GENERAL REPORT FOR SC A3
T&D Equipment

Date of the Meeting
Sept. 2, 2022

Chairman: N. Uzelac
Secretary: F. Richter
Special Reporters: R. Smeets, T. Minagawa, N. Gariboldi, W. Pepper, E. Sperling

SC A3 studies Transmission and Distribution (T&D) Equipment. For the CIGRE 2022 conference a call for reports was issued covering the following Preferential Subjects:

PS 1: Decentralisation of T&D equipment:
- New assets: e.g., DC switching equipment, fault current limiters.
- Influence of system changes on existing and new equipment.
- Equipment resilience against natural disasters.

PS 2: Decarbonisation of T&D equipment:
- SF_6 - alternatives for MV and HV application and HV vacuum application.
- Life cycle management and the impact on the design of T&D equipment.
- Health, safety and environment aspects of T&D equipment.

PS 3: Digitalisation of T&D equipment:
- Advanced sensors, low-power instrument transformers, monitoring and condition assessment.
- Digital twin and equipment reliability modelling.
- Pandemic influence on equipment.

For the first time a review round was set-up, for which 25 specialists were invited to review the submitted reports. Each report was reviewed by two or more reviewers. The review process led to the acceptance of 52 reports (7 more than in 2021). 34 Reports were revised by the authors, based on the reviews.
Preferential subject statistics:
10 Reports fall under PS 1, 25 cover PS 2 and 17 deal with PS 3.

Topics:
For the Special Report and the GDM the reports received were categorized into four topics, which serve as the guideline in the GDM which covered 51 prepared contributions:
1. Miscellaneous T&D equipment and systems (16 reports, 18 prepared contributions)
2. SF_6 alternatives (18 reports, 20 prepared contributions)
3. Asset management, monitoring and diagnostics (9 reports, 6 prepared contributions)
4. Instrument transformers and digitalization (9 reports, 7 prepared contributions)

GDM organization
The GDM was chaired by Nenad Uzelac (US), with Frank Richter (DE) as his secretary. For every topic, one of the Special Reporters was acting as discussion leader: Wayne Pepper (AUS) and Tadao Minagawa (JP) for topic 1, René Smeets (NL) for topic 2, Nicola Gariboldi (CH) for topic 3 and Erik Sperling (CH) for topic 4.
Interactivity manager was Martin Kriegel (CH) who managed the incoming questions through SparkUp.

Before the start of the prepared contributions, A. Zafris (US) presented her NGN contribution.

It was decided to have a 15-minute invited introduction presentation for every topic by the following specialists: W. Pepper and T. Minagawa for topic 1, N, Støa-Aanensen (NO) for topic 2, N. Gariboldi for topic 3 and P. Mazza (IT) presented a contribution prepared by L. Peretto (IT) on topic 4.

The session started at 8:45 and ended at 17:45 with two coffee breaks and a lunch break 12:40 - 14:00.
On average, 4 minutes of speaking time was allotted to each contributor, with 6 - 7 minutes for spontaneous contributions after every question.

All but two contributors were interviewed the day before the GDM; one announced contributor did not show up, another reported himself just before the GDM with a new presentation which was rejected.

GDM statistics
Of all 57 speakers (incl. invited) 5 speakers are female.
Of all 57 speakers (incl. invited) 37 are from Europe, 12 from Asia/Pacific and 8 from the Americas.
9 Speakers might be classified as “young”.
51 Prepared contributions were presented. 38 Speakers have a manufacturer’s background, 7 are from utilities, 3 from R&D - and 3 are from consultancy organizations.
The meeting was held in Salle Bordeaux.

The number of scanned participants was 266.

GDM interactivity:
SparkUp counted 194 participants during the session.
An early poll among 50 attendees showed 54% has a manufacturer’s background, 34% utility, 7% laboratories, 5% consultants.
35% Came as a first-time visitor, 45% were 2-3 times visitor, 4% up to 5 times, 14% up to 10 times and 2% more than 10 times.
A poll was set up to “vote” for the “hottest topic” in the A3 community”:

- 66 likes: Environmental and climatic impact
- 35 likes: Impact of renewables on equipment
- 29 likes: Sustainability

Through SparkUp, 18 questions were received.

GDM content

NGN contribution "Monitor Data Management for Asset Failure Prevention" (Abigail Zafris).
In this contribution it was discussed how a large US TSO deals with monitor data management for asset failure prevention. Rough outlines of data infrastructure, alarm ownership, stakeholder training was discussed. As case examples, long term analysis of a 345 kV transformer bushing monitoring campaign (based on oil temperature) was highlighted, as well as transformer dissolved gas monitoring. It was concluded that the methods discussed led to cost savings, greater reliability, and increased safety. As future work, automated data analysis with PI historian is defined.

In the remainder of the GDM, the 20 questions in the Special Report were used as guideline in ordering the prepared contributions.
Topic 1: Miscellaneous T&D equipment and systems

As an introduction, the Special Reporters covering this topic gave a very brief summary of the 16 reports received on this topic.

Q1: 10805 describes that the degree of asymmetry of fault current in a DFIG system can be suppressed by converter control and optimized crowbar resistance. If sufficient suppression is expected, can the test duty of delayed current zero in IEC/IEEE 62271-37-013, Annex K be omitted?
Prepared contributions came from two speakers.
1. The first contributor (FR) highlights the importance of arc voltage in generator circuit breaker interruption with very high degree of asymmetry, leading to delayed current zero. For this, she makes a distinction between SF_6 and vacuum generator circuit breakers. It is reported that Annex K of IEC/IEEE 62271-37-013 does not specify any test duty related to delayed current zeros.
2. The second contributor (DE) advocates not to omit the annex mentioned, but more details shall be included on generator parameters and the relevance of crowbar resistors.

As a spontaneous contribution, the convenor of WG A3.46 (DE), "Generator Circuit Breakers", commented about the effect of crowbar resistors in a DFIG system and requested audience to provide any experiences on the subject for further investigation in the working group.

Q2: HVDC switching equipment is on the way to become 'standardized' technology, while discussions are continuing based on the experiences in the field or laboratories as presented in 10545 and 10773. Can experts provide relevant issues or proposals for the standardization of HVDC switchgear?
Prepared contributions were received from five speakers. The first two speakers focussed on testing of HVDC circuit breakers, the other on miscellaneous subjects.
1. The first one (FR) is in favour of testing these devices with a rectifier DC circuit and gave examples of module tests in a 40 kV test-circuit.
2. The second speaker (JP) focussed to unit- and multi-part testing of HVDC circuit breakers for a typical 320 kV breaker. Conceptual examples were given on test-procedures. A question was raised from the audience how to ensure a proper voltage distribution across multiple units. The answer was in the use of proper voltage distribution for transients as well as DC.

3. The third speaker (NL) highlighted the progress in IEC standardization, showing that on all HVDC switchgear, progress towards standardization is under way. He emphasized the point that many subcomponents of HVDC breakers are standard AC components dealing with non-standard stresses and thus cannot be specified referring to their specific AC standards.
4. The fourth speaker (IT) went into HVDC air-break disconnector standardization. Distinction must be made between indoor and outdoor use, and reference is made to the draft standard IEC 62271-5. For indoor, the challenge is phase-to-earth insulation, whereas for outdoor use, pollution is the dominant factor.
5. The fifth contributor (FR) on the question goes into the system aspects of multi-terminal HVDC systems. Depending on fault clearing strategy, acceptable converter blocking and fault limiting devices, a chart is developed showing simplified protection concepts.

Q3: As described in 10401, 10876 and 10357, advancement of basic technologies contributes to the challenges targeting decarbonisation, decentralisation, and digitalisation in power grids. In addition, integration and coordination of such knowledges would play an important role for it. Can specialists give any prospective views of new technologies applicable to T&D equipment?

Four speakers address this question.

1. The first one (FR) discusses how controlled switching can avoid the "missing zero" phenomenon in switching long AC cables to offshore installations by application of a controlled switchable shunt reactor on land.
2. The second speaker (US) goes into the metal vapour deposition by vacuum arcing on the inner ceramic insulator surface of vacuum circuit breakers. Proper control of this and shielding can advance vacuum interrupter technology.
3. The third speaker (FR) presents a new type of high-temperature superconducting fault current limiter, together with simulations and testing up to 170 kV, using the combination of FCL and DC circuit breaker.
4. The fourth speaker (NL) discusses the impact of electro-magnetic and electro-static induced currents in various OHL configuration (with and without transposition) with more than one voltage level per tower.

Q4: The use of digital devices to enhance worker safety are shown in the reports 10105, 11133 and 10441. Can utilities show other examples where digitalization is being used to enhance worker safety?

Two contributors treated this question.

1. The first one (JP) shows how by proper monitoring of operation timing of HV circuit breaker acceleration sensors can eliminate work at elevated levels in the station.
2. The second speaker (AUS) demonstrates that the use of drones, fixed monitoring cameras and robots reduces risks for station workforce.

Q5: Can other long-term users of equipment installed in adverse climatic conditions with composite insulators also share their experiences, including HVDC composite insulators?

Four speakers addressed this question.

1. The first speaker (BR) highlighted briefly the results of WG A3.30 (TB 816: Substation equipment overstress management).
2. The second contributor (IT) calls for additional information on composite station insulators (AC, DC) in the same environment as found critical for line insulators.

3. The third contributor (AUS) also touched composite insulators, from a user perspective. The issues (in Australia, New Zealand) reported are organic pollution (algae, lichen) and UV radiation.
4. The fourth contribution (DE) is on French experience with composite insulators. Statistics of installed numbers of insulators for a large number of applications are shared, in harsh environments and in HVDC systems.

Q6: Data collection from on-line condition monitoring, system load and voltage measurements, and other operational data including events has created an industry of data processing, analysis, and storage. How much data do we really need to effectively run our networks, and is too much data a help or a hindrance? Is data storage in the future going to be a problem?
There is one contribution (IT).
He displayed the implementation of a monitoring system for air-break disconnectors that include presence and impact of pollution.

Topic 2: SF_6 alternatives

A general introduction was given to this topic, highlighting the need for SF_6 reduction, and its factors to consider. A development timeline was shown, demonstrating the equally quick and competing development of gas circuit breakers using fluoronitrile mixtures on the one hand and vacuum circuit breakers using technical air for insulation of the vacuum chamber. Various GIS products up to 170 kV are on the market, with 245 kV in single break coming in 1-2 years. Reference is made to three latest technical brochures (TB 802, 849, 871) that cover the field.

Q7: The filling pressure of equipment with natural-origin gases is often above 1 MPa. Is there any experience or an estimate on the long-term leakage or other lifetime limiting mechanisms, including mechanical damage, deformation of internal parts, e.g., vacuum interrupters at 0 MPa?
This question is treated by four contributors.
1. The first speaker (DE) emphasized that switchgear with high air pressure for insulation is not new, referring to 88 bays of a 170 kV GIS from 1980. Additionally, measured data of vacuum quality in interrupters (72.5 kV) during 8 years of service are shared, as well as leakage of compressed air from 420 kV instrument transformers.
2. The second speaker (FR) showed French SF_6 leakage data 2011-2020 from which it is concluded that no direct link between filling pressure and leakage rate can be established. Also, no change of oxygen content (in C4-FN mixture) was observed in two years of service.
3. The third contributor (FR) highlighted the different impact dielectrically of pressure loss of air and SF_6 into MV switchgear. He highlights that insulation at atmospheric pressure of air is better than that of SF_6 or F-gases.
4. The fourth contribution (JP) gives detailed information on studies on the impact of pressure and temperature on leakage and lifetime of O-rings. At higher pressure oxidation reduces lifetime.

Q8: Report 10103 states retro-fill can be realized with C4-FN/CO_2 without exchange of sealing material. This seems to in contrast with the findings of authors of 10656 who recommend replacement of the EPDM (SF_6) gaskets with buthyl type for CO_2 carrier gas and the use of N_2 carrier in retro-fill? Can specialist share experiences on the optimum gas mixture and material compatibility?

This question attracted one contribution (CH).
His point was that CO_2-based gas mixtures needs XIIR sealing material, whereas the EPDM material (as used in SF_6 installations) need not to be replaced (e.g. at retro-fill) when N_2-based gas mixtures are used.

Q9: There are conflicting reports on temperature rise performance of SF_6 alternatives. Report 10658 reports an issue, 10657 reports high values at 2500 A whereas authors of 10126 show results like SF_6. Can specialists shed some light on the various influential factors and how they are controlled?
Three contributors took part in this question.
1. The first speaker (FR) concluded that the same nominal current ratings and footprint can be achieved with C4-FN based gas mixtures by implementing small design adaptations.
2. The second speaker (US) studied MV switchgear and concludes, based on experiments and CFD simulation, that temperature rise in his design are 2-10% higher than in SF_6.
3. The third speaker (CH) also used simulation, with model calibration of contact resistance by measurement. He concludes that higher temperature rise with C4-FN gas mixtures compared to SF_6 can be compensated by higher filling pressure and small design changes.

Q10: 11068 reports high post-arc current impacts the series application of vacuum interrupters. Report 10317 observes also in C4-FN gas breakers post-arc current much higher than in SF_6. Can high/variable post-arc current potentially complicate series combination of C4-FN interrupters?
Two speakers deal with this question.
1. The first speaker (FR) observed high (> 10 A) post-arc current in a 420 kV double break C4-FN based breaker, but still could demonstrate adequate short-line fault interruption performance.
2. The second speaker (CH) showed post-arc current in the 500 mA range in a 420 kV double break C4-FN based breaker. She mentioned this is not an issue for application of a double chamber.

One specialist from the audience remarked that the clear difference in measurement is due to design, not due to the gas.

Q11: Report 10848 states that a double break 420 kV C4-FN based circuit breaker, including grading capacitor has similar bay-width size as a single-break SF_6 breaker of that rating. How would a compressed air-insulated 420 kV VCB (envisaged in 11068) compare with that?
Three specialist addressed this question.
1. The first speaker (DE) elaborated on the size of live-tank compressed air insulated vacuum breakers ≤ 420 kV: filling pressure and size comparable to SF_6. For 420 kV vacuum-based GIS slightly higher pressure and dimensions as 2012 generation 420 kV switchgear is concluded.
2. The second speaker (FR) reported that double break 420 kV C4-FN based GIS circuit breaker would have the same diameter as a modern single break 420 kV SF_6 breaker. A 420 kV C4-FN breaker is reported have passed testing in the speaker's laboratory regarding interruption duties.
3. The third speaker (JP) spoke on behalf of the Japan Electrical Manufacturing Association. The footprint of natural-origin gas-based breakers would be 30% larger than modern SF_6 switchgear but comparable in size to the older equipment that it would replace.

Q12: In different projects, different practices of mixing gas components are reported. Authors of 10102 prefer off-site mixing, whereas authors of 10656 describe on-site mixing as

"most beneficial". Can specialist (e.g., authors of 10799, 10966) report on experiences in other projects?
This question drew the attention of two contributors.
1. The first speaker (FR) went into gas management of SF_6-free gases. He explained the way misconnections are avoided by different threads and QR codes.
2. The second speaker (CH) explained the differences between pre-mixing and mixing on site.

Q13: A variety of C4-FN based mixtures (with and without oxygen) and composition ratios (some even undisclosed) is reported. With every manufacturer having its "proprietary gas" could "inter-operability" be realized? Can specialist predict whether a "one-gas-fits-all" solution is waiting at the horizon or at what time horizon convergence of various technologies can be expected?
Five contributors gave their opinion on this question.
1. The first specialist (JP) explained the roadmap of the Japan Electrical Manufacturing Association, having a list of 7 requirements for non-SF_6 switchgear 72 – 550 kV. It is expected that before 2032 SF_6 GIS, breaker will be available on the Japanese market up to and including 550 kV.
2. The second speaker (US) goes into harmonization among some North-American OEMs to harmonize the C4-FN mixture for MV switchgear to 13% C4-FN, 87% CO_2 and no oxygen.
3. The third speaker (FR) argued it is too early to freeze gas composition ratios, because adapting this it is necessary to optimize design and application (minimum temperature). Only on the amount of O_2, there is consensus (13%) among those who apply O_2 in the mixture. It is not likely that using any C4-FN mixtures could be used in any type of switchgear validated to be used with a specific amount of C4-FN.
4. The fourth speaker (CH) highlighted the compatibility process of LPIT with SF_6-free insulation gas. Software adaptations can enable the use of various gas compositions, after calibration.
5. The fifth speaker (CH) highlighted the importance of O_2 in the gas mixture. Addition of O_2 can prevent the formation of solid carbon. Tests regarding this on a CO_2/O_2 live tank breaker were reported.

A spontaneous contributor added to the last point that also breakers (up to 170 kV) with an oxygen-free alternative gas mixture have passed type tests. This statement, in return was commented by another contributor that sometimes breakers can pass type test with "good luck".

Topic 3: Asset management, monitoring and diagnostics

An introduction to this topic is given. First, an overview is given on the progress of WG A3.43: "Tools for lifecycle management of T&D switchgear based on data from condition monitoring systems". Reference is made to a large numbers of previous technical brochures in the field (TB 167, 422, 462, 510, 541, 597, 725, 737). Then, a summary of main points of the nine submitted reports on this topic was given.

Q14: Controlled switching technology, known for about thirty years, seems to experience a renewed interest and applied more and more frequently. What is the reason for that? Higher reliability, more trust in this technology, possibility to be integrated in IEC 61850 digital substations?
Three speakers went into this question.

1. The first specialist (FR) gave a general overview on the rationale and practice of controlled switching, quoting TB757 on the topic. Concerns raised were on lack of training, surveillance during operation and lack of standardization.
2. The second speaker (SE) hailed the successes of the technology, giving an example of a circuit breaker for a power plant, switching 3 times a day, resulting in a 57% reduction of ownership costs when applying controlled switching. In addition, a new application for switching long cables is highlighted, avoiding missing current zero.
3. The third speaker (AUS) highlighted some AUS/NZ experience, showing a catastrophic failure due to wrong setting through the IEC 61850 protocol in a 300 kV shunt reactor application. As challenges he sees accurate setting of remote switched transformers and the absence of a single point-on-wave controller for multiple vendors.

Q15: How high is energy consumption to power the cryogenic cooling system (CSS) and eventually the compensating heater when the continuous current is below 70% of the nominal value?
No prepared contributions were received on this question.

Q16: A general question to utilities: Which is the expected maintenance interval extension by applying condition-based approach in comparison to a time-based one?
Three answers were received on this question.
1. The first speaker (FR) detailed on preventive maintenance of a circuit breaker (switching several times per day) in a pumped storage power plant using gas, mechanical, current and coil current sensors. Monitoring is now considered as a part of the overall product.
2. The second speaker (JP) presents an approach evaluating the breaker main contact open/close operation time through correlation with the operation time of the auxiliary contacts and automatic acquisition by wireless transmission. The application of the stationary measuring device has increased the work efficiency of circuit breaker inspection by more than 70%.
3. The third speaker (JP) dealt with extension of periodic inspection interval with IoT technology. This interval could be extended from 6 to 24 years. An example is given on failure prevention of a breaker by monitoring the duration of control current.

Topic 4: Instrument transformers and digitalization

An educational introduction to this topic is provided. It treats the instrument transformer and its interface to the power system: the merging unit. Also, the standardization system and its development are covered including communication and synchronization. As open issues are defined: digital Its (incl. MV), management of the massive data flow and periodical verification of accuracy performance.
As the motivation for digital substations a reduction in production costs, a reduction in the amount of maintenance and operating costs are mentioned.

Q17: No passive cooling system is introduced. A dry insulation system typically has challenges with high temperatures at the primary conductor. What are the thermal limits of the rated current level?
One speaker (US) is going into this question.
He presents a cascade-type CT for 500 kV having novel dry-type insulation for the primary winding. Temperature rise results are shown.

Q18: One argument for using LPITs is their wideband characteristic for measurement of harmonics up to kHz ranges. In this report, only the frequency response up to 250 Hz is

presented. What is the expected frequency response behaviour of the voltage and current part?
This question attracts three contributors.

1. The first speaker (DE) shows frequency response plots of actual GIS sensor and highlights the requirements defined by IEC regarding overall accuracy. His statement is that accuracy better than 5% up to the 50th harmonic frequency is achievable and recommends CIGRE TB 814 for bandwidth considerations for various LPIT configurations.
2. The second one (FR) gives an overview of the relevant part (accuracy classes for high frequencies) in the IEC 61869 standard for LPIT, showing that frequency range above the 13th harmonics is optional. The new standard allows frequency response compensation by using correction settings.
3. The third speaker (CH) demonstrates LPIT frequency responses for quality metering up to 6 kHz based on rogowki coils and capacitive field sensors. He concludes that digital signal processing equalizes amplitude and phase response of the signal path and that the mentioned sensors can be characterized at higher frequencies with appropriate precision, simplifying the secondary system.

Q19: The base of all the simulations are the measured values provided by different types of instrument transformers or sensors. To prevent misinterpretation or wrong results, data validation on the side close to the sensor is becoming crucial. How to perform such a data validation provided by sensors?
There is one answering contributor (BR) to this question.
He discusses machine learning and anomaly detection for on-line defect identification in HVDC wall bushings. A practical project example is demonstrated focussing here on validation of data acquisition hardware and diagnostics algorithms.

Q20: A failure scenario of an instrument transformer depends on electrical and mechanical design parameters and varies between the manufactures. How do specialists see the complexity considering all manufacturers-dependent influences?
Two contributors go into this question.

1. The first one (BR) shares the analysis of a 500 kV GIS inductive VT GIS failure, supposedly due to winding resonance. With manufacturer-provided frequency characteristic she calculated that switching transients may produce 2.3 pu overvoltage between internal layers. The repetitive nature of the impulses (disconnector switching) may have been the cause of failure.
2. The second speaker (DE) discusses failure scenarios of GIS LPIT, by sharing MTBF data of the subcomponents of its primary parts. Also, the electronic IO module/merging unit is declared to have a MTBF which is strongly temperature dependent.

The meeting was closed at 17:45