

The Commutation Booster, a New Concept to Aid Commutation in Hybrid DC-Breakers

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SUMMARY

The difficulty in interrupting DC currents lies in the lack of a natural current zero crossing. In an AC-breaker, the current is interrupted by separating the contacts to draw an electric arc. When the current naturally goes to zero, the arc is extinguished and the current is interrupted. For DC, the current zero has to be forced by the breaker. Hybrid solutions with mechanical switches and power semiconductors have been proposed to combine low conduction losses with the ability to force a current zero.

This paper presents the commutation booster, a new concept to interrupt the current in a hybrid DC-breaker. In hybrid breakers, with parallel paths for the mechanical switch and semiconductor, the commutation from the mechanical switch to the semiconductor relies on the arc-voltage of the mechanical switch and a low stray inductance in the commutation loop. In a hybrid breaker with the commutation booster, the inductance is used to perform the commutation. The newly introduced advantage is that a fault current automatically leads to current zero crossings in the mechanical breaker, allowing it to interrupt the current in similar ways as an AC-breaker.

By inductively coupling the primary branch containing the mechanical switch with the secondary branch containing the semiconductors, the rising fault current is used to enhance the commutation. As the inductance in the secondary branch is kept lower than in the primary branch, the current will rush through the semiconductors in case of a fault. The natural behaviour of an inductor to preserve the magnetic flux will decrease the current in the primary branch and ensure a fast commutation.

The benefit of a hybrid breaker with the commutation booster is the lower demands on arc voltage. Since the commutation is ensured by the inductive coupling provided by the booster, the mechanical switch doesn't have to provide a high arc voltage and instead it can be optimized to interrupt the current in the same way as a conventional AC-breaker. The inductively driven current commutation will be faster the faster the rise of the fault current is. Hence, as long as the breaker is dimensioned to handle the commutation at nominal current, the operation will be faster with a lower fault impedance.

KEYWORDS

DC-breaker, hybrid breaker, commutation, inductive coupling

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DC-BREAKERS

If a DC current is assumed to flow through some inductive elements, it becomes hard to interrupt. Unlike an AC-system where the current crosses zero two times each period, the DC current has no natural zero crossings and has to be forced to zero by the breaker. This can be obtained either by a counter voltage across the breaker [1] or by causing an oscillation in the current larger than the DC current [2]. In both cases, the magnetic energy stored in the current carrying inductor has to be dissipated to demagnetize the circuit.

Power semiconductors have excellent switching capabilities making them attractive for use in DC-breakers [3]. However, they cannot provide the desired counter voltage for a sufficiently long time without destructively overheating. If the semiconductor is connected in parallel with a non-linear resistor in the form of a metal oxide varistor (MOV), both objectives can be fulfilled.

The other drawback of the semiconductors is the high on-state losses due to the inherent voltage drop of the semiconductors that are not as good conductors as metals. One possible solution to decrease the losses is to bypass the semiconductor with a mechanical commutation switch than can carry the nominal current with low losses and rapidly open to commutate the current into the semiconductor when the current is to be interrupted. The circuit diagram of such a parallel hybrid DC-breaker is shown in Figure 1.

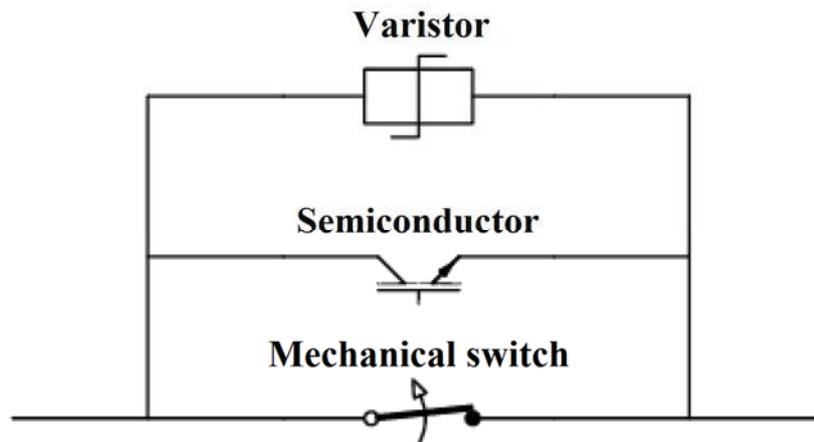


Figure 1: Basic layout of a hybrid DC-breaker where the nominal current is carried with low losses by the mechanical switch. When desired, the current can be commutated into the semiconductor branch where it is interrupted. The inductive energy in the circuit is absorbed in the Varistor.

The main idea of using the parallel hybrid configuration is to utilize the switching capabilities of the semiconductor without the high on-state losses. Hence the nominal current will flow only through the closed contacts of the mechanical switch. Figure 2 shows the typical shape of the currents in a hybrid DC-breaker when interrupting a rising current provided by a stiff DC source.

Before t_0 the nominal current, limited by the system or the load, flows through the mechanical switch. At t_0 the resistance in the circuit is suddenly decreased. The current starts to rise, limited by the inductance and remaining resistance of the circuit. The fault will be detected and the mechanical switch is triggered to open. The contacts of the mechanical switch separate at t_1 , causing an electric arc and hence a counter-voltage to appear in the primary branch. Due to the arc, the current will commutate over to the secondary branch containing the semiconductors. When the current in the primary branch reaches zero at t_2 , the arc will cease and the open switch will prevent any current to flow. The semiconductors carry the current for a short period to ensure that the plasma from the arc cools down and the dielectric strength of the mechanical switch is recovered. At t_3 the semiconductors are turned off and the current is forced into the MOV branch. This commutation is very fast due to the switching speed of modern power semiconductors. The MOV will provide a counter-voltage across

the breaker that is higher than the feeding voltage. Hence the magnetic energy is dissipated, the current decreases and reaches zero at t_4 .

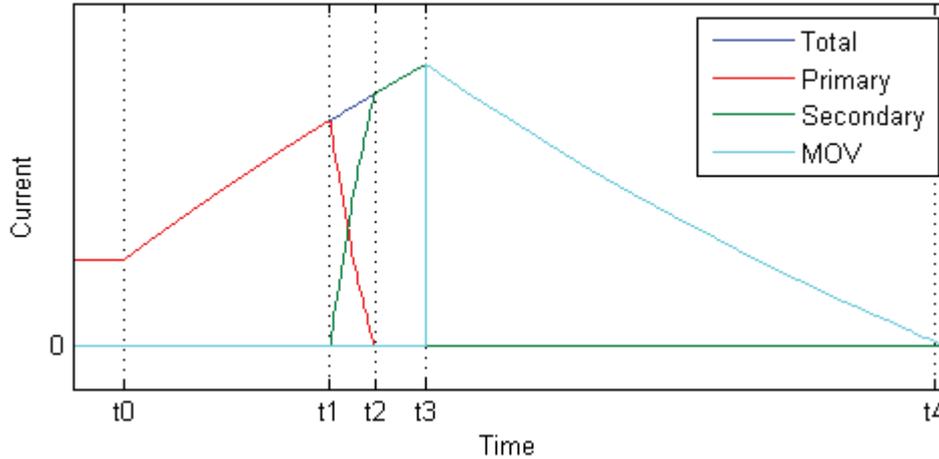


Figure 2: The three step interruption of the current in a hybrid breaker. At t_0 the resistance is suddenly decreased and current starts to rise. The mechanical switch opens at t_1 supplying an arc-voltage that will commute the current over to the semiconductor branch. The semiconductor carries the full current at t_2 to allow the mechanical switch to regain full insulation strength before turning off at t_3 . The current is rapidly forced into the MOV branch where the magnetic energy is absorbed and the current is forced down to zero.

The commutation from the mechanical switch to the semiconductor branch will be driven by the arc voltage between the open contacts and opposed by the forward voltage drop of the semiconductor. The speed of the commutation will be determined by the undesired stray inductance in the loop. Considering only the loop of commutation, the commutation can be described as

$$U_{arc} = U_{semiconductor} + L_{stray} \frac{di_{semiconductor}}{dt} . \quad (1)$$

Generally the arc voltage and the semiconductor conduction voltage are small compared to the source voltage and hence the main current will be unaffected by the commutation. It can be seen that for a fast and successful commutation, the arc voltage should be higher than the forward voltage drop of the semiconductor and the stray inductance should be kept low. As the semiconductor voltage drop also increases with the rising current, the mechanical switch should open fast enough to perform the commutation before the current rises too high.

Figure 3 shows the currents in a hybrid breaker where the commutation from the mechanical switch to the semiconductor fails due to insufficient parameters. The arc voltage is high enough to perform the commutation for a nominal current, but not for the higher fault current. As the contacts separate, the arc starts the commutation as expected but is limited by the stray inductance. Since the commutation is too slow, the rising current increases the voltage drop across the semiconductor to a level higher than the supplied arc voltage. Before a current zero is obtained in the mechanical switch, the current starts to rise again. At this point a large part of the current is still flowing through the arc of the mechanical switch and an interruption will not be possible.

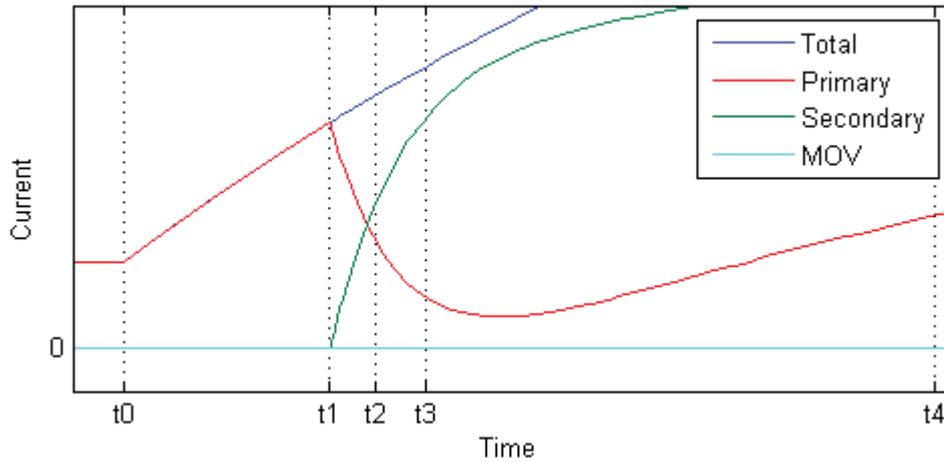


Figure 3: If the combination of arc voltage, stray inductance and semiconductor forward voltage drop is not sufficient, the commutation from the mechanical switch to the semiconductor branch will fail. As the fault current increases, there is no possibility to interrupt the current.

THE COMMUTATION BOOSTER

The newly introduced concept of the commutation booster [4] uses coupled inductances between the primary and secondary branches of the hybrid breaker to aid the commutation in the case of a fault. As the current rises, the rapid rise of current in the secondary branch will force the current in the primary branch to decrease and hence a natural zero-crossing will occur in the mechanical switch. The schematic diagram of the commutation booster is shown in Figure 4.

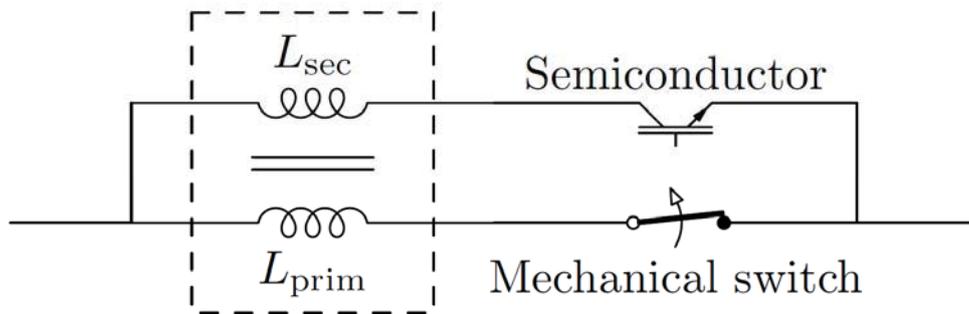


Figure 4: Outline of the commutation booster connected to a primary branch with a mechanical switch and a secondary branch with a semiconductor switch.

The commutation booster consists of two inductors wound on the same core so that the magnetic flux from the two inductors aligns. One end of the two inductors are connected together to one side of the breaker and the other ends connect to the semiconductor and mechanical switch respectively. The inductance of the secondary branch is smaller than the primary so that if a voltage is applied across the set-up the current would initially rush in the secondary branch.

The main idea behind the commutation booster is that an inductor will strive to preserve the magnetic flux. When a voltage is applied and the current starts to rush through the semiconductor in the secondary branch, the magnetic flux in the core will increase. A negative voltage will then be induced in the primary coil to decrease the current and oppose the increase in magnetic flux. If the rise of current and the coupling between the two inductors are high enough, the current in the primary coil will be reversed and cause zero-crossings in the mechanical switch.

SIMULATION MODEL

The hybrid breaker with commutation booster has been evaluated with a simulation model in MATLAB where several differential equations are solved numerically. The model is limited to a simplified network fed with a constant DC-source as shown in Figure 5. A resistance is connected in series to limit the current and a series inductor limits the rise of the current. On the opposite side of the breaker circuit, there is a load resistance that can be bypassed to cause a fast increase in the current. The forward voltage drop of the semiconductor is modelled as a constant voltage and a resistive component and the arc voltage is simplified to a constant voltage. The values of the circuit parameters are varied to give schematic graphs that show the principal behaviour.

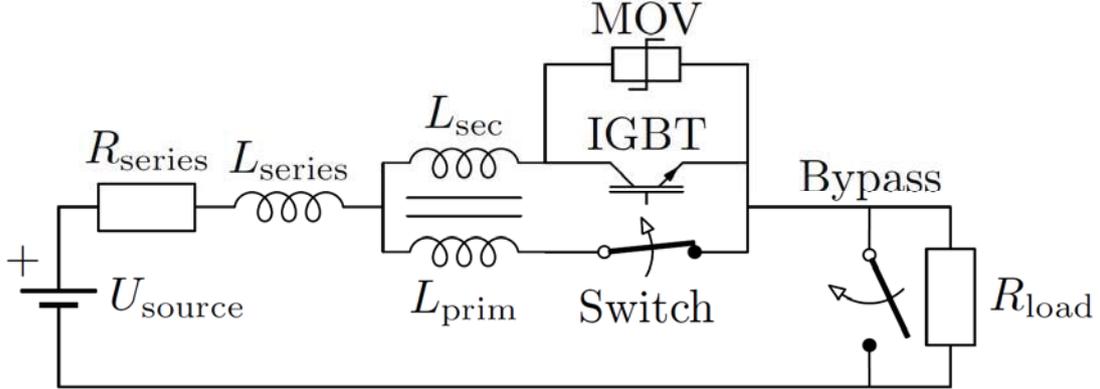


Figure 5: When evaluating the breaker topology, a simple set-up with a battery in series with a resistance and an inductor has been considered. The load resistance can be bypassed to simulate a transient case where the current rapidly rises.

The DC-circuit in Figure 5 shows an ideal case for interrupting an inductive DC-current. The relationship between the voltages and currents in the circuit can be easily set up as

$$(L_s + L_{prim}) \frac{di_{prim}}{dt} + (L_s + M) \frac{di_{sec}}{dt} = U_s - R_s (i_{prim} + i_{sec}) - U_{switch} , \text{ and} \quad (2)$$

$$(L_s + M) \frac{di_{prim}}{dt} + (L_s + L_{sec}) \frac{di_{sec}}{dt} = U_s - R_s (i_{prim} + i_{sec}) - U_{semiconductor} , \quad (3)$$

where it has been assumed that the load resistance is bypassed. The indices indicate the currents and impedances in the source, primary, and secondary branches respectively.

SIMULATION RESULTS

Figure 6 shows the interruption of a rising current by a hybrid breaker with the commutation booster. Even though the semiconductor is kept in conducting state, all current before t_0 will be conducted through the primary branch due to the lower resistance compared to the semiconductor. As the current rise is triggered at t_0 , the current will start to rush mainly through the low-inductive secondary branch. To oppose the magnetic flux in the core due to the increased current in the secondary branch, the current in the primary branch will decrease. At t_1 , the fault has been detected and the contacts of the mechanical switch will open. Even though this provides an arc-voltage, the commutation is still mainly controlled by the inductances, as seen in the graph. As the current in the mechanical switch reaches zero at t_2 , it is interrupted and the current is fully carried by the semiconductor. Just as in a hybrid breaker, the semiconductor is turned off at t_3 and the energy is absorbed in the MOV until it reaches zero at t_4 .

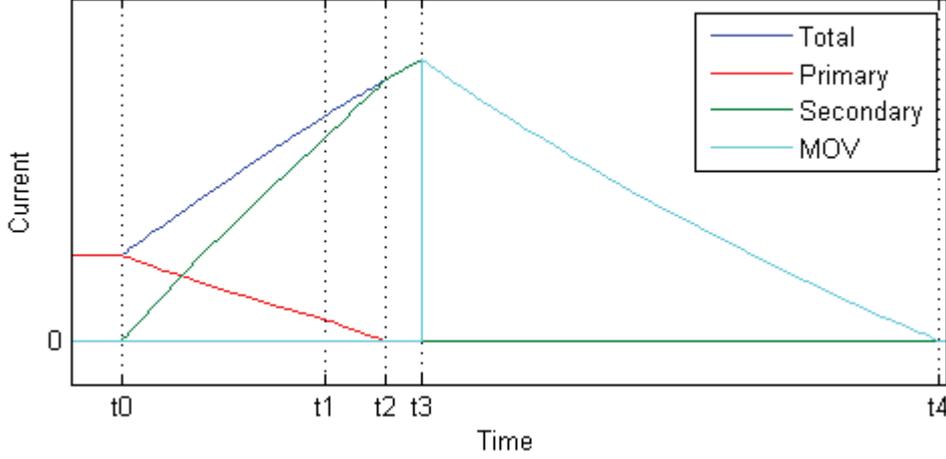


Figure 6: The interruption of a rising DC current with a hybrid DC-breaker equipped with the commutation booster. At t_0 , a fault is introduced causing the current to rise rapidly. Due to the rise, the inductive coupling of the commutation booster forces the current into the semiconductor branch. As the fault is detected, the mechanical switch is opened at t_1 and the current is interrupted at the first current zero. The main current now flows through the semiconductor branch and is interrupted as in a solid state breaker at t_3 .

Some limitations on the circuit parameters can be identified. One important aspect is the ratio between the primary and secondary inductances and the mutual coupling between them. As the inductance L_{sec} in the secondary branch should be lower than the inductance L_{prim} in the primary branch, it can be written $L_{sec} = \alpha L_{prim}$, where $0 < \alpha < 1$. By manipulating the equations (1) and (2) and considering the commutation loop between the primary and secondary branch it can be shown that to obtain a decreasing current in the primary branch, the inductors in the commutation booster has to fulfil

$$\alpha < k^2, \quad (4)$$

where $k = M / \sqrt{L_{prim} L_{sec}}$ is the coupling factor.

Further it can be noted that, as the semiconductor branch will have a higher voltage drop during conduction than the mechanical switch, the commutation booster doesn't have a stable operation point where the current is conducted by the secondary branch. A transiently rising current will cause a commutation into the secondary branch, but as the current becomes constant again, it will commute back to the state with lowest losses. This means the current will be shared between the two branches depending on their respective voltage drop. To enable as high current rise as possible in the secondary branch in the case of a transient current rise, it is beneficial to keep all the current in the primary branch in the nominal case. This leads to the conclusion that it is desired to use a semiconductor with an on-state voltage drop like an IGBT or GTO rather than a purely resistive component like a MOSFET. This way it is also possible to keep the semiconductor in an on-state without conducting current and hence with no losses during normal operation.

As the commutation of the current from the primary to the secondary branch in the commutation booster is enhanced by the current derivative, the commutation time will be shorter the faster the current rises. This means that the most difficult case to interrupt for this breaker will be a constant current. Compared to a pure hybrid breaker, the inductance between the mechanical switch and the semiconductor has been increased. Hence a higher arc voltage will be required from the mechanical switch to interrupt the nominal current when the commutation booster is used. However, in a pure hybrid DC-breaker the arc-voltage has to be dimensioned to guarantee a commutation at a fully rising current.

Figure 7 shows the commutation time in the hybrid breaker with the commutation booster depending on the remaining resistance in the circuit when the load is bypassed. As seen in the graph, the commutation is faster the lower the resistance is and hence as long as the arc-voltage in the mechanical switch is high enough to commutate a constant current, all transient cases will be handled.

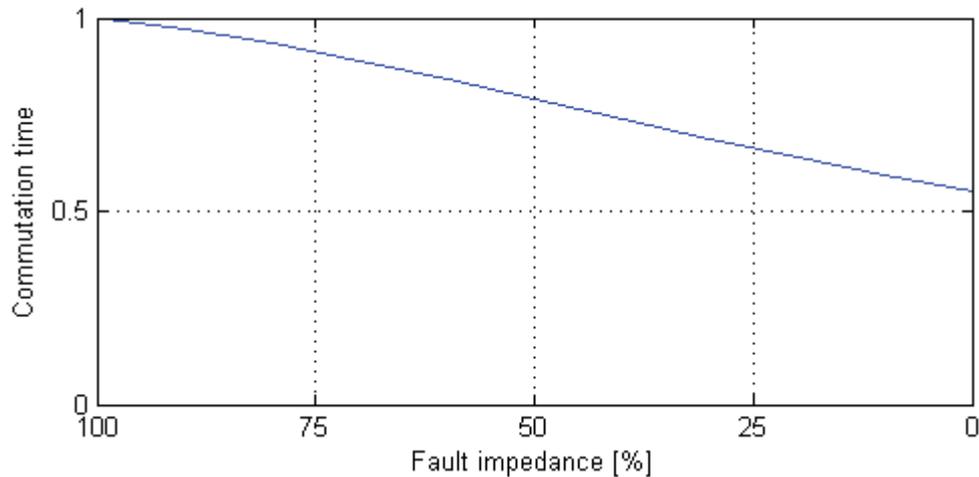


Figure 7: The commutation time of a hybrid DC-breaker with the commutation booster as function of the short circuit resistance during a fault. As long as the arc-voltage is high enough to commutate the nominal current, any rising current will be faster to commutate and interrupt.

CONCLUSIONS

The presented commutation booster can be used to aid the commutation in hybrid DC-breakers where the current derivative or the internal stray inductance is too high. With the inductive coupling of the primary and secondary branches in the hybrid breaker, the inductance is used to enhance the commutation rather than to limit it.

Compared to a conventional hybrid DC-breaker, the commutation will occur automatically when the current starts to rise. This means no time is lost by fault detection and the current might be limited at a lower level.

A hybrid DC-breaker with the commutation booster should be dimensioned to have a sufficient arc-voltage for a commutation of a constant current. As the breaker experiences a fast current rise, it will be used by the magnetic coupling of the booster to commutate the current safely to the semiconductor branch. This way the most difficult interruption case for a hybrid DC-breaker with a commutation booster will be the constant current and all transients will be easier to handle.

BIBLIOGRAPHY

- [1] Häfner J.; Jacobson B.; “*Proactive Hybrid HVDC breakers – a key innovation for reliable HVDC grids*”, paper 264, CIGRÉ symposium, Bologna, September 2011.
- [2] Eriksson, T.; Backman, M.; Halén, S.; “*A low loss mechanical HVDC breaker for HVDC grid applications*”, paper B4-303, CIGRÉ 2014.
- [3] Rahimo, M.; et al; “*The bimode insulated gate transistor (BIGT), an ideal power semiconductor for power electronics bases DC breaker applications*”, paper B4-302, CIGRÉ 2014.
- [4] Magnusson, J.; Liljestränd, L.; Saers, R.; “*Apparatus arranged to break an electrical current*”, Patent WO2014032692.