ENVIRONMENTAL INFLUENCE ON THE SAFETY AND RELIABILITY OF ELECTRICAL AND COMMUNICATION SYSTEMS

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Abstract:

Electrical systems may fail due to change in the properties of constituent materials under environmental influence. This failure may engender catastrophic events, such as material damage, environmental disasters or loss of human lives. For example, ships, as complex systems, are exposed to the aggressive nature of the marine environment. The influence of dominant factors on dielectric properties is analyzed in this paper through the relative dielectric constant, and the refractive index. Parameter changes are shown to alter the value of the constant by numerical examples. These different values can result in fatal system failures. Taking into account these facts, the influence of material on the electrical system is illustrated to make the reliability calculation more complex. The results were negative, as shown in the Calculation and results section.

1 Introduction

The quality of materials is considered in many references [1–5]. The ageing of materials is indicated as possible cause of problems, including human casualties, financial and environmental damage. A change in the properties of materials can influence safety even when construction materials are not taken into account. Furthermore, although changes in environment may affect the performance of electrical systems, they frequently do not fall within the scope of research. For example, environmental influences may affect the properties of fiber optic materials, eventually degrading signals [6] used for i.e. autopilots in ships, aircrafts, or other vehicles, including future cars. Environmental factors are likewise capable of degrading the dielectric properties of a ship's electro-energy system (dielectric loss, breakdown voltage, insulation aging, and dielectric constant). Similarly, electric circuit failures due to insulation wear and tear can have considerable consequences for any electrical system [7]. The failure of a single electric circuit signal may cause train collisions, plane crashes, ship stranding or collisions. The importance of temperature sensitivity in ship system

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design can not be overstated. Poor design has been known to cause ship malfunctions. For example, electronic/control components or sensors might have such temperature sensitivity that, if cooling fails, the entire ship comes to a standstill.

The influence of materials on the environment has been a frequent subject of study. In this paper, we do the opposite. We examine the influence of the environment on the properties of materials, and consequently, on the reliability and safety of electrical systems.

For example, we will present environmental influence on the relative dielectric constant, which is closely linked to the electrical capacity, and, consequently, to electrical breakdown of electrical insulators (if the usual electrical charges are applied and the dielectric constant changed, the capacity will also change, possibly causing the degradation of material or even a partial discharge) [8, 9], and to the refractive index in the optical materials. Both optical materials and insulators are dielectric materials. The importance of optic materials was emphasized in [10]. Optic materials are a crucial part of optical fiber sensing technology and optical communication systems. These technologies have a variety of applications, including the monitoring of traffic systems, such as bridges, tunnels or pipelines, the Internet, cable TV, etc. The issue of the influence of environmental conditions on electrical systems is very important in open environments, in which parameters considerably vary depending on weather conditions, season, climate changes or other factors. We are especially interested in the highly aggressive marine environment, the suppression of the influence of which requires a number of measures to be taken, i.e. corrosion prevention.

This paper is organized as follows. The second section describes mathematical expressions for dominant factors dependencies. The third section presents the methodology of the electrical system failure evaluation. The fourth section presents results for two considered cases – relative dielectric constant and refractive index. Finally, conclusions are given.

2 Dominant influential factors

Researchers are aware of the influence of environmental conditions on core materials in different products. Environmental impact on the dielectric constant was explored in many references, like [11–13] to name a few. The first step in our research was to identify dominant environmental factors contributing to the change of the dielectric constant. Some factors were identified in [6, 14] as: temperature, operational frequency, moisture of the materials, relative air humidity, and air pressure. The supposition that different atmospheric mixtures change the refractive index of air was not supported by the research in [6] for usual CO_2 concentrations (including a reasonable range of variations depending on geographical position).

Temperature dependence of the dielectric constant was a topic in [15–17]. Frequency was the scope of e.g. [18,19]. Moisture was studied in [11–13, 15, 20, and 21].

Since developing the exact mathematical method for each dependence would be painstaking, heuristic mathematical expressions were developed for specific materials and dependences. For example, the frequency dependence of the relative dielectric constant [22] can be expressed with (1):

$$\varepsilon_r(\omega)=\varepsilon_\infty+\frac{\varepsilon_{DC2}-\varepsilon_{DC1}}{1+\left(i\omega/\omega_r\right)^{1-\alpha_2}}+\frac{\varepsilon_{DC1}-\varepsilon_\infty}{1+\left(i\omega/\omega_r\right)^{1-\alpha_1}}\,, \quad (1)$$

where, symbols in (1) are denoted as:

- ε_∞ is the value of the constant at the infinity frequency (in practice, high frequencies in range where orientational polarization is negligible),
- ε_{DC1} and ε_{DC2} are the values of the constant at 0 (Hz) in case of two relaxation peaks (describing the spread of the relaxation peaks),
- ω_r material's resonant frequency.

Equation (1) is valid only if a material has two relaxations peaks. Otherwise, the mid part should be skipped.

Moisture in material can occur due to environmental conditions or manufacturing process. The correlation between the relative dielectric constant and moisture [13] is expressed by (2):

$$\theta=a\pm b\cdot\varepsilon_r+c\cdot\varepsilon_r^2\pm d\cdot\varepsilon_r^3, \quad (2)$$

where,

- θ is the moisture content, and
- constants *a*, *b*, *c* and d depend on type of material.

Constants *c* and *d* are optional (can be 0).

The combined influence of temperature and frequency was presented in [16] with (3):

$$\varepsilon_r(\omega,T)=\varepsilon_\infty+\sum_j\frac{S_j(T)\Omega_j^2(T)}{\Omega^2{}_j(T)-\omega^2-i\gamma_j(T)\omega}, \quad (3)$$

where, temperature contribution is introduced through equations (4-7):

$$\Omega_j(T)=\Omega_j(T_0)+a_j[T-T_0], \quad (4)$$

$$S_j(T)=S_j(T_0)+b_j[T-T_0], \quad (5)$$

$$\frac{\gamma_j}{\Omega_j}(T)=\frac{\gamma_j}{\Omega_j}(T_0)+c_j[T-T_0], \quad (6)$$

$$\varepsilon_\infty(T)=\varepsilon_\infty(T_0)+e[T-T_0], \quad (7)$$

where,

- ε_∞, Ω_j, S_j and γ_j are respectively the high-frequency value of the dielectric constant, and the transverse optical wave number, the dielectric strength and the damping of the *j*th phonon,
- e, a_j, b_j, and c_j are constant coefficients, and
- T_0 the reference temperature.

All of these take into consideration the response of material to some of the contributing parameters in the material. However, since material reacts with air, the characteristics of air should also be taken into account.

In order to evaluate the impact of air humidity on the change of the refractive index, the Ciddor equation is used [23, 24], which is also the frame for the incorporation of other air properties, such as pressure, CO_2 concentration, or temperature. Of course, the equation should be noted to take into account the refractive index of air. In case of three-layer optical structures or optical sensor technology, since air is one of the layers, any change in air refractivity has a direct impact on modes of optical signal propagation. Thus, any air and optic core material changes should be taken into account.

Details about Ciddor equation implementation can be found in [23] and at Engineering Metrology Toolbox. This equation establishes a correlation between the refractive index and atmospheric parameters as in (8):

$$n_{air}=1+\frac{\rho_a}{\rho_{aks}}\cdot r_{aks}+\frac{\rho_v}{\rho_{vs}}\cdot r_{vs}, \quad (8)$$

where, n_{air} is the refractive constant of air.
Other variables in (8) are defined with (9-14):

$$\rho_a=(1-x_v)\cdot p\cdot\frac{m_a}{z_m\cdot r\cdot T}, \quad (9)$$

$$\rho_v=\frac{x_v\cdot p\cdot m_v}{z_m\cdot r\cdot T}, \quad (10)$$

$$\rho_{aks}=p_{r1}\cdot\frac{m_a}{z_a\cdot r\cdot t_{r1}}, \quad (11)$$

and ρ_{vs} = 0.00985938 (kg/m^3). Further necessary details are (12, 13):

$$r_{aks}=r_{as}\cdot\left(1+5.34\cdot10^{-7}\cdot(\mathrm{x}_{\mathrm{cO2}}-450)\right), \quad (12)$$

$$r_{as}=\left(\frac{k_1}{k_0-s}+\frac{k_3}{k_2-s}\right)\cdot10^{-8}, \quad (13)$$

where,

- x_{cO2} is the concentration of CO_2 in air,
- k_0 = 238.0185 (μm^{-2}),
- k_1 = 5792105 (μm^{-2}),
- k_2 = 57.362 (μm^{-2}),
- k_3 = 167917 (μm^{-2}),
- $s = 1/\lambda$.

Parameter r_{vs} is defined with (14):

$$\begin{aligned}r_{vs}&=1.022\cdot10^{-8}\cdot\left(w_0+w_1\cdot s+\right.\\&\left.+w_2\cdot s^2+w_3\cdot s^3\right)\end{aligned}, \quad (14)$$

where,

- w_0 = 295.235 (μm^{-2}),
- w_1 = 2.6422 (μm^{-2}),
- w_2 = -0.03238 (μm^{-4}),
- w_3 = 0.004028 (μm^{-6}).

For clarity purposes, the change of the refractive index should be stressed to be directly linked to change in the relative dielectric constant through (15):

$$n = \frac{1}{\sqrt{\mu_r \varepsilon_r}} \approx \frac{1}{\sqrt{\varepsilon_r}}. \quad (15)$$

Equation (15) is applicable to all optic materials, which are also dielectrics.

3 The influence of the dominant factors on the reliability and safety of electrical systems

The influence of environmental factors on optic materials is rarely studied. There are partial studies of some aspects, such as corrosion [25], refractive index over ocean [26] or organic aerosols [27]. The actual impact on measurements, which could also be applied to fiber optic sensors, was investigated in [28, 29]. Although these topics are seemingly unrelated, they are related in a wider sense. Namely, we are interested in marine applications. Open connections of fiber optic networks or sensors, frequently found onboard ships, are under the influence of the changing marine/ocean atmospheric conditions, including mixtures of inorganic and organic aerosols, corrosion effects, etc.

Typical dielectric materials are insulators and optic materials. Optic materials are used in optic cables in optic sensing and optic communication systems, important in complex traffic systems and means of transportation.

They are used both in fiber sensing technology and communication equipment. Insulators are important in electric and electronic parts of any electrical, electronic, communication or even traffic system.

Figure 1. An example of mechanical degradation of paper insulator - enlarged by optic microscope by the factor of 10 (Laboratory for Marine Electrical Engineering, Faculty of Maritime Studies in Split).

The problem with dielectric degradation is that it is not visible by human eyes. Hence, a system might become unsafe, and someone might, e.g. touch the insulator and fall victim to an unsafe electric circuit. This is simultaneously the motive behind this paper – the safety of people operating or maintaining the electric part of the electric system. Furthermore, a short circuit caused by an unsafe insulator, can cause electric system failure.

Fig. 1 and Fig. 2 show paper insulator at the microscopic level. Fibers can be seen to fray, which is the beginning of crack propagation.

Figure 2. Paper - enlarged by microscope by the factor of 40 (Laboratory for Marine Electrical Engineering, Faculty of Maritime Studies in Split).

On the other hand, failure of a part of the sensing or communication system might be caused by a change of the refractive index in the optic material, even if there is no mechanical damage. We will try to assess such impact. The system is unreliable if propagation mode changes exceed tolerable range.

The evaluation of traffic systems can be performed at higher or lower level.

At lower level, failure of material might be said to imply system failure, and, consequently, endanger human lives.

At higher level, a system can be observed as a single whole with probability of failure, without delving into details of constituent materials.

In this paper, we decided to deal with failure of material, causing fatal malfunctions of electric systems. However, systems are usually designed to be robust at some tolerance, e.g., up to 10% change in any given parameter.

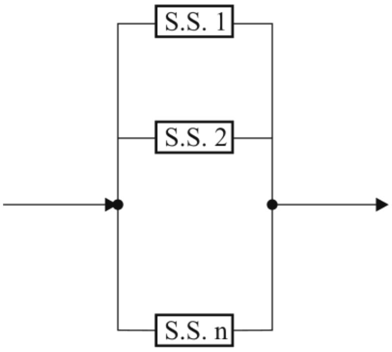
Proposition 1

If a material parameter is out of the designed range, the system will fail to deliver the desired response.
Proposition 1 describes the relationship between the micro-world and macro-world. This relationship requires the properties of the material and environmental impact to be incorporated in the reliability model of the analyzed system.
The greater the moisture, the lower the relative dielectric constant, and consequently, the lower the capacity and dielectric strength, reducing a system's resistance to, especially unplanned, disturbances.

Proposition 2

Environmental impact on the parameters of materials the system is made of should be taken into account in the reliability model in the serial branch, because failure of this component causes failure of the entire system or subsystem.

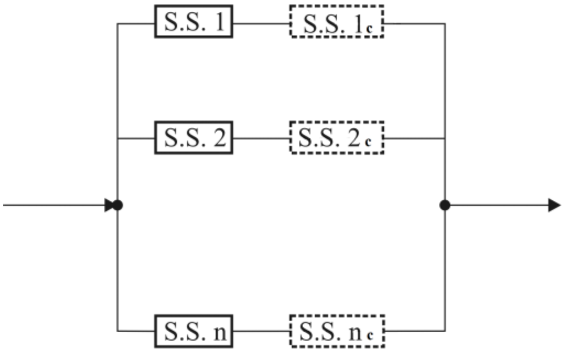
Fig. 3 and Fig. 4 illustrate a parallel component system (designated as S. S. – system component), and corrected system (with additional components designated as c, i.e. S. S. 1. c), respectively.



$$Q = P(S.S.1)\cdot P(S.S.2)\cdots P(S.S.n)$$

Figure 3. Reliability of a parallel component system.

Expressions in figures are denoted as:
Q – unreliability of a component or system,
P – probability of system/component failure, and
R –component/system reliability.
It can be seen (Fig. 4 in comparison to Fig. 3) that instead of parallel branches, the modified system consists of serial branches in parallel. It is actually a mixed system (serial-parallel combination). Expression in Fig. 4 is commonly used to study parallel systems.
Expression in Fig. 4 is modified to fit serial system's equation to parallel framework.



$$Q = \left[P(S.S.1\cdot(1 - R(S.S.1.c)))\right]\cdot$$
$$\cdot\left[P(S.S.2)\cdot(1 - R(S.S.2.c))\right]\cdots$$
$$\cdot\left[P(S.S.n)\cdot(1 - R(S.S.n.c))\right]$$

Figure 4. Reliability of a parallel component system with correction due to influence of the material.

Taking all this into account, the influence of material can be seen to make system reliability calculations more complex. However, as will be seen in the next section, they must be accounted for.

4 Calculations and results

In order to numerically simulate a change, two cases were chosen:
- impact of moisture on an insulator's dielectric constant, and
- atmospheric influence on the refractive index of an optical sensor.

Case 1

A simulation of the influence of moisture is introduced through Equation (2).

A change in moisture will cause a change in the dielectric constant. The new dielectric constant can be expressed with (16):

$$\theta' = a \pm b\cdot\varepsilon'_r + c\cdot\varepsilon'^2_r \pm d\cdot\varepsilon'^3_r. \qquad (16)$$

The change is expressed with (17):

$$\frac{\Delta\theta}{\theta} = \frac{a \pm b\cdot\varepsilon_r + c\cdot\varepsilon_r^2 \pm d\cdot\varepsilon_r^3}{a \pm b\cdot\varepsilon_r + c\cdot\varepsilon_r^2 \pm d\cdot\varepsilon_r^3} - \frac{a \pm b\cdot\varepsilon'_r + c\cdot\varepsilon'^2_r \pm d\cdot\varepsilon'^3_r}{a \pm b\cdot\varepsilon_r + c\cdot\varepsilon_r^2 \pm d\cdot\varepsilon_r^3}, \quad (17)$$

or with (18):

$$\frac{\Delta\theta}{\theta} = \frac{\pm b(\varepsilon_r - \varepsilon'_r)}{a \pm b\cdot\varepsilon_r + c\cdot\varepsilon_r^2 \pm d\cdot\varepsilon_r^3} + \frac{c(\varepsilon_r^2 - \varepsilon'^2_r) \pm d(\varepsilon_r^3 - \varepsilon'^3_r)}{a \pm b\cdot\varepsilon_r + c\cdot\varepsilon_r^2 \pm d\cdot\varepsilon_r^3}. \quad (18)$$

Depending on material, we can obtain linear, square and/or cube dependences. The simplest case is linear dependence (19):

$$\frac{\Delta\theta}{\theta} = \frac{\pm b(\varepsilon_r - \varepsilon'_r)}{a \pm b\cdot\varepsilon_r}. \quad (19)$$

The solution for "+*b*" case of (19) is given in (20):

$$\varepsilon'_r = -\frac{a\frac{\Delta\theta}{\theta} - b\varepsilon_r + b\varepsilon_r\frac{\Delta\theta}{\theta}}{b}. \quad (20)$$

If we take, e.g. *a* = 0.40283, *b* = -0.04231, *c* = 0.00194, *d* = -0.000022 (which are used in standard models available, not explored in maritime) [13], and a relative 10% change in moisture, and, for simplicity, if ε_r = 100, then the new (corrected) ε'_r = 90.9521. A 10% change in moisture can be concluded to cause a 9% change in the relative dielectric constant, which could be indicative of some new design guidelines. In case of polyethylene, this would imply a change of the relative dielectric constant from the referent 2.25 to 2.977 or by 32.31%. However, since moisture is only one parameter, the change of other parameters should also be taken into account since it could make the change of the relative dielectric constant deviate downwards or even upwards from 32%.

If ε_r = 5, a 10% change in moisture gives a new value of 5.4521, i. e., implies a 9% change in the relative dielectric constant.

The solution for "–*b*" case of (19) is given in (21):

$$\varepsilon'_r = \frac{a\frac{\Delta\theta}{\theta} + b\varepsilon_r - b\varepsilon_r\frac{\Delta\theta}{\theta}}{b}. \quad (21)$$

For the same numbers and the relative dielectric constant equal to 100, we calculated that ε'_r = 89.0479, i.e., an 11% change. In average, a 10% linear change in moisture produces a 10% average change in the relative dielectric constant. If ε_r = 5, we arrive at enormous and possibly unrealistic result (3.5479), which only tells us that we need new ways to obtain parameters *a* and *b* or a new model for different types of materials. However, it is a good illustration of damage which could be caused by environmental parameter change.

In the second case, we have linear and square dependences of the relative dielectric constant and moisture. The solutions for the square dependence are (22):

$$\varepsilon'_r = \frac{-b}{2c} \pm \frac{1}{2c}\left(b^2 + 4c^2\varepsilon_r^2 - 4c^2\varepsilon_r^2\frac{\Delta\theta}{\theta} + 4bc\varepsilon_r - 4ac\frac{\Delta\theta}{\theta} - 4bc\varepsilon_r\frac{\Delta\theta}{\theta}\right)^{0.5}. \quad (22)$$

For the same numerical example, the results are as indicated in (23) and (24):

$$(\varepsilon'_r)_1 = -73.5661, \quad (23)$$

$$(\varepsilon'_r)_2 = 95.3754. \quad (24)$$

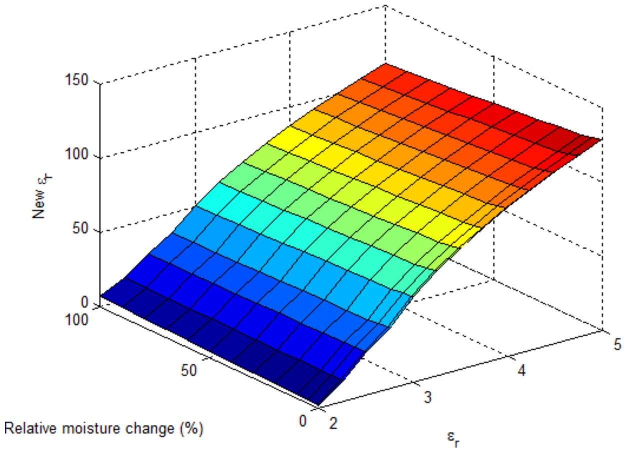


Figure 5. 3D surf diagram of dependence between old (ε_r) and new relative dielectric constant (ε'_r) with relative humidity (if materials belong to a group of materials to which the same empirical equation applies).

Fig. 5 illustrates that only limited range moisture and relative dielectric constant produce a reasonable new relative dielectric constant in the simulated model. Parameters *a*, *b*, *c*, and *d* should be corrected along with the dielectric constant and relative moisture to obtain realistic values.

Solution in (23) is obtained for the positive case of the quadratic equation solution. Solution in (24) is obtained for the negative case of the quadratic equation solution.

Negative solution is impossible in case of classic, known materials, but could be possible in the future due to advances in meta-material and femto-material design. A 10% change in moisture can be concluded to cause a 5% change in the relative dielectric constant.

The solution for the cube-dependence case is too extensive to be incorporated into this paper. However, if we take the same numbers as in previous cases, the results are real in (25), and complex in (26) and (27):

$$(\varepsilon'_r)_1 = 97.8894\,, \tag{25}$$

$$(\varepsilon'_r)_2 = -4.8538 + 53.3844i\,, \tag{26}$$

$$(\varepsilon'_r)_3 = -4.8538 - 53.3844i\,. \tag{27}$$

Solution in (25) shows that the value of the relative dielectric constant changes by approx. 3%. Solution in (26) and (27) could be dismissed at first sight, because real numbers are expected in the first place. However, complex solutions are not rare and are indicative of dielectric losses. The negative real part is the greatest problem, since it cannot be obtained by the currently known materials. These solutions should thus be dismissed at this stage of material science and technology. If the absolute value of complex solutions is considered, a 10% change in moisture can cause a 47% change in the absolute value of the relative dielectric constant, which could be promising in case of future meta-material and femto-material designs.

Case 2

The second case deals with the refractive index in fiber optics. The most extreme changes in parameters will be considered to calculate the extreme change of the refractive index, and, consequently, dielectric constant.

According to Ciddor [23], a 100°C change in air temperature causes a 1.000196605 change in the refractive index of air. Air temperature in Polar Regions frequently drops below zero, i.e., up to -40°C. This temperature corresponds to the value of the refractive index of air of 1.000339875. This could be a problem on ships which must be designed to operate reliably both at high temperatures, such as under the summer sun in the Equator, and at low temperatures, such as in the Polar Regions during polar night.

The Ciddor equation is technically reliable between 10 (kPa) and 140 (kPa), which correspond to 1.000026208 and 1.000372769 values of the refractive index or 0.999986896 and 0.999813668 value of the relative dielectric constant, respectively. However, these extreme pressures are not realistic in nature. If the relative humidity of air is 100% and other parameters are within standard values, the refractive index is equal to 1.000269205. If humidity is 0%, then n_{air} = 1.0002701.

Furthermore, the model used produces uncertainty. This uncertainty is neither linear nor fixed, but greatly varies. The pattern is depicted as higher when parameters greatly deviate from average values in nature. A parallel graph of uncertainty and the refractive index is shown in Fig. 6. Fig. 6 illustrates the interdependence of relative humidity, air temperature and the refractive index.

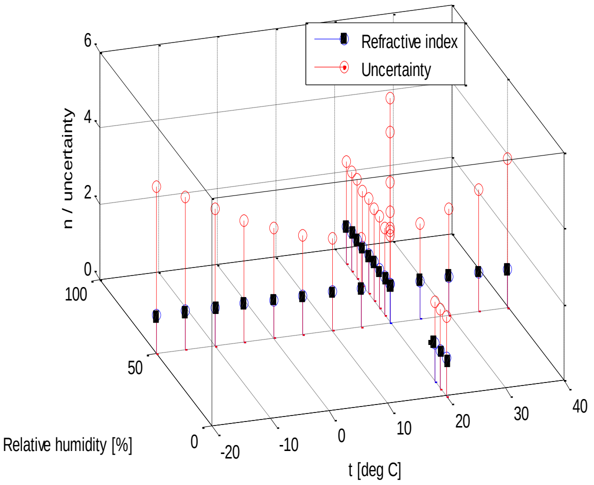


Figure 6. Simulation results: the dependence of the refractive index and uncertainty on changes in humidity and temperature.

Fig. 7 shows a change in the uncertainty of the model used in the simulation. Since uncertainty is very low, it had to be scaled by a factor of 10^8. It can be seen that uncertainty is smallest around standard room temperature.

Since uncertainty is not a major contributor to the refractive index, it could be erroneously dismissed from research as irrelevant. However, maximum change in refractivity index occurs at the third decimal place. The joint effects of different parameters and uncertainty can be observed at the third decimal place.

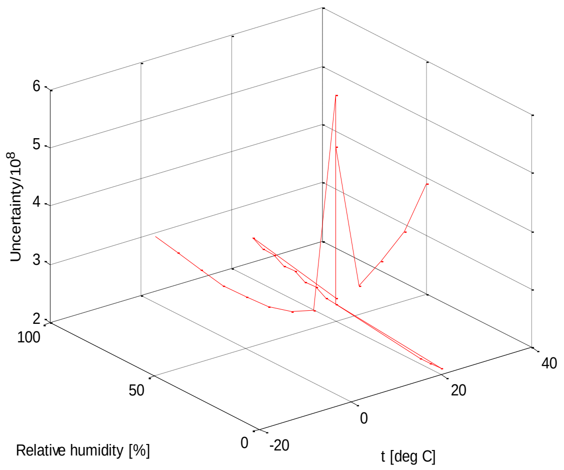


Figure 7. Scaled uncertainty shown as the result of two changing parameters in 3D graph.

Fig. 8 shows that changes in relative humidity and air temperature cause a change in the refractive index.

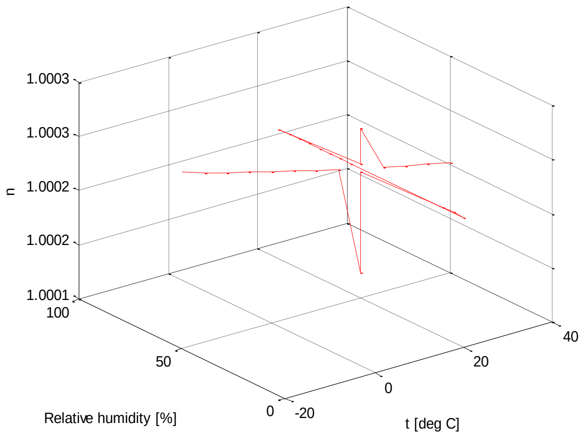


Figure 8. Simulation results: refractivity index vs humidity and temperature, a 3D plot.

A regular-shape 3D plot could not be obtained due to the absence of regular patterns in changing parameters. These parameters were taken as independent variables within reasonable (realistic) range.

5 Conclusion

Based on the Results section, we can conclude that the relative dielectric constant can change, perhaps even sufficiently to cause a short circuit (if the insulator is weakened so much that charges exceeding its new tolerance, but falling within the range of its former and designed tolerance, could cause it to break down), i.e. failure of traffic system beads in electric/electronic systems. Of course, redundant systems should be designed so as to avoid backup being made from the same material – otherwise the failure will repeat. Unfortunately, this is not the case in real life. Usually, duty and standby systems work in a cycle and are identical. This conclusion applies to the same material under the same conditions, and accounts neither for wear and tear, nor similar degradation processes.

Another problem in this research was the lack of theoretical models for materials used for electrical systems in marine engineering, forcing us to use approximations, which could, possibly, lead to incorrect results and conclusions. For example, in [13] only soils were covered. The formula was deducted empirically, which means that there is a possibility that it would not work on every material. Furthermore, case 2 applies only to air but not to other materials.

Since we are interested in the functioning of electrical systems as parts of a larger system, e.g., traffic systems or vehicles and since such systems are widely used in different climates, they should be resistant to environmental changes. The properties of materials used should therefore be taken into account in system design and reliability calculations. This paper intends to draw attention to this problem, create a framework for future work in the area, and inspire researchers to do experimental work in this field.

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