Special Report - Session 1
NETWORK COMPONENTS

Christophe BOISSEAU
Chairman - France
christophe.boisseau@enedis.fr

Arnaud ALLAIS
Rapporteur - France
arnaud.allais@nexans.com

Philippe PICOT
Rapporteur - France
philippe.picot@se.com

Introduction

Session 1 deals with all aspects related to the components used in the electricity distribution networks: cables, overhead lines, primary and secondary substations, transformers, switchgear plus their control, protection and monitoring systems, new active power electronics devices. It covers topics related to the life cycle optimisation of assets from design through installation, operation and maintenance, monitoring and diagnosis, to end of life management, including new techniques such as Big Data and Artificial Intelligence. The session also covers environmental aspects including eco-design and life cycle analysis, standardisation, ergonomics and safety for both the operating staff and the public. It aims at providing an overview of the state-of-the-art in component design and proposals for future components, including the ones needed for smart grids, e-mobility, smart cities and microgrids. This session is an opportunity for DSOs and manufacturers to share their objectives.

152 papers have been selected for the Session 1 – Network Components – of CIRED 2019. They have been organized in four blocks, which are the same for both this special report and the Main Session.

The structure retained for these blocks is as follows.
Block 1 "Asset management and condition assessment of Network Components – Cables, lines and associated components" (40 papers):
- New solutions for optimized installation and maintenance for cables and lines;
- Condition monitoring;
- OpEx/CapEx optimization.

Block 2 "Asset management and condition assessment of Network Components – Substations, switchgear and transformers" (40 papers):
- Asset management topics: ageing, behaviour, procurement and upgrading;
- Condition assessment by diagnosis tests and monitoring.

Block 3 "Innovation in Network Components – Cables, lines and new types of components" (34 papers):
- New designs;
- Dynamic rating, thermal modelling;
- Smart metering - energy flow & quality;
- Prospective.

Block 4 "Innovation in Network Components – Substations, switchgear and transformers" (38 papers):
- SF6 alternative solutions;
- New designs;
- Methods and tools for the development of network components.

6 papers per block have been selected for oral presentation in the Main Session (MS), but all the papers can be presented in the interactive Poster Session (PS).
In addition to the Main and Poster Sessions, three Round Table (RT) discussions and a Research and Innovation Forum (RIF) will take place within Session 1.
RT1 "New components for MV and LV DC network and integration in grid planning" (joint RT with Session 5) will discuss the maturity of the components capable of setting-up DC LV and MV networks, as well as the prospects of developing these networks in complementarity with the current ones.
RT2 "Alternatives to SF6: Feedback from field application in MV distribution networks and perspectives" will discuss the performances of identified possible alternatives, their advantages and drawbacks compared to SF6, the remaining challenges, the application of specific solutions in the MV distribution networks as well as the correlation with international standardization work.
RT3 "New sensors and algorithms for condition assessment of network components" will present advances in the performance and cost of sensors, in the generalization of connected objects, and in the availability of analytical techniques for information and big data processing, which open new perspectives for the condition assessment of network components.
Finally, 8 papers, presenting various results from research activity in the field of network components, have been selected for oral presentation and exchanges with the audience during the RIF.

Block 1: “Asset management and condition assessment of Network Components – Cables, lines and associated components”

The 40 papers are organized into 3 sub-blocks:
- New solutions for optimized installation and maintenance for cables and lines (11 papers);
- Condition monitoring (15 papers);
- OpEx/CapEx optimization (14 papers).

New solutions for optimised installation and maintenance for cables and lines (11 papers)

By a careful choice of accessories (cf. paper 0037) and environment (0054) of underground cables systems, one can increase the potential, the security or the safety margins. The limitation of the impact of failure or fault is also a daily concern for utilities and different strategy are proposed to either size the earthing system in urban areas (1497) or to prepare fast replacement by a contingency storage of spare submarine cables (0943).

Fig. 6 of paper 0037: Example of cross-bonding retrofitting on MV joints already in service, black bonding wires are visible.

When addressing long MV overhead lines in area with variable and aggressive climatic conditions, adequate solutions distributed on each pole of safety grounding (2154) and lightning protection (0263) become key to limit outage time and costly maintenance.

To prevent or to detect critical situation regarding overhead lines, the visual inspection is sometimes the only solution. To assist maintenance teams, solutions for always more autonomous monitoring are developed. In the case of broken lines, the low fault current is difficult to detect and recognition by camera has proven to be an easier to deploy alternative (2133). The surveillance of clearance to vegetation is a universal topic especially with climate change. The detection system using ground vehicle (0921), unmanned aircraft (0662) or monitoring of specific point of Interest (0052) are all based on the identification of critical situation assessed by machine learning using field expertise (0052, 0662) or correlation of data from different sources (0052, 0097, 0921).

Condition monitoring (15 papers)

The progress in the miniaturization and standardization of sensors and measurement devices for electrical grid monitoring give now the possibility to deploy IP based multi-purpose system (1189) including PD, High Frequency, earth impedance monitoring (1114) and high resistance connection (99). New levels of flexibility for monitoring system deployment are brought by the low power wide area network (0940) and local energy harvesting (1037), as well as measurement principle using magnetic fields (1128) requiring limited or no grid interruption. Using random forest algorithm allow to sort out PD pattern to prepare automatic recognition in the future (1390). The crossing of data from different sources (electrical, climatic, topological, geographical) is strengthening the conclusions (0099, 1114) and the analysis of history allows to switch from preventive to predictive maintenance (1114).

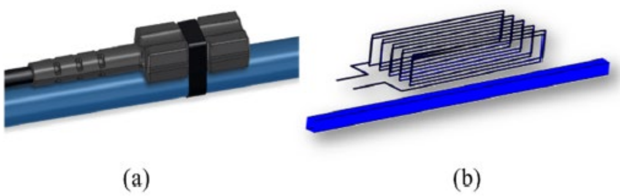

Fig. 2 of paper 1128: Retrofittable PCB current sensor (a) over-molded 3D model, (b) simulation model by MATLAB.

Whatever the progress in the collection of data from the grid, the quality and the correct interpretation of signals are of first importance. The understanding of the physical phenomenon linked to high frequencies pulses and signals propagation in cables (1146, 1492) and real grids structures with branches (1369, 0757) shows that critical information can be deformed or attenuated, and that electromagnetic emissions are carrying a lot of information (1128). The experience of the detection and interpretation of intermittent fault in MV network has been transposed with success to LV networks (0043).

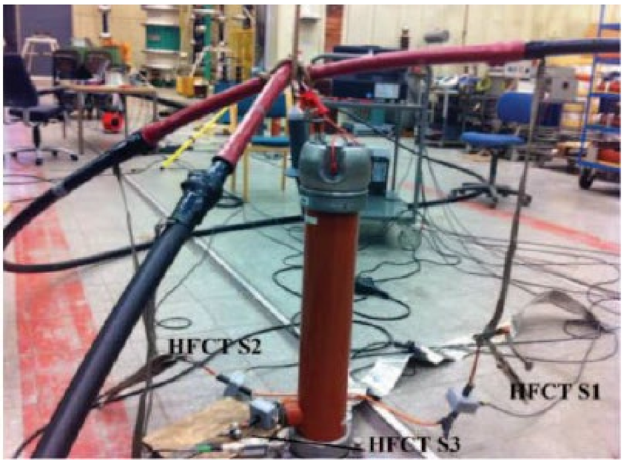

Fig. 3 of paper 1369: Measurement setup for branched (Y) cable joint.

To ensure proper installation conditions, the commissioning checks that the initial level of nondestructive measurement like dielectric losses or PD are below the standards' recommendations. For cable commissioning, PD has been identified as best suited (1866). To ensure commissioning of offshore 66 kV cable system, a modular system has been proposed (1890).

Since energy and telecommunication networks may be adjacent in some locations, the question of interference has been addressed when fault localization systems are used but the conclusions are reassuring (1149).

OpEx/CapEx optimization (14 papers)

Building and validation of predictive tools for distribution grids require the combination of real conditions data, ageing behaviors of critical components and the recorded failure data. The risk mapping coming from the predictive tools is used to optimize the timing and the type of investment (1739).

The most critical components are the less accessible like underground cable systems (0415, 0597, 0807, 1123) or the more exposed like poles (0569, 0774) or outdoor systems sensible to climatic conditions (1768).

The risks could also come from no longer valid hypothesis used for installed components designs, like ambient temperatures (1718).

The analysis of the outage records combined with the topology or the monitoring data is used to generate a risk mapping. Even if a failure rate as a function of the cables ages gives a trend, it is useful to have more precise information about the operating conditions and maintenance history of the cable, like for PILC cable in Denmark (1123).

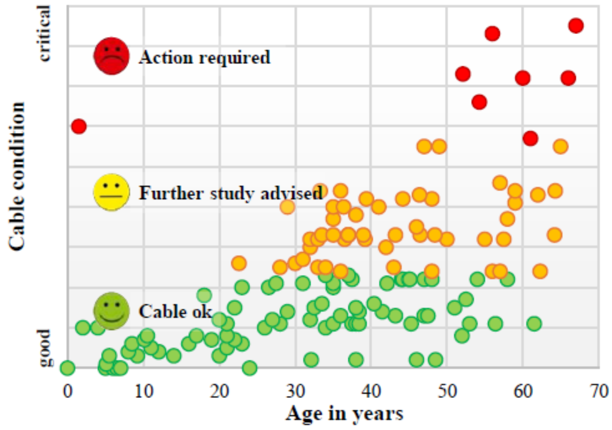

Fig. 1 of paper 0807: Distribution of cable condition versus duty period.

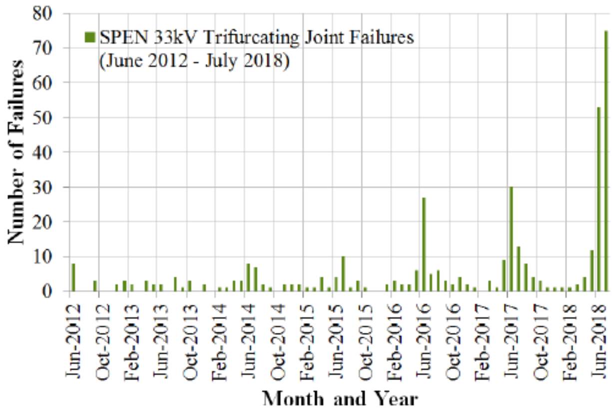

Fig. 1 of paper 1718: Trend of SPEN 33 kV trifurcating joint failures (June 2012 – July 2018).

The PD monitoring data allow a categorization of MV cable branch in term of risk (0535). The interpretation of the interruption data of the LV network produces a relative failure probability for each asset (0415).

A special care to the use phase of products and system secures the lifetime as well as the environmental footprint of components, such as bus bars (0694). Call for tenders are ideal opportunities to start a virtuous circle by introducing incentive to offer optimized grid components using recycled materials and reused parts (1749).

With the development of local electricity storage in combination with intermittent renewable energies, the batteries lifetime is becoming a key part in the viability of the system and of the OpEx/CapEx equation (1980, 1747).

Table 1 (first part, continued next page): Papers of Block 1 assigned to the Session (in numerical order)

Paper No. Title	MS a.m.	MS p.m.	RIF	PS
0037: Cross-bonding for MV cable systems: advantages and impact on accessories design				X
0043: Field study of intermittent faults in low-voltage underground cable systems	X			X
0052: Automated visual inspection – comparing computer vision to machine learning				X
0054: Dry zone formation surrounding underground medium voltage cables during load cycling				X
0097: A risk-assessed approach to overhead line corridor clearance management				X
0099: The application of advanced data analytics to smart meter data				X
0263: Lightning protection of unshielded overhead medium voltage power lines in South Africa				X
0415: Interpretation of statistical analysis on LV asset condition				X
0535: Asset management of HV cables on an electricity distribution network using on line condition monitoring				X
0569: The THOR hammer tester - a step change in the management of wooden utility pole assets				X
0597: Tracking the degradation of polyethylene insulation in medium voltage power cables				X
0662: A disruptive method for vegetation management on Enedis' medium voltage overhead lines		X		X
0694: Material efficiency for circular economy: from assessments to optimizations				X
0757: Measuring PD propagation in complex MV distribution network configurations	X			X
0774: Utility pole deterioration modeling by machine learning with big data of distribution facility inspection result	X			X
0807: A new approach for evaluating the condition of cable systems and estimation of remaining life time of MV underground power cables				X
0921: Automated identification technology of trees endangering to distribution facilities by using mobile mapping system				X
0940: Distribution surge arrester monitoring	X			X
0943: Standardization and contingency storage for submarine cable systems				X
1037: Energy harvesting technology applicable to distribution line				X

Table 1 (continued, last part): Papers of Block 1 assigned to the Session

Paper No. Title	MS a.m.	MS p.m.	RIF	PS
1114: Pioneer earth systems remote monitoring for secondary distribution substations				X
1123: Use of fault statistics for the management of aging medium voltage PILC cable systems				X
1128: Condition monitoring of surge protective devices by measuring the magnetic field of discharge currents in power distribution systems	X			X
1146: Characterization of the frequency-dependent transmission losses of the grid up to 500 kHz			X	X
1149: Impact of fault localization on MV cables on adjacent telecommunication cables				X
1189: Research and application of distribution network equipment remote monitoring and fault diagnosis system based on passive wireless technology				X
1369: Propagation characteristics of partial discharge signals in medium voltage branched cable joints using HFCT sensor	X			X
1390: Feature selection for partial discharge and interference recognition in HV cables based on random forest method				X
1492: Frequency response of a real cable network and its impact on field PD measurements				X
1497: Practical method for global earthing system determination of the urban area				X
1718: Ambient temperature influence on cable trifurcating joint failures				X
1739: Optimizing network replacement with AI				X
1747: Investment decision-making using probabilistic life cycle costing – comparing flooded lead-acid and lithium ion batteries for power supply backup in substations				X
1749: Integrating circular economy in asset management: a case study on circular asset development				X
1768: Deterioration trend analysis utilizing environmental data and asset management: the case of porcelain cutout				X
1866: Condition assessment of medium voltage underground cables based on tangent delta and partial discharge measurements				X
1890: On-site testing of 66 kV subsea array cables for off-shore windfarms				X
1980: A battery testing toolbox for real-world operating conditions				X
2133: Autonomous monitoring system for the detection of disrupting power cables on distribution networks using computer vision techniques				X
2154: Low voltage overhead distribution neutral wire multi-grounding by poles (NGP)				X

Block 2: "Asset management and condition assessment of substations components"

The 40 papers of this block have been organized in the following two parts:

- Asset management topics: ageing, behaviour, procurement and upgrading (21 papers);
- Condition assessment by diagnosis tests and monitoring (19 papers).

Asset management topics (21 papers)

The first part of this block deals with the following aspects of asset management for these components (substations, switchgear, transformers): ageing, behaviour, procurement and upgrading to "smart" (four sub-blocks).

The first sub-block (8 papers) addresses the ageing topic from different perspectives: ageing behaviour, modernization of the installed base (e.g. retrofit), end of life management.

Paper 1129 entitled "Ageing behaviour of medium-voltage substations" is a good introduction to this sub-block: it reports the progress done in a long-term research project led by the University of Wuppertal in collaboration with German DSOs, in order to get a more accurate knowledge of the ageing behaviour of MV/LV transformer substations, which represent a major part of the assets in distribution grids. Aggregation of many inspection results of aged substations in service, and of measurements made by laboratory testing for a large number of decommissioned aged components, allows to derive reliable condition-dependent ageing curves for these substation components. The work is on-going and will eventually provide the corresponding failure rate ageing (so-called "bathtub") curves of the components that can be used as inputs in asset simulation tools to optimize the maintenance and replacement strategies.

The 2nd paper 1333 presents the results of investigations and tests performed at the IPH Institute in Berlin on decommissioned MV circuit-breaker switchgear rated 12 kV – 16 kA of two different design types with ages of respectively about 25 and 50 years. The tests results of these aged switchgear were relatively satisfactory for insulation withstand and breaking capacity, but demonstrated a loss of performance in terms of short-circuit current withstand: these failures are attributed partly to ageing, but also to some initial design flaws or inappropriate maintenance. The internal arc protection provided by these old designs has also been tested and is clearly not at the level currently required for internal arc classified (IAC) switchgear. These findings lead the authors to question the validity of a retrofit approach consisting in the replacement of circuit-breakers in old switchgear for several reasons such as: the weakening of insulating supports due to ageing, the trend towards increasing levels of short-circuit current in the system, the difficulty to type test and validate the performance of a retrofitted switchgear on site.

Some of these concerns are addressed in the next paper 0384 which presents a retrofit solution that has been applied to a large installed base of obsolete MV switchgear in a petrochemical plant in South Africa. Using the "retrofill" concept (cf. figure 4 below), vertical racking bulk oil circuit-breakers and fixed contactors have been replaced by up-to-date horizontal racking vacuum circuit-breakers and contactors. Thanks to the availability of some original switchgear panels in warehouse, it has been possible to fully type test the retrofit solution. Although the old structure cannot be brought up to current standards in terms of internal arc classification, major improvements in terms of safety and operational hazards mitigation have been achieved through: the replacement of oil circuit-breakers by vacuum ones, closed door rack in operation, exhaust vents added to the rear section of the switchgear and the availability (in option) of motorized rack in.

Fig. 4 from paper 0384: Vertical racking bulk-oil circuit-breaker (A) and the retrofill installation steps (B to E).

Another aspect of retrofit is shown in the paper 1587 which describes the new solution used by Enedis to upgrade the protection and control system of their HV/MV substations from the hard-wired analog electronics to the current digital technology (PCCN) without going through complete replacement. The "mini-PCCN" approach integrates several modules of the PCCN system (such as supervision, automation, tariff management) to the existing protection panels by means of a specific interface which digitizes the input/output signals from these panels: the "smart terminal block" (shown in figure 5 below) on which the existing hard-wired connectors can be plugged-in, without requiring any wiring modification. The implementation of the "mini-PCCN" solution can be done quickly, with minimum disruption to operation, and allows flexibility in the future evolutions of older substations: towards full PCCN system, integration of advanced smart grids functions, migration to IEC 61850 communication, asset management tools.

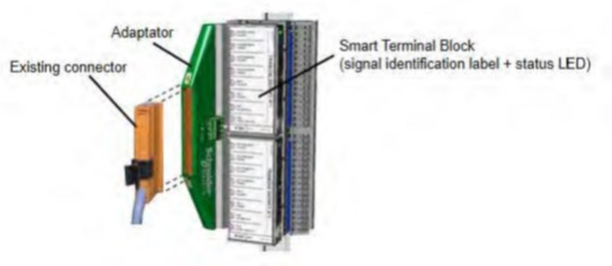

Fig. 5 from paper 1587: Existing connector plug and smart terminal block with adaptator.

Another type of retrofit problem is discussed in paper 2089 which proposes a new solution for replacing transformers by new ones compliant with the Tier 2 requirements of EU Regulation 548/2014 in existing compact substations where it is not possible to accommodate significantly larger transformers than the existing ones. Using a de-rated transformer (e.g. 125 kVA in replacement of a 160 kVA one) with higher temperature insulation (enhanced paper and ester liquid) would allow to keep same size and operating life. In addition, for rural network with low average loading factor, the total cost of ownership (TCO) of these transformers would be lower than for conventional Tier 2 transformers of same rating.

The last 3 papers of this first sub-block deal with the end of life management of transformers.

Paper 0417 presents the methodology applied by Edenor for prioritizing the replacement of ageing HV oil instrument transformers. It is considered that normal diagnosis alone (oil analysis and tan δ (TD) measurement) is not sufficient for prediction of the remaining life of transformers. Therefore, reliability indicators (or risk indices) were determined for the fleet of instrument transformers (about 1000 units) by taking into account not only their age in service, but also other criteria (voltage level, type of substation, background of failures for transformers of same type, possibility of performing diagnosis tests). The ranking of the whole fleet according to these indicators has allowed to determine a replacement strategy (over 5 years) that is optimized in terms of cost and improvement of the reliability of the HV network.

Paper 0865 presents the end of life evaluation process put in place by SP Energy Networks for decommissioned power transformers. The main results of this activity over an 8 years period are summarized: the predictions of diagnostic tools used during the life of transformers (e.g. dissolved gas analysis (DGA)) can be compared to their actual conditions, and their adequacy confirmed or questioned; some common or recurrent issues can be identified for some types of transformers, allowing to take preventive measures for those which are in service. The costs of these forensic inspections are to be put in relation with the benefits of an improved understanding of the condition and ageing characteristics of these transformers, which helps in optimizing their maintenance and replacement strategy.

A similar approach has been applied by EDP Distribuição to selected decommissioned power transformers: it is discussed in paper 1187. The measurements of water content and degree of polymerization for paper samples taken from these transformers have been correlated with the maximum level of 2-FAL marker recorded in DGA during their lifetime. The correlation curve obtained (from these measurements and confirmed by a theoretical curve) can be used to determine the remaining useful life of transformers in service from the 2-FAL values, thus allowing to make informed decisions about their replacement or refurbishment.

The next sub-block (4 papers) discusses the lessons learnt from the behaviour of various components in the network.

Paper 1312 presents the preliminary results of the investigations performed by the CIGRE working group A3.38 on the performance of shunt capacitor bank switching devices in the field. This new survey updates the previous 1999 CIGRE report on the same topic and provides more information about application in MV distribution networks and the relevancy of capacitive switching classes C1 and C2 introduced in the HV circuit-breaker standard IEC 62271-100 in 2001. Although the overall performance of capacitor bank switching devices is considered satisfactory by HV and MV users it should be noted that a significant amount of dielectric failures occur that are probably caused by restrikes at current interruption. Attention should be given to the fact that class C2 type tests represent only about 500 operations in the field, well below the thousands of operations typically performed by these switching devices: therefore, to prevent such failures, it is recommended to increase the use of inrush current (that can cause damages to the contacts, cf. figure 2 below) limiting inductors and of surge arresters.

Fig. 2 from paper 1312: Modification of the surface of vacuum interrupter contacts due to making operations.

In another domain, paper 0110 reports on electromagnetic transients simulations performed to investigate the residual magnetic flux in a transformer switched-off under fault conditions. It is shown by these calculations that the residual magnetic fluxes will vary depending on the fault conditions (single phase to ground, or phase to phase) and the timing of interruption by the circuit-breaker (at current zero or by current chopping shortly after separation of the contacts). The applicability of these results to improve the controlled switching strategies for mitigating high magnetizing inrush currents when re-energizing power transformers will be the subject of further work.

The next 2 papers are related to the ventilation of transformer substations.

Paper 1735 reports the results of a continuous thermal measurements campaign conducted in a (relatively) highly loaded building type MV/LV transformer substation of the French DSO Enedis, from March 2017 to March 2018. Analysis of the temperature measurements, and consideration of the thermal balance terms for the substation, show that the existing ventilation system is only efficient in case of high transformer loading and cold outdoor ambient temperature. Improvements of this ventilation system would be necessary to cope with high loads during hot periods (e.g. air conditioning) or with the anticipated increase of loads due to new applications (like EV charging).

Paper 2300 addresses this specific issue of high loading of transformer substations occurring during the hottest period of the year (in Iran). In this case the experience of existing indoor substations and thermal modelling confirm that natural ventilation may not be enough: a forced ventilation system with ducts and an extractor hood above the transformer was successfully implemented, providing a more cost-effective solution than upgrading the transformer to a higher rating.

The next sub-block (3 papers) addresses various aspects of the procurement process, and in particular of the evaluation of offers in the light of the experience gained from the installed base of components.

Paper 0835 shows how environmental impacts could be more effectively integrated in the procurement process of DSOs in order to foster sustainability in their asset management policy. To achieve this target, two challenges have been addressed successfully: (1) a simplified life cycle assessment (LCA) model has been developed, that can provide valid impacts assessment while requiring only limited input parameters (already available in the existing tendering process); and (2) monetization of the endpoint environmental impacts that can be added to the total cost of ownership (TCO) to obtain a true cost indicator (TCI) that is taken into account among the other tender criteria. This promising approach has been verified by applying it to past tender data, showing that it is practical and could have changed the assessment: it will be tested in upcoming tenders at Liander. This could allow to escape from a “Catch-22” situation where manufacturers have few environmentally friendly assets to offer because DSOs are not including these factors when evaluating their asset acquisition decisions.

The next paper 1593 presents the quality control activities that Enel is implementing to increase the quality and long-term reliability of the “smart” electronic components and systems. Field experience and failures show that improvements are needed to master the quality level of the production process and better define the reliability targets and mission profiles for these types of components.

Finally, the 3rd paper 1009 explains how the methodology of life cycle cost (LCC) analysis can be applied to select between two different types of on-line DGA monitoring systems for power transformers: in the case considered, the results show that the chromatography type presents a lower total cost of ownership (TCO) than the infrared type, in spite of larger initial capital cost and periodic need of consumables, thanks to its longer operating life expectancy (15 years versus 10 years).

The last sub-block (6 papers) of this first part discusses various ways of upgrading the network to the “smart grid” level.

Paper 1843 presents a comprehensive study performed by Enedis and EDF R&D division to assess different solutions for voltage regulation in LV networks: reactive power compensation at the level of producers or by specific devices, MV/LV transformers with on-load tap changers (OLTC, on the MV side) and LV online voltage regulators. 3 types of transformers with OLTC and 2 types of voltage regulators have been investigated and tested by EDF R&D. The outcome of this review is that currently the needs of voltage regulation on Enedis LV networks can be covered by reactive power management at the level of producers: however, the expected increase in PV generation and EV charging loads may require the application of specific components (such as transformers with OLTC and/or voltage regulators) in the future.

Paper 1030 describes the new solutions implemented by Tata Power for substations in Mumbai city in order to address the different challenges of footprint reduction, fast installation and commissioning, and energy supply at competitive tariffs to low end consumers. Some of them are already known (like E-house prefabricated substations for primary distribution, or padmounted substations for secondary distribution), others are more specific and original (like 3-levels primary substation, or “multi civic amenities” substations: cf. figure 7 below).

Fig. 7 from paper 1030: Architectural view of multi civic amenities substation during initial planning.

Paper 0541 explains what should be, from a DSO’s perspective, the new features and requirements for the 33/11 kV primary distribution substations of the future: safer by using synthetic ester instead of oil for transformer insulation (less flammability); environment-friendly by using SF6-free solutions for switchgear (air insulated switchgear (AIS) with vacuum circuit-breaker for 11 kV, gas insulated switchgear (GIS) with low GWP alternative gas for 33 kV); digital protection, control and communication systems for efficient engineering process and flexibility; comprehensive online monitoring systems and data analytics to allow preventive maintenance and improve the reliability and availability.

Paper 1613 introduces an additional step in the deployment of the smart (digitized) secondary substations in the networks. In the first step adding local intelligence and communication capabilities in the substations was for the purpose of introducing some smart grids features such as distribution automation, automatic network self-healing, power flow control and advanced meter management. It is possible to go further and allow also better asset management through diagnoses and online condition monitoring, by adding to the smart substations some complementary sensors (and data analytics) to gather relevant information for assessing the health condition of the main components in the substation. For instance, in the case of MV gas insulated switchgear, based on the knowledge of the main failure causes, it is proposed to add: partial discharges (PD) monitoring, gas density, service conditions and dedicated auxiliary contacts for mechanical condition assessment.

The next paper 0573 presents a new approach for the LV switchgear of MV/LV transformer substations, extending some of the smart features already deployed at the MV side, such as: voltage and current monitoring, remote control of switchgear, condition monitoring for asset management, communication capabilities. Pilots of this new generation of LV switchgear are being tested in the Enel Smart City Network in Malaga: in addition to the smart features listed above, they also bring improvements in terms of safety (arc-fault protection and fire hazard) and have been designed to allow easy retrofit of existing installations (without modification of the LV cables connections).

Finally, paper 1188 reports the first results of a pilot project launched in Viesgo network, consisting in the “smartization” of 200 existing secondary substations, by adding a low voltage control box (and sensors, or power analysers) to make these substations visible in the grid control room. The hardware and software architectures of the solution are explained. Some of the main improvements brought by this project are in the fields of transformer load information, power quality monitoring in the LV network, and alarming (to prevent critical situations).

Condition assessment (19 papers)

The second part of this block regroups the papers dealing with testing and monitoring (i.e. online continuous testing) methods for the condition assessment of substations components. It is organized in two sub-blocks for respectively switchgear (7 papers) and transformers (12 papers).

Paper 2017 provides a good introduction to the first sub-block: it can be considered as a kind of executive summary of the report published in 2018 by the CIGRE/CIRED joint working group (JWG) A3.32 on the non-intrusive condition assessment methods (NICAM) applicable to HV and MV switchgear. It introduces the notion of usefulness of a specific NICAM as an indicator of the economic benefits it can bring through the reduction of failure probability for aged switchgear (cf. figure 1 below). The results of a comprehensive survey among 49 utilities (in 18 countries) indicate that most of them are convinced by the economic interest of condition assessment methods and are deploying in priority those which are easy to use and do not require expert system for analysis. A review of the main relevant NICAM for MV switchgear is presented: from those which are already standard practice or commercially available (like partial discharges (PD) monitoring, evaluation of wear due to mechanical and electrical operations) to those which are still in development (like vacuum condition monitoring, analysis of vibration signals during operation).

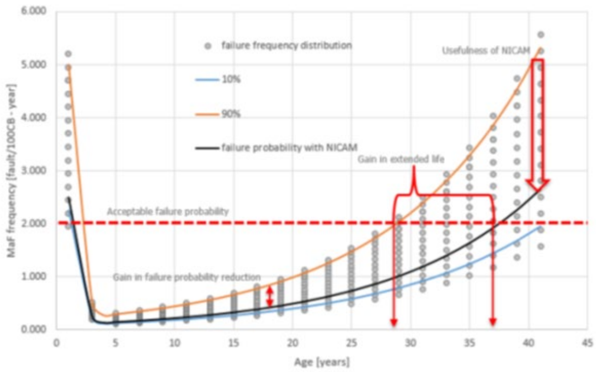

Fig. 1 from paper 2017: Principle representation of frequency of major failure and failure probability curves as a function of the age of asset.

The next paper 0884 describes the forthcoming evolution towards smart and digital switchgear, in particular MV circuit-breakers. Embedded sensors, local intelligence and communication capabilities will allow advanced monitoring and improved asset management, not only for the high-end controlled switching circuit-breakers, but also for the conventional ones. The proposed overall asset management system architecture is organized in three layers, as shown in figure 5 below, from connected products to cloud-based analytics and services, through the intermediate edge control layer.

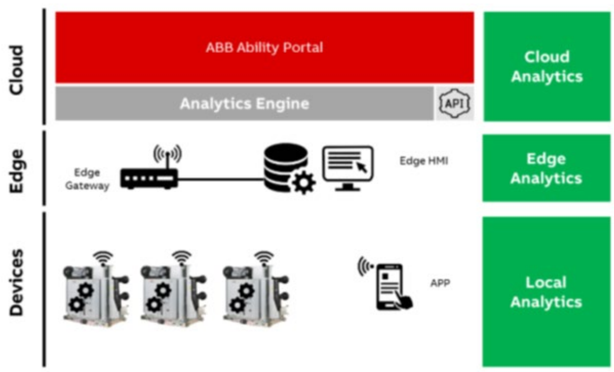

Fig. 5 from paper 0884: The three main system levels embedding from local to cloud services.

The technology trends in IoT (Internet of Things) sensors and intelligent electronic devices (IED) are presented: it is expected that new hardware and software platforms from consumer electronics (mobile devices) will be adopted and bring advantages in terms of computing power, wide range of accessories, operating systems, cybersecurity and cost. To implement the functionalities required at the connected circuit-breaker level a new type of IED, the central monitoring unit (CMU), will be embedded in the apparatus, providing the functions required for collection of data from the sensors, transfer to the cloud and also local computation capabilities for more efficient processing of the data. After presentation of this manufacturer's perspective, the paper calls for an open dialog between users and manufacturers to assess the proposed approach and move forward to the next generation of smart switchgear.

Another manufacturer's perspective is given in paper 2324 which presents a smart MV solution (online condition monitoring system) proposed for vacuum circuit-breaker (VCB) and switchgear. The indicators retained for assessing the condition of VCB are: time-travel characteristics of the drive mechanism, wear of the vacuum interrupter contacts (measurement of the wipe spring compression), current waveforms for the shunt trip release and charging motor. In addition, temperature measurements and thermal imaging are provided for the switchgear. Data analytics and a mobile application allow the user to have access to monitoring, diagnosis, control, maintenance and documentation services.

Paper 0093 presents new solutions implemented to progress from periodic diagnostic measurements (the trip coil current "signature") of MV circuit-breakers to permanent monitoring and automated analysis of the data, in order to predict and identify upcoming failures. These solutions consist in, for one part, a current sensor and acquisition system connected in series with the auxiliary power supply of the circuit-breaker and, for the other, a machine learning model able to predict 7 different types of failures from the features of the acquired data, with an accuracy higher than 92%.

The remaining 3 papers in this sub-block are related to the topic of partial discharges (PD) monitoring applied to switchgear.

Paper 0383 presents a new online PD monitoring system developed for easy installation inside air insulated switchgear (AIS) already in service ("brownfield" application). The two retained PD sensing principles are transient earth voltage (TEV) and capacitive coupling through the existing voltage presence indicating system (VPIS) dividers: both have been confirmed (by testing and simulation) to be suitable for PD detection even when long cables are connected to the switchgear. An alarming system has been developed to tackle the challenge of exploiting the online monitoring stream of data in order to provide useful indications to the asset manager: it is currently under field testing for validation.

Paper 1521 presents a new online PD monitoring solution applicable to MV secondary distribution switchgear such as ring main units (RMU). Radio-frequency current transformers (RFCT) or TEV sensors are used for the PD signal acquisition: the main advantage of the proposed system is the sophisticated signal processing (transposed from HV application) which performs clustering of the individual PD sources (cf. figure 1 below): alarming is done only in case of confirmed increasing trend, thus avoiding the false positive warnings that may happen with other online PD monitoring systems for MV grids.

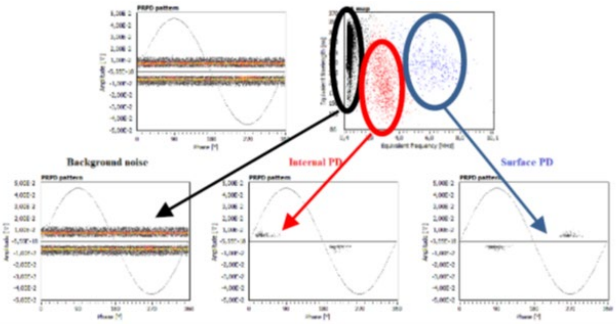

Fig. 1 from paper 1521: Example of separation of signals by means of the T-F map clusters.

At this stage it is worth mentioning also the paper 1714 which is listed elsewhere, in block 4, for the part in this paper which presents investigations performed to compare the performances of different types of internal PD sensors for continuous monitoring of gas insulated switchgear (GIS): UHF wireless sensors have been noted as a suitable solution for detecting all types of discharges inside a GIS tank.

Finally, PD testing (not monitoring) is discussed in paper 2260 which presents experience of PD measurements on solid insulation switchgear (SIS, in this case outdoor reclosers) in substations. Both off-line and online measurements were performed, using PD foil sensors (as described in the previous CIRED 2015 paper 1436) applied on the recloser poles insulation. These experiments show that it is possible to perform PD measurements in the field, but also that sophisticated signal processing is necessary to extract the PD sources from disturbances and background noise, and that PD expert analysis is still necessary for relevant diagnosis. The next enhancement of this PD test method will be the development of sensors that can be placed on live switchgear, without requiring a power outage.

The first 8 papers in the next sub-block are dealing with the monitoring and modelling of transformers.

Paper 1821 presents the new online monitoring solution that is being deployed by Enedis for their fleet of HV/MV substation power transformers. This home-made solution is targeting, on one side, improved maintenance (monitoring of cooling system, breather system, on-load tap changer (OLTC)) and, on the other, prevention of failures (hydrogen detection by dissolved gas analysis (DGA)). At this early stage of deployment (75 installed on a total of 1000 by the end of 2022) the monitoring system has already demonstrated benefits in the prioritization of maintenance activities; in the long-term big data analytics will allow to characterize each transformer by its health index and improve the operating and maintenance model of Enedis for these strategic components.

Paper 1931 reports on the first part of an innovation project launched by Electricity North West (ENW) in UK to assess the benefits of continuous monitoring for on-load tap changers (OLTC): in the period 2017-2018, 42 power transformers were equipped with these monitoring systems and the data collected (tap positions, loads, motor currents, temperatures, vibrations and acoustic signatures) are under analysis to detect correlations and anomalies. The first results are that simple threshold alarming is difficult to implement due to the large variability of some recorded parameters in normal conditions: it is therefore proposed to apply machine learning (ML) algorithms in order to detect anomalies in an automated way. The next step of the project will consist in testing the validity of the developed ML algorithms.

Paper 1924 describes the development and prototyping of a new non-invasive and self-supplied “multi-sensor” for online remote condition monitoring of MV/LV distribution transformers. This device has the following features: mounting on the external top surface of the transformer tank, PD detection by ultrasound and UHF sensors, oil temperature measurement, noise monitoring, energy harvesting by thermoelectric generator, Bluetooth LE communication with the secondary substation gateway.

Paper 1479 discusses monitoring systems that can be implemented for distribution transformers. The parameters to be monitored are mainly the electrical values and temperatures. Data analysis can be performed at different levels, from basic alarming when some thresholds are exceeded, to advanced algorithms that can exploit multiple simultaneous parameters, combined with time, to determine trends and provide inputs for preventive maintenance and optimized operation. The distribution transformer monitoring is considered as an integral part of a global “digital monitored substation” system.

Paper 0887 presents the latest developments in the “soft sensor” solution (for monitoring of transformers) presented in previous CIRED conferences, which consists in an electrical and thermal model of oil distribution transformer embedded in a smart meter, that allows to determine oil temperatures and ageing rates from the electrical parameters measured by the meter only. In its last evolution this model is also capable of accurately predicting the temperatures in the case of non-linear loads with high harmonics content. To achieve this the model uses as additional electrical inputs two power quality indices calculated in real time by the smart meter.

Paper 1744 reports on the thermal modelling of oil power transformers in order to evaluate the possibility of increasing windfarm generation without upgrading the existing transformers in MV distribution grids. Comparisons with measurements of oil temperatures performed on a wind turbine generator (WTG) transformer in two different periods of 2017 (winter and summer) have shown that the “Susa” thermal model can be retained for this evaluation. In the case of this WTG transformer this model indicates that it is possible to increase by 45% the wind power generation without reducing its design life time: this safety factor is also probably applicable to similar transformers in the MV distribution grids, allowing to consider a higher level of wind power integration without reinforcement of these components.

Paper 0676 presents a new method for temperature monitoring of oil transformers able to provide early warning in case of oil temperature defect. A predicted oil temperature, determined from input parameters (such as power, ambient temperature, etc.) by a model based on a machine learning (ML) algorithm, is compared to the measured oil temperature: deviation between prediction and measurement can be used for providing an alarm about a defect in the transformer, well before the limits of oil temperature have been reached.

Finally paper 0658 presents a new online monitoring system under development for HV oil insulated current transformers. The diagnosis is based on the value of tan δ (TD) determined from the voltage and leakage current measurements. Taking in consideration also the oil temperature a constant α is computed, which gives an indication of the condition of the HV current transformer insulation.

The last 4 papers in this sub-block are related to different types of transformer testing.

The first 2 papers, from the same company, address the topic of transformer testing respectively in factory (routine tests at the end of production) and on-site.

Paper 1881 describes a new automated testing system for routine tests of distribution transformers. To reduce and optimize the testing time, automation is applied at different levels: acquisition of the test parameters from the identification of the transformer, switching of the test connections between the different required configurations (by means of specially designed motor-operated HV disconnectors with very high mechanical endurance), export of the acquired test data to the documentation. Integration of the automated testing equipment in the enterprise resource planning (ERP) software will in addition support the implementation of statistical process control (SPC) by connecting the test data with product design data, production data and documentation.

Paper 1865 describes the development of a new portable test source system for on-site testing (induced voltage and

PD) of distribution transformers. This requirement has emerged due to the premature ageing of some wind turbine generator transformers (which are subjected to additional stresses due to harmonics from the power converter). The test system is compact and easily transportable (in several cases): it has been successfully field-tested in the demanding conditions of wind turbine nacelles (cf. figure 9 below). A further extension of the test system is under way to expand its application also to losses, short-circuit impedance and temperature measurements to be done on-site for distribution transformers.

Fig. 9 from paper 1865: Working conditions at a wind turbine nacelle.

The next paper 0697 reports on a research work performed to evaluate the suitability of sweep frequency response analysis (SFRA, already applied to power transformers) for detecting different types of mechanical or electrical damages in distribution transformers. The outcome of these investigations is that SFRA is indeed an effective method of condition assessment also for distribution transformers, even if some operator training and experience are needed for proper interpretation of the deviations between the measured and reference SFRA curves. It is therefore recommended to include SFRA in the type testing of distribution transformers, in order to ensure the availability of SFRA reference curves for the different types of transformers used in the network.

Finally paper 0227 presents an original testing method developed for the purpose of detecting fraud as regards the winding conductor material for dry-type transformers: in some cases, aluminium winding transformers are sold as copper winding transformers, and visual inspection alone is not sufficient to find the difference. A winding material identification system has been designed and successfully tested: its operation is based on the thermoelectric effect (used for temperature measurement with thermocouples) which occurs when junctions of different materials are submitted to different temperatures.

Table 2 (first part, continued next page): Papers of Block 2 assigned to the Session

Paper No. Title	MS a.m.	RIF	PS
1129: Ageing behaviour of medium-voltage substations	X		X
1333: Investigations at operational aged switchgear with the age up to 50 years			X
0384: Installed base modernization and monitoring solution at a petrochemical company			X
1587: Digital remote IOs to simplify substation retrofits & upgrades: Enedis PCCN example			X
2089: Mitigation of lock-in effect for compact substations with transformers meeting future EU efficiency regulations	X		X
0417: Criteria to prioritize the replacement of HV instrument transformers in a distribution utility: a practical approach			X
0865: End of life evaluation of power transformers			X
1187: Forensic studies on 9 teardown power transformers - correlation between DPv paper and 2-FAL and extrapolation to estimate the remaining useful lifetime of relative transformers in service			X
1312: The performance of in-service shunt capacitor switching devices as investigated by CIGRE WG A3.38			X
0110: Residual magnetic flux at transmission accident for three phase transformer			X
1735: Thermal measurement on a HV/LV substation installed in a building: study and thermal balance on ventilation			X

Table 2 (continued, last part): Papers of Block 2 assigned to the Session

Paper No. Title	MS a.m.	RIF	PS
2300: Practical study on ventilation & cooling of MV distribution substations and providing effective ventilation solution			X
0835: Integrating sustainability in asset management decision making: a case study on streamlined life cycle assessment in asset procurement	X		X
1593: Quality and reliability of smart grid components			X
1009: Life cycle cost analysis of online dissolved gas analysis monitors			X
1843: Study of new smart technical solutions for voltage control of LV distribution networks in France: tests and performance analysis of LV regulators and MV/LV transformers with OLTC	X		X
1030: Compact solutions for electrical installations in urban infrastructure			X
0541: Smart distribution substation design for a sustainable and efficient DSO model			X
1613: Smart secondary substation: a reality and a big opportunity for innovative solutions for predictive maintenance and life extension	X		X
0573: New generation of smart LV switchgear and controlgear assembly			X
1188: MV/LV transformer substations monitoring gives rapid response to faults (case studies-new technologies)			X
2017: Overview of non-intrusive methods for switchgear condition assessment (CIGRE/CIRED JWG A3.32)			X
0884: Towards smart digital circuit breakers enabling advanced control and diagnostic features			X
2324: Smart solution and application for MV class switchgear			X
0093: Fingerprinting made easy by machine learning			X
0383: Partial discharge alert system in medium voltage switchgear	X		X
1521: On-line PD monitoring of medium voltage assets: an innovative approach to improve asset management			X
2260: Field PD testing on solid dielectric MV switch			X
1821: Online monitoring of large fleet of substation power transformers			X
1931: Anomalies in on-load tap changers: failure prevention through continuous monitoring and advanced data analysis techniques			X
1924: Smart distribution transformers: non-invasive sensing to enable business transformation			X
1479: Distribution transformer integration in eco-grid			X
0887: Distribution transformer modelling and monitoring			X
1744: Dynamic thermoelectric modelling of oil-filled transformers for optimized integration of wind power in distribution networks			X
0676: Research on intelligent diagnosis method of oil temperature defect in distribution transformer based on machine learning			X
0658: Asset management application: instrument transformers online monitoring system			X
1881: Automated testing of distribution transformers and utilization of test information			X
1865: On-site testing of distribution transformers			X
0697: Sweep frequency response analysis test as tool for distribution transformers management			X
0227: Identification of copper or aluminum for winding material of dry type transformer			X

Block 3: "Innovation in Network Components – Cables, lines and new types of components"

The 34 papers are organized into 4 sub-blocks:
- New designs (13 papers);
- Dynamic rating, thermal modelling (3 papers);
- Smart metering - energy flow & quality (8 papers);
- Prospective (10 papers).

New Designs (13 papers)
To ensure reliability of underground cable solutions, comparative performance tests and analysis are carried when new insulation material is proposed like for thermoplastics (1601, 1606) or when no standard or recommendation has been issued like for ground screen connection (0409). By integrating an eco-design approach in the early development phases, it was shown that we can reduce by a factor of 2 the environmental impact of an elbow connector (1033).

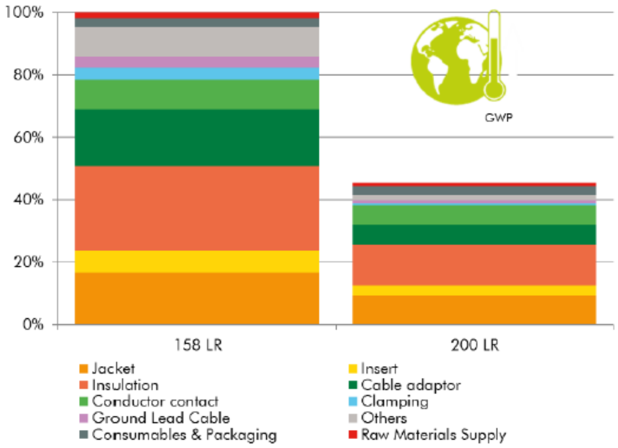

Fig. 9 of paper 1033: Comparison on the global warming potential of the manufacturing phase for elbow connector by using eco-design in the early development (200LR) or not (158LR).

The robustness of existing solution for cable joint can also be improved through the strengthening of interface (0709) or by assessing the real deformation and stress through optical sensors (1366). New installation or repair could be the occasion with simple approaches to improve the reliability of temporary connection (1528) or to envisage to use ducts or spacers to allow respectively easier monitoring (1642) or higher rating (1944).

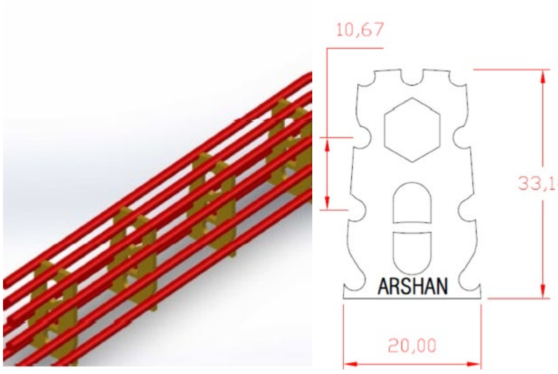

Fig. 3 and 4 of paper 1944: "Arshan spacer design" provides arrangement of cable adapted to smaller trench.

The MV overhead line are exposed to various aggressive environment and interesting and efficient compromise can be found by using optimized aerial MV insulated cable (2316) or protective coating for insulators (1442). New shape of pin insulators has been developed to withstand to increasing pollution level (1921) and a passive system based on well-designed spring damper is releasing the forces on poles during heavy snow (1233).

Dynamic rating, thermal modelling (3 papers)
The power flow data through past years has highlighted that distribution underground lines are sized for permanent maximum loads whereas thermal inertia of various components and limited duration of maximum load would allow to operate at higher loading levels (2167) or to optimize the dimensioning of new circuits (1696). The papers are highlighting that the models are not always taking in account electrical or thermal contacts quality (2167) or non-homogeneous thermal environment (1696) that could lead to deviation of nearly 10% (2117). A good knowledge of real cable installation is recommended to ensure more accurate results of rating in general and particularly dynamic rating.

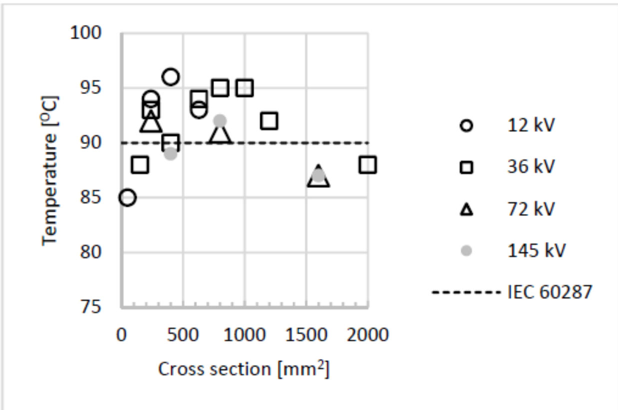

Fig. 2 of paper 2117: Resulting conductor temperature for single-core cables in trefoil formation of different conductor cross-sections and insulation thicknesses using from the FEA model when the thermal limit current calculated by IEC 60287 is applied.

Components for smart metering - energy flow & quality (8 papers)
The deployment of advanced distribution automation is sometimes not homogeneous throughout a network, but progress in the ease of installation and the higher reliability are noticeable (1282): in communication, especially wireless, and sensors, especially in underground cable, to monitor accurately power flow (0098) and transient phenomena (1282, 1550).

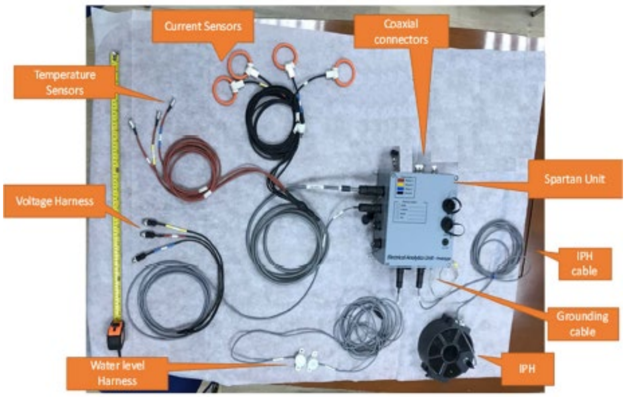

Fig. 4 of paper 1282: Underground sensing and monitoring system (USMS) including electrical analytic unit (EAU), sensors, inductive power harvester (IPH).

Systems for accurate measurement and metering of harmonics are needed to check IEC standards compliance (0103, 1689) and to assess and evaluate the risk of EM perturbation or accelerated ageing of assets, particularly with renewable energy generation.

The infrastructure deployed in the frame of advanced smart metering allow to develop new offers (1784), predictive maintenance (2171) but also self-administered meter for low income population (0306).

Prospective (10 papers)
The theoretical benefit of fault current limiters (FCL) for a distribution grid is obvious and the papers are proposing different and original approaches with a 36 kV saturated core reactor thanks to superconducting MgB2 coil (0036), a 25,8 kV resistive fault limiter based on high temperature superconducting module (1549), a 11 kV rated combination of power electronics and mechanical switches (2050) or by seeking for a way to stack several FCL modules to reach higher voltages (2059).

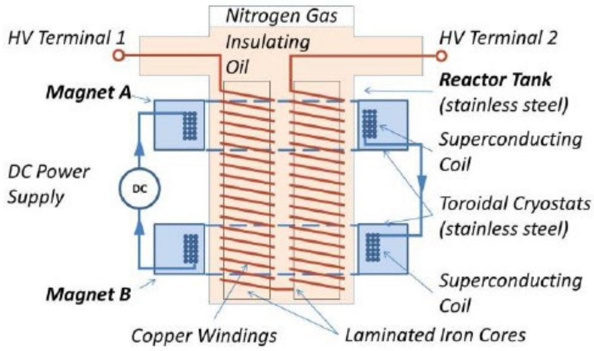

Fig. 1 of paper 0036: Schematic diagram of a saturated core fault current limiter (FCL).

DC components are more and more present in building, energy generation and storage, as well as telecom infrastructures like datacentre and future 5G network. One of the key components is the DC breaker, a compromise must be found between breaking time and loss with a quite wide variety of fault types that must be better characterized and detected (513). The association of IGBT and standard breaker (1555) is giving acceptable losses and breaking time of 4 ms. The use of power electronics with an increasing level of voltage leads to higher frequencies, then both linear and non-linear behaviour must be addressed for inductive core components (1837).

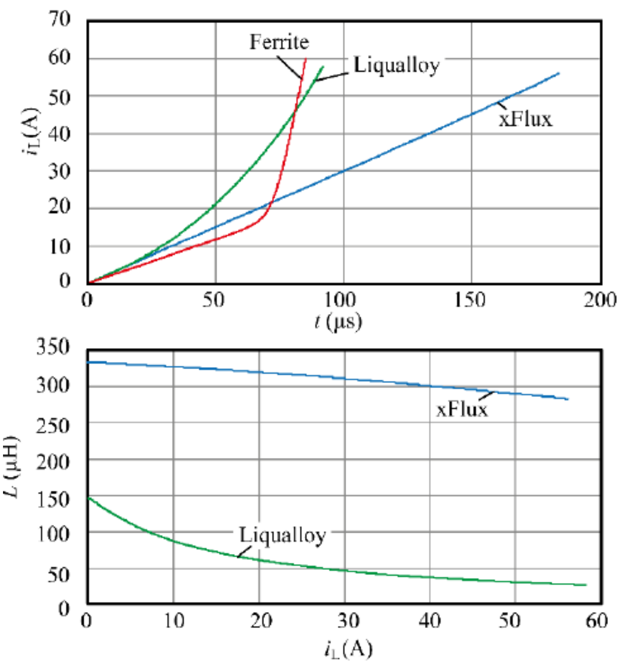

Fig. 13 of paper 1837: (top) Measured inductor current for different magnetic cores and (bottom) Calculated inductance dependence.

By combining PV, battery and an intelligent energy device (IED), a versatile LVDC system optimizing energy exchanges with the AC network is described (1529). Other approaches using multiterminal MVDC grid structures (0645, 1617) are proposed.

Table 3 (first part, continued next page): Papers of Block 3 assigned to the Session (in numerical order)

Paper No. Title	MS p.m.	RIF	PS
0036: Modelling and testing of saturated core fault current limiter		X	X
0098: Accurate revenue metering with low power current and voltage sensors according to the recent IEC 61869-10 and IEC 61869-11 standards			X
0103: Low-power instrument transformers frequency response and accuracy requirements for harmonics			X
0306: Use of self-administered energy meters - Accessibility of the population with low income resources to sustainable energy			X
0409: Screen connection for MV cables with laminated aluminium screen			X
0513: Design and verification of DC 1000 V air circuit breaker for broad range of protection in LVDC distribution			X
0645: The development and application of a multi-terminal power electronics soft open point device			X
0709: A new installation technology of mid-voltage cable joint using RTV silicone rubber adhesive			X
1033: Lessons learnt from the eco-design process for an elbow connector for medium voltage networks	X		X
1233: Presenting new equipment called “variable spring damper” to reduce the possibility of failure of distribution poles in medium-voltage overhead lines			X
1282: Underground distribution network monitoring so much easier			X
1366: A study of the optical bending sensor characteristic for distribution underground cable joint			X
1442: Application of RTV coating on insulators and their benefits			X
1528: Temporary or semi-permanent single core power cables: a new way to safe and reliable yet fast installation			X
1529: Application of LVDC distribution switchboard system with new and renewable energy source on the demonstration site			X
1549: Conceptual design of a 25.8 kV, 2 kA resistive SFCL for bus-tie section			X
1550: Online monitoring leads to improve the reliability and sustainability of power grids			X

Table 3 (continued, last part): Papers of Block 3 assigned to the Session

Paper No. Title	MS p.m.	RIF	PS
1555: Development of high-speed DC circuit-breaker using IGBT drivers			X
1601: Special tests on MV joints			X
1606: Comparative research between XLPE and P-laser MV-cable	X		X
1617: The operational performance and benefits of an MVDC device integrated within a 33 kV distribution network	X		X
1642: Smart common utility duct system for underground power cables			X
1689: Experience on diagnosis of MV cable in wind farm			X
1696: Comparison of different thermal models for optimized dimensioning of HV cable cluster grids as means of efficient integration of large scale renewable DER			X
1784: Smart metering 2G – Evolution of a smart metering experience	X		X
1837: Benchmarking linear and nonlinear behaviour of power inductors for switched mode power supplies		X	X
1921: Numerical simulations of a new design of pin insulators			X
1944: Improve underground cabling projects by designing a special spacer			X
2050: Fault current limiting circuit breaker in distribution systems		X	X
2059: Research on the improved fault current limiter based on high coupled split reactor		X	X
2117: Development of a web-based user-friendly cable ampacity calculation tool	X		X
2167: Technical recommendations for implementation of dynamic cable rating system – Cable modelling			X
2171: Development and implementation of smart metering infrastructure: the Eletropaulo experience			X
2316: Aerial MV covered networks: worth a new look?			X

Block 4: "Innovation in substations components"

The 38 papers of this block have been split in three sub-blocks:
- SF6 alternative solutions (13 papers);
- New designs (16 papers);
- Methods and tools for the development of components (9 papers).

SF6 alternative solutions (13 papers)

Finding low global warming potential (GWP) solutions to substitute the SF6 gas in its applications for HV and MV switchgear is a topical subject: it was already discussed in a roundtable at the CIRED 2015 conference, was addressed in one block of the S1 main session in 2017, and will be again the topic of the 2019 roundtable entitled "Alternatives to SF6: Feedback from field application in MV distribution networks and perspectives".

The 13 papers related to SF6 alternatives present new designs and solutions, feedbacks from pilot installations, assessments of candidate gases and research works from different perspectives (manufacturers, producer of gases, users and academics).

The table inserted below is an attempt to show how (for the first 12 papers, sorted by numerical order) they address different aspects of this subject, and from which point(s) of view:

	authors		insulating/breaking medium				LBS switching principle (cf. typology in paper 340)				topics		
paper	manufacturer	user	C5-FK	C4-FN	HFO	natural gases	#1 main VI (idem VCB)	#2 auxiliary VI	#3 rotating arc	#4 puffer	EHS	diel perf	decom-position
28	GE			X							X		X
340	Siemens					X	X	X	X	X			
511	Ormazabal		X	X	X						X	X	X
561	SE		X	X	X						X		X
770	SE		X	X	X	X		X					X
874		Guangzhou PSB	X	X								X	X
1031	ABB	Liander	X				X						X
1084	ABB		X			X				X			X
1346	3M		X	X							X	X	
1552	ABB	ENEL	X				X					X	
1714	Nuventura	Westnetz				X	X					X	
1909	Siemens					X					X		X

The authors columns are self-explanatory; the insulating/breaking medium columns indicate which alternative gases are considered in the paper (either fluorinated compounds, or natural gases); the load-break switching principles refer to the typology proposed in paper 0340; and the main (not exclusive) topics listed are environment, health and safety (EHS), dielectric performances and decomposition products.

A first group of 3 papers present new solutions for eventually succeeding in substituting SF6 for MV secondary distribution switchgear, typically ring main units (RMU). A good introduction is provided by paper 0340 which presents a review and comparison of 4 potential principles for MV load-break switches using natural gases instead of SF6. The first one (#1) is having a (fully rated) vacuum interrupter (VI) in series with a disconnector and earthing switch: it is already applied for primary distribution power GIS and circuit-breaker functions in RMU. The second one (#2) is using a vacuum interrupter in an auxiliary path of the switch (like the solution described in paper 0770). The third one (#3) is using a rotating arc principle as applied in some existing SF6 switches. The fourth one (#4) is using a puffer-type load-break switch (like the solution described in paper 1084). The assessment of these 4 principles is summarized in the table 1 below: principle #1 is known but not cost effective (compared to the current SF6 technology), #3 is not suitable due to insufficient breaking capacity in natural gases, the two remaining principles #2 and #4 seem both capable of providing viable solutions for SF6-free RMU, from both the cost and performance perspectives. They are discussed in more detail in the next 2 papers.

Criterion	Principle			
	#1	#2	#3	#4
Breaking capability	high	high	low	medium
Technical complexity	high	high	low	high
Cost	high	low	not evaluated	low
Overall space require-ments	high	low	not evaluated	low
Degree of industriali-zation	high	low	high	low
Operating philosophy	medium	simple	simple	simple

Table 1 from paper 0340: Evaluation result of presented load-break switch principles.

Paper 1084 presents the results of the work performed by ABB (since several years: cf. the CIRED 2017 paper 0614 for prior results) to develop a new type of MV load-break switch suitable for use with SF6 alternative solutions (e.g. air at 12 kV, fluorinated mixture at 24 kV). The simple blade designs of SF6 switches currently used in most RMUs are no longer efficient with these gases which have a much lower interrupting capability: it is necessary to implement a new puffer technology to get sufficient breaking performances. The know-how of the manufacturer in gas breaking technology for (SF6) HV circuit-breakers has been applied to improve the current MV puffer switch design (e.g. implementation of "stagnation-point flow" in the puffer nozzle) and get sufficient and reliable performance (class E2 load current switching at 630 A, 24 kV 800 A transfer current for fuse-switch combination). With this approach it will be possible to propose a more cost-effective solution for SF6-free secondary distribution switchgear than the current solutions using conventional vacuum interrupters in series with a 3-positions gas disconnector/earthing switch (#1 in the typology of paper 0340).

Another innovative approach is proposed by Schneider

Electric in paper 0770: the shunt vacuum interruption (SVI) technology (cf. figure 2 below). The principle is to use an auxiliary vacuum interrupter (VI) only for performing interruption of the switch current: this VI is not used to carry the continuous current (it is in a shunt circuit, parallel to the main contacts), to provide the rated insulation level or to make the current. Hence it can be more compact and manufactured at a lower cost than the conventional load-break switch VIs. This concept allows to keep the same 3-positions switch configuration as in current SF6 switchgear: with pressurized air insulation it is possible to use it up to 24 kV in the same dimensions as the SF6 switches used in the SM6 range of secondary distribution AIS, thus providing a convenient SF6-free alternative to the current offer. The same concept is also applicable to gas insulated switchgear such as RMU. It will be interesting to follow in the coming years the competition between this SVI technology and the puffer technology proposed in the previous paper.

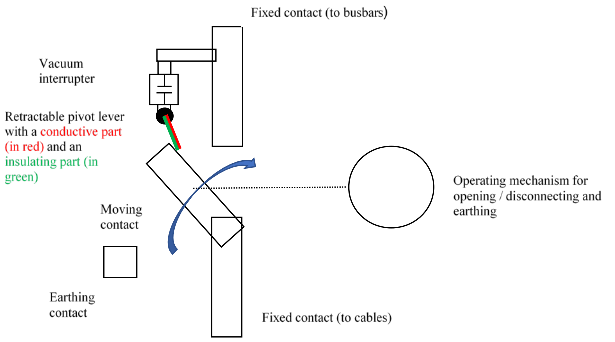

Fig. 2 from paper 0770: an innovative solution with Shunt Vacuum Interruption (SVI) technology.

The next 3 papers present different pilot experiences launched with SF6 alternative solutions.

Paper 1031 provides a follow-up of the paper 0658 presented at the previous CIRED 2017 conference regarding the behaviour of 4 RMUs filled with the AirPlus^{TM} SF6 alternative mixture, which have been installed during 3 years in the Liander network in Netherlands. Gas sampling and analyses have been performed regularly on 2 of the 4 units over this period: no significant change in the C5-fluoroketone (C5-FK) concentration and no trace of decomposition products have been observed. The other 2 units have been decommissioned and retrieved by ABB for testing and inspection of the internal parts: this has confirmed the absence of material ageing due to the gas. Therefore, this experimentation confirms the suitability of the test procedures implemented to qualify the compatibility of selected materials with this insulating mixture. Considering the stability of the condition of the RMUs over the field test period of 3 years, it is expected that their life duration will be similar to that of SF6 insulated switchgear.

Paper 1714 presents a new solution designed by the start-up Nuventura in Germany for SF6-free power GIS applications up to 36 kV. Compressed air insulation is proposed to keep same dimensions as current SF6 switchgear: this has been made possible by careful design for dielectric and thermal performance. One of the advantages of using air is that it is possible to provide relatively easy accessibility to the internal parts of the tank (cf. figure 3 below), for repair or upgrade (e.g. adding sensors or replacing them in case of failure): with pressurized air insulation this solution may be considered as a kind of hybrid between GIS and AIS, combining the advantages of both types of switchgear. A pilot test is currently on-going in Westnetz network, with continuous monitoring of the air insulation and possible decomposition by corona effect. In parallel investigations have been performed to compare the performances of various types of internal PD sensors for continuous monitoring: UHF sensors have been noted as a suitable solution for detecting all types of discharges (also mentioned in block 2 of this special report).

Fig. 3 from paper 1714: Accessibility to the core components through the gas insulated tank and the AFLR gas duct.

Paper 1552 explains how, using the AirPlus^{TM} fluorinated mixture instead of SF6, it has been possible to design new cubicles of same dimensions and ratings as the current ones according to the Enel's specification DY 800. This has required careful redesign for solving the dielectric and thermal technical challenges, and also it was necessary to replace some materials to ensure the long-term compatibility with the gas. The advantages of this solution are notably: low GWP (< 1), low carbon foot-print, same filling pressure level. A first batch of more than 100 SF6-free DY 800 cubicles (cf. figure 1 below) have been purchased by E-distribuzione and the first switchgear are installed in pilot sites (in various environment conditions): periodic checks will be done to evaluate the stability of the gas insulation in the tank. Further extensions of this technology to load-break switch cubicles are also considered (with the puffer breaking technology presented in paper 1084).

Fig. 1 from paper 1552: First homologated devices.

The next group of 5 papers deals with the assessment of new gases for replacement of SF6.

Paper 0511, entitled "Assessing possible alternatives to SF6 in MV switchgear" is a good introduction to this section. It points out some difficulties encountered for a proper assessment of SF6 alternative solutions: lack of standardization framework, lack of knowledge and experience on the long-term behaviour, lack of standardized and widely accepted testing procedures for evaluating the health and safety aspects. Three main concerns are listed: compatibility and ageing of gases and materials, health and safety for the new products and their decomposition by-products, stability of performance in the long-term. It also reports the results of investigations performed by Ormazabal to assess the dielectric strength of different candidate mixtures (C4-fluoronitrile (C4-FN), C5-fluoroketone (C5-FK), hydrofluoroolefin (HFO, aka tetrafluoropropene)) and their stability under electrical stress. Regarding this last point, significant amounts of decomposition have been noted for some mixtures, but the influences of different factors (like the level of electric field applied, materials in presence, the humidity content) are still to be evaluated.

Paper 0561 reviews different SF6 alternatives from the environment, health and safety perspective. Although all considered alternatives have low or negligible GWP, their decomposition in atmosphere may produce hazardous products and all potential environmental impacts have not been assessed: therefore, at this stage, recovery and recycling of these gases at the end of life should be considered in the same way as for SF6 currently. Regarding toxicity (CMR, etc.) assessment some candidate gases are still at the beginning of the REACH evaluation process as the quantities produced are still low compared to SF6 or other potential alternatives (such as HFO-1234ze already used as refrigerant and blowing agent). Therefore, it is recommended to pursue the toxicity (and environment) assessment tests in order to avoid validating too early some SF6 alternative which may be discovered later as not fully satisfactory. Finally, the use of some fluorinated mixtures for breaking raises the concern of arcing by-products, similarly to SF6, or possibly at a higher level since the recombination rates of these unstable molecules are much lower than for SF6. This concern however can be removed if the vacuum breaking technology is used for interruption, and SF6 alternative gases only for insulation purpose.

Paper 1346 presents the two molecules (cf. figure 1 below) developed by 3M to be used as low GWP alternatives to SF6 in electrical equipment: C4-FN (commercial name Novec 4710) and C5-FK (Novec 5110). Both gases have relatively high boiling points compared to SF6: therefore, they must be used in mixtures with a carrier gas such as CO2 or air. In mixtures their dielectric strength is lower than the SF6 one, which may lead to increase the pressure to get equivalent performance. The GWP of these gases is lower than the SF6 one thanks to their much lower stability and atmospheric life (30 years and 0.04 years for C4-FN and C5-FK respectively, versus about 1000 years for SF6). Regarding toxicity, the 8-hour time weighted average (TWA) occupational exposure limits (OEL) established by the 3M medical department are 65 ppmv and 225 ppmv for C4-FN and C5-FK respectively, which are values not likely to be reached in substations, or even factory workshops.

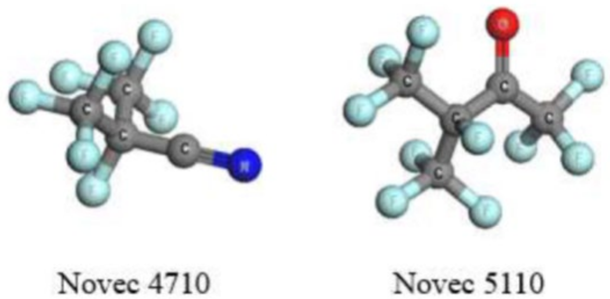

Fig. 1 from paper 1346: Molecular structures of Novec 4710 and Novec 5110 insulating gases.

Paper 0028 reports on the experience gained in the application of the g^3 gas mixture (CO2 + C4-FN + O2) in HV switchgear over the past three years through several pilot projects (145 kV GIS installed in Switzerland in 2017, 420 kV GIL installed in England in 2016 and in Scotland in 2018). The specificities of g^3 gas handling on site are explained: in order to ensure the homogeneity of this mixture of different components being either in liquid or gaseous phases, it is necessary to heat the mixture before filling in order to obtain the super-critical state of CO2. This gas-handling process has been fully validated thanks to the above-mentioned projects for filling, recovery and re-filling on site, also in severe environment conditions. A comparative life cycle assessment performed on two 145 kV GIS circuit-breakers (CB), one SF6 and the other with g^3, shows well the advantage of the g^3 technology in terms of climate change, without adverse impact on the other indicators (as the g^3 CB keeps globally the same size as the SF6 one).

Finally, paper 0874 presents the results of investigations performed for Guangzhou Power Supply Bureau in China on two types of gas mixtures (with C4-FN and C5-FK) considered as potential SF6 alternatives. The studies covered the following aspects: decomposition of the gas mixture at high temperature and in a plasma (cf. figure 2(a) below); vapour pressure and maximum ratios of C4-FN and C5-FK in gas mixtures for -25°C and -5°C minimum temperatures, considering total pressures of 1 bar and 6 bars; and finally, dielectric strength of the mixtures defined for these conditions. The outcome is that C5-FK mixtures are not suitable for HV applications (where C4-FN is the best choice) but are a possible alternative to SF6 for MV switchgear, with a dielectric strength close to the SF6 one in the lower range of pressures.

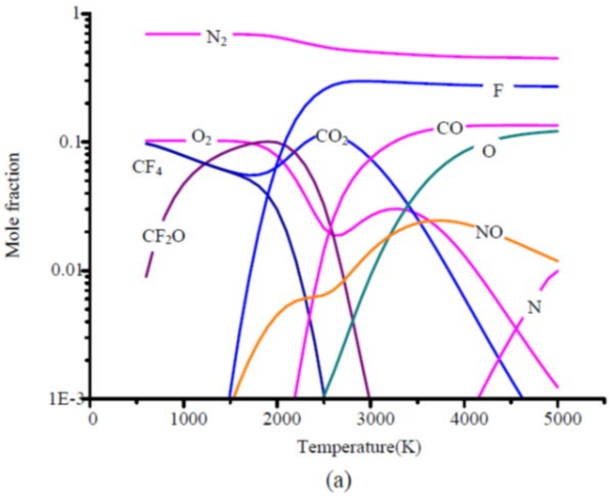

Fig. 2(a) from paper 0874: Decomposition of C5-PFK/Air mixture at the pressure of 0.4MPa.

The last 2 papers in this sub-block present results of research works related to the SF6 alternatives topic.

Paper 1909 reports the results of decomposition tests performed on different compositions of gas mixtures considered as possible alternatives to replace SF6 as an insulating medium. These mixtures, based exclusively on natural gases (such as N2, CO2, O2), were subjected to arcing caused by the making (only, no breaking) operations of MV switches, representative of the service life for the switchgear: the main decomposition products identified by Fourier-transform infrared spectroscopy (FTIR) were CO and NOx. Although these products are toxic, the quantities produced were sufficiently low not to exceed the occupational exposure limits (OEL) even in case of a full discharge of the switchgear volume in a substation room: therefore, the health risk is not a concern for the studied gas mixtures in this type of application.

The last paper 1845 (not listed in the introduction table above) reports the results of experimental research performed in Japan on the plasma dynamics for arcing in air, CO2 and SF6. Sophisticated diagnostic techniques have been used for visualizing the turbulences in an electric arc representative of what occurs close to current zero in the nozzle of a HV gas circuit-breaker. In addition, the electron density decaying behaviours have been measured: as expected, it is fastest for SF6, followed by CO2, then air (in the decreasing order of their known interrupting capabilities). The specific structure of turbulences observed in SF6 could contribute to a faster cooling of the arc by mixing cold gas into the remaining plasma column: this research should eventually help in building a simulation model of the arc behaviour, and in developing the interrupting technologies using eco-friendly gases such as CO2 or air.

New designs (16 papers)

The second sub-block, consisting of papers presenting new designs for substations components, can be divided by types of components: switchgear (8 papers), transformers (5 papers), fuses (1 paper) and power electronics solutions (2 papers).

First in the group of switchgear papers, paper 2078 introduces a new type of MV circuit-breaker (CB) switchgear for ANSI markets: the “plug-in” (or disconnectable) CB as an intermediate solution between the withdrawable CB (typically used in metalclad switchgear according to IEEE C37.20.2) and the fixed circuit-breaker (used in metal-enclosed switchgear according to IEEE C37.20.3). The plug-in CB combines the advantages of compact footprint and quick access to the CB for maintenance or replacement. Going one step further, for those applications where access to the CB is only done after de-energizing an entire line-up of switchgear (for safety considerations, this is becoming rather frequent), a compact plug-in switchgear design is proposed (cf. figure 4 below), where no disconnecting switch is used for isolation or grounding of the circuit. With low power voltage and current transformers (LPVT and LPCT), this new type of switchgear can be quite simple and compact, while providing the same safety level as the conventional types. The next step to be considered is standardization and listing of this new concept.

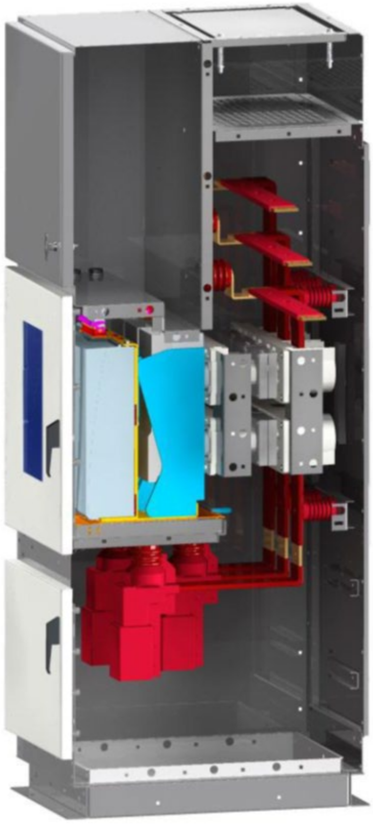

Fig. 4 from paper 2078: Side view of a compact switchgear design with plug-in circuit breaker.

Paper 0596 proposes another innovative approach to provide safer operation of MV withdrawable air insulated switchgear (AIS), and new functionalities, while simplifying the design and increasing the reliability. The idea is to generalize motorized operation for all the components of the cubicle (CB, racking truck, earthing switch) and to implement digital and electrical interlocks in replacement of most of the current complex mechanical interlocks. The new functionalities that could easily be added with this type of solution are: live cable interlock for the earthing switch, self-discharge of the CB drive mechanism at racking out, motorized shutters and busbars earthing. This is still prospective investigation and may not be compatible with the current standards and specifications, but the claimed advantages might be sufficient to give due consideration to this type of solution.

Paper 0883 presents a recently developed MV circuit-breaker for electric arc furnace transformer switching and protection in the steel industry. For this very demanding application a new type of actuator has been designed for improved controlled switching and mechanical performances: brushless servo-motors (cf. figure 3 below) are used to drive individually each pole of the vacuum circuit-breaker. This solution provides optimal switching conditions for the vacuum interrupters, resulting in reduced current transients at making and reduced overvoltages at breaking, and a mechanical endurance up to 150000 operations.

Fig. 3 from paper 0883: VD4-AF System Architecture - the operating mechanism consists of a shaft operated by a digital-controlled AC servomotor drive directly coupled with the pole structure.

Paper 1100 from G&W Electric describes the solutions which have been developed to offer smart features for MV switchgear installed in very severe environment conditions, such as subsurface electrical vaults which are typically regularly or permanently flooded by water (cf. switchgear covered by IEEE C37.74). Different types of submersible and hardened components and sub-assemblies are necessary for this purpose, such as motorized actuators (for remote control), monitoring sensors (e.g. SF6 density), protection and control panels, cables and connectors, etc. To ensure reliable operation under these extreme environment conditions, difficult technical challenges have been solved by careful design and selection of materials and components: also, to ensure long-term performance, it may be necessary to test beyond the existing standard requirements. These solutions can be considered for the retrofit of existing installations with smart switchgear, in cases where it is not possible to use solutions with better protected enclosures, such as padmounted switchgear.

Paper 2058, from the same manufacturer, describes the technology used for MV solid dielectric switchgear: these vacuum switchgear are intended for recloser or load-break switch applications, also in submersible conditions. They represent a compact alternative to SF6 insulated switchgear for harsh environment conditions. However, some technical challenges had to be addressed to provide visible break indication (by adding a disconnecting blade in series with the vacuum interrupter, cf. figure 3 below) and voltage sensing on both sides of the switch in the screened solid insulation module.

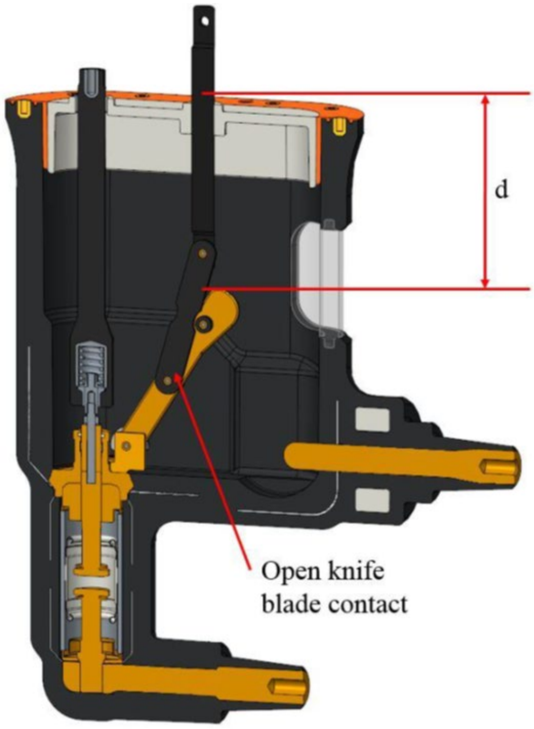

Fig. 3 from paper 2058: Solid dielectric module showing a vacuum interrupter in series with a knife blade disconnect switch (both interrupter and disconnect switches in open state).

This last feature is also discussed in paper 0259 which presents the advantages of integrating dual voltage sensing (at both terminals of poles) in an automatic circuit recloser: suitability for implementing various schemes of feeder automation, automatic transfer of sources, connection of generators to the grid, conservation voltage reduction (CVR) strategy. With no increase of dimensions, and a limited extra-cost versus the conventional recloser with single side voltage sensing capability, this new type of recloser may become a standard solution allowing future upgrade of the network functionalities, without need for replacement or retrofit.

Paper 0617 describes the active arc-flash protection system (APS) recently developed by LSIS for MV switchgear (cf. figure 1 below). It consists in light and current sensors, a dedicated arc protection relay (with very fast response time of about 1.5 ms) and an arc-killer installed on a withdrawable truck in the switchgear and connected to the busbars (with a closing time of about 3.5 ms, thanks to fast Thomson coil type actuators): therefore, the arc fault is short-circuited in about 5 ms after initiation, which provides efficient protection to the people and the equipment. The ratings of this arc-killer are: up to 25.8 kV, 40 kA – 1 s, 2 making operations, 10 no-load operations. SF6 insulation is used between the contacts. It is noted that the duty of short-circuiting an arc-fault 5 ms after its initiation is different from the making of short-circuit current by an earthing switch and may be more severe for the arc-killer: this should be considered in a future standard for APS.

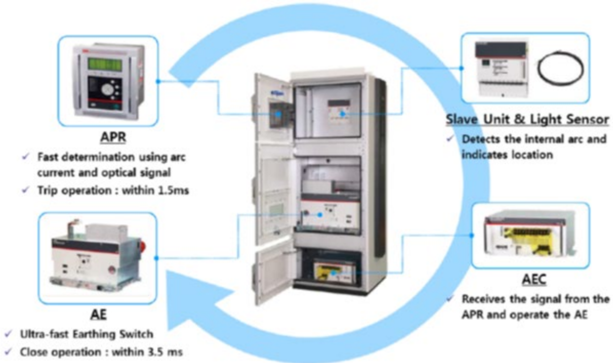

Fig. 1 from paper 0617: the composition of LSIS APS.

Last in the switchgear group, paper 1035 explains the magnetic fluid seal technology which has been used in China since 2002 for ensuring SF6 gas tightness at the level of the rotary seals around operating shafts of circuit-breaker poles or GIS. It is an application of the recently developed magnetic fluids (containing magnetic solid particles of nanometric size, typically < 10 nm) that can be maintained around the shaft by a magnetic field of suitable configuration generated by permanent magnets. These annular liquid seals are more reliable and gas-tight than the conventional rubber seals systems (this has also been demonstrated by other types of liquid (typically oil) seals which have been applied in HV switchgear for a long time).

First in the transformer group, paper 1646 presents a new evolution of the smart distribution transformer with on-load tap changer (OLTC), already presented by Ormazabal at the previous CIRED conference (cf. paper 0832 of CIRED 2017), which is specifically targeting the connection to the grid of intermittent renewable generation (such as solar or wind). An additional tap position has been implemented in the OLTC to allow it to perform also as a pre-insertion resistor device when energizing the transformer. The resistors, as well as the OLTC, can be integrated in the transformer tank: this system provides a very efficient reduction of the magnetizing inrush current transients, at a lower cost than by using a controlled switching technology. It is therefore possible to disconnect frequently the transformer when the renewable generation is off: this “start & stop” feature can save up to 2/3 of the no-load losses of the transformer for a solar plant.

Paper 1654 presents another potential application of this smart distribution transformer with OLTC for voltage regulation: in industrial sites it can be used also for applying a conservation voltage reduction (CVR) strategy in order to reduce the energy consumption (and peak demand). Tests have been performed at Ormazabal’s own transformers manufacturing plant, which is supplied by a smart distribution transformer, and have shown that CVR can effectively be applied to these industrial loads and is also compatible with the existing reactive power compensation system (capacitor banks).

Paper 2108 presents a new type of insulation paper for oil-filled transformers: the aramid enhanced cellulose paper is an intermediate solution between the thermally upgraded papers and the aramid papers (like Nomex) used for special transformer applications. The thermal class of the insulation system achieved with this paper is 130°C in mineral oil and 140°C in ester fluid (versus 105°C for conventional insulation). The benefits of using this kind of high temperature insulation system have been demonstrated for high overloading profiles or in case of size limitations for low average loading (for low losses transformers: cf. paper 2089 in block 2). In the case of ester insulated transformers, there can be also advantages in using this type of solid insulation, either when there is no limitation on losses, or for the higher power ratings (power transformers, rather than distribution transformers).

Paper 1625 reports the results of an experimental study carried out to assess the respective impregnation times (impacting the manufacturing process) in mineral oil and synthetic ester for different types of insulating papers used in the solid insulation of power transformers. As expected from the higher viscosity of synthetic esters the impregnation times tend to be longer in these fluids than in mineral oil, but large differences are also observed depending on the types of papers considered (capillarity effects).

Paper 2053, the last one in the transformer group, describes a customized solution developed for providing an adaptable power transformer that can be deployed as a mobile back-up unit to replace a substation transformer in case of emergency. This solution is remarkable by its rating of 550 MVA (made of three single phase units of 183 MVA), multiple voltage ratios (400 kV / 220 kV / 138 kV / 66 kV / 33 kV / 20 kV), OLTC with +/- 10% voltage range and a semi-hybrid insulation system (which allows to reduce the weight by 7%).

Paper 0678 is the only one dealing with HV fuses: it presents the improvements brought by the new generation of current-limiting fuses from SIBA. While keeping the same time-current characteristics and minimum breaking currents as previous generations, in order to continue ensuring a proper protection coordination in the networks, the new fuses offer lower power dissipation (by about 30%) thus reducing the carbon foot-print in the operation phase. For high breaking capacity fuses the innovation of a double layer body has been introduced: with an internal ceramic tube for high arc-quenching performance and an external flexible organic material tube for keeping the structural integrity in case of ceramic cracks caused by the high arc energy dissipated at interruption of the fault current.

The last 2 papers in this sub-block deal with more prospective topics, involving power electronics (PE) components.

Paper 2173 presents the LV Engine innovation project launched by SP Energy Networks to introduce more flexible, intelligent and active LV network operation, in order to cope with renewables integration and deployment of electric vehicle (EV) charging infrastructure. The main innovative component considered by LV Engine is a smart MV/LV transformer (ST) consisting in a solid-state transformer (SST) and its smart control system (SCS). This type of component is not yet commercially available: in its first year the LV Engine project has defined the preliminary technical requirements of ST, which are detailed in the paper. The next steps will consist in designing and manufacturing ST prototypes (rated 500 kVA) for live trials in the network. It is expected that ST will provide the following functionalities: phase voltage regulation, bi-directional (active and reactive) power flow control, and LV DC supply (for EV charging infrastructure). Wide-bandgap semi-conductors are expected to be an enabler of SST technology at affordable cost (however the acceptable levels of losses and efficiency for SST remain to be discussed). Regarding application of the ST in the network it is considered that, rather than replacing existing transformers, it could be introduced as a complement in existing transformer substations (up to about 15% of them) to provide the required new functionalities.

Last in this sub-block, paper 0398 presents the different solutions that can be considered for an integrated substation for e-mobility. Such secondary substation will include several types of PE converters: for EV charging; for local connection of renewables generation; for connection of a battery energy storage system (BESS). Different architectures are considered: AC common bus, DC common bus (cf. figure 4 below) and MV AC/DC converter.

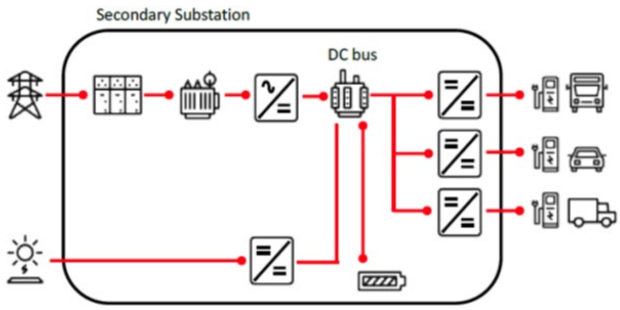

Fig. 4 from paper 0398: Common DC bus power architecture.

Although not the most efficient, the AC common bus seems preferable as it allows easy upgrade of existing substations. For peak shaving (case of fast chargers) and balance of local loads and generation a BESS seems to be the most convenient solution. The energy management system (EMS) required to control the different elements of the substation will be able to provide also monitoring and asset management functionalities.

Methods and tools for the development of components (9 papers)

The last sub-block regroups papers dealing with various methods and tools for the development of substations components.

Standards and specifications for the dielectric design and testing of MV switchgear are discussed in the first paper 0771. The insulation levels and test requirements in the standards are explained. Some complementary tests performed by manufacturers to ensure the long-term insulation withstand are also described. The impact of ageing for air insulated switchgear (AIS) submitted to severe environmental conditions has been tested: it can lower the insulation withstand by more than 30% under the effects of pollution and humidity. Therefore, it is reasonable to require for AIS the higher insulation level specified in the standards for a rated voltage, even if not actually required (in new condition) when the insulation co-ordination practices in the network are considered. For gas insulated switchgear (GIS) on the contrary there is no effect of the environmental conditions on the insulation level, hence no ageing and degradation of performance in this respect. For this reason, it is sufficient for GIS to specify the lower insulation level (if consistent with the insulation co-ordination) for a given rated voltage: differentiating the specified insulation levels for AIS and GIS of same rated voltage is justifiable and may be useful to help introducing the new SF6-free technologies in GIS.

The next 3 papers present the application of various numerical modelling and simulation tools for the development of substations components.

Paper 0380 explains the basics of arc interruption in LV air circuit-breaker (ACB, cf. figure 6 below) and shows how finite element method (FEM) can be used to compute the electromagnetic driving forces applied to the arc column for different geometries of the arc-chutes. Higher electromagnetic forces obtained by optimized design, thanks to numerical simulation, will lead to faster arc elongation and cooling, thus improving the current limitation and interruption performances: this has been confirmed by experiments and testing.

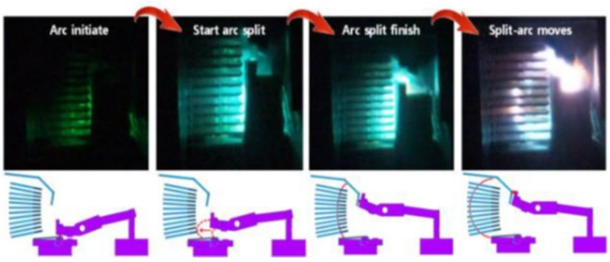

Fig. 6 from paper 0380: steps of arc extinction procedure in LV ACB.

Paper 1637 presents how finite element modelling of transformer windings has been used to accurately evaluate the losses due to harmonics in the load current, taking into account the frequency-dependent skin and proximity effects in the conductors. This improvement opens the way for optimized thermal design of transformers connected to inverter-based generation (e.g. wind or solar).

Paper 1862 shows how the thermal network method (TNM) can be applied for verification of the temperature-rise values in LV switchgear assemblies operated at their rated currents. Although the creation of the initial thermal network model (based on analogy with an electrical network model, it is solved by the same method) is very time consuming, it is possible to store in a library modular models of the components and sub-assemblies: when this has been done it is easy to build the TNM for any given configuration of a LV switchgear. This method is therefore effective and sufficiently accurate to check the performances for a large variety of possible LV switchgear designs (cf. figure 1 below).

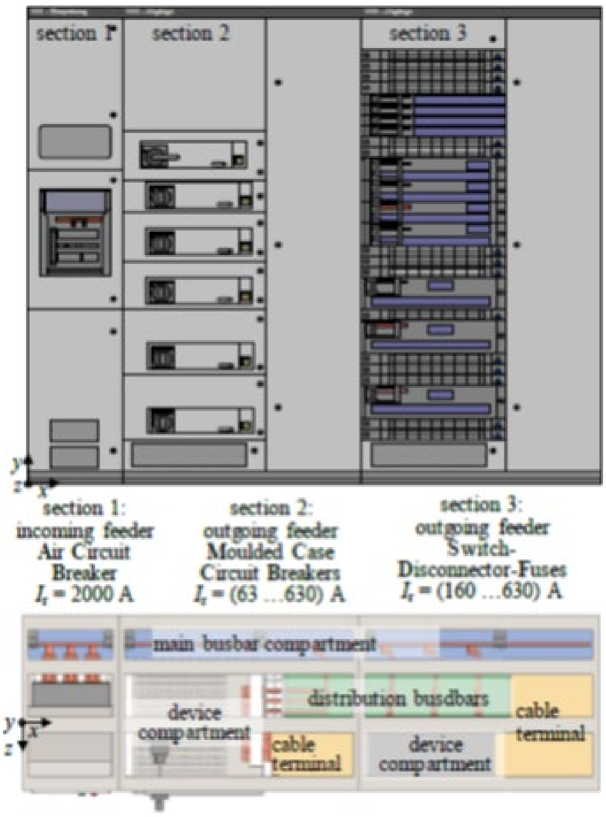

Fig. 1 from paper 1862: Test model of a LV-Assembly with Ir = 2000 A (front and top view).

The next 3 papers present different methods aiming at improving the reliability of the developed components.

Paper 0557 presents some tools and methods used in the design phase to assess the reliability of an automatic circuit recloser (ACR) electronic controller board located in the frame of this pole-mounted switchgear. First thermal simulations (by TNM and also computational fluid dynamics (CFD) modelling) were performed to evaluate the maximum temperatures applied to the board, taking into account the solar radiation in severe environments: both methods indicated temperatures in the order of 60-65°C for a Dubai location. Based on this maximum temperature (conservative approach) failure rates of the different electronic components were determined from the IEC/TR 62380 handbook, and a global failure rate was determined (corresponding to a MTTF of about 75 years). The reliability study included in addition a risk analysis and a design FMEA which allowed to split this global failure rate between the different kinds of failures: it was shown that for the critical failures the probability of occurrence was less than 1% for the lifetime of 25 years.

Paper 0376 describes the application of a multi-body dynamics simulation software to estimate the endurance life of some critical components in the spring-operated mechanism of GIS HV circuit-breaker. The modelling of the mechanical system, adjusted with actual speeds measured during tests, allows to perform dynamic stress analyses. With these data, and the fatigue curves of the materials, it is possible to predict the endurance life of the components. The results have shown good correlation with those of mechanical endurance tests: this simulation tool is useful to speed-up the development process and reduce the number of testing iterations.

Paper 0967 reviews the accelerated corrosion test protocols applicable to the stainless-steel (SS) tank of GIS. These accelerated tests should provide indications regarding the suitable materials and processes to be used in order to prevent stress corrosion at the level of welds when the switchgear is subjected to harsh environment conditions (e.g. coastal area, industrial sites). Two types of cyclic corrosion test (CCT) protocols have been applied to different test samples with stress applied to the weld zone (2 types of SS material, 2 types of welding process, 2 types of passivation …): although these test protocols have not been initially designed for SS characterization, the results are showing significant differences and helping to make suitable choices for robust corrosion performance under harsh environment. The work is on-going to define customized test protocols dedicated to the application of GIS SS tank and determine their acceleration factor with respect to the actual behaviour in service under severe conditions.

Finally, the last 2 papers in this sub-block present solutions for the simulation of network phenomena and their interaction with components.

Paper 2116 presents research work performed to improve the stability of power hardware-in-the-loop (PHIL) simulations with dynamically changing systems. A new interface algorithm (adaptative ideal transformer method) has been investigated, which gives better results than the known algorithms, but it requires that more accurate stability conditions (the Routh-Hurwitz criterion, instead of the usual Bode or Nyquist criteria) are applied for the control of this algorithm.

The capacitance parameters of MV distribution transformers are required for modelling the transient behaviour of these components. They can be calculated from theoretical equations when the geometric characteristics of the transformer design are known, but this information is not usually provided by the manufacturers. To overcome this difficulty, paper 2096 proposes to establish a correlation between these capacitances and the ratings and losses characteristics of the transformers, which are readily available, by means of artificial neural network (ANN) machine learning tools. The correlation obtained seems good for the range of designs considered for the evaluation: however, a comparison of the results of this virtual approach with actual Schering bridge measurements on real transformers remains to be done to fully confirm the validity of this approach.

Table 4 (first part, continued next page): Papers of Block 4 assigned to the Session

Paper No. Title	MS p.m.	RIF	PS
0340: Comparison of SF6-free load-break switching principles			X
1084: Eco-efficient puffer-type load break switch for medium voltage applications	X		X
0770: Innovative SF6 free switch with shunt vacuum interruption technology	X		X
1031: RMU with eco-efficient gas mixture: Evaluation after three years of field experience			X
1714: Pilot of an environmentally friendly SF6-free MV switchgear technology and assessment of sensor technologies			X
1552: An Enel-ABB partnership to develop an eco-sustainable alternative to SF6 for MV switchgear, dimensionally compatible with existent apparatus using SF6			X
0511: Assessing possible alternatives to SF6 in MV switchgear			X
0561: Comparison of alternatives to SF6 regarding EHS and end of life			X
1346: Emission reductions through use of sustainable SF6 alternatives			X
0028: SF6 alternative – What to learn from the high voltage experience	X		X
0874: Decomposition and electrical strength of C5-PFK/AIR and C4-PFN/AIR mixtures as possible SF6 substitute gases		X	X
1909: Decomposition of SF6-free gas mixtures by energy impacts		X	X
1845: Comparative study on turbulent flow structure under AIR, CO2 and SF6 gas blasting visualized by band-pass filtering schlieren system		X	X
2078: A new medium voltage circuit breaker type for the ANSI market			X
0596: Fully motorised cubicle leads to more safe, reliable and easy to use AIS switchgear			X
0883: High performance smart MV apparatus for arc furnace applications			X
1100: Smart switchgear for extreme installation environments	X		X
2058: Improving system safety and reliability with solid dielectric switchgear			X
0259: Integrated dual voltage sensors based reclosers improving power distribution in developing countries			X
0617: Reliable arc flash damage mitigating system in MV switchgear			X
1035: Magnetic fluid seal for switchgear			X
1646: Start&Stop system for more efficient smart transformers at renewable power plants. Beyond the Ecodesign directive	X		X
1654: Using smart distribution transformers to reduce both industrial energy consumption and peak demand by means of a CVR strategy			X
2108: Innovative insulation materials helping in cost reduction of modern transformers			X
1625: Performance of synthetic ester and mineral oil in an experimental study of impregnation of cellulose insulation papers used in power transformers			X
2053: Fast recovery adaptable transformer for renewable generation			X
0678: High-voltage fuses – Next generation with improved performance			X
2173: Technical requirements of smart transformer for deployment in grid application	X		X
0398: Integration, analysis and optimization of components in secondary substations for e-mobility			X

Table 4 (continued, last part): Papers of Block 4 assigned to the Session

Paper No. Title	MS p.m.	RIF	PS
0771: Dielectric stress: Design and validation of MV switchgear			X
0380: Arc phenomena and method of arc extinction in air circuit breaker			X
1637: Advanced finite element calculation of losses due to the harmonic content of current and design optimization of high voltage distribution transformers			X
1862: Adaptation of the thermal network method (TNM) for use in low-voltage switchgear and controlgear assemblies			X
0557: Hardware dependability study of an automatic circuit recloser			X
0376: Endurance life prediction of gas-insulated circuit breaker and spring operating mechanism components			X
0967: Comparison and selection of accelerated corrosion test protocol for gas insulated switchgear			X
2116: Assessment and development of stability enhancing methods for dynamically changing power hardware-in-the-loop simulations			X
2096: Virtual Schering bridge for capacitances in medium-voltage transformer using artificial neural network			X