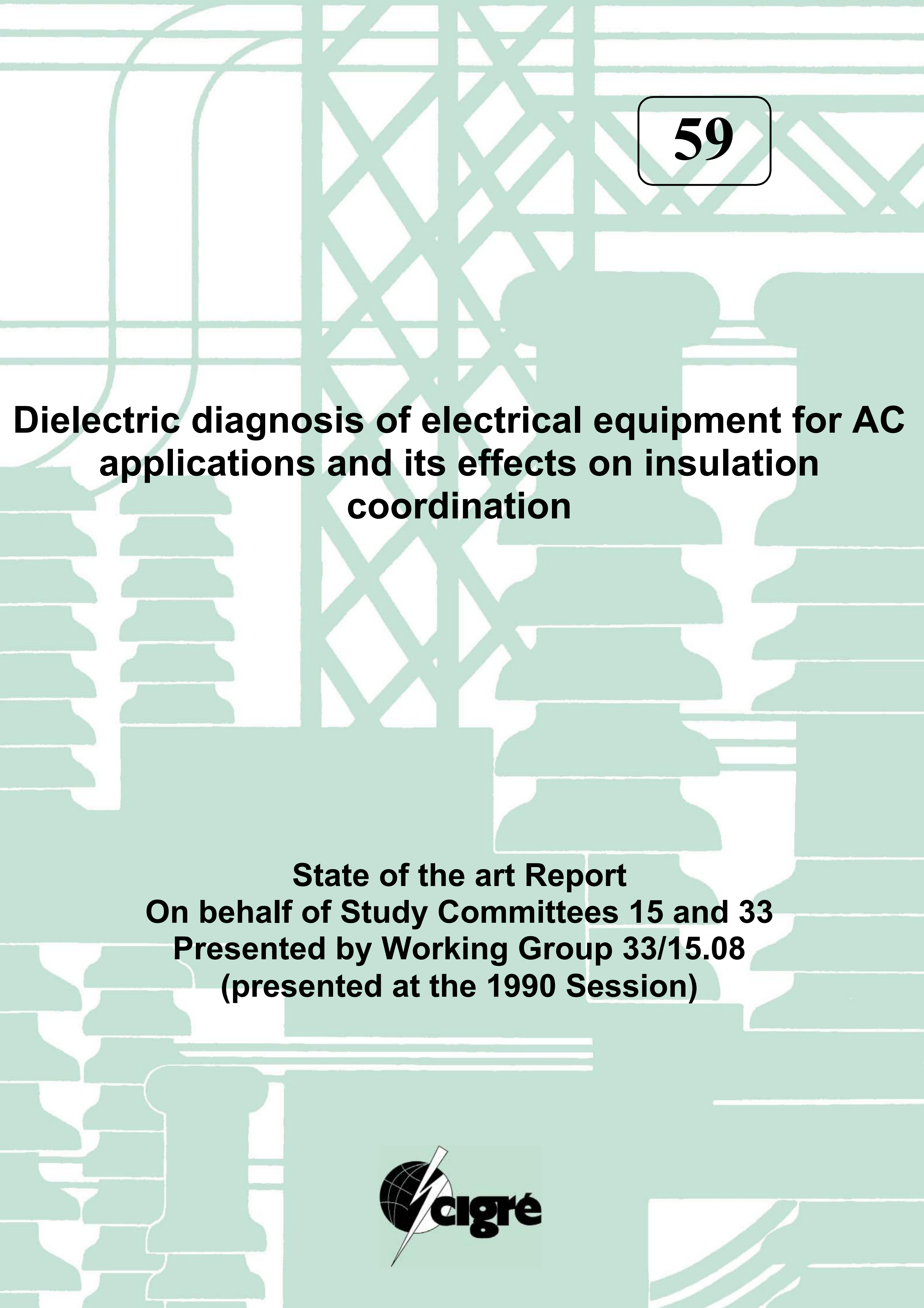

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Dielectric diagnosis of electrical equipment for AC applications and its effects on insulation coordination

State of the art Report
On behalf of Study Committees 15 and 33
Presented by Working Group 33/15.08
(presented at the 1990 Session)

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for on-line diagnosis so that efforts in performing investigations of equipment removed from service can be concentrated where they will best be served, while at the same time minimising the need for off-line diagnosis based solely on periodic time intervals. Many of the ideas that are presently being used for on-line diagnostics are relatively new and experience is limited. It is therefore, of critical importance that more of us become involved in using these newer methods, even if some of these methods are still classified as research. It is only through a concerned and intensive world-wide effort that the final solution to the proper formula of on-line monitoring and off-line investigation and diagnosis can result.

We must all appreciate and understand that the primary goal in this entire effort is that we not only understand what is necessary to make up a good insulation system design, but that we also understand the significance of results presented to us through a coordinated effort of on-line and off-line diagnosis. The relationship that exists between insulation coordination and DD is graphically represented in Section 4. While it is obvious that an insulation system that has been damaged in any way (electrically, mechanically, or thermally), cannot be expected to perform to its specification, it is not as obvious when we go one step further, how to predict how well that same system will or will nor perform if allowed to remain in service.

The report of this Working Group is a key consideration in the continued reliability of any electric system. This is certainly of major interest to everyone throughout the world and it is only through active dialogue followed by action that we can achieve our goal. This is the challenge to all power producers.

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Assuming that these rhetorical questions resulted in the expected answer, we can move to quadrant II. The ordinate shows the actual value of the withstand voltage considered, U, while the abscissa shows the value of the measured quantity, q. The solid line U(q) represents the intrinsic relationship for the insulation considered. This line was drawn with a negative slope, since it is always possible to adopt a scale for q so that the higher the value of q, the higher will be the deterioration of the insulation. If q is measured as part of the type tests and again after commissioning, its values should be higher than Q_w and Q_c respectively, if these are known. Otherwise, they could be adopted, being on the safe side, as Q_w and Q_c for future diagnosis. The value, Q_r, of q corresponding to U_r, is the critical value that cannot be reached if the equipment is to survive its programmed service life under all expected conditions.

Quadrant III, with co-ordinates t and q already defined, is the quadrant where the measurements of the insulation diagnosis are plotted. If continuous measurements could be performed on equipment subjected to the expected service conditions, a curve q(t) similar to the solid one would be obtained, with q starting from Q_c and reaching Q_r at T_f at the end of the expected service life. It is the aim of DD to follow the evolution of curve q(t), in order to take preventive measures in case the deterioration becomes quicker than expected. That is, when the measured value of q is found to be higher than that corresponding to the hypothesised ageing.

At the present state of knowledge, very few of these relationships are known. However, when on the basis of a DD, we decide to either leave the equipment in service or, which is certainly more serious, to remove it from service for further investigation, whether we admit it or not, we assume to know something about the relationships just described. That is, if we leave the equipment in service, we practically assume that the measured value of q is lower than Q_r. At the very least, we certainly have concluded that q can be expected to remain lower than Q_r, until the time of the next diagnostic tests. On the other hand, if our decision is to take the equipment out of service, this assumes that q either is already higher than Q_r (immediate investigation is required), or that it will become higher than Q_r sooner than originally anticipated (action is required, but can be delayed for the time being).

The quantity Q that has been examined up to now can be considered a "static" diagnostic, in the sense that its values are correlated to the values of the withstand voltage U considered. There exist other types of quantity, which can be considered as correlated to the rate of decrease, $dU/_{dt}$, of U with time. They can be marked S, and referred to as "dynamic" diagnostics. The value of these quantities in regular service should be zero, or negligible, as their presence will lead to a reduction of U below U_r sooner than originally expected for the life of the equipment. The large majority of the current diagnostic methods refer to these quantities, since they aim to detect abnormal conditions of the insulation, due to accidental causes. In principle, also these dynamic quantities can be dealt with in a similar way as the static ones, as they are governed by the same philosophy: the equipment can remain in service until all co-ordination withstand voltages are met. Further development and refinement of the matter are left to the future work on DD.

Before closing, one more thought related to the last of the three questions: "Why is this matter being raised only now?". Apart from the sarcastic answer that we must always find something more to do, one can find that increased interest in the DD is due to the fact that the age distribution of the equipment in service is changing. This is at least due in part to a decrease in the rate of increase of power consumption. Actually, when this rate was 7% per year (famous "doubling every ten years"), only 12.5% of the equipment was older than 30 years. With a rate of increase of 3% per year, this figure increases to 41% Even more shocking is the comparison at 50 years, the usually considered canonic age of retirement: 3% against 23%

5. CONCLUSIONS

This Report is meant to be a starting point for more intensive discussions on the critically important topic of DD. In the three meetings that this working group has had between March and November of 1989, they have come to appreciate that the assignment presented to them, as outlined in the PREFACE to this Report, became far more involved and complicated than was at first believed.

As the deliberations between the WG members progressed, both at the meetings and by separate communications, it became evident that we needed to better define exactly what we were trying to achieve. We all needed a mutually acceptable understanding of what DD is and how it relates first to the general integrity of the equipment insulation at any given moment in time, and second how it will be used to forecast how well the insulation will meet all co-ordination withstand voltages for some future period of time. The diagnosis must take into account both physical and electrical properties and how they are inter-related to the ageing, degradation and deterioration of equipment insulation systems.
As the WG looked more carefully into exactly what we meant by terms such as "ageing", it was found that we had to compose our definitions carefully so that our deliberations (and eventually our conclusions and recommendations), were consistent and understandable to everyone studying this Report.

Since electrical deterioration is closely associated with any and all types of electrical stress which can occur both in situations where system conditions are considered normal as well as when abnormal, it is imperative that the diagnostic tools be able to detect a variety of defect types.
For example, as already discussed in Section 2.2., two of the major specific conditions that could result in reduced electrical strength are moisture and voids.
In another area, excessive thermal or mechanical stresses could further reduce the insulation capability to perform as intended.
Hence the tools that we use to monitor equipment insulation in service as well as those used to perform specific tests as part of any investigation after removal from service, must cover a broad range of technology. There is no one single tool that would be more helpful than others.

Accordingly, in the work done thus far, the WG has addressed each type of equipment and has attempted to include the tools that are known to be of some value in the industry in Tables under each major equipment heading. Each Table uses the same format to categorise the specific problems for which each tool is generally used. It is the hope of the Working Group to be able to produce one single Table, where the comparison of the various application is more immediate.

As noted in Section 3.12., the history of experience in the use of off-line diagnosis now spans more than fifty years. The trend today is to develop more tools

In other cases (e.g. GIS), the development activities carried out by manufacturers and/or Utilities, the quality of the available sensors and the progressive introduction of digital techniques have created the option for dielectric monitoring and diagnosis to become associated with and later on integrated to the substation control and protection systems.
Other functions such as a computerised support system for maintenance and operation could also be integrated in the system.
In this case the diagnostic system is not to be considered an auxiliary unit of GIS but an independent system to improve the reliability of substations.

4. DIELECTRIC DIAGNOSIS AND ITS EFFECTS ON INSULATION CO-ORDINATION

The first reaction to this title is a series of questions: "What relationship can exist between insulation co-ordination and DD?" or, even more simply, "Can a relationship exist?"; and, if it exists, "Why was the matter not considered before?".

It is considered useful to recall here the procedure of insulation co-ordination. The various voltages to which the insulation is subjected in service are grouped in several classes. For each class a "representative" voltage is chosen to represent the effect on the insulation of all voltages belonging to that class. The co-ordination procedure, on the basis of these voltages and of the dielectric strength of the insulation, determines the "co-ordination withstand voltages" that is the voltages (power frequency, switching impulse, etc.) that the insulation strength should simultaneously meet in service conditions, and during all service life in order to satisfy the co-ordination criterion (e.g. the acceptable failure rate). The standard rated withstand voltages of the insulation are selected to prove that, if the insulation passes the relevant withstand tests, its actual withstand voltages are not lower than the co-ordination withstand voltages, during all service life.

From a philosophical point of view, one can ask oneself what the ultimate scope is in performing the various tests, which we consider under the heading of: type, acceptance, routine and commissioning tests. One could look at the question from all possible sides, but the only answer is: to forecast that under the service conditions hypothesised when designing the insulation, this last will meet the co-ordination withstand voltages for its whole service life.

The comparison of the procedures of insulation co-ordination and of DD, shows that both procedures refer to insulation strength in service. The first selects it and establishes the basis of all suitable tests that will help to show that the insulation design will meet the co-ordination withstand voltages in service. The second checks, on the basis of other less destructive tests, whether insulation deterioration will prevent the insulation design from reaching its normal life.

A relationship, therefore, must exist between the two procedures. This provides a positive answer to the first question. What about the second? What is this relationship between insulation co-ordination and DD? This is, really, a complicated question. In order to reach a rational answer, for the moment we should put aside the enormous difficulties involved with its practical application.

The relationship between insulation co-ordination and DD is based on the "during all service life" already mentioned several times. Some graphs are needed.

The upper left quadrant (I) of Figure 3 shows as the ordinate the actual value, U, of one of the co-ordination withstand voltages of the insulation (e.g. the one-minute power frequency withstand voltage) and as the abscissa (right to left) the time, t (t=0 at the beginning of the service).

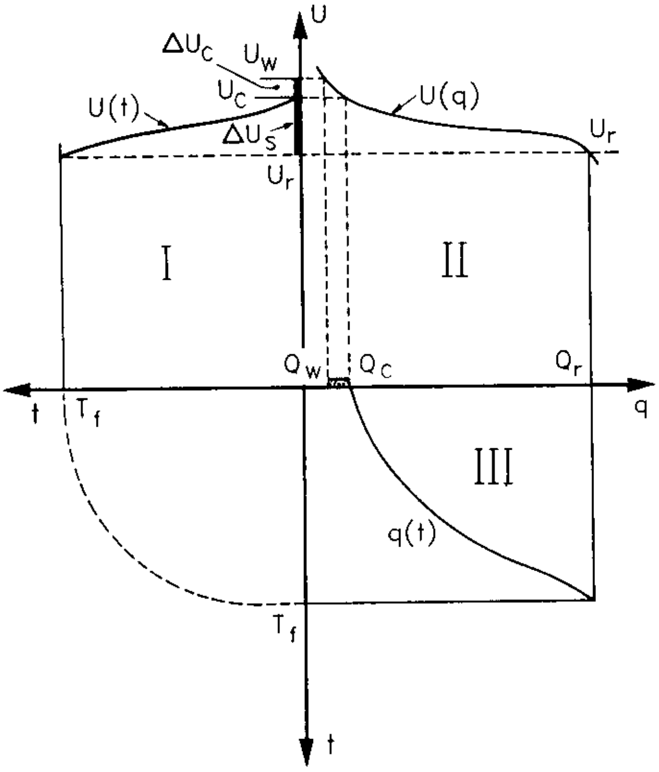

Figure 3 - Diagnosis and insulation co-ordination

The horizontal dotted line $U(t)=U_r$ represents the value determined with the insulation co-ordination procedure. Assuming that we know the law, U(t), of deterioration of the insulation expected during "normal" service, the user can start to plot it backwards from the finite time T_f (the life he requires for the equipment) towards t=0 (solid line). The value $U_c = U(0)$, gives the co-ordination withstand voltage at the beginning of service life, that is just after commissioning. $\Delta U_s=U_c-U_r$ represents the margin required to account for insulation deterioration over service life. Furthermore, if a reduction in the actual withstand voltage is expected after type tests and before commissioning, an additional margin ΔU_c should be introduced to account for it. The co-ordination withstand voltage to be verified with the type tests will, therefore, be $U_w=U_r+\Delta U_s+\Delta U_c$.

Let us now think about DD. From its definition we are entitled to assume that "suitable measurements" refers to the measurement of a quantity q, related to the reduction of at least one of the co-ordination withstand voltages of the insulation. Actually, why should one be worried, unless the deterioration reduces at least one of the co-ordination withstand voltages? If this does not happen, the insulation withstands all the voltages to which it will be submitted, and, therefore, can remain happily in service. And what is the meaning of measuring a quantity, if it is not related to the deterioration of the insulation, that is to the reduction of at least one of the co-ordination withstand voltages?

TABLE X - Most important diagnostic techniques used for surge arresters

PROBLEMS	DIAGNOSTIC TECHNIQUES	SERVICE CONDITIONS OF THE EQUIPMENT	STATUS OF THE DIAGNOSTIC TECHNIQUE	PROVEN EFFECTIVENESS OF THE DIAGNOSTIC TECHNIQUE	REFERENCE
	CONVENTIONAL SURGE ARRESTERS				
External pollution	- Visual inspection	ON	A	L	
	- Measurement of external leakage current	ON	?	L	
Heating of grading resistors	Thermovision	ON	A	M	
Deterioration of grading system	- Leakage current under controlled voltage	OFF	A	H	3.11-3
	- Watt loss under controlled voltage	OFF	A	M	3.11-3
	- 50Hz sparkover voltage	OFF	A	H	3.11-3
	METAL-OXIDE SURGE ARRESTERS				
External pollution	- Visual inspection	ON	A	L	
	- Measurement of external leakage current	ON	?	L	
	- Integral charge	ON	C	M	3.11-4
Deterioration of varistor blocks	- Leakage current	ON	A	L	3.11-1
	- Harmonic decomposition of leakage current	ON	A	M	
	- Peak of resistive current	ON	A	H	3.11-3
	- 3rd harmonic of resistive current	ON	B	H	3.11-2
	- Reference voltage	OFF-L	A	H	

Many techniques are based on the measurement of the arrester leakage current. This current has capacitive and resistive components. The resistive component comes from the active elements inside the arrester and from any conductive layer on the surface of the arrester housing. When necessary, the simplest way to eliminate the external surface current is to do the measurements in dry weather.

Even in the absence of external surface currents, the "total" leakage current is still not very representative of the state of the active elements, because the resistive component (the interesting part) is hidden behind the capacitive component which is an order of magnitude higher.

A way to improve the effectiveness is to discriminate for the resistive component, but this requires the measurement of the arrester voltage. This is somehow equivalent to a measurement of watt losses in service. Another method is to focus on the third harmonic of the current which is more sensitive to the actual non-linear characteristic of the active elements. This can be further refined if a compensation can be made for the third harmonic component present in the network voltage [3.11-3].

The same equipment can be used to check arresters of different makes, but for the interpretation, specific data by type and manufacturer are necessary.

Many of the diagnostic techniques are rather easy to carry out and the relative cost of testing equipment is modest; therefore, even in the absence of definite trouble, it seems justified to either include diagnostic tests in the station maintenance plans or to simply carry out preventive controls on limited numbers of samples.

It is expected that "permanent service monitoring" will be used in extremely rare cases like in stations with severe pollution or in very strategic points of a network.

However, as deterioration of arresters is generally a slow process and also because spot measurements do not always lead to straightforward interpretations, utilities will certainly appreciate portable systems which could be plugged-in for a couple of days or weeks in order to register an evolution over a significant period.

3.12. Summary considerations

The usefulness of performing off-line diagnosis on the above mentioned electrical equipment at periodic time intervals has been agreed on internationally and in some cases more than 50 years of experience exist. Today many test results are recorded on site by means of suitable acquisition systems including PCs and are stored and processed in central computers with the help of dedicated software programs. The trend toward increased computer use is expected to continue.

In order to reduce unforeseen outage problems associated with an unexpected failure, many Users are developing on-line condition monitoring systems. The development of new digital measuring methods, associated with the application of computer-based on-line analytical techniques, such as for example Fast Fourier Transform and Transfer Function, will aid the implementation of these predictive methods.

The application of new measurement techniques and modern analytical methods will allow engineers to study phenomena that could not previously have been monitored and that were previously considered intractable.

However, the successful introduction of these systems will depend on the development of suitable sensors, especially for some equipment (e.g. transformers and circuit breakers). At present, for example, SC 12 is assessing sensors for thermal applications, but sensors to monitor other transformer conditions will be studied and classified in the future.

Moreover, the knowledge for the interpretation of the monitored data is not complete at all. In the first step of introducing new and advanced diagnostic methods into HV-systems, service experience must be gained to help to formulate more exact practical criteria for action decisions. In the long run this could become the basis for expert-systems.

sampling numbers should be used, as explained in [3.10-5].

"Insulators testers" have been used on the line to find cracked or punctured porcelain insulators, usually on a statistical basis.

Composite insulators are still considered as being relatively new, in spite of more than 15 years of operating experience.
During these fifteen years, a number of problems have occurred due to bad designs, faulty manufacture, abuse during handling or operation (vandalism), degradation or gradual deterioration.

The following diagnostic techniques for composite insulators have been tested in the field:

- Acoustical noise to try to determine the occurrence of unusual corona. For example, a bullet embedded in a fibre glass core was found this way.

- Light amplifiers are also used to observe unusual corona patterns on insulators.

- Infrared thermography has been tested with some positive results in the laboratory but has been so far unsuccessful in the field.

As these methods are still in an early stage of development, the DD is currently made, as mentioned before, by sampling the insulators and testing them according to the design tests reported in [3.10-1].

There is a strong demand for the development of "online" diagnostic techniques that could assess the remaining life of the composite insulators before actual failure.

3.11. Surge arresters

3.11.1. General

Surge arresters are used as protective devices to limit the amplitude of possible overvoltages in the electrical network; however, for most of the time, they are expected to function as insulators. According to service experience, most of the trouble caused by surge arresters comes from the deterioration of this "insulator function".

The majority of arresters in service is still of the so called conventional type, i.e. made of the series combination of active gaps and non-linear SiC resistors, encapsulated in a porcelain housing. For this type, the insulator function relies mainly on the gaps and spacers. A very important feature is that the voltage distribution across the several gaps in series is controlled by "grading" non-linear resistances and also sometimes by internal capacitors.

Nowadays, Metal Oxide Varistors (MOV) are able to perform the voltage clamping function as well as the insulator function: several tens of non-linear ZnO resistors are connected in series and gaps are no longer needed in MOV arresters.

3.11.2. Stresses acting on surge arresters

In addition to the obvious electric stress, arresters are exposed also to substantial thermal stress. Sizeable temperature increase is caused by normal duty operation or by external potential redistribution due to pollution or salt in combination with rain or fog. In the latter case internal discharges may also occur generating reactive species which can cause internal surface deterioration in the arrester.

Mechanical stresses are normally taken entirely by the porcelain insulator whereas the active arrester parts are well protected.

3.11.3. Deterioration factors and failure mechanisms

The insulator function of arresters can be deteriorated in several ways:

- Moisture ingress: condensation and corrosion inside the arrester can affect the dielectric withstand of insulating pieces and surfaces; the spark-over characteristics of the gaps can also be affected. For good performance of arresters, tightness is a must!

- Heavy external pollution: the surface currents on heavily contaminated housings, especially for multi-unit arresters, affect the voltage distribution and may create important temperature rises and jeopardise the grading system of conventional arresters or the blocks in MOV arresters.

- Discharges inside the arrester: decomposition products resulting from gas discharges in the arrester can impair the chemical stability and the dielectric surface properties of the internal parts, especially of the varistors.

- Varistor deterioration: ZnO blocks in MOV arresters, as well as grading resistors in SiC gapped type arresters, may suffer from changes of their characteristics during service. This results in higher leakage currents and losses. For conventional arresters, the final stage is sparking at service voltage, and for the MOV arresters, the final stage is thermal runaway.

- Grading capacitor deterioration: less frequent than grading resistor deterioration, but essentially the same effect.

- Gap deterioration by arrester duty: spark-over characteristics will be affected.

The failure rate of arresters depends on the keraunic level, on the system voltage and on the margin used in the selection of the rated voltage. For healthy and well designed arresters, the failure rate should not be higher than about 1/1000 per year. Once a particular category of arresters (make, environment, age) suffers from one of the above mentioned problems, the failure rate becomes much higher.

Diagnostic techniques are then necessary to make decisions on the replacement policy. Otherwise, diagnostic techniques are not likely to be more intensively used than just being included in the maintenance programs.

3.11.4. Diagnostic methods

Table X summarises the diagnostic techniques most widely used for surge arresters, together with their field of application, present status, effectiveness and specific references [3.11-1 to 3.11-4].

COMMENTS

MOV arresters have less internal parts and, therefore, diagnosis in service is more effective.

the mechanical strength decreases? As the line was designed for certain loads, the safety might actually be reduced.

- electrical characteristics: two aspects have to be considered:
  - pollution: the degree of pollution decreases the withstand voltage of the insulators. What margin of safety is left on a contaminated line insulator string? This problem depends on the operating environment of the insulators and is not covered in this document;
  - electrical strength: some insulators may be cracked, punctured or shattered, thereby reducing the effective dielectric characteristics of the complete string, even in a clean and dry state.

3.10.4. Diagnostic methods

Diagnostic techniques for overhead line insulators must take into account the following considerations:

- Insulators have a relatively simple design, with one or two passive dielectric parts (porcelain or toughened glass body for cap and pin insulators, fibre glass rod and housing for the composite insulators) and metal connecting parts.

- They are a cheap (compared to the other elements of the line), mass-produced component. It is essential that insulators be designed, manufactured and controlled for reliability.

- There are large numbers of insulators on a line and the mechanical separation of only one of them can lead to a catastrophic line drop.

At the present time, no diagnostic techniques allow the full knowledge of the reliability of the insulators on the operating line. The best approach is still to sample the insulators and to test them in the laboratory for mechanical and dielectric strength.
In the case of composite insulators, the reliability can be assessed in the laboratory by using the design tests described in [3.10-1].

Table IX reports the diagnostic techniques most widely used for ceramic and composite insulators, together with their field of application, present status, effectiveness and specific references [3.10-1 to 3.10-4].

COMMENTS

On-line diagnostic techniques for ceramic insulators have been little developed for the following reasons:

- The insulators are numerous and spread out among all the towers of the line, making the labour cost of the inspection very high.

- The insulators are out of reach and under voltage on the towers where they support the conductors.

- They do not have constituents like oil or gaseous dielectrics that can be analysed.

Moreover, their mechanical strength is impossible to measure in the field reliably and it is necessary to take a representative sampling of insulators to the laboratory. The dielectric soundness can be evaluated on the line, at least on a representative sampling. The sampling must be made randomly on both the towers and the insulators in the strings. A table of random

TABLE IX - Most important diagnostic techniques used for line insulators

PROBLEMS	DIAGNOSTIC TECHNIQUES	SERVICE CONDITIONS OF THE EQUIPMENT	STATUS OF THE DIAGNOSTIC TECHNIQUE	PROVEN EFFECTIVENESS OF THE DIAGNOSTIC TECHNIQUE	REFERENCE
	CAP AND PIN INSULATORS (Porcelain or glass) PORCELAIN LONGROD INSULATORS PORCELAIN LINE POST INSULATORS				
MECHANICAL STRENGTH Deterioration with time due to ageing of varnish, sanded degradation	- Mechanical tests in the laboratory on a representative sampling*	OFF-L	A	H	3.10-2 3.10-3 3.10-4
DIELECTRIC STRENGTH The porcelain dielectric body can be cracked by thermal stresses, or defects in the material, and for cap and pin insulators by cement growth or pin corrosion. The dielectric body can also be punctured following a steep-front wave.	- Electrical tests (application of Dc or impulse voltages) to each porcelain insulator**	OFF-S	A	M	
	- Electromechanical test in the laboratory on a representative sampling	OFF-L	A	H	
	- Acoustic tests: when hit a cracked shell does not ring as a sound one	OFF-S	A	M	
	COMPOSITE INSULATORS				
- Fiber-glass core: . Mechanical strength can be affected by ageing, the environment (brittle fracture) or creepage	- Mechanical tests in the laboratory on a representative sampling	OFF-L	A	H	3.10-1
. Electrical puncture due to progressive lengthning of internal conductive channels consequent to arcing associated with defects	- Design tests according to IEC 36-71 on a representative sampling	OFF-L	A	H	
- External housing: can erode or track due to surface arcing associated with environmental stresses (UV, ozone, moisture, etc.)	- Visual examination using a telescope	ON	A	M	
- Interfaces between housing and core end-fittings, or between sheds.	- Visual examination using a light intensifier at night	ON	A	M	
Localised deterioration due to surface arcing may affect housing and core.	- IR measurements - Corona noise measurements	ON ON	C B	L ?	

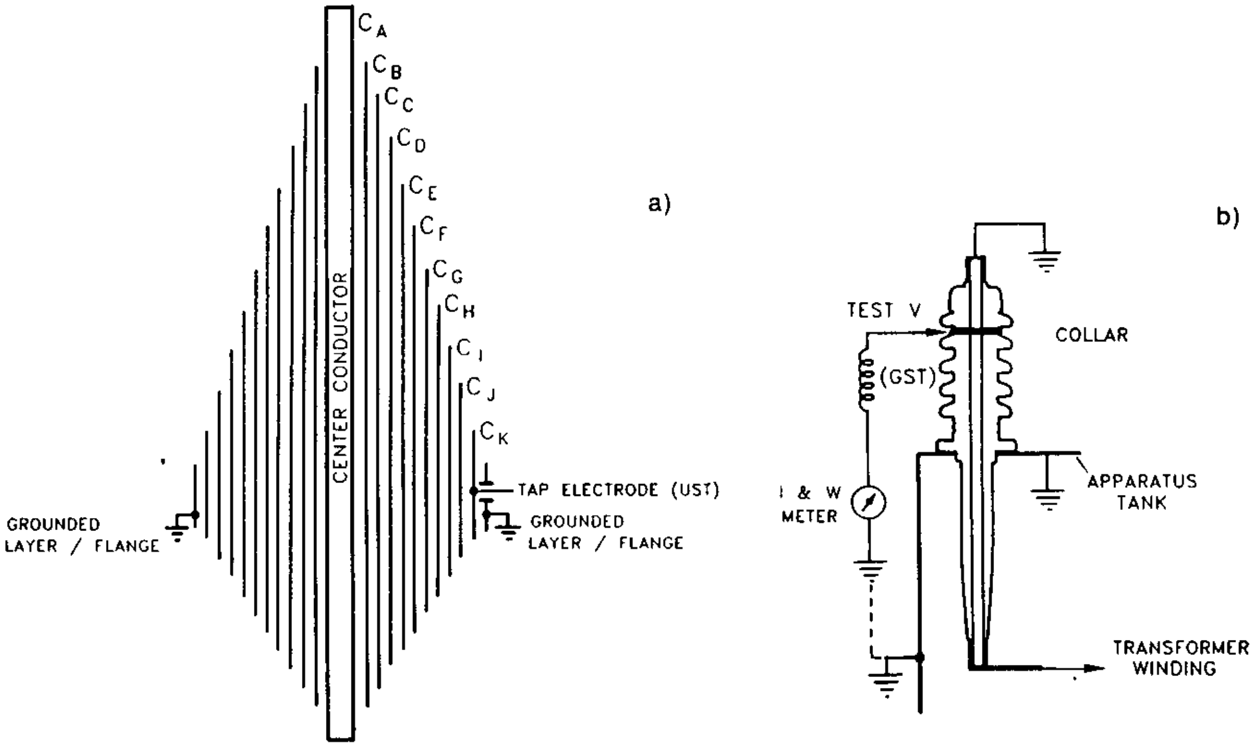

Figure 2 - a) Typical condenser bushing design
b) Hot-collar test (GST) on bushing

voltage or applied test voltages (see Figure 2), and will detect severe deterioration or short-circuiting of condenser layers which cause increased tap voltage and early failure.

DC resistance measurements detect increased leakage through and/or over the surface of bushing insulation, resulting from deterioration which produces lower-than-normal insulation resistance. Tests at lower voltages may be insensitive to non-continuous leakage paths.

Infrared scanning of bushings is a relatively simple field process, using portable equipment, for the detection of higher-than-normal temperatures or hotspots. It is particularly sensitive at line terminals of bushings, resulting from poor or corroded connections. Overheating can result in gasket and insulation damage.

One other test is worthy of mention as part of the laboratory investigation of any bushing: combustible gas analysis (CGA) can be helpful in determining whether internal PDs have occurred. Care must be exercised in securing the sample.

3.10. Line insulators

3.10.1. General

Overhead line insulators have two major functions:

- MECHANICAL, as they must withstand, without breakage, the weight of the conductors and hardware during the lifetime of the line and withstand overloads due to wind, ice, low temperature (in tension), etc. Temperature variations induce further stresses which are superimposed to the service stresses.
- ELECTRICAL, as they must withstand, without puncture or deterioration, the service voltage of the line even under polluted conditions (but the proper leakage distance must be provided) and various overvoltages due to switching operations or lightning strokes.

Different types of AC insulators are used in overhead lines: suspension cap and pin, suspension long rod and cantilever line post are made with ceramic materials (porcelains or glass according to IEC 672-3 (1984): porcelain (IEC C110, C120 and C130 for siliceous and aluminium porcelain), toughened glass (IEC G120)).

A new generation of suspension or cantilever insulators is made of composite material (fibre glass core, rubber or cast housing). The metal fittings are usually ductile or malleable galvanised cast iron, galvanised steel, aluminium or brass.

3.10.2. Stresses acting on insulators

As stated above, overhead line insulators are submitted to all the mechanical and electrical loads and overloads of the line, and they also have to withstand the existing outdoor environment: ambient temperature, moisture, ozone, U.V. light, pollution, arcing on the surface, etc.

3.10.3. Deterioration factors and failure mechanisms

The reliability of the insulators must be evaluated during a diagnostic operation for the following properties:

- mechanical strength: is it constant in spite of the permanent dynamic loads applied to the insulator? Is there a risk of breakage in service if

The wound paper core may be:

1) oil-immersed in porcelain;
2) oil-impregnated, oil immersed;
3) resin-bonded, either oil or gas immersed;
4) resin-impregnated, oil immersed.

3.9.2. Stresses acting on bushings

Apparatus bushings are subject to the effects of internal apparatus voltage, current, temperature and contamination; but are also subject to external atmospheric and environmental conditions, and mechanical stresses.

3.9.3. Deterioration factors and failures mechanisms

Bushing insulation integrity degrades in normal service from internal moisture, internal PD and tracking; from external corona, flashover and tracking; from ageing, and from physical damage.

Despite the intention that outdoor bushings be hermetically sealed devices, inadvertent entrance of moisture resulting from defective gasket seals and physical strain or damage is a major cause of insulation deterioration.

Internal PD and tracking can be a symptom and result of internal moisture contamination, physical shrinkage of plastic or compound fillers, system overvoltage or marginal designs where there is inadequate stress distribution. External surface contamination effects can be minimised by proper housekeeping and/or by use of coatings. Bushing insulation systems do not usually deteriorate due to time alone except where they have been subject to unusual service conditions such as excessive temperature or operating at voltages above nameplate rating over long periods of time.

3.9.4. Diagnostic methods

Bushings are ideally suited for field testing by DD to detect and analyse defects or deterioration resulting from the conditions previously described. Bushings are commonly field tested, when new, to confirm factory test data and to monitor for shipping damage, and then periodically, following system disturbances or apparatus failures and routine outages.

Table VIII reports the diagnostic techniques most widely used on bushings alone or installed, together with their field of application, present status and effectiveness and specific references [3.9-1 to 3.9-5].

COMMENTS

The most commonly used tests for bushings are capacitance and loss angle measurements. Experience has shown that they are sensitive to most conditions of bushing insulation deterioration. Factory data are often available to compare with field-test results.

Tests may be performed on the bushing alone or utilising test circuitry and technique for electrically isolating the bushing insulation from other components such as transformer winding insulation by energising the bushing conductor with the potential tap (or test tap for bushings rated 72 kV and below) connected for un-grounded specimen test (UST) (see Figure 2).
To compare loss angle tests on bushings, the measured results are corrected to a common temperature, usually 20°C. Correction factors are available.

Where installed bushings do not have a capacitance or test tap, the exposed portion of the bushing can be tested by energising a conducting collar, referred to as Hot-Collar, with the bushing conductor grounded. The collar can be placed at any position on the exposed porcelain (insulating) bushing surface (see Figure 2). Hot-Collar tests detect moisture deterioration in the internal insulation and compound (plastic) filler, and problems with dry, liquid or gas filled solid porcelain bushings.

Measurements of capacitance and AC dielectric loss (not dissipation factor/power factor) are evaluated by comparison with similar tests done at the same position on other similar bushings, all tested at the same time or under the same atmospheric conditions. Additional collars, connected to the test set guard circuit, when placed above and/or below the test collar will help minimise any losses due to surface contamination.

PD and RIV measurements detect internal discharges, primarily in dry-type and resin-bonded bushings. Field testing of oil-impregnated bushings is less extensive. Tests for PD and RIV are most effective on isolated bushings, and not when installed in apparatus.

Tap-voltage measurements on condenser bushings with capacitance (potential) taps are performed at system

TABLE VIII - Most important diagnostic techniques used for bushings

PROBLEMS	DIAGNOSTIC TECHNIQUES	SERVICE CONDITIONS OF THE EQUIPMENT	STATUS OF THE DIAGNOSTIC TECHNIQUE	PROVEN EFFECTIVENESS OF THE DIAGNOSTIC TECHNIQUE	REFERENCE
Moisture	Capacitance/loss angle	OFF-S	A	H	3.9-1,2,3,4
	Tap voltage	ON	A	M	3.9-1,2,3,4
	DC resistance	OFF-S	A	L	3.9-1,4
	Hot-collar	OFF-S	A	H	3.9-4
Corona	Partial discharge (PD)	OFF-S	B	M / L	3.9-4
	Radio-influence voltage (RIV)	ON	B	M	3.9-4
Ageing	Capacitance/loss angle	OFF-S	A	H	3.9-1,2,3,4
	DC resistance	OFF-S	A	L	3.9-1,4
Short-circuited condensers	Capacitance/loss angle	OFF-S	A	H	3.9-1,2,3,4
	Tap voltage	ON/OFF-S	A	M	3.9-1,4
Internal surface leakage	PD/RIV	OFF-S	A	M / L	3.9-1,4
	Capacitance/loss angle	OFF-S	A	M	3.9-1,4
	AC dielectric loss	OFF-S	A	H	3.9-4
Poor connections	Infra-red scanning	ON	A	H	3.9-4

TABLE VII - Most important diagnostic techniques used for capacitors

PROBLEMS	DIAGNOSTIC TECHNIQUES	SERVICE CONDITIONS OF THE EQUIPMENT	STATUS OF THE DIAGNOSTIC TECHNIQUE	PROVEN EFFECTIVENESS OF THE DIAGNOSTIC TECHNIQUE	REFERENCE
POWER FACTOR CORRECTION CAPACITORS					
Breakdown of parallel fused elements	Decrease of capacitance	ON	A (routine)	H	
Deterioration of dielectric in paper capacitors	Increase of power factor	ON	A (routine)	H	
Deterioration of dielectric in both paper and film capacitors	Increase of PD level	OFF-S	A (periodical on samples)	M	
Breakdown of series elements	Increase of capacitance	ON	A (routine)	H	
Ionisation in metallised paper of film capacitors	Decrease of capacitance	ON	A (routine)	H	
OIL-IMPREGNATED COUPLING AND VOLTAGE TRANSFORMERS					
Breakdown of series elements	Increase of capacitance	OFF-S	A (occasional)	H	
Ionisation	Analysis of liquid impregnant	ON	A (occasional)	M	

short-circuit, is of minor consequence and diagnostic methods are not widespread. With medium and high voltage banks the consequences are much more important and, to detect the units in which elements may have broken down, most utilities perform periodical measurements of the capacitance of each unit of the bank.
Up to a certain number of faulty elements, the units can be retained in service, possibly rearranging them in the bank to maintain balance between phases. To increase the number of faulty elements which can be tolerated, the practice of manufacturing large units with internal fused elements tends to become general.

Additionally, in banks of capacitors made with paper dielectric, the periodical measurement of the loss angle and the comparison of results with the original values may, in a number of cases, be effective in detecting faulty units before any breakdown.
This is not the case with banks of capacitors made with polypropylene film, because the measurement of the loss angle in the field is not possible, values being so low as to prevent the use of industrial instrumentation.

Moreover, important as it certainly is with paper capacitors, the monitoring of the loss angle is of limited validity; in most cases breakdown occurs in units which have maintained their loss angle - and, for the matter, all other characteristics - unaffected.
This is because, as already mentioned, the electrochemical deterioration of the dielectric may proceed in such small areas as to pass undetected to any external measurement.

For capacitor banks as a whole, a useful diagnostic practice is the periodical performance of PD tests on even a very limited number of units. These tests may be effective in revealing whether the bank has undergone abnormal service conditions (e.g. repeated overvoltages caused by switching operations or by atmospheric surges) as a result of which it may have deteriorated.

PD tests, which include the measurement of partial discharge inception and extinction voltages, cannot be carried out on the field but checks in laboratory may be indicative for the whole bank, since results do not depend on the presence of small localised defects in the dielectric, but rather on the state of the whole units: in particular deterioration of the foil edges and chemical modification of the dielectric in contact with same, and gassing of the impregnant fluid.

Methods of detection of partial discharges and of measurement of their level have been the subject of an extensive literature, and presently both electric and ultrasonic methods are in use, the former being the more common.

In high voltage coupling capacitors and in capacitor voltage transformers which consist of a number of series elements, the breakdown of one or possibly a few of them may be tolerated during the acceptance tests, but is very dangerous in service.

Check of capacitance is a good practice; it is also possible to extract small quantities of the liquid impregnant from the top of the unit while in service: the analysis of the dissolved gases and infrared spectroscopy can provide useful information as to the possible ionisation inception and state of ageing of the unit.

3.9. Bushings

3.9.1. General

Bushings provide insulated terminals carrying current into and out from power apparatus such as transformers and circuit breakers. They additionally serve as mechanical supports for external bus and lines, as well as for internal supports such as circuit breaker contacts.

Bushings are constructed to numerous design considerations but commonly consist of:
1) centre conductor,
2) mounting flange, and
3) insulation (solid, fluid, plastic or in combination) between conductor and flange.

The wound core may consist of only two terminals - the bushing centre conductor and the mounting flange-/ground sleeve system, in which case the voltage stress will be concentrated between the conductor and the flange (non-condenser design), or may include strategically placed conducting wrappings or layers to equalise axial and radial voltage stresses in the core (condenser design). Most high-voltage bushing designs are the condenser principle.

The insulation system may be:
1) dry: bulk porcelain, gas or air;
2) wound paper.

not be suitable for operation at the installation site where external interference is present.

Techniques suitable for both factory and site testing are acoustic techniques (method 11) with sensors mounted on the enclosure, and techniques for measuring the electromagnetic pulses due to partial discharges using Fourier transformations and correlation techniques.

The gas density/pressure is monitored to determine if any leakage is occurring. Gas sampling can be made to determine if there are any major discharges occurring in the gas, but will not show any deterioration effects in insulators. Gas sampling for buried systems may be limited to the regions next to the terminations.

Up to now the more promising applications of diagnostic testing seem to occur in the field of extruded cables, if the influence of water, as deterioration parameter, is taken into account; although up to now only limited practical experience has been collected. The more sophisticated techniques for material evaluation need much further developments before an effective application can be expected. The major future development will go into the direction of complete non-destructive electrical testing at site and related monitoring techniques.

3.8. Capacitors

3.8.1. General

The variety of applications of capacitors in the field of energy systems reflects in a variety of technologies for their manufacture and consequently in diversities in the deterioration and failure mechanisms and diagnostic practices.

Capacitors for low voltages, up to say 400 V, are mostly of the dry metallised film type; electrodes are deposited on the film by evaporating under vacuum a layer of aluminium which is destroyed when the film punctures allowing the capacitor to "heal".

Medium voltage power capacitors employ as dielectric layers of polypropylene or alternate layers of paper and polypropylene and for electrodes aluminium foils; they are impregnated with synthetic dielectric liquid.

High voltage coupling capacitors and capacitor voltage transformers, although making use of a similar technology, differ in the quality of the materials and in many assemblage characteristics.

3.8.2. Stresses acting on capacitors

Dry metallised capacitors are designed for very high electric stresses. Their healing properties insure that occasional punctures do not result in their destruction. Stresses are also high at the metal edges and may cause ionisation. Heating of these capacitors, in addition to that generated internally, may result from application in restricted spaces as are frequently encountered in lighting appliances.

Larger power capacitors are designed either with paper insulation for lower electric stresses or with polypropylene for very high dielectric stresses, but for them the heating from dielectric losses must be taken into consideration: it is of minor importance for film capacitors, but may become the limiting factor of design in mixed paper/polypropylene capacitors.

Capacitors, assembled in banks, installed in energy systems may also receive additional stresses from long-term overvoltages and from switching impulse overvoltages. These are particularly severe for non-energised banks if energised at very low temperatures.

Coupling capacitors and capacitor voltage transformers are designed with wide safety margins: however, in the latter severe overvoltages may result in the case of ferro-resonance phenomena.

3.8.3. Deterioration factors and failure mechanisms

In small dry metallised capacitors, due to the high working electric stress and because the dielectric is made of a single film layer, failures due to weak spots may occur; although these do heal, each contribute to a slight deterioration of the dielectric. An additional deterioration factor results from the even higher stress at the edges of the metal layer which may initiate partial discharges. Both phenomena lead to a progressive deterioration of the dielectric, to consequent overheating and/or non-healable breakdowns and possibly to capacitor fire. For this reason capacitors which are to be installed in appliances placed in locations difficult to keep under inspection are provided with devices which disconnect them from the mains before they take fire.

With larger power factor correction capacitors, when they are correctly designed and applied, the deterioration depends on the slow electrochemical modification of the dielectric, brought about by the combined electric and thermal stresses: both stresses being important in the paper dielectric, only the former in the polypropylene film dielectric. The phenomenon is very slow and well designed and properly manufactured capacitors have a very long life: their decommissioning is usually dependent on obsolescence rather than on physical deterioration.
The electrochemical deterioration may be concentrated and proceed in small areas and may pass undetected to any external measurement. This makes diagnostic procedures very difficult to implement.

High voltage coupling capacitors and capacitor voltage transformers are subjected to the same deterioration phenomena but at a much slower rate, because they are designed with large safety margins. Since, however, their failure could result in serious consequences, to facilitate diagnostic many manufacturers provide for the possibility of extracting samples of the liquid impregnant from the top of their containers.

3.8.4. Diagnostic methods

Table VII reports the diagnostic techniques most widely used for capacitors, together with their field of application, present status, effectiveness and specific references [3.8-1 to 3.8-14].

COMMENTS

Small power capacitors are dispersed in fluorescent lamps or in domestic appliances with capacitor-start motors: diagnostic methods are not consistent with the very minor technical and economic consequence of their failure.

Larger power factor correction capacitors may be assembled in low, medium or, less frequently, high voltage banks.

At low voltage the breakdown of one or even a few units of a bank, provided fuses clear the insuing

TABLE VI - Most important diagnostic techniques used for cables

PROBLEMS	DIAGNOSTIC TECHNIQUES	SERVICE CONDITIONS OF THE EQUIPMENT	STATUS OF THE DIAGNOSTIC TECHNIQUE	PROVEN EFFECTIVENESS OF THE DIAGNOSTIC TECHNIQUE	REFERENCE
	OIL-FILLED PAPER CABLES				
Dielectric (accessories)	1. PD detection (acoustical method)	ON	A	H	3.7-1
Thermal (accessories)	2. Oil analysis	OFF-S	A	M	3.7-1
Dielectric (accessories)	3. Oil analysis	OFF-S	A	M	3.7-1
Thermal	4. Degree of polymerisation	OFF-S	A	M	3.7-1
	EXTRUDED CABLES				
Dielectric + water	5. Insulation characterisation test	OFF-L	A	H	3.7-4
	6. Dual polarity test	OFF-L	C	?	3.7-5
	7. Non-destructive electric tests DC-resistivity, loss angle, etc.	OFF-S	B / C	L	3.7-6 3.7-7
	8. Oscillating wave test	OFF-S	C	?	3.7-8, -9
Dielectric	9. PD detection	ON	C	?	3.7-10
	COMPRESSED GAS-INSULATED CABLES				
Dielectric	10. PD detect. (electrical method)	ON	A	M	3.7-11
	11. PD detect. (acoustical method)	ON	A	H	3.7-11

ming because a piece of cable has to be taken from the installation.

As a general practice a piece of cable is taken out after failure to carry out diagnostic testing in the laboratory.

Extruded cables

Synthetic insulating materials (XLPE, EPR, PE) are widely used, for extruded cables. Only very limited information is at present available about their long-term performance.
There is therefore an interest for characterisation tests to collect information about changing of properties and related ageing processes and particularly to know if certain processes can be responsible for deterioration resulting in a significant reduction of cable life.

In [3.7-2] an extended survey is given of various analytical techniques for characterising insulating materials to be used for extruded cables. Applying these techniques a greater understanding will be obtained of phenomena involved in the ageing of high-voltage cables. The most useful techniques according to [3.7-2] are those being capable to detect defects, differences in density, the nature of antioxidants and water content.
However, as already stated in subsection 3.7.3., up to now synthetic dielectrics used in extruded cables do not appear to exhibit changes that can easily be detected or that can be claimed to be significant in terms of cable life reduction, when the influence of water is excluded [3.7-3]. In [3.7-4] extended information is given about the deterioration mechanism due to the combined influence of water and electric stress (water-treeing) and related testing procedures.

The insulation characterisation test (method 5), proposed by CIGRE WG 21.11, enables to establish the rate of deterioration of a cable affected by water-trees. The test results, level of breakdown voltage and maximum size of tree, qualifies the cable with respect to the level of deterioration and related life expectancy. For this characterisation test, to be carried out in the laboratory, about 60 meter of cable is necessary.

In the dual polarity test (method 6) [3.7-5], cable pieces are subjected to impulse breakdown, while being pre-stressed with DC-voltage of opposite polarity. The degree of ageing can be related to the threshold voltage V_{thDC}, above which the value of impulse breakdown is decreasing: so far no practical experience is available.

In [3.7-6] and [3.7-7] non-destructive electric tests (method 7) such as, loss-angle, DC-resistivity, DC-component in AC-current and DC-relaxation are described to be carried out immediately at site, in order to collect, in general, global information about the quality of cable affected by water-trees. So far only in Japan and USA some experience has been collected, however more statistical analysis of data is needed; besides, the strong impression is given that only very heavily degraded cables can be detected, of which water-trees have almost crossed the insulation.
In [3.7-8] a proposal is given to stress aged cables at site (method 8) with a voltage of low frequency (0.1 Hz). Apart from the practical advantage, the 0.1 Hz is supposed to have the advantage of being more sensitive in detecting water-trees; so far not practical experience is available.

The oscillating wave test method, intended and recommended as after laying test on new cable systems [3.7-9], may be extended also for application as diagnostic test to aged cables. The DC-test is certainly not recommended as a diagnostic test, because of the dangerous risks [3.7-9].

PD detection at site (method 9), although not suitable for detecting water trees, could become a diagnostic tool to check the general quality of cable and particularly accessories, if very sensitive detection at site could become possible. In [3.7-10] first experimental work is described on PD detection using impulse voltages. No information is available to detect partial discharges at site using 50 Hz voltage.

Compressed Gas-Insulated cables

Diagnostic techniques are important to detect and locate partial discharges [3.7-11]. The conventional PD techniques (method 10), used in factory testing, may practical cable systems, is about 750 kV. Their way of installation can be underground, overground or submarine. The required lifetime is generally 30-50 years.

There are three main types of high voltage cables:

Oil-filled paper cables

The classical oil-filled paper cable dielectric consists of lapped paper layers filled with a low viscosity mineral oil, or nowadays frequently used synthetic oil, at a small overpressure. The insulation is enclosed by a lead or aluminium sheath in case of self-contained oil-filled cables, by a steal pipe at a high overpressure in case of pipe-type oil-filled cables.

Extruded cables

The dielectric is a synthetic material, mostly XLPE, PE or EPR, placed around the conductor, generally in combination with two semiconducting layers, by an extrusion process. High voltage cables are usually provided with a metal sheath to protect them against water ingress.

Compressed Gas-Insulated cables (CGI)

CGI-cables are in general built up in separate sections. These sections consist of a central conductor, coaxially supported by cast epoxy spacers within a metal enclosure. The system is filled with pressurised SF6 gas.

3.7.2. Stresses acting on cables

During service the cable is subjected to the following stresses which directly or indirectly influence the insulation deterioration processes.

T (thermal):	due to operating current under normal and abnormal (emergency) conditions. The maximum operating temperature depends on the insulating material and operating conditions.
E (electrical):	due to operating voltage under normal and abnormal conditions. The maximum operating stress depends essentially on the voltage level.
A (ambient):	due to environmental conditions and parameters such as corrosivity of soil, resistivity of water, presence of U.V. light, etc.
M (mechanical):	due to mechanical (for instance in bends) and/or thermomechanical stresses (cyclic and short-circuit behaviour). The maximum stress depends on the installation and operating conditions.

3.7.3. Deterioration factors and failure mechanisms

Causes of insulation deterioration and related failures are dependent on the type of cable and therefore are to be distinguished for the cables mentioned in subsection 3.7.1.

Oil-filled paper cables

Deterioration of paper oil dielectric because of thermal or electrical ageing (partial discharges) can result into failures. The metal enclosure of this type of cable is of vital importance to maintain the overpressure and to avoid water penetration into the dielectric. Generally, a serious damage of the metal enclosure (lead or aluminium sheath) caused by mechanical deterioration (fatigue) or chemical deterioration (corrosion) or any other external effect can be detected immediately because of the decrease of pressure.

In case of overground installations, U.V. light may cause stress-cracking of the outer jacket (PE) with increased risk of corrosion of the metal sheath.

Extruded cables

Up to now synthetic dielectrics used in extruded cables do not show significant reduction in electric properties because of thermal, electrical or chemical ageing, when the influence of PDs or presence of water is excluded.

The detrimental effect of partial discharges, as deterioration factor of solid dielectrics, has already been mentioned in section 2.2.1. The effect of water in combination with electric stress appears to be a very serious deterioration factor, resulting in the formation of so-called water-trees and subsequent failures.

Compressed Gas-Insulated cables

Spacer surface deterioration due to flashovers, presence of impurities and partial discharges in the gas or in the insulators are possible deterioration factors that can lead to complete failures.

3.7.4. Diagnostic methods

Table VI reports the diagnostic techniques most widely used for power cables, together with their field of application, present status, effectiveness and specific references [3.7-1, 3.7-4 to 3.7-11].

COMMENTS

Oil-filled paper cables

Apart from electrical measurement techniques as loss angle or PD detection, which are not very sensitive and not easy to be applied at site, except acoustic detection (method 1) for accessories, a more interesting diagnostic technique is the analysis of gases dissolved in insulating oil (method 2, 3) [3.7-1].

The sampling can take place at site, causing a minimum of disturbance of the system. The interpretation of results from cable oil has not reached the same degree of sophistication as for transformers. In principle the presence of C_2H_2 is referring to (partial) discharges, the presence of major quantities of CO or CO_2 refers to thermal deterioration of mainly paper, and the presence of H_2 can be related to both (mainly thermal) deterioration of paper and oil. The major problem, when applying this technique for cables is the lack of representativity of samples with respect to the overall quality of the cable, because of the relatively long system length. This technique could be more usefully applied in case of diagnostic testing of accessories, where the oil sample is taken from the immediate vicinity of the relevant component. Design defects by diffusion of SF6 into oil at sealing ends can be detected simultaneously.

Another technique, although far less simple than the oil analysis, is the measurement of the DP of insulating paper (method 4) [3.7-1]. For this measurement the sampling technique is expensive and time consutems are reached. In principle, the DD of a GIS is the combination of the DDs of the individual equipment. But they have been normally applied to the GIS as a total system. The diagnostic system is not an auxiliary of GIS but an independent system to improve the reliability of the substation.

The function of the system should be discussed in relation to the performance of whole power system and not that of GIS. The new recognition of the function will be crucial to justify a wider application of the system.
In future, the system may come to be integrated as a part of the digitalised control and protection system for a substation in future. Other functions such as a computerised support system for maintenance and operation will also be integrated in the system.

3.6.2. Stresses acting on GIS

Under service conditions, the stress of each component in a GIS is generally the same as those of conventional devices in open-type substations.

In addition to the common stresses, however, GISs are also subjected to the very fast transients which occur during a disconnector or an earthing switch operation with open ended gas-insulated busbars [3.6-1]. With these stresses, however, the design dielectric stresses of GISs are well below the critical levels to cause dielectric deterioration discussed in Section 2, and the ageing in that sense needs not to be taken into account.

3.6.3. Deterioration factors and failure mechanisms

Possible causes of insulation deterioration in GISs are some kinds of anomalies in the gas-insulation structures such as metallic foreign particles, loose bolts, etc. Deterioration of the surface of epoxy insulators by decomposition gases of SF6 due to arcing may be an other example of the anomalies. These causes of insulation deterioration have been the objects of DD for GIS.
In the case of GIS, the metal enclosure normally prohibits a visual check of the high voltage parts from the outside of the enclosure. If an internal inspection is carried out, dismantling and reassembly at high costs is inevitable. Therefore, diagnostic techniques have been studied from the very first stage of the development of GIS and are desired in operation to detect potential and existing defects.
Diagnostic techniques for GIS has long been an important subject in CIGRE WG 23.03. The results of a survey are summarised in [3.5-1]. Recent studies are presented in [3.5-2] and in other papers to come for the 1990 General Session.

3.6.4. Diagnostic methods

Table V presents the diagnostic techniques most widely used for GISs, together with their field of application, present status, effectiveness and specific references [3.5-1, -2].

COMMENTS

Introduction of metallic particles is a common cause of dielectric deterioration of GIS. Detection of PDs due to the particles and other kinds of defect is the most important item of DD for GIS. Internal PDs are detected by either electrical or vibrational means from outside of the tanks.
Electrical methods measure the electrical pulses induced on the grounded tank of GIS. Since the electrical pulses travel along GIS bus with minimal attenuation, the methods are efficient to monitor defects continuously in GIS in operation.
Vibrational transducers attached on the surface of GIS enclosures are used in vibrational measurements. Because of the high attenuation of vibrational signals along GIS bus, the methods are efficient to locate a defect after it is detected by an electrical method.
Since these diagnostic means are applied in high voltage substations with very high background noise levels, opto-electronic signal transmission and digital data processing are key technologies to get rid of the noise problem.
Performance of the gas-insulation is a key factor: the density of the filling gas is always monitored as an important parameter to detect any possible leaking of the gas.
Impurity of the gas does not significantly deteriorate the performance of gas-insulation and it is not usually the item for DD. However, chemical detection of the decomposition products of SF_6 is often applied to check the dielectrics conditions of the gas and to locate the internal faults or internal discharges when they are found by some other means.

DD of GISs are widely applied in some countries like Japan in combination with the diagnostics on mechanical and other kinds of defects as an integrated system [3.6-3 to 3.6-5]. Since dielectric problems are only a fraction of all the field problems of GISs, the integration is essential for GISs.

3.7. Cables

3.7.1. General

High voltage cables are used to transport energy, as an alternative to overhead line transmission. The maximum transmission voltage, presently used for

TABLE V - Most important diagnostic techniques used for Gas-Insulated Systems (GIS)

PROBLEMS	DIAGNOSTIC TECHNIQUES	SERVICE CONDITIONS OF THE EQUIPMENT	STATUS OF THE DIAGNOSTIC TECHNIQUE	PROVEN EFFECTIVENESS OF THE DIAGNOSTIC TECHNIQUE	REFERENCE
Metallic particles	Electrical discharge pulse	ON	A	H	3.5-1
	Mechanical vibration	ON	A	H	3.5-1
Imperfection in epoxy spacer	Electrical discharge pulse	ON	B	L	3.5-1
Loose bolt	Mechanical vibration	ON	B	L	3.5-1
Bad contact	Electrical discharge pulse Mechanical vibration	ON	B	H H	3.5-1
Internal fault	Gas analysis	ON/OFF-S	A	H	3.5-2

TABLE IV - Most important diagnostic techniques used for circuit breakers

PROBLEMS	DIAGNOSTIC TECHNIQUES	SERVICE CONDITIONS OF THE EQUIPMENT	STATUS OF THE DIAGNOSTIC TECHNIQUE	PROVEN EFFECTIVENESS OF THE DIAGNOSTIC TECHNIQUE	REFERENCE
Insulation defects	Measuring				
	- gas density	ON	A	H	3.5-...
	- PD at coupling capacitor	ON	D	M / H	-1
	- HF current probe	ON	D	M	-2
	- HF capacitive probe	ON	D	M	-3
	- ultra-sonic	ON	D	M / H	-4
Dielectric gas-quality	SF6 Quality control				
	- dielectric check	ON	D	L	2-14
	- gas analysis				
	* gas chromatography	ON	R	L	3.5-2
	* infra-red spectrography	ON	R	L	3.5-2
	* colour detector	ON	D	L	3.5-2
	* air contents	ON	A	L	3.5-2
	* moisture contents	ON	A	L	3.5-2
Wear of circuit-breaker	Measuring				
	- location of shaft position	OFF-S	D	L	3.5-2,3
	- contact wear $\Sigma n*I=K$	ON	A	M	3.5-5
	- dust and powder contents in SF6	ON	D	L	3.5-5
Abnormal mechanical operation	Measuring				
	- at potentiometer on moving contact	OFF-S	A	H	3.5-...
	- optical markers on moving parts	OFF-S	A	H	-1
	- friction of driving elements	OFF-S	A	H	-2
	- tripping time	ON	A	H	-5
Over heating	Measuring				
	- infra-red camera	ON	D	L / M	3.5-...
	- contact resistance	OFF-S	A	M	-1,-2,-3

The wear of the circuit breaker contacts in the interrupting chamber is very difficult to measure. The measurement of the location of the operating shaft position corresponding to the moment of closing gives only very imprecise information, as contact erosion can be distributed very differently on the contact surface. The amount of by-product concentration does not indicate the contact wear, because absorbers in the breaker can neutralise and reduce the by-products.

Most promising is the general law for contact wear, which gives information about the total deterioration of a breaker chamber:

$$\Sigma n_i * I_i^{\alpha} = K$$

The cumulative effect of interrupted currents can be evaluated in order to estimate the lifetime of the CB which has been used up. Values of the parameters in the above equation are available from the breaker manufacturers. It must be emphasised, that this equation is related to the "electrical" ageing (and not to the dielectric), i.e. the switching performance of the breaker. Compared to the electrical deterioration, the dielectric deterioration is a minor effect. The maintenance interval for the switching chamber is determined by the electrical ageing, i.e. by the reduction of switching performance.

A few diagnostic methods are available to measure abnormal operation. Contact movement, slower than normal and contacts which are not fully separated in the OPEN condition can be detected by space-time diagram of the moving contacts. The operating time for OPEN/-CLOSE can be easily measured for the auxiliary contacts by means of the tripping signal. Abnormal friction, which can cause a low contact speed, can be detected by resistance sensors.
These diagnostic methods are often used during development tests but they can be applied in service too. This is normally done OFF-LINE, with circuit breaker out of service; generally the ON-LINE application is possible.

Overheating of breakers can be observed ON-LINE by an infrared camera, which can detect an abnormal temperature outside the breaker. This gives indirect information of the temperature of the inner conductors.

3.6. Gas-Insulated Systems (GISs)

3.6.1. General

For important substations where high reliability performance is absolutely required, or for those difficult applications where space requirements or heavy contamination is a problem in using a conventional bus arrangement, GISs are available at voltage classes up to 765 kV.
GISs are a combination of busbars, circuit breakers, disconnectors and other switchgears, surge arresters, instrument transformers and other substation equipment.
High voltage parts of GISs are completely enclosured in ground metal tanks and supported by epoxy insulators in clean dry compressed SF6 gas. They are free from the influence of oxygen and water which are recognised as major causes of insulation deterioration in other kinds of high voltage apparatus.
Current transformers normally form an integral part of GISs with a common encapsulation. The annular magnetic core and the secondary windings (coils) are electrically shielded by a grounded electrode.
Inductive voltage transformers are generally situated in a separate housing flanged to the GIS; in many cases they form separate gas rooms. An epoxy bushing is therefore present between the main body of the GIS and the voltage transformer. High voltage electrodes generally shield the various design of windings (coils).
Capacitive voltage dividers using an SF_6 insulated high voltage capacitor - e.g. a short length of coaxial line - need an electronic amplifier at the low voltage side to fulfill the present-day power requirements of most protection and measuring equipment in use. Diagnosis on the electronics are outside the scope of this paper.

GISs are normally considered to be maintenance-free, in the sense that no maintenance is necessary on live parts, unless a specified number of operations or current interruptions of switchgears and driving sys-

The insulating media inside the circuit breaker, used for current interruption, for arc extinction and for insulation, are liquids or gases. While oil-breakers are disappearing and breakers operating with compressed air are still in operation, SF6 gas circuit breakers are mostly used today (vacuum breakers are not dealt with in this Report).

3.5.2. Stresses acting on circuit breakers

The main stresses acting on the circuit breaker are:

ELECTRICAL stresses, due to:
- AC rated value and temporary overvoltages
- Transient Recovery Voltage (TRV) after opening of short-circuits
- Lightning impulses and BIAS, where LI+AC are superimposed
- Switching impulses and BIAS, where SI+AC are superimposed
- Very Fast Transients (VFT) with disconnector- or CB-operation
- VFT especially after a period of DC-voltage
- DC from trapped charges after opening CB or Disconnectors

MECHANICAL stresses, due to:
- forces consequent to driving operations (rods, pipes)
- forces created by the short-circuit currents
- gas shock waves and hot gas streams from power arcs
- tensions from internal gas pressure
- subsonic oscillations with earthquakes

THERMAL stresses, due to:
- temperature rises due to high currents
- additionally high ambient temperatures
- temperature differences between inside and outside the breaker

CHEMICAL stresses, due to:
- hot gas-stream of by-products during switching operations
- high concentration of by-products after switching operations
- dust and powder produced by arc-erosion during switching operations
- additive moisture in combination with by-products

3.5.3. Deterioration factors and failure mechanisms

The withstand voltage of a breaker insulation can be reduced in service due to the effects discussed in the following.

Insulation failures inside the breaker can be determined by:
- aggressive chemical by-products,
- conductive particles,
- defects in solid dielectrics (e.g. voids, poor adhesion, cracks, humidity, conductive particles).

The first two items produce conductive areas on insulators surfaces or protrusions on conductors, leading to local field enhancement and finally to a flashover. The third item creates PDs which are activated from service stresses and may lead to a breakdown.

The dielectric quality of the gas can be reduced. Small amounts of air or moisture in SF_6 do not strongly affect the gas withstand values, as long as there is no additional quantities of by-products. The combination of moisture and SF_6 by-products causes a strong reduction of the flashover voltage on insulator surfaces.

The dielectric properties of compressed air are also reduced by moisture.

The wear of contacts in the circuit breaker interrupting chamber produces rough electrode surfaces, which can reduce the breakdown voltage across the contact gap. The melted contact material can produce dust, metallic particles and conductive layers on the surfaces of insulators.

Abnormal operation of mechanical elements are not generally classified as a deterioration factor, but they can cause dielectric failures. As an example, the slow movement of the driving components, which cause an increasing arcing time with higher amount of hot by-products, can cause breakdown during switching operations. If the switching contacts are not in full open position, this reduced insulation gap gives a lower breakdown voltage. In this sense the mechanical conditions are related to the dielectric aspects.

Overheating can also be the origin of a dielectric breakdown. An abnormal increase of temperature usually indicates a defect at the contacts. It can be caused by a lost metallic component, e.g. a screw which, being loose, can also become the origin of a breakdown. Moreover, if the insulator is heated, its dielectric strength is normally reduced.

Programmed maintenance for circuit breakers is carried out after periodic intervals or after a specified number of switching operations.
With the introduction of DD, the maintenance activities can be adapted according to the CB conditions. In case of good conditions maintenance intervals can become longer, while dangerous conditions could indicate the necessity of an earlier intervention, in order to avoid failures in service. The possibility of on-condition maintenance leads to cost reduction for maintenance and for failure repair.

3.5.4. Diagnostic methods

Table IV reports the diagnostic techniques most widely used for circuit breakers, together with their field of application, present status, effectiveness and specific references [3.5-1 to 3.5-5, 2-14].

COMMENTS

A number of small defects inside the breaker, e.g. metallic particles, conductive layers, etc. can be detected by PD measurements, but this is only possible with GIS breakers.

During commissioning on site, PD measurements are not always effective, as background noise considerably reduces very much the sensitivity. For PD detection in service there are different types of sensors available: they detect the PD high frequency signal either by current measurements or by voltage measurements via a capacitive pick-up probe.

Direct measurements of the SF_6 gas characteristics (i.e. breakdown voltage or field in a special test cell [2-14]) is a valid quality control dielectric check. Gas analysis by means of gas chromatography or infrared spectroscopy respectively gives accurate composition results, but is difficult and very expensive. At least the interpretation of the by-product concentration remains. Devices and procedures for detecting air contents in SF_6 are available and quick working. Measurements of moisture in gas is also possible on a sample basis.
Insulation weaknesses caused by a too low gas pressure, can be detected by monitoring the gas-density. This is a simple and very essential method.

lowest capacitive grid (the one nearest to earth potential) has been connected and earthed. Therefore, it is possible to measure the loss angle of the main insulation between this terminal and the bottom flange of the CT.
With IVTs, it would be possible to measure the loss angle of the insulation between the shielding grid and the secondary winding, but this is not common practice.
It is to be noted that the value of the loss angle depends on a number of factors such as voltage, temperature, design features, etc., so that the interpretation of the measurements is not easy. In particular, it would be convenient to carry out the measurements at high temperature (about 90°C) at which the presence of contaminant can be detected as a function of the voltage [3.4-9, -10].

b. Analysis of gases dissolved in oil
Most types of ITs are provided with an oil valve from which is possible to take samples of oil. However, this must be done with caution if performed in service.
For gas analysis and their interpretation, the same methods as with power transformers are in use [3.3-16, -17].

Precautions are to be taken during oil sampling, because the volume of oil is quite small and may require a refilling. The presence of a large amount of hydrogen is generally connected with the presence of PDs in the oil between the paper layers. Formation of X-wax in these areas is typical.
Recently, a number of IVTs have been provided with H_2 detection probes: The H_2 concentration in oil may be checked after diffusion from the oil through a membrane by a thermal conductivity detector [3.4-8].

c. Ultrasonic detection of PDs in service
Some Utilities employed this technique to detect PDs in ITs transformers in service by means of an ultrasonic detector installed on the outside of the tank and fixed with magnets [3.4-8].
The method is reliable for detecting the presence of large PDs (more than 1000 pC) and could be included in diagnostic programs.

d. Zero sequence check on CVTs
The presence of PDs in capacitor layers has resulted in some failures.

These phenomena, which resulted initially in a slow variation of secondary voltage, were capable of leading to the explosion of the equipment.
To detect the existence of failed elements test devices are available to measure the zero sequence voltage across the secondary of a set of three CVTs [3.4-8].

e. Check by thermovision
This technique is now used systematically in large substations. Basically, it reveals overheating at the level of the connecting contacts. It might be possible to detect the oil level within sealed apparatus. It was also reported that PDs in CVTs were detected by means of thermovision [3.4-8].

f. Other oil checks
After several years of service it is suggested to perform some inspections of the internal insulation [3.4-11].
Even with leak-free terminations, ageing can occur and may result in the formation of water from the paper or of other substances that can have adverse chemical effects on the insulating oil. This, in turn, influence the breakdown strength or the thermal stability of the insulation in an unfavourable manner.
As all these phenomena can result in physical and chemical changes of the insulating oil, certain basic measurements are important. These are: breakdown strength, water content, neutralisation value, dielectric interfacial tension, dielectric loss angle, etc.

In the near future the checking of ITs should be systematically included in the diagnostic programs provided for high voltage substation equipment.
The application of computer-based techniques with advanced procedures for data acquisition and processing is in favour of on-line methods. However, the extensive application of these techniques depends on the availability of simple and reliable diagnostic sensors.
Internal pressure, gas detection and bellow position sensors could be already systematically mounted, at least on ITs for extra and ultra high voltage systems.
Considering that ITs are located near to other expensive components, such as power transformers and circuit-breakers, it would be convenient to provide for a local computerised system at which all the diagnostic signals of the surrounding equipment will be transmitted for a preliminary treatment.
As it is expected that on-line application of gas-in-oil analysis will be provided for power transformer, it should be easy to extend the use of gas analyser also to CTs and IVTs.
This solution should reduce considerably the total cost of the diagnostic system and advanced methods would be justified also for those components of relatively low cost.

As regards the future development in the IT field, the following aspects should be pre-eminent:

- the reduction of explosion risk on conventional ITs;
- the improvement of response time to fast transients;
- SF_6 instrument transformers.

It is evident that also new diagnostic tools especially conceived for these applications should be developed.

3.5. Circuit breakers

3.5.1. General

High voltage circuit breakers are used to switch ON/OFF different kinds of current loads. Moreover, in case of failures in the electrical network, they have to interrupt short-circuit currents.

Contact electrodes and nozzles are designed to extinguish the electric arc and interrupt the current. In OPEN condition they have to isolate the contact electrodes, until disconnectors are opened.

There are three different types of circuit breakers (CBs) existing:

- the Dead Tank breaker type (DTB), which contains all the active parts in a grounded metallic vessel, with bushings at each contact side;
- the Live Tank breaker type (LTB), which contains the current-interrupting elements in insulating tubes at HV potential.
- the metal-enclosed breaker type (GIB), which has all its elements integrated in a metallic enclosure.

of the insulator can endanger, under certain circumstances, persons and other substation equipment nearby.

Meticulous maintenance and diagnostic programs, should do much to prevent such breakdown and are accordingly strongly recommended. In this regard, it is of great importance to adhere to the manufacturer's operating and maintenance instructions.

3.4.4. Diagnostic methods

A diagnostic program should be preferably based on methods that do not interfere with operation, leaving off-line tests to periodic and special occasions [3.4-7, -8].
Table III reports the diagnostic techniques most widely used for ITs, together with their field of application, present status, effectiveness and specific references [3.4-8 to 3.4-11, 3.3-16].

COMMENTS

In order to facilitate the checking of the IT conditions, it may be convenient to provide for some monitoring systems of low cost, fully justified in the case of EHV and UHV systems.
The types of devices to be used depend on the sealing and oil compensation systems adopted. They may include pressure sensors, pressure valves, bellow position indicators, gas detection systems, and so on [3.4-8].
Visual checks should be performed for traces of oil originating from hair-line cracks on the porcelain and for connection discoloration indicating overheating of poor contact.

The following diagnostic methods are also applied according to the circumstances.

a. Loss angle measurements
Some types of current transformers are provided with a loss angle measurement probe, to which the

TABLE III A - Most important diagnostic techniques used for instrument transformers (paper-oil)

PROBLEMS	DIAGNOSTIC TECHNIQUES	SERVICE CONDITIONS OF THE EQUIPMENT	STATUS OF THE DIAGNOSTIC TECHNIQUE	PROVEN EFFECTIVENESS OF THE DIAGNOSTIC TECHNIQUE	APPLICATION TO			REFERENCE
					CTs	IVTs	CVTs	
MECHANICAL	1. Pressure inside enclosure	ON	B	M / H	X	X	X	3.4-8
	2. Pressure valve	ON	B	H	X	X	X	3.4-8
	3. Bellow position	ON	B	H	X	X	X	3.4-8
	4. Oil level indicator	ON	A	M / H	X	X	-	3.4-8
	5. Inspection for oil leakage	ON	A	M / H	X	X	X	
	6. Water content in the oil	ON	A	M / H	X	X	-	3.3-16
THERMAL	7. Inspection of contacts	ON	A	H	X	-	-	3.4-8
	8. Gas-in-oil chromatography	ON	B	M / H	X	X	-	3.3-16
	9. Thermovision checkings	ON	B	M / H	X	-	X	3.4-8
CHEMICAL	10. Oil testing (neutralization value, corrosive sulphur, oxidation, viscosity, etc.)	ON	A	M	X	X	-	3.4-11
DIELECTRIC	11. Gas-in-oil chromatography	ON	B	M / H	X	X	-	3.3-16
	12. H2 detection	ON	B	M / H	X	X	-	3.4-8
	13. Oil dielectric strength	ON	A	M	X	X	-	3.4-11
	14. Ultrasonic PD detection	ON	B	L / M	X	X	-	3.4-8
	15. PD measurement	OFF	A	M / H	X	X	X	3.4-9
	16. Zero sequence checking	OFF	B	M / H	-	-	X	3.4-8
	17. Loss angle measurement	OFF	A	L	X	-	X	3.4-9
	18. Error checking	OFF	A	L	X	X	X	

TABLE III B - Most important diagnostic techniques used for instrument transformers (SF6)

PROBLEMS	DIAGNOSTIC TECHNIQUES	SERVICE CONDITIONS OF THE EQUIPMENT	STATUS OF THE DIAGNOSTIC TECHNIQUE	PROVEN EFFECTIVENESS OF THE DIAGNOSTIC TECHNIQUE	REFERENCE
Loss of gas; partial liquefation of gas due to low temperature	Pressure monitoring, density monitoring	ON	A	H	
Water condensation on insulator surface due to low temperature	Check of dew point	ON/OFF-S *	A	H	
Prolonged PD causing SF6 decomposition	PD measurement Chemical detection	OFF ON/OFF-S *	A A	L / M H	
Dilution of SF6	Electric strength of the gas Sound velocity Heat conductivity	ON/OFF-S * ON/OFF-S * ON/OFF-S *	B A A	H / M H M / H	
Environmental pollution of secondary bushings	Electrical resistence	OFF-S	A	H	
	MAINLY FOR GIS				
Discharges	Light detection	ON	A	H	
PD from surface and internal epoxy imperfections	PD measurement	OFF-S	B	L / M	
Bouncing particles	PD measurement Acoustical detection	ON/OFF-S ON	B A	M H	

* During gas sampling, in many places the high voltage is switched off.

ITs are intended to transmit information signals to measuring instruments, meters and protective or control devices. The capacitive voltage dividers of CVTs are normally used also as coupling capacitors for high-frequency communication transmission systems.
CTs and IVTs transfer the quantity applied to one winding (primary winding) to another winding (secondary winding) electromagnetically coupled to the first one, while a CVT is essentially a capacitive voltage divider associated with an electromagnetic unit.

Oil-impregnated paper is the most frequently employed system used for the main insulation of CTs and IVTs.
In CTs where insulation thicknesses of the order of a few centimetres are provided, the electrical stress is equalised by adopting capacitive stress grading foils, similar to condenser bushings.
In capacitive voltage dividers of CVTs, the dielectric of the elements may be mixed (paper and resin film) or all resin film.
Mineral insulating oil is used as an impregnant for both dielectric and cooling purposes.

The active parts of ITs are normally mounted inside a porcelain enclosure in order to prevent moisture contamination of the internal insulation. This enclosure is externally shaped in order to obtain the creepage distance required for installation in polluted areas.

ITs are being manufactured also based on gas-insulation, mainly for GIS applications: some considerations on these particular components are presented in section 3.6.
CTs mounted on breakers or bushings are not considered as their dielectric requirements are relevant to the components of which they are a part.

3.4.2. Stresses acting on instrument transformers

The internal insulation of ITs is submitted to combinations of stresses of different nature whose effects are the deterioration of the mechanical and dielectric properties of paper or other insulating materials.

As regards DIELECTRIC stresses, the insulation strength lies in the IT capability to withstand service voltage, temporary overvoltages at power frequency, switching and lightning overvoltages [3.4-1].
Generally speaking, the design of internal insulation of an IT mainly depends on the service voltage and lightning overvoltages, while external insulation is more sensitive to switching overvoltages and to service voltage when operated in severe polluted conditions.
Ferro-resonance overvoltages may occur on IVTs and CVTs when their non-linear inductances and capacitances of the network form a resonant circuit. ITs may be damaged by over-heating and overvoltages stresses [3.4-2].

As far as the MECHANICAL stresses are concerned, severe conditions are meet during transportation and in occasion of seismic phenomena.

ELECTRODYNAMIC stresses due to failures on the system involve only CTs, and correct countermeasures are to be adopted to avoid insulation damages.

THERMAL stresses due to the heat produced inside the windings are more important for CTs than for other ITs.

3.4.3. Deterioration factors and failure mechanisms

The sensitivity of oil-impregnated cellulose to the combined influence of heat and voltage stress acquires special significance in high voltage CTs. Because of the absence of oil circulation, heat transfer takes place mainly by conduction and any local concentration of contaminants can only be relieved by slow diffusion processes.
The process is started either by local overheating or by permanent or transient enhancement of the field strength.
Both types of mechanisms, frequently coexisting, interact and evolve into each other.
In CTs for HV systems, a significant part of the total losses is represented by dielectric losses. Moisture and soluble polar contaminants are the most common causes of increased dielectric losses at elevated temperatures. Sometimes the contamination can be traced back to the manufacturing process, either to incorrect selection of materials or to inadequate processing or quality control.
High dissipation factors associated with wax-like residues of polymerised oil molecules have been observed in CTs known to have undergone extensive ionisation phenomena [3.4-3, -4].

A second deterioration process is associated with PDs. While occasionally the discharges may be initiated by lightning or switching overvoltages, more often they originate in more complex phenomena, generally related to local enhancements of the electric field. Discontinuities in the dielectric typically consist of gas filled voids within which discharges can initiate even at the rated field strength.
Four mechanisms are generally recognised by which gas bubbles are generated:

- poor impregnation of paper;
- thermal decomposition of cellulose;
- supersaturation of the oil with air or blanket gas;
- local breakdown of the impregnating oil by electrical discharges.

For CTs a source of field enhancement is from high frequency current pulses associated with switching operations [3.4-5]. This situation arises for instance when a disconnector switches off and on a substation bus system.
The response of CTs depends on the design of its field grading shields and in case of uneven distribution of the current field along the shields and their connecting leads, dangerous voltage stresses may arise at particular locations.
These phenomena acquire critical importance for electric systems at and above 400 kV.
With CVTs the deterioration of the dielectric of capacitive voltage dividers is mainly due to PDs initiated by overvoltages at the edges of the capacitor unit sections. The presence of moisture or negative pressure inside the porcelain insulators, as well as manufacturing defects are usually responsible for this phenomenon.

ITs rated at 72.5 kV and above, consisting of paper-oil insulation system, have been considered in a recent survey on failures carried out in the framework of CIGRE WG 23.07 activity [3.4-6].
Over a population of about 130,000 units, the failure rate was of the order of 0,6%, irrespective of the function of ITs.
With regard to the cause of failure, the large majority of the events has been attributed to inadequate design, bad quality control and lightning, but the opinion is that the information available is not totally reliable as the criteria followed in collecting data have been different in the various countries.
Among CTs and IVTs, about 30% of reported failures were classified as violent failures. These failures have as an extreme consequence, the destruction and explosion of the equipment. The resulting fragments

TABLE II - Most important diagnostic techniques used for power transformers

PROBLEMS	DIAGNOSTIC TECHNIQUES	SERVICE CONDITIONS OF THE EQUIPMENT	STATUS OF THE DIAGNOSTIC TECHNIQUE	PROVEN EFFECTIVENESS OF THE DIAGNOSTIC TECHNIQUE	REFERENCE
MECHANICAL	1. Excitation current	OFF-S	A	M	
	2. Low voltage impulse	OFF-S	A	L	3.3-2
	3. Frequency response analysis	OFF-S	B	L	3.3-3
	4. Leakage inductance measurement	OFF-S	A	M / H	3.3-4
	5. Fourier analysis	ON	C	?	3.3-5
THERMAL	GAS-IN-OIL ANALYSIS				
	6. Gas chromatography	ON	A	H	3.3-6, -7
	7. Equivalent Hydrogen method	ON	A	M	3.3-8
	OIL-PAPER DETERIORATION				
	8. Liquid chromatography-DP method	ON	B	L / M	3.3-9
	HOT-SPOT DETECTION				
	9. Invasive sensors	ON	B	L	3.3-10
DIELECTRIC	OIL ANALYSIS				
	10. Moisture, electric strength, resistivity, etc.	ON	A	M	3.3-11
	11. Turns ratio	OFF-S	A	L	
	PD MEASUREMENT				
	12. Ultrasonic method	ON	B	M / H	3.3-12,-13
	13. Electrical method	ON	B	M / H	3.3-14
	14. Loss angle measurement	OFF-S	A	M	3.3-15

Some of these tools are suitable for a possible on-line application, using advanced information systems: this would allow a better correlation between service stress levels and trends of diagnostic indicators, thus increasing the reliability of the diagnosis itself. Further improvements could be obtained by introducing more invasive-type sensors (e.g. temperature, dissolved gas, ultrasonic, etc.), but this is acceptable only if no additional weak points are created.

COMMENTS

Some simple tests for the detection and localisation of faults in transformers have been included in Table II to acknowledge their wide use over many years (methods 1 and 11). They have less relevance to DD but deserve to be included.

Methods 2, 3 and 4, although not strictly oriented to DD, are considered very important to evaluate the potential risks of dielectric failures consequent to mechanical movements. While for the leakage inductance measurement technique a certain degree of standardisation has been reached, the responses of the other two methods are not easily interpretable.

Method 5 is under development using Fourier Analysis techniques to increase the sensitivity of detecting small changes of impedance using on-line measurements of voltage and load current.

Analysis of the transformer oil to determine water content, electric strength, dielectric loss angle, volume resistivity, interfacial tension and acidity is the traditional and successful approach to the diagnosis of insulation deterioration (method 10).

Method 6, gas-in-oil analysis using gas chromatography, is now the most widely used diagnostic tool for transformers: much experience is available, together with an adequate level of standardisation [3.3-16, -17]. The limitations concern its poor capacity to detect fast-developing dielectric troubles; moreover, a rigid interpretation of the limit values of gas content, without a precise knowledge of the relevant source, may lead to erroneous evaluations.

The development of low-cost, simplified systems for gas analysis have also allowed an on-line application, particularly when based on the detection of hydrogen alone (method 7).

Method 8, based on the determination of the DP of insulating paper cellulose due to thermal deterioration, presents limitations very similar to the ones considered for method 6.

Hot-spot detection in windings can be performed using a variety of devices (method 9), mainly during laboratory testing; problems still to be resolved with these systems include reliability, life-expectancy and calibration techniques to verify the readings obtained.

Methods 12 and 13 are the most powerful tools for DD. PD measurements using ultrasonic systems can be used both for the on-line detection and localisation of the sources of internal discharges. Electrical PD measurements have been used on-line in a limited number of cases: more often the method has been applied as an off-line occasional check using a mobile power supply system. Method 14 is used as a simple technique to determine the general overall condition of transformer insulation and is especially sensitive to moisture and other conditions that can cause increased dielectric loss.

3.4. Instrument transformers

3.4.1. General

The electrical components considered in this section are:

. current transformers (CTs),
. inductive voltage transformers (IVTs),
. capacitive voltage transformers (CVTs),
. combined transformers.

Special attention is paid to instrument transformers (ITs) used on extra- and ultra-high voltage systems, even though many considerations are valid also for lower voltages ITs with similar insulation designs.

The surge winding test is being used to additionally determine the insulation strength conditions between the turns of form wound coils. A capacitor charged to the desired test voltage is usually discharged to the winding part to be tested, and a surge voltage oscillation with a frequency of approximately 100 kHz that decays with time is generated in this manner.

The recommended time intervals in which winding diagnosis checks should be performed is 3-5 years.

Since no single method is known that can provide adequate information on the actual condition of the machine windings and the operational reliability, a combination of several methods is recommended. The methods must be selected depending on the type of machine and its economic significance.

Winding monitoring methods will be more used, particularly with machines of high ratings, to evaluate the effects of the electrical stress and temperature. The objective is, in connection with the diagnostic methods, to detect possible changes in the winding system at an early stage.

Incorporating knowledge of these changes with information of the ageing characteristics of the particular system [3.2-4, -1], at the actual operating conditions, may in the future enable an estimation of the remaining insulation life.

3.3. Power Transformers

3.3.1. General

Power transformers are considered to include generator step-up transformers, inter-tie transmission transformers and DC converter transformers, together with such associated equipment as shunt, series and saturated reactors.

Power transformers are used to reduce the costs of power transmission by transforming the voltage at which current is transmitted. Shunt and series reactor components are similar to transformers, but need to absorb reactive power and to limit fault currents respectively.

The insulation generally used in power transformers is based on oil-impregnated paper in the form of Kraft paper as a turn-to-turn insulation, or as cotton- and/or Kraft-based transformer board used for winding spacers and as major insulation between windings and from windings to earth. Mineral insulating oil is used as an impregnant for dielectric and cooling purposes.

A new class of transformers is being manufactured based on gas-insulation with cooling through either gas circulation or by a two-phase cooling system using a low vapour pressure insulating fluid.

3.3.2. Stresses acting on power transformers

The major stresses acting on the windings of a power transformer, either individually or in conjunction, are:

- MECHANICAL stresses between conductors, leads and windings, due to overcurrents or fault currents, mainly caused by system short-circuits.

- THERMAL stresses, due to local overheating, overload currents and leakage flux when loading above nameplate rating, or due to malfunction of the cooling system.

- DIELECTRIC stresses, due to system overvoltages, transient impulse conditions or internal resonance within a winding.

A definitive analysis of the subject of diagnostic tests on power transformers must take into account that the majority of diagnostic indicators are sensitive to all three fundamental stresses acting on the transformer. Therefore, the general interpretation of the outputs of the diagnostic indicators, including the localisation of faults, can be problematic for a reliable evaluation of the risk of failure.

Moreover, the situation is more complicated due to the fact that dielectric failure is often the final stage consequent to the mechanical and/or thermal stresses, especially if moisture and/or oil deterioration have already placed the transformer in a hazardous condition. This fact determines the importance of assessing the service stresses (overvoltages, overcurrents, temperatures, etc.), jointly with a detailed knowledge of the design technology and materials.

The interpretation of the values and trends of the diagnostic tools must therefore be tailored on the different units in order to avoid unjustified alarms.

3.3.3. Deterioration factors and failure mechanisms

Deterioration of the paper-oil insulation is caused by thermal stresses and is accelerated by the presence of moisture. The insulation is unlikely to exhibit a lower dielectric strength after deterioration, but it is more subject to rupture under mechanical stress leading to dielectric failure as a consequence.

However, few transformers die due to old age; they usually fail as a consequence of:

(a) short circuit faults;
(b) local overheating due to circulating currents, current missharing or the effects of leakage flux;
(c) as a result of insulation failure under electric stress, perhaps as the final stage of a scenario involving (a) or (b) above.

Faults can be classified as developing in one of three time-scales:

(a) an immediate fault where electrical breakdown occurs within seconds of a short-circuit or lightning impulse surge;
(b) a local fault developing over days, weeks or months;
(c) a deterioration of HV insulation over a period of months or years.

Diagnostic techniques have been introduced mainly to detect the presence of small local faults, and to monitor their development over a period of weeks or months. They provide evidence to plan for further investigation and remedial work to take place on a planned basis, rather than as an emergency.

The use of diagnostic tests developed for this purpose was addressed as a Preferential Subject in CIGRE SC 12 Session for 1986 [3.3-1].

3.3.4. Diagnostic methods

Table II reports the diagnostic techniques most widely used for power transformers, together with their field of application, present status, effectiveness and specific references [3.3-2 to 3.3-15].

TABLE I - Most important diagnostic techniques used for stator windings of rotating machines

PROBLEMS	DIAGNOSTIC TECHNIQUES	SERVICE CONDITIONS OF THE EQUIPMENT	STATUS OF THE DIAGNOSTIC TECHNIQUE	PROVEN EFFECTIVENESS OF THE DIAGNOSTIC TECHNIQUE	REFERENCE
Detection of major external changes in condition, e.g. as a consequence of loose parts, corona discharges or inadmissibly high temperatures	Visual inspection	OFF-S	A	M / H	3.2-1, -3
Evaluation of the influence of moisture and contamination	Insulation resistance measurement winding to earth (usually after 1 min at 500-1000 V DC)	OFF-S	A	L / M	3.2-1, -3
Detection of local inhomogeneities in the stator winding, e.g. cracks in the insulation or surface conductivity (tracking)	Insulation leakage current measurement as a function of DC voltage to earth, usually up to 2.4*Un (Un=rated voltage of the machine)	OFF-S	A	M	3.2-1, -3
Detection of local weak-points in the insulation and verification of a minimum winding insulation level	Voltage test winding to earth at 1.5*Un for 1 min (usually AC, occasionally DC)	OFF-S	A	M	3.2-1, -3
Evaluation of dielectric losses, of the homogeneity of the insulation, as well as of the winding capacity	Loss angle measurement as a function of voltage to earth (usually up to 0.6 or 1.2*Un)	OFF-S	A	M / H	3.2-1, -3
Evaluation of PDs and their value in the solid insulation and especially outside, e.g. end winding or between conductor and core in the slots	PD measurement as a function of winding voltage to earth up to Un	OFF-S ON (monitoring)	A A / B	M M	3.2-1 to 3.2-4
Evaluation of the mechanical fixation of winding bars in laminated core	Check of stator slot wedging (mechanical and electrical methods)	OFF-S	A	M	3.2-1, -3
Evaluation of the insulation and voltage strength between turns of multi-turn coils	Voltage surge test with coil winding by means of oscillating voltage surge	OFF-S	A / B	M	3.2-1, -3

Legenda for Tables I to X:

SERVICE CONDITIONS OF THE EQUIPMENT:
OFF-S = equipment out of service at site
OFF-L = equipment out of service in laboratory
ON = equipment in service.

STATUS OF THE DIAGNOSTIC TECHNIQUE:
A = generally applied;
B = development stage;
C = research stage.

PROVEN EFFECTIVENESS OF THE DIAGNOSTIC TECHNIQUE:
H = high
M = medium
L = low
? = unknown

In some countries the high voltage test (either AC or DC) is still a controversial matter because of the risk of causing prior damage or weakening of the insulation. To overcome this, overvoltage testing at low frequency (e.g. 0.1 Hz) but at 1.6 to 1.8*U_n has been adopted. Alternative testing has also been proposed using a single application of a 50 Hz half-wave with an amplitude of 2.5*U_n.
In most countries the AC voltage test is the preferred method for finding localised weak points.
Because of the reduced capacity and size of the test apparatus, DC voltage testing at 1.6 to 1.7 times the AC test voltage level has gained acceptance as an alternative to power frequency testing.

The loss angle measurement is widespread and there are a lot of empirical results; in many cases it is already being used for quality control in winding manufacture. The results are affected by various machine related factors. Chiefly, the absolute values of the loss angle at a low applied voltage are assessed, as well as their variations as a function of the applied voltage. With a certain experience, an exact analysis of the results permits interesting conclusions, e.g. on the performance of the corona protection.

The PD measurement in connection with rotating electrical machines was not introduced on a broad basis world-wide until recent years. One reason is that the mica-based insulation is very resistant against discharges. The discharge pulses are usually filtered out with coupling capacitors on the high voltage side. With regard to the further processing of signals, uniformity is not yet recognisable. Typical of rotating machine winding systems is that, even with new windings at service stress, PDs will occur, so that it is not necessary for the measuring system to be very sensitive. Selective narrow-band measuring devices that measure the partial discharge energy in the frequency range of a few kHz to MHz are relatively widespread.

The stator slot wedging control has gained importance as a diagnostic method with machines of high rating. In addition to the striking method using a hammer and evaluation by means of human hearing that was used for years, new person-independent measuring systems were successfully introduced. With this system the slot wedge to be evaluated is excited mechanically by a pulse generator or a hammer, and the tightness is evaluated by energy or vibration measurement. As an alternative for machines with ripple spring wedging systems, the pre-stressing force is measured.

- commission new power apparatus, substations or transmission lines
- determine experimentally critical parameters of fast transients
- measure overvoltages for insulation co-ordination studies
- monitor power apparatus [3.1-18]

In general, transients are generated by switching operations during service, external transients (lightning) or by system faults. Monitoring of random transients call for an automatic recording system with pre-trigger possibilities. Current measuring channels have in general a higher dynamic range than voltage channels. The frequency band-width of the recording system should be designed up to 1 MHz, to cover lightning transients.

As sensors for voltage measurements, voltage transformers, special voltage dividers, capacitively-graded bushings or electric field sensors are used. For the current measurement, the sensor is a current transformer, a Rogowski coil or a shunt.

The transmission of the signal from the sensor to the recording instrument is done by coaxial cables or by an optical transmission system.

Nowadays, the recording instruments are transient recorders, especially built for this task with a large memory, with up to 15 channels, with 8, 10 or 12 bits, with a sampling rate of more than 1 MHz, and with the ability of on-line data reduction.

3.2. Rotating electrical machines

3.2.1. General

Rotating electrical machines represent important key components in both the power generation and industrial fields, in the former as generators with highest unit outputs of approximately 1600 MVA and rated terminal voltages up to approximately 30 kV, and in the latter as motors with power up to approximately 40 MW and rated voltages up to 15 kV.

From the dielectric point of view, the stator windings of these machines with a rated voltage above approximately 3 kV are of particular importance with respect to availability and operational reliability and, therefore, are especially considered here. Moreover, the stator winding is the part of the machine in which the full electrical power is generated.
The insulation of the field windings is mainly mechanically-stressed and the behaviour of the insulation itself is less important.

The stator winding insulation system separates the wire conductor (mostly copper) from the stator core (laminated from iron sheets). The insulated conductors are embedded in the stator slots in form of bars (generators) or as form wound coils (motors).

Up to approximately 1960, the solid stator insulations employed world-wide consisted of a combination of mica splittings, cellulose paper with shellac or asphalt compound as the binder, which were built up in the form of wide sheets, and were wrapped around the conductors. As there are many generators with this insulation still in operation [3.2-1], these systems maintain their importance.

Today mica paper/synthetic resin combinations (polyester, epoxy and silicone resins) are employed almost exclusively in the form of tapes, which are wrapped around the conductor and later impregnated, mostly at low pressure, and afterwards cured.

3.2.2. Stresses acting on rotating machines

During machine operation, the stator windings are mainly subjected to the following TEAM stresses:

. T (Thermal): up to approx. 140°C (thermal class F)
. E (Electrical): 1-4 kV/mm (lower figure for older machines)
. A (Ambient): dependent upon type of machine and operation, above all humidity and contamination
. M (Mechanical): dependent upon output and type of duty.

3.2.3. Deterioration factors and failure mechanisms

It is prominently the combination of T/E stresses which particularly affects the stator insulation and determines the deterioration processes. In larger units, mostly the action of E/M stresses has to be considered.

In the case of machines with form wound coils (motors), voltage transients coming from the power supply system must also be taken into consideration.

3.2.4. Diagnostic methods

Several international surveys have shown that the reliability of electrical rotating machines depends mainly on the behaviour of the stator winding. Therefore, systematic winding diagnostic methods were developed and used for electrical machines more than 30 years ago [3.2-2].

Today a number of standardised diagnostic methods are employed for the assessment of stator windings of electrical machines in many countries as shown in an analysis recently completed by CIGRE WG 11.07 [3.2-3]. Table I summarises the diagnostic techniques most widely used for rotating machines, together with their field of application, present status, effectiveness and specific references [3.2-1 to 3.2-4].

COMMENTS

The visual inspection is generally considered to be very important. It requires very good knowledge of the machine construction and presumes the corresponding experience. Detailed checklists are recommended as working aids.

Insulation resistance measurement is used very widely and performed at low DC voltage, the value after 1 minute of application of such voltage being of primary interest. The minimum insulation resistance values that are still admissible for service are dependent on the machine design (e.g. 500 kΩ for directly water-cooled windings, 100 MΩ for gas-cooled windings)

Determining the apparent insulation resistance, using a series of increasing DC test voltages, is also frequently used. The variation of apparent resistance gives an indication of the state of the winding. The test voltage is applied in steps, held for relatively long times so that the influence of polarisation effects of the insulation is theoretically proportional to the voltage applied. The current flowing in each phase tested is measured, as well as that in the other two phases. The use of DC voltage instead of AC results in different stress distributions in the windings compared with service conditions, and this needs to be taken into account when selecting the DC test voltage.

Before doing this, some consideration must be given to the advanced measuring techniques that are used for on-line applications. The measuring techniques developed in laboratories and also those off-line commonly applied at site are not dealt with.

3.1.2. **Measuring techniques**

3.1.2.1. Partial Discharge measuring techniques

It is generally agreed that the measuring techniques which detect PDs in an apparatus are effective tools for non-destructive testing or monitoring of materials or insulation systems. The PD measuring technique is well established in research and laboratory testing [3.1-1], but many problems exist if this technique is applied for on-line diagnosis on insulation systems in service. Therefore research efforts have concentrated on the improvement of on-line PD measurements [3.1-2 to 3.1-8]. The main research goals are to improve the sensitivity of PD detection under heavy noise signals and to develop expert systems.

PD measuring techniques use quantities from the partial discharge to detect the discharge itself. The PD technique can be classified according to the following measured quantities:

- current pulses (conventional PD measuring technique)
- electromagnetic waves
- acoustic waves
- chemical products

Conventional PD measuring devices [3.1-1] measure the current pulses at the earth side of the object. To get a certain sensitivity the return path for the PD has to be a low impedance, e.g. a coupling capacitance. This is normally applicable in the laboratory. The Standard for PD measurements [3.1-9] presents definitions, requirements for circuits and measuring devices, calibration methods, disturbances and test procedures. The main measuring quantity is the apparent charge of a PD pulse, additional quantities are its phase position, the repetition rate n, and integrated quantities such as the cumulative apparent charge q, the discharge power or the average current.

The apparent charge can basically be determined in the frequency domain or in the time domain. The commonly used PD instruments determine the charge in the frequency domain. Two types of basic circuits are in use, the narrow-band ($\Delta f \approx$ 10 kHz) or the wide-band ($\Delta f \approx 100 \div 500$ kHz) measuring instruments. Radio interference voltmeters are also used and are of the narrow-band type. The frequency response is determined by tuned band-pass filters having a variable response frequency and a narrow band-width. The instrument does not directly indicate the apparent charge, but gives a general indication of the PD magnitude. The peak value may increase or decrease with the repetition rate n, because of superposition pulses.

Newly developed PD instruments extend the frequency range to more than 1 MHz. In this case the integration of the current pulse to get the apparent charge is done in the time domain after the amplification of the current pulse [3.1-3].

For the measurement of the PD current pulse, an impedance or a current transformer working in the relevant frequency range is used. For on-line use, the current transformer principle has certain advantages.

The principles when measuring the electromagnetic wave of the PD use either the conducted [3.1-5] or the radiated [3.1-3] waves. The conducted electromagnetic wave can only be used for equipment with travelling wave behaviour, like GIS or cables. The measuring frequencies are some 10 MHz to some 100 MHz. Both principles have the ability to locate the PD.

For the conducted and radiated principle, an electric field sensor, e.g. a flat sensor in the GIS-housing or in a transformer tank is used as primary sensor [3.1-5].

The acoustic wave of the discharge is measured with accelerometers or acoustic emission sensors [3.1-4] at the earth side of the apparatus. The highest sensitivity for typical defects in GIS is in the ultrasonic range (25 ÷ 100 kHz).

The chemical methods of PD detection measures the amount of different gases in oil (e.g. in transformers) or in gases (e.g. in GIS). Different sensors for on-line applications have been developed.

Because for on-line monitoring in service the absolute value of the apparent charge of a PD is of less interest, further principles giving a qualitative information on the increase or decrease of PD activity can be applied.

Noise reduction in PD measurements

All the mentioned measuring principles can be applied for on-line monitoring, but the noise level in PD field measurements has to be reduced for a successful application. The following principles are used or under development:

<u>Bridge method</u>
This well-known conventional measuring technique suppresses the external common mode noise in a balanced bridge. An additional PD-free reference object is needed. Therefore, it can only be applied for off-line measurements [3.1-10, -11].

<u>Pulse discrimination method</u>
External interferences are recognised by e.g. pulse polarity and eliminated by electronic circuits [3.1-12].

<u>Window method</u>
A measuring window, synchronised with the AC voltage, adjustable in time duration and phase angle is used. This method can especially eliminate interferences fixed to the phase angle of the AC voltage. An improvement of this method is the electronic interruption of the PD measurement for a short time period, if the interference is recognised, e.g. with a separate pick up antenna [3.1-13].

<u>Mathematical methods</u>
An effective reduction of interferences in PD measurements can be achieved by the application of mathematical methods connected with PD data processing. Such methods are the averaging procedure [3.1-14], the cross correlation technique [3.1-15] or the application of digital filters [3.1-7]. In addition expert systems will help to differentiate between noise signals and PD signals by using different algorithms like phase angle analysis of apparent charge and PD energy, or statistical analysis of PD data [3.1-16, -17].

3.1.2.2. Recording systems for field measurements of HV transients

Field measurements of transients in HV power systems are conducted in order to:

- validate analog or digital models of power systems

- the stressed volume of an insulating system in a power apparatus is much larger than that of a test specimen so that the volume effect has to be considered.

Nevertheless, the experience gained with material samples is a general base for the evaluation of equipment, since the sensitive criteria which have been found for materials are in most cases also important criteria for the whole insulating systems.

Material investigations must be continued with the goal of obtaining more basic knowledge about deterioration mechanisms and effects, in order to be finally able to reduce the large gap between intrinsic strength and permissible service stress.

3. INSULATION DETERIORATION OF ELECTRICAL EQUIPMENT

3.1. General

3.1.1. Dielectric Diagnosis of electrical equipment

In the present treatment it is assumed that the electrical equipment complies with the required performance, since the type tests guarantee the correctness of the design, the routine and acceptance tests guarantee that each individual piece of equipment corresponds to the prototype and the commissioning tests guarantee that the degradation due to the installation did not exceed prescribed limits. This is not always true, and failures in service due to this cause, even catastrophic ones, have been experienced by almost all Utilities throughout the years. One of the aims of DD is also to detect this inconvenience.
Moreover, any equipment is subjected in its service life to combined stresses (electrical, mechanical, thermal, environmental) that may cause its premature failure in short times (e.g. lightning strokes or short-circuits) or in longer periods (e.g. overloads, service in severe conditions, etc.).

The purpose of DD is to check the conditions of the equipment in service, in order to detect defects, anomalies and malfunctioning which may eventually lead to a failure. In this sense diagnosis is the ultimate and perhaps most decisive action towards the achievement of reliability of equipment and installations.

The appearance of critical conditions is generally related to changes in particular physical quantities, the so-called diagnostic indicators; periodic or continuous monitoring of these quantities represent, therefore, an important way to follow in time the conditions of the components of the electrical system.

Figure 1 shows the flow-chart of the diagnostic procedure adopted by several Utilities. As can be seen, off-line diagnostic checks are used occasionally or at periodic intervals, generally in correspondence of maintenance operations. The checks can be conveniently performed by means of test and measuring devices installed on board mobile units, which may be also used for a number of other on-site tests and measurements. When being checked, the component or apparatus under consideration must be disconnected from the network.

This approach is suitable for small electrical components in large numbers (for which a dedicated diagnostic system would not be economically justified) and also for large apparatuses as first level of diagnostic control.

On the contrary, on-line diagnosis is based generally on a continuous monitoring of the equipment under control and requires the use of instrumentation permanently installed in the site and properly connected to the apparatus, the latter being normally connected to the network.
This type of diagnosis is best suited for critical and/or large electrical apparatuses, for which a dedicated diagnostic system is economically justified.

Research activities in the field of DD for complete components have included in the last years the understanding and modelling of the physical mechanisms of deterioration and failure, the study and selection of suitable diagnostic indicators, the design, construction and testing, both in laboratory and in the field, of prototypes of diagnostic systems (hardware and software).

In the following sections the most important equipment present in electrical installations are reviewed dealing briefly with the major stresses to which they are subjected, the main deterioration factors and failure mechanisms experienced so far, and the diagnostic techniques, either off-line or on-line, that have been developed in order to examine the conditions of the components and foresee their behaviour in time.

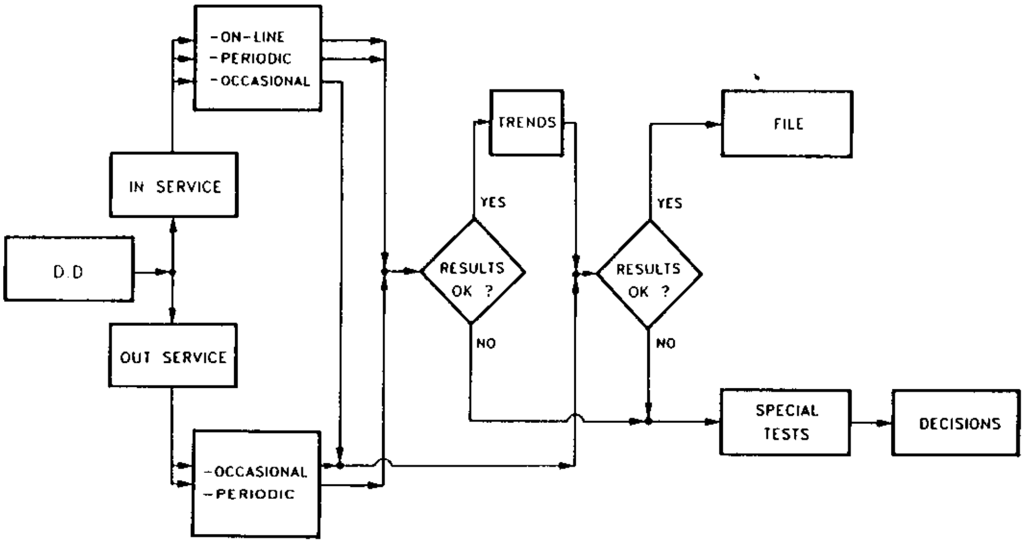

Figure 1 - Flow-chart of a possible diagnostic procedure for electrical equipment.

bility of breakdown in many gas gaps can be considered statistically independent of the previous voltage applications.

The main interest in the following is focused on compressed gas-insulation. Uniform field breakdown data for the technically important gases, i.e. nitrogen, air, SF_6, hydrogen, CO_2 and helium were collected by CIGRE WG 15.03 "Insulating Gases" and published in [2-13]. These "Paschen curves" show a steady increase of breakdown voltage for increasing values of the product of the gas density times the electrode distance for HV compressed gas-insulations.

The rated dielectric strength of compressed gas-insulated equipment requires a gas density higher than the minimum design value. An excessive loss of gas will therefore degrade the insulation withstand ability. For that reason the gas pressure and/or density are generally monitored in such equipment. Furthermore, a compressed gas might get diluted by another gas leading to degraded insulation ability. To check the dielectric strength of compressed gases (mainly SF_6) a suitable test procedure was proposed by CIGRE WG 15.03 [2-14].

Rough electrode surfaces, edges or needles cause local electrical field enhancements which will decrease the onset voltage of discharges. At moderate gas pressures and moderate rates of voltage rise (e.g. standard switching impulse voltage), this may lead to corona stabilisation (PDs), or it will lead to a disruptive discharge. For several applications high voltage commissioning tests are therefore complemented by PD measurements.

In typical designs, such as GIS with SF_6 insulation, PDs must not occur under normal operating conditions. The reason is that any discharge will decompose a small amount of the SF_6 leading to secondary decomposition products, e.g. metal fluoride powder. The decomposition of SF_6 also leads to typical gaseous byproducts which can be detected chemically in gas samples. If the discharges are not noticed, in the long run there will be enough powder in the gas gap that a complete failure can occur.

Foreign particles can cause severe deterioration in insulations with high electric fields. Under the influence of an electric field the particle becomes charged, stands up and is lifted by the electrostatic force against the force of gravity. Under AC voltages the polarity and the force in the field will reverse after each half cycle and the particle will bounce erratically.

Conditioning will be achieved if the particle can move into a harmless low field region where it will remain inactive. Under DC voltages the particle will cross over to the opposite electrode, reverse charge polarity and cross back to repeat the cycle. As the particle approaches an electrode, it discharges at the close tip leading to a sudden change of the voltage at the other particle tip; this can cause breakdown without corona stabilisation. Impulse voltages are especially dangerous if they are superimposed on AC or DC voltages and particles are close to highly stressed electrodes just at the moments of the impulses. Bouncing particles on their touch of the electrodes cause acoustic waves as well as PDs. Acoustic detectors are mainly effective in the ultrasound region, PDs have an erratic pattern.

Charges from PDs in gas gaps move along electric field lines; these charges will accumulate on insulator surfaces which cross the field lines. If the charge density exceeds a certain value, a surface discharge will occur. Similar effects can be caused by conducting particles adhering to an insulator surface. Such surface discharges can be detected mainly by their light emission.

Low temperatures may cause liquefaction of a part of the insulating gas. The remaining gas will then have a lower density than the original filling, resulting in degraded insulation ability as mentioned above. In gas mixtures liquefaction of the components can occur at substantially different temperatures.

In compressed gas-insulated equipment, a drop in temperature may cause water condensation on the insulator surface if the humidity of the gas is excessively high, i.e. if the dew point is too high. The water will lead to flashover on highly stressed surfaces. The dew point can be checked by gas sampling.

In SF6 insulated switches, thin layers of powdered decomposition products can develop on the surfaces. If humidity is added (e.g. normal air moisture during maintenance periods), acidic products will result which in turn can significantly impair the electrical surface resistance of some common materials (e.g. silica-filled epoxy insulators).

The energy of a disruptive discharge during testing of gas-insulated equipment may alter the gas gaps and/or insulator surfaces:

- the electrode surface can get smoother (spark conditioning) or it can get damaged by a small crater
- a foreign particle can get burned away (spark conditioning)
- a small amount of gas will be decomposed; many gases with high insulating ability will release free carbon and thereby degrade the dielectric strength
- traces from gas and/or solid decomposition products developed during test flashover may be deposited on insulator surfaces [2-15]. As a consequence, the surface resistance may be reduced resulting also in a decrease of the flashover voltage.
  Conditioning of the degraded surface is possible by applying low energy flashovers [2-16].

The insulating ability of open air gaps is variable according to changing climatic conditions, but in general there will be no pronounced degradation effect. On the surfaces of the insulators in open air, however, significant degradation effects result from pollution in combination with climatic conditions (including precipitation). These effects are frequently decisive for the size of equipment. Generally, long service experience is available for this degradation parameter.

2.3. Summary considerations

Concerning the deterioration of materials, many influencing factors have to be considered. Intensive research and actual field experience have produced many results, and it has improved scientific knowledge about deterioration mechanisms and endurance phenomena. However, so far only in a few cases has it been possible to establish quantitative relationships between stresses and life or other important properties. The transfer of such results, which were obtained on material samples, to real insulation systems, however, should be performed with caution for the following reasons:

- experiments in laboratories are done with samples produced under pharmaceutical conditions, while an industrial fabrication on an economic scale leads necessarily to a higher amount of impurities and inhomogeneities;

formative to establish the deterioration laws of the insulation not on samples, but directly on capacitors.

Thermal deterioration

Liquids - In the case of hydrocarbon oils, the deterioration is identified mainly as an oxidation process, highly temperature dependent. As a proof of this, oils maintained at 160°C under vacuum for one year showed no change in their properties [2-9].

Consequently oxidation of oils has been the subject for a large amount of research. Until the sixties, oxidation stability was the most important criterion to purchase an oil and acidity, sludge, interfacial tension, dielectric losses and dielectric breakdown the main degrading criteria in the laboratory and in service. It was also felt that acid products would have a deleterious effect on the solid insulation and that sludge deposits would impair the cooling process.

Nowadays the improvement in the oxidation stability of modern oils, sometimes owing to oxidation inhibitors, the increased protection against oxygen in equipment, the increased consideration to PD deterioration have reduced the consideration given to oxidation effects. It must nevertheless be borne in mind that oil oxidation gives rise to peroxides which are very active and may affect the surrounding solid insulation well before acid and sludge become noticeable. Accordingly, the basic tests mentioned above remain important.

Compared to hydrocarbon oils, the other presently used liquids usually exhibit by far better oxidation stability. Their actual service temperature limits are related to other considerations, such as direct thermal, decomposition or environmental effects.

Liquid-impregnated insulation - Thermal deterioration of paper-oil systems may be considered as exemplary when looking at all the information gathered on the specific materials used. In a very condensed way, the paper-oil deterioration can be described as follows: the cellulose chain, composed of a large number of elementary glucose rings, is progressively broken into smaller chains. The degree of polymerisation (DP) initially equal to around 1300 comes to around 150 at the end of paper life, i.e. when its mechanical strength has been reduced to nearly zero. A correlation was established between DP and the mechanical strength of Kraft paper. It is thus possible to appreciate the remaining life, not by the mechanical criterion but by the DP, easy to measure on a small paper sample, even when it has become very brittle. And, what is more, the DP at time t, D, and the initial DP at time 0, D_o, can be combined to introduce a "Deterioration Factor" ϵ

$$\epsilon = 1000 \quad (1/D - 1/D_o)$$

which is, in other terms the number of broken bonds to decrease DP from D_o down to D. ϵ may be used as a criterion describing the remaining life [2-10].

At each temperature, $\epsilon - \epsilon_o = kt$ as may be checked experimentally. k is thus the rate of deterioration, which obeys the Arrhenius law.

The thermal deterioration of the paper is accompanied by the formation of gases, such as CO and CO_2, which may be either dissolved in oil, or evolved under the shape of a bubble, depending on the gas amount, the temperature, the electrical field and the gassing properties of oil. As mentioned in the previously, if bubbles are present, PDs will be produced and deterioration under the effect of combined stresses will finally take place [2-11].

A new question not answered so far is the following: is the CO and CO_2 formed the result of oil- or paper-deterioration? And if the answer is "paper", can the temperature of the paper be considered as the cause of defect, or is it a normal deterioration process? That is the reason for the development of new techniques, proposed several years ago. These are based on HPLC (High Performance Liquid Chromatography) which permits the detection of specific components of aged papers. It is quite sure that these techniques will become excellent complementary methods to gas chromatography within the years to come.

The knowledge about the thermal deterioration of other impregnated systems has not received until now the same attention as paper-oil for two reasons: shorter terms of service, better resistance to thermal deterioration. In those cases usually the effect of electric stress is of prime importance, and temperature is considered only as a factor of acceleration of those effects.

Environmental deterioration

The main factors to be considered in this section are: humidity, particles, and compatibility. The last two factors are not usually listed, in most classifications, in the environmental group, but are of such importance in this context that they have to be taken into consideration [2-12].

Humidity drastically affects the properties of all liquid dielectrics, as may be observed by the decrease of the breakdown voltage. This decrease can be related to the combined effects of water and particles. The breakdown voltage was in the past and still is, but to a lesser extent, a most important criterion of the state of an equipment. As mentioned in the previous clause, humidity is formed also by the deterioration of the paper. For some liquids and some solids, it is also a deterioration factor by a mechanism of hydrolysis: esters and polyesters are known to be of this type. It is true also, to a considerable extent, for paper, although this is not always recognised for its actual value. Important is also the combined effect of temperature and humidity on paper deterioration. The speed of deterioration of a Kraft paper is 25 times higher at 130°C when the relative humidity of the paper is 4% instead of 0.2% at the beginning of ageing.

Particles may be the result of the deterioration of the solid components of an insulation as well as a factor coming from the environment of the equipment. Their combination with humidity is of major influence on the electric behaviour.

Lack of compatibility: if paper and oil combination is an excellent association, this is not the case for all solid-liquid combinations. Lack of compatibility is often a reason for premature failures. This may be the result of chemical interaction, which leads to accelerated deterioration of one of the components, or both of them. It may also be a physical effect, when there is a mismatch in the permittivities, resistivities or lack of wettability of the components.

2.2.3. Insulating gases

Gas gaps are shaped by electrodes, and the surface of these electrodes can play a major role on the insulating ability of such gaps. However, during typical test voltage applications, the insulation of a gas gap can be considered, in many cases, as self restoring, i.e. it recovers its full insulating ability after a disruptive discharge. Furthermore, the probaby effecting a surface deterioration in form of the build up of deposits or erosion. Pure weathering leads to aereal deterioration: as a diagnostic test to check the resistivity of a material, the weather-O-meter test seems very useful. Under electrical stress, surface erosion will be mainly dominated by electrical discharges which may develop temperatures high enough to decompose the material.

The very important hydrophobic properties of outdoor polymers can easily be checked by measuring the contact angle with water, and for the evaluation of the tracking and erosion resistivity, methods and devices are available like the inclined plane test, the salt fog test and the carousel test [2-7]. The surface hydrophobicity is a dynamic property which may be lost temporarily after surface discharges. Physical procedures like secondary ion mass spectroscopy or electron spectroscopy for chemical analyses may be useful tools to investigate this phenomenon.

In the bulk, water attacks the main dielectric properties. Water absorption follows the diffusion laws, and it has been observed that up to 3% of the volume of a polymer can be occupied by water under saturated conditions. Both the breakdown strength and the dielectric loss, but also the conductivity and the permittivity, are properties of polymers which exhibit remarkable deterioration after wetting [2-8]. In filled or composite materials, interfacial polarisation is the main effect. On the other hand, hydrolytic decomposition of polymers has been observed, especially when the diffusion process was accelerated by the application of elevated temperatures. Both the dielectric loss and the permittivity are sensitive quantities for diagnostic testing.

The dominating problem of combined stresses for cables, the electrochemical treeing, will be dealt with in the relevant section.

2.2.2. Liquids and liquid-impregnated insulations

This section deals with the subjects relevant to liquids and liquid-impregnated insulations. As a matter of fact, there are only very few cases where the insulation is made only of liquids; the vast majority of equipment is insulated with a combination of solids and liquids. The characteristics of the liquids are of prime importance and much has been studied about their behaviour and their deterioration. Generally speaking, in the following subsections liquids will be dealt prior to the liquid-impregnated insulations.

In the range of liquids for HV equipment, hydrocarbon oil has been and still is the most widely used. It was employed in many types of equipment: capacitors, bushings, cables, switchgear, instrument and power transformers. Practically only this last group of electrical components is still using oil as the insulating and cooling liquid.
Due to the banning of Polychlorobiphenyles (PCB), nearly everywhere in the world, many replacement liquids have been proposed and are used at present. In most cases they exhibit properties which in some respects are better than the corresponding ones for mineral oils.

With the words "impregnated systems" various types of insulations are covered where the solid may be paper like: cellulose papers or non-woven plastic materials, or alternatively film layers. The well known paper-oil system is certainly the best example of a liquid-impregnated system, and its use for approximately eighty years enables us to present considerable background. Ranking second in the past was certainly the paper-PCB system, no longer accepted in new equipment, but still present in transformers as well as in capacitors.

Again, the banning of PCB has resulted either in the association of paper with other liquids in some small and medium range transformers (esters, silicone, fluorocarbons, etc.), or in the association of films (mainly polypropylene) with a long list of liquids of very different chemical types.

Electrical deterioration

Liquids - There is presently a consensus on the following fact: in normal, dry conditions, liquids do not degrade due to the electric stress itself.
But if PDs exist for any reason, like local stresses or gas bubbles, then the following facts have to be taken into consideration. The PD inception voltage for most liquids ranges from 25 kV to >80 kV in the test cll to be standardised, capacitor liquids being at the upper end of the range. This seems to be related more to the chemistry of the liquid (in oils to the presence of specific additives) than to its conditioning.

The evolution of the situation after the appearance of the first discharges is governed by the "gassing" properties of the liquid. In other words this property describes the way a bubble of gas trapped in the liquid and subjected to electric stress will behave: it will expand if the liquid is "gas evolving", it will shrink if the liquid is "gas absorbing". This property is stress- and temperature-dependent. At high stresses and temperatures, a deterioration of the gassing properties is always observed.

Liquid-impregnated insulation - In a similar way, a dry, well-impregnated insulation is not reported to degrade under the application of an electric stress only. But deterioration mechanisms may result from PDs, tracking, electrochemical deterioration, and often at the solid-liquid interface. Undoubtedly, the existence of water and/or air/gas bubbles in the insulation is the cause of such phenomena. As far as PDs are concerned, when the process has started, its evolution will strongly depend upon the characteristics of liquids. The effect of stress on paper oil insulation is described in [2-4] and gives the relationship between gases evolved from both paper and oil and the PD energy. This is very useful for the diagnosis of the deterioration by the gas in oil analysis using gas chromatography as will be explained later.

The other field-induced degrading processes vary according to the types of insulation. For example, composites that have components with high intrinsic conduction and/or high dielectric losses can trigger a thermal breakdown.

The case of capacitor insulation is a good example for a situation where ecological laws have led to a noticeable improvement in the quality and performance of insulation. The new association of all film solid insulation (normally polypropylene) with some highly aromatic liquids such as PXE (phenyl-xhylene-etha) MIPB (mono-iso-propyl-biphenyle) or more recently developed and manufactured M/DBT (mono/di-benzyl-toluene) has resulted in a considerable increase in the working stress up to 60 kV/mm compared to 18 kV/mm in the paper-PCB case. This is due at the same time to a reduction of dielectric losses of both solid and liquid, in the swelling of the film by the liquid, and in the improved breakdown voltage of the polypropylene compared to paper and of the new types of liquids compared to PCBs. But the deterioration laws of the new impregnated systems have not been systematically studied as such, for it is generally found more in-

Electrical deterioration

It is commonly accepted that electrical deterioration in solid dielectrics is normally connected to the existence of partial discharges (PDs). PDs may exist in voids which are present in the solid according to an imperfect manufacturing process, or which have been produced by treeing in the solid. In the latter case, also the pre-treeing effects are to be considered as deterioration phenomena [2-1, -2]. Normally, inorganic materials are much less sensitive to PDs than organics.

In gas filled voids, PDs bridge the gap. Ions and electrons are generated by the gas discharge, and they attack the walls of the void with the consequence of erosion and finally of tree inception from the eroded walls. Such trees may bridge the whole dielectric effecting a total breakdown. The PDs which are the cause of deterioration appear as steep-fronted current or charge pulses which are detectable at the terminals of the test set-up. Only recently it became clear that PDs may occur in a pulsed or "pulseless" form; the latter expression is incorrect in so far as detailed investigation showed that "pulseless" PDs consist of pulsed events with very low peaks and high repetition rate, and, therefore, a better name of these PDs is "microdischarges". It was also demonstrated that the mode of PDs may change in the same void from pulsed to microdischarges which is believed to be caused by changes of the gas pressure, the gas composition and/or the surface resistance of the walls. Experiments also showed that microdischarges lead to deterioration effects.

The measurement of the charge or current impulses of internal PDs has been a diagnostic tool for many years; actually, PD detection and evaluation is a main dielectric diagnostic procedure.

The PD resistivity of solids is an important property, and many efforts have been made to develop relevant test procedures and test samples to be used as diagnostic tools for the evaluation of materials [2-3]. The life time reduction caused by internal PDs of the deterioration of other important properties, e.g. the breakdown strength, has been clearly demonstrated. However, for several reasons, a clear relationship between PD quantities and the rate of deterioration is still missing so that intensive research must go on. A good approach might be to evaluate the degrading PD quantity not according to the apparent charge but by estimating the PD energy [2-4], or, still better the energy density. Nevertheless, certain PD limits have been introduced for different apparatus according to long term field experience.

Whichever quantity may influence the deterioration process, the final effect is a reduction of electrical strength with time. The voltage-time curve is an inclined line with a negative gradient. Over a long period it has been believed that the inverse power law describes in a satisfactory way the correlation between stress (field-strength) E and time t:

$$t \cdot E^n = k$$

where k is a constant, and n is the voltage endurance coefficient. When plotting the inverse power law in a logE - logt scale the well known inclined straight line with the slope -1/n is obtained. The weak part of the inverse power law is the fact that it predicts a limited life even for very low stresses. If PDs are believed to be the only degrading effect in solids, life must be infinite for stresses lower than a PD onset stress Eo. Assuming such a threshold stress Eo, the life time law may better be expressed in the following empirical expression [2-5]:

$$\log [t (E - E_o)] = k_1 - k_2 (E - E_o)$$

where k_1 and k_2 are constants, and t is the life at stress E. The existence of a threshold is backed by many investigations and has been found true for instance for epoxy bonded mica, polyethylene, epoxy resin and some more materials.

Life time laws for multi-stress conditions are dealt with in [2-6].

Thermal deterioration

The main effect of thermal deterioration is the acceleration of physical/chemical processes by elevated temperatures. Normally, all chemical reactions accelerate with increased temperature, and this holds true for oxidation as well as for polymerisation and depolymerisation processes. Of course, the absolute upper temperature limit must be lower than the decomposition temperature.

Many important electric and dielectric properties are strongly influenced by elevated temperature. Due to an increasing ion mobility with rising temperature, both the conductivity and the dielectric loss increase. Especially the response of dielectric loss to temperature changes is an important, simple and reliable tool for DD. But also the breakdown strength depends on the temperature: in most cases it decreases with increasing temperature.

The combined application of electrical and thermal stresses may result in a thermal instability, the thermal breakdown. The increasing dielectric losses under rising temperatures produce more heat with the effect of even more increase in loss and so on, and in the case that the heat production exceeds the heat transfer to the surrounding, the thermal instability is unavoidable. A stable value of the loss angle indicates thermal stability.

Mechanical deterioration

Concerning mechanical stresses, problems may arise with creepage (for instance PTFE), with crack propagation in the case of brittle materials (for instance porcelain), or material fatigue when the solid material is subjected to an oscillating bending stress. The mechanical strength is normally reduced by the application of elevated temperature.

Combined stresses may cause severe deterioration in the case of simultaneously existing high mechanical and electrical stresses; by excessive mechanical stress which may be caused by temperature gradients in the interface area of materials with different thermal characteristics, microcracks in the material can be produced which are the place of PDs. The same phenomenon can happen close to electrodes when the mechanical stress is higher than the adhesive power of the insulating material, and, consequently, a void or crack appears in the vicinity of the electrode.

In the case of fibre reinforcement, the time dependency of mechanical failing loads must be considered. Due to the failure mechanism, the permissible permanent service load can be remarkably lower than the short time failing load. In the case of fibre glass-reinforced epoxy rods under low tensile stress, brittle fractures have been observed which most probably are caused by acids produced by stress corrosion in the glass fibres.

Environmental deterioration

The environment influences insulating materials on their surface and in the bulk mainly by oxygen, humidity, contamination, radiation and temperature changes. Concerning surface properties, contamination, radiation and oxygen play the dominating role

2. DETERIORATION PARAMETERS FOR INSULATING MATERIALS AND DIAGNOSTIC CRITERIA APPLICABLE ALSO TO EQUIPMENT

2.1. General

In the present treatment it is assumed that the insulating materials do not present fundamental manufacturing defects, considered avoided by proper manufacturing process, or detected by the tests performed before manufacturing the equipment and by the tests on the equipment. Therefore, at the beginning of their life, the insulating materials do comply with the required performance. During life, ageing and deterioration may occur due to the effects of various stresses, which normally result in a deterioration of physical/chemical properties.
Generally, for a given material, a three-dimensional construction can be built to describe deterioration with the following co-ordinates:

- TIME: this is the parameter which runs inexorably and causes ageing.

- STRESS: this is the cause that makes materials suffer some modifications in their physical/chemical nature, resulting in deterioration.

- PROPERTY: the deterioration, depending upon its type, affects more or less all the properties of the material. If one property is of prime interest,
  - either because it is a fundamental property of the material in the equipment,
  - or because it is a useful tool to identify the deterioration,

  this property can be selected as a deterioration criterion.

Usually the three-dimensional construction is decomposed into two plane figures: the first is property versus time at various constant stresses, the second is stress versus time for a given failure criterion. A well known example is the so called V/t curve for gases, another one is simply the Arrhenius plot for solids.

This approach is valid for each type or family of materials, but for various reasons (specificity of a material, habits from the past, etc.), it is presented separately for each of them. Before doing so in sections 2.2.1. to 2.2.3., some general features which are common to all materials need to be introduced.

Stressing factors

It is necessary to deal with electrical, thermal, mechanical and environmental stresses. Depending on the type of equipment, one of them may be predominant.

- ELECTRICAL stress: even at the same rated voltage, the actual electric stresses are very different from equipment to equipment and are in decreasing order: capacitors, cables, bushings, transformers, rotating machines.
This fact is mostly related to the ability of the insulation to withstand the electric stress during its life.

- THERMAL stress: during operation, elevated temperatures may be reached, due to dielectric losses, ohmic losses in conductors, or by heat absorption from the surroundings.

- MECHANICAL stress: there may be either permanent stresses (rotating machines, circuit breakers), or they may appear occasionally, for instance as the result of short-circuits or thermal creepage.

- ENVIRONMENTAL stress: environmental factors include pollution, radiation, humidity, particles, etc., and may be either a deterioration factor in itself or a "revealing" factor which has the property of increasing the effects of deterioration.

- COMBINED stress: indeed, in equipment normally some of the stressing factors mentioned above are present simultaneously (multi-stress conditions). It depends on the type of material and equipment whether or not the interaction of stresses taking place will result either in an acceleration or in a slowing of deterioration.

Properties - Deterioration Criteria

This is a fast moving subject for materials, insulation and equipment. The trend is that the criteria are either tailored to the material or to the equipment. A rough classification may be introduced as follows:

- DIRECT criteria: these are directly connected with the properties required in service: e.g. electrical strength, flexural strength, etc.
If the values of the property decrease below an acceptable limit, the material fails. Some tests to verify these criteria are destructive, and, therefore, are applicable to material samples only.

- INDIRECT criteria: such criteria have a relationship with properties required in service: e.g. loss angle, insulation resistance, partial discharge, water content, non-ohmic behaviour, etc.
Changes of these indirect variables may indicate a deterioration of important properties. Since the tests to verify them are usually non destructive, indirect criteria are of vital importance for the diagnosis of equipment conditions.

- OTHER TYPES of criteria: these are more specific to one kind of material or to one type of equipment. They are mostly of physical or chemical nature, have demonstrated relationship with the deterioration itself, and, usually, a correlation between properties useful in service and these criteria has been established, either theoretically or statistically.

New criteria may be developed in the future from the application of physical/chemical tools like structural, morphological and cristallinity investigations or spectroscopical procedures, etc., which have not been in extended use so far for DD.

2.2. Insulating materials

2.2.1. Solid dielectrics

Solids are parts of the insulation systems of all equipment. For HV applications, both indoor and outdoor, we have to deal with inorganic materials like the conventional porcelain and glass (for insulators), and with organic dielectrics, the main groups being cast resins, thermoplasts and elastomers (for spacers posts, cables, etc.). In addition, we have to look to composite materials like fibre-reinforced plastics, filled cast resins, etc., due to their increasing use (insulators, terminations).

As it is impossible to deal in detail with all the various materials in different equipment, only some basic aspects of deterioration of solids which are valid for most materials in their main applications can be dealt with in the following sections.

1. INTRODUCTION

First of all, in order to be consistent throughout the paper with the language used, it is necessary to premise the definitions of a number of terms that will be used with specific meanings that might be different from the general sense.

DIELECTRIC DIAGNOSIS (DD): is the application of suitable measurements and procedures to evaluate insulation degradation and deterioration caused by service conditions. It is performed to forecast the period for which the insulation of equipment will meet the required withstand voltages.

DIAGNOSTIC:

adjective - of or pertaining to diagnosis, e.g. "diagnostic methods", "diagnostic procedures", etc.

substantive - any characteristic quantity which is measured for diagnosis, e.g. "water content in oil", "partial discharge level", etc.
Note: The singular form is sometimes used for "methodology of diagnosis". The collective plural ("diagnostics") is occasionally used for "diagnosis".

OFF-LINE DIAGNOSIS: is any diagnostic technique that requires the equipment under consideration to be taken out of service.

ON-LINE DIAGNOSIS: is any diagnostic technique that can be applied leaving the equipment under consideration in service.

AGEING: refers to the passage of time and is only linked to changes of properties in the presence of an influencing factor (a stress).

DEGRADATION: the physical meaning is a temporary reduction of properties which disappears with the removal of the influencing factor (a stress); e.g. the reduction in withstand voltage of the external insulation due to the humidification of a pollution layer. The chemical meaning is a reduction to simpler molecular structure.

DETERIORATION: is a permanent reduction of physical/-chemical properties caused by the the application of an influencing factor (a stress) during time; e.g. the reduction in withstand voltage of paper insulation due to tracking.

Usually the deterioration involves more severe and more important reductions of the properties than the degradation.

The subject of DD has been treated from the points of view of insulating materials and of electrical equipment.

Section 2 of the Report deals with dielectric materials which are used in the manufacture of electrical equipment insulation. The most important deterioration processes characteristic of these materials and the relevant laws for different stresses and the types of criteria that best describe the deterioration are considered. Diagnostic methods available at this level of investigation, i.e. to check the degree of deterioration of insulating materials are summarised and discussed.
In most cases the present knowledge is fragmentary, but even thus it can help, or has already helped, to provide a diagnosis for the insulation of various equipment.

Section 3 of the Report deals with the electrical equipment as such, manufactured with different subcomponents each having suitable insulation. In this case the failure mechanisms are considered and the relevant diagnostic techniques are discussed in general terms. References are made to publications where details can be found.

Section 4 is an attempt to determine the correlation between DD and insulation deterioration and its feedback to insulation co-ordination concepts.

Finally Section 5 attempts to draw possible conclusions on this wide and difficult subject.

112, boulevard Haussmann
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1990 Session
26th August — 1st September

DIELECTRIC DIAGNOSIS OF ELECTRICAL EQUIPMENT FOR AC APPLICATIONS AND ITS EFFECTS ON INSULATION COORDINATION

State of the art Report

On behalf of Study Committees 15 and 33
Presented by Working Group 33/15.08

(presented at the 1990 Session)

PREFACE

At the 1988 CIGRE General Session, Study Committees 33 and 15, in co-operation with Study Committees 11, 12, 13, 21, 22 and 23, decided to set up a new joint Working Group, WG 33/15.08, to deal with the subject of Dielectric Diagnosis (DD).

The terms of reference for the newly-established WG were defined as follows:

a) Define DD and its scope.
b) Identify the parameters characterising insulation ageing.
c) Determine how to account for insulation ageing when selecting insulation levels.
d) Analyse the procedures in use for DD.
e) Analyse existing type, acceptance and commissioning tests as starting reference for DD.
f) Prepare a report on state-of-the-art to be presented as Study Committee-sponsored Report at the 1990 CIGRE General Session.

The appointment of all the WG Members was completed, for several reasons, only at the end of March 1989 and thus the WG had less than nine months to carry out the specific goals assigned.

The present Report, prepared after three WG meetings, presents the state-of-the-art of the diagnostic methods available today, to the WG Members knowledge, to verify the dielectric conditions of insulating materials used in electrical equipment for AC applications.

In writing the different parts of this Report, the WG Members have taken into account, as much as possible, all the previous work on the subject performed within CIGRE Study Committees and Working Groups and references to the relevant published papers have been made. Moreover, the present Report, far from being exhaustive on the subject, is intended to stir up a lively discussion during the 1990 CIGRE Conference.

Finally, it must be stated that the contents of the Report reflect the personal views of the individual WG Members and not necessarily those of the Study Committees to which they belong.

GENERAL INDEX

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Publié par le CIGRÉ
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FR-75 008 PARIS
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