Multiobjective Optimization of Dielectric Material's Selection in Marine Environment

I. Kuzmanić, I. Vujović and J. Šoda

Abstract In this paper, a multiobjective approach to the optimal material's selection for dielectrics in marine environment is proposed. The starting point is the definition of the Pareto optimal criteria for the material selection. The proposed method is visualized and the proposed algorithm is explained step by step. The dielectric material is identified from the lookup table by the relative permittivity. Dominant dependences are simulated through the influence to the relative permittivity.

Keywords Complex relative dielectric constant · Pareto optimization · Visualization · Partial discharge current · Capacity

1 Introduction

Marine environments present a demanding ambient for electrical insulation materials or dielectrics in general. Dielectric materials play a vital role not just in insulation, but also in optical communications (fiber optic materials), LCDs, and similar applications. The demanding environment can cause electrofracture of the materials. Even when an ambient is not as demanding, there are a lot of cases where the insulator's surface becomes contaminated by e.g. moisture, pollutants deposition, dust, salt spraying, etc. The contaminated surface develops sufficient surface conductance to enable discharge between parts of the electric circuit even below the

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I. Kuzmanić (✉) · I. Vujović · J. Šoda
Faculty of Maritime Studies, University of Split, Zrinsko-Frankopanska 38,
21000 Split, Croatia
e-mail: ikuzman@pfst.hr

I. Vujović
e-mail: ivujovic@pfst.hr

J. Šoda
e-mail: jsoda@pfst.hr

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material's breakdown strength [1–4]. Therefore surface tracking occurs. This mechanism can also lead to insulator aging [5, 6].

This paper is organized as follows. The second section overviews references relevant to this field of research. The third section considers the influential parameters and explains the multiobjective approach to the topic. The forth section presents steps of the proposed algorithm for dielectric material selection. The final section presents conclusions.

2 Literature Overview

Dielectrics' performance is greatly influenced by various parameters, which are mainly determined by an application. In our area of research, maritime traffic is of interest. So, it was important to find out, which influential factors to dielectrics' properties are important in maritime applications. Firstly, it can be seen that quite different pieces of equipment and machinery are used aboard ships. Hence, some factors could be important in one application and others in another application aboard. Based on different research studies [7–15], we selected the three most important factors that influence dielectrics' performance. Such influences can be introduced through different manners, so we selected to model the influence through the relative complex dielectric constant (permittivity). The three dominant factors that influence the dielectric constant are identified in [7, 8] as temperature, frequency and moisture. Works in [9, 10] do not model such an influence through the relative dielectric constant. Research in [11] deals with ecological aspects—finding an oil spill by radar and the influence of the change in surface dielectric constant to the radar reflectance. Since we are interested in the electrical and electronic equipment aboard ships, it was not of vital interest to our research. The research in [12] deals with molecular dynamics simulation, but only with water, which could be a part of electrical components. Research in [13] deals with a dielectric breakdown, which is introduced through an equivalent capacitor in the cable insulate. This is of interest to the aboard applications. Findings in [14] resulted in the conclusion that the real part of relative permittivity does not show significant changes due to salinity, but only to moisture. However, an imaginary part increases when there is no salinity and decreases when there is salinity. The covered frequency range was 1–4 GHz. This influence is important in satellite communications, but not in electro-energy transmissions aboard the ship. Similar research was performed in [15]. In the case of high voltage, the assessment of partial discharges gives important information in the reliability analysis of the high voltage equipment [16]. Therefore the authors developed a simulation model to investigate this influence.

The multiobjective approach can be found in many references covering different applications [17–21]. Material selection was a topic in [21], but not concerning dielectric or marine applications.

It is obvious, that the data sets would be large and therefore it is important to find a tool for handling such an amount of data. Therefore the tensor approach should be used. An example of tensor usage in large datasets is given in [22]. An example of designing new materials based on physical properties was presented as a case study. A data set contained a small set of melting point measurements in function of the concentrations of several different materials. A question arises if such a methodology can be used for dielectric material selection for specific applications, for instance considering the influence of various environments, such as marine, space, desert, polar, high-pressure conditions etc.

A novel approach to optimal dielectric selection is presented in [23]. It is based on theory of sets.

3 Theoretical Approach

This type of problems arises in many engineering/science fields due to the fact that some problems cannot be optimized considering only one scalar metric. Generally, such problems can be defined as in Definition 3.1 [17].

Definition 3.1 A multiobjective approach is defined by maximizing the objective vector:

$$\underset{x}{maximize}\ g(x) = [g_1(x), g_2(x), \ldots, g_M(x)]^T, \tag{1}$$

where x∈χ, and M is a number of objectives.

Generally speaking, the problem can be defined as finding the extreme value.

Considering a model of a void in the insulator [4, 16], our problem of minimizing effects of dominant factors to the reliability can be seen as minimizing the partial discharge (denoted as PD) current through the equivalent capacitor circuit. If the phenomenon is extensive, then the PD current can become a breakdown current.

The natural course of action is to recalculate the capacity for each parameter change and to use the so called Pareto approach to find an optimal solution. The optimal solution should lead to a material in the database with such a relative permittivity. By applying the famous Ohm's law for the part of the circuit and the expression for reactance of the capacitor, it can be easily seen that we should maximize the function, which has the approximate equation:

$$\frac{1}{i(\theta, T, \omega)} \approx C(\theta, T, \omega) \tag{2}$$

where C is the capacitance of a void in the dielectric material considered, i the PD current, θ the volumetric percentage of a moisture, T the temperature and ω the cycling frequency.

The objective is obtained by setting partial differentiates to zero:

$$\frac{\partial C}{\partial \theta} = 0, \quad \frac{\partial C}{\partial T} = 0, \quad \frac{\partial C}{\partial \omega} = 0 \tag{3}$$

It is not highly likely that the solutions for all dependences in (3) will coincidence. Therefore the boundary conditions of tolerances should be added and evaluated in order to find an intersection for all three conditions in the range of tolerances for the relative dielectric constant. Then, the materials are chosen by the unified ε at the operating temperature, which is not so straight-forward as it seems. For example, capacitance does not depend only on temperature, since materials can compress or extend in some or all dimensions due to the temperature influence and dimensions are also responsible for the total value of the capacitance.

So, as it was described there is a question of a multiobjective formulation for the proposed problem.

The same problem can be defined by applying several approaches. In this paper, we decided to follow a multiobjective approach. We will extend the problem formulation in finding an optimal dielectric material for maritime applications in dependence on the operating conditions and boundary tolerances. This means that we need to obtain strait lines of dependences around the operating point, which should be parallel to the x-axis. Then, the partial derivates would be equal to zero.

Definition 3.2 Selection of the dielectric material for the specific application can be performed by maximization of the goal that the breakdown does not occur in the specified operating conditions, including the range of possible variations of the conditions.

Definition 3.3 The goal in Definition 3.2 is obtained by setting the partial derivates of the relative dielectric constant dependences to the dominant factors to zero. The optimal solution is obtained by minimizing the vector: $\left[\frac{\partial \varepsilon_r}{\partial \theta}, \frac{\partial \varepsilon_r}{\partial T}, \frac{\partial \varepsilon_r}{\partial \omega}\right]^T$. Hence, there are three objectives, which must be fulfilled to find an optimal solution:

$$\frac{\partial \varepsilon_r}{\partial \theta} = 0, \frac{\partial \varepsilon_r}{\partial T} = 0, \frac{\partial \varepsilon_r}{\partial \omega} = 0.$$

We will derive the equations for all three objectives.

3.1 Frequency Dependence

A usual approach to address the problem of frequency dependence is to apply Debye's equation, which can be in generalized in the form [1, 7, 8]:

$$\varepsilon_r = \varepsilon_{r\infty} + \frac{\varepsilon_{rDC} - \varepsilon_{r\infty}}{\left[1 + (j\omega\tau)^{\alpha}\right]^{\beta}} \tag{4}$$

However, due to simplicity, we will assume that the materials for selection obey the classic Debye's equation. By separating the real and the imaginary part, we obtain:

$$\varepsilon_r = \varepsilon_{r\infty} + \frac{\varepsilon_{rDC} - \varepsilon_{r\infty}}{1 + (j\omega\tau)} \cdot \frac{1 - (j\omega\tau)}{1 - (j\omega\tau)} = \varepsilon_{r\infty} + \frac{(\varepsilon_{rDC} - \varepsilon_{r\infty}) \cdot (1 - j\omega\tau)}{1 + (\omega\tau)^2}$$

$$\frac{\partial\varepsilon_r}{\partial\omega} = \frac{\left(1 + (\omega\tau)^2\right)((\varepsilon_{rDC} - \varepsilon_{r\infty}) \cdot (-j\tau)) - (\varepsilon_{rDC} - \varepsilon_{r\infty}) \cdot (1 - j\omega\tau) \cdot 2(\omega\tau)\tau}{\left(1 + (\omega\tau)^2\right)^2}$$

Solving for zero, we obtain:

$$\left(1 + (\omega\tau)^2\right)(\cdot(-j)) - (1 - j\omega\tau) \cdot 2(\omega\tau) = 0$$

$$\omega_1 = \frac{1}{\tau}, \omega_2 = 0$$

This is only a simple solution for the electronic type of polarization. It can be seen that the ideal solution depends on the relaxation time of the material and only one frequency is the ideal solution.

3.2 Moisture Dependence

There are two types of moisture, which could be considered: gas moisture from the environmental atmosphere and water molecules which penetrated the material's structure in the manufacturing process or during operation time. A ship's environment is full of unwanted moisture, with the addition of salt. Mostly, researchers were investigating the relationship between the relative dielectric constant and volumetric moisture in different soil classes. There are no explicit studies considering the moisture content within the product's material.

Let us assume that soil dependences are the same as in the product's material. In such a case, moisture can be modeled as [24]:

$$\theta = a \pm b \cdot \varepsilon_r\left(+c \cdot \varepsilon_r^2 \pm d \cdot \varepsilon_r^3\right) \tag{5}$$

For a simple linear model, we can derive:

$$\theta - a = -b \cdot \varepsilon_r$$
$$\varepsilon_r = \frac{a-\theta}{b}$$
$$\frac{\partial \varepsilon_r}{\partial \theta} = -\frac{1}{b}$$

So, there is no optimal solution, unless b tends to infinity, which is not realistic. Fortunately, there are materials with cubic dependence. It is possible to obtain the result if it satisfies the result:

$$\frac{\partial \varepsilon_r}{\partial \theta} = \frac{1}{-b + 2c\varepsilon_r - 3d\varepsilon_r^2} \rightarrow 0$$

which is satisfied only if b, c or d tends to infinity.

The relation between the moisture content in the atmosphere and physical parameters of a leaf should be defined experimentally and in X-band (satellite communications and satellite radar surveillance applications) these are [25]:

$$\mathrm{Re}(\varepsilon_r) = a \cdot e^{b\theta} - c$$
$$\frac{\partial \mathrm{Re}(\varepsilon_r)}{\partial \theta} = ab \cdot e^{b\theta} = 0$$

which means that a or b should be 0 or b should tend to -∞. All of these conditions are not realistic.

$$\mathrm{Im}(\varepsilon_r) = d \cdot e^{e\theta} - f$$
$$\frac{\partial \mathrm{Im}(\varepsilon_r)}{\partial \theta} = de \cdot e^{e\theta} = 0$$

which could be satisfied only if d or e are 0 or e should tend to -∞, which is also not realistic.

3.3 Temperature Dependence

In classic materials, it can be observed that electronic and ionic polarization is weakly temperature dependent, while dipolar orientational polarization is strongly dependant [1]. It is observed that the relative dielectric constant (permittivity) decreases with temperature. Dipolar orientational polarization is of interest in MHz or lower frequencies (not in satellite communications, but in the range of some marine communication frequencies). Dipolar orientational polarization is normally exhibited by polar liquids and gases and solids with structures such as in glasses.

Temperature dependence of the relative permittivity is often considered as a two-variable function of temperature and frequency. For example, a temperature dependence of the relative permittivity of PET at 1 kHz can be approximated by the function (calculation performed for this paper by authors):

$$\mathrm{Re}(\varepsilon_r) = 0.14 \cdot tanh(T - 140) + 2.75 \tag{6}$$

which is interpolated by the measurement points:

T = [50, 100, 150, 200] and Re(ε_r) = [2.6, 2.680766, 2.87692, 2.884612]. After 230 °C, the experimental curve increases exponentially, which is not modeled in this simplified case. The condition for the temperature dependence should be:

$$\frac{\partial \varepsilon_r}{\partial T} = 0.14 \cdot \frac{1}{\cosh^2(T - 140)} \tag{7}$$

or the general case for such types of materials:

$$\mathrm{Re}(\varepsilon_r) = sc \cdot tanh(T - shf) + DC \tag{8}$$

$$\frac{\partial \mathrm{Re}(\varepsilon_r)}{\partial T} = sc \cdot \frac{1}{\cosh^2(T - shf)} \tag{9}$$

where *sc* is a scaling constant, *shf* the shifting parameter, and *DC* the offset from the horizontal axis.

It can be seen that the conclusion is non-encouraging again. Namely, the hyperbolic cosine function cannot become zero. Also, the reciprocal value of the square of the hyperbolic cosine function cannot become zero. Hence, the scale determines the pick at the inflection point, the offset has no influence in the first derivation. However, the value of the real part of the relative permittivity is 5.9×10^{-73} at 57 °C, which could be considered zero. So, actually, the solution can be anything except a small temperature range in the proximity of the inflection point.

The analytic representation of the dependence is shown in relation to the experimental measurement points for PET in Fig. 1a.

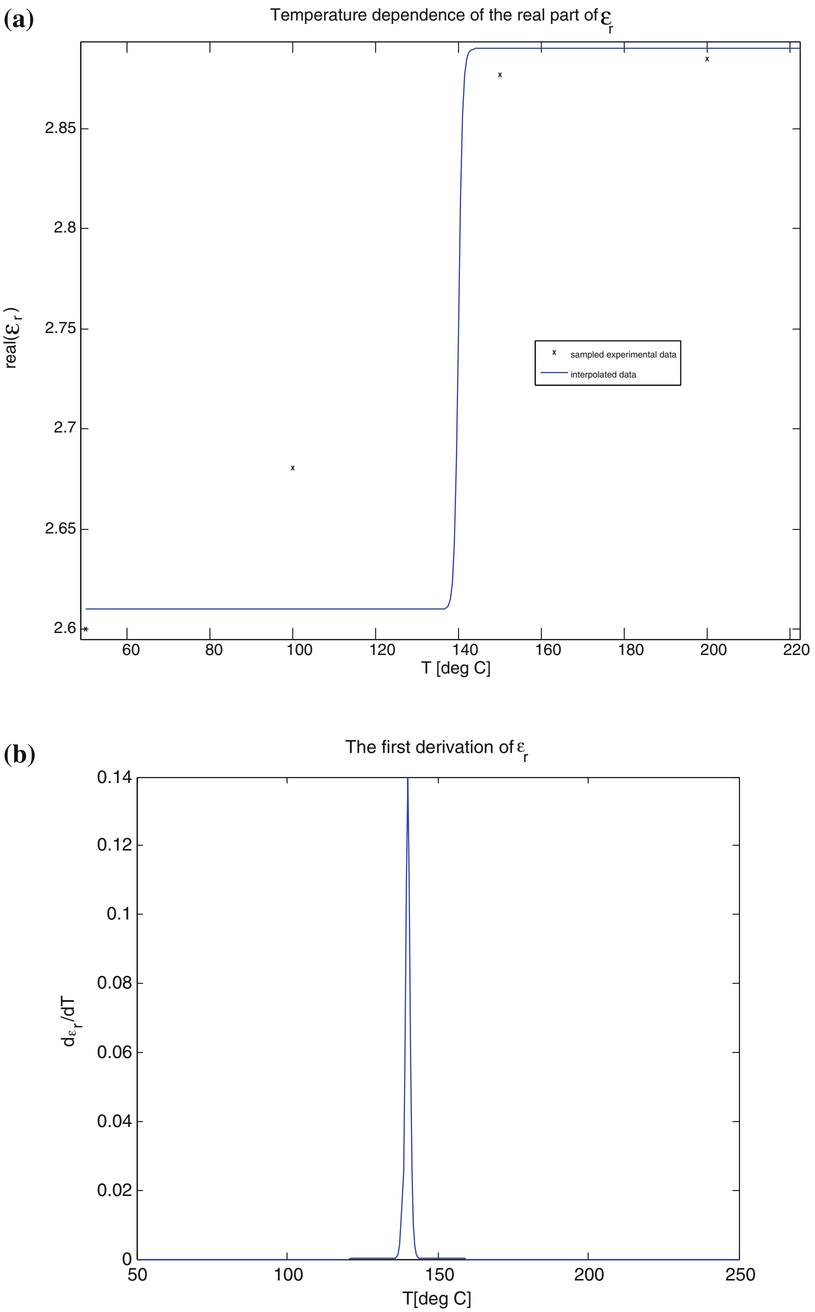

Fig. 1 Temperature dependence of: **a** the real part of the relative permittivity, **b** the first derivation

4 Proposed Solution

A trivial solution of the problem defined in Eq. (3) is to design a material with no dependences to the considered parameters. Materials can be temperature-independent, frequency independent or moisture-independent in some limited range. Therefore, a multiobjective approach can lead to a finding material which is not dependent of important factors in the operating ranges of frequency, temperature and moisture. Unfortunately, most of the materials are not dependent on temperature at one frequency range, and most of them are hygroscopic. Some materials can be formed to be moisture-independent by impregnation with oils, compound masses, or similar. Due to variety of dielectric applications, such trivial solutions cannot hold in many real cases. Therefore, the multiobjective approach is necessary in the generalized case.

Sections 3.1, 3.2 and 3.3 illustrate the complexity of the problem. It is shown that, in many cases, it is not possible to find any analytical solution at all, not to mention an optimal solution. Firstly, it is not possible to include all types of the polarization in a single integrated analytic expression. Secondly, it is not possible to evaluate in the same way all types of materials. Therefore, it is necessary to establish an alternative, non-analytic method of finding the optimal material for some application.

In order to do this, it is obvious that numeric data and fitting will be of vital importance, due to the fact that it is not possible to obtain experimental or analytical data for every possible change. Therefore, the pre-algorithm steps should be (in the case of a non-trivial solution):

Firstly, it is necessary to identify dependences that are of importance for the specific application. In the case of the marine environment, the dominant factors are temperature, frequency and moisture [7, 8].

Next, a data collection process should be performed. In this phase, a data of dependences are collected for all materials that are of interest. This process includes data about the type of polarization, dependence on frequency, moisture, and temperature for the entire range of interest (in our case of marine applications). Data can be obtained experimentally or from references, published data, etc. The collected data forms the lookup table, which is used to select the optimal material. Every material is represented by its relative dielectric constant for every triple of the dependences (for example, a value of the relative permittivity of some material for specific temperature, moisture and frequency).

Figure 2 illustrates an example of the proposed algorithm operation: based on the desired ranges, a volume (slice) in the figure is found. The relative dielectric constant corresponding to the found volume slice is input to the lookup table. The optimal material is identified from the table.

After these preliminary steps, an algorithm for the material's selection can be performed.

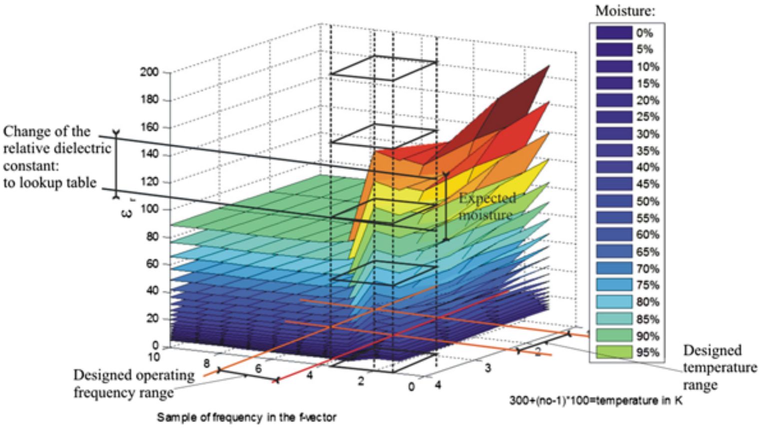

Fig. 2 Visualization of the multiobjective approach: designed temperature and frequency range and expected moisture for material selection based on relative dielectric constant

Algorithm 4.1 (Multiobjective Selection of Dielectrics)

Step 1: Input the design frequency and temperature range and the expected moisture content.

Step 2: Calculate the first order partial derivate by temperature, frequency and moisture.

Step 3: Find the intersection of the solution for all three dependences. If there is the answer go to step 8.

Step 4: Extend solution to desired ranges around the operating point and find the intersectional slice in the 4D tensor (ω, T, θ, ε_r). If there is the intersection go to step 8.

Step 5: Reduce 4D tensor to 3D by removing the least significant dependence.

Step 6: Find the intersectional slice in the obtained 3D tensor. If there is the intersection, go to step 8.

Step 7: If there is no the intersection set of data for the 3D tensor, exit algorithm with failure message. Conclusion is that there is no optimal material in the known set of data. Data should be updated with a new class of materials or a novel material should be developed.

Step 8: If there is more than one material that satisfies intersection criteria, ask for additional selection criterion (price, availability, standards, etc.).

Step 9: Perform the additional selection criteria and present the final result on the material's selection. The material is identified from the lookup table (dielectric constant vs materials name).

It has to be noticed that algorithm does not include research in methods for handling multidimensional tensors or search method for the lookup table (step 9). Therefore, one can select it arbitrarily.

5 Conclusions

In this paper, a multiobjective approach to the optimal material's selection for dielectrics in marine environments is proposed. The first idea was to make an easy dielectric material selection by visualization of the dominant factors for the dielectric's properties. In the research, we found out that a simulation can be performed through capacity of the equivalent model of the partial discharge. Change of the relative dielectric constant should be introduced through the change in the capacity.

Finally, we selected dominant factors and proposed an algorithm for the material's selection based on a multiobjective approach and an optimization, which could be described in an essence as the Pareto optimization. We considered parameters that we found important for marine environments. A similar approach could be used for other applications simply by addressing different dominant dependencies.

References

1. Kasap SO (2006) Principles of electronic materials and devices. McGraw Hill, New York
2. Singh N, Debdas S, Chauhan R (2013) Simulation & experimental study of partial discharge in insulating materials for high voltage power equipments. Int J Sci Eng Res. 4:1677–1684
3. Kavitha D, Alex N, Nambiar TNP (2013) Classification and study on factors affecting partial discharge in cable insulation. J Electr Syst 2013:346–354
4. Sabat A (2011) Simulation of partial discharge in high voltage power equipment. MSc Thesis, National Institute of Technology, Rourkela, India
5. Pethrick RA, Banks WM, Brodesser M (2014) Ageing of thermoplastic umbilical hose materials used in a marine environment I—Polyethylene. P I Mech Eng L MDA. doi:10.1177/1464420713482827
6. Pethrick RA, Banks WM, Brodesser M (2014) Ageing of thermoplastic umbilical hose materials used in a marine environment II—Nylon. P I Mech Eng L MDA. doi:10.1177/1464420713482828
7. Vujović I, Kulenović Z, Vujović Kežić S (2014) Proposal of new method for dielectric materials selection in ship system applications. Naše More 61:28–32
8. Vujović I, Kuzmanić I, Kulenović Z (2014) Dielectric materials' selection for marine applications. Lambert Academic Publishing, Berlin
9. Cheng YM, Ku H, Snook C, Baddeley D (2004) Impact strength of vinyl ester composites cured by microwave irradiation: preliminary results. P I Mech Eng L MDA. doi:10.1177/146442070421800495
10. David-West OS, Banks WM, Pethrick RA (2011) A study of the effect of strain rate and temperature on the characteristics of quasi-unidirectional natural fibre reinforced composites. P I Mech Eng L MDA. doi:10.1177/0954420711404635
11. Yang CS, Park SM, Oh Y, Ouchi K (2013) An analysis of the radar backscatter fromoil-covered sea surfaces usingmomentmethod and Monte-Carlo simulation: preliminary results. Acta Oceanol Sin. doi:10.1007/s13131-013-0267-7
12. Gereben O, Pusztai L (2009) On the accurate calculation of the dielectric constant and the diffusion coefficient from molecular dynamics simulations: the case of SPC/E water. http://arxiv.org/ftp/arxiv/papers/1009/1009.5958.pdf. Accessed 24 Feb 2015

13. Heidari M, Nekoubin A (2014) Performance improvement of photovoltaic systems through harmonics elimination of system and minimizing of THD. Res J Recent Sci 3:53–57
14. Lasne Y, Paillou P, Ruffié G, Serradilla C, Demontoux F, Freeman A, Farr T, McDonald K, Chapman B, Malézieux JM (2008) Effect of salinity on the dielectric properties of geological materials: implication for soil moisture detection by means of remote sensing. IEEE T Geosci Remote 46:1674–1688
15. Li YY, Zhao K, Ren JH, Ding YL, Wu LL (2014) Analysis of the dielectric constant of saline-alkali soils and the effect on radar backscattering coefficient: a case study of soda alkaline saline soils in western Jilin province using RADARSAT-2 data. Sci World J. doi:10.1155/2014/563015
16. Gopinath S, Sathiyasekar K (2014) Simulation of partial discharges in solid dielectric material: a study on PD magnitudes to the parallel and perpendicular axis of a cylindrical cavity. Int J Eng Tech 6:1786–1792
17. Björnson E, Jorswieck E, Debbah M, Ottersten B (2014) Multiobjective signal processing optimization—the way to balance conflicting metrics in 5G systems. IEEE Sig Proc Mag. doi:10.1109/MSP.2014.2330661
18. Lampinen J (2000) Multiobjective nonlinear Pareto-optimization, a pre-investigation report. Lappeenranta University of Technology, Laboratory of Information Processing
19. Bentley PJ, Wakefield JP (1997) Finding acceptable Pareto-optimal solutions using multiobjective genetic algorithms. In: Chawdhry PK, Roy R, Pant RK (eds) Soft computing in engineering design and manufacturing. Springer, London
20. Caramia M, Dell'Olmo P (2008) Multi-objective management in freight logistics, increasing capacity, service level and safety with optimization algorithms. Springer, Berlin
21. Tang X, Bassir DH, Zhang W (2011) Shape, sizing optimization and material selection based on mixed variables and genetic algorithm. Optim Eng. doi:10.1007/s11081-010-9125-z
22. Vervliet N, Debals O, Sorber L, De Lathauwer L (2014) Breaking the curse of dimensionality using decomposition of incomplete tensors. IEEE Sig Proc Mag. doi:10.1109/MSP.2014.2329429
23. Vujović I, Kulenović Z, Kuzmanić I (2015) New algorithm for optimal dielectric material selection in marine environment. Brodogradnja 66:39–48
24. Kaiser DR, Reinert DJ, Reichert JM, Minella JPG (2010) Dielectric constant obtained from TDR and volumetric moisture of soils in Southern Brazil. Rev Bras Ciênc Solo 34:649–658
25. Helhel S, Colak B, Özen S (2007) Measurement of dielectric constant of thin leaves by moisture content at 4 mm band. Prog Electromagn Res Lett 7:183–191