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Design of a New Parallel-Plate Capacitor to Increase the Capacity Value

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Abstract

The demand for dielectric materials has increased rapidly since the energy storage systems have an important place in many areas such as medical, defense, military, telecommunication and aerospace applications. The interaction of the electromagnetic waves with matter provides valuable information about the stored energy by material. Hence, the capacitor as an example of energy applications, which owes its energy storage capability to the internal dielectric material, is designed by using Ansys Maxwell software program to indicate the dependence of the capacitance on the dielectric constant and different design. The relationship between energy storage capacity and different design is shown by using different structures which are parallel plate and multi layered models. Furthermore, a new model has been designed and analyzed to increase the performance of capacitance value of capacitor. It is aimed to increase the interaction between surface area of dielectric material and conductive pipes/wires with this operation.

Keywords: Ansys maxwell, complex permittivity, capacitor design, dielectric materials, energy.

1. INTRODUCTION

Energy and energy production costs have a crucial factor on the development and sustainability the countries [1]. Hence, the alternative energy sources are important to reduce the unfavorable effects of fossil fuel energy sources. Therefore, research on wind, solar, and thermal energies are increasing rapidly. However, the storage and supply of the generated electricity become an important issue [2]. The energy storage devices are generally divided into two groups as short and long term. The capacitor is short term one, while the battery is long term.

The dielectric materials have a key function for capacitors to expand the performance of capacity value. Therefore, a new dielectric material should be developed for high performance of capacitance value and capacitance.

Researchers are working on this to design for more efficient energy storage devices. But, there are some requirements which are sorted as low dielectric loss, high-level dielectric constant of insulator, and wide range of temperature for applying. Shortly, when the material has a very high dielectric constant, its tangent loss should be very low that means close to zero [2-4].

The capacitance is defined as energy stored ability of capacitor. This parameter depends on the permittivity of the dielectric materials and dimension of conductors. It shows that the capacitance does not depend on the potential difference between conductors and total charge. The permittivity of materials is a dielectric property which determines the interaction of material and electromagnetic radiation and defines density of charge under an applied electric field [2,5].

The capacitor can be defined as a device which stored the electric energy. It can be used in many areas such as radar systems, electric cars, aerospace, security, military, renewable energy system, medical test and scan equipment [2]. Furthermore, they can be used in integrated circuits as memory storage, circuit element, and coupling circuitry. In addition, it has a great importance in energy harvesting applications. It should not be forgotten; the capacitor is environment friendly as well as abundant.

The dielectric capacitors, which are currently available electrical energy storage devices have highest power density since their fast charge/discharge capability [6,7]. Therefore, many capacitors were designed by developers to show the features of capacitor. One of them is 3D capacitor design that the parameters of capacitor have been evaluated to enhance the capacitor capacitance to focused on the close relationship between manufacturing and design process [6]. Bilayer ceramic capacitor was designed for improving the coefficient of temperature which effects the performance of capacitor applications [8]. Furthermore, a novel BMN-based transparent tunable capacitor was designed with an average

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optical transmittance [9]. Moreover, it is possible to obtain a new material with high dielectric constant by mixing up two different materials which have lower dielectric constant [4].

The capacitor was used for RF filter and EMI filter depending on recent rapid development on technology [7,10]. Tunable capacitors of RF MEMS have great prospects for many RF applications as sorted tuning filters, voltage-controlled oscillators, and matching circuits due to their low insertion loss, large tuning ratio, and high-quality factor, [11]. Herewith, the electromagnetic property of capacitor was carefully studied using 3-D electromagnetic simulation software CST [12].

Frequency response, which is one of the important factors for application area of capacitor, evaluation can be supplied with a capacitor from 100kHz to 1 GHz [12]. A capacitor bank was designed for size optimizing the switched capacitor array to increase the equivalent capacitance value [14]. Besides, the correlation between dielectric constant and band gap was showed that the band gap increases while the dielectric constant of insulator decreases with decreasing solid size [15]. In addition, the capacitor is used for noise suppression techniques from 40MHz to 5GHz to enhance the performance of split power bus [16]. Although, the illuminated capacitor array can be used as a source for tunable THz radiation [17]. Moreover, the new design capacitor was used a novel THz source: Miniature Photoconductive Capacitor Array (MPCA) [18].

By examine existing capacitor designs, it is considered which different type design might be more useful to increase the capacitance value. Two different improvements are predicted for high capacity of capacitor: production of a new material with high dielectric constant or optimization of existing geometric structure. Therefore, a classical parallel plate capacitor is designed to calculate the capacitance of it for use as a reference as well as cylindrical capacitor. Thereby, it has been aimed to improve energy storage capacity by making changes on reference capacitor. A new conductor plate or pipes are inserted into dielectric material by keeping fix the distance (d) between the conductor plates to increase capacitance value. Furthermore, the large conductive plate is replaced by piece of conductive material (pipes) to make light the capacitor. As a result of the analysis of the new design by Ansys Maxwell, an increase in capacity value has been achieved. This increase is about six times the value of the reference capacitor. However, it is expected that the energy intensity will decrease while the capacity increases against the heating problem. Meanwhile, the importance of being cheap has also been noted in terms of materials used.

2. Complex Permittivity and Capacitors

The capacitance of capacitors changes with increasing frequency. Because, the dielectric constant of materials decreases as frequency increases since the dielectric properties depend on frequency bands [7]. Therefore, the dielectric materials used in capacitor should be selected to increase the capacitance. Besides, the variable temperature, low loss and more energy capability properties are required for energy storage performance [4]. Dielectric materials are used in capacitors to store the energy which are placed between two conducting plates. The dielectric materials should offer some advantages for capacitor such as high breakdown strength, light weight, facile process ability, and scalability to store high energy [19]. A solid dielectric material with high dielectric constant is preferred for capacitor to increase the capacitance value. The complex permittivity of a dielectric material can be expressed as follows:

$$\varepsilon^* = \varepsilon' - j\varepsilon' \tag{1}$$

where ε' is real part of complex permittivity while ε'' is imaginary part. These parameters depend on the frequency of applied electric field. This is related by Kramers-Kronig relation as shown below:

$$\varepsilon'(\omega) = \varepsilon_0 + \frac{2}{\pi}\int_0^\infty \frac{u\varepsilon''(u)}{u^2 - \omega^2}du \tag{2}$$

The real part of complex permittivity is given as follows:

$$\varepsilon' = \varepsilon_0\varepsilon_r \tag{3}$$

where ε_0 is the permittivity of vacuum $(8.85x10^{-12}\ F/m)$ and ε_r is called dielectric constant of a material. The magnitude of dielectric constant indicates the capability of stored energy from the electric field. When a parallel plate capacitor is considered with area (A) and thickness (the distance between two plates or thickness of dielectric material, d), the capacitance of capacitor given by

$$C = \varepsilon_0\varepsilon_r A/d \tag{4}$$

The calculation of capacitance is different in cylindrical and spherical capacitors. However, all capacitor types depend on geometrical design of it [2]. The conductor area can be increased with multilayer shape design. Hence, the overall capacitance of the capacitor can be increased, while its size is small and in a single body.

The dielectric strength is an important parameter for capacitor design. This parameter can be a disadvantage for dielectric material as it has a limit on maximum voltage setting. All materials have an upper voltage limit that is called breakdown voltage. For example, the air is an insulator until the emergence of lightning. Therefore, the maximum rated voltage of a capacitor is not exceeded to prevent damage.

The energy is stored in capacitor by applying voltage (V, potential difference) to capacitor plates. The lower-case q represents the charge amount on the capacitor plate. Using

$C = Q/V$ equation, the stored energy amount can be expressed as follows:

$$U = \frac{1}{2}QV \quad or \quad U = \frac{1}{2}CV^2 \qquad (5)$$

U represents the energy stored in the capacitor. V represents the voltage across the capacitor. The upper-case Q represents the amount of the final charge amount. When this equation is examined, the type of dielectric material being used affects the capacitance of the capacitor.

Moreover, the capacitance of capacitor will decrease at high frequency applications. As mentioned above, the small size effects the capacitance due to capacitor area (A). In addition, there are some factors to select the more proper capacitor in applications such as size, maximum voltage, leakage current, tolerance. The types of capacitor can be classified as ceramic, film, paper, mica aluminum and tantalum electrolytic. The using dielectric materials can be made from insulating materials glass, paper, mylar, ceramic, rubber or plastic etc. Furthermore, the conductor plates are made from a conductive material silver, tantalum, and aluminum etc.

3. RESULTS AND DISCUSSION

The aim of the study is to increase the C capacity value associated with equation 4. For this reason, the importance of capacity value is emphasized. Firstly, a classical parallel plate capacitor was designed as shown in **Fig. 1a**. The dimensions of capacitor are 120 mm and 120 mm as square plate. The distance between the conductor plates was chosen as 4 mm. The conductive material can be selected as Aluminum, Tantalum, Silver etc. It is sufficient that this material is a good conductor. The capacitance of capacitor will be not depended on choosing of conductive material types, therefore, the thickness of conductive plate can be changed, and it was not given here.

The Teflon was preferred as dielectric material since it is easily available, and its dielectric constant is close the dielectric constant of air. The capacitance of capacitor changes due to **Eq. 4**. Therefore, the air and polyimide were used as a dielectric material to show its dependence on the dielectric constant.

The voltage was applied as 5 V to conductive plates. The capacity values were obtained by finite element analysis as 33.8 pF, 66.93 pF and 111.56 pF for air, Teflon and polyimide dielectric materials, respectively. Furthermore, the different dielectric materials, which are RO3003, Ultralam 3850HT and L1000HF, can be chosen as good dielectric materials. While lightness is an advantage of these materials, their costliness may prevent them from being preferred. Therefore, the dielectric material to be treated should be both cheap and polarized.

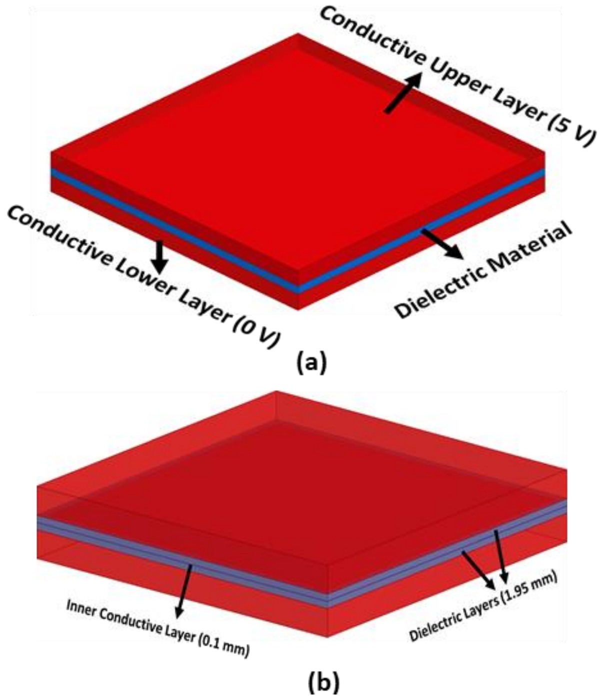


Fig. 1. a) A classical parallel plate capacitor b) The new design of capacitor with very thin inner conductive layer

To increase capacitance value of capacitor, a new plate was inserted between two dielectric plate as shown in **Fig. 1b**. The distance (d) was divided as two dielectric layers (1.95 mm) and one conductive layer (0.1 mm). After analysis, the capacity was obtained as 68.65 pF. Furthermore, the distance (d) was divided into three equal pieces and its capacitance value was obtained as 100.41 pF. Moreover, the distance (d) was divided into three parts as two dielectric layers (1 mm) and one conductive plate (2 mm). Hence, the capacitance value has increased, and it was obtained as 133.88 pF. Although the ferromagnetic material (M36) was used as inner plate instead of conductive material for same design, the capacity value has not changed, and it was obtained as 133.88 pF.

A voltage was not applied to the inner conductive plate for new designs. That is, there is no connection between the outer conductive plate and inner conductive plate which was placed in dielectric material. The multilayered design has patents as seen in ref [20]. However, the inner conductive plates were connected the conductive materials. Furthermore, there is no any information about the ratio of inner conductive layer thickness to dielectric layer thickness. As shown in **Fig. 2**, by changing the thickness of dielectric and inner conductive plates, it has been shown that the value of capacitor can be increased about four times when the thickness of dielectric plates and conductive plate are 0.5 and 3 mm (total 4 mm), respectively. By this way, the capacitance was obtained as 267.42 pF. Moreover, it is possible to increase the capacity value further by reducing the thickness of dielectric plate with the technological possibilities.

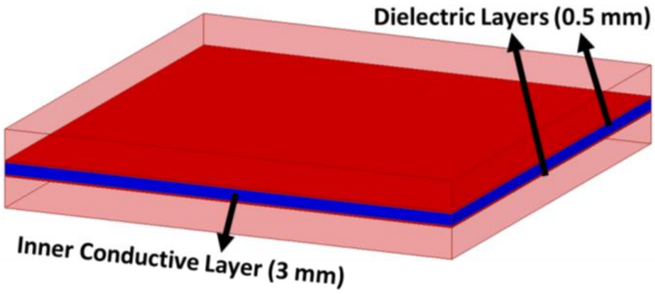


Fig. 2. The new capacitor design with energy density in volume

A new capacitor was designed to show the change in capacitance of capacitor. Here, the distance (d=4mm) was divided into five equal pieces as three dielectric plates (0.8x3 mm) and two conductive (0.8x2 mm) plates. Hence, two inner conductive layers were placed between three dielectric layers. However, the expected increase amount has not became in last design.

The theoretical calculations were made by **Eq. 4** since the designed capacitors can behave like a parallel connected capacitor. Thereupon, the theoretical and simulation results were compared to understand the difference between them. Although the capacity has shown a great increase for only one inner conductive layer (3 mm), the capacitance of capacitor, which has 0.5 mm dielectric layer, is obtained as 535.44 pF under same conditions. Therefore, it would not make much sense to prefer this. Nevertheless, this design can be an alternative solution due to it has high capacitance when a system requires only one capacitor.

Meanwhile, a potential difference (voltage) has occurred on inner conductive layers that are not connected to the conductive terminals due to the polarization on dielectric materials. This voltage value can become between 2-2.5 V in one inner conductive layer. If there are two inner conductive layers, the potential differences are 3.3 V on the upper side and 1.7 V on the lower side. Therefore, a novel capacitor was designed using 8 cylindrical conductive materials in dielectric layer (4 mm) as shown in **Fig. 3a**. The capacity increase is also higher than the previous designs.

The capacitance of novel capacitor was obtained as 349.32 pF and this value is about six times the initial design. However, the simulation time was very long due to geometrical structure. To decrease the simulation time, the conductive materials were designed as pipes instead of cylindrical materials as shown in **Fig. 3b**. Hence, the simulation time was short when compared to the other. But the capacitance value has decreased very few and it was obtained as 347.53 pF. Besides, the capacitance value was obtained as 91.16 pF, when three pipes were used in same design. In addition, the analysis of energy density is shown in dielectric layer with red color in **Fig. 3c**.

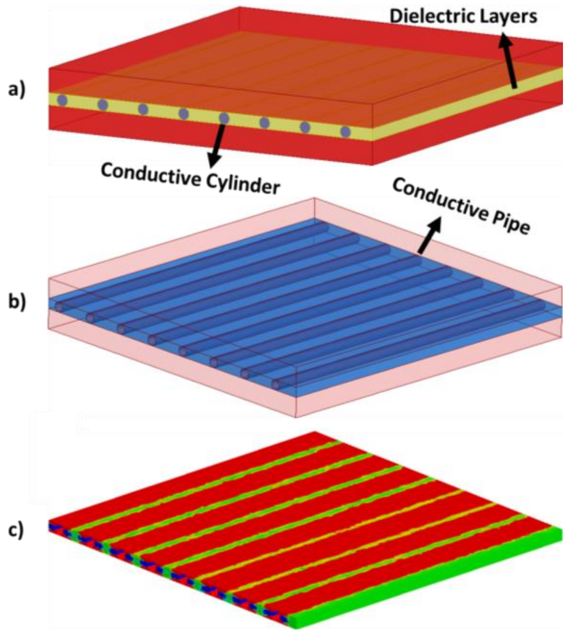


Fig. 3. A new parallel-plate capacitor design, a) using conductive cylinder b) using conductive pipe c) energy density in dielectric layer (4 mm) for 4b.

As shown in **Fig. 4**, the cylindrical capacitor is designed unlike the parallel capacitor. In this design, a cylindrical capacitor analysis was performed as 0.5 mm inner radius and 1.8 mm outer radius, and 30 mm height. The Teflon sample was selected as dielectric material. The conductive pipes with 0.4 mm radius were placed between the inner and outer conductors. The capacitance value was 3.20 pF before placing the conductive pipes, however, the capacitance value was obtained 7.34 pF after the conductive pipes were placed.

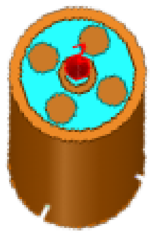
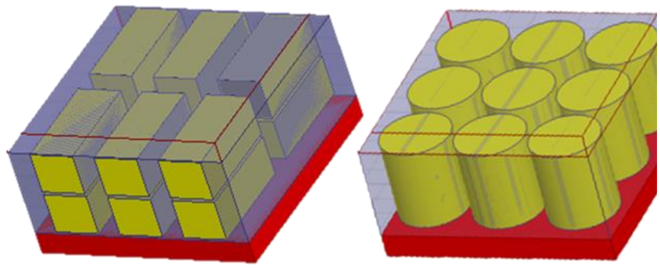


Fig. 4. A new cylindrical capacitor design

The placement of conductive pipes into insulating material (layer) increases the capacity value for both parallel and cylindrical capacitors. It is considered that the capacity value can be increased when the design of **Fig. 4** is developed. In addition to this design, a smaller size parallel plate capacitor is designed and conductive materials with different geometric shapes are placed into it. The capacity value was measured as 0.46 pF before any conductive material was placed. As shown in **Fig. 5**, instead of the conductive pipes, rectangle prism (4.5*2*1.85 mm) and cylinder (1.5 mm radius and 3.5 height) were used to enhance the capacitance value.



(a) (b)

Fig. 5. A new parallel-plate capacitor design a) rectangle prism b) cylinder

The capacitance value of rectangle prism type capacitor was obtained 4.24 pF, while this value was obtained 3.18 pF for the cylindrical type. Hence, the increase value at the capacitor was determined as about 10 times. Some results obtained for parallel plate capacitor are given in **Table I** where DL is Dielectric Layer, CL is conductive layer, CP is conductive pipe, CR is conductive rectangle prism, and CC is conductive cylinder. The initial values given in the table consisting of two parts are both theoretical and simulation results. As a result, the high capacitance values were obtained by **Fig. 2**, **Fig. 3** and **Fig. 5** designs. Furthermore, the amount of dielectric material used is reduced by adding a cheap conductor into it. This can be an advantage for inexpensive capacitor design. This design is much more valuable since it is not important which conductive material is used in the dielectric layer.

Table 1. The Capacitance Value of Designed Parallel-Plate Capacitors

	Features	Capacitance (pF)
Dimensions 120*120 mm	DL=4 mm (without additional part)	66.93
	2 DL=0.5 mm and CL=3 mm	267.42
	1 CP	73.44
	3 CP	91.16
	8 CP	347.53
	8 CC	349.32
Dimensions 10*10 mm	DL=4 mm (without additional part)	0.46
	9 CC	3.18
	12 CR	4.24

4. CONCLUSIONS

The capacitor can be made more useful for many applications by increasing the storage capacity. Furthermore, the dielectric constant can be enhanced to increase the performance of energy storage in dielectric materials. However, it has been shown that the capacitance was increased by geometric optimization made on the dielectric material part. The capacitance value of the capacitor has been successfully increased about six times by using new designs. In addition, the cost and lightness parameters were re-evaluated for each design. The proposed novel design can be useful for nano-dimension applications. Thus, new designs should be considered in accordance with nanotechnology. In addition, the high-value capacitors will be more efficient for energy harvesting and battery technologies. It should be mentioned that the effect of temperature and breakdown voltage did not analyzed for different capacitor designs.

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