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INNOVATIVE T&D SWITCHING EQUIPMENT AND DEVELOPMENT OF ITS TESTING TECHNOLOGY

INOVATIVNI T&D RASKLOPNI APARATI I RAZVOJ TEHNOLOGIJE ISPITIVANJA

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Abstract: A short overview of the developments in the overall transmission and distribution industry in South East Europe is presented in this contribution. Furthermore, as the present journal focuses on breaking and switching in HV and MV switchgears, several technology innovations in T&D switchgear have been identified, at global level. In almost all cases, the ongoing energy transition is the main driver of these innovations. In this contribution, based on test-experience and overview of the industry, innovations are grouped by drivers, with each of them having its impact on testing technology.

These drivers are the following:

1. Increase of ratings: the ongoing trend of co-existence of micro-, local- and super-grids. The consequences for testing of switchgear for UHV and very large current are highlighted:
2. Offshore transmission: compactness and reliability are requirements stretched to the limit for this application. Very long cables for AC and HVDC power transmission, even in a multi-terminal topology will have impact on switchgear.
3. Health safety and environment: here, the major switchgear related discussion is on SF_6 replacement and reduction of electrical losses. Various issues related to SF_6 replacement will be highlighted. In addition, a recent project intended to quantify the hazard of aluminium bus bars in power stations affected by long duration fault arcs is described.
4. HVDC and power electronics: circuit breakers are going to be installed in multi-terminal HVDC grids. Testing of HVDC breakers, regarding the complete interruption current process is described.
5. Digitalization: switchgear is going to be communicating with the IEC 61850 communication protocol. This will impact testing for which laboratories need to prepare. The introduction of smaller micro-electronics (sensors, IED) closer to primary HV components and its high-frequency transients need careful consideration regarding operation, endurance, and lifetime.
6. Resilience and fault mitigation: Resilience against severe weather conditions, vandalism and cyber-attacks calls for resistant equipment and robust mobile equipment/substations that can be deployed very rapidly still having an extreme degree of readiness and availability.
7. Quality assurance of products in the face of a pandemic and a lockdown requires adequate methods of a remote digital access to test, and factory sites for type testing and inspection.

Keywords: South East Europe, T&D Industry, testing, high voltage, switchgear, short-circuit, energy transition, HVDC

Sažetak: U ovom prilogu dat je kratak pregled razvoja u ukupnoj industriji prenosa i distribucije u Jugoistočnoj Evropi. Nadalje, kako se ovaj žurnal fokusira na VN i SN postrojenja i aparate, identificirano je nekoliko tehnoloških inovacija u T&D rasklopnim aparatima na globalnom nivou. U gotovo svim slučajevima, tekuća energetska tranzicija glavni je pokretač ovih inovacija. U ovom doprinosu, koji je zasnovan na iskustvu u oblasti testiranja i u pregledu industrije, inovacije su grupirane po faktorima koji imaju svoj utjecaj na tehnologiju ispitivanja.

Uticajni faktori su sljedeći:

1. Povećanje rejtinga: stalni trend suživota mikro-, lokalnih i super-mreža. Istaknute su posljedice ispitivanja rasklopnih uređaja na UVN i vrlo jakim strujama:
2. Offshore prijenos: kompaktnost i pouzdanost su zahtjevi razvučeni do krajnjih granica za ovu aplikaciju. Vrlo dugi kablovi za AC i HVDC prijenos, čak i u višeterminalnoj topologiji, imat će utjecaj na rasklopne uređaje.
3. Zdravstvena sigurnost i okoliš: u ovom slučaju, glavna rasprava, koja se veže sa rasklopnim uređajima, je o zamjeni SF_6 i smanjenju električnih gubitaka. Istaknut će se različiti problemi vezani za zamjenu SF_6. Pored toga, opisan je nedavni projekt čiji je cilj kvantificirati opasnost od aluminijskih sabirnica u postrojenjima pogođenim kvarovima unutrašnjeg luka dugog trajanja.
4. HVDC i energetska elektronika: prekidači će se instalirati u višeterminalne HVDC mreže. Opisana su ispitivanja HVDC prekidača u pogledu kompletnog procesa prekidanja struje.
5. Digitalizacija: rasklopni aparati će komunicirati s komunikacijskim protokolom IEC 61850. To će utjecati na ispitivanja za koja se laboratorije trebaju pripremiti. Uvođenje manje mikroelektronike (senzora, IED) bliže primarnim visokonaponskim komponentama i visokofrekventnih prijelaznih signala treba se pažljivo razmotriti u pogledu rada, izdržljivosti i vijeka trajanja.

6. Otpornost i smanjenje vjerovatnoće kvara: Otpornost na teške vremenske prilike, vandalizam i cyber napade zahtijeva otpornu opremu i robusnu mobilnu opremu/trafostanice koje se mogu vrlo brzo razmjestiti i dalje imaju visoki stupanj spremnosti i raspoloživosti.
7. Osiguranje kvaliteta proizvoda u slučaju pandemije i "lockdown-a" zahtijeva odgovarajuće metode daljinskog digitalnog pristupa mjestima za testiranje i tvornicama za tipska ispitivanje i inspekciju.

Ključne riječi: Jugoistočna Evropa, T&D industrija, ispitivanje, visoki napon, rasklopni aparati, kratki spoj, energetska tranzicija, HVDC

1. T&D INDUSTRY IN SOUTH EAST EUROPE

The electromechanical industry in South East Europe (SEE) has a long history having its roots at the early electrification trends across Europe in the 19th century [1]. Manufacturing of the primary electrical equipment embraces a wide of range of industrial processes including heavy metalworking, moulding, extruding, heat treating, etc. Often, complex installations are necessary in terms of machinery, workshops, cranes, heat chambers, gas and oil processing facilities, test laboratories, storage areas. Furthermore, wide-enough economy of scale is necessary in order to compete in local and international markets, requiring a large space impacting the size of buildings and land consumption.

As result, huge capital investments are necessary to start up such manufacturing plants. For this reason, it is not a frequent phenomenon to observe start-ups of new companies in the electromechanical sector in Europe, except for a few rare cases in Turkey where significant incentives for industrial development still exist.

Although there are no new players in the primary equipment manufacturing sector, the industry remains driven by pre-existing and well-established historical companies who manage to cope with the present challenging market conditions. A positive trend in SEE industry can be observed due to the following factors:

- Re-localization of factories from the Western European countries to SEE due to decreased labour costs and tax efficiencies.
- Investments of Russian capital in the SEE region, targeting international markets.
- Joint ventures with Chinese industry in order to access local markets.
- Expansion of power transformers factories, which have proven being able to deliver high quality and lower costs compared to Western European countries.
- Expansion of power cables factories to face the growing demand at European and extra-European level. This demand is pushed forward by the undergrounding of power lines in urban areas but also in the field of renewable systems. There are also notable examples of submarine cable factories targeting off-shore developments in the North Sea and some Mediterranean areas.

The opportunities for the SSE electromechanical industry are divided in two macro-areas: export markets and local markets.

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Export markets are driven by the advantage of being able to manufacture inside the EU Community, albeit containing labour costs compared to Western European countries. In some rare cases, local industry exponents have an excellent positioning even outside the European community.

Local markets are still characterized by lack of investments, but the outlook in the short to medium term is very promising. South Eastern European countries will be investing huge capital in transmission and distribution infrastructures in order to foster the ongoing energy transition. The main processes being implemented (along political debate) in the region are:

- integration of electricity markets in a wide area South-East European Market, which requires intensive investments in communication and data-exchange for operating purposes, but also increased cross-border transmission capacity.
- integration of renewable energy systems to facilitate decarbonisation processes in the region.
- refurbishing of old transmission and distribution assets.
- refurbishing of old power generation assets.
- environmental constraints and incentives to a circular economy.

The main industrial innovation projects are set up in order to follow these developments. The number of certification activities is one of the key indicators how the electromechanical industry invests in R&D in order to deliver new products to the market and copes with the infrastructural innovations in transmission and distribution networks. The number of certification projects at KEMA Labs, as being the world's leading company in Testing, Inspection and Certification of electrical equipment, is a representative indicator of the state of new developments in the industry. Figure 1 shows the aggregate trends in Certification at all KEMA Labs platforms (KEMA, CESI, IPH, FGH, ZKU, KEMA US) of new equipment manufactured in South East Europe.

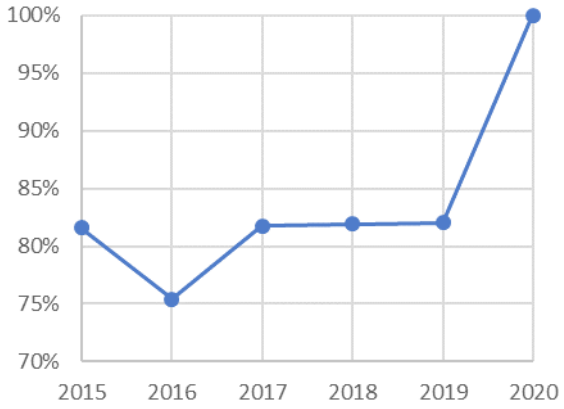


Figure 1: Overall certification projects in South East Europe at KEMA Labs.

The index values are reported as a percentage of the revenues compared to the reference year 2020. It can be observed that the number of R&D projects remains constant in the period 2015-2019, besides new competitors targeting these markets and cost-pressure introduced by final users.

2020, the year of the first Covid-19 pandemic, shows an interesting positive trend, due to the joint action of some interesting factors:

- The industry was able to face the pandemic and quickly adapt to the "new normal".
- The positive impact of remote testing services introduced by KEMA Labs to support technical managers and R&D teams of the industry despite travel bans between countries. This topic will be presented in more details in chapter 3.6.
- Two large high voltage circuit breaker projects as joint venture of Turkish and Chinese industries.

It is possible to observe another interesting trend by focusing on substation secondary equipment (metering, protection, substation automation equipment). Figure 2 shows the aggregate trends in certification at KEMA Labs (Smart Technologies Department) of secondary equipment manufactured in South East Europe.

The index values are reported as a percentage of the revenues compared to the reference year 2019. Aggregate results for 2020 are still under evaluation. It is obvious that the secondary equipment market is growing fast in the SEE region, thanks to the combined effect of the following factors:

- Digitalization trends in the region
- Presence of young and dynamic workforce mastering and combining IT and Electrical Engineering
- High standing universities and academic systems with long history in Electrical Engineering
- Lower capital investments necessary to establish manufacturing of secondary equipment. The main focus is hardware and software development combined with import of full printed PCBs from other regions

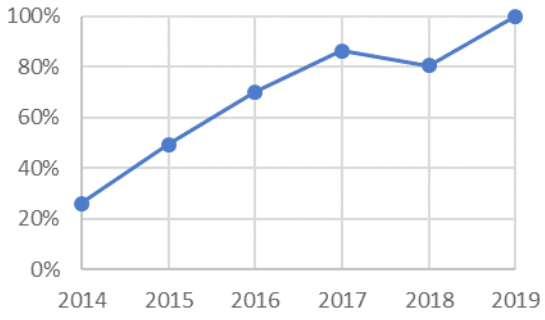


Figure 2: Metering, protection and substation certification projects in South East Europe at KEMA Labs.

It is expected that infrastructure investments will be an important part of economic-crisis recovery after the Covid-19 pandemic. The prospect is that the future of the SEE electromechanical industry will keep facing interesting opportunities and positive trends in the upcoming future.

Brain-drain is the main threat for this industry [2]. The emigration of well-educated workforce is a dramatic issue for countries with a lower standard of living in South-Eastern Europe, with an average between 40% and 70% of higher educated migrating for a better life.

When focusing on the main topic of this journal, breaking and switching in HV and MV switchgears, and on the country where it is released, Bosnia and Herzegovina, it cannot be avoided a mention to the history of Energoinvest: after decades of experience in research, development, construction and testing of high voltage switching devices, this corporation has stopped the manufacturing activities. Its pivotal role in the former political constellation as an initiator and knowledge generator for many activities in electromechanical industry, in SEE and beyond, keeps being alive thanks to visionary ideas of farsighted experts who spent their professional lives at the Energoinvest Research and Development Centre for Electric Power [3]. Nowadays, thanks to these individual's efforts, the next generation of experts in HV and MV circuit breakers actively participates in global mainstream technological developments.

This example shows that brain-drain is not the only solution according to the authors in [4]. "If there is knowledge, initiative and entrepreneurship, in addition to today's technology and global market, there is certainly a chance to live and work in Bosnia and Herzegovina, and at the same time to be in the first line in the development of science and top-class technology" [4].

South-East European countries which have been considered for the scope of this contribution are: Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Greece, Hungary, Kosovo, North Macedonia, Montenegro, Romania, Serbia, Slovakia, Slovenia, Turkey, Ukraine. The selection was made to follow, with some minor exceptions, the CIGRE SEERC member countries.

2. INNOVATIONS IN T&D SWITCHING TECHNOLOGY

Recent (2018) studies on the role of T&D equipment in future grids suggest that by 2050, 3.8 PW-km of transmission line capacity will be needed in the voltage range between 320 - 800 kV, which is roughly 50% of the total world transmission capacity forecasted for 2050, and an increase of almost 250% compared to that of 2020 [5]. Regarding technology, it is forecasted that by 2050 85% of this capacity will be in HVAC-, and 15% in HVDC systems. The same study forecasts that the annualized power grid capex + opex will increase from ≈ 0.5 T€ in 2020 to ≈ 1.5 T€ in 2050, mostly for power lines capex.

A large part of these investments can be attributed to the energy transition that will innovate T&D switching technology in various measures, both in applications related to local generation as in super-grids as well as in bulk transmission systems accessing remote renewables.

The following trends and innovations having their impact on switching technology are identified:

2.1. Increase of system power and super-grids

This is reflected in higher system voltage, both AC and DC, in order to facilitate long-distance transmission of renewable energy as well as grid connections for stability and electricity trade.

System voltages of 1100 kV AC (most powerful connection 7.5 GW, 3324 km) and 1100 kV DC (most powerful connection 12 GW, 3293 km) are in commercial operation in China, whereas India is developing a 1200 kV AC system. AC circuit breakers having as few as two breaks for these voltage level have been developed and tested [6], as well as DC switchgear [7] for load transfer switching and isolation.

Also, short-circuit power is rising in cases of concentration of generation, interconnection and changing network structure. Due to reduction of losses, the X/R ratio at certain grid locations, especially near transformers, is rising. Very large short-circuit current implies momentary very high electrodynamic stresses (forces), which occur before any breaker can act during an asymmetrical current peak. Circuit breakers need to reduce the duration of faults but cannot avoid the electrodynamic stresses. This means all T&D equipment needs to withstand the impact of very large fault current [8]. Transformers are most at risk, given the fact that at short-circuit testing, 20-25% of distribution and power transformers offered for testing in the range 10 – 800 kV does not pass the standardized tests [9].

2.2. Offshore transmission

Offshore application of switchgear is becoming a fast-growing market. Switchgear up to 66 kV is nowadays commonly installed in wind turbines; EHV AC GIS is installed on platforms, and application of offshore HVDC GIS will soon be realized. Compactness of offshore equipment is a major requirement, minimizing insulation distances and reducing maintenance extremely, since platform space is in the order of 100 k€/m2 while maintenance costs far exceed the ones in onshore practice. Switchgear having combined functions will be introduced.

Special circuit breakers are needed to act in cases when generating units need to be decoupled or synchronized. Generator circuit breakers are special devices that differ from standard circuit breakers. In case of AC connected offshore wind farms, very long cables are often used. This means switching of high capacitive currents well above the standardized values. In addition, compensating reactors are installed onshore, which can lead to situations of missing current zero, unheard of in onshore cable switching applications [10].

2.3. Health, safety and environment related

Safety of switchgear, awareness of internal arc risks is high on the agenda [11]. More and more power is being installed in smaller and smaller switchgear rooms, and becoming located closer to the general public. Therefore, testing of safe pressure relief is in high demand.

A major trend is SF_6 replacement. Whereas in distribution, SF_6-free (air-, solid insulated) equipment is readily available, this is not yet the case in transmission. SF_6 alternative gasses for insulation and switching have been proposed and demonstrated in product development tests [12] ,[13] ,[14] ,[15]. Several pilots up to 170 kV are running. CIGRE working groups are making an inventory of the state-of-the-art, user's considerations and pilot experiences for switchgear (WG A3.41), stations (WG B3.45) and dielectric aspects (WG D1.67).

At the same time the development of vacuum switchgear for transmission voltages proceeds steadily. An overview is prepared by CIGRE WG A3.27 [17], being updated by CIGRE WG A3.41. SF_6-free metal enclosed circuit breaker up to 145 kV is now announced [18].

High-voltage vacuum switchgear has its own features for testing, see section 3.3.

2.4. HVDC technology and power electronics

HVDC is no longer a niche market, and a large array of special HVDC switchgear is already available for years. A comprehensive overview of HVDC switchgear is compiled by CIGRE JWG A3B4.34 [7].

A distinction shall be made between current transfer and interruption. Switches transfer current, deal with currents up to the normal load current and are not designed to interrupt fault currents, whereas circuit breakers interrupt any current up to their rated short-circuit breaking current. Interruption is a far more onerous duty for a switching device than transfer [ ]. The main difference is the voltage across the switching device, during the switching operation. In case of transfer, a sudden increase of resistance, usually an arc, forces the through current to continue in a parallel path of lower impedance. After the completion of transfer, the voltage across the open contacts of the switch is only the voltage drop across that parallel impedance. This voltage is much lower than the system voltage, that would appear when no parallel path would be present. The situation is outlined in Figure 3, showing interruption (left) and transfer (right).

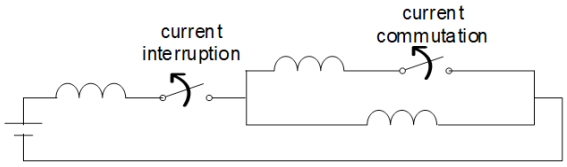


Figure 3: The two switching duties: current interruption and current transfer.

In addition, the current level to be dealt with by a transfer switch is up to the continuous current. Another major difference is the required speed of operation: transfer processes in DC switchyards do not need to be performed with great urgency, whereas fault currents need to be cleared extremely rapidly because of the high rate-of-rise of the fault current and (in VSC systems) to avoid a quick collapse of the system voltage after a fault.

Apart from transfer switches, several types of bypass-, earthing-, disconnecting- and paralleling switches can be found at the DC yard of HVDC stations [7].

With the concept of large meshed HVDC grids, e.g. to evacuate several hundreds of wind gigawatts from the North Seas, HVDC circuit breakers are key protective devices [19] and are under development, see section 3.4. In China, a 500 kV HVDC grid is under commissioning, including various technologies of HVDC circuit breakers [20]. CIGRE WG A3.40 studies MV DC switchgear and systems, whereas CIGRE JWG B4A3.80 is focussing on HVDC circuit breakers. Standardization of HVDC switchgear (circuit breaker, transfer switch, disconnector, bypass switch, earthing switch) has started in 2019 by establishing relevant IEC working groups.

DC- and power electronics-based generation has significantly different dynamic response and performance than conventional generation and AC lines during faults in the AC network (for example reduced inertia, insufficient voltage support, low short circuit current, impacts on power quality); in many cases, if applied with judicious and properly coordinated design and controls, these techn¬ologies can provide great benefits and performance enhancements to overall system reliability [21].

Laboratories need to prepare measurement with unprecedented accuracy and calibration against higher frequency content (including DC) due to harmonic pollution while (pre-)standardization committees need to assess its impact on T&D equipment.

2.5. Digitalization

Also, switchgear is rapidly becoming part of the Internet of Things. The operation of “digital substations” is more and more managed between distributed Intelligent Electronic Devices (IED) interconnected by optical communication networks following the IEC 61850 protocol.

Sensors are the messengers at the interface of the physical and the digital world, and as such their role as big-data provider is gaining importance. Sensors monitor, control and protect power grid (components). Low-power ITs are replacing the electromagnetic ones, test-methods are being developed [22].

In all these developments, micro-electronics is located in close vicinity to strong EM sources of transient nature, like arcs, corona, rapid changing of currents/voltages etc. In order to assess the correct functioning of electronics in switchgear, it may not be sufficient to perform stationary EMC testing on the secondary equipment separately, but to adopt integral testing, verifying the correct data supply- and fault-ride-through capability of protection / monitoring equipment in a harsh EM environment. An example of integral testing of a MV station, including IED is given in [ ], the test object of which is shown in Figure 4.



Figure 4: MV station with tele-controlled 12 kV RMU with wireless communication and IED in an integral test, verifying the correct functioning of electronics under switching operations in the author’s laboratory [23].

2.6. Resilience and fault mitigation

Climate change will cause more environmental stress on switchgear, which calls for the need of water resistant submersible, vault mounted switchgear [24] but also for intelligent auto-reclosing and fast reacting pole mounted switchgear in distribution systems exposed to severe environment.

Fast and ultra-fast drive technologies offer opportunities for fault current limitation and fault impact mitigation. Ultra-fast bypassing of internal arc faults in MV panels is demonstrated by an ultra-fast earthing switch based on airbag and vacuum technology [25]. Thompson-type ultra-fast electromagnetic repulsion drives potentially revolutionizes switchgear technology. Sub-millisecond contact opening times of a commutation switch in combination with a power electronics circuit breaker enables very fast fault current limitation at distribution level [26].

At HV level, system-size experiments with fault current limitation and rapid arc breaking at 320 kV level are being carried out with HV vacuum switchgear having rapid repulsion mechanisms [27].

Also, DC circuit breakers, up to 500 kV, are equipped with mechanical (vacuum, SF_6) switches and vacuum circuit breakers that operate within a few milliseconds.

Separate electromagnetic servo drives per pole allow programmable contact travel curves and are claimed to have extreme mechanical endurance for MV circuit breakers [28]. For the low(er) voltage, miniature vacuum interrupters with piezo-electric drives have been demonstrated [29].

3. IMPACT ON TESTING OF T&D SWITCHGEAR

In this section, it will be described how test methods have been developed and demonstrated by KEMA laboratories in order to verify a number of new requirements that switching devices with rated voltage 10 – 1200 kV face in the light of the innovation trends identified in chapter 2.

3.1. Increase of system power and super-grids

Nowadays, a clear trend of increase of system voltage to 800 kV AC and above can be observed in the world. This calls for the need of having test facilities to verify the fault current interruption performance of circuit breakers for such "super grids". Work of CIGRE WG A3.22 [30] led to standardized requirements for the highest system voltages up to 1200 kV, anchored in the IEC requirements.

KEMA's laboratory expansion, now in operation, consists of two new short-circuit generators (added to the four existing ones) and four step-up transformers (added to the six existing ones), see Figure 5, and now creates a short-circuit power of up to approx. 15000 MVA, available in the test-bay.

KEMA Laboratories have developed test-circuits and test-methods to be able to carry out a full test-program of short-circuit tests on circuit breakers up to 1200 kV [6] and transformers in the 800 kV class [9].



Figure 5: New short-circuit generator, 2500 MVA 16.7 – 60 Hz and 4 short-circuit transformer.

For the circuit breaker tests, separate, well-synchronized sources for the supply of fault current (from short-circuit generators) and transient recovery voltage (from pre-charged capacitors) are required, combined to synthetic test circuits. A system of a two-stage synthetic TRV application has been demonstrated, with actual tests carried out of 800 and 1200 kV circuit breakers, for which TRV's in excess of 2000 kV are required. A key feature of the test-circuit is that the circuit breaker under test can remain on ground, which greatly facilitates efficient testing compared to test approaches in which the breaker must be installed on an isolated platform.

Having multiple synthetic installations available also enables full three-phase synthetic testing, even under effectively earthed conditions, where every phase-to-clear needs its own TRV condition, as shown from a 145 kV breaker in Figure 6. This is required per IEC standard for circuit breakers in a single common metal enclosure.

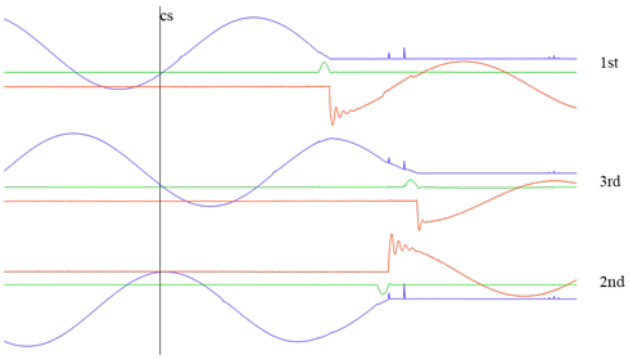


Figure 6: Three-phase synthetic test of a 145 kV three-phase enclosed circuit breaker for effectively earthed system conditions.

Three-phase circuit breaker closing ('making') tests, including the full power testing of switches, designed to activate closing resistors in an 800 kV GIS circuit breaker have been demonstrated [6].

EHV shunt reactor switching is also a rapidly growing demand. More and more EHV air-core reactors are directly being connected to OH lines. New circuits and measurements have been implemented [31].

3.1.1 Testing of UHV circuit breakers

The most severe test for HV circuit breaker is the short-line fault test, representing the situation of a fault on an overhead line near the station. In this case, the line breaker experiences a very high fault current and a very steep rising TRV from the voltage wave travelling between fault and breaker. From an analysis of 190 type test-series (2011-2016), it was concluded that 58% of all HV circuit breakers did not pass this test initially [32]. A new compact artificial line was developed for testing EHV / UHV circuit breakers, see Figure 7. One of the challenges is to replicate real service conditions of OH lines having distributed elements with a lumped-element circuit, and to build-in the flexibility to cover a large range of test-object parameters like rated voltages, short-circuit breaking current. One key feature is the requirement of a very short time (0.5 μs) between fault current interruption and TRV application.



Figure 7: New artificial-line circuit (back right) in a short-line fault test set-up of an 800 kV circuit breaker.

The new artificial line is applied in the full-pole testing of an 800 kV circuit breaker, see Figure 7.

In Figure 8, the measured TRV response in the full-pole L75 test is shown.

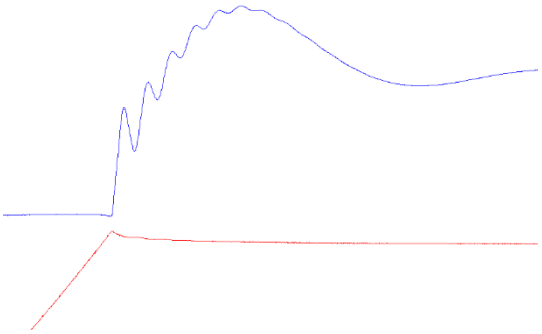


Figure 8: TRV responses (blue) of the artificial line circuit from Figure 7 in a full-pole 800 kV L75 short-line fault test. First line peak 317 kV, time- to-first-peak is 42 µs. Current (red) is 0.75*50 kA

Figure 9 shows the set-up of a full-pole synthetic make test, as part of the T100s(a) duty for an 800 kV circuit breaker.



Figure 9: Specially designed UHV making gaps (front right) for performing full-pole synthetic make tests T100s(a) with breakers of 800 kV and above

A new key component is the specially designed series of ultra-high current triggered spark gaps, in order to initiate the main short-circuit current immediately upon pre-strike of the breaker gap, as part of a synthetic make test.

Based on a large number of full-power tests, a practical arc model for short-line fault current interruption has been developed, useful for studying the impact of various parameters on the interruption process [33].

3.1.2 Auto-reclosure

Auto-reclosing is a requirement for breakers that need to restore power quickly after a transient fault on an overhead line. From CIGRE studies, it is clear that around 70% of the phase-to-earth faults in OHL systems are removed by a single reclosure followed by an opening operation (O-CO), and even more after another opening [34]. Testing the O-t-CO-t'-CO sequence is a challenge, especially at short times between the opening operations. The standard IEC circuit breaker requirement IEC 62271-100 asks for t = 0.3 s and t'= 180 s. Of the three opening operations, the last two need to be realized under full TRV application, whereas the first can be without HV TRV. In this case, a time interval of 180 s is considered a reasonable time to recover the generator's power capability and to re-charge the TRV capacitor banks. However, at much short times, such as required by the Russian GOST 52565 standard, where t'= 20 s is required this becomes a major challenge.

Nevertheless, having available special control of generator power and two synthetic installations, this fast sequence could be realized, see Figure 10.

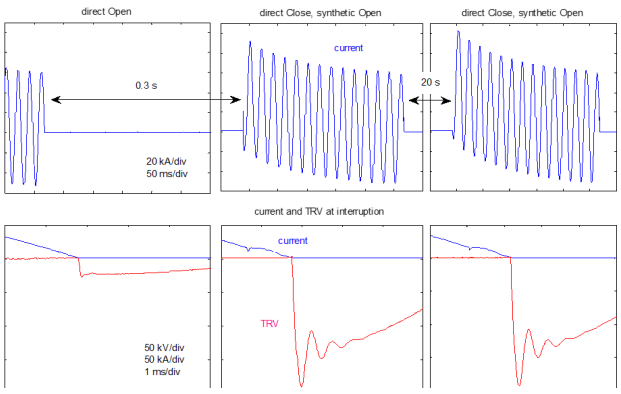


Figure 10: Oscillogram of a O - 0.3 s – CO – 20 s – CO synthetic short-circuit test of a 110 kV circuit breaker

More challenging is the testing of rapid auto-reclosers (covered by IEC 62271-111 "automatic circuit reclosers"). These are mostly MV auto reclosers with rated sequence O – 0.3 s – CO – 2 s – CO – 5 s – CO. Here, the availability of multiple generators comes in essential, since the total short-circuit current can be shared between six generators in order to keep the current per generator well below the maximum. In this case, by keeping the current moderate, reduction of output voltage ("generator depression") is kept to a minimum, while at the same time keeping the frequency decay limited. This creates the possibility to perform auto- recloser tests in a direct (non-synthetic) three-phase circuit.

Direct three-phase rapid auto-recloser tests have been carried out up to 72.5 kV, 31.5 kA.

3.2. Offshore transmission

Various testing projects on the verification of offshore related equipment have been finalized, such as switchgear for sea-bed installation, for wind-turbines, platforms and generator circuit breakers.

Apart from offshore applications, generator breakers are needed for large (hydro) power plants. The very large ratings (for power plants up to 2 GW) are equipped with SF_6 arcing chambers [35], whereas vacuum circuit breakers are available up to 500 MW [36].

Generator circuit breakers need to be tested in accordance with IEC/IEEE 62271-37-013, which differs in many aspects from the "standard" AC circuit breaker standard. This brings several challenges to testing. One on them is the requirement of a very large fault current, combined with a very fast rising TRV, as occurs in practice in case of a fault at the generator side of the breaker, causing the HV grid to feed into the fault.

Testing of generator circuit-breakers at this rating needs to be carried out by the synthetic test method. This implies that a realistic arc duration needs to be guaranteed by artificially prolonging the arc duration by forced re-ignition. In case of vacuum circuit breaker technology, standard arc prolongation technology, very effective in testing SF_6 breakers, cannot be applied. Therefore, in such tests, ultra-high frequency current injection is needed to demonstrate the correct arc duration. KEMA Laboratories realized this through novel "super re-igniters", developed in cooperation with Darmstadt Technical University, Germany. This new technology is based on a cascade of triggered vacuum- and air gaps, supplying a very fast high-current pulse.

The photo in Figure 11 shows the test set-up in KEMA High-Power Laboratory, with the breaker under test (and a series connected auxiliary breaker) in the foreground, and two super re-igniter units behind it.

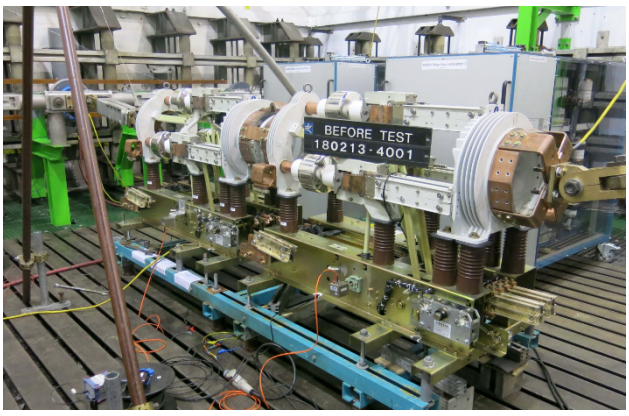


Figure 11: Generator circuit breaker with three vacuum interrupters in parallel (with series connected an auxiliary breaker) and two super re-igniter units behind it

Having verified this technology, more opportunities arise to test high-voltage vacuum circuit breakers in a synthetic method, since the arc prolongation methods commonly applied for HV SF_6 breakers cannot be used for HV vacuum breakers.

3.3. Health safety and environment

3.3.1 SF_6 alternative gases

HSE aspects gain more and more attention. Most visible, regarding testing, is the demand for testing equipment with SF_6 alternatives. A variety of gas compositions has been developed and have been demonstrated in switchgear up to 170 kV, mostly circuit breakers. Type-testing is now carried out along the SF_6-based standard IEC 62271-100. In parallel, discussion is going on, among others in CIGRE WG A3.41 and the IEEE Switchgear Committee, whether wide scale application of SF_6 alternatives deserves special provisions in future switchgear standards, similar to the approach brought in after vacuum was well accepted as an interruption medium.

Test laboratories need to be prepared to handle the new gas mixtures (for certification tests) and need to verify the exact gas composition independent from the manufacturer. Proper measuring system, using optical absorption techniques, are commercially available from third parties. This is important, since a variety of different compositions of the same mixture components can be offered under the same commercial name, e.g. depending on ambient temperature. Gas composition for a MV switchgear application is usually different from HV applications.

Preparation of the handling and disposal of gas mixture after testing needs another approach than SF_6, but is not less challenging. These topics have been discussed in CIGRE WG B3.45 [37].

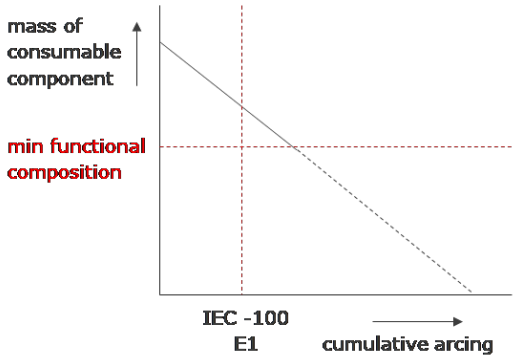


Figure 12: Loss of mass of a component of an SF_6 alternative gas consumed by arcing activity (not to scale)

A key component of two prominent gases proposed so far, one a mixture with fluoronitrile and another a mixture with fluoroketone, is being consumed by the arc at a rate of 0.3 - 0.5 mol/MJ of arc energy [12]. In SF_6 consumption of gas due to arcing does not occur, since it recombines after arcing. However, it is reported by manufacturers that the gradual loss of an effective constituent due to arcing is of no concern regarding practical lifetime [13], [14], be-

cause other parts of the breaker will define the end-of-life, similar to the SF_6 breaker case. The situation is depicted schematically in Figure 12, that shows the loss of mass of an effective (fluoronitrile, fluoroketone) gas mixture component. After a certain cumulative arc activity, a "minimum effective composition" of the gas mixture will be reached. For successful certification this minimum effective composition should be reached at higher cumulative arcing than required for standard certification tests of a specific test-duty.

3.3.2 Internal arc consequences

MV switchgear panels are being installed with ever higher short-circuit power in ever smaller rooms. For the sake of safety of personnel and integrity of buildings, the internal arc test (IEC 62271-200) is designed to demonstrate that personnel or civilians are not affected by exhaust gas directly escaping from a fault arc in a compartment towards an accessible location. Switchgear shall be designed to withstand the pressure rise and vent the exhaust gases into a safe location [38].

High-energy arcing faults are high-power electrical discharges between two or more conductors that can release tens of thousands of amperes of current. They can result in plasmas that reach about 35,000° C, vaporize steel and eject hot metal particles into the air. (Nuclear) power plants typically evaluate risks from arc faults by knowing their zone of influence, or the distance that neighbouring cables and equipment would be damaged beyond functionality. Bus bars in power plants were traditionally made of copper, the metal of which zones of influence have been determined over the past 50 years. Recently, however, it has been identified that many bus bar systems use aluminium conductors, or a combination of copper and aluminium. Aluminium, while less expensive and lighter than copper, is more reactive during a high-energy arc fault: every mole of aluminium (27 g) produces 0.85 MJ of excess energy when reacting with oxygen. This difference affects the energy and material an arc fault emits [39]. Figure 13 shows the impact of a 26 kA 4 s high-energy arc fault test recorded with advanced multi-angle high-speed videography.



Figure 13: High-energy arc fault (video still - courtesy of Sandia labs [39] recorded in KEMA labs)

Internal arcs in GIS having an aluminium enclosure are even five times more reactive than with air, due to the violently exothermal reaction between SF_6 and aluminium [40]. Therefore, realistic tests regarding internal arc withstand capability (IEC 62271-203) can only be carried out with SF_6 in the GIS.

In order to prevent polluted SF_6 gas to escape into the environment, test laboratories need to put the GIS section under test in a hermetically sealed pressure vessel, an example is shown in Figure 14.

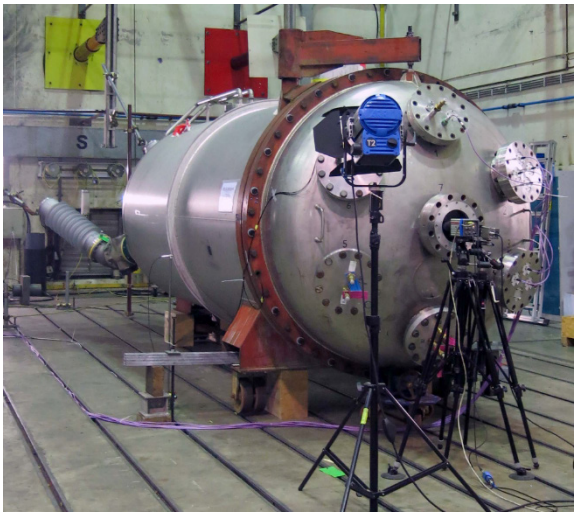


Figure 14: Internal arc testing with SF_6 filled GIS section in pressure resistant enclosure

3.4. HVDC and power electronics

Between 2016 - 2020, the author's laboratory was a partner in the EU Horizons2020 project "PROMOTioN" (Progress on Meshed Offshore HVDC Transmission Networks") [41] responsible for the testing of HVDC circuit breakers of various technologies.

HVDC circuit breakers differ significantly from HVAC circuit breakers because:

- they must act much faster (the mechanical switch is actuated by electromagnetic repulsion coils),
- they must create a current zero (by forced oscillation current or by stacks of semi¬conduct¬ors),
- they must absorb the magnetic energy stored in the grid with Metal Oxide Surge Arrester (MOSA) banks.

These new requirements have strong impact on testing. Most prominent is the verification of the complete short-circuit breaking process, including energy dissipation. During the energy dissipation phase of the interruption process, the mechanical switching device of all HVDC breakers experiences a transient interruption voltage (TIV). Meanwhile, the MOSA bank is stressed by significant thermal energy. The authors developed test circuits that combines this dynamic dielectric stress with the thermal stresses [42]. While the synthetic test method, applying high fault current and high TRV voltage sequentially and from different sources is very efficient for HVAC breaker, for HVDC breakers' fault current and TIV voltage must be applied at the same time.

For full-power testing, multiple AC short-circuit generators running in low power frequency mode, together with a DC voltage application (from another source) after interruption to represent the recovering system voltage, can fulfil these requirements. Because of the short duration of the interruption process in HVDC breakers (5-15 ms), adequate current and voltage stresses can be provided by low-frequency AC sources in combination with step-up transformers. In this project, 16⅔ Hz was used, having power in a single loop of current available during > 50 ms, a significant part of which can mimic DC short-circuit conditions. Test requirements were agreed among three manufacturers to harmonize testing of different technologies and ratings.

The agreed test methods were used to test a 350 kV, 20 kA hybrid HVDC circuit breaker, see Figure 15, Figure 16 and two different technologies of active current injection type of HVDC breakers up to 160/200 kV DC with 20 kA [42,43], see Figure 17 [44].

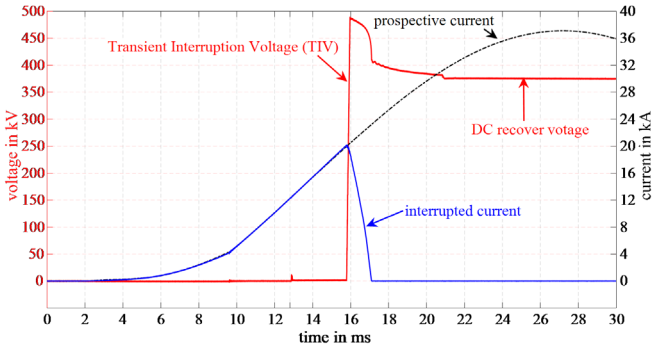


Figure 15: Fault current interruption test oscillogram of 20 kA of HVDC fault current of a 350 kV HVDC hybrid circuit breaker



Figure 16: Testing of a 350 kV hybrid HVDC circuit breaker



Figure 17: Testing of an active current injection HVDC circuit breaker in the high-power laboratory

Research work on the stresses of internal components of HVDC circuit breakers [45] was carried out.

Standardization of test requirements of HVDC breakers is going on in IEC TC17/17A WG 64 that has prepared a draft technical specification IEC TS 62271-313. CIGRE JWG B4/A3.80 will issue a Technical Brochure in 2021. CIGRE WG A3.40 is collecting knowledge in the field of MVDC switchgear and systems.

Also, in the framework of the PROMOTioN project [41], a one-year test campaign was designed and carried out on the dielectric withstand capability of a 320 kV SF_6 - filled prototype GIS installation towards long duration DC stress under intermittent thermal load, including regular super-imposed lightning tests [46].



Figure 18: Testing of a 320 kV HVDC GIS in the KEMA high-voltage laboratory

A technical brochure to be drafted by CIGRE JWG D1/B3.57 will include a non-mandatory prototype installation test in line with PROMOTioN specifications. In IEC SC 17C work on IEC 62271-5 (common clauses for HVDC switchgear) and IEC 62271-317 (HVDC GIS) has started in 2020.

3.5. Digitalization

The digital control, communication and supervision of substation equipment through the IEC 61850 protocol, forces test laboratories to install the proper digital and optical equipment in order to control switching devices, more and more through attached IEDs (Intelligent Electronic Devices). Author's labs, are finalizing a project of interconnecting four laboratories (high-power, high-voltage,

secondary equipment, and power electronics lab) with an optical IEC 61850 ring, see Figure 19 [47].

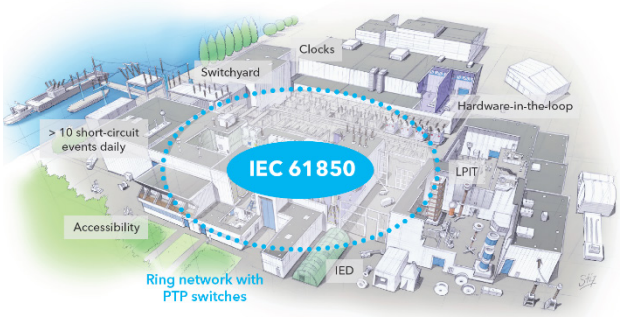


Figure 19: IEC 61850 optical data ring interconnecting four Netherlands test laboratories for testing T&D equipment

The direct electrical control of actuators of switchgear in order to initiate action is being replaced by sending data packages with GPS time stamps - like GOOSE (Generic Object-Oriented Substation Events) messages - to digital interfaces.

Also, the advantages of autonomously switching devices in (overhead line) distribution networks, like auto-reclosers for medium voltage, Wi-Fi-based fault sensing breaking devices, fault current limiters and DC breakers are being recognized.

Apart from the EM compatibility cyber security hazards also need to be considered. Testing/ certifying bodies and laboratories need to expand their scope beyond the classical electrical stresses towards integrated testing, including (components for) communication networks, protection and metering, digital interfaces, low-power instrument transformers (LPIT) etc. [23]. By taking advantage of existing high-power laboratories, a controlled environment for digital system testing can be created, which reduces the costs and risks involved in the implementation of digital substations [22].

Figure 20 shows recently installed low-power current transformers (LPCTs) and optical current measurement in the author's laboratory. Test-methods and circuits are under development [48].

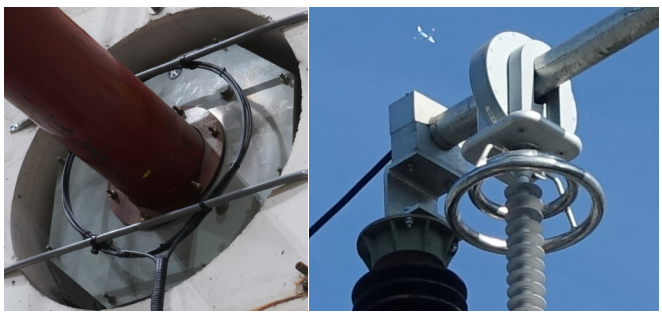


Figure 20: Examples of optical current measurement installed in various locations in the laboratory

Power- (and control) hardware-in-the-loop technology, using a real-time digital simulator, coupled to two 200 kVA power amplifiers has been implemented in the power electronics laboratory now for creating realistic fault scenarios for protection relay testing.

3.6. Resilience and fault mitigation

3.6.1 Mobile substations

Increased dependence on electricity requires the preparedness for catastrophic events like cyber attacks, floods, fires, explosions and, last but not least, pandemic. Floods may arise from sea (tsunami, broken sea-defence), rising rivers or heavy rainfall. Submersible equipment is deemed to be required for underground solutions, where flooding is a risk to be mitigated [24]. Automatic, self-power-restoring switchgear can, to a certain extend, mitigate outages due to dysfunctional MV overhead lines. Critical restoration strategies are being developed to withstand natural events, physical- and cyber-attacks, while advanced data analytics, Artificial Intelligence (AI) and machine learning will provide early warnings to detect and prevent direct attacks.

The availability of mobile HV substations and emergency restoration lines, that can be rapidly deployed after an unintended significant outage greatly mitigates the risk of social unrest and huge compensation claims. Moreover, the deployment for planned outage of certain key grid components/stations makes availability of mobile stations attractive by increasing the operational flexibility of the system [49. Testing options that should ensure the correct functioning of all components of a mobile station, immediately and unconditionally after site assembly are being developed now by major TSOs.

Operational differences with conventional stations are:

- Mobile stations are expected to be used infrequently and for a short time, remaining mostly in idle storage mode. The impact and conditioning of this operation mode must be investigated since manufacturers often advice storage times much shorter than operational times. For example, long storage of GIS can lead to contamination/oozing of grease.
- The transportation, multiple assembly, cable (un) winding, multiple use of cable termination, bushing (dis)mounting causes additional stresses. Nevertheless, the must-run capability must be verified, e.g. by mobile (dielectric) test facilities on site;
- Necessary weight/size reduction (400 kV transformer in a three single-phase configuration, multiple filling, reduced lightning impulse withstand requirements [49]) for the sake of transportability must not compromise reliability and stress withstand capability.
- Equipment must be plug-and-play, fool-proof, maintenance-free, fit-for-purpose and modularly designed to allow assembly by less-experienced personnel as well.
- Mechanical and electrical endurance needs to be ascertained, given the unusual and intermittent stresses and the expected impact on availability. Due to its operation mode, the probability of terminal faults in mobile substations higher is than in permanent substations.
- Since it might be expected that cyber-attacks are a reason to activate a mobile station, tele-control and external data access must be extremely well shielded or even made non-existing.

Functional testing at regular intervals must verify continued availability of the key (standard) components operated in a non-standard manner.

3.6.2 Remote testing

Resilience against the consequence of a pandemic is an issue that popped up immensely and unexpectedly in 2020. The industry adapted practices in various ways in order to continue its services.

For testing laboratories, the main obstacle is that customer crews that usually accompany test objects cannot travel. Therefore, rigorous methods are developed for remote testing. Herein, the test-object is sent to the laboratory while the customers stay in their premises or at home having extensive digital access to the test station, its stationary and mobile cameras, measurement- and communication systems [50], see Figure 21. In many cases, the local laboratory crew can assemble the objects under the designer's close supervision.

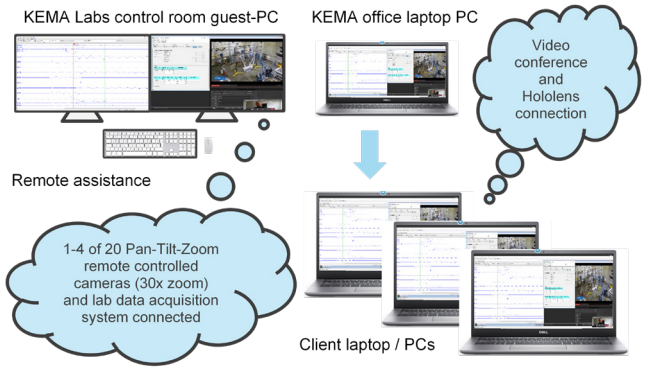


Figure 21: Principle of remote testing [50]

As a part of further and future development, the use of Mixed Reality tools such as HololensTM, might be expanded to Augmented/Virtual Reality (AR/VR) applications. This enables the use of a digital twin technology to directly link the real test-object, subjected to real stresses in the test-laboratory to a model in the manufacturer's digital design platform. This will lead to development of "virtual testing", as an addition to physical testing.

AR applications are already in pilot use in the industry, mainly for maintenance of substations.

For laboratories, having multiple locations in the world, systems are in development to remotely supervise, control and manage testing in satellite labs from a master laboratory.

This way, the limitations enforced by the COVID-19 situation accelerate the "remote testing" technology, at the same time increasing efficiency and reducing costs.

4. CONCLUSIONS

T&D switching technology is going through a massive innovation, driven by the ongoing energy transition and electrification. Independent testing and certification are crucial to the acceptance of new technologies in the market, where reliability and availability are perceived to be under pressure due to cost reduction and globalization.

Drivers that have an impact on switchgear design, operation and maintenance and testing are identified in this contribution: increase of ratings (UHV), offshore application (compactness and low maintenance), HSE (SF_6 alternatives, arc fault mitigation), HVDC and power electronics (HVDC circuit breakers), digitalization (digital protocols and LPIT), resilience (robust switchgear and emergency restoration substations) and recently the COVID-19 pandemic.

The authors demonstrate how their test-facilities and methods are coping with the ongoing innovations in the industry. From every trend, outlined above, examples are demonstrated.

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