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PERMANENT ON-LINE MONITORING OF MV POWER CABLES BASED ON PARTIAL DISCHARGE DETECTION AND LOCALISATION – AN UPDATE

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ABSTRACT

A new on-line measuring system that is able to measure and locate partial discharges (PD's) in MV cables was presented at Cired 2005 [1]. This system is called PD-OL, which stands for PD testing on-line with localisation. Since 2007, this system is commercially available. First experience with PD data is presented in this paper. Apart from the first experience, for people who are not familiar with this new way of PD measurements, a summary of the ins and outs of PD-OL is given.

KEYWORDS

power cable, medium voltage, partial discharge, PD-OL, on-line, defect, localisation, noise, monitoring, degradation

INTRODUCTION

Because of the large impact of cable failures in the MV network on outages as experienced by customers, network owners show much interest in diagnostic tools for their network. For this reason, off-line PD testing has become popular and is being applied since the early 1990-s. After a couple of years of Dutch research activities [3], [4], a prototype of a measuring system became available in 2005 that was able to measure and locate on-line PD's in a MV power cable. At Cired 2005, the basics of the PD measuring system called PD-OL, was fully presented for the first time [1]. PD-OL stands for Partial Discharge testing On-line with Localisation. This paper also includes references to further details. The measuring system is protected with a patent [2]. Since 2005, energy was spend in realising commercial equipment which has become available recently (2007). PD-OL systems based on this got in operation. The first results are shown in this paper.

Compared to off-line PD diagnostics (performed once per couple of years for a certain cable circuit), PD-OL is seen as a step forward in diagnosing MV power cables for the following reasons:

1. PD trends can be seen. This may give a better estimation of risk on failure and maybe also of the actual the remaining life.
2. Since PD-OL is based on inductive sensors clamped around the earth lead just below the termination, no galvanic connection with the MV is needed. From a safety point of view this is an advantage.
3. PD-OL units can easily be removed and installed on another cable circuit. This is because the sensors that can be clamped around the cable consist of two parts.
4. In many cases (depending on the actual termination type and safety regulations) no MV switching operation is needed to install the PD-OL sensors. This is both a safety and cost advantage.
5. In case that PD's from a specific defect are only measurable during a short period of time (hours, days, weeks, or months) before breakdown, PD-OL has a far better chance of interception these PD's.
6. In case that PD's from a specific defect are only measurable during short intervals, also here PD-OL has better chance to intercept PD's.

Background information for arguments 5 and 6 is given in Figure 1. Here, an example (measured in the KEMA laboratories) is given of PD activity form a joint that showed PD activity in intervals over a period of a couple of days only before breakdown. Overheating of the joint due to a bad connector caused this breakdown.

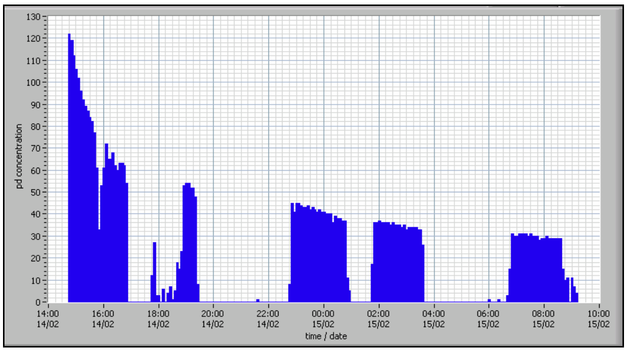

Figure 1: PD concentration form a failing joint as a function of time. The x-axes represents almost 1 day, until the moment of breakdown.

PD-OL – HOW IT WORKS

Lay-out

One PD-OL system consists of two separate PD-OL units, each of these to be installed at one of the cable circuit ends in either substation of RMU(s) (Ring Main Units).See for an illustration Figure 2. In Figure 4 a real life situation at one cable end is shown with

a) sensor/injector unit (PD-OL - SIU). Such an SIU has two parts which are bolted together and in this way is clamped around the cable earth lead The sensor/injector unit is connected with an optical fibre to the …

b) controller unit (PD-OL - CU) where PD data from the sensor/injector unit is collected. This controller unit (which is in fact a small dedicated computer) has also communication facilities on board (LAN, modem or mobile phone,GPRS, card) making it possible to reach the PD-OL unit via internet. In this way, PD data can be communicated from both cable ends to the control centre at KEMA for further interpretation. Such communication also makes it possible to remotely update the PD-OL - CU computer software if needed. All is performed automatically and remotely, so no physical access to the units is necessary once installed.

Measurement set-up

The control centre will instruct the PD-OL units to perform PD measurements on a regular basis, for instance every 10 minutes. One cable end will behave as a master, the other cable end as a slave. In this example, each 10 minutes, the master unit will send a pulse from one cable end (via its own sensor/injector unit and the power cable) to the other end of the cable circuit where the slave unit is detecting this large pulse. Sending this large pulse (about 10 V, from the master side) and receiving this large pulse (at the slave side) means in fact that both sensors have to start PD detection over a full period of the power frequency, i.e. about 20 ms. This is illustrated in Figure 3. In fact the handshaking of both cable end is more advanced as described above, to eliminate all kind of side effects and improve accuracy, this is the basic principle. All PD's, passing the sensor/injector units in the time slot will be detected. Part of the signals that will be detected is noise of course.

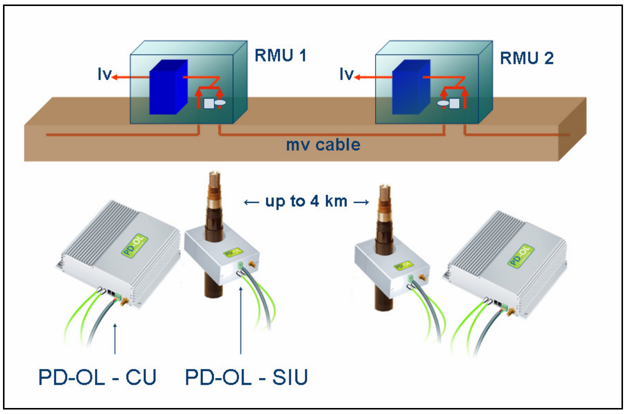

Figure 2: PD-OL installation, at each cable end there is a computer unit (PD-OL - CU) for data handling and communication via internet and a sensor/injector unit (PD-OL - SIU).

There are several criteria that help to select whether a pulse is indeed a valid PD pulse:

1. The most important requirement is that he difference in arrival time at both sensors should be less than the cable propagation time ΔT. In the example drawn in Figure 3, this is only valid for the second pulse with Δt_2, which for that reason must originate from somewhere in the cable circuit. The other pulses (with Δt_3 and Δt_4) come from sources outside the cable and for that reason have a Δt that is similar or larger than the cable propagation time ΔT.
2. The polarity of two corresponding (valid) PD pulses should be the same (assuming correct installation of the PD-OL - SIU's).
3. The pulse shape should be such that it is possible to trace it back to a unity pulse. Tracing back should take into account the transfer impedances of (a) the cable part between the defect spot in the cable circuit and (b) the transfer impedance of the RMU. Further details on this subject are given in this paper in Section "PD-OL Important Characteristics"
4. The pulse content received at RMU 1 and RMU 2 should not differ much more than can be expected from the difference in attenuation of the related cable circuit part (between the defect spot and RMU) and the RMU itself.

For a valid PD, the location can be found by applying the well known formula (1)

$$l_{pd} = \frac{L}{2}\left(\frac{\Delta t}{\Delta T} + 1\right) \qquad (1)$$

in which

l_{pd} = defect location that caused the PD pulse
L = total cable length
Δt = difference in arrival time at both cable ends of the PD pulses coming from the same origin
ΔT = cable propagation time.

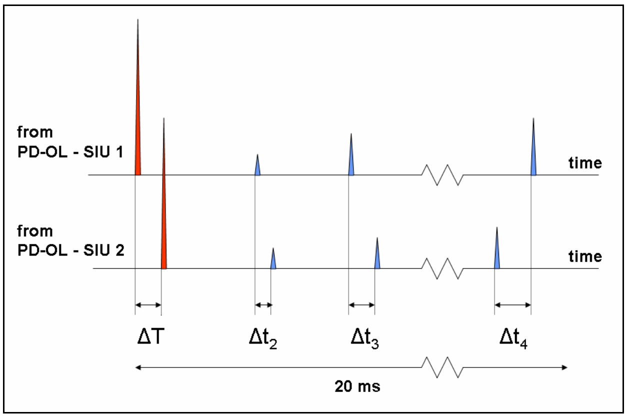

Figure 3: Injected, PD and noise pulses received by the PD-OL - SIU 1 and PD-OL - SIU 2 at both cable ends in respectively RMU 1 and RMU 2. The cable propagation time = ΔT (from the injected pulse). In this example is $\Delta t_2 < \Delta T$, $\Delta t_3 = \Delta T$ and $\Delta t_4 > \Delta T$.

PD-OL – THE FIRST RESULTS

While writing this paper, the first commercial PD-OL units are being installed in cable circuits of network owners in the

Netherlands. For this paper, the first two PD-OL results obtained under practical circumstances will be used.

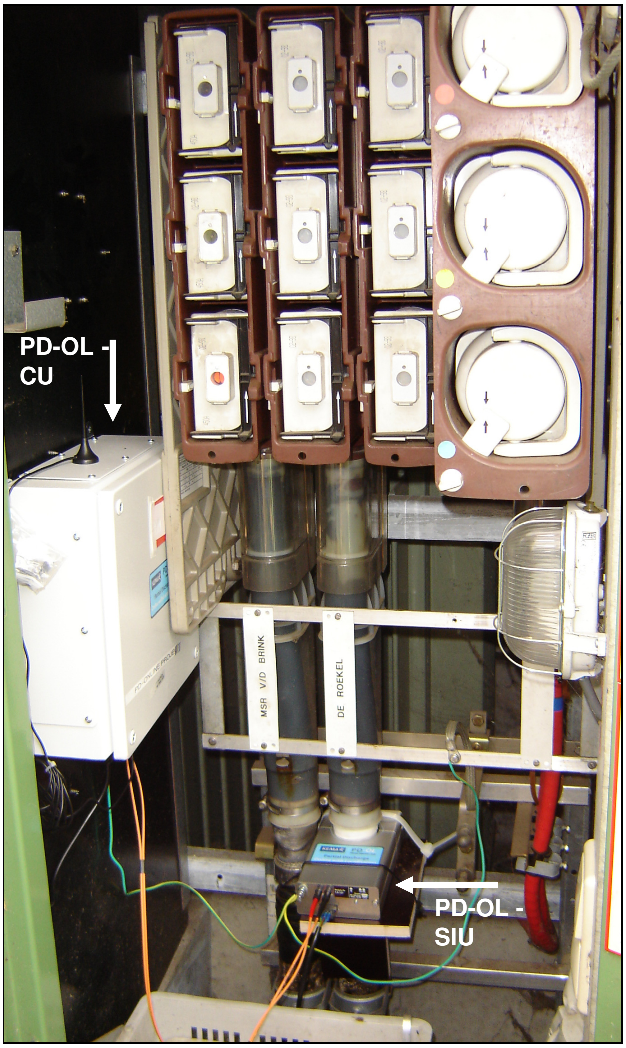

Figure 4: The PD-OL - SIU and PD-OL - CU after installation in an RMU.

PD-OL result from cable circuit A

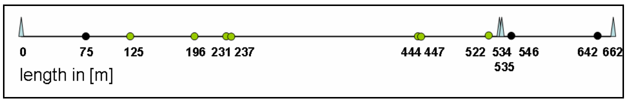

Figure 5: Cable circuit A set-up

The first result comes from a cable circuit from the Dutch network owner Essent. This circuit is called cable circuit A. The cable circuit length is 661 m. In fact, the cable circuit is consisting of two cable circuits, with an RMU in between at 534.5 m. For PD pulses, the RMU is hardly an obstacle in this case, making it possible to diagnose with one PD-OL system various cable circuits in series as is done here. In the cable circuits there are a number of joints and four terminations. The two joints at 231 m and 237 m are liquid filled.

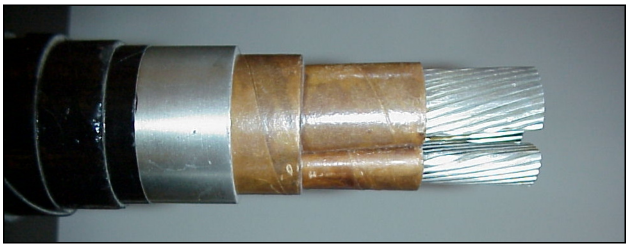

Figure 6: PILC belted cable, 10 kV voltage class

The cable in the circuit is a PILC cable (Paper insulated lead covered cable) of the 10 kV voltage class. It is a so-called belted cable, which means that there is a common insulation layer around both cable cores and under the screening lead sheath, see Figure 6 for a general impression of PILC belted cables as being applied in the Netherlands. This type of cable is normally producing some PD's as can be observed in the results shown below. This is usually not (really) a sign of degradation.

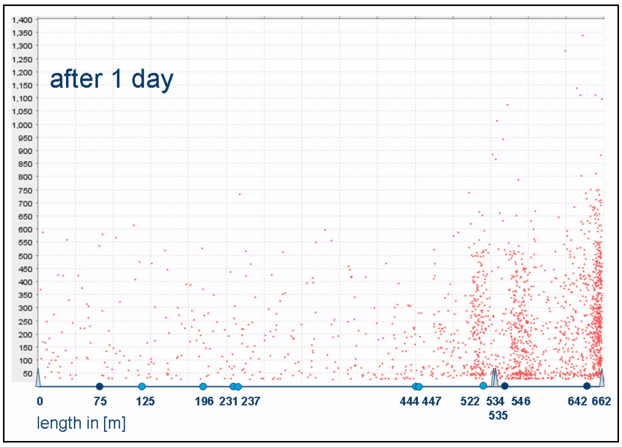

Figure 7: Cable circuit A, PD-OL result after 1 day measurements. The y-scale has as maximum value 1400 pC. PD activity found mainly in the PILC cable parts around the RMU at 534.5 m and near the termination at 662 m.

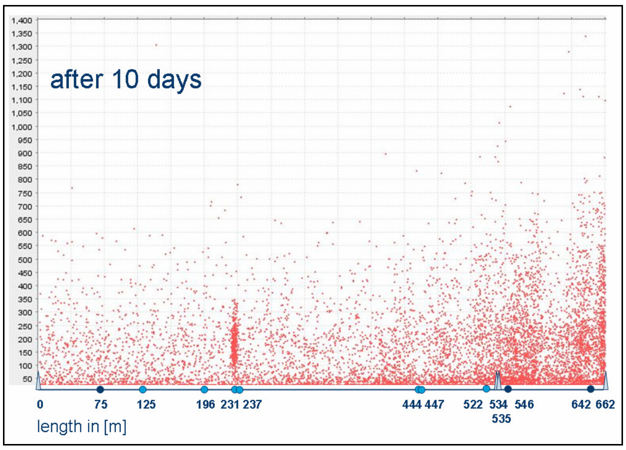

Figure 8: Cable circuit A, PD-OL result after 10 days measurements. The y-scale has as maximum value 1400 pC. A new PD source has grown near or in the liquid filled joints at 231 m and 237 m.

It is clear already from this early experience, that over time certain parts in the cable circuit start generating PD's (here mainly around the location 231 m to 237 m) under certain conditions which have not been there during the first day of measurements. At this moment there is no reason yet to suspect this circuit or draw further conclusions but this result already shows that future PD measurements will very probably show many interesting surprises.

PD-OL result from cable circuit B

The second circuit B is part of the network of the utility Continuon. Its length is 368 m. There are two terminations and four joints. The cable is a PILC belted cable as described before in this paper (and shown in Figure 6). The circuit layout and the PD-OL results after about one week of measuring PD's is presented in Figure 9.

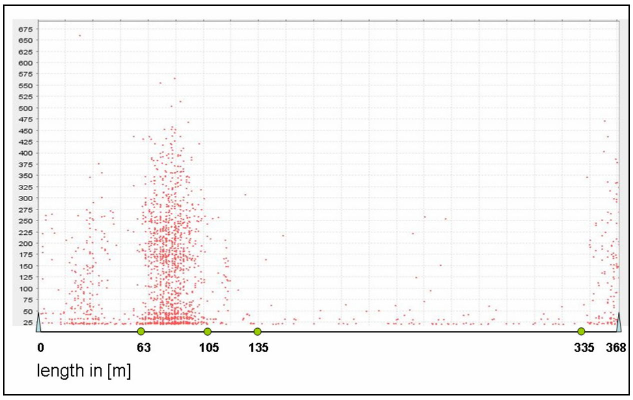

Figure 9: Cable circuit B, PD-OL result after about one week measurements. The y-scale has as maximum value 675 pC. PD activity found mainly in the PILC cable between the joints at 63 m and 105 m.

Note the relatively high PD density in the cable part between the joints at 63 m and 105 m. This can be explained by the fact that this part of the cable circuit has another type (more modern) of PILC belted cable with a more open insulation set-up, which explains the higher PD intensity Also here, the results show that already from its beginning PD-OL gives interesting results.

PD-OL – IMPORTANT CHARACTERISTICS

Time synchronisation

Because of the fact that power cables in an on-line situation are in many cases connected to a next cable, PD's do not reflect at all or only to a minor degree. This makes it necessary to apply sensors at both sides of the cable circuit, which is the chosen solution with PD-OL. That simple fact implies that the PD-OL - CU's installed at both cable ends do need some trick to get in time synchronisation with each other. The patented solution [2] is that via the PD-OL - SIU's not only PD's can be measured, but also pulses can be injected via an inductive coil. This pulse injection at the master PD-OL - SIU is the accurate starting time of measuring PD's. The slave PD-OL - SIU at the other cable end will start doing the same immediately after receiving this injected pulse, which is exactly the cable propagation time later. Since the propagation time of the cable is known, accurate time synchronisation between the two PD-OL units has become possible. Advanced filtering techniques ensure that this method achieves sufficient reliability and accuracy.

It is worth to know that both the master and slave PD-OL - CU's are instructed via internet from the control centre that they both have to start their measurements at a certain time (normally once per about 10 minutes). Of course, the accuracy of this starting moment is in the range of seconds. But this is accurate enough to perform windowed triggering in combination with pulse pattern recognition.

Sensor set-up

PD-OL uses inductive sensors to measure PD pulses coming from a defect in the cable. Such PD pulses travel with about 50 % of the speed of light between two conductors. In most cables the related charges of one polarity travel through the power cable conductor and the charges of opposite polarity use the earth wire screen. An inductive sensor that is placed around the power cable will only measure PD pulses if this sensor measures (a) the charges in the conductor only or (b) the charges in the earth screen only. In Figure 10 this is illustrated for three types of terminations / switch configurations: A = metal closed, B = metal half closed and C = metal open.

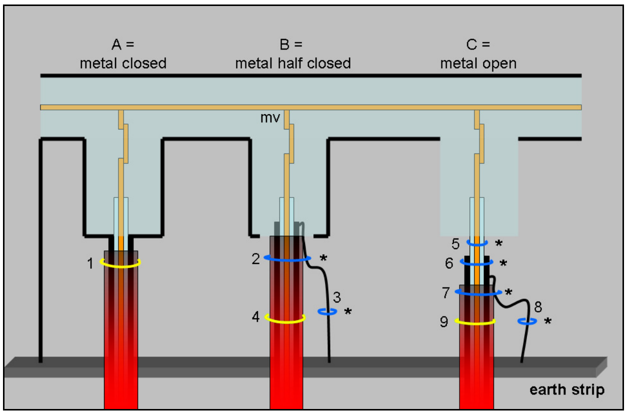

Figure 10: Possible sensor locations. PD pulses can be measured effectively at sensor locations 2, 3, 5, 6, 7 and 8 (identified with a *).

Taking this into account, sensor locations 3 and 5 will certainly measure PD pulses effectively. But also the sensor locations 2, 6 and 7 are suitable. This is because the PD charges in the earth screen are here effectively zero and thus only the PD charges in the conductor are being measured. From these suitable sensor locations 2, 3, 5, 6, 7 and 8, the best locations are 2, 5, 6 and 7 because here noise currents (common mode currents) are considered to be less severe. Further details are given in [1] and [3] and in many references mentioned in [1].

Calibration

PD-OL applies pulse injection for time synchronisation. However, the injected pulses are also used for calibration. This is because they have a known pulse shape and by measuring the pulse shape of these injected pulses with the sensors at both cable ends, it is possible to calculate the transfer impedances of RMU 1 and RMU 2 (in Figure 2) and the propagation characteristics of the cable circuit between the RMU's. This information can be used for two things:

1. The actual PD charge can be calculated from the measured PD pulse shape and amplitude
2. The expected pulse shape from a PD can be predicted, which is important to discriminate PD pulses from noise. Here, matched filter techniques are applied in the PD-OL - CU.

The calibration is repeated each time a new record of PD data is measured, so in fact every 10 minutes. As a result, any change in the RMU configuration (number of cables in parallel with the cable circuit under test for instance) or cable circuit configuration will be detected on-line and its consequences will be implemented immediately in the software for PD measurements, among which noise reduction.

Maximum cable lengths

At present, tests are running to find the maximum cable circuit lengths that can be measured effectively with PD-OL. Taking into account all experiments from the past, it is expected that PD-OL can measure cable circuits with length up to 4 km at least, even if there are small RMU's in the cable circuit. In fact, circuit A in this paper was the first cable circuit of a network owner and here is a small RMU part of the cable circuit.

Types of cables that can be diagnosed

There is no limitation with respect to voltage class or cable type as long as the terminations are suitable for performing PD measurements. The related requirements are discussed above. It can be concluded that practically all MV power cables can be diagnosed as long as the termination / switch arrangement is metal half open or open. In case of a metal closed termination / switch arrangement it is only possible to apply PD-OL if this arrangement is adjusted, for instance by making a sheath interruption in the cable just below the termination or interrupting the earth connection of the termination itself.. This is certainly not something network owners will like to do, although it could be done if PD measurements are needed and there are no alternative ways to measure PD's.

Also branched cables can in principle be diagnosed without any problem since the principles of PD-OL measurements are not reflection based. But also here, limitations are dictated by the before mentioned termination / switch arrangements.

One must be aware that HV cables (above 50kV) often have cross-bonding systems. Since each cross-bonding joint is an obstacle for travelling PD pulses, the maximum cable length that can be measured here is probably limited. There is also another reason why HV cables are not suitable for PD-OL as it is at this moment. This is because such cables often have metal closed terminations / switches where inductive sensors cannot measure PD pulses. Finally, such terminations often are connected to an overhead line with a characteristic impedance which is much higher than from the cable, making inductive sensors less effective.

Control centre and knowledge rules

Together with the Dutch utilities, KEMA has set up a control centre. From here, all PD-OL units in operation get instructions how often and how long a specific cable circuit should be diagnosed. Its default mode yet is each 10 minutes a PD record of 20 ms. However, these parameters can be changed easily if needed. Future experience will help to define an optimal measuring interval.

PD data from all cable circuits diagnosed is collected in this control centre. This data will be evaluated on trends and especially in case of suspected cable parts, joints or terminations in order to prevent a cable breakdown. In case of breakdown all PD data obtained prior to this breakdown will obviously be evaluated too, to improve future interpretation even further. At this moment the PD data is interpreted with the knowledge rules obtained from 15 years of off-line PD measurements. As soon as certain trends can be discovered, such trends will become part of knowledge rules. Then, trend evaluation will be automated as much as possible of course.

PD-OL – FUTURE DEVELOPMENTS

In the near future various important and critical cable circuits in the Netherlands will be equipped with PD-OL. In 2007 this will be 70 at least for the Netherlands only.

The control centre will collect the PD data and with help of a PhD student the quest will start for knowledge rules that can predict the rate of degradation of defects, to be translated in a risk on failure. Of course, it would be challenging to solve remaining life questions too. Here, however, one must be careful. Identifying a risk on failure is much easier then predicting the remaining life. One can compare this with someone who is driving a car with failing brake lights. Everyone will recommend the car owner NOT to use the car and to perform repair as soon as possible. But it is not possible to predict the moment of an accident if no repair work is done, because this is partly depending on things that are outside the influence of the car owner, for instance sudden bad weather or busy traffic.

Coming back to PD-OL. Another PhD student will work on methods to optimize the applicability of PD-OL. One of the questions here is the number of PD-OL units needed to cover a specific cable network part.

On the long term, PD-OL can be integrated with other intelligent network tools, for instance by plotting PD generating sites on a map where also local circumstances have been made visible that could influence the cable performance via thermal aspects as plant and tree growth and soil water table level or via mechanical disturbance as heavy traffic that cause vibrations in the ground, etc. In this way, the background of cable degradation can be correlated easier to external circumstances.

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