Improved substation design at lower cost with SF_6 free Disconnecting Circuit Breakers

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1. Introduction

A disconnecting circuit breaker (DCB) combines the function of a traditional circuit breaker and adjacent disconnectors. The idea was formed in the end of the 90's and the reason was that disconnectors had the highest grade of maintenance. The circuit breakers had improved, and had longer maintenance intervals than disconnectors. Therefore, the need for disconnectors to isolate circuit breakers for maintenance, to increase circuit and busbar availability, was no longer valid. [1][6] Svenska Kraftnät, the transmission system operator in Sweden, has adopted the DCB system as standard for new substations and for renewal of old. [2][5] By decreasing the number of apparatus and introducing alternative breaking mediums such as carbon dioxide (CO_2) multiple benefits are gained; lower environmental impact, less space, less land preparation, less power losses etc. [3] In addition to the above mentioned benefits, the investment cost as well as the total life cycle cost of the substation is decreased.

2. Composite insulators with silicone sheds

Explosion safety - Silicone insulation provides the highest security with minimized risk of scattered material in case of internal overpressure or sabotage. This is to be compared to porcelain that can cause big pieces with sharp edges scattered at high speed against nearby equipment or personnel.

Self-cleaning and lowest creepage current - More than an explosion safe properties the silicone rubber insulation also have superior creepage current and dust withstand characteristics.[7] Due to the hydrophobicity of silicone, a unique self-cleansing property is achieved when silicone oil embedded in the material constantly diffuse to the surface of the insulator. The oil on the surface provides the ability to form water droplets in case of rain, which results in minimized leakage currents and no danger for flashovers in water channels. This property also results in a clean surface. In case of long term service in heavy pollution areas and the insulators may take on a polluted look at the surface when pollution particles are encapsulated in the silicone oil, but the creepage properties and performance is still not significantly affected. [10]

Excellent earthquake withstand suitability - Due to the low weight and good flexibility of composite and silicone, the insulation is also well suited for areas where there are risks for severe earthquakes.

3. CO_2 an excellent environmental alternative to SF_6

Sulphur hexafluoride – The use of sulphur hexafluoride (SF_6) as the breaking medium in high voltage (HV) switchgear has been dominant since mid-1950s. The previously used techniques with compressed air and oil had limitations in breaking capability and/or high maintenance requirement. SF_6 is a stable gas which has very good dielectric and thermal properties i.e. SF_6-gas is ideal for HV switchgear. However, one drawback with SF_6 is its very strong greenhouse gas properties. SF_6 has a Global Warming Potential (GWP) which is 23900 times stronger compared to carbon dioxide (CO_2), see Table 1. Therefore the usage of SF_6 gas should be minimized whenever possible. Today modern HV switchgear is regulated by tough requirement to minimize the leakage both from international standards such as IEC, regulatory bodies and from customers. The usage of SF_6 is also connected to the taxation on greenhouse gases. Currently multiple governments imposes special greenhouse gas taxes depending on the GWP of a specific gas i.e. SF_6 will have a higher tax than CO_2. Additional aspects of SF_6 gas is the cost of production. SF_6 gas is normally manufactured from sulphur and fluorine using energy intensive processes under high pressure, making the production both expensive and complicated. It is important, from an environmental point, to minimize the leakage during the whole life cycle of SF_6, from production to operation and finally destruction.

Vacuum - One alternative to SF_6 is to use vacuum which has good properties and is today the dominate technology on the medium voltage (MV), up to 52 kV. However there are limitations in scaling vacuum technology to higher voltages than the MV range. Using vacuum on high voltage levels (e.g. 145 kV and higher) will either require multiple breaking chambers in series or to increase the size of the vacuum interrupters. Both approaches have inherited problems; increasing the number of components or engineering and manufacturing a bigger sealed chamber in a cost effective way. Another drawback with vacuum above medium voltage levels is need for insulating the vacuum interrupter from ground (either in live or dead tank breakers) which necessitates use of alternative gases

Carbon dioxide - An excellent alternative from an environmental point of view is to replace SF_6 with CO_2 which has viable dielectric and thermal properties for many HV system requirements (even if “weaker” than SF_6). The greenhouse effect caused by the CO_2 is 23900 times lower than SF6. Since the dielectric rating for CO_2 is lower than SF_6 an increase in gas pressure is required to meet equivalent open contact voltage ratings. The thermal interruption (i.e. kA) properties of CO_2 are lower than for SF_6 and generally limit the short circuit breaking capacity one step lower than that for SF_6 (for a nearest comparable interrupter). [8] The superior interrupting capacity of SF_6 has allowed the delivery of circuit breakers with short circuit ratings often in excess of those needed on many power networks. [11] While CO_2 interruption ratings are likely to be in the lower ranges, they can still be adequate for a large number of networks and applications.

The CO_2 technology is scalable for applications at higher voltage levels, just the well known SF_6-gas. It should be noted that even with the superior capabilities of SF_6 it took more than a decade for the development of SF_6 HV breakers to extend from 72 kV to 245 kV.

Table 1: General data for gases used as insulation and breaking medium in HV switchgear.

		SF_6	**CO_2**
Molecular weight	[g/mol]	146,06	44,01
Density	[kg/m^3]	5,9	1,8
GWP [1)		23900	1
Chemically stable		Stable	Stable

$^{1)}$ GWP = Global Warming Potential

4. Disconnecting Circuit Breaker

4.1. Standards

The disconnecting circuit breaker (DCB) is type tested for and fulfills the requirements for circuit breakers (IEC 62271-100), disconnectors (IEC 62271-102) and disconnection circuit breakers (IEC 62271-108). The disconnecting circuit breaker standard describes how to test, interlock and lock the disconnecting circuit breaker in order to secure highest safety during maintenance and service conditions.

4.2. Operation

The disconnecting circuit breaker is based on the well proven traditional SF_6 circuit breakers. The disconnector requirements are fulfilled by an increased insulation level between the breaker contacts. The disconnected condition is thereby achieved in a safe SF_6 gas environment, preventing harsh outer conditions to affect the function of the contacts as for traditional disconnectors. The DCB concept consists of a breaker and a locking device. It can be configured with or without grounding switch on the same structure, depending on what is most suitable for the substation layout. Simplified interlocking and locking systems compared to traditional equipment ensure the highest safety for personnel and nearby equipment. The disconnecting circuit breaker can be interlocked in accordance to the golden rule of insolation; open, isolate, lock, voltage check and earth.

Electrical interlocking - A grounding switch can only be operated once the adjacent breakers are open and locked (can be interlocked to instrument transformer). The locking device can only be operated if the breaker is in open position and the adjacent grounding switches are open. The breaker can only be operated once the adjacent grounding switches are open and the locking device of the breaker is in un-locked position.

Mechanical locking - Mechanical locking of the breaker is achieved by a motor operated steel rod that disables the contacts to close, thereby the disconnected condition is achieved.

Padlocking - There are two padlocking devices for maintenance purposes. One is to padlock the locking device, mechanically disabling operation of locking device. The other is to lock the grounding switch in closed position for extra safety against unintentional operation.

All these security steps together with composite insulators with silicone rubber will ensure highest safety for the personnel doing maintenance.

4.3. Availability considerations

Availability of power supply from a substation is mainly dependent of the factors:

- Availability of incoming power
- Numbers of transformers which are able to feed actual load
- Availability data for switchgear apparatus
- Substation configuration

In this paper it is presumed that the availability of incoming power and the transformer configuration is sufficient and thus, the paper will concentrate on the availability impact of the switchgear apparatus and the substation configuration.

In switchgear availability calculations, often only the busbars and switching apparatus, circuit breakers and disconnectors have to be regarded. Other switchgear components such as instrument transformers and surge arresters have lower maintenance and failure rates, compared to the switching apparatus and are hence be neglected in this paper. Calculations on different substation types are described in [4].

When looking at availability of a HV component or substation, the maintenance time and maintenance rate, in combination with failure rate and repair time is considered. Data for failure rate and repair time is based on statistics, while maintenance rate and time normally is based on the manufacturer's operation manuals.

The maintenance rates for circuit breakers have changed by the time due to improvements of design, material, extinguishing medium etc. and a typical interval between maintenance of modern SF_6 based circuit breakers is 15 years. This can be compared with an air blast breaker which required maintenance yearly.

For a modern disconnector of open air type, the maintenance interval is normally set to 2-6 years. By comparing the maintenance interval for modern breakers and disconnectors, it is seen that the purpose for disconnectors to isolate circuit breakers for maintenance, to increase the availability of busbar, is no longer valid. Table 2 shows typical data for 145kV live tank circuit breakers and disconnectors.

Table 2: Maintenance data for 145 kV circuit breaker/disconnecting circuit breaker and disconnector.

Maintenance	Interval [year]	Time [h]
Circuit breaker/disconnecting circuit breaker	15	10
Disconnector	5	4

4.4. Substation Design

Placing the most critical/high-maintenance component (disconnector) next to the most important object (busbar) will decrease the availability of the busbar. Therefore, the use of disconnecting circuit breaker provides the possibility to go from traditional double busbar, or double busbar with transfer bus, to sectionalized single busbar with increased or equal availability as a result.

Due to the maintenance rate of disconnectors (2-6 years) compared to the disconnecting circuit breaker (15 years) it is seen that, by replacing the disconnectors and regular circuit breaker with the disconnecting circuit breaker, the availability will increase. The disconnecting circuit breaker also enables simplified substation designs that give major space savings. These space savings now enables building of compact indoor and outdoor air insulated switchgear (AIS) substations with minimum environmental effects at low costs.

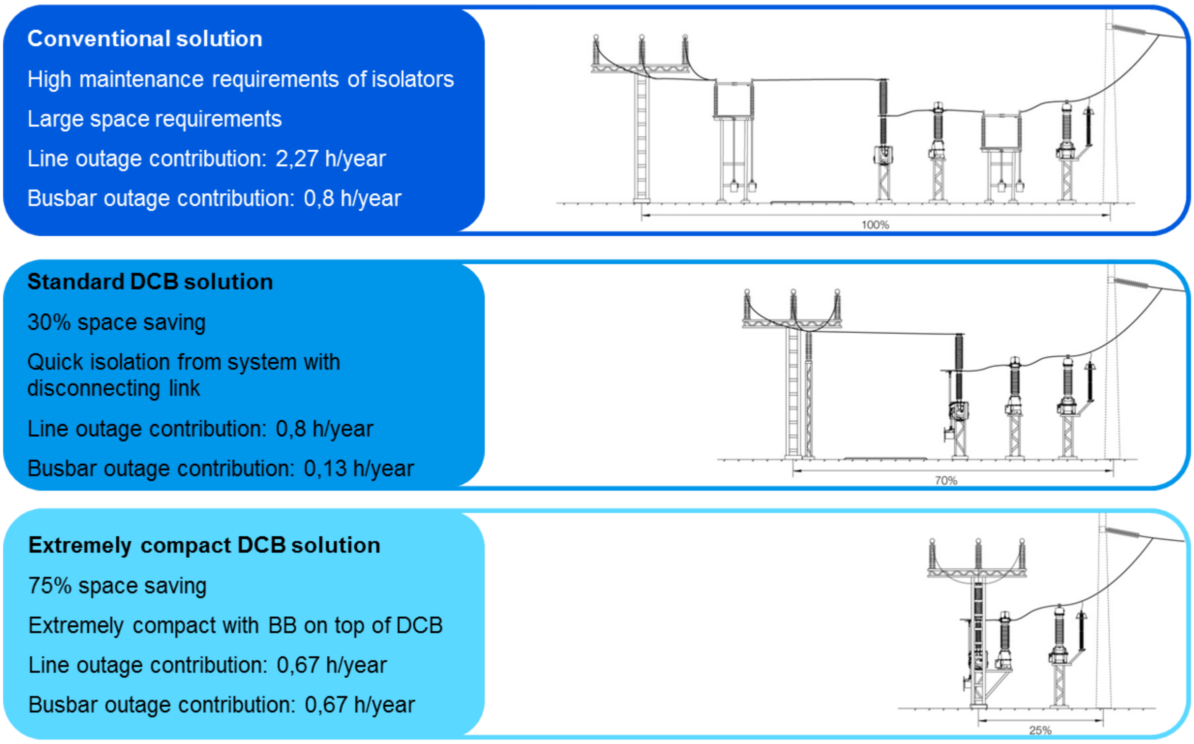

Figure 1: Illustration of space requirement and outage contribution in conventional and DCB single bus configuration.

4.4.1. Disconnecting Link

Usage of disconnecting links for the disconnecting circuit breaker will furthermore increase the availability of the busbar and bay, see Figure 1. With disconnecting links, removal of the disconnecting circuit breaker from the system can be done in short time, in the rare cases of maintenance or failure. The disconnecting link is composed of standard substation hardware. The link is a bolted joint which provide convenient manual disconnection from, or reconnection to, the disconnecting circuit breaker. When the link is disconnected, the DCB will have ample safety distance to live parts thus maintenance is allowed. [5]

4.4.2. Examples of availability calculations and area comparisons

Traditional double busbar → DCB Sectionalized single bus - A comparison between traditional double busbar with bus coupler and sectionalized single busbar with disconnecting circuit breaker will show both space savings and availability increase by using the disconnecting circuit breaker, see Figure 2 and Figure 3.

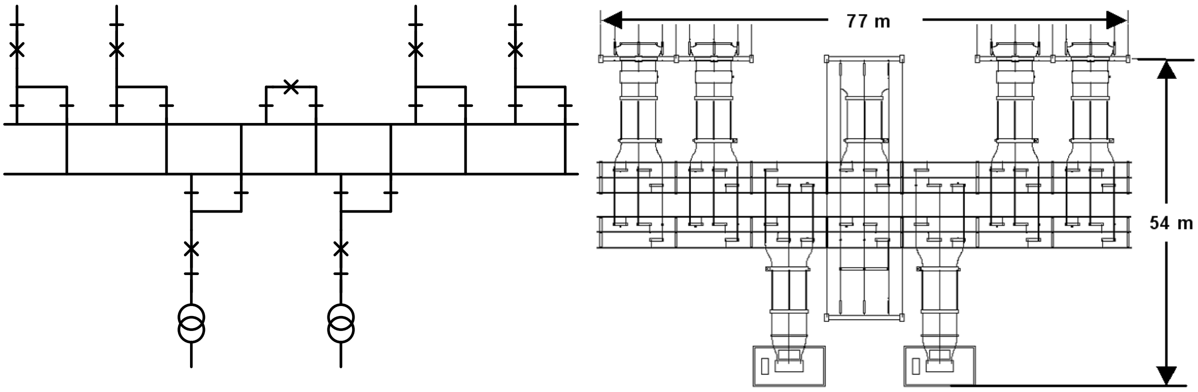

Figure 2: Single line diagram (left) of traditional double busbar with bus coupler. Layout illustration (right) of the traditional 132 kV double busbar with bus coupler.

In a substation, using double busbar and traditional equipment, the line is normally only connected to one busbar at a given time. Hence when looking at the connection scheme, the substation is operated as a sectionalized single bus. Maintenance on any of the disconnectors in the line bay will cause outage on the line. Maintenance on the two disconnectors connected to the busbars will directly affect the busbar availability. During maintenance of a disconnector connected to a busbar in a traditional double busbar solution, it is possible to switch all load, except for the bay of maintenance, to the other busbar. The total maintenance need in the traditional solution is very high due to the short maintenance interval of disconnectors. By instead using a sectionalized single bus with disconnecting circuit breaker and disconnecting link, it is possible to decrease the number and length of outages in the substation, see Figure 4. This is due to the long maintenance interval of the disconnecting circuit breaker and utilizing disconnecting links. In both the traditional setup and DCB setup the outage time on medium voltage side of the transformers is close to zero, due to parallel transformers feeding the medium voltage side.

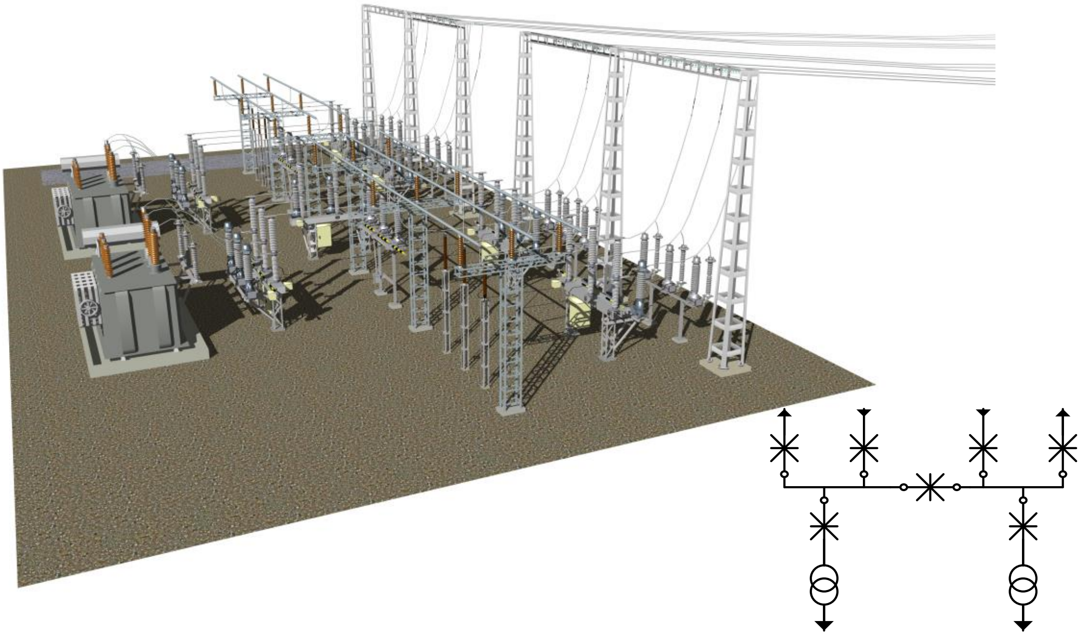

Figure 3: Single line diagram (right) of sectionalized single busbar with disconnecting circuit breaker and disconnecting links. The arrows indicate power flow direction. Layout illustration (left) of the sectionalized 132 kV single busbar.

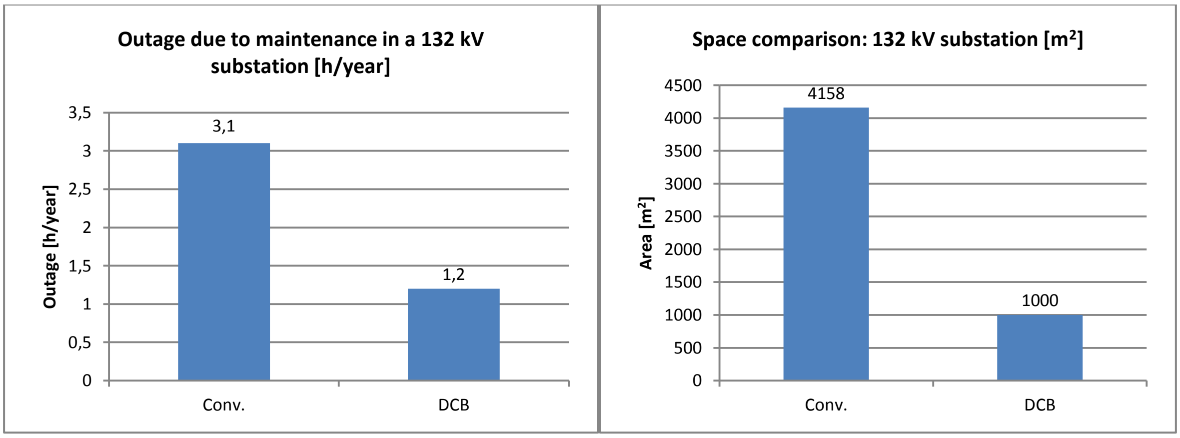

Figure 4: Space requirements for the two switching arrangements, in Figure 2 and Figure 3, and outage time of one line due to maintenance. (Data in the availability calculations are taken from Table 2)

In this example the space requirement is 4158 m^2 for the traditional double busbar solution, while sectionalized single busbar with disconnecting circuit breaker only requires 1000 m^2. This means approximately 70% less space required for sectionalized single busbar with disconnecting circuit breaker compared to traditional double busbar solution. The availability with disconnecting circuit breaker and single busbar is still better than the traditional solution with double busbar

4.4.4. Safety in the substation with DCB

DCB give a minimized number of equipment in a substation which means a decrease in maintenance. Less equipment also gives a better overview and understanding of the configuration of the substation. With the remote motor operated grounding switch, personnel do not need to enter an energized substation area. Due to fewer hours spent in the high voltage substation, the risk of accident is decreased.

5. Cost and environmental comparison

5.1 LCC comparison DCB vs. Conventional

Life Cycle Cost (LCC) comparison for one diameter in a breaker-and-a-half substation can be found in Figure 5. Initial cost is based on realistic market prices and labor cost. The life span of the substation is assumed to be 30 years and includes maintenance and repair is based on similar value as Table 2 and Cigré statistics. Electrical losses are based on a 50% of the rated current flowing at each busbar to (or from) the busbar and the adjacent feeder. Electrical losses are also caused by current flowing through; circuit breaker, disconnectors, DCB etc. and heaters in operating mechanisms. Important noticing is the lower initial cost as well as a total cost reduction of the substation by approximately 15%.

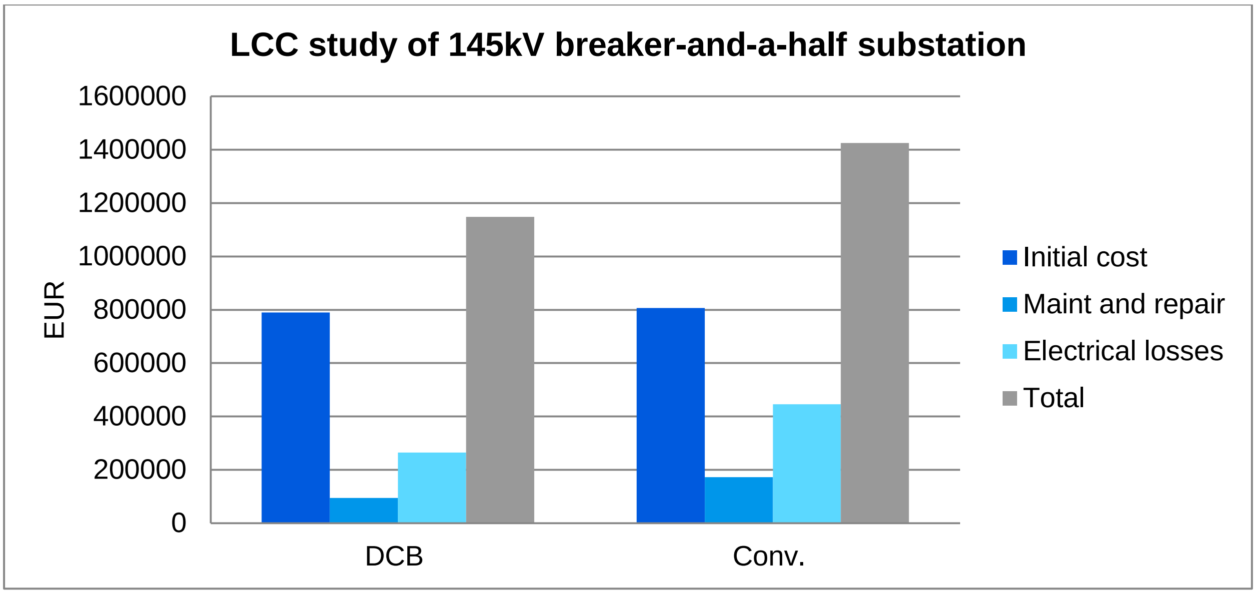

Figure 5: LCC study 145 kV one diameter breaker-and-a-half substation between a DCB setup and a conventional setup using circuit breaker and disconnectors.

5.2. CO_2-equivalent evaluation

Life Cycle Assessment (LCA) of CO_2-equivalent emission between a circuit breaker using SF_6 and a circuit breaker using CO_2 shows an approximate difference of 18% or ~10 tons over a total of 30 year life time. The comparison is based on modeling developed in accordance to Intergovernmental Panel on Climate Change (IPCC). Most or the saving can be found in the change from SF_6 to CO_2 gas.

Note: the above LCA analysis is considering a 0.5% leakage rate and a complete destruction/recycle of SF_6 gas after the life time - which unfortunately not always is the case. Hence by using a CO_2 circuit breaker rather than SF_6, the risk of emitting an approximate of 170.000 kg CO_2-equivalent into the atmosphere, if the SF_6 gas is not properly handled, is completely eliminated.

6. Conclusion

The disconnecting circuit breaker provides an option to design substations with higher availability, less space, increased safety, lower cost and decreased environmental impact, compared to the traditional substation. The disconnecting circuit breaker and the DCB solutions can always substitute the traditional breaker and traditional breaker solutions.

Form the previous discussion it follows that CO_2 offers an excellent environmental alternative to SF_6 gas in HV switchgear. Today most demands can be covered with the alternative CO_2-gas, only on high end requirements with very high nominal current and short circuit breaking current SF_6 still has to be used.

Using the combination of DCB with CO_2 as breaking medium will give most benefits; less space, lower life cycle cost, higher availability and lower environmental footprint.

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