

Hybrid switches in protective devices for low-voltage DC grids at commercial used buildings

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Abstract

The joint undertaking “Direct Current Components and Grid” (DCC+G) takes on the strategic challenge to reduce energy consumption and thus the reduction of CO₂ emission caused by commercially used buildings. This is proposed by using low voltage Direct Current (DC) grids at a voltage level of +/- 380 V. The major energy consumers in these buildings (heat pumps, ventilation systems, air conditioning units, cooling units, LED lighting systems and information technology), ready for the “net-zero-energy“ goal of the European Union, are in the most energy efficient versions executed with a rectifier system as interface to the alternating current (AC) grid. Furthermore these buildings get local producers of electrical energy (photovoltaic, wind energy, energy storage systems) which is provided also as DC. Avoiding the repeated conversion from DC to AC and vice versa reduces conversion losses and will save energy. Another effect is the transition from many small rectifiers to a small amount of very high efficient central rectifiers. Nowadays the established 400V/230V, 50 Hz, 3-phase AC power distribution systems in commercial buildings could be substituted by a direct current distribution and give a contribution to CO₂-reduction.

Fuses, mechanical and electronic safety switches and their combinations must, like in the AC grid, detect electric faults and switch off and if needed isolate electrical equipment just in time to protect it. Nominal currents in the distribution of a 380 V DC grid should be typical not exceeding 50 A. Plugs and sockets for DC grids in data centers are already available with nominal currents of 20 A offering already higher power levels than todays standard 230 V, 16 A sockets of 1-phase AC grids.

Controlled power converters offer well defined DC short circuit currents. Beside the possibilities to switch DC-currents on various ways with an arc system, DC grids can make use of electronic switches. To reduce transmission losses in semiconductors during standard operation mode the focus is more on the hybrid switches. Basic investigations on a close to production prototype of a hybrid switch are realised and its limitations and performances are highlighted.

1 Introduction (DCC+G project)

The European Community has defined that new buildings must become much more energy efficient [1]. To reach the requested net-zero-energy status, future buildings have to combine energy saving construction designs, energy saving applications with renewable power sources. Today photovoltaic solar power systems are the most prominent renewable power source for these buildings [2]. The solar cells of solar power systems generate DC current and interestingly lighting, energy efficient building heating, ventilation, air-condition and cooling as well as computer of information technology are all operating with an internal DC supply voltage already today (see figure 1). Thus it would be just consequent to connect DC power sources with DC loads by means of an even more energy efficient DC power grid like it is shown in figure 2. A Direct Current distribution grid within buildings would avoid the repeating conversion from DC to AC and

vise versa and therefore reduce conversion losses as can be seen by comparing figure 1 and figure 2.

The joint R&D project “Direct Current Components +Grid” (BMBF FKZ 16N12113; ENIAC Nr. 296108 “DCC+G”) [3] [4] targets to evaluate the efficiency of a 380V DC distribution system by setting up a large building demonstrator.

The assumed energy efficiency advantages of a direct current distribution grid within buildings can be roughly divided in three areas.

- A central AC/DC rectifier of 10 kW rated power or higher can save about 3 % power compared with rectifiers and power factor correction circuits up to 50 W used e.g. in lamp drivers and many other applications.
- Power cables operating with the proposed DC voltages can save up to 2 % of power compared with a power cable for a 3-phase AC grid. Alternative, 56 % of the copper in power cable can be saved when operating a power cable with DC and same efficiency as with 3-phase AC.

- The transfer of solar DC power via a DC/DC MPP converter in local DC loads saves 7 % of solar power compared to a solar system connected to a 3-phase AC grid.

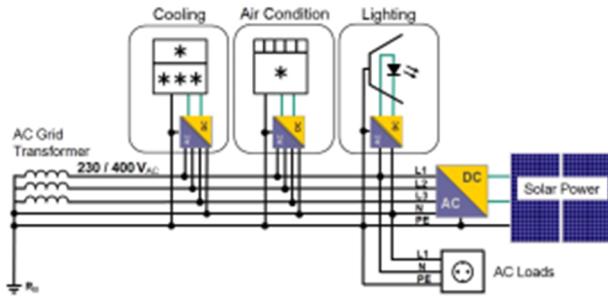


Figure 1 State of the art AC power distribution architecture

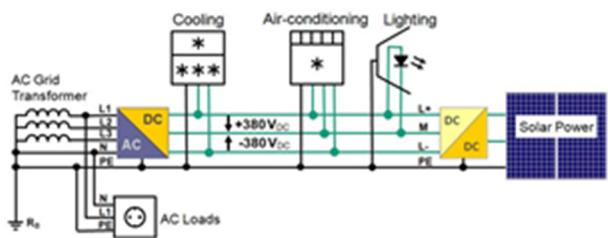


Figure 2 High efficiency DC power grid distribution architecture

2 DC Switching with electronic elements

Electronic switching elements offer a number of advantages compared to mechanical or electromechanical switches like e. g. almost negligible delay times during turn-on and turn-off, wear-free switching or avoiding of arcs. However, most electronic components offer a high blocking capability only for one polarity of the voltage direction which is a major drawback when used in AC grids. In AC applications anti-serial connection of electronic switches or devices like thyristors or triacs are needed to control currents in both directions, increasing the disadvantage of the conducting losses compared to mechanical contacts. As a result, in AC grids electronic elements were used only in niche applications.

For DC grids, turning-off an electric current with a mechanic contact will lead to arcing and as a consequence to increased efforts for (electro-) mechanic switches. During a failure mode, e. g. short circuit of the load, the current in the line will rise limited by the inductance of the line. Thus, delay times for switching in the μs range instead of ms range enable to turn-off the line at a much lower current levels reducing stress of the components affected. As a consequence, electronic switches gain attractiveness compared to pure (electro-) mechanical solutions.

Depending on the boundary conditions of the given application, either MOSFETs or IGBTs are best choice since both offer immediate control via a gate and high ruggedness. For 380V DC grids absolute minimum blocking voltage of electronic switches should be 600V to ensure some immunity against voltage transients. Depending on voltage spikes during turn-off of the switch even higher voltages could be advantageous.

Competitive MOSFETs today use the super-junction approach which was first introduced more than a decade ago [5] and enhanced so that the area specific resistance could be further reduced by more than a factor of 3 [6].

MOSFETs offer an ohmic characteristic with an on-state resistance that can be linearly scaled down by increasing the area of the silicon chip used or by paralleling the devices. However, the area specific on-state resistance of MOSFETs is scaled with the required blocking voltage BV by $BV^{2.5}$ [7] which makes higher blocking voltages very inconvenient: the area of semiconductor material and thus device cost increase.

IGBTs offer the advantage of easier scaling of the blocking voltage without such a high penalty in increasing on-state losses. As shown in Figure 3, IGBT show a knee voltage which – for silicon – is about 0.7V. Increasing the area of an IGBT chip will result in a smaller reduction of the on-state losses in the electronic switch.

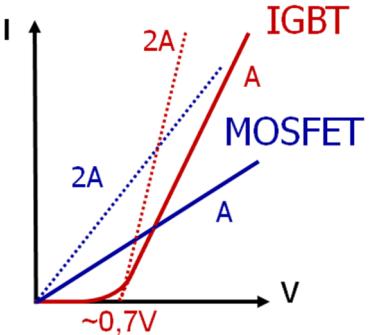


Figure 3 Basic IV-characteristics of an IGBT (red lines) and a MOSFET (blue lines) in on-state. Dotted lines show the behaviour of a semiconductor chip with double area compared to solid lines

As a consequence, MOSFETs are best choice for application requiring least losses, e. g. when only insufficient cooling can be provided. IGBTs are best choice when higher blocking voltages in the range of $> 1\text{kV}$ are needed or when a bypass for the current, e. g. in hybrid switches, can be provided.

3 Hybrid switches for 380 V DC grids

Although semiconductor switches have many advantages such as the frequency of operation and the quick current quenching, their disadvantages include the power loss, the missing isolation function and EMC problems [8, 9]. Hybrid switches (Figure 4) are used to diminish the men-

tioned disadvantages at least partly. These concepts have the electronic component operating mainly during the switching function. The current flow in the ON position is provided by the mechanical switch.

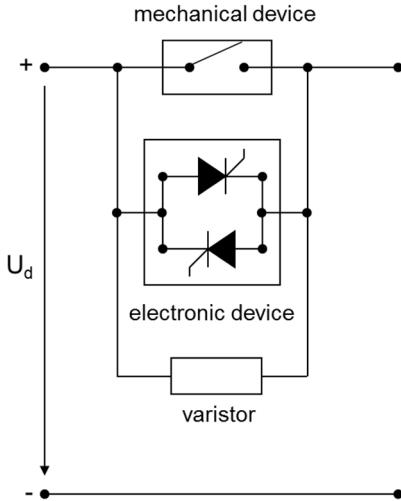


Figure 4 Hybrid switch with thyristors

This kind of hybrid switch is used for the electrical disconnection in smart grids up to 380 V DC. Its application is engineered for electrical equipment and load with a power consumption up to 70 kW. Inside DC grids the hybrid switches will be installed in switching cabinets and are used as circuit breakers. Causing of the high operating cycle load flow in isolated or smart grids can be controlled with hybrid switches as well.

3.1 Hybrid switch with galvanic isolator

The working principle (Figure 5) is based on three mechanical contact systems (S_1 , S_2 and S_3) connected in series with an electronic switching element in parallel to one of these mechanical switches (S_1). The electronic switching element is de-energized during standard usage (S_1 enclosed) and will only be loaded with rated voltage during switching and in open condition.

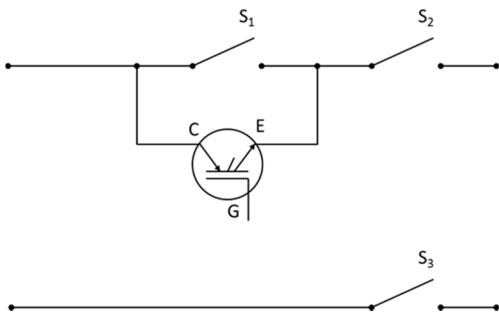


Figure 5 Working principle of a DC-Hybrid switch

The mechanical contacts (S_1 , S_2 and S_3) are opened to open the contact system. The created arc causes an arc voltage, which supplies the electronic switching element with energy. The electronic switching element is connected and adopts the current from S_1 . The arc in S_1 goes out.

After commuting the current onto the electronic switching element the latter changes over to the locking state and disconnects the current flow. S_2 and S_3 provides physical isolation. To close the contact, the switches S_1 , S_2 and S_3 are closed. The electronic switching element does not have any influence on this switching process [9]. During fault currents with more than 1,25 times rated current (I_{rated}) the electronic device stays in locked state and the commuting operation will not be initiated. In this case the three mechanical contacts in series open the electric circuit up to 5 kA.

3.2 Electronic switch element

The schematic diagram of an electronic switching element is depicted in Figure 6. The gate of the IGBT is activated by the resistor R when opening the contact system. The Zener diode Z_1 prevents the IGBT from activating to an extent where there would be more than the Zener diode voltage. The timing element actuates the cascade connection. The total current is conducted over the electronic switching element.

In order to lock the switching device, the logic element disconnects the MOSFET. The emitter potential of the IGBT is increased by the voltage drop of the MOSFET, as is the gate voltage at the IGBT. The gate load discharges via the Zener diode Z_1 . The IGBT and the MOSFET lock. Current flow is nearly zero and the original state is re-established [6].

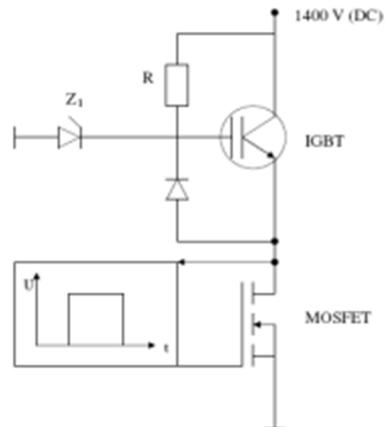


Figure 6 Working principle of the electronic device

4 Test set up and results

The function of the principle described above has been proven [10], [11]. The present investigations on current segmenting between mechanical and electronic device will be arranged with the measurement set up in Figure 7. For this a demonstrator is used, which is prepared with instrument shunts and voltage measuring points. The instrument shunts are configured in a way, that the current sharing process during the electronic device is working not been affected. The test are executed on a short circuit test bed with a voltage of 400 V and currents between 30

A and 160 A. Time constants are varied up to $L/R = 1$ ms (inductive load)

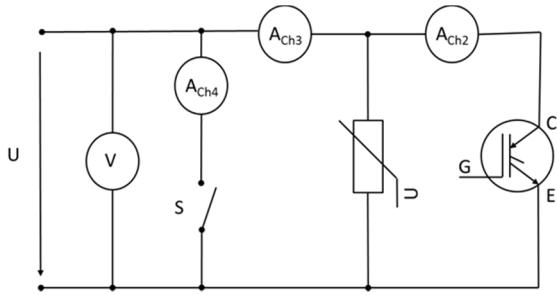


Figure 7 Circuit diagram of test set up

Resistive load:

The oscillographs shown in **Figure 8** (entire switch-off operation) and **Figure 9** (detail of first commutation process) show the switch-off operation at resistive load with 405 V and 36 A.

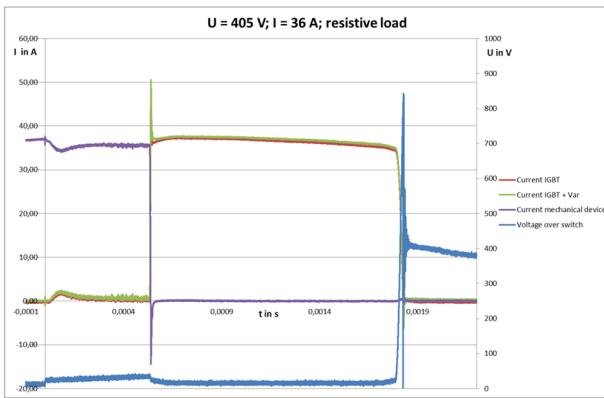


Figure 8 Arc voltage and currents at resistive load (entire switch-off operation)

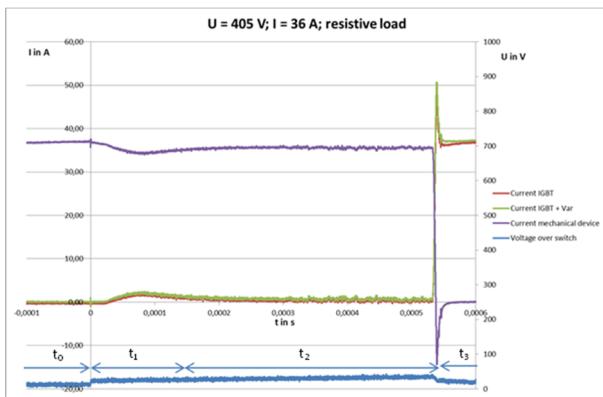


Figure 9 Arc voltage and currents at resistive load (detail of first commutation process)

After the end of t_0 (**Figure 9**) the mechanical contacts start to move towards open and build up an arc voltage of approx. 18 V. After approx. 0.5 ms ($t_1 + t_2$) this phase

ends and the electronic control unit of the hybrid switch adopts the current flow (from t_3). The process during t_1 is a characteristic capacitive interconnection of non-activated IGBTs. The IGBT first tries to lead through uncontrolled in its undefined condition and will subsequently (rising edge at the end of t_2) be activated by the gate. The IGBT will now be activated in a defined way for 1.5 ms, afterwards the IGBT will lock the current flow and will disconnect the circuit.

Inductive load:

Figure 10 (entire switch-off operation) and **Figure 11** (detail of switch-off operation) show the oscillographs of an inductive switch-off operation. Here the hybrid switch is also subjected to a load of 405 V and 37 A. The time constant L/R at this measurement is only $t = 1$ ms. Nevertheless a high re-iterating voltage can be detected shortly before zero crossing which causes the varistor (response voltage 1200 V) to connect through.

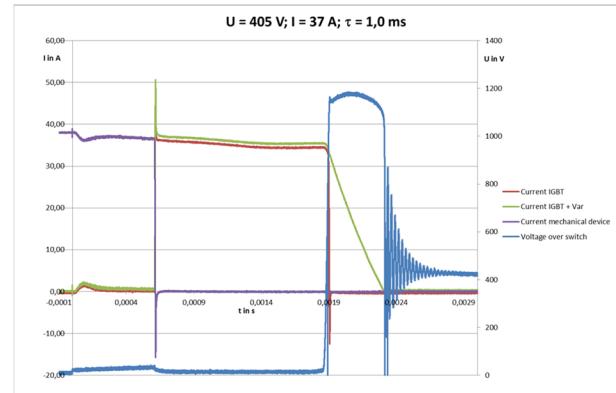


Figure 10 Arc voltage and currents at inductive load (entire switch-off operation)

The processes until the defined activation of the IGBT are similar to those with resistive disconnection. Afterwards the IGBT also remains in the defined activated condition for 1.5 ms. As expected there is a vital change compared to the resistive behaviour with regard to the disconnection. After disruption of the current, external circuitry induces an attenuated voltage fluctuation. Overvoltage must not exceed the value of the reverse peak voltage and/or peak blocking voltage. Therefore the circuit of the IGBT has to ensure a limitation of the overvoltage. In this case a varistor is used. The induced voltage fluctuation is in this case far beyond the varistor response voltage of 1200 V. This overvoltage is successfully cut by the varistor and will then quickly (< 1 ms) and strongly attenuate oscillate to the generator voltage. For measuring reasons it was only possible to record the current through varistor and IGBT together (green curve) and that through the IGBT (red curve). The varistor current can mathematically be calculated by the subtracting the two values from each other. It is clearly discernible that the varistor becomes conductive during the overvoltage for 0.5 ms (green curve) and takes over the current flow. Operating fast switching semi-conductors in inductive circuits caus-

es internal overvoltage through the whole storage effect [11]. Overvoltage caused by the hole storage effect occur at the end of the on-state interval of a semi-conductor after a steep current drop, e.g. at the end of switch-off operations and/or commutation processes (through the varistor becoming inductive). They can be put down to the fast fading of the return current peak when suddenly reaching the blocking capacity. Disruption of the return current causes overvoltages in the upstream inductivities. The constantly available switching capacity C_s will cause a high-frequency oscillation which will be attenuated by the resistive load part. The voltage fluctuation superimposes the reverse voltage of the semi-conductor and can lead to exceeding the max. reverse voltage. The oscillation has a frequency of $f = 5$ kHz. From there a switching capacity of $C_s = 90$ nF can roughly be calculated. In this case and with a reverse current of 12 A there will be an overvoltage of

$$U = I_R \sqrt{\frac{L}{C_S}} \approx 4 \text{ kV}$$

superimposed on the circuit voltage of 400 V and causing the the varistor to connect through until it has been attenuated sufficiently. The switching operations up to 160 A were also successful and show identical curves.

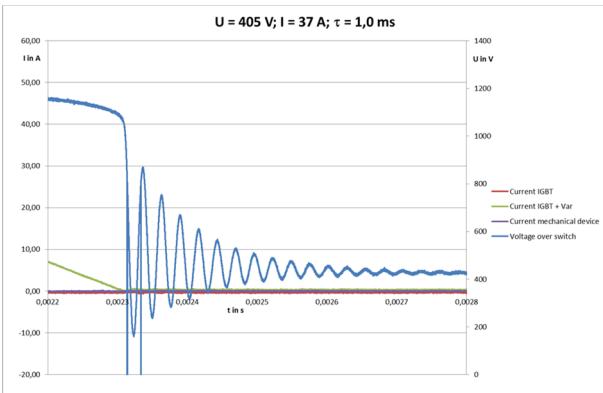


Figure 11 Arc voltage and currents at inductive load (voltage oscillation after turn-off operation)

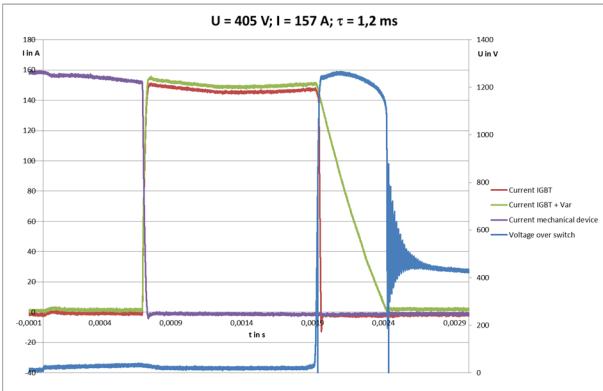


Figure 12 Arc voltage and currents at inductive load (entire switch-off operation at rated current)

5 Conclusion and future work

By combining standard mechanical switches with electronic devices it is possible to get hybrid switching devices with high efficiency and all combined advantages. Switching up to rating current is handled by the electronic device with long life-span. Short circuit current switching and the standard current flow tasks are taken by mechanical devices.

Next step planned are tests with CoolMOS from Infineon. Future works are expected to reduce complexity in electronic device. If possible, reducing shut down time (first for resistive load).

6 Acknowledgment

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