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An Isolated Voltage Injection Based Hybrid Circuit Breaker for MVDC Applications

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***Abstract*— A MVDC hybrid circuit breaker (HCB) is proposed in this paper that consists of an electro-mechanical switch (EMS) in series with a voltage injector building block (VIBB). The VIBB-HCB does not employ any semiconductor devices in the line current path and utilizes a magnetic structure for injecting purpose that is unbiased in the normal operation, not interfering in line power path and without loss except the negligible winding copper losses. The EMS is being opened under zero voltage and zero current which makes the structure more reliable and the design of energy absorber easier. The injection circuit is isolated from the line. Hence, any surge or fault current does not impact the injection circuit. Also, by employing full bridge in the auxiliary converter, bidirectional fault clearing option is achieved for the proposed structure. Further, the design does not require large pre-charged capacitors for interrupting the fault. The proposed concept is validated through Finite Element Analysis, followed by experimental verification on a scaled down hardware prototype.**

Keywords*— Hybrid Circuit Breaker (HCB), Voltage Injector Building Block (VIBB), Pulsed Power, Integrated Magnetic Structure.

I. Introduction

MVDC distribution and transmission have performance advantages over their AC counterparts as the generation footprint moves from centralized (burning fossil fuels) to decentralized power stations (making use of renewable energy sources). Fault currents in MVDC systems rise much faster than those in AC systems. Adding controller, time delays for fault identification and tripping result in interrupting very high DC currents that do not have zero-current crossings. Therefore, isolating faulty sections in MVDC quickly is necessary for ensuring system integrity, especially in multi-terminal systems.

MVDC breakers can be broadly divided into electromechanical circuit breakers (ECB), solid state circuit breakers (SSCB) and hybrid circuit breakers (HCB). Both SSCBs and HCBs have higher initial cost than their ECB counterpart for a given power level. ECBs have the highest efficiency in comparison to SSCBs and HCBs, but they suffer from long response time and poor lifetime. SSCBs have the lowest efficiency but offer fast response and longer lifetime. The lower efficiency is due to the significant losses in the normal operation as semiconductor devices are connected in series with ECB in the main DC line. HCBs offer trade off characteristics between fast response time and low loss [1], [2]. Table I includes the comparison of the performance of few prominent MVDC breakers.

Among the existing protection solutions, HCBs are the most common implementation and is approaching to the point of commercialization. HCBs consist of three parallel branches as shown in Fig. 1. (in some structures the secondary and tertiary branches are combined in a single branch [7]). The primary branch contains the isolating mechanical switch. The secondary branch contains the power semiconductor devices, which have blocking capability of the main DC line voltage. The tertiary branch is the energy absorption branch, which contains varistors such as MOV. During normal operation, the line current flows through the primary branch. When fault occurs, the isolating switch is being opened and during fault, the semiconductor branch is triggered and brought in the circuit. This causes the current to commutate to the secondary branch. The transient recovery voltage that appears during fault interruption is snubbed by the tertiary branch.

However, the structures proposed still face some challenges like non-isolated injecting/blocking branch, using large pre-charged capacitor as an energy source for injection, losses in normal operation and turn off of EMS under high current or voltage [3]. Features of a desirable HCB includes low or zero impedance during normal operation; ability to handle different levels of fault current or alleviate the transients of the system; high reliability, and fast response [8]. In this paper, a VIBB- based HCB structure is proposed that engulfs these characteristics. In HCBs proposed in [8-11], there are semiconductors in the line path in series with EMS to alleviate the arc caused by opening the EMS, causing significant conduction losses in normal operation thereby reducing the efficiency of the system. Besides, the main branch requires water cooling system. However, the HCB structures presented in [10] and [12] do not have semiconductors in series with line, they suffer from the insertion of the injection winding in the line path which changes the system behavior and incurs both winding losses and core losses. In the topology proposed in this paper, the injection winding is connected in series with the line, but it does not impact the performance of the system.

TABLE I. Performance Comparison of MVDC Circuit Breakers

Reference	Technology	Rated Voltage (kV)	Loss	Response Time (ms)
[3]	SSCB (Fault Isolation Device Generation II)	12.47	High (472 W at 50A)	0.1
[4]	HCB	20	Low	10
[5]	SSCB	10	High	0.01
[6]	Proactive HCB	80	Low	5

In addition to this, the isolation of the injection circuit from the line is a prominent feature which makes the proposed structure reliable in comparison to the topologies with non-isolated injection circuit in [7] and [13-15] or having secondary branch including semiconductors as a path for the commutated current ([9] and [11]). In the proposed topology the injection of power or alleviating the transients of the system by injecting required amount of current is possible. However, this will not be possible with the structures using pre-charged capacitor in the secondary branch ([12] and [14,15]).

Further, in all literatures except [10], at first, the EMS is opened. After that, the secondary branch or injection circuit is energized to quench the spike of the energy produced due to interruption of high DC current. Also, the voltage stress of the parallel branch is across the EMS during normal operation in structures which use pre-charged capacitor [12] and during post-current interruption in structures which use external injection circuit [7]. Hence, the opening of EMS happens neither at zero current nor zero voltage. However, in the proposed structure, the EMS is in series with the injection circuit. It is configured to open when the current flowing through it is zero. Therefore, EMS operates under both zero current and voltage. Further, although in [10], the injection circuit is in series with line, it is not isolated from the line and the series inductor causes losses and change of behavior in the normal operation.

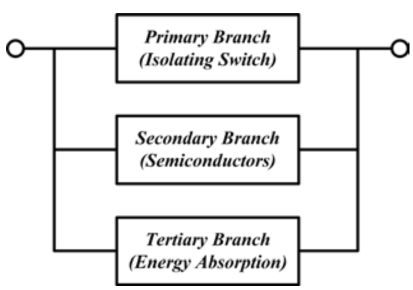


Fig. 1. Generic HCB block diagram

In the rest of the paper, the proposed VIBB-HCB structure is first introduced. Then, the operational modes are discussed, which is followed by the simulation and hardware results.

II. VIBB-HCB Structure

A new concept for HCB is proposed, which doubles as a voltage regulator and a fault current limiter. It retains high efficiency by only using an EMS in the main commutation loop (Fig. 2). It contains an auxiliary circuit that uses a voltage injector building block (VIBB), driven by low-voltage power semi-conductor devices. No semiconductor device is connected in series in the line, resulting in ultra-low losses during normal operation.

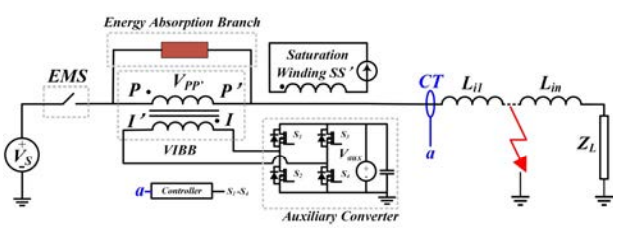


Fig. 2. Schematic of the proposed VIBB-HCB.

The VIBB's secondary winding is connected in series with the EMS and the primary winding is connected to a low-voltage, high-current auxiliary converter. Under normal operation, current flows through the EMS and the voltage-injecting winding. Only minor copper losses are expected due to the canceled flux in the proposed core structure. During fault, the auxiliary converter provides a high-current pulse to the secondary winding, quickly generating a grid-supporting voltage in opposite direction of the DC source voltage at the voltage-injecting winding in series with the fault. Fault current amplitude can be controlled by controlling this grid-supporting voltage so that the current from the DC source side can be quickly reduced to zero and EMS can be opened. With no semiconductor devices in series with the EMS, the overall loss under normal operation is low, and fault isolation does not require high-voltage devices. The proposed VIBB-HCB can realize both grid control and circuit breaker functions, making it an integrated DC grid solution. Furthermore, due to zero current and voltage, the transients during opening of EMS are less severe, simplifying the design of the energy absorption branch.

III. VIBB Structure And Operation

The key part in the proposed HCB is the magnetic structure of the VIBB. Since, the nominal line current flows through secondary winding of VIBB, the core is biased, and it lowers the voltage injection capability due to less B-H curve swing available for the core. As a result, the injection time decreases, and a simple two-winding transformer type of structure is not suitable. This can be exemplified through a simple toroidal injector transformer in which secondary side is connected in series with a normal DC line having a fault current i_F (Fig. 3).

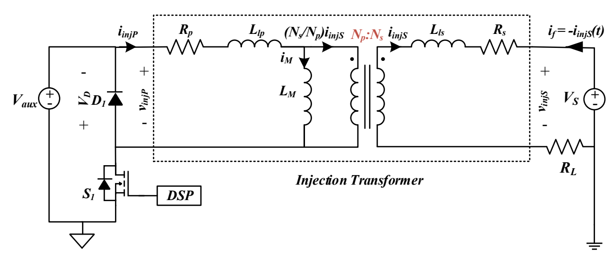
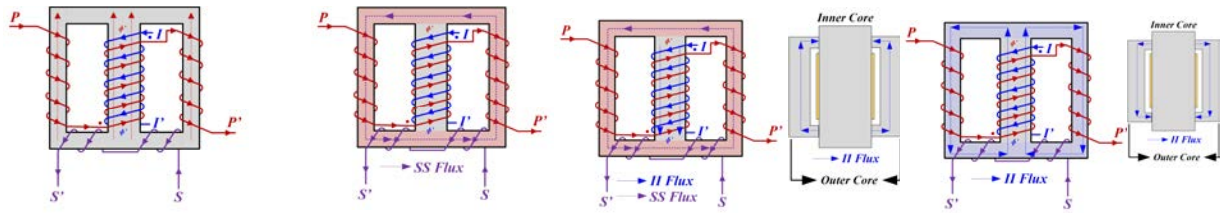


Fig. 3. Equivalent circuit for a simple two-winding transformer

As fault current flows through the secondary winding, the core is biased with magnetic field intensity H_{bias}. When the switch S_1 is turned ON, a current is injected in the secondary winding. The injection will continue till the core is saturated. The saturation occurs when the total magnetic field intensity is equal to H_{sat}. As the core is biased, the injection time T_{inj} is reduced with net magnetic field intensity $(H_{sat} - H_{bias})$. For a toroidal core with mean effective path length L_e, the injection time can be approximated as:

$$T_{inj} = \frac{L_M(H_{sat} - H_{bias})L_e}{V_{aux}N_p} \quad (1)$$

Since H_{bias} is dependent on the fault current profile, there is a chance that fault current biases the core with $H_{bias} = H_{sat}$. In this case, the injection time will be zero and fault cannot be interrupted. Instead the excessive fault current can heat up the windings and the core. To overcome this issue, a new magnetic structure is proposed for VIBB. The VIBB is



a) Normal state b) Fault State 1 c) Fault State 2 (Front and Side View) d) Fault State 3 (Front and Side View)

Fig. 4. Operational states of the proposed VIBB

consists of two E-shaped cores, which form the inner core and two U-shaped cores that form the outer core, surrounding the center limb of the inner core (Fig. 4(c)). The inner core contains three windings: PP', SS' and II'. The PP' winding is wounded on both side limbs and center limb of the inner core with equal number of turns. It is connected in series with the main DC line. The II' winding is wounded on the center limb and is connected to the auxiliary converter. The SS' winding is used to saturate the outer part (side limbs and yokes) of the inner core.

Four operational states of VIBB and corresponding waveforms of EMS and all three windings are shown in Fig. 4 and 5, respectively. In normal state, the fluxes generated by the main DC line current flowing through PP' winding gets cancelled in the inner core and the net flux is zero. Hence, VIBB behaves like a normal conductor, without affecting the dynamics of the external circuit. Also, the core is unbiased and whole B-H curve is available for injection, leading to smaller size of the core. When fault occurs, the VIBB operates in three states. In the first state (t_1 to t_2), fault is sensed by the controller, SS' is energized to saturate side limbs and yokes of the E-core which inhibits the induction of voltages in the side limb windings of PP' as they are in deep saturation. The VIBB then enters state 2 (t_2 to t_4) where voltage is injected into the center limb winding of PP' through II' winding. The outer core that surrounds the center leg provides a path for injection flux to flow. As the injection proceeds, the current falls and reaches zero. The EMS is then being opened. Finally, the last state (t_4 to t_5), involves resetting of the outer core and absorption of residual energy by the absorption branch in circuit.

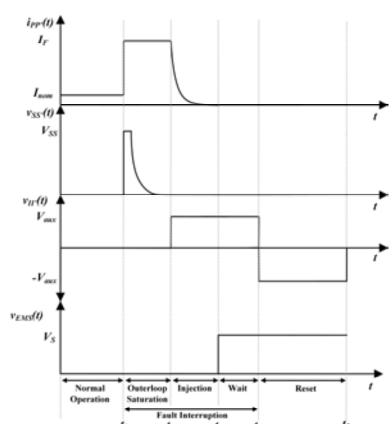
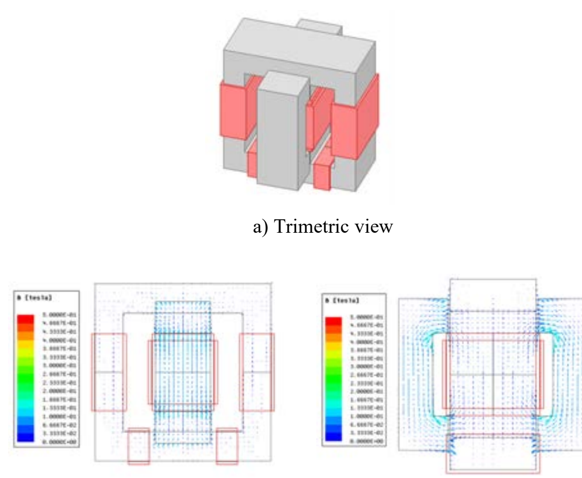


Fig. 5. VIBB Waveforms

IV. Simulation Results

A transient simulation is performed in Ansys Maxwell for low voltage and current prototype. The core material chosen is N87 from TDK with $B_{Sat} = 490\ mT$. A fault current of 5 A with DC voltage equal to 40 V is considered for the simulation. The simulated structure and the flux distribution in normal operation is shown in fig. 6. During normal operation, the flux produced by the nominal current gets cancelled and the core is not biased. The flux in both the inner and outer core is negligible and the core behaves like a common-mode choke.

The transient simulation results are shown in Fig. 7. The first, second and third subplot contains the individual limb voltages of PP' winding; total voltage of PP' winding, which is the sum of all PP' winding legs, and PP' winding current, respectively. The SS' winding is energized at $t = 0\ \mu s$ to saturate the outer limbs of the inner core. This is followed by injection through II' windings at $t = 20\ \mu s$ and the fault current falls to zero. During injection, no voltage is induced in the side limbs as they are in deep saturation and only center limb has voltage induced. The injection flux flows through the outer core (Fig. 8). The EMS can be opened at any instant after current falls to zero.



a) Trimetric view

b) Normal Operation (Front View).

c) Normal Operation (Side View).

Fig. 6. Simulated structure and flux distribution during normal operation

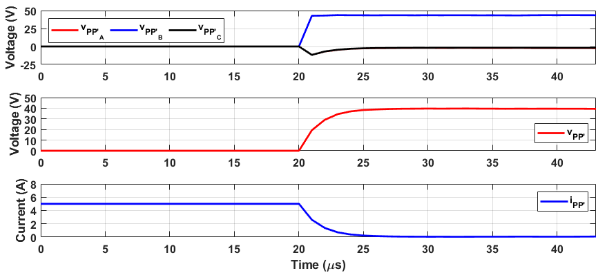


Fig. 7. Transient simulation results

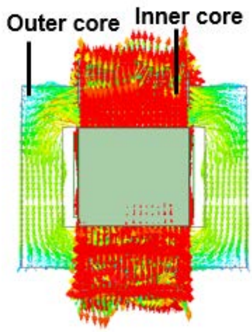


Fig. 8. Flux distribution during injection (side view)

V. Hardware Prototype Testing

To verify the effectiveness of the proposed VIBB on hardware, a low voltage prototype is developed and tested. The specifications of the prototype are given in Table II. The inner and outer cores are composed of N87 ferrite from TDK and are constructed using two E-cores (B66344G0000X187) and two U-cores (B67362GX187) as shown in Fig. 9. The N87 ferrite material has a saturation flux density B_{Sat} of 490 mT at 25 °C. The auxiliary converter is built using SiC half-bridge evaluation board from CREE (KIT8020CRD8FF1217P-1).

TABLE II. Prototype Specifications

Parameter	Value
DC Voltage	30V
Fault Current	2.75 A
PP' Turns	9 (Side limbs)
II' Turns	9 (Center Limb)
SS' Turns	9

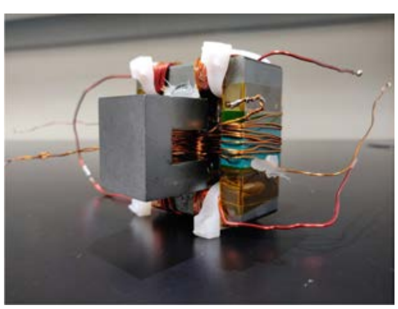


Fig. 9. VIBB prototype

The fault is emulated using a DC supply and a power resistor with secondary side of VIBB connected in series. The control signals are generated using DSP. For prototyping, the energy absorption branch is realized using a RC snubber. The fault interruption test results are presented in fig. 11. The fault clearing process starts with energization of SS' winding. A constant current of 5 A is injected through the SS' winding. The voltage across the SS' winding drops and decays to zero, indicating that the outer loop of the inner core is saturated. Excitation is then applied to the II' winding, a voltage equal and opposite to the main DC line voltage is generated across the terminals of the PP' winding. The opposing voltage causes the fault current to fall quickly to zero. The EMS is opened after 35 μs. The fault is cleared and the voltage across the EMS rises. The total fault clearing time is around 200 μs, which can be further be decreased by optimizing the structure of VIBB to achieve less leakage inductance.

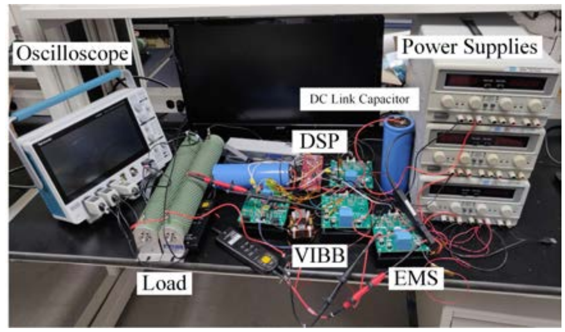


Fig. 10. VIBB-HCB test setup

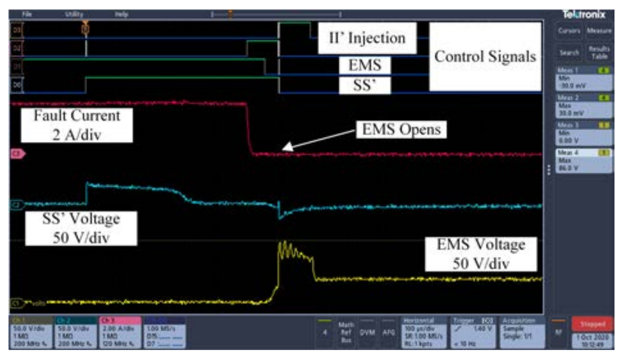


Fig. 11. Fault interruption test results

VI. Conclusion

HCBs have become optimum choice for protection in MVDC applications. They combine the advantages of less conduction loss in ECBs and fast fault interruption in SSCB. A MVDC HCB based on voltage injection is presented that does not require any power semiconductor devices in series in the line. The VIBB core is not biased during the normal operation, leading to smaller size of the magnetics and negligible losses during the normal operation. Further, the zero voltage and zero current operation of EMS, bidirectional fault clearing capability, isolation of the injecting circuit and line and no pre-charged capacitor requirement are other merits of the proposed VIBB-HCB.

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