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NEW ALGORITHM FOR OPTIMAL DIELECTRIC MATERIAL SELECTION IN MARINE ENVIRONMENT

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Summary

The materials' selection demands knowledge from different disciplines, depending on application. Very important parameters that influence dielectric material's properties in, for example, marine applications are operating frequency, expected temperature in practice and moisture. The proposed optimal solution for the dielectrics choice is based on theory of sets. Instead of using function to find best value for the dielectric constant, the parameters' dependences are used to produce sets of possible values, which are used to find the optimal material for the desired application. The intersection of the three sets of possible solution is the optimal solution if the material with such value exists. If not, maximum acceptable deviation is used to find the acceptable material.

Key words: *relative dielectric constant; frequency dependence; temperature dependence; moisture dependence; material's resonant frequency*

1. Introduction

Dielectric materials are widely used for many purposes. Classic usage is in covers, masks, materials which enable ergonomy, efficiency and compactness of final products, but main usage is to ensure correct and safe ship power system operation trough insulator properties (shielding of cables, capacitors, etc.). Cutting-edge of their usage is in the optic communications for fibre optics, and bleeding-edge is in the LCD technology (liquid crystals exhibit dielectric properties), but it is not primary goal of the paper. One of the important characteristics of the dielectric materials is the relative dielectric constant (permittivity).

Dielectric materials in the marine environment, as an example, are under negative influence of many parameters. These parameters are present in the shore applications as well. Due to adverse weather and atmospheric conditions, change of properties of dielectric materials plays an even more important role in marine applications.

In this paper, an algorithm for optimal dielectric material selection is presented. It is based on above mentioned parameters. In the second section, a literature background is presented. The third section covers mathematical background. The fourth section describes the proposed algorithm and illustration of an example of the material. Simulation results are presented in the 3D graph. Conclusions are presented in the final section.

2. Literature background

Researches on influence of various parameters to the materials' characteristics are scope of many papers, but none specifically deals with marine applications. Some of them are briefly mentioned. Literature will be grouped by parameters of their studies. Moisture was studied in [1, 3, 4, 6, 8, 11, 17]. Various types of frequencies dependences (operating, which is the most relevant for operating characteristics, natural, resonant) are the scope in e.g. [5, 9, 13]. A combination of frequency and temperature dependences is researched in [7, 10, 16]. Temperature dependence for the dielectric constant is the topic of [2, 12, 15].

An attempt to model moisture influence by math is presented in [3]. The paper deals with the implementation of dielectric constant change to measure moisture (in moisture-meters).

Influence of moisture on electrical properties and reliability of materials is researched in [1]. It is pointed out that porous dielectrics with low dielectric constant absorb more moisture than dense ones. Furthermore, chemically-adsorbed moisture degrades the electrical and reliability performance of the dielectrics with low dielectric constant. It is also reported that higher temperature anneals at 400 °C can decompose physically-adsorbed water and restore reliability performance. Mechanism for degradation of performance is the electromigration of the copper interconnections.

The aim of [8] was to determine the mathematical model for soil moisture (but not for materials for the off-shore applications) and dielectric constant. The experimental results are compared to different mathematical models and one of polynomial model was shown as the best match. Similar is covered by [4], but as the response to different frequencies. Although investigation of soil types is not the equivalent to investigation of dielectric material in engineering, the value of research is in experimental data, which are connected to exact mathematical expressions, and shows the framework for research in engineering materials. Dielectric constant is used as an input to moisture calculation in [11], which is the opposite of the research in this paper, when the aim is to find out the influence of moisture to dielectric constant. Research in electromagnetic for the moisture-dielectric constant dependences is presented in [6].

Thin films, which are popular in nowadays technology, were investigated for GHz range in [5]. The problem observed in references is that articles deal with experimental properties of the specific material, and the conclusion is not usually generalized except in some specific group. For example, operating frequency dependence based on a type of modified Debye equation named by Havriliak and Negami is considered for elastomers in [13]. The experimental data is fitted to the theoretical curve.

Since it was observed that both operating frequency and temperature dependence play an important role in the final result, some authors manage to cope with both parameters. For example, in [7], composite material Epoxy/$BaTiO_3$ is researched and Poly Vinylidene Fluoride (PVDF) in [16]. An interesting experimental data are presented in [10], where printed circuit board (PCB) substrate is considered. Investigated operating frequency range is between 1 kHz and 1 MHz. It was shown that dielectric constant falls when temperature is increased. However, frequency dependence in the considered range is not so clear.

Temperature dependence of dielectric permittivity is considered on very popular materials in [15]. Ferroelectrics'' dielectric constant is considered in [2] and ice in [12].

3. Mathematical background

Operating frequency dependence is expressed depending on type of polarization. The polarization type existing in broad frequency range is the electronic polarization. It can be used as a framework to define the resonant frequency of the material. The resonant frequency is an input to Debye equations. The model to calculate resonant frequency can be explained in a simple manner. In the absence of an electric field, the centre of mass of the nucleus and the electrons' orbital motions coincide. There are no dipoles and dipole moment is zero. Electrons become displaced if the electric field producing dipole moment is applied. The restoring force, F_r, is proportional to the displacement x with a constant β [9]:

$$F_r = -\beta \cdot x \tag{1}$$

In the equilibrium:

$$Z \cdot e \cdot E = \beta \cdot x \tag{2}$$

Magnitude of the induced electronic dipole moment is:

$$p_e = (Z \cdot e) \cdot x = \left(\frac{Z^2 \cdot e^2}{\beta} \right) \cdot E \tag{3}$$

The equation of motion is:

$$-\beta \cdot x = Z \cdot m_e \cdot \frac{d^2 x}{dt^2} \tag{4}$$

Displacement can be expressed with:

$$x(t) = x_0 \cdot \cos\left(\omega_r \cdot t\right) \tag{5}$$

where the oscillation of the centre of mass of the electron cloud is actually electronic polarization resonance frequency:

$$\omega_r = \sqrt{\frac{\beta}{Z \cdot m_e}} \tag{6}$$

Depending on material, model of one or two relaxations can be used to describe the dependence of complex dielectric constant on frequency. Debye and Col-Cole models are widely used to mathematically describe the dependence. For one relaxation, the dependence is described with [4]:

$$\varepsilon_r(\omega) = \varepsilon_\infty + \frac{\varepsilon_{DC} - \varepsilon_\infty}{1 + \left({}^{i\omega}\!/\!{}_{\omega_r} \right)^{1-\alpha}} \tag{7}$$

where $\varepsilon(\omega)$ is complex relative dielectric constant, ε_{DC} the value of the constant when DC field is applied, ε_∞ is the value of the constant at high operating frequencies (ω) in range where orientational polarization is negligible and α is exponent that describes the spread of the relaxation peak. For two relaxations, the dependence is expressed with:

$$\varepsilon_r(\omega) = \varepsilon_\infty + \frac{\varepsilon_{DC2} - \varepsilon_{DC1}}{1 + \left({}^{i\omega}\!/\!{}_{\omega_r} \right)^{1-\alpha_2}} + \frac{\varepsilon_{DC1} - \varepsilon_\infty}{1 + \left({}^{i\omega}\!/\!{}_{\omega_r} \right)^{1-\alpha_1}} \tag{8}$$

where ε_{DC1} and ε_{DC2} are values of ε_{DC} at the first and the second relaxation peak respectively and α_1 and α_2 coefficients that describe spread of the first and the second relaxation peak.

Real and imaginary part of complex relative dielectric constant is expressed according to Debye [3, 9]:

$$\varepsilon'_r = \varepsilon_\infty + \frac{\varepsilon_{DC} - \varepsilon_\infty}{1 + \left(\frac{\omega}{\omega_r}\right)^2} \tag{9}$$

$$\varepsilon''_r = \frac{(\varepsilon_{DC} - \varepsilon_\infty) \cdot \frac{\omega}{\omega_r}}{1 + \left(\frac{\omega}{\omega_r}\right)^2} \tag{10}$$

Figure 1 shows an example of the resonant frequency's contribution to relative dielectric constant. It shows the behaviour of the same group of materials with a different resonant frequency. The rule of the operating frequency dependence is the same, but the values are different. Every curve represents another material. Therefore, one can develop an algorithm for materials' selection based on resonant frequency and required relative dielectric constant.

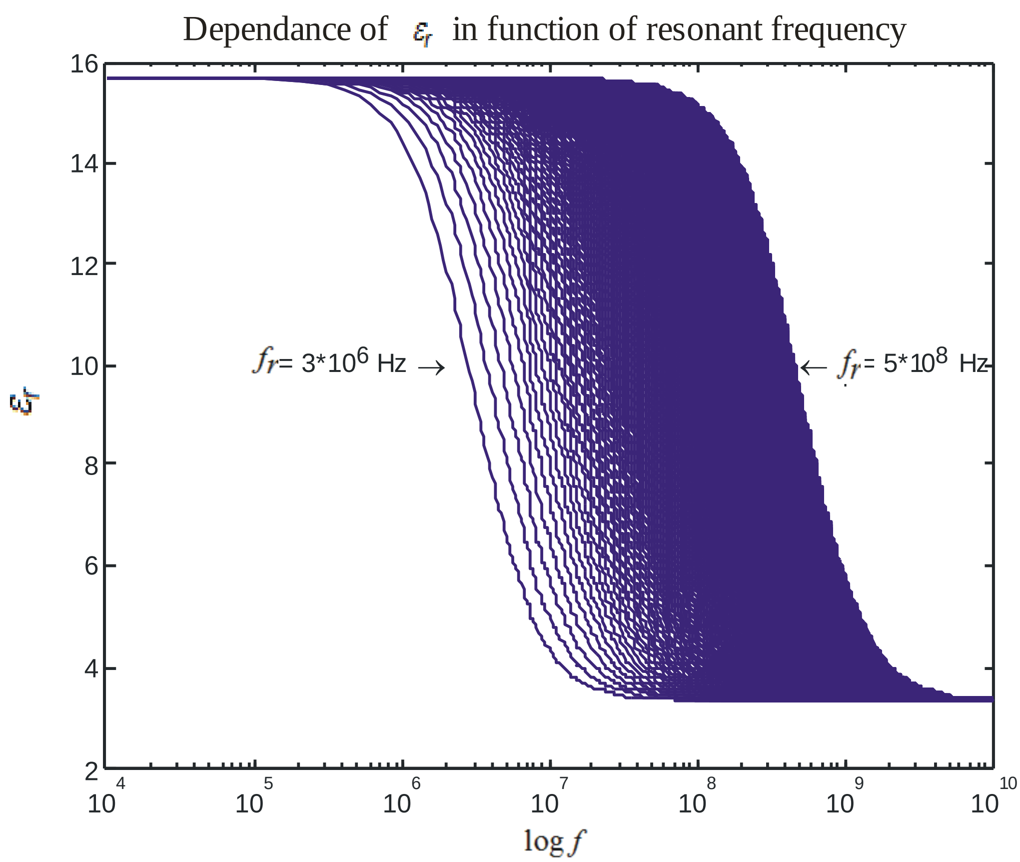

Fig. 1 Resonant frequency vs. relative dielectric constant graph

The maximum value (15.66) of the relative dielectric constant is the value at DC or low-frequency electric field. The minimum value (3.33) is at the frequency where orientational polarization is negligible. Starting material for this simulation is 1-pentanol. Instead of ω_r, relaxation time, τ, can be used.

Since, modern polymeric materials are more widely used every day, original Debye equations have been modified to cope with broad relaxation peaks that have been observed [9]. The modified expression for complex dielectric constant is:

$$\varepsilon_r = \varepsilon_\infty + \frac{\varepsilon_{DC} - \varepsilon_\infty}{\left[1+(j\omega\tau)^\alpha\right]^\beta} \tag{11}$$

where α and β are axis constants (less than 1). This model enables inclusion of the temperature dependences through relaxation time, which is temperature-dependent.

In [14, 15], frame of classical dielectric model is used to describe dielectric function:

$$\varepsilon_r(\omega) = \varepsilon_\infty + \sum_j \frac{S_j \Omega_j^2}{\Omega_j{}^2 - \omega^2 - i\gamma_j \omega} \tag{12}$$

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. This description does not include lattice anharmonicities and phonon interactions. In order to include temperature, (6) is modified to:

$$\varepsilon_r(\omega,T) = \varepsilon_\infty + \sum_j \frac{S_j(T)\Omega_j^2(T)}{\Omega^2{}_j(T) - \omega^2 - i\gamma_j(T)\omega} \tag{13}$$

Temperature dependent parameters in (13) are:

$$\Omega_j(T) = \Omega_j(T_0) + a_j[T - T_0] \tag{14}$$

$$S_j(T) = S_j(T_0) + b_j[T - T_0] \tag{15}$$

$$\frac{\gamma_j}{\Omega_j}(T) = \frac{\gamma_j}{\Omega_j}(T_0) + c_j[T - T_0] \tag{16}$$

$$\varepsilon_\infty(T) = \varepsilon_\infty(T_0) + e[T - T_0] \tag{17}$$

where e, a_j, b_j, and c_j are constant coefficients, and T_0 a reference temperature.

Moisture is modelled by a few functions, depending on application. In [8], the relationship between dielectric constant and volumetric moisture is obtained in dependence of soil class as polynomial of the first or the third order:

$$\theta = a \pm b \cdot \varepsilon_r \left(+ c \cdot \varepsilon_r^2 \pm d \cdot \varepsilon_r^3\right) \tag{18}$$

where a, b, c and d depend on soil type.

In [6], the relationship between the moisture content and leaf parameters is given for X-band applications. For X-band, real and imaginary parts of the dielectric constant are given as:

$$real(\varepsilon_r) = a \cdot \exp(b \cdot Mc) - c \tag{19}$$

$$imag(\varepsilon_r) = d \cdot \exp(e \cdot Mc) - f \tag{20}$$

where a = 3.95, b = 2.79, c = 2.25, d = 2.69, e = 2.15 and f = 2.68.

As it can be seen, the dependences mentioned can be combined by substituting (14) – (17) into (13) and then the result into (18). However, this approach has many limitations, such as the range of materials to which it is applicable, limited frequency range, etc. Therefore, no one suggested the usage of such unified equation. Instead of it, the approach in this paper is to try to use the known experimental/theoretical data to find optimal material for the desired application, in our case usage in ocean atmosphere. In order to describe data, a lookup table is used. The material is represented by the relative dielectric constant.

4. Proposed algorithm with an example

Relative dielectric constant is a characteristic of the dielectric's properties of the material. It depends on temperature and moisture, which degrade the material's properties. It is obvious that the optimal solution must be found by defining the function, which represents temperature, frequency and moisture dependences, but it is not obvious and often impossible to explicitly define such dependences. Since interdependences are too complex to be covered by one multidimensional function, a different strategy is tried in this paper – the theory of sets.

Instead of calculating the optimal number for relative dielectric constant, we will find a range of possible values for it based on temperature dependence, frequency dependence and moisture dependence. Then, the optimal result can be found in the intersection of these three sets of possible values. The algorithm proposed can be modified for computer and for manual graphical solution. Figure 2 illustrates the basic idea of the proposed. The simulated material is used for PCB, which consists of resin, glass fibre and copper foil. In electronics it is very important to know dielectric properties of PCB [10].

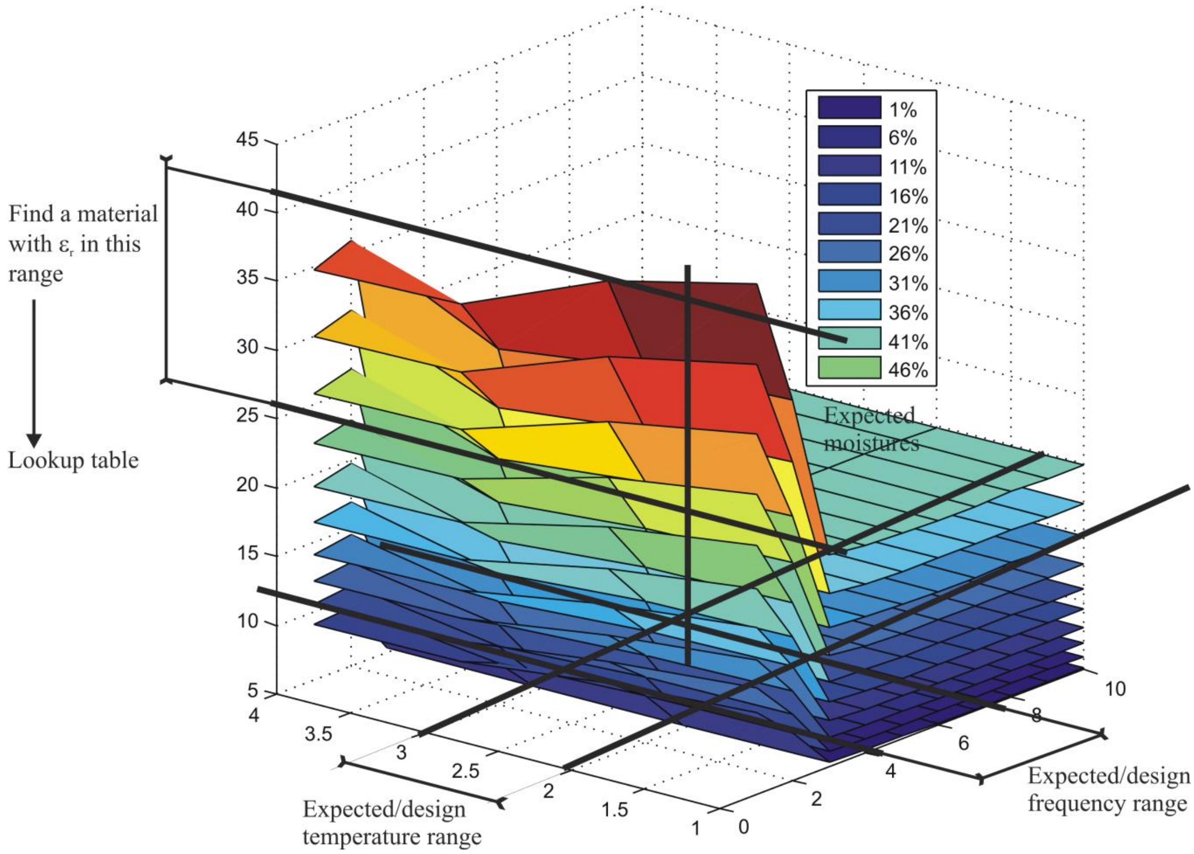

Fig. 2 Illustration of the operational principle for the developed algorithm

In order to retrieve temperature in Kelvins from Fig. 2, one should use:

$$T\,[\mathrm{K}] = 300 + (no - 1)\cdot 100 \tag{21}$$

where *no* is the number at the axis in the Fig. 2.

The numbers in the frequency axis represent the number of elements in frequency vector programmed in Matlab/Octave simulating environment. Frequency, temperature and moisture vectors are taken in order to execute a fast algorithm. In theory, all values of any parameter could be taken into account, but range and step of such operation are limited with memory and processor capacities. In our simulation, for Fig.2, the vectors are:

f = [50, 100, 500, 1000, 5000, 10000, 50000, 100000, 500000, 1000000] [Hz]

T = [300, 400, 500, 600] [K]

Moisture = 1:5:50 [%]

Vector *Moisture* is described in the Matlab/Octave expression and it is designation for 1, 1+5, 1+5+5, 1+5+5+5, etc.

Since related groups of materials exhibit similar dependences, it is easy to simulate dielectric constant dependence on frequency and temperature with specific moisture. After all moistures are taken into account, the 3D graph is obtained. The next step is to take account the range of possible values of ε_r. The range of possible values for ε_r and consequently corresponding dielectric material is determined. In the example from Fig. 2, the optimal material should have the relative dielectric constant between 27 and 42 (if there is such a material in the domain set of materials). It should be noted that simulation of dependences can be performed only for the group of similar materials. If someone would like to know which group is better, the procedure should be repeated for all the groups of interest

The proposed algorithm consists of several steps (see Fig. 3) and two pre-steps. The first pre-step is to form a lookup table, which consists of materials and values of the relative dielectric constant. Of course, the materials which cannot be used in such an application due to important reasons (such as galvanic currents, corrosion mechanisms, etc.) should not be entered into the lookup table. The second pre-step is to delete such materials from the lookup table.

Step 1: Input of necessary data. The necessary data are: operating frequency, expected temperature and moisture. If the actual computer realization does not include data such as constants, such data should be entered as well.

Step 2: The optimal solution is found by the expression:

$$\varepsilon^{optimal} = \arg\bigcap\left\{f_1(T),\, f_2(M),\, f_3(OF)\right\} \tag{22}$$

where T stands for temperature, M for moisture, OF for operating frequency and f_1 stands for dielectric constant dependence on temperature, f_2 for dielectric constant dependence on moisture and f_3 dependence on frequency.

Equation (22) is the variation for the typical optimal function definition. The difference from most of the references is in the function of optimization. Namely, the most common are maximum or minimum, such as minimization of oil consumption or profit maximization. In this case, intersection of the sets is used.

Step 3: Lookup table is used to find the optimal material. The value of dielectric constant is connected to the material.

Step 4: If the material with the desired dielectric constant exists in the lookup table, then the algorithm finishes. If it is not the case, one can choose to find optimal solution based on two more important factors or by entering the maximum tolerable deviation from the desired values.

Step 5 (additional): If two factors are chosen, then the new intersection is calculated by these two parameters by:

$$\varepsilon^{optimal} = \arg\bigcap\left\{f_x(x),\, f_y(y)\right\} \tag{23}$$

where x is the first important factor, y the second, and f_x, f_y corresponding dependence functions.

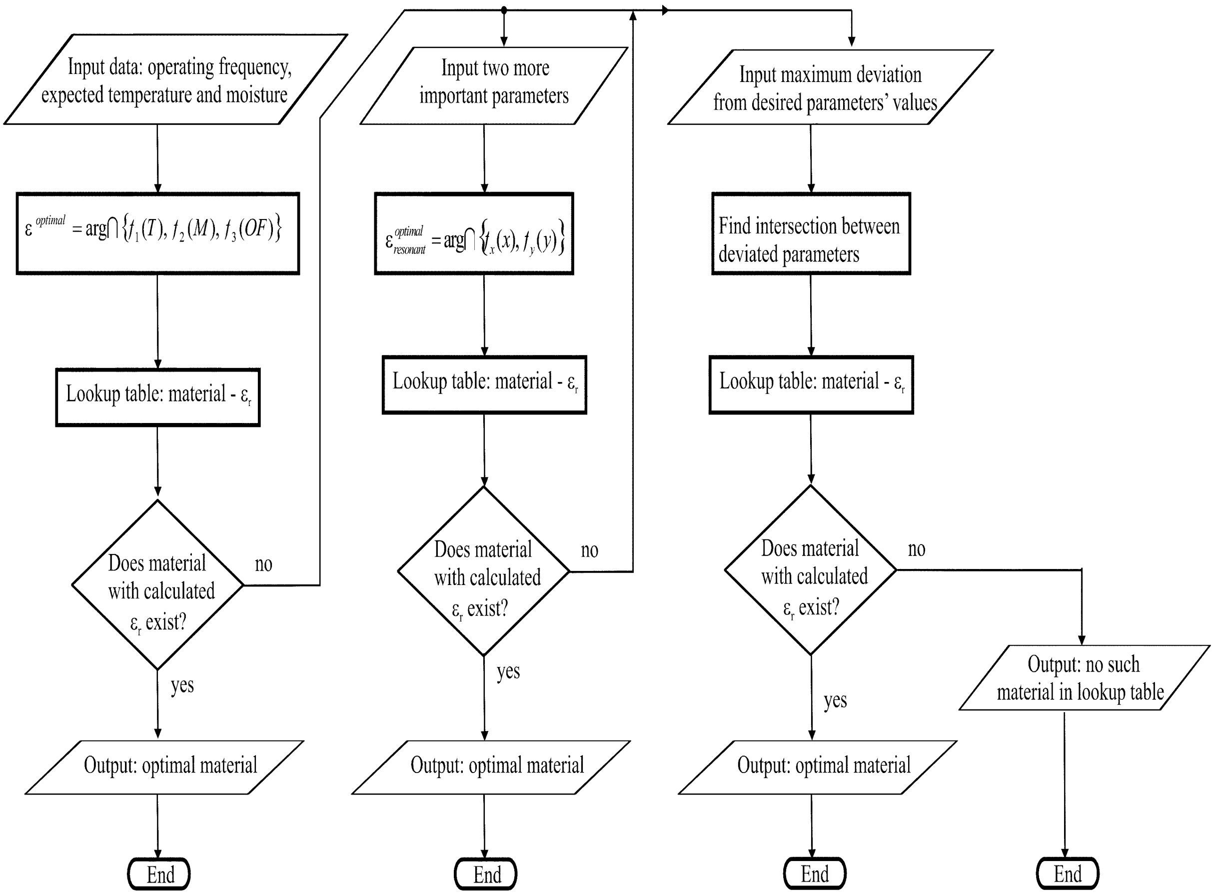

Fig. 3 Proposed algorithm for optimal selection of dielectric materials

Step 6 (additional): From lookup table, the optimal material is chosen. If there is no optimal material in the table, the maximum deviation from desired parameters' values can be entered as the input to the next step.

Step 7 (additional): Intersection is calculated. If the optimal material exists, then the algorithm finishes successfully. However, if there is no match, the only conclusion is that there is no such material in the lookup table.

5. Conclusions

In this paper a new algorithm which can be used to find optimal material is presented. For marine purposes, dominant factors for materials' selection are identified and analysed, but not specific factors, which depend on actual location of the material aboard ship (e.g. deck or engine room). However, the proposed algorithm can be used for other properties, such as deck salinity, oil and fuel impact, dust, fumes, cross-resistance to punctures, etc. There are just domain sets. Even more, the proposed algorithm can be extended to include all specific parameters by including more than three sets and finding the intersection between more sets. The final goal of the paper is to develop automated method for the material selection based on necessary parameters in specific applications. Further work should include such specific factors as: deck salinity, impact of oils, fuels, dust and fumes to cross-resistance to punctures, surfaces, etc. In some cases, such as in the case of an insulator or mount switch, the contact must be characterized by appropriate hardness and elasticity.

An approach to marine application is explained in the paper. Identified dominant factors are operating frequency, moisture and temperature. Theory of sets is used to find the optimal solution and lookup table to find the optimal material.

The possible shortcomings of the proposed are limitations in computer capacity and different dependences for the same parameters depending on material's group.

The advantage is in the framework to find the optimal material, which is flexible to different inputs, such as ranges for frequency, temperature and/or moisture. This could help shipyards to make ships with higher additional value and quality.

The proposed algorithm can be used in different applications, because the input of ranges is dictated by the application and explicit expressions dictate different behaviours of different groups of materials.

For example, marine engineering is an interesting area of application, because the knowledge of several disciplines has to be considered in the materials' selection, such as meteorology, law, electrical engineering, mechanical engineering, chemistry and physics. The materials in the marine environment are under impacts from atmospheric conditions, type of vessel, place of installation, special maritime regulations that have to be fulfilled, etc.

Finally, an example is simulated. The simulated case deals with the determination of the material for PCB based on relative dielectric constant.

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