LATVIAN JOURNAL OF PHYSICS AND TECHNICAL SCIENCES
2017, N 3

DOI:

EVALUATION OF FIBRE LIFETIME IN OPTICAL GROUND WIRE TRANSMISSION LINES

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In the research, measurements of polarisation mode dispersion of two OPGWs (optical ground wire transmission lines), in total four fibres, have been carried out, and the expected lifetime of the infrastructure has been assessed on the basis of these measurements. The cables under consideration were installed in 1995 and 2011, respectively. Measurements have shown that polarisation mode dispersion values for cable installed in 1995 are four times higher than that for cable installed in 2011, which could mainly be explained by technological differences in fibre production and lower fibre polarisation mode dispersion requirements in 1995 due to lack of high-speed (over 10 Gbit/s) optical transmission systems. The calculation methodology of non-refusal work and refusal probabilities, using the measured polarisation mode dispersion parameters, is proposed in the paper. Based on reliability calculations, the expected lifetime is then predicted, showing that all measured fibres most likely will be operational within minimum theoretical service life of 25 years accepted by the industry.

Keywords: *dispersion, lifetime, optical fibre, polarisation mode, reliability, telecommunications.*

1. INTRODUCTION

Polarisation Mode Dispersion (PMD) is the differential arrival time of the different polarisation components of an input light pulse transmitted by an optical fibre. This light pulse can always be decomposed into pairs of orthogonal polarisation modes. These polarisation modes propagate at different speeds according to a slow and fast axis induced by the birefringence of the fibre, which causes pulse spreading in digital systems and distortions in analogue systems. Polarisation mode dispersion testing is becoming essential in the fibre characterisation process, but still one of the most difficult parameters to test due to its sensitivity to a number of environmental constraints [1], [2].

The existence of birefringence in the fibre implies that fibre supports two orthogonally polarised modes that have different refractive indices and, hence, propagate with different group velocities in the fibre. An optical pulse launched into such a fibre would be split into two orthogonally polarised pulses, which would then propagate with different propagation constants and group velocities. The two pulses thus reach the output end of the fibre at slightly different times and with different phases. The superimposition of these two pulses leads to the generation of an optical pulse that is more broadened compared to the input pulse. Therefore, the pulse becomes dispersed due to the effect of fibre birefringence, and the phenomenon is called polarisation mode dispersion. PMD becomes important in the case of high-bit-rate (> 10 Gbit/s) fibre communication links, as it limits the transmission bit rate of a link as well as causes errors in transmitted data. In a long-distance fibre communication link, the fibre experiences stresses, bends, temperature changes, twists, etc., in a random fashion along the length of the link. Therefore, the birefringence along the fibre keeps changing both in magnitude and in direction. As a result, the birefringence is no longer additive; hence, the PMD does not grow linearly with the fibre length. It should be noted that due to random time variation of the birefringence along a long-length fibre link, PMD also varies randomly; therefore, a statistical approach must be adopted when studying PMD [1].

2. INTERFEROMETRIC METHOD (GENERAL ANALYSIS) FOR MEASURING POLARISATION MODE DISPERSION

Using a general analysis interferometric method (GINTY) for measuring polarisation mode dispersion, the measured value represents root mean square (RMS) PMD over a broad measurement wavelength range of typical broadband sources, such as light-emitting diode (LED), combination of super LEDs or amplified spontaneous emission (ASE) source in the 1310 nm or the 1550 nm optical transparency windows or any other window of interest. The PMD is determined from an interferogram containing the autocorrelation and cross-correlation function of the emerging electromagnetic field at one end of the fibre under test (FUT) when illuminated by the broadband polarised source at the other end. The main advantage of this method is that the measurement time is very fast and the equipment can be easily used in the field. The dynamics and stability are provided by the well-established Fourier transform spectroscopy technique. The fibre should be single mode in the measured wavelength range. A general analysis interferometric method (GINTY) does not have limiting operating conditions but requires a modified setup compared to a traditional analysis interferometric method (TINTY) [2].

A generic set-up is shown in Fig. 1, which is the basis of GINTY experimental implementation. Variations of this set-up are possible – the interferometer can be an air path type or a fibre type; it can be of Michelson or Mach-Zehnder type and it can be located at the source or at the detector end [2].

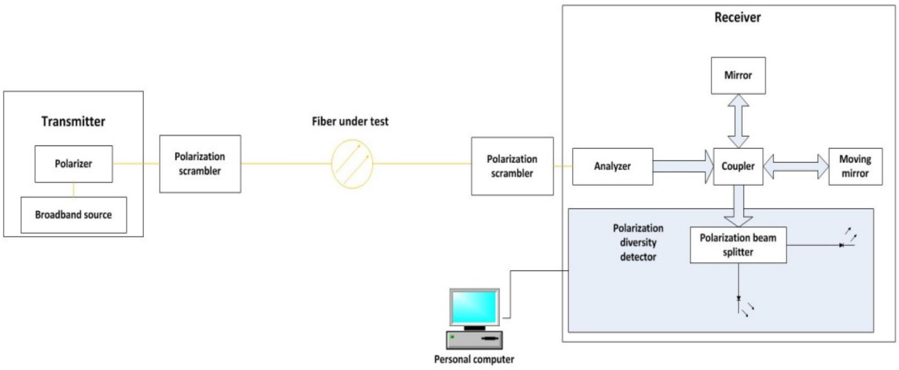

Fig. 1. Generic set-up for the interferometric technique.

For fibre links with strong mode coupling (e.g., long-distance optical fibre link), the result is an interferogram with random phases and the polarisation mode dispersion value is determined from the standard deviation of the curve. The two signals of the polarisation diversity detection allow removing the contribution of the source auto-correlation peak. It is possible to obtain the interferogram without the central peak thanks to the polarisation beam splitter [2].

3. DESCRIPTION OF MEASURED OPGW TRANSMISSION LINES

Selected OPGW transmission lines for PMD field measurements were not chosen randomly. OPGW transmission line infrastructure of JSC Latvenergo offers a unique opportunity to take measurements in two OPGW transmission lines, which are mutually comparable in terms of optical fibre length and geographical position. In addition, they are manufactured and installed with a time interval of almost twenty years. Therefore, it is possible to compare polarisation mode dispersion in two OPGW transmission lines that are created in different periods of time, using different methods of production and installation, as well as to assess whether more than twenty-year-old OPGW cable parameters meet the modern requirements of the telecommunication networks. OPGW transmission line A is positioned above the 330 kV high-voltage line built in 2011. OPGW transmission line B is positioned above 110 kV high-voltage line built in 1995. The two high-voltage lines connect together Broceni substation of JSC Augstsprieguma tikls (58 Lielcieceres Str., Broceni, Latvia) and Grobina substation of JSC Augstsprieguma tikls (Grobina parish, Ares, Latvia). Characteristic parameters of OPGW transmission lines are presented in Table 1.

Table 1

Characteristic Parameters of OPGW Transmission Lines

	OPWG transmission line A	OPWG transmission line B
Production year	2011	1995
Manufacturer	NSW	Nokia Cables
Installation year	2011	1995

Number of fibres	48	24
Optical fibre type	SSMF, ITU-T G. 652. D	SSMF, CCITT G. 652
Optical fibre length (km)	91.55	93.27
Geographical location	parallel to the road Riga-Liepaja (A9)	parallel to the road Riga-Liepaja (A9)

Lengths of optical fibres in OPWG transmission lines A and B are obtained from optical time domain reflectograms shown in Figs. 2 and 3.

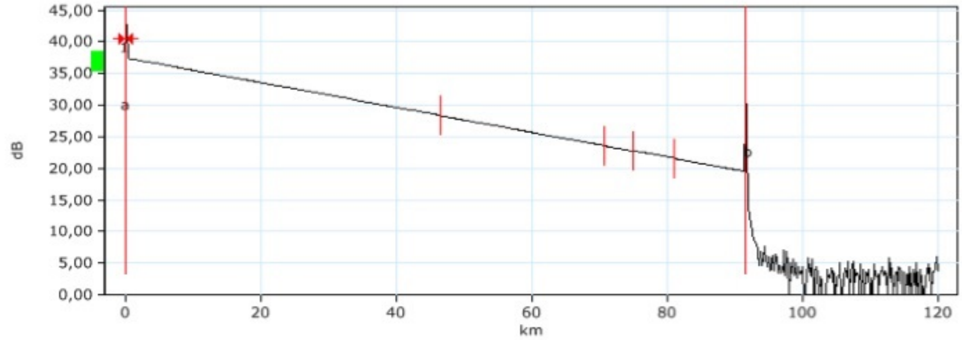

Fig. 2. Reflectogram – OPGW transmission line A (fibre No. 7).

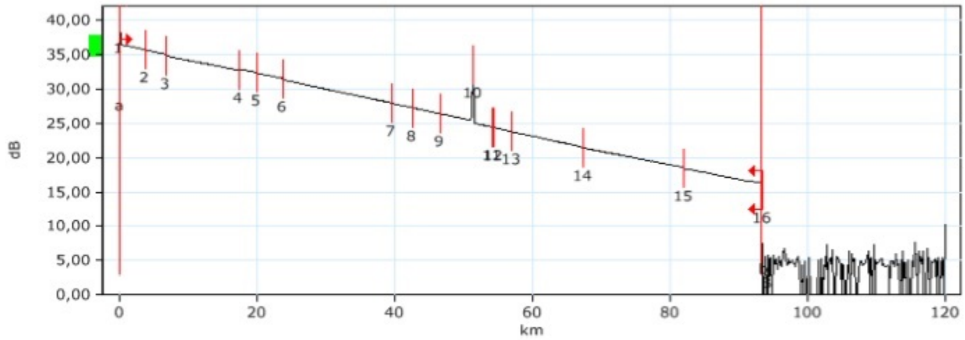

Fig. 3. Reflectogram – OPGW transmission line B (fibre No. 1).

4. OPGW POLARISATION MODE DISPERSION MEASUREMENTS

EXFO FTB 500 platform + EXFO FTB-5500B modulus (near end) and broadband light source (far end) were used to measure polarisation mode dispersion in OPGW transmission lines. Operating principles of EXFO FTB-5500B modulus are based on GINTY polarisation mode dispersion measurement method. Optical wavelength range for polarisation mode dispersion measurements: from 1526.86 to 1624.25 nm (C and L optical bands). The manufacturer (EXFO) provides the following formula for polarisation mode dispersion measurement confidence interval (CI):

$$PMD = PMDmeasured \pm (0.002 + 2\% \times PMDmeasured)$$

Polarisation mode dispersion of OPGW transmission line A (fibre No.7) was measured one hundred times (the averaging period of approximately 12 minutes) during the continuous time period of nineteen hours.

Fibres of OPGW transmission line B (fibres No. 1 and No. 2) were measured in short-term period – measurement of dispersion of each polarisation mode took approximately one and a half minutes (each fibre polarisation mode dispersion was measured 10 times).

The source of information about air temperature and wind speed during the measurements was the database of State Ltd “Latvian Environment, Geology and Meteorology Centre”.

Measurement results are summarised in Table 2.

Table 2

Measurement Results

	OPGW transmission line A		OPGW transmission line B	
	Fibre No. 7	Fibre No. 8	Fibre No. 1	Fibre No. 2
Measurement time	09.02.2016, 15:49 – 10.02.2016, 11:17	09.02.2016, 15:17–15:33	09.02.2016, 14:05–14:21	09.02.2016, 14:25– 4:41
Air temperature fluctuations during the measurements, (^{0}C)	from +2 to +7	+4.5	+4.5	+4.5
Wind speed fluctuations during the measurements, (m/s)	from 3 to 6.5	6.5	6.5	6.5
Average PMD, (ps)	0.2208 ±0.0064	0.5172 ±0.012	1.9746 ±0.0415	0.9994 ±0.0219
Average polarisation mode dispersion coefficient, PMD_Q, (ps/√km)	0.0231 ±0.0007	0.0541 ±0.0012	0.2048 ±0.0043	0.1037 ±0.0023
Maximum polarisation mode dispersion value, PMD_{max}, (ps)	0.2905	0.5529	-	-
Minimum polarisation mode dispersion value, PMD_{min}, (ps)	0.1118	0.4755	-	-
Standard deviation, σ, (ps)	0.0323	-	-	-

In the case of OPGW transmission line A (fibre No. 7), maximum allowed polarisation mode dispersion for optical fibre with the length of 91.55 km, according to ITU-T G.652 D standard, is 1.9235 ps [3]. Polarisation mode dispersion fluctuations during the period of 19 hours are shown in Fig. 4.

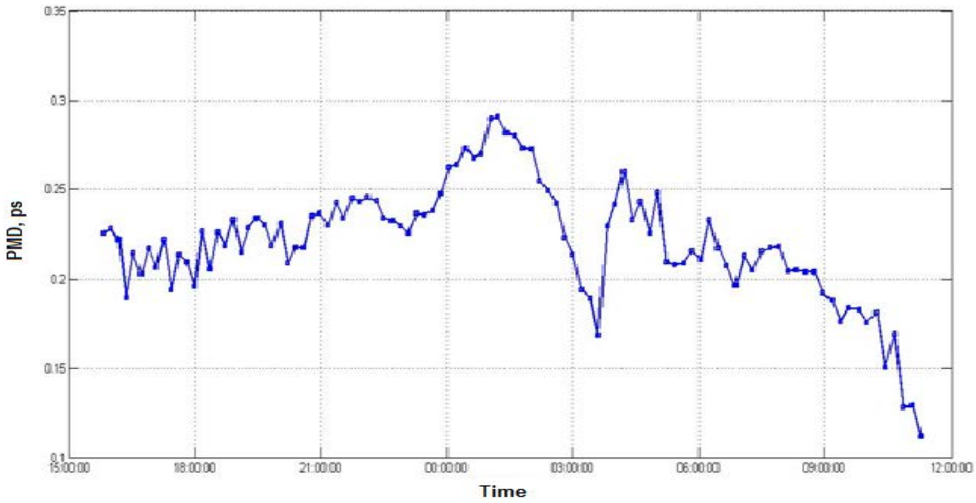

Fig. 4. Polarisation mode dispersion fluctuations during 19 hours (OPGW transmission line A, fibre No. 7).

Maximum allowed polarisation mode dispersion for optical fibre with the length of 93.27 km (OPGW transmission line B, fibres 1 and 2), corresponding to ITU-T G.652 D standard, is 1.9408 ps [3]. Polarisation mode dispersion measurement results for optical fibres 1 and 2 in OPGW transmission line B are shown in Fig. 5.

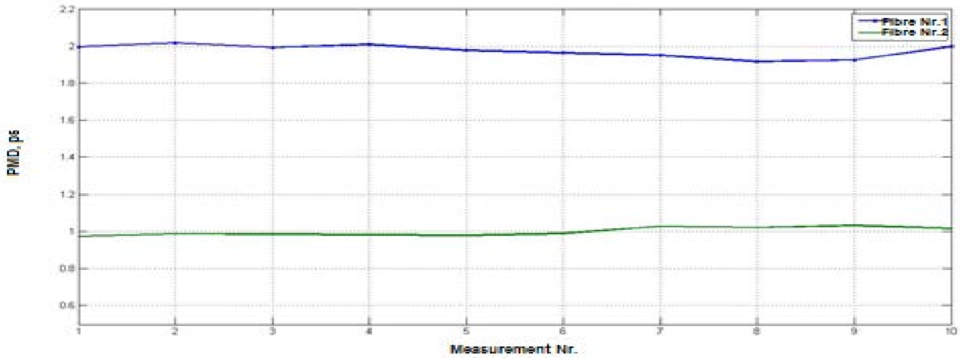

Fig. 5. Polarisation mode dispersion values of fibre No.1 and No. 2 in OPGW transmission line B.

5. ASSESSMENT OF LIFETIME

Mechanical and optical properties of optical fibre are important characteristics of optical fibre cable because they have to be as stable as possible to ensure the long-term reliability after many years of use in extreme operating conditions. Optical fibre parameters affect signal transmission in optical cable lines. It is particularly important to assess the PMD for the overhead cable lines because PMD in these lines is not stationary. It is caused by temperature changes, varying load, wind-induced cradling and other external factors. Transition to higher data transmission rates also increases requirements for maximum allowable PMD. PMD measurements are important to evaluate the long-term stability of optical signal transmission [4]. PMD should stay in certain limits and should not exceed the defined maximum threshold. If this happens a cable may become non-operational and its lifecycle ends.

One of the main parameters describing reliability is non-refusal work probability (NRWP), the probability that in given continuous operation time under certain conditions a cable will not be out of order in the case of refusal. Non-refusal work probability has a random nature that can be expressed as follows [5]:

$$0 \leq P(t) \leq 1. \quad (1)$$

Refusal probability (RP) is also used and is opposite to non-refusal work probability [7]:

$$Q(t) = 1 - P(t). \quad (2)$$

Non-refusal work probability *P(t)* and refusal probability *Q(t)* are the main indicators of reliability prediction [6].

Non-refusal work probability for single fibre can be calculated by the following equation [5]:

$$P(t) = e^{-\lambda t}, \quad (3)$$

where t – continuous lifetime (h); λ – refusal intensity or failure rate [7].

The fibres under consideration have reached the period of normal operation where λ-curve is linear and failure rate is constant [6].

Based on the measured PMD, a failure rate function is proposed as follows:

$$\lambda = \frac{PMD_{Q\ rep} - PMD_{Q\ ini}}{PMD_{Q\ max}} \cdot \frac{1}{t_0}, \quad (4)$$

where $PMD_{Q\ rep}$ – repeated measurement of PMD coefficient ($ps\ /\ \sqrt{km}$); $PMD_{Q\ ini}$ – initial measurement of PMD coefficient ($ps\ /\ \sqrt{km}$); $PMD_{Q\ max}$ – maximum PMD coefficient ($ps\ /\ \sqrt{km}$) according to ITU-T G.652; t_0 – time interval between PMD_Q measurements (h). Expression (4) calculates the speed of PMD coefficient development versus a maximum allowable PMD coefficient value.

Unfortunately, there is a lack of initial PMD coefficient measurements for both OPGW lines. The reason is that internal standards of operating organisation did not require PMD measurements as part of acceptance testing of transmission lines. Moreover, even ITU-T (former CCITT) Recommendation G.652 [8] valid in 1995 did not specify PMD parameters of optical fibre cables. For cable installed in 2011, PMD measurements were not provided again due to the operator's internal standards and considering the fact that the transmission line was not supposed to provide transmission with high data rates (>10 Gbit/s). For the research purposes, it was assumed that typical PMD coefficient values for single mode fibres produced in 1995 would be 0.10 ps/√km and for fibres produced in 2011 the PMD coefficient would be 0.02 ps/√km. These values were used as initial PMD coefficient values for NRWP and RP calculations.

Results of NRWP and RP calculations are presented in Figs. 6 and 7. Both probabilities for each fibre were calculated for 25 years of operation period as theoretical service life of fibre optic infrastructure accepted by the industry [9].

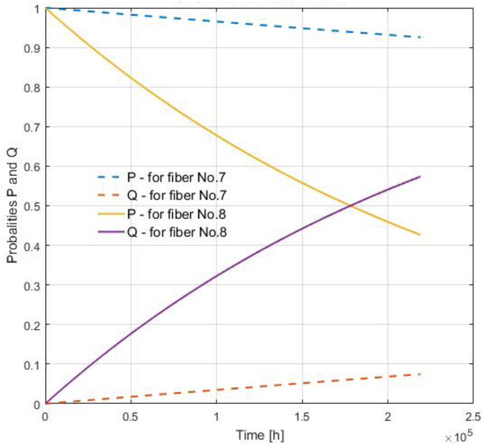

Fig. 6. Non-refusal work probability (P) and refusal probability (Q) for fibres No.7 and No.8 of OPGW line A.

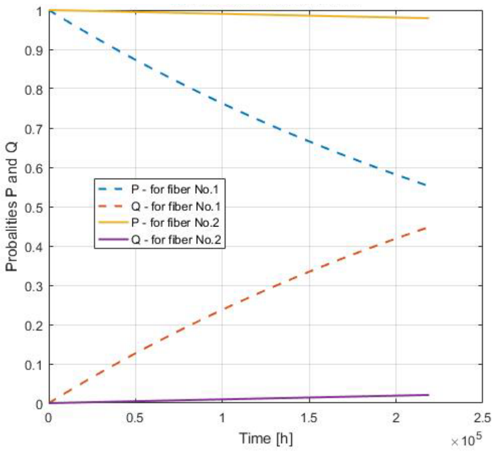

Fig. 7. Non-refusal work probability and refusal probability for fibres No.1 and No.2 of OPGW line B.

6. CONCLUSIONS

PMD values vary in OPGW cable different fibres: optical ground wire transmission line B, fibre No. 1 – 1.9746 ps; fibre No. 2 – 0.9994 ps; optical ground wire transmission line A, fibre No. 7 – 0.2208 ps; fibre No.8 – 0.5172 ps. To get complete understanding regarding PMD in OPGW transmission line, it is necessary to measure PMD values for each fibre in the transmission line.

It is worth mentioning that OPGW A (installed in 2011) fibres and OPGW B (historical – installed in 1995) fibre No. 2 correspond to ITU-T G.652.D attenuation and polarisation mode dispersion requirements (OPGW B fibre No. 1 violates the maximum allowed PMD threshold limit in six PMD measurements out of ten).

OPGW B (installed in 1995) cable fibres have as much as 4.03 times higher polarisation mode dispersion value than OPGW A (installed in 2011) cable fibres.

In order to get more precise PMD evaluation for each individual fibre, it is necessary to perform approximately 24 hour-long measurement, because a polarisation mode dispersion value is stochastic and significantly fluctuates over time mainly due to external weather conditions. In a long-term field measurement, the PMD value (OPGW A, fibre No. 7) fluctuates from 0.1118 ps to 0.2905 ps. It can be concluded that if short-term PMD measurement is performed, some part of information about PMD could be missing.

It is seen from the calculated NRWP and RP that most likely all studied fibres in both OPGW transmission lines will be in working order during 25 years of operation. However, certain attention should be devoted to fibre No. 8 in OPGW line A, where in 20 years of operation (14 years from now) refusal probability is expected to exceed non-refusal work probability. One the other hand, PMD parameters become essential when a transmission bit rate exceeds 10 Gbit/s. This means if an operating company does not require systems with 10 Gbit/s or higher, the studied OPGW lines may satisfy demands even with higher PMD values. As already mentioned, considering stochastic nature of PMD, more measurements with longer measurement time would be required especially if the PMD parameter is used to predict infrastructure lifetime. In addition, these measurements should be made on a regular basis (for instance, once a year for five years) in order to accumulate measurement results and obtain precise understanding how PMD changes over a longer time period. In the current research, initial measurement information is missing and it has been assumed that PMD evolves linearly over time.

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EKRĀNTROSĒ IEMONTĒTAS PĀRRAIDES LĪNIJAS OPTISKĀS ŠĶIEDRAS DZĪVES CIKLA NOVĒRTĒJUMS

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K o p s a v i l k u m s

Pieaugot pieprasījumam pēc datu pārraides ar lielākiem datu pārraides ātrumiem, ļoti būtiski ir novērtēt iespējas palielināt datu pārraides ātrumu jau pastāvošā optisko pārraides līniju infrastruktūrā. Lai to paveiktu, ir nepieciešams analizēt parametrus, kas ierobežo datu pārraides ātruma palielināšanu. Viens no būtiskākajiem ierobežojošajiem parametriem ir polarizācijas modu dispersija.

Pētījuma teorētiskajā daļā ir analizēti polarizācijas modu dispersijas rašanās cēloņi, kā arī analizēta vispārējā interferometriskā polarizācijas modu dispersijas mērīšanas metode.

Pētījuma praktiskajā daļā veikta polarizācijas modu dispersijas analīze un novērtējums, balstoties uz AS „Latvenergo" OPGW kabeļu līniju mērījumiem ekspluatācijas apstākļos. Pētītās kabeļu infrastruktūras dzīves cikla paredzēšanai izmantoti polarizācijas modu dispersijas koeficientu mērījumi, uz kuriem balstoties veikti bezatteikuma darba varbūtības un atteikuma varbūtības aprēķini optiskajām šķiedrām. Pamatojoties uz aprēķinātajām varbūtībām, tiek novērtēts vai kabeļu līnijas saglabās darbaspējīgu stāvokli laika intervālā, kas nozarē ir vispārpieņemts kā šāda veida sakaru infrastruktūras minimālais kalpošanas laiks.

Nobeigumā pētījuma autori apkopo rezultātus, izdara secinājumus un sniedz rekomendācijas, balstoties uz veiktajiem mērījumiem OPGW kabeļu līnijās reālos ekspluatācijas apstākļos.