, the capacitor current iC is seen in Fig. 3 to increase until it matches iL . At this point, iSCR will go to zero causing the SCR to commutate off. A simple circuit can then detect that the SCR has switched OFF, removing the gate voltage from the SCR. After the SCR switches OFF, the z-source components are configured as two-series LC branches connected to the load and fault. These circuits start a resonance where they are supplying the fault, but since the source has been disconnected and the fault impedance is low, the output voltage collapses to zero. By Kirchhoff's voltage law (KVL), with the output voltage at zero, vL must be equal to vC . In Fig. 3, it can be seen that the inductor and capacitor voltages become equal when the output voltage goes to zero. Also, by KVL, it can be shown that when these voltages reach half of the source voltage vs , the SCR will become forward biased.

Therefore, the time when vSCR is positive is the amount of time available for the control circuit to remove the gate pulse and the SCR to undergo its reverse recovery transient. The resonance continues until the inductor voltage attempts to go negative. At this point, the diode will turn ON. The current in the capacitor will switch OFF and the current will continue in the inductor/diode/resistor loop until it decays to zero. It can also be shown by KVL that since the inductor voltage does not go negative, the SCR voltage will not go above the source voltage. Fig. 3 also shows the source current iSCR immediately going to zero when the fault occurs, as desired. After the SCR goes OFF, the fault has successfully been isolated.



PROTOTYPE SETUP

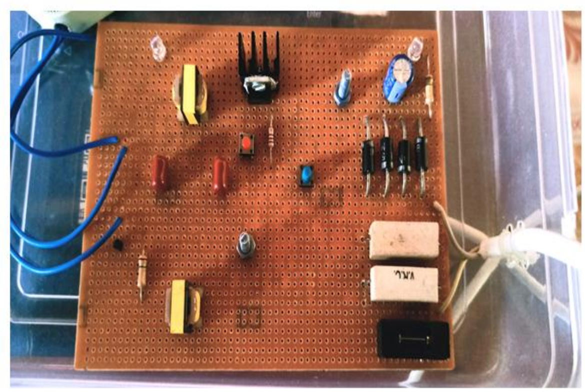


Fig Setup realization of the proposed prototype: SCR, Capacitor, Inductor

III CONCLUSION

In this paper, the z-source dc circuit breaker has been modified to incorporate tolerance to step change in load and bi-directionality. An external control has also been developed for coordinating multiple z-source breakers. The new developments were studied using simulation of star- and ring-connected power systems with a view towards medium-voltage dc ship power systems as an application. The simulations demonstrate that certain types of faults are automatically isolated by the z-source breaker and others are effectively isolated by the coordinated control.

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REFERENCES

[1] IEEE Paper by Daniel Ryan received a BE (hons.) in Electrical and Computer Systems engineering in2015, from Monash University, Melbourne, Australia. Currently, he is pursuing a PhD. at Monash University. His research interests include protection of DC power systems, grid integration of energy storage, and power system dynamics and control.

[2] D. Ryan and Bahrani are with the department of electrical and computer system Engineering, Monash University, Melbourne3800, Australia

[3] H. Torresan is with the defense science and Technology Group, Melbourne 3207, Australia