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Solutions to improve DSC dependability and return of experience from field

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SUMMARY

This article reveals how the reliability and the availability (dependability) of HV disconnectors in the AIS substation can be improved thanks to combined and dedicated solutions taken from theoretical analysis and confirmed and reinforced by feedback of experiences on field.
Design and techniques that have had a positive effect on the improvement of this aspect over the last 20 years will be described: the use of proper components and material together with new coating techniques prevent fast aging and reduce specific maintenance, so to increase lifespan. Dedicated analysis like FEM applied to live parts and bases, and specific redesign of the cinematic chain, allow minimizing the weight of the disconnector and reducing hot spots.
The use of standard solutions in term of subassembly allows having effective statistical data from experience return about the performances and on the reliability of the products in the HV sub station.
The return of field experience and real needs in sub station become more and more important when it is necessary to optimize the existing technology to adapt it to disconnector needs.
In addition to the aforementioned improvements for improving disconnector reliability, also the implementation of a digital operating mechanism will be described.
This new solutions allow performing a continuous monitoring of relevant parameters of the disconnector together with planned mini invasive checks that help extend DSC lifetime and perform maintenance with the consequent benefits in terms of cost, reliability and availability.

KEYWORDS

HV switchgear; disconnector; FEM; reliability; design; maintenance; service.

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I. INTRODUCTION

The disconnectors are used in grid applications to connect and disconnect high-voltage circuits. They are mainly composed of a base, insulating elements, live parts and a mechanism. The mechanism is used to move a cinematic chain that allows the coupling of two (or more) components of the live part that may have different geometries and that can be coupled with each other by different mechanical systems. The perfect functioning of all the elements making up a disconnector plays an important role in guaranteeing safety in the high voltage substations.

For this reason the design, manufacturing and testing phase must follow the highest quality, safety and reliability standard, and be in accordance with the product reference standards requirements.

Moreover, customers' expectation about the reliability of disconnectors has increased during the last few years. A low number of maintenance required is strongly appreciated, together with a minimization of problems during service, and an overall lifetime estimated at 30-40 years. [1] In order to make this possible, it is important to focus on multiple design aspects and follow an intensive testing activity and the analysis of the field service results.

The evolution of the techniques and the analysis programs has, over the last 20 years, truly changed the approach to design. Until a few years ago, the acquired experience was the most used method to design disconnectors and to fulfil standards requirement. Long and expensive test campaigns were necessary to prove compliance safety and reliability requirements. Nowadays, the development of new software for stimulating both mechanical and dielectric behavior of disconnectors, has provided substantial support to the designer, in all the development phase; through FEM (Finite Element Method Analysis) it is possible to simulate the mechanical behavior of components and assemblies. The use of dedicated 3D programs prevents the insurgence of interference problems during assemblies, and provides important information on the stress and the strain that mechanical parts will incur in service, thus predicting possible failure. Also for the dielectric design, dedicated FEM software is available; these software programs allow predicting electric fields of components and making comparisons between different geometries and assembling. Results of dielectric FEM analysis can be validated through the use, during test activities, of new, sophisticated and dedicated instruments like the UV Camera.

The new approach to design of disconnectors, together with a continuous analysis of the field experience, and the introduction of new monitoring devices allow improvements on reliability and availability of disconnectors.

II. ELECTICAL SIZING

A. *Reference standards*

The prescriptions for dielectric tests on high voltage disconnectors are defined in the IEC62271-102 par. 6.2 [2] and IEC 62271-1 [3]and all dielectric tests must be in compliance with recommendations from IEC60060-1 [4]. Another important standard to be considered in the dielectric sizing of a high voltage components is the IEC60071-2: reference standard for the dielectric insulation coordination [5].

B. *Disconnector clearances and gap factors*

Air insulated switchgears use the insulation capabilities of air in order to guarantee the insulation to earth and across open contacts. These airs gaps shall be sized properly in order to withstand not only stress during normal conditions but also the abnormal stress caused by over-voltages in case of fault or abnormal conditions. For air gap the withstand voltage is significantly influenced by the configurations of the electrodes and the shape of over-voltage applied. The worst electric configuration for air gap is the rod-plane configuration because it provides the lowest withstand voltage. Considering that air insulated high voltage disconnectors provide the insulation between contacts with different types of configurations (horizontally or vertically), with different gaps (single or double) and different types of breaking (centre, vertical, double), GE Grid Solution, in order to optimize the sizing and the dimensioning of each disconnector type, performs in accredited laboratories dedicated research of discharge tests and withstand tests (in dry and wet conditions) with the aim of evaluating the exact gap factors for the whole isolating distance and to earth and determine the minimum isolating distance required with adequate safety factors.

C. Evaluation of the "k" gap factor

The calculation procedure is as follows:

1. Research of discharges tests with "Up & Down" test method in accordance with IEC60060-1
2. Determination of the minimum applicable air gap distance using theoretical calculations (from IEC-60071-2 Annex G or other theoretical formula like the "Gallet formula") [6]
3. Calculation of the disconnector gap factor K from experimental data
4. Verification of requested Lightning Impulse, Switching Impulse and Power Frequency withstand values by using the air gap and height to ground defined

Thanks to this calculation, during the design phase it is possible to anticipate the performance having a better confidence on the results of test. Gap factor "k" depends on three parameters: the disconnector geometry, the height of the support structure and the sizing and design of the live parts and the anti-corona rings. This procedure allows minimizing and standardizing main clearances dimensions of disconnectors, offering a predictive method to ensure dielectric withstand.

D. Disconnector geometry and height of structure

Regarding the optimization of disconnector geometry, GE Grid Solution has performed extensive research on discharges tests on disconnectors with a single gap (like horizontal semi-pantograph) and disconnectors with a double gap (like double side break). Due to the capacitance distribution, the intermediate electrode reduces the withstand capability of about 6%.

Furthermore, the support structure has a significant influence on the withstand capability to earth: the same disconnector supported by a double height increases the switching withstand capability to earth of about 7%.

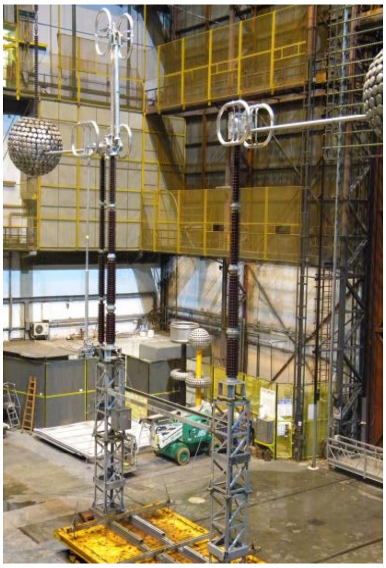

Fig. 1 Single pole disconnector with single open gap - set up for dielectric test

Fig. 2 Two pole disconnectors with double open gap - set up for dielectric test

E. Sizing and design of live parts and Anti-corona ring

The air insulating capability is strictly influenced by the leader pre discharge formation on the electrodes. This pre discharge can be avoided through a properly sizing of the electrodes. For this purpose GE Grid Solution performs two main actions during the design and test phases: analysis of the electric field, radio interference voltage test and visual corona tests.

F. Visual corona and RIV tests

Corona phenomena in air is a sum of small electrical discharges around a conductor that is electrically charged. The corona will occur when the gradient of the electric field around the conductor is higher than the local insulating capability of air. It has three types of manifestation: the first is the visual corona which appears as a violet colored light coming from the regions of electrical overstress in the dark. The second is the audible corona, which appears as a frying sound. The sound waves are produced by the disturbances set up in air near the discharges. The third and last manifestation is the radio interference or R.I. All these manifestations cause a loss of energy so it is better to avoid it [7].

Fig. 3 Knee type disconnector1000-1200kV project – Outdoor dielectric test set-up

The sizing and the design of electrodes can be done only by simple theoretical calculations or nowadays thanks to several specialized software tools, by a 3D model that gives the value of the electric field expected. This allows a proper sizing of caps and a proper design of the live part (including anti-corona rings).

For switchgears with rated voltage greater than 123kV, IEC62271-1 at par. 6.3 prescribes the R.I.V test. This test permits measuring the radio interference voltage caused by the corona phenomena.

The IEC prescribed a limit of 2500µV. GE Grid Solution in the validation of a new design considers an amply lower limit (usually 500µV or below). This permits complying with other relevant standards worldwide. In addition to the tests prescribed by IEC62271-1 at par. 6.3 in order to prevent any manifestation of "visual corona" GE Grid Solution performs also the visual corona test. In the past this test was performed in a dark room with a "reflex" photograph machine. Nowadays, the imaging system used to visualize & locate electrical discharges (Corona and Arcing) is the UV Camera.

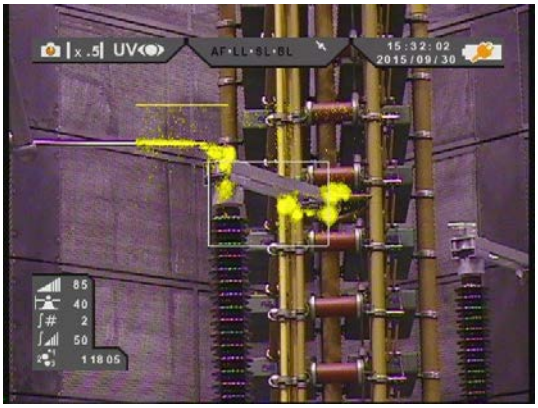

Fig. 4 Visual corona test with UV camera

The UV Camera gives an added value to the result of a type test, in fact, with a RIV type test, it is possible to have a numerical information about the radio interference level (expressed in µV) emission of the tested object, and check if this value is lower than the maximum limit prescribed by the standard, but no information is given about "where" the maximum of emission is recorded. During the research phase this can lead to hard attempts to detect the problem step by step. The use of a UV camera allows detecting directly "where" the electrical field is most concentrated. As already explained, this is an

innovative and important tool, both in the design phase and in the validation phase of the FEM analysis. It is also a powerful instrument for supporting the designer during the research and development phase.
Resuming, the combination of dedicated software tools and dedicated research of discharge procedures together with the use of instruments to detect corona phenomena manifestation, permit designing a more reliable disconnector.

III. SIZING OF LIVE PART

The sizing and design of the live part of the disconnector is related to the two main functions that a disconnector shall be able to perform: conduct the rated current without abnormal heating during normal service conditions and withstand the electrodynamics and thermal effects during a short-circuit event. The capability of carrying the rated current without abnormal heating is verified with a dedicated test: the temperature rise test. The test shall be performed in accordance with IEC 62271-1 sub clause 6.5. When rated current flows on the live part, the temperature is measured in the prescribed points and its rise shall not exceed the limits specified in the standard.
The factors which allow the temperature to rise are: test current, material and cross sections of the live part, external surface area and related treatments.
With the infrared thermos-vision it is possible to have an immediate and global check of the temperature of the tested object. As shown in the following figures, an example of contact details during a research temperature rise test. The infrared camera gives a very clear distribution of the heating and gives evidence of the hot points.

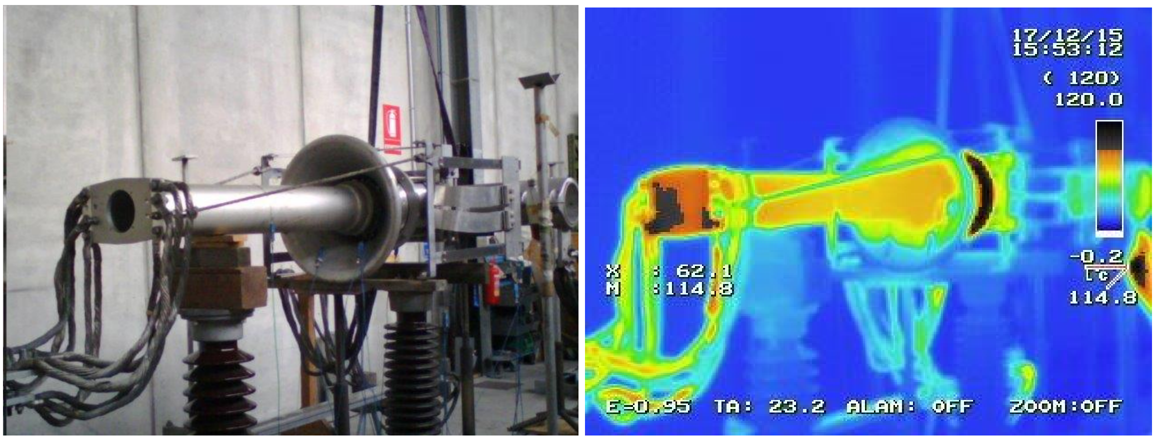

Fig. 5 Comparison between normal view and infrared camera view

The electro heating phenomenon takes considerable time to simulate with high precision, for this reason GE uses a different strategy that takes into consideration the return of experience and the type tests, in order to deduct concentrate parameters of heating exchange and adopt the electrical similitude for the thermal phenomenon. A statistical approach is used, during the design phase, to deduct the best matching parameter for each sub part of the disconnector, in order to evaluate the thermal effect.
The live part of a disconnector must be able also to conduct the short-time withstand current test usually for a duration of 1 or 3 seconds. This over-current produces a significant over-temperature. As the short duration of the phenomena is mainly adiabatic, the only important aspect to size is the material type and so the cross section is involved. To evaluate the withstand capability, the over-temperature that each component of the live part will reach shall be calculated due to the energy of the short-time withstand current test. The density of current admitted is related to the duration of the phenomena and the material of the component. In relation to the safety reasons, for each type of material a maximum over-temperature must be admitted for few seconds. In conclusion, the sizing of the live part is an important aspect for the reliability of the disconnectors.
For this check, with dedicated software analysis, calculations during the design stage and use of materials with very high quality, help significantly in the optimization of the cross sections and in the optimization of weights of the live part. A lighter disconnector means: less material, lower stress to the

support structures, smaller operating torque and so less stress on the kinematic chain. These advantages will help significantly in the final reliability of the product. In addition there will be some economic and environmental benefits:

- Cheap solution: overall cost reduction
- Less impact on the environment, due to a lesser use of material

IV. MECHANICAL SIZING

In the mechanical sizing of an equipment there are two main types of stresses. The first are internal stresses due to weights during the steady state and also during the operation of the equipment. The second are external stresses due to external factors (like electrodynamic forces, wind and seismic actions, ice).

In accordance with TB-511 "Final Report of the 2004 – 2007 International Enquiry on Reliability of High Voltage Equipment", Part 3 refers to Disconnector and earthing switch" [8], the "loss of mechanical integrity" is one of the biggest contributions to MaF modes, together with "Does not operate on command". Consequently, a strong effort must be made in mechanical design, also to overcome manufacturing technological limits, especially regarding:

A. Sizing and Optimization of kinematics and balancing of the disconnector

B. Mechanical sizing of supporting structure and lower parts

C. Sizing of insulators and configuration definition

D. Design of operating mechanism

A. Sizing and Optimization of kinematics and balancing of the disconnector

In the past, only a calculation by hand was possible. Nowadays, the mechanical design and dimensioning techniques are supported by simulation analysis tools that allows predicting mechanical behaviors and preventing manual calculation. The use of CAD & FEM software is widely used to perform 2D/3D drawings and to perform static and dynamic analysis, verification of dimension, encumbrance and movement, to design a kinematic and optimize balancing during operation. The static analysis is used, for example, for the dimensioning of the lower part of the disconnector, which allows minimizing the thickness and size before the production of prototypes for test. Deflection and stresses are calculated and evaluated before production, to predict problems and weakness points, and reduce the number of prototypes produced. Also the kinematic behavior is analyzed with kinetodynamic multibody software, that allows performing dynamic analysis of cinematics, starting from a given geometry of linkage, to calculate torque, load and reaction on the constraints and coupling. In the graph below an example of an optimized operating torque obtained at the drive shaft of a motor operated mechanism is reported. The trend observed experimentally is very close to the results calculated from the model.

The motion analysis is applied to simulate and study the effects of mobile elements (including forces, springs, dampers, and friction) on the 3D model assemblies. Motion analysis accounts for material properties as well as mass and inertia in the computations, and its results can also be used for further analysis, such as, for example, finite element analysis.

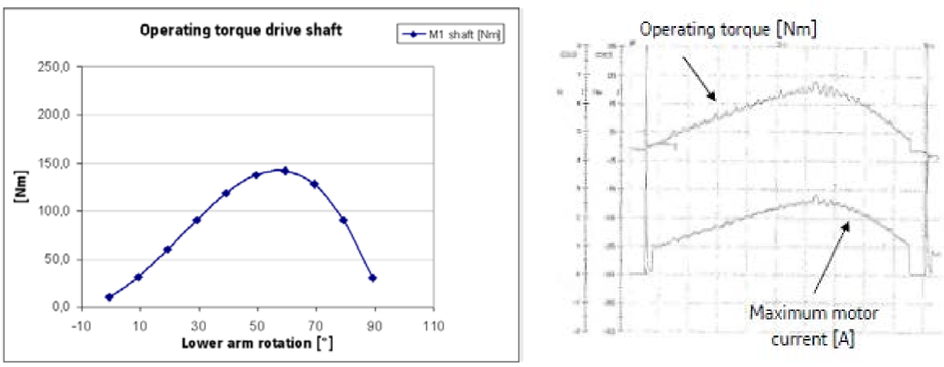

Fig. 6 Operating torque calculation (left) and record during mechanical test (right)

The mathematical model for the motion study is obtained from a CAD solid model, which is substantially an assembly of three-dimensional bodies (i.e., the parts composing the equipment) located in a Cartesian coordinate system and opportunely bound together.
A set of coupled differential and algebraic equations is built to define the equations of motion of the model. Then, a numerical solution to these equations is drawn by integrating the differential equations while satisfying algebraic constraint equations at every time step.
By means of the “motor” element, it is possible to apply motion to a component and transmit it to other linked parts. Motion due to a motor supersedes motion due to any other element in the simulation. Moreover, any element that tends to resist motor motion increases the power consumption of the motor, but does not slow down the motor motion. However, if something causes the reference of the motor direction to change, the motor motion is applied in the new direction.
Regarding “force” elements, they do not prohibit or prescribe motion. Therefore, they do not add or remove degrees of freedom from the mathematical model. Forces may resist motion or they may induce motion. In the motion analysis the following types of force elements can be used:

- **Gravity -** A uniform acceleration field that moves components around an assembly by applying a simulated gravitational force. All components accelerate at the same rate under the effect of gravity regardless of their mass.
- **Springs, dampers, friction, and bushings -** Forces apply to translational springs, torsion springs, translational dampers, torsion dampers, static friction, dynamic friction, joint friction, and bushings.
- **Forces -** Applied forces define loads and compliances on parts so that they move in certain directions.
- **Contact -** Forces are generated between contacting components, or components are constrained to touch continually. Contacts can be defined to prevent the components from passing through each other during the motion analysis.

B. Mechanical sizing of supporting structure and lower part

The supporting structure and lower parts should be sufficiently rigid to allow the correct operation of the disconnector (according to type), but it is also mandatory to consider that: the supporting structure itself influences the behavior of the whole equipment during an earthquake, depending on proper modal response and frequencies. With a very high stiffness structure, the soil acceleration is transferred directly to the base of the disconnector. Lower stiffness structures can positively or negatively influence the behavior of the system, enhancing or damping the soil acceleration according to the flexibility of the system. GE Grid Solution designs and tests support structure able to withstand a very high value of seismic acceleration.

- Static analysis by Finite element

The structural analysis of complex parts of the equipment is carried out by means of a finite element (F.E.) program. The modeling of the components is carried out using three-dimensional elements of “brick” type, opportunely constrained and loaded. The aim is to correctly reproduce the conditions of the part under examination in terms of mutual interaction with the connected elements.

- Static and Dynamic analysis for seismic conditions

The mechanical design constraints for earthquakes relate to: the mass distribution of the disconnector (considered as a system: supporting structure, base, insulators and live parts), the stiffness and the damping. Therefore, the main parameters considered in the design are:

- Height, type and architecture of supporting structures
- Material with different damping effect (brittle material like porcelain has very low damping)
- Number, layout and material of insulators: different weights, stiffness and modes of vibration
- Type of disconnector (horizontal/vertical air gap)
- Load combinations with other external actions such as electrodynamic forces, terminal loads, wind, etc.

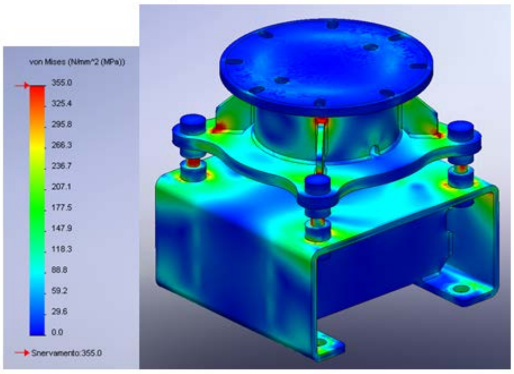

Fig. 7 Stress map with Finite Element Analysis

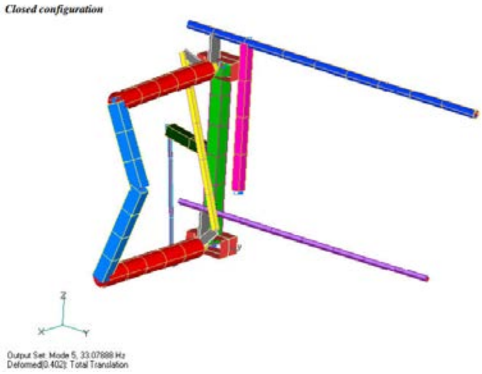

Fig. 8 Finite Elements Model of single pole disconnector

The seismic qualification should demonstrate the equipment's ability to withstand seismic stress and to maintain its specified function, both during and after the seismic event. Qualification can be carried out by test or by analysis.

- Static and Dynamic sizing short-circuit withstand capability

The test shall be performed in accordance with IEC 62271-1 sub clause 6.6. During a short-time and peak withstand current test (STC) the disconnector is subject to thermal stresses and electrodynamic forces. The second ones are relevant for the live part, the lower part and the insulators and it reaches the maximum level during the asymmetric part of the short-circuit event. The repulsive forces established during the current flow in the conductors, as part of the test arrangement for the STC, depend upon the reciprocal distances and positions of the conductors and they are proportional to the square value of the current. The maximum tensile force due to the effect of a short circuit on main conductors is proportional to the square of the peak current.

C. Sizing of insulators and configuration definition

The choice of insulators is another important aspect during the design phase that is regulated by international standards (IEC 60168 - regarding test [9]; IEC 60273 -regarding dimensions [10]; IEC TS 60815.2 - regarding shed profile and creepage distance [11]). The correct choice of insulators influences deeply the reliability of the disconnector because it gives the necessary rigidity to withstand mechanical static and dynamic load and influence safety of installation. The main parameters involved in the dimensioning of the insulators are:

- Height: Normally, when talking about AC, the height is determined by the lightning and switching impulse withstand level: standard creepage distances of 25 or 31 mm kV can be obtained without major problems for the values of the height indicated in IEC 60273 (valid for ceramic insulators).

- Mechanical resistance: This characteristic is strictly connected to the technology and the equipment of the manufacturer of the insulator (wet or dry technology).

- Deflection under bending load: This parameter is important to assure the correct behavior of the disconnector. The insulator must be rigid enough in order to not bend over the limits imposed by the dimension of the disconnector contacts.

- Quality assurance: GE, in order to guarantee the best quality to the clients, is involved also in the design and control of insulators provided with their disconnector. Special requirements have been added to the international standard requests to ensure the long term performance in different service conditions, these requirements are collected in the GE Technical Specifications for the supply of porcelain post insulators and driving rods for rated voltage ≥ 110 kV (BIL 550 kV). The special requirements concern several aspects of routine tests: glaze defects, deformation, control of the main dimensions, special mechanical routine test procedure, more severe than relevant standard. A production test is also carried out: use of Portland cement for flange; and two different additional requirements in sample tests: bending test, mechanical sample and type test.

D. Design of operating mechanism

Concerning the low voltage part of a disconnector, that is the operating mechanism, many improvements have been done in the last years in order to ameliorate performances. Endurance tests on electrical and mechanical parts are performed to assure the adequate number of operations. IP tests on enclosure are performed to evaluate protection against solid and liquid external hazardous parts. This test represents a guarantee for the performance of the operating mechanism because of the sensibility to moisture and water of the electrical low voltage components inside the cabinet.

The choice of the low voltage components, moreover, must be performed following all the constraints of the application: for example, the external area subjected to high variability in terms of temperature humidity, possible high levels of electromagnetic interference coming from HV side during normal service and in particular during commutation phenomenon in the substation. These aspects have a relevant impact in terms of reliability of the mechanism because the CIGRE TB 590 reveals that the main reason for not working on low voltage components is the failure on low voltage parts, for instance relays. If we control the above aspect, the expectation of life will be in line with the declared value of the components.

All the above described improvement and right choice of components in the design phase have, over the last years, helped the reliability of disconnectors by reducing the failure on low voltage side to minimum term.

V. COATINGS AND MATERIALS

As described in the previous paragraphs, most of times disconnectors are installed in outdoor sub stations, without protection against atmospheric agents. Their reliability is proved by the different external conditions they have to face, different weather (hot, extremely cold, tropical), seismic conditions, air pollution. Due to the fact that the disconnectors are safety equipment, the behavior and the protection against corrosion have a big importance.

Here below are some examples of research activities to select the best coating to optimize protection of particular components of disconnectors: flexible joints.

The study reported below has been performed during an internship [12] dedicated to the analysis of the corrosion resistance of some typical treatment applied to a foil of alloy (1050) that is the constructive material of a particular flexible connection used in the disconnector to connect two conductive moving parts.

The comparison between six different chemical treatments has been realized and three tests to verify the performances against the corrosion have been performed. The different protection techniques and the withstand capability against corrosion have been evaluated comparing the polarization curves, obtained during the potentiodynamic test. The tested coatings belong to the “eco-friendly” category, containing trivalent chromium or entirely cromo free.

The treatment that assures best performances between anti-corrosive performance and the environmental sustainability, is the trivalent chromium based, with and without resin.

A salt fog corrosion test, very much used in the industrial field to evaluate withstand to corrosion, showed that the presence of the resin in the trivalent chromate coating, assures better resistance against corrosion. The temperature rise test, according to IEC 62271-102 has been performed letting the rated current flow on the flexible connection assembled as in service conditions on the disconnector. These tests give evidence of an unacceptable temperature rise with trivalent chrome coatings with resin if compared to the one without resin.

The treatment that better fits the environmental sustainability, withstand capability against corrosion and good heat exchange in service conditions with current flow is the trivalent chromate treatment without resin.

VI. MAINTENANCE

Nowadays, maintenance plays an important role in the considerations about reliability of a disconnector, being one of the main key factors to evaluate efficiency. The typical strategy to reduce the risk of MaF has passed in the last years from a time based planning to a predictive based maintenance.

A. *Predictive maintenance*

The foundations for predictive maintenance are based on the implementation of regular monitoring activities of the disconnector and its operating parameters. Standards operating parameters and acceptable limits have to be declared to assure that only the strictly requested number of outages are performed, minimizing the number and the cost of these activities. This modus operandi will improve the overall availability of the substation and the cost of maintenance will be greatly reduced.

The regular monitoring of the actual conditions of machines and systems has been proved as a satisfactory method to reduce by an average of 55% the number of catastrophic, unexpected machine failure, according to the time based program of monitoring and maintenance.

Another parameter linked to availability of a device in a substatiton is the MTBF (Mean Time Between Failures). Implementing predictive maintenance approach allows the automatic ability to monitor the MTBF, and to have the time to replace the object if the replacing is less expensive than the maintenance cost. The MTBF varies each time the functionality of the substation is compromised due to a request of repair or a rebuild. When the balancing point between the cost of continued operation and maintenance exceeds the replacement cost, the machine should be replaced [13].

This new approach to a continuous monitoring has pushed through the need to have an automatic way of collecting data.

The most cost effective solution to this problem is represented by a disconnector directly equipped with a digital mechanism with microprocessor. These mechanisms are equipped with a CPU , implemented to define and establish the limit and the alerts, based on the design of the disconnector. This CPU is the core of the system and the design phase must be carefully conducted in order to define the aging rules and to implement it in the computer. It is preferably up to the manufacturer to identify these rules. Internally, GE has developed, and protected with patent, specific rules against aging and admissible temporary overloading to apply to its disconnector.

B. *Monitoring*

The new orientation of the utilities to predictive maintenance induces the manufacturer to focus the attention on the monitoring of the substatin. Thanks to new methods to perform the condition monitoring it is possible to predict the necessary maintenance and so to plan it during operations or at determinate intervals.

The main disconnector components must be part of this monitoring process, and one of the most important things for monitoring during the operation is that the open gap prescribed is maintained. This check is done monitoring the proper position of the indicating device of the cinematic chain. Part of the cinematic chain is the operating mechanism that is a low voltage component, placed in an accessible position, and contains the electrical parts that allow giving mechanical energy to open and close the disconnector.

A smart solution for the operating mechanism has been invented by GE: the patented solution Dwatch mechanism consists in a common operating mechanism with a computer integrated system that allows monitoring the disconnector based on its electrical parameters input (like torque absorbed, position and speed of the live part, number, data and time of operations, temperature of the mechanism itself and live part).

An algorithm inside the CPU is able to analyze the stored information and to provide, in real time, important information for condition monitoring.

Moreover, the device can control the speed of the live part during operations thanks to a pre-defined optimized travel curve shapes.

C. *Reliability evaluation of substation*

To evaluate the overall reliability of a substation is very important in order to evaluate the best layout to implement. The method to evaluate reliability is well known in the literature and the key parameters are the failure rate of the products installed. From the survey of CIGRE it is evident that the model of components in substation is not so ideal and the age effect is relevant. Another aspect to consider is that a failure can compromise or not compromise the availability of the network. For example, in a double bus bar the availability is bigger than single bus line, for this reason a good choice of failure rate of the component of the substation is fundamental to avoid mistakes in the global failure rate calculation. For example, usually the disconnector is operated mainly for maintenance purposes of other equipment like Circuit Breaker, transformer or reactance [14] [15] [16]. In order to analyze the Failure Rate (FR) of different devices it is necessary to compare homogenous FR for each component, in this way any kind of misunderstanding is avoided. For example, only MaFr on live parts that compromise the functionality of the bay can be taken into consideration for comparison calculation. Usually failure on electrical component on low voltage side can reduce the tele control system and can be classified as Minor Failure.

In conclusion, using an average failure rate for a global evaluation of availability can generate an unclear understanding of availability, especially for substation, because an average value can mask the specific environment of failure.

In a global evaluation of the reliability of several different equipment devices of the substation, it is necessary to use specific FR for the specific availability to analyze and to compare. To deduct a comprehensive FR, it is necessary to also properly weight each FR for homogenous status of failure, otherwise it is difficult to decide proper investment for equipment and scheme of substation.

In particular, for disconnectors, the failure rate has a trend that generally reflects the so called bath tub curve. The bath tub curve, shown in fig. 9, is divided into three different periods: the infant mortality phase, with a decreasing failure rate, followed by the normal life period, called "Useful life", with a low constant failure rate. The last and conclusive part of the bath tub curve, is the wear-out period, where the failure rate increases. The initial breakdown, is mostly caused by material defects or assembly mistakes of the disconnector. This type of failure creates undesirable situations in terms of cost and delay of the commissioning of the device. In the normal operation phase, there are some random failures, related to high performance requests, typically "stress exceeding strength" or depending on specific environmental conditions. The conclusive part is characterized by general mechanical depletion, that causes an increase of the failure rate [17].

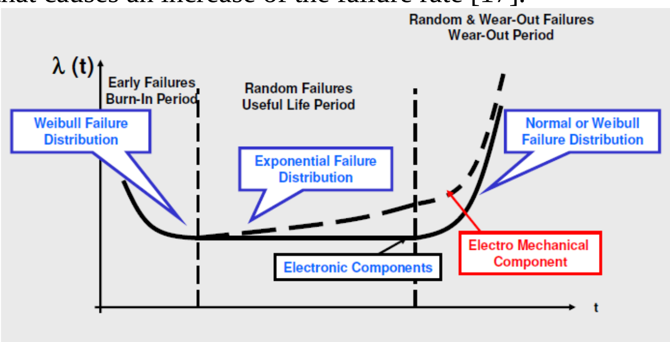

Fig. 9 Comparison bath curve for electronic and electromechanical components [18] [19]

The disconnector's useful life is limited by its shortest-lived component. GE designs the disconnector in order to ensure that all specified materials and sub assembly are adequate to function through the intended product life. In real life, moreover, the disconnector is exposed to several atmospheric agents, that they may affect the normal function of the equipment. In particular, the corrosion, over the time, may create excessive stress for the device and generate an anticipated malfunction. For this reason the study of protective coating and treatment of the materials is more and more important to have a longer useful life period.

D. Disconnector failure rate analysis

Every year, GE quality collects and classifies all the information that comes from the field for the statistical analysis. In particular, to evaluate the dependability performance of its disconnectors, GE adopts the IEC 60605-4 [20] to evaluate and forecast the failure rate. The fundamental hypothesis for this kind of evaluation are:

- the failure rate of each device is constant with respect to the time;
- following failure, each device is replaced, as far as possible, by another identical device;
- the test is time terminated.

VII. LIFE EXPECTANCY OF THE EQUIPMENT

A power system is composed of a number of components, such as lines, cables, transformers, circuit breakers (CBs), disconnectors, and so on. Every component in a power system has an inherent risk of failure. It is often assumed that the lifetime of installed electrical equipment is about 35–40 years.
Multiple outside factors influence the possibility of component failure; for example, the current-loading of the component, damage by third parties (human, animal, trees). Atmospheric conditions such as temperature, humidity, pollution, wind, rain, snow, ice, lightning, and solar effect may play a significant role in the component failure. However, when trying to estimate the life of equipment it is necessary to consider multiple factors such as the range of extreme operating conditions and environments, and the different levels of past maintenance. For example, if the electrical equipment is located in a high-rise, modern building, there will be a good chance of a clean environment and moderate temperatures. For the same equipment working in a paper mill in a dust-filled environment, or in a hot and humid climate, the life expectancy cannot be the same. Therefore, the typical life expectancy of the equipment may depend on the conditions of service and the environment and the adopted design rule by manufacturer. Generally, the useful life of such power system components depends upon the level of care given to them and their duty cycles. For example, a disconnector life cycle is 40–50 years.

A. *Aging factor*

During its useful life, electrical equipment experiences several stresses that may affect its performance. These factors are electrical stresses (voltage, current, on−off cycling, overloading), electrostatic discharges (PD and corona), mechanical stresses (vibrations, shocks), extreme temperatures and temperature changes, humidity, corrosive environment, dust, and so on [21].
The effect of all these stresses gradually build up, leading to mechanical damage of the parts, corrosion of conductive parts, deterioration of insulation and eventually the failure of one or several components of the structure. The most significant aging is found on connections when they are exposed to oxidation and contamination, high humidity or fretting corrosion. Cables may be mechanically damaged and chemically attacked. The insulation may degrade due to moisture, high temperature or radiation. Electromechanical components may get corroded, the contacts may be oxidized or contaminated, and the coils may burn out.
The longer the electrical equipment like disconnectors is subjected to all these stresses without due attention and maintenance, the shorter its useful life. However, aging of power equipment seldom leads to a sudden, catastrophic failure. Instead, the effect of all stress factors is cumulative (red dotted curve in the bath chart); it is slow but inevitable worsening each year.

VIII. CONCLUSION

Considering evaluations exposed in the above paragraph, it is possible to state that the advanced way to improve the disconnectors dependability and availability is to define rules of design based on standard requirements, experiences in the field and continuous research activity. The use of FEM and creation of physical model and analysis in early stage of design in conjunction with high performance instruments helps control and predict of malfunctioning and avoid huge and expensive test campaign.
A greater attention on the selection of materials of high quality and on their treatments and coatings helps in the protection of disconnector against atmospheric agent.
Moreover great attention must be given on the failure mode of components and on the calculation of failure rate of the systems in order to implement and sustain new reliable method of predictive maintenance. The conditional monitoring of substation is a great support in this field.
For this reason the design and use of digital devices, able to continuously monitor the status of disconnector is a competitive advantage to have time real information on the functioning parameter of the sub stations; and the extension of time interval between maintenance defined on assessment of the performance of disconnector improve the availability and reduces overall costs.
Design and productions phase are strategically studied to produce disconnectors with expected service life of 40-50 years.

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