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Future of Electromechanical Switchgear

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Abstract

The current development of the electrical networks towards a DC system imposes certain changes in the design and functionality of several network components. This paper aims to offer an overview of the challenges and the opportunities that are raised by the DC system over the electromechanical switchgear in order to identify its future path in the electrical network. The paper starts with a review process of the previous statements regarding the future of the low-voltage (LV) electromechanical switchgear. In the second part, the existing developments in the LV technology towards a mixed (centralized and decentralized) DC grid are presented. The third part presents the main influencing factors and the developments in the classic electromechanical switchgear as well as in the relatively new switchgear technologies represented by the hybrid and power electronic switches. Following, several questions concerning the standardization and the DC ageing behaviour of the insulating materials will be presented and discussed. The last part will present the conclusions of the current overview.

1 Introduction

The low-loss transmission and distribution of electrical energy and its resource-saving use has played an increasingly important role in recent years in the discussion regarding the future of electrical power engineering and thus also on the future of electromechanical switchgear technology.

The energy transmission and distribution technology based on high-voltage direct current transmission (HVDC) as well as the worldwide massive expansion of renewable generation plants, especially in the medium and low voltage range, require a wide range of studies on new network topologies that consider mixed AC and DC networks, microgrids as well as switching and protection devices adapted to the technical requirements imposed by them [1 - 3].

The observations on the future of electromechanical switchgear begins with a brief summary of previous forecasts on this subject.

2 Previous forecasts and factors influencing the development of electromechanical switchgears

Electromechanical switchgear, e.g. contactors, relays or circuit breakers, are among the oldest components of electrical power engineering. Their partial or complete replacement by power electronic components, e.g. thyristors, IGBTs or FETs has been discussed for a long time.

The switching characteristics of electromechanical and power electronic switches are being compared for more than 30 years [4]. The advantages of electromechanical switches are:

- the low power losses associated with the current carrying function,
- the safe and visible galvanic separation gap,
- the high breaking capacity,
- the small construction volume and the low cost of the devices
- the ability to withstand temporary overload.

A decade later, the development of the switching principles for low-voltage switchgear was envisioned by [5,9] along the following directions:

- an increased use of vacuum switching technology in low voltage,
- optimization of the AC and especially the DC extinguishing principles concerning a better switching capacity, the prevention of reignitions as well as the improvement of the current limitation in AC networks,
- improved methods and algorithms for early detection of short circuits in low-voltage networks,
- new methods for diagnosis and determination of the remaining service life of contactors and
- development and use of hybrid switching devices.

In [6], it is emphasized that innovations in low-voltage switchgear technology will secure the future of electromechanical switchgear. These innovations are:

- the introduction of vacuum switching technology in the low voltage range,
- better control of larger short-circuit currents through new current-limiting effects (e.g. conductive polymers, liquid current limiters),
- condition and remaining service life monitoring and display for selected switchgear,

- the control and adjustment of electromagnetic contactor drives,
- the arc fault detection and shutdown and
- power electronic switching by means of Si-MOSFETs and Si-JFETs.

In the Morton Antler Lecture held in 2016 and celebrating 50 years of the Holm Conference on Electrical Contacts the future trends for switches were expected in the following fields [7]:

- electronic sensing and tripping systems applied to switches of all types will expand,
- $AgSnO_2$ will be gradually the contact material for currents below 4 kA and Ag and AgNi will be for low current relays,
- higher voltage (> 100 V) DC switches with permanent magnets will produce a new range of compact relays for automotive and photovoltaic applications,
- MEMS switches will find a commercial application and may become hermetically sealed with a non-oxidizing gas.

A concluding remark of this anniversary lecture concerning the topic “switching with arc” was presented in the following generalized statement:
„Circuit switching using electrical contacts has not been superseded by electronic switching except for special operations. Electrical contacts plus electronic detection, sensing and tripping systems will be the partnership for the future”.

It must be mentioned that the most of the forecasts presented so far where obtained from scientific publications concerned with the future development and optimization of electromechanical switching devices based on the AC grid structure. This implies the existence of typical AC sources and consumers as well as the classical electrical energy flow from the high voltage grid via medium voltage grid towards the low voltage distribution network.

In the first decade of the new millennium, new challenges for electrical power distribution have been emerging.

Due to the growing population and increasing demand for electrical energy, the earth's fossil fuels will not be able to meet the increased demand for electrical energy as it can be concluded from analyzing Table 1 (IEA, World Energy Outlook 2014) and Figure 1.

Renewable energy generation plants (photovoltaic and wind power), sustained by appropriate storage media are future drivers of the electric networks and implicitly for the next generations of electromechanical switchgear.

Region	PwE (mil.)	ER (%)	Urban ER (%)	Rural ER (%)
Developing countries	1283	77	91	64
Africa	622	47	68	26
North	1	99	100	99
Sub-Sahara	621	38	59	16
Asia	620	84	95	74
China	3	100	100	100
India	304	80	94	67
Latin America	23	90	99	82
Middle East	18	88	98	78
OECD	1	100	100	100
WORLD	1285	82	94	68

PwE – Population without Electricity
ER - Electrification Rate

Table 1: Global status of electrification

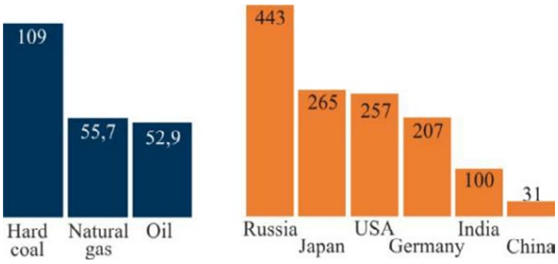


Figure 1: Fossil fuel reserves

DC distribution networks, DC on-board power supplies, electromobility and DC microgrids set new challenges for switching and protection devices and their corresponding protection criteria.

For these new challenges, an electromechanical switchgear requires a significantly improved DC switching capacity. Due to a series of advantages, nowadays, the hybrid and electronic switches seem to be a genuine alternative to the classic electromechanical switchgear.

The new requirements for the switching technology are specified in [8,10] on the basis of the new network architectures as follows:

- increased reliability,
- higher power values,
- integrated security,
- encapsulated switching arc, and
- the use of hybrid switches and power electronic switching devices.

In conclusion, it can be stated that the previous development of electromechanical switchgear was characterized by:

- developments meant to improve the switchgear itself (contact material, contact and extinguishing system, drive system)

- miniaturization,
- innovations (controlled drive, vacuum switching technology, current limitation, remaining service life, etc.),
- improvement of the price-performance ratio as well as
- new requirements for switchgear resulting from the development of electrical distribution networks, in particular those resulting from future DC low-voltage networks, see Figure 2.

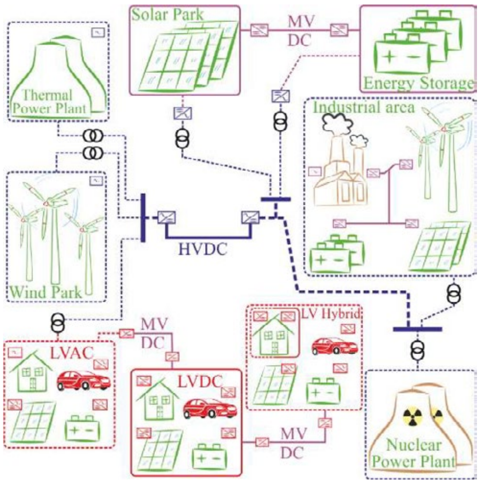


Figure 2: Typical structure of modern power systems

3 DC Low Voltage Networks

The existing development towards an increased number of DC low voltage networks results mainly from the following factors:

- the number of renewable energy generation plants with corresponding storage media is increasing globally,
- DC island grids or microgrids are easier to interconnect to form larger grid connections,
- the stability and regulation of DC grids requires less effort than for AC grids,
- the 3-wire layout imposed by three-phase current system usually results in a 2-wire layout for DC system (cost savings for cables or conductors).

These benefits, characteristic for a LVDC network, have been analyzed and implemented in test projects, for different applications. Exemplary in this regard are the envisioned LVDC networks for home applications, presented in Figure 3, or for computer centers as described in Figure 4.

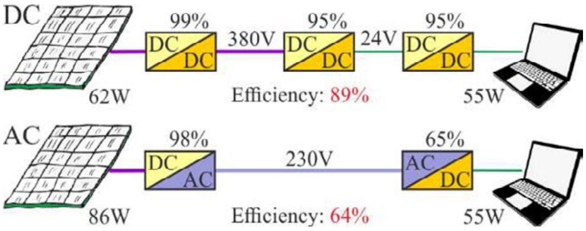


Figure 3: Comparison of efficiencies in AC and DC distribution for home applications [11]

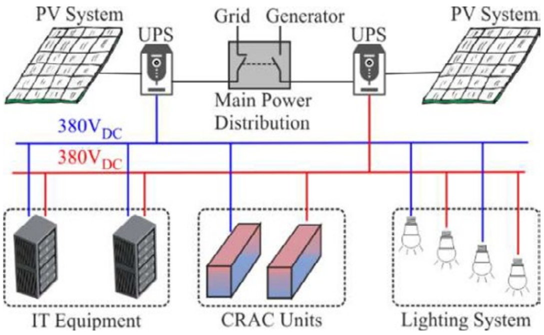


Figure 4: DC -Network for computer center

Common to all these new DC networks is that:

- the losses in the distribution of electrical energy are approx. 10...20% higher in AC systems than in DC systems, because DC-systems have no skin, proximity, hysteresis and dielectric losses,
- many applications, e.g. in the household, are based on DC voltage; the AC/DC conversion losses can be avoided by using a pure DC system and DC-DC conversion is more efficient than AC-DC conversion,
- the components used for household applications have a lower cost, size and weight due to the reduction of transformers.

The wide application of DC networks in the low-voltage range sets known and new challenges for switchgear and components. In the following these are mentioned:

- switching off the current when there is no current zero crossing,
- new switching requirements created by the very high di/dt values generated by the new electrical sources and by the new loads (IEC 60947-4-1 DC utilization categories with time constants up to 15 ms (DC-5)),
- material migration and erosion in electromechanical switches,
- new protection concepts caused, on the one hand by the new consumers, and on the other hand by connecting the DC grid to the existing AC grids,
- national and international standardization,
- profitability,
- acceptance by the population.

4 DC Switching Principles

Figure 5 shows a systematic representation of the DC switching principles that can be used from low voltage to high voltage [12].

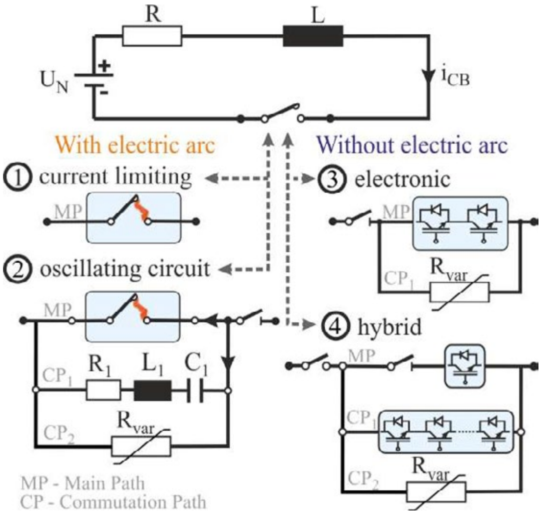


Figure 5: Systematization of the DC switching principles

Low-voltage switchgear is special due to the fact that, if the contact and extinguishing system is appropriately designed, electromechanical switchgear alone is capable of successfully switching off DC currents and providing galvanic isolation. At other DC voltage levels this cannot be achieved without special effort and additional switching elements.

The switching principle with electric arc based on the current limiting method uses several methods meant to increase the arc voltage above the network voltage in order to create the arc current zero crossing required for the arc quenching. The methods used to quickly achieve this purpose (e.g. arc splitting, arc elongation, etc.) are presented in Figure 6 as a schematic illustration. Their functionality is used in real switching devices through certain design and material features.

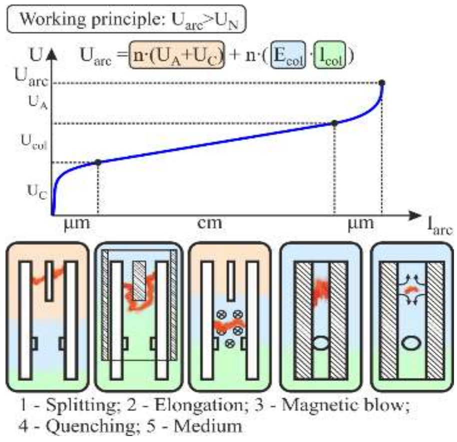


Figure 6: Arc quenching principle

The voltage characteristics obtained from experimental investigations on DC contactors using different arc quenching principles in the design of their contact and extinguishing system are shown in Figure 7 [13].

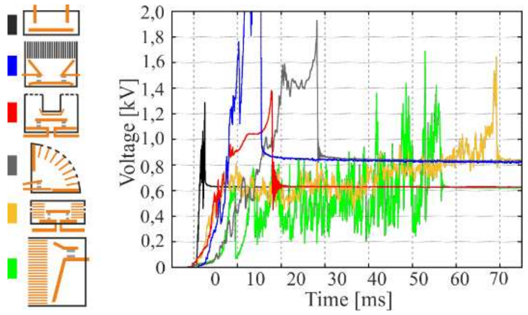


Figure 7: Arc voltage structure with different contactor designs

Depending on the design and the dimensions of the devices, a very different arc voltage structure in terms of time and magnitude can be recognized.

From these results it can be concluded that there is still considerable improvement potential in the classic switching principle to achieve the best possible DC switching behavior.

A further challenge involves minimizing the contact material migration phenomena occurring during DC switching operations. With respect to this, the main influences are analyzed in [14].

The switching principles with electric arc based on resonant switching have been intensively studied in the field of high-voltage [15] and medium-voltage technology. In the low voltage area there are currently only very few aspects considered.

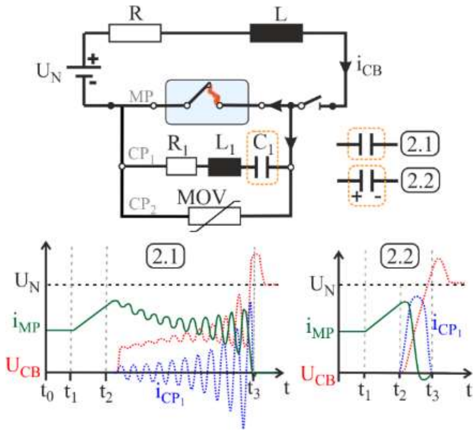


Figure 8: Arc quenching by means of passive and active resonance

The principles, presented in Figure 8, consist in creating a current oscillation between the main current path, where the mechanical switch is connected, and the elements (R_1, L_1, C_1) of the parallel path. The resulting current will oppose the main current and decrease its value creating a current zero crossing, when the arc quenching will occur.

For dimensioning, however, the oscillating system formed between the circuit breaker, situated in the main path, and the RLC elements of the first parallel path must be considered.

Hybrid Switch

The switching principle of the hybrid switches consists of a parallel connection of an electromechanical switching device, found usually in the main current path, and power electronic components (MOSFET, IGBT, Thyristor) as well as overvoltage arresters (MOV) placed in parallel to the main current path [15 - 17].

Referring to the occurrence of a switch-off arc, a distinction is made between hybrid arrangements with and without arc formation [18 - 22].

In arrangements with arc formation, the fast and high arc voltage build-up serves to change, in a short time interval, the breaking current path from the main path to the power electronics path.
There are setups providing the switching voltage for the power electronics by using the arc voltage but most of the hybrid switches mentioned in the literature use an additional auxiliary voltage supply to control the power electronic elements.
Figure 9 shows a typical switching arrangement without auxiliary power supply. S1 is the main switch and the switches S2 and S3 serve for galvanic isolation.

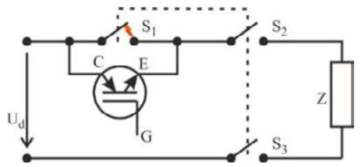


Figure 9: Hybrid Switch with arcing switching [16]

For the contact system of the mechanical switchgear, mostly circuit breaker, single and double break systems, placed in air or vacuum, are used. In some cases, a series connection of the contact system is realized.

The main task of the mechanical contact systems is to provide a low contact resistance path in the switched-on state and the build-up of a high arc voltage (e.g. very fast mechanical contact opening) with the corresponding high arc resistance required for a fast current commutation in the power electronic components, which then switches off the current in the µs or ms range. For the optimization of these processes, a decisive role is played by the contact material, by the arcing processes, by the metal bridge explosion or by the metal vapor arc created at very short distances after contact separation. When compared to a classical breaker, it can be observed that the mechanical breaker in a hybrid configuration must provide a different functionality. The first aspect to account for is that the contact material is highly affected by short bouncing arcs with high di/dt values during the switch-on procedure and by very short arcs during the switch-off procedure. The second aspect that must be regarded during a switch-off procedure is the extremely small arc quenching period imposed in order to create a fast commutation of the current path. These two requirements provide a new set of physical characteristics for the contact materials as well as for the circuit breaker design in general.

If very short commutation times, in the µs range, are desired, hybrid switches arrangements without arc commutation are used, see Figure 10 [19].

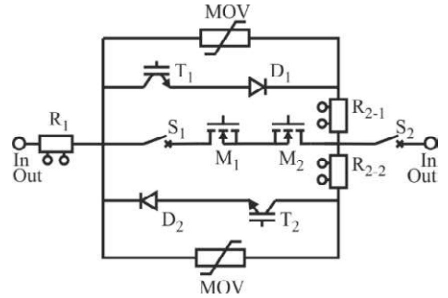
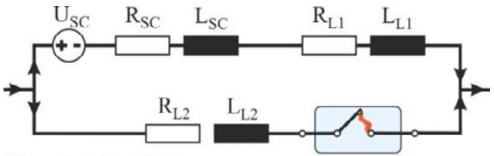


Figure 10: Hybrid Switch with arc-free switching

In these arrangements, a very low impedance power electronic component (e.g. SiC-MOS-FET) is used in the main path with the mechanical contact system S1. During the switch-off process the auxiliary electronics (MOSFET M1, M2) are switched off, while the mechanical switch S1 is still switched on. Due to the high resistance, the current commutates to the other paths, and the mechanical switch will be switched off without arcing. The switchgear S2 realizes the galvanic isolation. For such switching arrangements the optimization of the mechanical contact system must be accompanied by an optimization of the electrical properties of the commutation circuit (e.g. loop inductance).
In addition to the power electronic elements, the cabling and connection conditions of these elements with the mechanical contact system plays a decisive role. These arrangements can be optimized in terms of short commutation times by computer simulation of the corresponding equivalent circuit diagrams. Figure 11 shows such a basic equivalent circuit diagram.



U_{SC} - Semiconductor
R_{SC}; L_{SC} - Resistance and Inductance semiconductor
R_{L1}; L_{L1} - Resistance and Inductance loop 1
R_{L2}; L_{L2} - Resistance and Inductance loop 2

Figure 11: Equivalent circuit for current loop of switch-off operation

A successful function of the hybrid switches can only be achieved when no reignitions occur at the mechanical contact system.

The overvoltage caused by the switching process on the power electronics is usually limited by means of surge arresters. This voltage must be lower than the reignition voltage of the opened contact system.

Typical hybrid switch arrangements are additionally equipped with current measurement technology and algorithms for early detection of short circuits and monitoring of the hybrid switch itself. Successful switching tests have been achieved for the following parameters:

- $U_{network}$: 380 V DC,
- Current ratings: 50 … 125 A,
- I_K" up to 25 kA, Current limitation up to 1 - 3 kA,
- Switch-off times: ~ 10 ms … 500 µs with time constant of the DC network of 10 ms … 0.02 ms

Solid State Switch [23,24]

A typical layout of a Solid State Switch is presented in Figure 12. By using components with reduced on-stage losses (Wide Band Gap, R_{on} 2 ... 4 mΩ), 180 A could be switched off within 0.8 µs. In general, however, it has been found that despite already optimized power electronic components, the Solid State Circuit Breaker still have an on-state resistance R_{on} that is 100 ... 1000 times higher than the typical contact resistance of Electromechanical Switchgear.

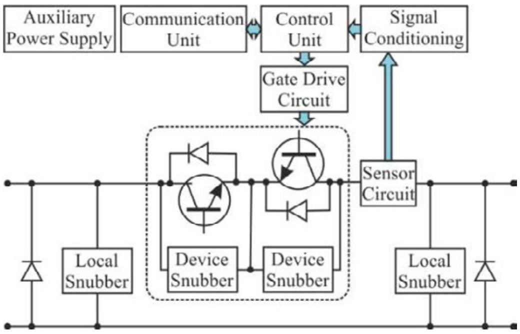


Figure 12: Solid State Circuit Breaker

Even so, it must be considered that the power semiconductors used in different Solid State Switches arrangements up to now were designed for other applications. Information from manufacturers of power electronic components indicates that nowadays, and in the future, power semiconductor elements will be developed and adapted for the switchgear functionality in order to substitute the electromechanical switching devices.

As an existing alternative to the Solid State Circuit Breaker, the Hybrid Switch is suggested.

Conclusions on the DC Switching Principles

In classic DC low-voltage networks, the electromechanical switchgear based on the arc quenching principles can fulfill the requirements for switching capacity well.
Due to the development of electrical networks with small time constants, where extremely high di/dt can be observed, the hybrid switches are gaining in importance according to the author.
A reasonable use of these switching devices in combination with other features, such as: early fault detection, monitoring or even power flow control within the networks, may provide the most economically feasible way to implement this new technology in the future DC low voltage networks.

5 Visible galvanic separation gap

Another important fact that must be considered in the analysis regarding the future of electromechanical switchgear is the visible galvanic separation.
A major advantage of electromechanical switchgear is that they can provide by default a visible galvanic gap. Power electronic components lack such characteristic because a temperature-dependent leakage current in µA range flows, even if a certain reverse voltage is applied. Galvanic separation is therefore not achievable. The international normative IEC 60364-5, "*Selection and Installation of Electrical Equipment, Switchgear and Control Devices"*, states that "Semiconductors must not be used as isolating devices ".

This means that switching arrangements with Hybrid Switches or Power Electronic Switches must additionally be equipped with an isolating switch to fulfil the requirements of galvanic separation.

Overview of regulations and activities for visible galvanic separation

In IEC 60947-3 standard on low-voltage switchgear and disconnectors, and in the IEC 60947-2 standard on low-voltage switchgear and circuit-breakers, a reference is made to the IEC 60947-1 standard on low- voltage switchgear and general specifications. These specifications further reference the IEC 61140 standard "Protection against electrical noise-common requirements for installations and equipment".

IEC 61140 specifies the requirements imposed for devices used for disconnecting electrical circuits and for protection against electric shock. That standard imposes that:

“The position of the contacts or other disconnecting devices in the disconnected position must either be visible from the outside or be clearly and reliably indicated.“
The devices for separation must meet two requirements:
“In new, clean and dry conditions with contacts in the open position, the device must resist a surge voltage applied between the input and output terminals.”

“The leakage current via the open contacts must not exceed the following values: 0.5 mA contacts when new, 0.8 mA contacts at the end of the agreed lifetime.”

The standard IEC 60204-1 on Electrical Equipment of Machines, also refers to the standard IEC 60947-1 ... 3. The specification IEC 60934 on Equipment Circuit-Breaker, specifies the minimum air gap of the opened contacts for the corresponding rated impulse withstand voltage.
The IEEE Switchgear Committee, the visible break discussion group, provided the following definition in 2018: ”Visible break – a gap between conductors that can be visually verified and meets the dielectric withstand requirements in the relevant product standard.”

These regulations play an increasingly important role due to the growing use of power electronics (generation of transients) as switching elements in electrical networks.

6 Insulation

The further miniaturization of electromechanical switchgear and their compact design require safe insulation, galvanic separation and a long service life even at increased operating temperatures, e.g. 120 °C.

Recently, partial discharges have been observed in low-voltage switchgear, which considerably accelerate the aging of the insulating materials and can lead to insulation failure [25, 26].

When using the switchgear under DC voltage, it must be considered that the voltage stress is based on different physical principles compared to AC voltage, as described in Figure 13.

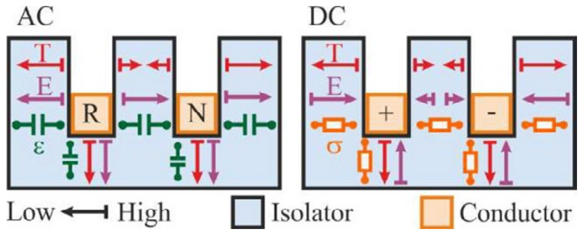


Figure 13: Difference in insulation material stress for AC and DC

For AC voltage stress, the geometric arrangement and the dielectric constant ε, showing a low temperature dependence, determine the field strength stress in the insulating material system (e.g. contact air gap, housing wall).
For DC voltage stress, the decisive material constant is the conductivity κ, which is for plastic/synthetic insulation material often specified with the following temperature (T) and electric field strength (E) dependency:

$$\kappa(T,E) = \kappa_0.* e^{\alpha*T} * e^{\beta*E}$$

This dependence on temperature leads to the so-called electric field strength inversion, i.e. the maximum field strength stress of the insulation system changes with the temperature distribution in the insulation arrangement. Areas which initially show the highest electric field stress are slowly relieved as the temperature increases inside the insulating material and modifies its electric conductivity. In this manner the cooler areas will present, under DC stress, the highest electric field stress. As a rule, temperature fluctuations and DC voltage stress results in larger insulation material areas with a higher field strength than in AC voltage stress. This has a significant influence on the ageing behavior of the insulating materials. The aging process has already been investigated for high-voltage and medium voltage cable constructions, and this research is currently being carried out for low-voltage cables and switchgear [27].

The situation is further aggravated by the fact that due to the diverse use of power electronic switching elements, in the DC networks there are no pure DC voltages but the so-called mixed voltages representing a superposition of the DC voltage with higher-frequency oscillation components.

7 Conclusion

Electromechanical Switchgear is a cost-effective, proven and continuously developed technology of the electrical power engineering that has been optimized for various switching applications. Due to worldwide developments and the changes that take place in the low-voltage grid new demands are being placed on the electromechanical switchgear. In addition to the existing optimizations required for the classic DC switching devices (i.e. improvement of the arc quenching phenomena, contact and insulating materials, etc.) nowadays it must be accounted that these switching devices are increasingly being used in hybrid switchgear arrangements. This fact creates a new set of requirements for the contact materials as well as for the circuit breaker design. Another important aspect that we must account for is the development of dedicated power electronic switching elements that, under certain conditions, may entirely replace the mechanical breaker.

The increased use of power electronic switching elements, in combination with and without electromechanical switchgear, will make it possible in the future to implement improved measuring and diagnostic functions in the switchgear. This will allow the execution of the protective functions in a quick and selective manner and even to regulate power flows within the low-voltage grid.

Even so, it can be concluded that the existing limitations of power electronic switching elements with regard to power loss, thermal and insulating stress, the lack of a visible galvanic isolation gap, standardization and cost will continue to make the electromechanical switchgear necessary in the future.

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