External Electromagnetic Influences upon Optical Cables

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Abstract–**This moment electric coupling is realized generally by means of optical fiber. Optical fiber cables are usually buried or suspended nearby earth surface. Electrical and magnetic fields of different sources can to exist in vicinity of optical fiber cable. Under influence of these fields the polarization plane of light rotates for some angle. As there is a small eccentricity of fiber, there are two main axes in a fiber, some birefringence springs up. If fiber cable has no metal in its design, the influences of transverse electrical field and of longitudinal magnetic field upon fiber stimulates turning of polarizations plane of lights in fiber. These effects are known as effects of Kerr and Faraday. Basic sources of external electromagnetic fields are lightning, high-altitude nuclear explosion and high-voltage lines. Lightning and high-altitude nuclear explosion can cause heavy current in metallic elements of cable and cable damage by gamma-rays. Exposure is of short overlooked depending on transmission type, but some times it can have severe effects.**

I. Introduction

It is supposed usually, that only optical cables with metallic elements in design can be subjected to lightning influence and other sources, but entirely dielectric fiber cable is not subjected to external electromagnetic field influence of lightning and other sources. But it dos not always conform to reality. If the dielectric fiber cable is lying in earth and lightning stroke takes place nearby, the lightning electromagnetic field causes rotation of the polarization plane of light wave that is transmitted in cable. This interaction of fields was opened in XIX century and is called effects of Kerr and Faraday. Rotation of polarization plane can cause information transfer failure, particularly if great number of wave is transmitted simultaneously in this fibre and it is used equipment that is sensible to polarization (for example Raman amplifier). This action is not too big, but sometimes it can have severe effects. Recent discoveries in study of lightning have shown, that during lightning stroke gamma-ray emission arises, that attenuated usually when arrived at earth surface. However the optical cables lying in in the mountains can be subjected to influence of lightning gamma emission, because distance between cloud and earth in the mountains diminishes. In this paper there are some individual cases of external electromagnetic field influence upon optical fiber cables.

II. Lightning Impact upon Laying in Ground Fiber Cables with Metal in Construction

During lightning stroke to earth nearby laying in ground fiber cable, current part rushes for cable and is spreading its metallic elements (armor, sheath, cores). At the same time an electric arc origin is possible from lightning stroke point to cable. In the arc volume sudden water evaporation takes place and on the rising edge the water vapor pressure can reach some hundreds atmospheres. It is electrohydraulic effect. It can cause cable damage until lightning current hits to the cable. By current spreading along cable, potential difference between cores and armor rises owing to different spreading parameters of circuits armor-earth and cores-earth, that can cause insulation breakdown in some different remote points. If current amplitude is big near some tens kiloampere, it can cause the cable or its elements melting [1]. The probability of these events depends on thunderstorm activity, resistivity, soil moisture and cable parameters. Protection of such cables is realized by parallel buried metallic conductors, that take part of current, or protection by periodic connection of earth to metal cable sheath.

V.Rakov et al. (Florida University) have examined the mechanism of compact introcloud discharges that are responsible for radiation in the spectrum up to 30 MHz [2]. If a cloud is situated at a height of near 6 km, discharge development put usually to stroke to earth. However if a cloud is situated at a height 12-15 km, discharge development occurs in another way. These discharges happen in thunderstorm clouds at high altitude (10-15 km), where field magnitude is insufficient for breakdown to earth. Clouds bottoms are negatively charged usually. When electric field strength reached the extreme value, discharge is beginning from cloud bottom to positive charged cloud top. The discharge advances at a speed of near 200 m/μs, and in a time of microsecond parts reaches the cloud top. Here coming discharge partly is absorbed and partly is reflected backwards. It is «bouncing wave». Reflection coefficient is contained

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within the limits from 0 till -0.5. Next the wave advances downwards and on the bottom of cloud the new reflection takes place. This wave has duration about some tens microseconds and its duration is a lot more than time of reflected waves passing up and down. The wave acquires form of impulse with applied numerous jumps of reflected waves. Distance between jumps corresponds time of motion up and down that is part of microsecond. The electric field of introcloud discharges has inductive, static and radiation component. Inductive components prevail distantly 2 km (across) so the field is similar to current shape. Distantly 200 km the electrical field is radiation component and measured impulse peak had 1.5 V/m when current has 50 kA. Radiation flash has spectrum till 30 MHz.

III. Polarizations Plane Rotation of Light in Fiber under Influence of Electrical Field

When cable without metal in construction is lying in earth, and the lightning stroke is happening near it, upon influence of transverse electrical field of lightning stroke, the polarizations plane of transmitted lights wave in cable turns on angle φ [3]:

$$\varphi = 2\pi K E^2 L \tag{1}$$

K is the constant of Kerr. For wavelength of light λ=1.55 μm , $K = 0.402\cdot 10^{-3}$ m/v^2, *L* is length of the fiber under influence of electrical field.

During lightning stroke to earth powerful electrical and magnetic fields arise in the vicinity of buried optical fiber cable. If lightning stroke occurs at distance *a* from fiber cable and the cable is buried on depth *h*, the electric field magnitude can be found from the expression:

$$E = I \frac{\sqrt{a^2+h^2}}{2\pi\sigma(a^2+h^2+x^2)^{\frac{3}{2}}} \tag{2}$$

I is amplitude of lightning stroke, A; σ is conductivity of earth, 1/ Ω·m, σ = 1/ρ.

Axis x is directed along fiber, point x=0 corresponds to the point of fiber, which is the nearest to point of lightning stroke on the earth surface. If to substitute (2) into (1) and to integrate to both sides from x=0 we shall find that angle of polarizations plane rotation (PPR) of light in fiber under influence of electrical fields of lightning is

$$\phi = \frac{3}{16} K \frac{(I\rho)^2}{(a^2+h^2)^{\frac{3}{2}}} \tag{3}$$

If average values of parameters in (3) are I = 50 kA, ρ = 1000 Ω·m, a =10 m, h =1 m we shall find, that φ = 1º, that is one-shot lightning impact in one point creates a small effect. There have calculation of polarizations plane rotation (PPR) carried out on conditions that a = 2, 3, 5 and 10 m; ρ = 100, 200, 500, 1000 and 2000 Ω·m; I = 30, 50 and 100 kA; h = 1 m. The calculations have shown if lightning stroke with amplitude under 100 kA takes place within 5-10 m from cable the PPR does not exceed 10°. If lightning stroke occurs at a distance less than 5 m from cable and the current amplitude has some tens kA and earth resistivity is more than 500 Ω·m the PPR can have some tens degrees. The lightning stroke at distance more than 10 m from purely dielectric optical cable has not an influence on signaling and cable functioning. Only in some cases when earth resistivity and lightning current are too big and the short lightning point distance (for example a = 1 m) effect size can rise. The author has not experimental verification of calculations datas.

IV. Rotation of Polarization Planes when there are Some Different Waves

The Wavelength Division Multiplexing (WDM) systems development with increasing number of carriers brought to transmission in the same transparency window some tens or hundreds waves. They are shifted relative to each other for some parts of nanometers. Therefore the polarization plane rotation (PPR) will be different for each wave (other conditions being equal): the short waves rotated greater long waves. If fiber cross-section is some ellipse and all the waves have the same polarization (for example, vertical), then after rotation the short waves will have major components lengthwise horizontal axis and the long waves will have rather major vertical components. In the issue by subsequent propagation the long waves will have in preference the vertical polarization and the short waves will have horizontal polarization. On input of optical amplifier there will be packet of waves with different polarizations, and it can produce problems to filters, optical insulators and amplifiers, to Raman amplifiers specially, which are sensitive to polarization. It is known that short and long waves are moving with different velocity as refraction index depends upon wave length. In addition the refraction index can vary through discontinuity in cross-section on axes along fiber. The velocity of waves with different polarization will be different, and as a result of influence of lightning there will be sui generis additional PMD. More aberrations it should be awaited during polarized multiplexing when there are two wave sets channelized at the same time with different (vertical and horizontal) polarization. After close stroke influence wave amounts will have the different polarization on every axis and will contain components, that had other polarization earlier. At moment of influence signal can be spoiled. Disturbances will happen in all channels at the same time. When it is considered that the every wave has temporal multiplex, the number of spoiled channels can be very big (tens of thousand). However duration of all components of lightning current passing is not exceed some seconds and at this moment there are PPR possible and other disturbances of transmission. Thus duration of disturbances will evidently only some seconds. Negative consequences are depending on whether service interruption during some seconds is significant. If there is conversation transmitting, then disturbance during some seconds will not large complication and it can overlooked. If there is data transfer or switching - switching off signal, after-effects can be serious. Disturbances scale is depending too if PPR is remained in-line spread. However it should be remembered that wave multiplexing WDM is used only to some lines and serious consequences are possible only on some important lines.

V. Polarizations plane rotation of light in fiber under influence of magnetic field

The turning of polarizations plane under influence of longitudinal magnetic field is:

$$\psi = V \cdot L \cdot B$$

B is magnetic induction; *L* is length of the fiber under influence of electrical field;

V is the constant of Verde. The constant of Verde depends on physical state, wavelength of light and dn/dλ.

For silica glass with λ = 1.55 мкм we have:

$$\psi = 1.66 \cdot 10^{-5} \cdot L \cdot H \text{ grade.} \quad ,$$

where *H* is in A, *L* is in m.

At the depth z field value differs from field value close to earth surface. If field pulses are short, taking into account conduction and bias currents in range of lightning time, we can approximately to take for field H on the depth z:

$$H(z,t) = H_0(t - z\sqrt{\mu_з \cdot \varepsilon_з}) \cdot e^{-\gamma \cdot z} \quad ,$$

where H_0 is the field on the earth surface; $\mu_з$ and $\varepsilon_з$ - magnetic and dielectric permeability;

γ – propagation constant of field in earth,

$$\gamma = (\sigma/2) \cdot (\mu_з \cdot \varepsilon_з)^{1/2} ;$$

σ – earth conductivity. If σ is represented in 1/Ωm, then γ = 56σ 1/m.

Process delay in time has not significance in such a case, therefore we can write that the field on the depth h is:

$$H_x = \frac{Ia}{2\pi(a^2 + x^2)} e^{-56 \cdot \sigma h} \quad ,$$

$$\Psi \cong \frac{fI}{2} e^{-56\sigma(h+a)} \quad .$$

In addition not all current of lightning take part in field generation along cable, but only that part which is inside some solid angle where cable under review is situated. But this mistake is not essential.

Supposing $I = 50 \cdot 10^3$ A; $\rho = 10^3$ Ωm; $h = 1$ m, we find, that if λ =1.55 μm Ψ = 0.4 grades. Evidently the turning of polarizations plane in optical cable under influence of longitudinal magnetic field during lightning stoke, which has middle parameters, is small.

The cross section of fiber is not a real circle, but looks like an ellipsis, and there are two main orthogonal components of fields and signal that can give rise to polarization mode dispersion. Aftermath of large magnetic field influence, as of electric field, are depending of transmitting information form, it can be serious and it can be overlooked.

VI. Gamma-rays of lightning influence upon dielectric fiber cable

Investigations of Dwyer et al. [4], [5] have shown that lightning produces X- and Γ-rays radiation during leader stage of discharge. The origin of gamma radiation take place during the first stage of leader process at descending (downward) lightning. Leader process can be as descending (negative) and ascending positive (bottom-up) which is beginning from earth. The ascending leader appears during reduced distance between cloud and earth, for example in mountains or near high structure (skyscraper, tower). Flash of radiation of gamma rays in this case occurs when ascending positive arrow-shaped leader arrived to cloud at some kilometers above earth surface. Interesting results have been found during trigger-lightning investigations. On the earth surface there are strong radiation observed of quanta with energy more then 10 MeV. Originated on the altitude 6-8 kilometers quanta flux has very strong energy and density. Gamma radiation attenuates strong in atmosphere and quanta number on the earth surface is equal to some units through square centimeter. Half-value thickness of gamma rays for some materials is shown in table I. It is thickness of layer going through quanta density diminishes half.

TABLE I. Half-value thickness of gamma rays for some materials

Material	thickness of layer, cm	specific weight, g/cm^3
Lead	1.8	11.3
Concrete	6.1	3.33
Steel	2.5	7.86
Packed soil	9.1	1.9
Water	1.8	1.00
Wood	29	0.56
Standard air	15000 (150 m)	0.0012

It can suppose that atmospheric density is constant up to altitude 4-5 kilometers and half-value thickness does not changes although atmospheric pressure drop a little. The normal pressure at sea level is 101.3 kilopascal. During lifting the pressure decreases by 12 kilopascal for 1 kilometer, so on the altitude 3 kilometers the pressure will be 65.3 kilopascal. It do not change strongly half-value thickness. With altitude increasing by 1000 meters the temperature fall for 6°C. If on the sea level the temperature is 25°C, on the altitude 2750 meters it is - 10°C. So temperature influence will not be essential. Humidity fall too but it appears in mountains weakly. Usually lightning stroke is brachiate and multiple and discharge reaches the earth in some points (on average 3), which are located distantly till some kilometers. It is unknown if γ-quanta appear only during leader stage or during iterated strokes too. We shall suppose for reliability that γ-quanta arise only once during leader stage. Spreading (flying off) is going to all directions. Total expansion area in cross-section can have near 1 square kilometer, so new strokes near to this place can cover already radiation-exposed area during preceding lightning stroke. It can suppose, that half-value thickness is invariable within 3-4 kilometer above sea level and it is equal 150 meters. Quanta number dependence on altitude is:

$$N_{\text{whs}} = N_{\text{w0s}} \cdot 2^{H/150}$$

N_{whs} - number of quanta with energy w, that are passing by section S at altitude H; N_{w0s} - number of quanta with energy w, that are passing by section S at sea level; H – altitude at sea level, meter; S – horizontal section (cm^2 or mm^2).

Number of quanta with high energy, that are passing by section S = 1 mm^2 at altitude H run up to some hundreds of thousands. Gamma-ray impact on fiber causes displacement process, lattice defects and color centers formation that lead to additional attenuation and other curses. Low hydroxyl group content reduces fiber radiation resistance. Polymeric fiber is particularly sensitive to radiation in consequence of polymer chain destruction. When fiber lines are laid in mountains it is necessary to take into account. Table II shows information about energy exposure, that single-mode fiber core with d = 10 micrometer receives at different height above sea level.

TABLE II. ENERGY AND POWER EXPOSURE, THAT SINGLE-MODE FIBER CORE WITH D = 10 MICROMETER RECEIVES AT DIFFERENT HEIGHT ABOVE SEA LEVEL

H, meter	Total energy of gamma quanta, MeV	Radiation dose, radian	Power exposure, radian/second
1050	12	10^{-2}	65.5
1500	143	0.136	780
2100	2703	2,230	$14900 \sim 1{,}5 \cdot 10^4$
2550	18428	15	10^5
3000	292570	238	$1.6 \cdot 10^6$
3600	2307700	$1890 \sim 2 \cdot 10^3$	$1.25 \cdot 10^7$

It is seen from Table II that radiation dose and power exposure begins rise sharply after altitude 2000 meters above sea level. Radiation dose is tens radian for single-mode fiber at altitude 2500 meter and hundreds radian at 3000 meter. Quanta with energy more than 5 MeV are carrying the most part of energy to fiber. The contribution of quanta with energy 1-2 MeV is little. Power exposure increase especially sharply, it can be 10^4 radian/second at altitude 2000 meter and 10^7 radian/second at altitude 3000-3500 meter.

If optical fiber cable is laid in mountains at the altitude over 2000 meter, attenuation can rise till tens dB/km during thunderstorm with continuous and unpredictable relaxation time. Susceptibility and relaxation time are closely related bond type and structure, impurities, microcrack and deformation availability, OH content, fabrication technique, drawing out conditions, chlorine presence, geometrical dimension (upsizing reduce internal stress). Destruction time of absorption centers can swing from some seconds till some years. Lifetime of absorption centers depends of temperature, dopant, power transmission. It reduce with temperature lowering. Absorption centers lifetime is some minutes at temperature -55°C. Boron dopant shortens relaxation time. The pure quartz multimode fiber are the most stable to radiation. Polymeric fiber has enhanced vulnerability to radiation.

We have considered single leader process consequences only and we have not take into account that lightning discharge density is more than 1/km^2 during stormy season in area majority. If there are repeated lightning strokes in laid fiber cable area, new absorption centers can add to already in existence, and fiber state will become worse. This problem is serious and it is in need of complex study and experimental checkout.

VII. ELECTROMAGNETIC PULSE OF HIGH-ALTITUDE NUCLEAR EXPLOSION

During high-altitude nuclear explosion conductive «pancake» of huge proportions arises [6]. In this area there are the heavy-currents that generate a big strength of field on earth surface. The radius of this area is about

$$R \cong 113\sqrt{H} \quad \text{km} ,$$

H is altitude of explosion, km.

During explosion at altitude 60 km influence zone radius is near 875 km. The electromagnetic pulse has some components, the worst-possible component is E1 that is like lightning pulse but shorter in time with pulse rise time 10^{-7} second and overall duration 10^{-6} second. Standard form of E1 pulse is 2,5/23 billiseconds. The electric field intensity near earth surface is from 10 till 100 kV/m. Magnitude E_m depends on distance from epicenter and weakly (logarithmic) on explosion power. The picture is symmetric relatively magnetic meridian. Absolute maximums of radiating current are situated on magnetic meridian. Maximal influence at earth surface will situated on magnetic meridian line to the south of epicentre at point r ≈ $0.36\,H$ (r is distance to epicenter). The second maximum will distantly r ≈ H northern of epicenter. However its magnitude is smaller considerably. The current wave magnitude in cable depends on its length. If cable length is 1 m, the current can have magnitude 50 A, if cable length is 10 m, the current can have magnitude 200 A. If cable has big length in latitudinal direction the current can reach 2.5 kA. Equipment and its parts, that are hanged to cables, can subject to challenges. Magnetic field on the earth surface can reach some tens A/m.

VIII. INFLUENCE OF HIGH-VOLTAGE POWER LINE

Suspended fiber cable close to high voltage line or electrical railway is under the electrical field influence . There are some different processes causing the cable damage. A dusting and moistening of sheath leads to current flow and surface sheath breakdown. The corona on the clamps gives rise to release of ozone and nitrogen oxides that can damage as metallic and dielectric constructions. The current flowing along aramid threads leads to water boiling and polyethylene thermal deformation and to swelling rise. Some aspects of these effects are considered. Longitudinal electrical field intensity component along cable can exceed 20 kV/m magnitude. It is true particularly at points that are close by supporting structure, where pylon cable distance is minimal. Breakdown initiation process has been described in [7], [8]. It was shown, that dirty surface during rain or fog is conducting and a current flows through cable surface. Non-conducting ring areas are forming by drying up of moistened layers. Voltage that is applied at the ring area gives rise to electrical breakdown. Electric arc traces appear on the cable sheath surfaces and due to that its step-by-step destruction occurs. A new cable clean sheath has surface resistance about 500 MΩ/cm. Cables subject to wind bearing load, thermal and ultraviolet sunlight impact and other external influences when it rains. As a result of that the surface microstructure is changed. It becomes uneven rugged. Great number of microjuts and micronicks are appearing. Dust and moisture fasten to up the roughness relief. The surface resistance is significantly decreasing.

Optical cable of some a length L can be considered as a bar of the length L, diameter D and dirty layer thickness Δ. The dirty layer resistance R is equal

$$R = \rho L/\pi D\Delta,$$

ρ is three-dimensional resistivity of the dirty layer. It can have value of 1 to 100 kΩ·cm. If we consider the surface resistivity as $\sigma_s = \Delta/\rho$, than the dirty layer resistance will take the form

$$R = \frac{L}{\pi D \sigma_S}$$

The dirty cable plastic sheath surface has conductance similar to insulator dirty surface conductance. The insulator dirty surface conductance values σ_s , as that is shown in table III below.

Sheath surface current is equal to $I = E_L\, \sigma_s\, \pi\, D$, current density is $j = E_L\, \sigma_s$. Under this consideration point E_L is dependent of placement and dampening intensity. Close by pier electrical field horizontal component intensity is more than in the middle of span. According to the table we can roughly estimate the surface current. It will be from 0.3 to 12 mA. This fact has confirmed by experiences. For instant, the surface current of fiber cable, which had been suspended close by to electrical railway, is equal from 1.3 to 4 mA. It should be note, that currents exceeded these limits substantially had been also observed. Conducting layer heated up during current flowing and the moisture evaporates non-uniformly, the resistance of some sections and voltage drop increase until dry surface discharge occurs. Breakdown strength value depends on wetting intensity, level of impurity, drying up rate. Surface conductance determines breakdown field intensity. This dependence for insulators was obtained by Kostenko [10] and has shown on Fig.1.

TABLE.III. INSULATOR DIRTY SURFACE CONDUCTANCE Σ_S (AVERAGE VALUES)

Surface condition	σ_s, µSiemens
Clean	≤ 2
Weak dirty	≤ 4
Heighten dirty	5 ÷ 10
Strong dirty	10 ÷ 20
Strong dirty close to manufacture, factory	20 ÷ 40

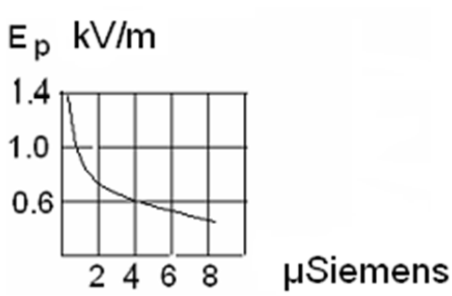

Fig.1. Values of average 50%- breakdown intensity of electrical field E_p depending on surface conductivity σ_s

Before stable arc discharge, partial and sliding surface discharges are possible .With the lapse of time the fiber cable surface becomes degraded. The surface microstructure changes; bulges, hollows, cavities emerge on the surface. This promotes slush, dirt and dust adhesion with cable surface. With the lapse of time cable surface resistance reduces and power dissipation increases. According to [4], power dissipation achieves peak with surface resistance about 2 kΩ/sm. The new effect was visualized on fiber cable that had suspended to electrical railway contact system pylons. Supporting clamps make a contribution to possibility of cable failure because corona can occur and corona discharges lead to surface degradation at stringing point, to thermal damage and even inflammation. Observations of fiber cables, which had suspended to the Trans-Siberian Railway contact system pylons, have shown that corona process goes with ozone and nitrogen oxides release, which attacks and inflicts damage on both metallic and dielectric constructions. Polarization processes in dielectric also give rise to additional heat generation, and they can provoke in aggregate with outward heating to cable sheath swelling, if sheath has aramid yarn.

Sheath damage is possible as mechanical or in consequence of corona discharges in the points of fiber cable fastening to pier. Condition appears for aramid threads moistening and for current flowing. The current flowing leads to water boiling and polyethylene thermal deformation and as a result to swelling rise on the sheath. It takes temperature near 105-120º C.

A number of measures are offered to make it better (state and for control):

1) cable sheath washing by special solution every side pieces from supporting clamp 0.5 meter long;
2) change supporting clamp size for corona reduction;
3) application of plaited polymer rope instead of supporting clamp;
4) an earthing improvement.

CONCLUSION

The optical cables can be exposed to serious influence of external electromagnetic fields. But their after-effects depend on content is transmitted by cable. Condition of laying play a decisive part in failure origin, but since action time and drop-out are often smallish (some seconds), aftermath is essential not always. If there is conversation transmitted, then a failure can be not noticed. If there are transmitted signals of activation or alarm, aftermath of glitch can be serious. So protection is not always closely related with mounting of safety devices, but with transmission procedure.

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