# CONDITION BASED MAINTENANCE OF CABLE ACCESSORIES USING A NEW ACOUSTIC MONITORING METHOD

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## SUMMARY

*Terminations and joints are the part of a cable system, which most often lead to outages. Most of these failures are related to partial discharges.*

*As a tool for condition based maintenance, a method for on-line periodic discharge measurements based on ultrasound detection of acoustic signals emitted from the discharges has been developed. The method has proven to be quite efficient.*

*The cost benefit will depend heavily on the rate of defects.*

## INTRODUCTION

In Norway preventive condition based maintenance has obtained more attention in the later years, and reliability centred maintenance (RCM) and risk management methods are introduced in several utilities. This is due to the shift to a new regime where governmental bodies establish limitations for what a utility may charge for transport of electricity. Maintenance and reinvestments are one of the sectors where a utility has a possibility to influence on. In the near future there will be introduced a system where the utilities have to pay substantial penalties for non-delivered energy due to planned and unplanned outages. This will bring even more focus on optimising maintenance costs and extending the lifetime of equipment.

In a cable network, cable accessories are the most frequently failing component. Therefore a method for after laying quality control and in-service condition monitoring has been asked for. Partial discharges (PD) - occurring either due to incorrect assembly or to ageing phenomena - are believed to cause the majority of the forced outages. The type tests specify that the PD level should be below 10 pC [1]. Hitherto, quality control after mounting of either a termination or a joint has never been performed. This is mainly due to noise problems in the field; the electrical methods for PD detection have rarely been used in the field.

A method based on detection of acoustic signals emitted from the discharges has been developed. This paper will explain the measuring technique; what sensitivities may be achieved, how frequently defects are found in service and finally estimates of cost-benefit from taking the method in use.

## THE ACOUSTIC METHOD

In a partial discharge electrostatic energy is released locally within a short period (i.e. nanosecond scale). This gives a localised heating and acts as a small "explosion", exciting mechanical waves that propagates away from the source. The mechanical waves will be shaped (i.e. mode conversions) by the geometry and materials of the test object. In a termination and in a joint the materials used will normally act as sound absorbers. The mechanical waves will – provided they are not absorbed – get to the outer surface of the test object. As there is a large difference between the acoustic impedance (sound velocity times density of material) of a solid and a gas insulation, very little energy is transmitted into the surrounding air. Therefore, ultrasonic corona detectors are not suited for detection of *internal* discharges. In order to get the acoustic signal "out of " the termination/joint the detecting sensor has to have mechanical contact.

The designed detector with an electrically insulating acoustic wave-guide, that transports the signal from the test object to the acoustic sensor, has shown feasible for use in the field. It introduces an extra attenuation of some 10 dB compared to applying the sensor directly to the test object. The extra attenuation is mainly due to the extra discontinuities in the acoustic impedance. The main issue is that the probe is practical and safe in use during in-service tests. The sensor used has a resonance at some 30 kHz. These give a reasonable sensitivity, and mechanical environmental noise seldom causes a problem.

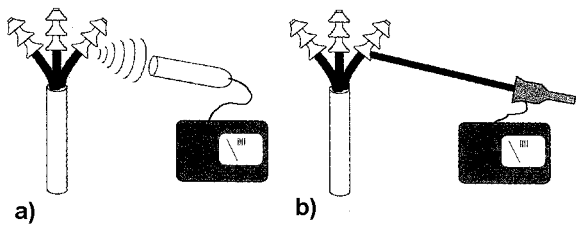


Figure 1: Corona "gun" (a) for detection of external discharges and fibreglass probe (b) for detection of internal discharges.

Usually, also a corona gun is used when testing terminations to detect if there are external discharges, which could be inferred as internal discharges during the subsequent test with the waveguide technique. External "noise" discharges are normally removed by cleaning and/or drying the terminations.

For 12 and 24 kV terminations for XLPE-cables the sensitivity of the method is found to be in the 5-10 pC regime. To achieve sensitivity in this range one has to measure as close to the defect as possible as the absorption in the materials are quite high [2].

A wave-guide, which is bent at the end like a walking stick, has also been developed to access the back of the cable termination.

Measurements have shown that the method also may be suited for joints. For 24 kV heat shrink joints discharges of 3-4 pC were detected before the copper mesh and the outer heat-shrinkable sheath with hot-melt adhesive were mounted. Mounting the outer jacket reduced sensitivity to 10-20 pC.

It must be stressed that to have good sensitivity for a joint there must be “hard wood” from the source to the sensor. A copper mesh would – unless it later is filled with a glue – act as a cushion and stop the acoustic signals.

More research has to be carried out to find the feasibility for the higher voltage levels. However, lately the method has also – on a test basis – been applied on 115 kV components and several defects were detected. Nothing specific can this far be said about the sensitivity. We do expect that increased material thickness may be an obstacle to get as good sensitivities as for the medium voltage accessories. Switching to lower frequency range may reduce problems with absorption.

## THE INSTRUMENTATION

A portable instrument has been designed to support measurements.

Figure 2: Portable instrument (AIA) and wave-guide probe used on a XLPE termination.

The instrument checks the periodicity in the signals relative to the power frequency/power cycle. It can be powered either from the mains or from a rechargeable battery. In the instrument 18 measurements may be stored for later download to a PC. There are also high- and low-pass filters to help removing noise and increasing sensitivity. Signals can also be monitored by an oscilloscope if desired.

## FIELD EXPERIENCE

In order to check the feasibility of the method it has been applied in the field. In general the experiences from the laboratory have been verified.

However, in small substations in coastal areas where the relative humidity is rather high due to poor circulation of the air, external discharges due to moisture and contaminations were in some cases found to disturb the detection of internal discharges. These external discharges were easily detected by the corona “gun”. It is therefore recommended to apply the corona “gun” before looking for internal discharges. Use of an industrial fan heater for a few minutes before measurement may remove these discharges.

To date about 3000 terminations (single-phase units) have been investigated, and -as an average-about 1% were found to have internal discharges. Some of these terminations have been removed and tested in the laboratory with a positive verification of internal discharges. Some cables, where field grading mastic was used in the area where the insulation screen was cut, showed discharges in the field, but not in the laboratory. This was attributed to instabilities in voids created in the soft mastic-material.

In an early case 12 three-phase terminations installed on 12 kV mass-impregnated cables erected at a hillside, were scanned. In general the acoustic level was highest for cables going downhill, with draining of the mass as a probable effect. Two of these (the units that showed the highest signal level) had a breakdown two years later.

The method has proven to be quite efficient. About fifty three-phase units per day may be measured. Better knowledge of where the end of the cable’s insulation screen is located within the termination may further improve this effectiveness, as fewer measuring points then will be needed for each termination.

## SERVICE EXPERIENCE ON ACCESSORIES

The Norwegian failure statistics concerning XLPE cables is based on information from utilities. Since this work was started in Norway in 1985, all Norwegian utilities have received a questionnaire every year. The percentage of utilities that have returned the questionnaires has varied between 50 and 80 %.

Figure 3 summaries the Norwegian XLPE-cable statistics.

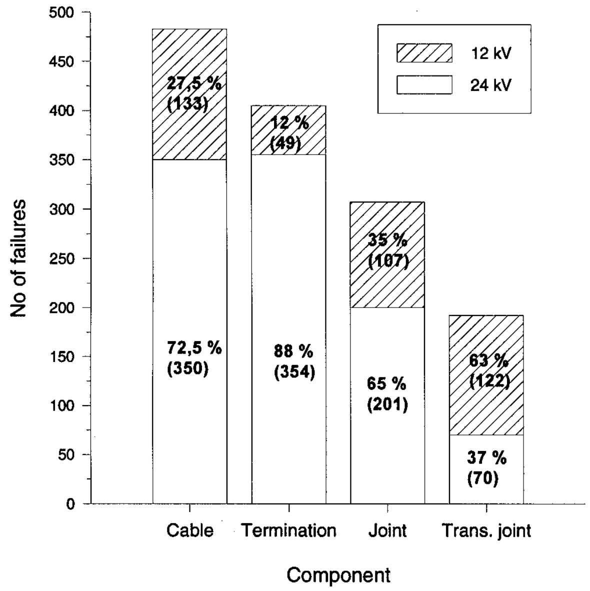


Figure 3: Total number of reported failures grouped on components.

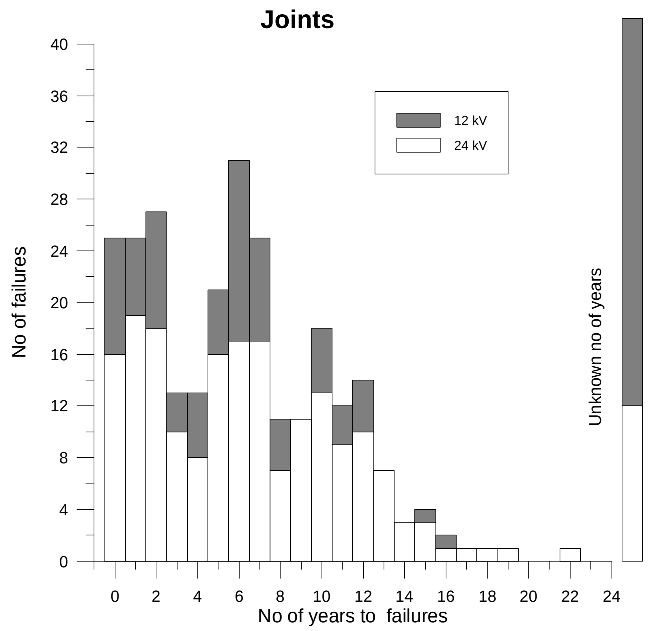


Figure 5: No of failures as a function of service life for joints

Altogether 1386 failures are reported on XLPE-cables and accessories to the end of 1996. Figure 3 shows the distribution of failures on component and voltage.

As can be seen, the number of failures for 24 kV terminations are a factor 7 higher than for 12 kV, even if the total length of 24 kV cables are only twice the length of 12 kV cables

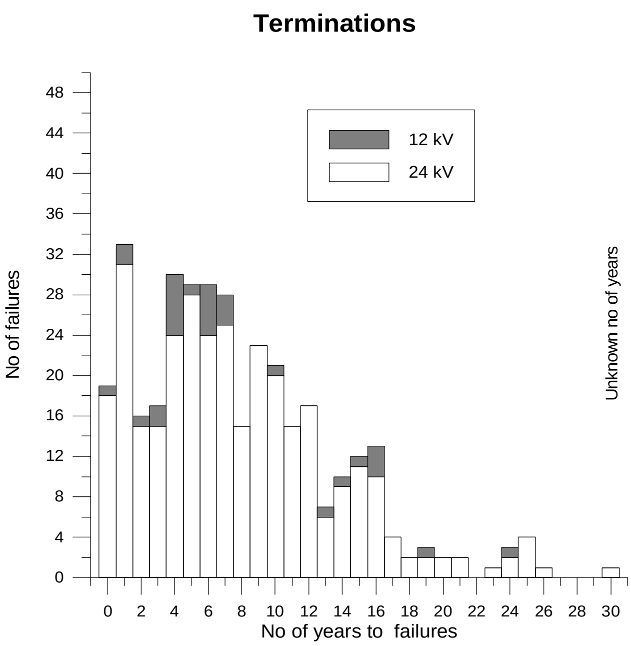


Figure 4: No of failures as a function of service life for terminations

In Figure 4 and 5 are shown the number of failures as a function of service life for terminations and joints.

It is a fact that many of the accessory failures are due to “defects” made by the jointer during installation. One of the main reasons, especially for terminations, is knife cut into the XLPE insulation where the strippable insulation screen is terminated. If the jointer use a knife to remove the insulation screen he might, often without being aware of it, make a little cut into the insulation. This can give partial discharges and gradually degradation of the insulation. Depending on the voltage level, the time to failure is assumed to lie in the range from five to ten years, as a 24 kV accessory is exposed to higher electrical field than a 12 kV.

In Norway, the problems with knife cut have been considerably reduced during the last years because the insulation screen from 1992 was changed to fully bonded type. Now the jointer has to use a special tool to remove the insulation screen, making a smooth transition area between the insulation screen and the insulation.

Other fault reasons can be bad fitting of the different parts, service ageing like deterioration of grading paint and absorption of silicone grease by the XLPE or the accessory material. For joints, overheating of the conductor splice is also a common failure.

If we look more closely on the failure rate for terminations, which is the accessory where this method for in-service condition monitoring is most relevant, we can calculate the failure rate per 100 km cable and year.

Assuming that the mean length for a cable is 500 m and knowing that the number of failures given in figure 3 are for a period of 12 years, we can calculate the following failure probability:

For 12 kV terminations: 0.006 % per phase per year
For 24 kV terminations: 0.02 % per phase per year

The fact that one observes a higher defect rate for field measurements than the failure rate in the statistics indicates, can be explained from the fact that breakdown usually occurs after a long period with discharge stress. The discharges detected will therefore – unless corrective actions are taken – contribute to the failures occurring over a period longer than one year.

The risk evaluation is fairly simple for XLPE-cables; discharges can not be accepted and once detected they have to be removed. The laboratory tests and experience with mass-impregnated cables are not as extensive as for XLPE-cables. However, from the point of view of risk management the need for a diagnostic method is maybe even higher for these cable circuits than for XLPE-cables.

The failure rates for mass-impregnated cables are less documented than for XLPE cables. A survey covering the period 1991-1995 has been done. From this and from knowledge about the population of mass-impregnated cables one has estimated the failure probability to be [4]:.

For 12 kV terminations: 0.02 % per phase per year
For 24 kV terminations: 0.15 % per phase per year

Impregnated paper insulation can withstand discharges better than XLPE insulation. Probably more information than only occurrence of an acoustic signal is needed to take the decision of a corrective action. More information both on signal levels, sensitivities and acoustic signatures are needed to improve the decision criteria for mass-impregnated cables.

## COST BENEFIT ANALYSES

The proposed penalty system for outages lasting longer than 3 minutes will have a differentiation between planned and unplanned outages. The system also differentiates between customer types (e.g. household/industry). Unless otherwise agreed between the utility and the customer, standard rates have to be used. The proposed penalty rates are as showed in Table 1.

Table 1: Values [NOK/kWh] for non-delivered energy

| Customers | Unplanned | Planned |
|---|---|---|
| Farming/household | 2.00 | 1.40 |
| Industry/commerce | 35.00 | 24.50 |

To reduce this cost the utilities can both focuses on reducing of duration of the outage (e.g. diesel generators, hot work procedures) and on reducing risk (e.g. condition-based maintenance for important customers).

The cost of one failure in a cable circuit ($C_{failure}$) may easily be calculated if the load ($P_{cable\ failure}$) and expected outage duration ($T_{failure\ outage}$) and the value of the lost energy ($V_{penalty\ -\ forced}$) is known:

$$C_{failure} = P_{cablefailure} * T_{failure\ outage} * V_{penalty-forced}$$

This has to be compared with the total cost of the condition based preventive maintenance ($C_{preventive}$) consisting of the cost of finding one defect under development ($C_{detection}$), the cost of instrumentation ($C_{instrument}$), the cost of the correction of the failure ($C_{correction}$) and the energy lost during the planned outage ($C_{penalty\ planned}$):

$$C_{preventive} = C_{detection} + C_{instrument} + C_{correction} + C_{penalty\ planned}$$

The cost for revealing one PD-defected termination or joint will depend on the efficiency (i.e. time spent per phase) of the diagnostic procedure ($DT_{measurement}$), the cost of manpower ($C_{manpower}$) and the probability of finding a defect ($P_{defect\ :}$ 0 -1):

$$C_{detection} = \Delta T_{measurement} * C_{manpower} / P_{defect}$$

The cost of instrumentation per detected defect will depend on the cost of the instrument ($Price_{instrument}$), the time chosen to write off the instrument ($T_{writeoff}$), the time the instrument is in use per year ($T_{use}$), the time to check one item ($DT_{measurement}$) and the probability of finding a defect ($P_{defect}$):

$$C_{instrument} =$$
$$( Price_{instrument} / T_{writeoff} / T_{use} ) * ?T_{measurement} / P_{defect}$$

The cost to correct a defect can often be considered constant.

Finally, the cost of one failure in a cable circuit ($C_{penalty\ planned}$) may easily be calculated if the load [$P_{cable\ maintenance}$] and expected outage duration [$T_{maintenance\ outage}$] and the value of the lost energy [$V_{penalty\ -\ planned}$) is known:

$$C_{penalty\ planned} =$$
$$P_{cablemaintenancee} * T_{maintenance\ outage} * V_{penalty-planned}$$

In a preventive maintenance programme terminations are the most relevant accessory. One can from the above see that the cost of finding one defect is heavily dependent on probability of a defect occurrence. We have calculated the cost benefit for varying defect probabilities and costs for forced outages based on the above equations, and using the following input data:

- Experience indicates that 50 three-phase units may be measured per day.
- Instrument cost: 150 000 NOK.
- Personnel cost: some 800 NOK/ hour.
- Writing off period: 3 years
- Time in use: 3 months per year.

- Cost of corrective action: 15.000 NOK
- No outage necessary due to corrective action

The curves in Figure 6 show that the possible cost benefit will depend heavily on the rate of defects and the cost of an unplanned outage. The results of the cost benefit analyses indicate that in industrial areas and city centres the acoustic method will always give a good pay-off, while in rural districts and suburban areas the cost benefit is more questionable and that more careful analyses of the costs involved should be carried out. If the utility already has purchased one instrument, then the investment cost may be disregarded and the situation will be more favourable for a condition based maintenance scheme.

To assess the expected future cost due to termination failures one should remember that the failure probability for a cable system is of course six times the given probability rates, as each cable connection has six single phase terminations.

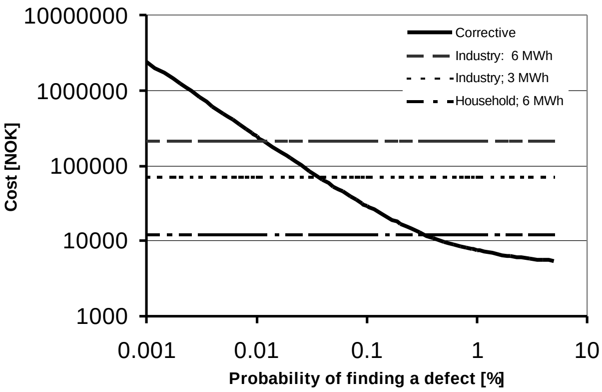


Figure 6: Cost calculation for corrective maintenance scheme.
a: Cost of finding one defect
b: Outage cost; unplanned industry 6 MWh
c: Outage cost; unplanned industry 3 MWh
d: Outage cost; unplanned household 6 MWh

**CONCLUSIONS**

An acoustic method for on-site in service detection of partial discharges in cable terminations has been developed and successfully tested in the field. A commercial equipment for field use has been developed and tested.

The method has proven feasible both for quality assurance and maintenance assessment of medium voltage cable accessories.

Calculations, based on national rules for penalties for non-delivered energy, shows a clear cost benefit for a condition based maintenance programme for cables terminations compared to a programme based on corrective maintenance.

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[1] CENELEC HD 628 and HD 629

[2] L. Lundgaard, W. Hansen: ”Acoustic Method for Quality Control and In-Service Periodic Monitoring of Medium Voltage Cable Terminations”, IEEE EIC Conference, Washington, 1998

[3] H.Faremo, J.T.Benjaminsen, P.B.Larsen and A.Tunheim:
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