10132 Session 2022
A3 - TRANSMISSION & DISTRIBUTION EQUIPMENT
PS2 - Decarbonisation of T&D Equipment

Substation Equipment Overstress Management
CIGRE Technical Brochure 816 Compilation

Antonio CARVALHO
ATIVA Engineering

Jorge F. AMON
Consultant

Marta LACORTE
ATIVA Engineering

Brazil

Christian LINDNER
AXPO

Reto KARRER
Hitachi Energy

Switzerland

antonio.carlos@ativa.eng.br

SUMMARY

The end-of-life considerations for HV equipment are generally based on the equipment's condition and performance. Another specific aspect affecting it is related to the possibility that substation equipment might be subject to stresses not considered in planning/specification phase. This kind of stresses beyond the equipment's capabilities are classified as overstress. CIGRE Working Group A3. 30 "Substation Equipment Overstress Management" carried out investigation to identify practices for detecting and mitigating potential overstresses to substation equipment. The result of this investigation was published in CIGRE Technical Brochure (TB) 816 [1]. The initial part of TB 816 is devoted to clarifying the difference between overstress and ageing concepts for HV equipment and to classify the different kinds of overstresses that might affect them. Most of the system and environmental stresses can be managed to avoid overstresses to substation equipment. A follow up process to identify the possibility of occurrence of these most common overstresses is suggested, as well as some mitigation measures are discussed. A special set of overstresses are those classified as abnormal. They are typically environmental stresses with low frequency of occurrence whose intensity is beyond maximum standardized values, like hurricanes, tornados, tsunami, earthquake above 8 Richter scale, atmospheric discharges with extremely high impulse current, severe heat, severe flooding, severe rain and humidity, severe cold, snow and ice, severe wind, sandstorms, volcano activity and major solar magnetic storm. These kinds of overstresses are generally not taken into account in the planning studies and equipment/installation specifications, since they fall apart of planning reliability criteria. They belong to the so-called "high impact and low frequency" events (HILF) and should be considered in a wider and more complex context of resilience of power systems. A discussion on the needs for stablishing of resilience concept for system infrastructure is also presented in this paper. WG A3.30 identified some kinds of overstresses requiring a better understand and standardization. Equipment ageing is not considered in this report. It was thoroughly discussed by CIGRE A3.29 and published in TB 725 [8].

KEYWORDS

Asset management, overstress, end-of-life, resilience, environmental stress, HILF.

1. INTRODUCTION

CIGRE WG A3.30 reviewed HV substation equipment life management with respect to overstresses, as well as overstresses management practices. Major motivation for the identification of overstresses in due time is to put not in risk HV equipment performance, which could have bad consequences for personnel safety or system reliability, among others.

The traditional approach for end-of-life management asks for permanent follow up of equipment performance, operation conditions and maintenance practices. A robust database on equipment's life allows asset managers to define performance indicators that are fundamental input for identifying approaching of end-of-life and thus deciding for refurbishment or replacement. The way utilities deal with this challenging subject is widely discussed in CIGRE literature. Particularly, CIGRE Technical Brochures 309 [6] and 486 [7] give a clear and practical picture on how to manage it.

For the purposes of the present discussion, it is important to clarify the concepts of ageing and overstress. This can be visualized by means of stress X strength probability distributions plots shown in Figure 1. While ageing is the consequence of the deterioration of equipment's withstand capabilities[1] overstress is a consequence of the worsening of the stresses the equipment is subjected to during operation. In other words, overstresses can be defined as stresses beyond HV equipment withstand, as defined by standards and/or by technical specification. Once overstress is identified, either in system operation or in short-term planning studies, decision must be taken to eliminate it. Typical actions are equipment upgrading, replacement, or application of mitigation measures [2].

This document is structured to present compiled discussion on overstress classification, overstress prioritization, applicable mitigation measures and further necessary investigation. This last topic also covers the concept of resilience in the context of overstress management, since overstresses are direct consequence of HILF environmental phenomena or malicious action of humans, like sabotage, terrorism or cyber-attacks.

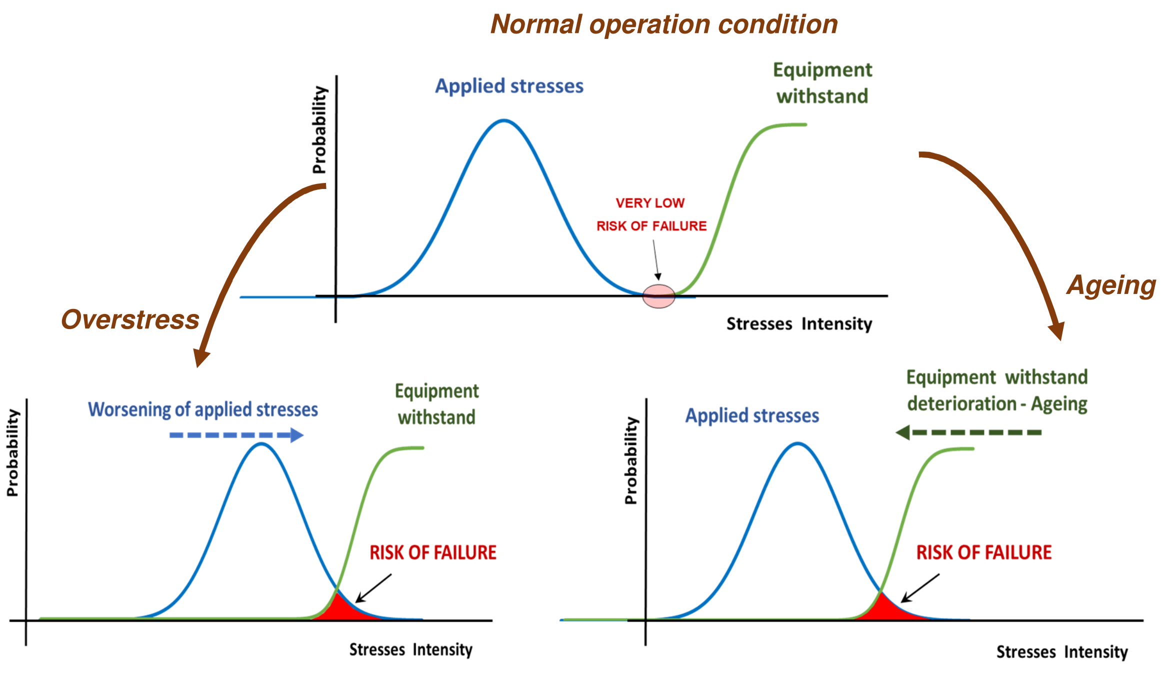

Figure 1 – Conceptual difference between overstress and ageing of HV equipment

[1] WG A3.29 definition: "Ageing can be defined as a process that causes change in equipment properties as the equipment is exposed to stresses. The change in equipment properties is likely to affect its performance against its intended function."

2. CLASSIFICATION OF STRESSES IMPOSED TO HV EQUIPMENT

Power system installation are planned, projected and operated to according to technical requirements derived from normal stress patterns identified by planning studies, system operation experience, environmental phenomena statistics (e.g. atmospheric discharge pattern, earthquake intensity, ambient temperature, etc.), among others. These so-called normal pattern stresses are translated into technical standards, regulatory and grid code requirements, technical specification for equipment and installation. Under abnormal stresses fall those events and phenomena of very low frequency of occurrence, but high impact (HILF) that cannot be captured by contingency scenarios nor considered in regular reliability criteria due to the excessive high costs associated. Most common examples of abnormal stresses are earthquake above level 8 in Richter scale, volcano activity, tornado, flooding, tsunami, malicious acts like sabotage, etc. More recently, the list was expanded to include cyberattacks and pandemics. Therefore, for the purpose of WG A3.30 work, the HILF events were not considered in overstress management process. In spite of that, the discussion on strategies to face these kinds of events is also presented in this paper (Item 7) and it falls under the umbrella of resilience of power systems [10].

3. RELEVANT OVERSTRESSES FOR HV EQUIPMENT PERFORMANCE

The correlation of the different kind of stresses with the main performance parameters for HV equipment make possible to draw the matrix *stresses X equipment* (see Table 1). Although power transformers and shunt reactors were not part of the investigation carried out by WG A3.30, they were included in the matrix as reference in order to offer to the reader a general picture for most of the standard substation equipment.

The upper part of the matrix (green background) corresponds to the "normal stresses" which can be predicted by calculation/simulation, measurements, observation or statistical treatment of historical data. Therefore, they can be taken into account in planning phase, during system operation and in asset management process aiming at maintaining the performance of HV equipment, which is a necessary pillar to keep system reliability under control. The boxes with a cross ("**X**") in the matrix correspond to the stresses were prioritized by the Delphi analysis [9] carried out by the WG A3.30 [1] and indicates the most commonly identified stress parameters that could impose overstresses to the set of analysed equipment. This set of stress X equipment pairs are the recommended candidates to be included in a regular process to monitor the possibility equipment could be overstressed.

The boxes with a dot ("●") correspond to the stresses which are also relevant for the equipment and its inclusion on the referred process shall be decided on region-based experience, depending on utility geographical location, environmental parameters, network characteristics, system operation history and asset management philosophy.

The lower part of the matrix (yellow background) corresponds to events of very high impact and low frequency of occurrence – HILF. Consequently, they are considered neither in regular reliability criteria applied to system planning. HILF events are taken into account in the context of power system resilience [18], which has been gaining more recent attention of electric systems [19].

4. OVERSTRESSES MANAGEMENT PRACTICES

WG A3.30 recommended utilities to stablish a process to check the worsening of stresses applied to HV equipment that could lead to overstresses. Two frequencies to carry out these checks are suggested, as presented in Table 2 and 3. Table 2 indicates the stress parameters that should be checked for selected substation equipment in a regular basis. This was called the *systematic analysis* and it is recommended to be applied once a year or couple of years, depending on utility practices.

Table 3 indicates the stress parameters and substation equipment for which the intervals for overstresses check could be longer. The so called *non-systematic analysis* could have a checking interval of some years, based on the utility practices, of network expansion patterns, weather/environmental changes, among others. Another possibility is to take action only if the utility get evidences from system operation data, maintenance process, monitoring systems, or system planning process indicating the risk of overstress.

Tables 2 and 3 were updated in relation to [1] based on the experienced gained with practical application of overstress management process in some countries. More details on the overstress management practices are described in the CIGRE TB 816 [1].

Table 1 – Correlation matrix between HV equipment and relevant stresses for their performance

Origin of stresses applied to HV equipment			Equipment Impacted ==================▶	CB GIS	CB AIS	Disconnector	Earthing switch	Surge arrester	Post insulator	Instrument transformer	Capacitor bank	Power Transformer	Shunt Reactor
	Normal Stresses	Electric System	Continuous operation at degraded topology (N-x) leading to load current overstress	●	x	x				x		●	
			Continuous operation at degraded topology (N-x) leading to voltage overstress	●	●			●		x	x	●	●
			Temporary stress due to load current	x	x	x				x		●	
			Temporary stress due to operation voltage	x	x	x		x		x	●	●	●
			Current and voltage overstresses due to switching	●	x	x		●		x	x	●	●
		Human activities	Pollution		●	x	●	●	x	●			
			Improper erection & commissioning	x	x	●	●	●	●	●	●	●	●
			Improper maintenance	x	x	x	x	●	●	●	●	●	●
		Environment Normal events	Wind		●	●	●	●	●				
			Ice		●	●	●	●	●	●	●		
			Low & high ambient temperature		x	x	x	●			●	●	●
			Fire	●	x	x	●	●	●	●	●	●	●
			Lightning	●	x	●		x	●	●	●	●	●
			Salt fog		●	●	●	●	x	●	●		
			Heavy rains						x				
			High humidity		x	x	x	●	●	●	●	●	●
			Sand storm		●	●	●	●	●	●	●		
			Eartquake (< 8 Richter scale)		●	●	●	●	●	●	●	●	●
		Animals	Trespassing of animals			x	x		●		x	●	●
	HILF Events	Human activities	Pandemics	High impact and low frequency events impairing the whole grid. Shall be considered in the context of power systems "RESILIENCE".									
			Malicious actions										
		Environment Abnormal events	Tsunami										
			Tornado & hurricane										
			Earthquake (> 8 Richter scale)										
			Volcano activity										
			Big solar magnetic storm										
			Severe heat, severe flooding, severe rain and humidity, severe cold, snow and ice, severe wind and sand storms – above standard values										

Notes: "X" corresponds to the stresses prioritized by the WG A3.30
"●" corresponds to also relevant stresses, but utility shall decide on its prioritization based on local experience.

5. MITIGATION MEASURES

Overstresses to HV equipment should be ideally anticipated by utilities, thus avoiding equipment being stressed above ratings. In some situation, overstresses are identified lately and equipment has already been operated under this undesirable condition. Both cases action must be taken either on equipment level or applying mitigation measures to reduce stresses to the originally specified levels.

The more straightforward solution is equipment replacement by other with higher ratings and able to fulfil the evolving stress requirements. Uprating measures might also be possible under specific circumstances, but attention shall be paid to the associated costs under the life management context.

Mitigation measures might be an efficient solution and the generally applied ones are discussed in [1]. They are shortly described in the sequence.

5.1. Mitigation measure for current overstress

Mitigation measures for current overstresses are discussed in TB 816 [1]. They are: busbar splitting, reconfiguration of circuits, sequential tripping, application of current overload criteria, transformer grounding impedance, opening of transformer tertiary delta connection, limiting reactors in series with transmission lines, transformers or generators, fault current limiters (FCL).

Table 2 – Systematic overstress check on short-term horizon

Kind of stress	Equipment considered				
	Circuit breaker	Disconnector	CT	Line trap	All substation equipment
Short-circuit current	X	X	X	X	
Asymmetrical short-circuit current peak	X	X	X	X	
Load current	X	X	X	X	X (**)
Time Constant (X/R)	X		X		
Operation Voltage (*)	X	X	X	-	X

(*) continuously monitored by the SCADA system (**) all current carrying equipment - not considered

Table 3 – Non-systematic overstress check on short-term horizon

Kind of stress	Equipment considered			Not considered in the Technical Brochure [1]				
	Circuit breaker	Surge Arrester	All substation equipment	Grounding Transformer (*)	Busbar	Grounding Mesh	Power Transformer	Shunt Reactor
Short-circuit current					X	X	X	
Asymmetrical short-circuit current peak					X		X	
Load current					X		X	
Time Constant (X/R)								
TRV	X							
X0/X1				X				
Temporary overvoltage		X		X			X	X
Dissipated energy		X						
Lightning			X					
Salt fog			X					
Heavy rains			X					
High humidity			X					
Pollution			X					

(*) applicable only to sub-transmission

5.2. Short circuit current time constant for circuit breakers

For substation equipment the influence of system time constant is indirectly taken into account by the specification of the asymmetrical short circuit current. If the ratio X/R of the busbar where the circuit breaker is installed changes with respect to the specified value, an analysis of the influence of the new time constant on the behaviour of the circuit breaker must be made. The possibility to apply a de-rating factor for the symmetrical short-circuit specified is described in IEC application guide for circuit-breakers [23] and discussed in [1].

5.3. Overstress Criteria for Current Transformers

This is thoroughly discussed in [24] and is divided in two independent evaluation phases:

- Simplified Evaluation: It is a steady state evaluation considering load current and short-circuit current.
- Full Evaluation: provides the evaluation of the current transformer's performance, considering the protection relay times and fault elimination time.

5.4. Controlled switching as overstress mitigation measure

Switching of transformers, reactors, capacitor banks and overhead lines can produce transient over-voltages and inrush-currents of significant magnitude. Although these transients are taken into account in the planning/specification phase, the rapid evolution of the grid topology and generation resources can lead to undesired transient stresses due to these kinds of switching. The application of this efficient mitigation solution was described in detail by WG A3.07 and more recently by WG A3.35 [15].

5.5. Substation monitoring

Monitoring can be an efficient mean to follow up of equipment's performance can be used to prevent future failures. Not only the deterioration of the equipment performance can be assessed, but also the evolution of the external stress variables can be obtained by monitoring systems combined with adequate data bases and analytics technics. CIGRE TB 462 [12] presents the technologies currently available and analyses the factors to determine the ideal solution for each application. CIGRE TB 737 [14] deals with modern non-intrusive techniques for assessment of HV switchgear, most of them allowing in service evaluation.

5.6. Overstress mitigation due to severe climate conditions

CIGRE WG B3.31 produced a document dealing with severe climate conditions affecting substations [5]. Substation design properly fitted to cope with sever climate conditions are discussed, as well as long- and short-term mitigation measures. In each specific application the utility shall evaluate which approach best fits their needs, considering regulatory, economical and responsibility issues. The severe climate conditions considered in this work are heat and drought, rain, flooding and humidity, snow and ice, wind. It is recommended to consider CIGRE WG B3.31 [5] as a basic guidance to mitigate severe climate condition overstresses affecting substation equipment. Extreme earthquakes are discussed in [3] and heavy snow and severe pollution are discussed in [4].

6. ABNORMAL STRESSES

A relatively large set of stresses that might be imposed to HV equipment was identified by WG A3.30, which was complemented by more recent discussions. These HILF events are listed in Table 1 and most of them are consequence of abnormal environmental phenomena, like tsunami, tornado and hurricane, earthquake (>8 Richter scale), Volcano activity, big solar magnetic storm, severe heat, severe flooding, severe rain and humidity, severe cold snow and ice, severe wind and sandstorms (all above standardized values). A quite good reference list of papers dealing with these events can be found in item 5.3 of TB 816 [1], among them CIGRE TB 614 [5], discussing possible measures to be taken in order to mitigate the effects of severe climate conditions. One of the conclusions of this work carried out by WG B3.31 – AIS Substation Design for Severe Climate Conditions – is: *"Total prevention of an outage due to weather is not always the most optimal design when it comes to total cost. Designing a substation to restore service in a short or expedient manner can be low-cost and effective"*. This concept of fast recovery after a major event is fully in line with the resilience concept for power systems and will be discussed latter in this paper.

Another set of abnormal stresses leading to major events are those provoked by mankind. Under malicious actions falls a bunch of possibilities, being the most common: sabotage, terrorism, cyberattacks and pandemics. Those are typical events having the resilience concept as a proper mitigation measure.

In the last years, cyberattacks have called the attention of utilities, regulators and governments, since the number of attempts to invade corporate (IT) and operational (OT) systems has been increasing steadily. Fortunately, measures already practiced by power utilities have been able to prevent these attacks. Power system community and different sectors of the economic activities, e. g. like banking system, as well as security agencies are giving priority to define processes, standards and countermeasures to prevent it [20]. CIGRE has already published two technical brochures on this topic [16][17], where the philosophy to protect communication and operational systems are thoroughly discussed, as well as the need for planning the cyberphisical security. EPRI´s future vison and gaps presently identified are presented in [21]

Newly pandemics experience brought some lessons for the power system community. Electrical power utilities showed a high level of preparedness to this kind of event, although most of them have not prioritized this specific kind of event in their plans to come over and recover from big events or catastrophes. The nature of power system operation activity, which takes into account its essentiality for modern society, has been always a drive to discuss and stablish processes and standards to recover from blackouts and from major events. Fast restoration is the key point and it was also analysed by CIGRE WG C2.25 from a resilience point of view.

Beyond power system operation horizon, the effect of pandemics in other fields of power industry were also discussed recently. Utilities personnel maintenance work aspects, supply chain, remote testing of HV equipment at factories and laboratories are some of these topics and SC A3 Utility Advisory Group published a paper discussing them [11].

One of the key aspects from pandemics lessons learned is the need to consider this kind of event in large-scale incidents affecting power system. Pandemics requires risk-averse or risk informed decision-making process and proactive rather than reactive thinking to develop holistic resilience enhancement frameworks that are able to fast recovery from such incidents.

7. SYSTEM RESILIENCE IN THE CONTEXT OF INFRASTRUCTURE

According to CIGRE WG C4.47, power system resilience is *"the ability to limit the extent, severity, and duration of system degradation following an extreme event"* [10]. This concept is well understood and practiced at system operation level and CIGRE SC A2 – System Operation – is fully involved in this discussion [18]. However, the role of the grid infrastructure for system resilience must be better discussed and understood, particularly in the context of asset management.

Reliability concepts are routinely applied for expansion planning and operation. The criteria are well consolidated and consequently the costs for reliability. However, the investment costs for dealing with HILF events mostly having disruptive nature are unaffordable, if analysed in a reliability context. The difference between reliability and resilience events must be clearly stated (Figure 2) to allow the definition of the applicable measures.

Figure 2 – Spectrum of the reliability and resilience events [19]

Resilience events must be analysed in a risk-based framework, allocating priority of actions in each phase of disruptive event [10]:

- ✓ anticipation, preparation, absorption, sustainment of critical system operations, rapid recovery, and adaptation.

The timeline for the resilience of the grid infrastructure, considering the sequence of events adopted by Mahrzania et all in [22] for the operational resilience is shown in Figure 3. The time frames for planning, responding and restoration are clearly different for system operation resilience and infrastructure resilience. For the purpose of this paper the latter concept is the one of interest and each event phase is shortly discussed.

7.1. Planning for infrastructure resilience:

The stresses to be considered for planning the resilience of electrical grid infrastructure with focus on substation equipment is already identified and presented in Table 1 under "HILF Events". Measures to face pandemics and cyberattacks will not be included in this discussion, because there are already stablished groups with this focus.

For the resilience planning phase each of the stress parameters that can lead to a high impact event shall have the consequences analysed, aiming at defining strategies for the preparedness to survive major disruptive events and provide a fast infrastructure restoration from disaster.

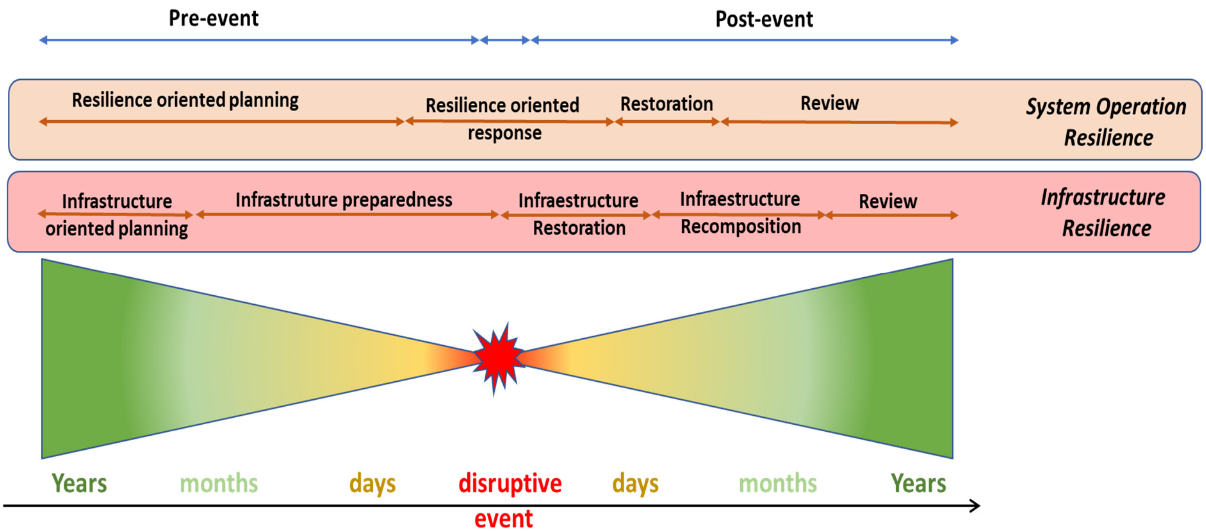

Figure 3 – Timeline of power system resilience

Infrastructure restoration phase can be planned in two steps. The first one, immediately after a major event, intends at keeping a minimal infrastructure in operation to allow system restoration, even if reliability and operation criteria have to be relaxed. This can take several days, depending on the severity of the event. In a second moment, the focus will be on the recomposition of the infrastructure to the state previous to the major event. Generally, many days to months can be necessary. However, the duration of restore and recompose infrastructure will be totally dependent on planning for infrastructure resilience in the pre-event time frame. This shall necessarily include the following issues:

- ✓ Build up scenarios for each HILF event identified with focus on possible consequences to the grid infrastructure,
- ✓ For each scenario prioritized, plan to mitigate and/or restore minimal infrastructure, thus clearing tolerances to the adverse consequences and defining asset management procedures for this kind of critical situation,
- ✓ Plan to reconstruct infrastructure, taking into account availability of local spare parts, components, or equipment, regional stock pillars, logistic, specialized personnel, etc.

Besides the direct planning for major events that might occur, a higher level discussion at National basis, including relevant stakeholders like, government agencies, regulators, power utilities, equipment suppliers, costumers associations, etc. It is of major relevance to define what level of degradation after a major event is acceptable for society and how much are them willing to pay for that.

The financial aspect of a infrastructure reconstruction after a major event has to be clearly stated and regulator must have exceptional rules for the flexibilization of regulation commands, which generally are developed for normal life situation. Government and financial sector support to special financial schemes supporting infrastructure reconstruction have to be previously discussed.

As in any kind of critical event a clear communication and command chain processes have to be defined, to provide agility of response.

8. CONCLUSIONS

Overstress is quite relevant sub-process of asset management. Utilities shall be aware about the possibility of overstresses affecting HV equipment. asses its risk and allows application of mitigation measures, decision on equipment replacement or equipment upgrading. The work of WG A3.30 give guidance to utilities for stablishing equipment overstresses management process, having focus on electrical overstresses form the network and normal overstresses from environmental nature.

The working group concluded that there are some specific stress asking for deeper analysis to provide better understand of the effects on substation equipment and more precise requirements for technical standards. However, the role of the grid infrastructure for system resilience must be better discussed and understood, particularly in the context of asset management.

The topics suggested for further investigation are:

8.1. Operation voltage above ratings

Operation at a voltage above the maximum operating voltage values of transmission equipment is usually a consequence of the intermittent pattern of renewables generation, including distributed generation. This can lead to insufficiency of voltage regulation resources in the network, thus imposing operation voltages above equipment ratings. More stringent PD requirements could improve the resilience of the equipment.

8.2. Temporary overvoltage withstand ability

The lack of specific testing for this kind of stress, as well as the lack of guidance on equipment standards in defining equipment limits for TOV asks for specific investigation. A joint working group was created should cover temporary overvoltage and voltage above ratings – JWG A3/A2/A1/B1.44 *Consequence of High Voltage Equipment operating exceeding highest system voltages*.

8.3. Controlled switching for MV switchgear

Controlled switching has been quite explored by CIGRE WG A3.07 [25] and A3.35 [15]. The focus has been transmission switchgear. However, the benefits of controlled switching for system transient and equipment stresses mitigation can be as well extended to medium voltage equipment. Performance specific aspects of MV switchgear should be considered in future work.

8.4. Instrument transformers performance

Failures reported for different types of instrument transformers in transmission systems is attracting the attention of specialists. A possibility for these occurrences is overstresses due to unforeseen Very Fast Transient Overvoltage (VFTO) caused by compaction of AIS substation arrangements. CIGRE Working Group A3.42 (Failure Analysis and Risk Mitigation for Recent Incidents of AIS Instrument Transformers) was created to investigate these occurrences and try to track the possible reasons and discuss applicable mitigation solutions.

8.5. Overstress due to pandemic, abnormal environmental events and malicious acts

The COVID-19 pandemic initiated in the beginning of 2020 brought a new aspect affecting world´s Economy [11]. Besides that, cyber-attacks to power utilities as well as the occurrence of disruptive major impact events from environmental nature are becoming more frequent. Due to their HILF nature this kind of events are not considered in reliability studies. They shall be treated in the level of power system resilience, whose focus has been primarily system operation. Therefore, it is strong recommended to initiate discussions and perhaps to stablish a joint working groups to discuss and come to common understanding about power system infrastructure resilience, as discussed in item 7 of this paper.

9. BIBLIOGRAPHY

[1] CIGRE Technical Brochure 816 (2020), "Substation Equipment Overstress Management", WG A3.30, www.e-cigre.org.

[2] Carvalho, A., Amon, J. F., Lindner, C., Bourdeau, J-F, Sardi, B. N., Vàquez, P. R., Richter, F., Moreau, P., "Challenges for managing overstresses and end of life of HV equipment", CIGRE Session 2016, paper A3-201, Paris.

[3] Ohno, T. Ito, H. Nakakoji, T. Kobayashi, H. Sato, "Study of seismic design and guideline of substation equipment based on the Great East Japan Earthquake", CIGRE 2014 Session, A3-304.

[4] H. Miyakawa, H. Takada, Y. Ito, M. Toyoda, J. Kida, H. Koyama, "Investigation of composite insulators in extreme environments – Heavy snow and severe pollution", CIGRE 2014 Session, paper A3-305.

[5] CIGRE Technical Brochure 614 (2015), "Air Insulated Substation Design for Severe Climate Conditions", WG B3.31, www.e-cigre.org.

[6] CIGRE Technical Brochure 309 (2006), "Asset management of transmission systems and associated CIGRE activities", WG C1.1, www.e-cigre.org.

[7] CIGRE Technical Brochure 486 (2012), "Integral decision process for substation equipment replacement", WG B3.06, www.e-cigre.org.

[8] CIGRE Technical Brochure 725 (2018), "Ageing High Voltage Substation Equipment and Possible Mitigation Techniques", WG A3.29, www.e-cigre.org .

[9] Sackman, H., Delphi Assessment: Expert Opinion, Forecasting and Group Process, R-1283-PR, 1974.

[10] Ciapessoni, E., Cirio, D., Pitto, A., Panteli, M., Van Harte, M., Mak, C., Defining Power System Resilience, CIGRE Reference Paper by WG C4.47, ELECTRA No. 306, October 2019.

[11] UZELAC, N.* (US), RICHTER, F. (DE), CARVALHO, A. (BR), LE ROUX, R. (IE), NOVAK, P.L. (DE), AMON, J. F. (BR), "Impact of Covid-19 to System Operators and Electrical Equipment Manufacturers" - Utility Advisory Group A3 by– Invited Paper - CIGRÉ SCIENCE & ENGINEERING - October 2020.

[12] CIGRE Brochure 462: Obtaining Value from On-Line Substation Condition Monitoring, 2011.

[13] CIGRE Brochure 715: The future of reliability: definition of reliability in light of new developments in various devices and services which offer customers and system operators new levels of flexibility, by WG C1.27, 2018.

[14] CIGRE Brochure 737: Non-intrusive methods for condition assessment of distribution and transmission switchgear, by JWG A3.32/CIRED, 2018;

[15] CIGRE Brochure 757: Guidelines and best practices for the commissioning and operation of controlled switching projects, by WG A3.35, 2019.

[16] CIGRE Brochure 796: Cibersecurity: Future threads and impact on eletrical power utilities organizations and operations, by WG D2.42, 2020.

[17] CIGRE Brochure 840: Electrical power utilities' cibersecurity for contingency operations, 2021.

[18] CIGRE Brochure 833: Operating strategies and preparedness for system operational resilience. By WG C2.25, 2021.

[19] Schwarz, L., Utility Investments in Resilience of Electricity Systems, Lawrence Berkeley National Laboratory, under the assignment of the U.S. Department of Energy, 2019, https://emp.lbl.gov/publications/utility-investments-resilience

[20] ISO/IEC 27007 / ISO/IEC 27009 / ISO/IEC 27014 / ISO/IEC 27001 - Cybersecurity And Privacy Protection Package, ANSI 2020, https://webstore.ansi.org/Standards/ISO/ISOIEC27007270092701427001

[21] EPRI, Cyber Security Vison for 2030, August 2021, https://www.epri.com/research/products/000000003002022715.

[22] Mahzarnia, M., Moghaddam, M. P., Baboli, P. T., Siano P., A Review of the Measures to Enhance Power Systems Resilience, IEEE SYSTEMS JOURNAL, January 2020.

[23] IEC/TR 62271-306, TECHNICAL REPORT, Guide to IEC 62271-100, IEC 62271-1, 2012-12.

[24] IEC 61869-2, IT – Part 2: Additional requirements for current transformers, 2012.

[25] CIGRE Technical Brochures 262, 263 and 264 (2004), "Controlled Switching of HV Circuit Breakers", WG A3.07, www.e-cigre.org