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# A New Type of Capacitive Machine

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## Abstract

**The paper proposes a new type of the synchronous capacitive machine operated on a principle of the electric field effect. The proposed machine has smaller size and lighter weight than the standard electromagnetic synchronous machines with the same rated parameters. Another important advantage is a simple structure of the machine, which simplifies the production process and reduces the costs of the motor. The paper also presents extensive simulation results of the proposed capacitive machine. The simulation results show that the proposed machine is able to reach the same power output as the electromagnetic machines.**

## Keywords

**Capacitive Machine, Electric Field, Torque, Synchronous Machine**

## 1. Introduction

Today, most of the electrical machines operate on the principle of magnetic field effect at which the electric energy is converted into mechanical energy and vice versa. The magnetic field is produced by the current flowing in the stator and rotor coils.

On the other hand, it is also possible to construct the electrical machines that operate on the electric field principle, where the electrical energy is stored in an electric field [1]. It is known that the electric and the magnetic fields are always linked to each other and it is impossible to separate them. However, the electric field in the electromagnetic machines is much weaker than the magnetic field, and, practically, is negligible.

The electric machines operated on the electric field principle would have mechanical structure based on capacitors [2]-[4] while the mechanical structure of the electromagnetic machines is based on the inductors. While the development of the electromagnetic machines has reached the most advanced state, the electric field machines (capacitor machines) remained somehow ignored. The reason is low electric permittivity-$\varepsilon$ of most dielectric materials. However, recently, new dielectric materials have been developed. These materials possess relatively high electric permittivity of up to $\varepsilon_r = 104$. Therefore, the capacitor motors acquire an interest again.

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The greatest difficulty in the development and production of capacitive machines is preventing friction between the stator and rotor plates which occurs when the dielectric materials are solid. A common method to prevent the friction is to ensure an air gap. However, in the capacitive machine this method is not suitable because even small air gap diminishes the advantages of using dielectric material with high dielectric permittivity $\varepsilon$. One possible solution could be to use liquid electric materials with low density and high values of $\varepsilon$. Another possible solution might be changing the air gap to plasma, which can be accomplished by using high voltage and a narrow air gap.

The main factor determining the efficiency of electric power mechanisms for energy conversion is the density of the electric or magnetic energy stored in the electromagnetic or electric fields. The electromagnetic and electric field machines could be compared from the energy point of view [5] [6]. The energy density of the magnetic field in electromagnetic machines could be calculated by:

$$w_m = \frac{B^2}{2\mu_0\mu_r} \tag{1}$$

where $B$ is the magnetic flux density of the magnetic field, $\mu_0$ is the magnetic permeability constant $\left(\mu_0 = 4\pi\times10^{-7}\ \text{H/m}\right)$ and $\mu_r$ is the magnetic permeability of the air (in magnetic machines the process of energy conversion occurs within the air gap between the rotor and the stator so $\mu_r = 1$). By using the ferromagnetic materials (particularly electric steel), the magnetic field of the electromagnetic machines can have magnetic flux density of $B = 1-1.6\ \text{Wb/m}^2$. The density of the magnetic energy would be (for $B = 1.4\ \text{Wb/m}^2$):

$$w_m = \frac{1.4^2}{2\times4\pi\times10^7} = 800000\ \text{W/m}^3 \tag{2}$$

The energy density of the electric field in the electric machines could be calculated by:

$$w_e = \frac{1}{2}\varepsilon_r\varepsilon_o E^2 \tag{3}$$

where $\varepsilon_0$ is the electric permittivity constant $\left(\varepsilon_0 = 8.86\times10^{-12}\ \text{F/m}\right)$ and $E$ is electric flux density of the electrostatic field. Today's technology allows usage of very strong electrostatic fields, but because of low electric strength of most insulating materials, the electrostatic field is practically limited to 2 - 20 MV/m. Therefore, in the machine whose operation is based on the electric field principle and in which the process of energy conversion also takes place in the air $\left(\varepsilon_r = 1\right)$, the energy density of the electric field, for $E = 10^7\ \text{V/m}$, could be determined by Equation (4):

$$w_e = \frac{8.86\times10^{-12}\times\left(10^7\right)}{2} = 450\ \text{W/m}^3 \tag{4}$$

Lately, new dielectric materials have been developed, such as ceramics based on a paratitanite bar, which has a relatively high electric permittivity of up to $\varepsilon_r = 10^4$ [F/m]. In electric machines, where the energy conversion process takes place in the new dielectric materials and not in the air, the density of the electric energy could be significantly increased.

For electric permittivity of $\varepsilon_r = 10^4$, the obtained density of the electric energy, for $E = 10^7\ \text{V/m}$, would be:

$$w_e = \frac{10^4\times8.86\times10^{-12}\times\left(10^7\right)}{2} = 450\times10^4\ \text{W/m}^3 \tag{5}$$

Such a result is even greater than the result obtained with the electromagnetic machines, a fact that encourages development of new electric machines based on the electric field effect.

The electric field machines have several advantages upon the electromagnetic machines. The main advantage is that the electric field machines are much smaller in size and lighter in weight than the electromagnetic machines with the same output parameters. This could be explained by the fact that magnetic force lines of any electromagnetic machine are formed in a closed loop. The magnetic force lines are formed by the magnetic circuit, built from a very heavy material like electric steel. The magnetic circuit is used for the power transfer, while the energy conversion process takes place in the air-gap itself (between the stator and the rotor). The air-gap volume is relatively a small part of the volume of the whole machine.

In the electric field machines, the power lines of the electric field start and end in electric charges, *i.e.* the rotor and stator plates. The energy conversion process takes place in the gap between the stator and rotor, which takes up a sizable part of the volume of the whole machine. Assuming that the specific energy is equal for both electric field and electromagnetic machines, the machines based on the electric field effect will be significantly smaller. And since the dielectric materials (e.g. ceramics and plastics) are much lighter than the ferromagnetic materials, the electric machines based on the electric field effect will be also lighter. As a result of these two factors, the production of the machines based on the electric field effect will be cheaper.

Just like magnetic machines, the capacitive machines can be of two kinds, in dependence of the current/voltage used for their operation: direct current (DC) machines with commutator or alternative current (AC) machines: synchronous or asynchronous.

Section II shows how the sectored capacitor could be used as a practical solution for the DC capacitive machines. Section III presents the proposed AC capacitive machine based on the sinusoidal capacitor. Section IV presents the simulation results of the proposed capacitive machine. Section V presents the conclusions of the paper.

## 2. The Sectored Capacitor as a Practical Solution for the DC Capacitive Machines

The simplest DC capacitive machine can be constructed from a round capacitor having two or more sectors, as shown in **Figure 1**. In this machine, two positively charged rotating sectors form the rotor and two negatively charged static sectors form the stator. In the position shown in **Figure 1**, the attractive force between the stator and rotor sectors establishes a moment, which rotates the rotor on a quarter of a circle until the sectors coincide. At the moment of a coincidence of the sectors, the applied voltage polarity is changed between the positively and negatively charged sectors. In other words, this machine should be constructed with a commutate or (like regular DC machines). If the number of plates will be increased, the machine operation will be smoother. In order to ensure smooth operation, at least three couples of plates should be used.

The torques of the capacitive machine could be calculated by differentiation of the energy stored in the electric field of the capacitor [6]. In the case of angular movement, the differentiation is performed by an angle $\alpha$:

$$M(\alpha)=\frac{\mathrm{d}}{\mathrm{d}\alpha}\left(\frac{C(\alpha)V^2}{2}\right) \tag{6}$$

where $C(\alpha)$ is varying capacitance of the capacitor plates as function of the rotor angle $\alpha$ and $V$ is the voltage applied to the capacitor plates (this formula is adequate when the capacitor is connected to a power source). With the movement of the rotor, the capacitance between the rotor and the stator varies proportionally to the surface of coincidence between sectors. The surface of coincidence between the sectors is proportional to the rotor angle $\alpha$ and could be calculated by:

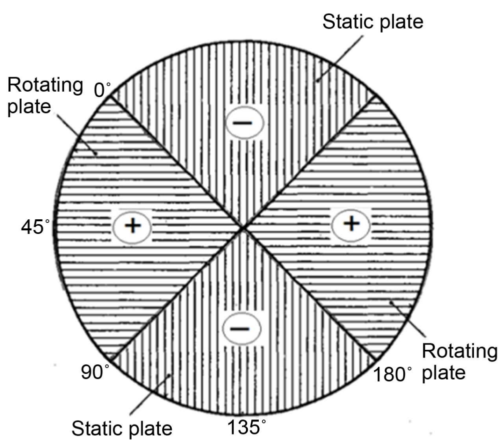



**Figure 1.** DC capacitive machine constructed from round capacitor with four sectors.

$$s = \rho^2 \frac{\alpha}{2} \quad (7)$$

where $\rho$ is the radius of the plates. The capacitance of the round capacitor with four sectors (two couples of plates) could be calculated by:

$$C(\alpha) = 2\frac{\varepsilon\varepsilon_0\rho^2\alpha}{d} \quad (8)$$

where $d$ is the distance between the plates.

The axial torque of the capacitive machine with three couples of plates could be calculated by substituting Equation (8) in Equation (6):

$$M(\alpha) = \frac{\varepsilon\varepsilon_0\rho^2V^2}{d} \quad (9)$$

Equation (9) shows that the moment of this capacitive machine is constant and independent of the rotor angle-$\alpha$. The speed of capacitive motors is a function of the supplied power and the number of revolutions per minute could be calculated by $= 9.55\times(P/M)$. For example, for the 130 W motor with insulating material which has dielectric permittivity of $\varepsilon = 10^4$, two couples of plates, the distance between the plates $d = 2$ mm, the radius of the plates $\rho = 10$ cm and applied voltage $V = 1$ kV, the moment will be $M = 0.44$ Nm. The motor speed will be $n = 955$ rpm.

## 3. The Proposed AC Capacitive Machine Based on a Sinusoidal Capacitor

This paper proposes novel synchronous machine operating on the principle of the electric field effect. The proposed machine is constructed from a variable capacitor having static and rotating plates.

The capacitance be haves as a sinusoidal function and depends on the plates movement angle. The proposed sinusoidal capacitor machine with rotating plates (rotor) above static plates (stator) is shown in **Figure 2**.

The plates are constructed in such a way that their radius-vector is dependent on the angle and their overlapping surface is a sinusoidal function of the angle. The stator plates are constructed as standard sectors. This form allows more efficient usage of the plate's surface and as a result, increases the maximum capacity of the capacitor. The variable surface of the plates is a function of the $\alpha$ angle and could be calculated by:

$$S(\alpha) = \frac{1}{2}\int_0^{\alpha}\rho^2(\alpha)\,\mathrm{d}\alpha \quad (10)$$

On the other hand, the variable surface is sinusoidal and it could be also expressed as:

$$S(\alpha) = S_m\frac{1-\cos(2\alpha)}{2} \quad (11)$$

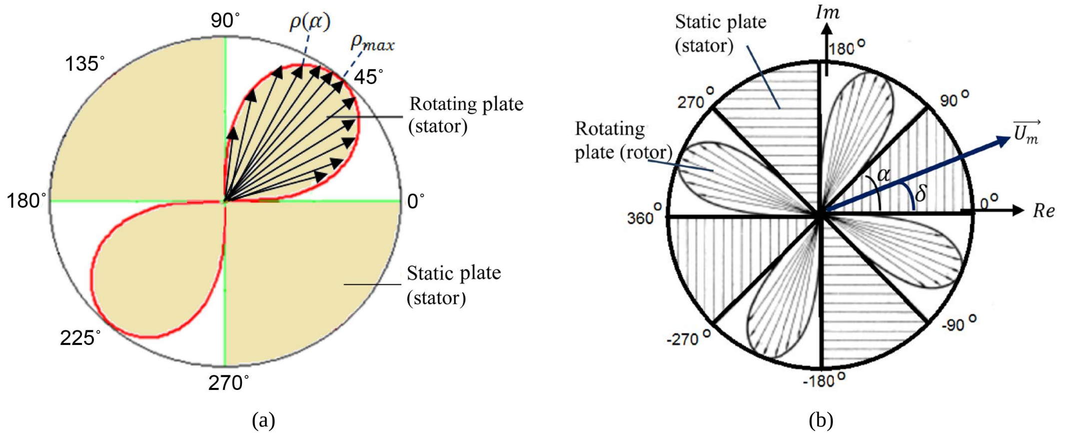



**Figure 2.** (a) The proposed capacitive motor with two rotating plates (rotor) and two static plates (stator); (b) The proposed capacitive motor with four rotating plates (rotor) and four static plates (stator).

where $S_m$ is the maximum overlap surface of the capacitor (when the plates of the stator and the rotor are fully overlapped one above the other). The variable surface versus the rotating angle $\alpha$ is shown in **Figure 3**.

The radius of the capacitor plates $\rho(\alpha)$ could be calculated from Equations (10) and (11):

$$\rho(\alpha) = \sqrt{2S_m \sin(\alpha)} \tag{12}$$

By using Equation (12), the diameter of the capacitor plates could be obtained:

$$D = 2\rho_m = 2\sqrt{2S_m} \tag{13}$$

where $\rho_m$ is the maximal radius of the rotating plates.

When the rotor plates rotates above the stator plates, the capacity of the machine varies according to:

$$C(\alpha) = C_m \frac{1-\cos(2\alpha)}{2} = \varepsilon\varepsilon_0 k \frac{S_m}{d} \frac{1-\cos(2\alpha)}{2} \tag{14}$$

where $d$ is the distance between the static and the rotating plates, $\varepsilon$ is the relative electric permittivity of the insulating material between the plates, $k$ is the number of pairs of the rotor/stator plates and $C_m$ is the maximal capacitance of the machine with $k$ couple of plates.

The torque of the capacitive machine could be calculated by the differentiation of the energy stored in the electric field of the capacitor. If the capacitor is supplied by the voltage-$u$, the axial torque of the capacitive machine could be determined by substituting Equation (14) into Equation (6):

$$M(\alpha) = \frac{C_m u^2}{2} \sin 2\alpha \tag{15}$$

As it seen from the Equation (15), if the proposed capacitive machine was supplied by a DC voltage source, the average torque would be zero. In order to obtain efficient average torque (different than zero), the applied voltage should be an alternating voltage $(u = U_m \sin(\omega t))$ and the angular speed of the rotor should be equal to the angular frequency of the applied voltage.

The angular velocity could be defined as $\omega = \frac{\mathrm{d}\alpha}{\mathrm{d}t}$. Therefore, the rotor angle could be obtained by an integration of the angular velocity:

$$\alpha = \omega t + \frac{\delta}{2} \tag{16}$$

where $\delta$ is the angle between the starting line $(\alpha = 0^\circ)$ of the rotor plate and the phase angle of the alternating voltage (see **Figure 3(b)**). The meaning of the angle $\delta$ could be also explained by using a complex plane having "Real" and "Imaginary" axes. The alternating voltage applied to the sinusoidal capacitor could be represented by the rotating vector $\boldsymbol{U_m}$, which rotates with the angular velocity $\omega$ on the complex plain. The capacitor rotating plates (rotor) are referred to the zero degree line. Therefore, the $\delta$ angle is the angle between voltage vector $\boldsymbol{U_m}$ and the rotor axis.

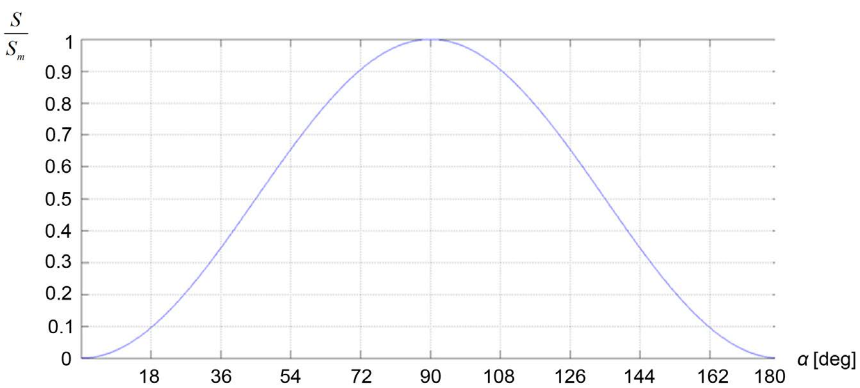



**Figure 3.** The variable surface of the capacitor versus the angle $\alpha$.

The angular velocity of the rotor could be obtained by:

$$\omega_r = \omega/k \tag{17}$$

where $k$ is the number of pairs of the rotor/stator plates. The speed of the machine in revolutions per minute (rpm) could be calculated according to the following formula:

$$n = \frac{60f}{k} \tag{18}$$

where $f$ is the frequency of the applied AC voltage.

The torque of the proposed machine as a function of time could be calculated by substituting the Equation (16) into the Equation (15):

$$M(t) = C_m U_m^2 \sin(\omega t)^2 \sin(2(\omega t + \delta/2)) \tag{19}$$

$$M(t) = \frac{C_m U_m^2}{2}(1 - \cos(2\omega t))\sin(2\omega t + \delta) \tag{20}$$

$$M(t) = \frac{C_m U_m^2}{2}\left[\sin(2\omega t + \delta) - \frac{\sin\delta}{2} - \frac{\sin(4\omega t + \delta)}{2}\right] \tag{21}$$

The average torque, *i.e.*, the effective torque, would be:

$$M_{\text{avg}} = \frac{1}{2\pi}\int_0^{2\pi} M(t)\,\mathrm{d}t = -\frac{C_m U_m^2}{2}\sin\delta \tag{22}$$

The meaning of the minus sign in the formula of torque is that the torque resists motion, *i.e*. that machine operates in a generator mode and the conversion is from mechanical energy into electric energy. In the generator mode, the rotor precedes the alternating voltage (positive $\delta$ angle). In the motor mode, where the $\delta$ angle is negative, the rotor lags behind the alternating voltage. The generator and the motor operation modes are shown in the torque diagram, **Figure 4**.

The machine would develop maximal torque when the angle $\delta$ would be equal to $\pi/2$:

$$M_{\max} = \frac{U^2 C_m}{2} \tag{23}$$

The obtained diagram is similar to the torque diagram of a synchronous machine. It can be seen from the presented analysis, that a rotating field is not needed for the capacitive machine operation as for the three-phase electromagnetic machines, and that a capacitor machine can also operate as a single-phase machine. There are no differences between the analysis of single-phase capacitor motor and the three-phase one.

## 4. Simulation of the Proposed AC Capacitive Machine

The proposed AC capacitive machine was simulated by using the Matlab program. The parameters of the simulated machine are: 4 couples of plates $(k = 4)$, the maximal overlap surface of the rotor and stator plates is

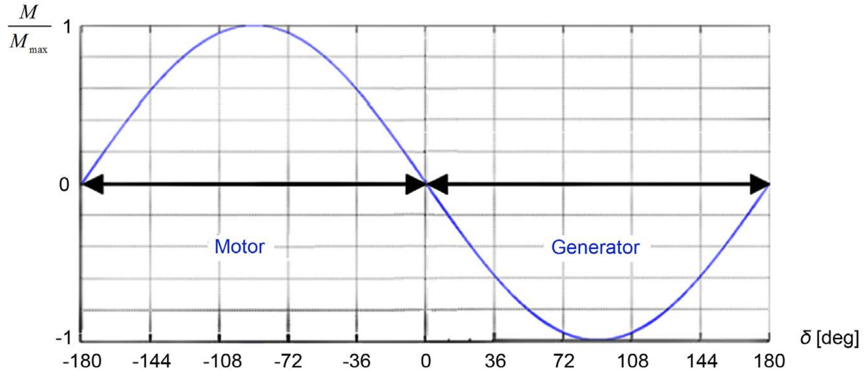



**Figure 4.** The torque diagram of the proposed capacitive machine.

$S_m = 50\ \text{cm}^2$, electric permittivity of the dielectric material is $\varepsilon = 10^4$, the distance between the plates is $d = 3\ \text{mm}$. The applied AC voltage is $U_m = 6\ \text{kV}$ and the frequency is $f = 50\ \text{Hz}$. The simulation results for $\delta = 30^\circ$ (generator mode) are shown in **Figure 5**. It can be seen that the capacitance varies in a sinusoidal shape: $C(\alpha) = 0$ for $\alpha = 0,\ \pi,\ 2\pi$; $C(\alpha) = 6\ \text{uF}$ for $\alpha = 0,\ 0.5\pi,\ 1.5\pi$. The obtained average torque is negative −54 Nm (see **Figure 5(a)**). Therefore, the machine operates in the generator mode. The spectrum of the instantaneous torque has three harmonics: DC, 100 Hz and 200 Hz. This result is logical because $M(t)$ consists of $-\frac{C_m U_m^2}{2}\frac{\sin\delta}{2}$ which is represented by DC harmonic, $\frac{C_m U_m^2}{2}\left[\sin(2\omega t + \delta)\right]$ which is represented by 100 Hz harmonic and $-\frac{C_m U_m^2}{2}\frac{\sin(4\omega t + \delta)}{2}$ which is represented by 200 Hz harmonic.

The simulation results for $\delta = 0^\circ$ are shown in **Figure 6**. In this case, the machine operates on the boundary of generator and motor modes. The obtained average torque is zero. The spectrum of the instantaneous torque has 100 Hz and 200 Hz harmonics. The DC harmonic is zero because $\frac{C_m U_m^2}{2}\frac{\sin\delta}{2} = 0$.

The simulation results for $\delta = -30^\circ$ are shown in **Figure 7**. In this case, the machine operates in the motor mode. The obtained average torque is 54 Nm.

The Matlab simulation results could be validated by numerical calculations. The maximal capacitance could be calculated by Equation (14):

$$C_m = \varepsilon\varepsilon_0 k \frac{S_m}{d} = 10^4 \times 8.86 \times 10^{-12} \times 4 \frac{50 \times 10^{-4}}{3 \times 10^{-4}} = 6\ \text{uF}$$

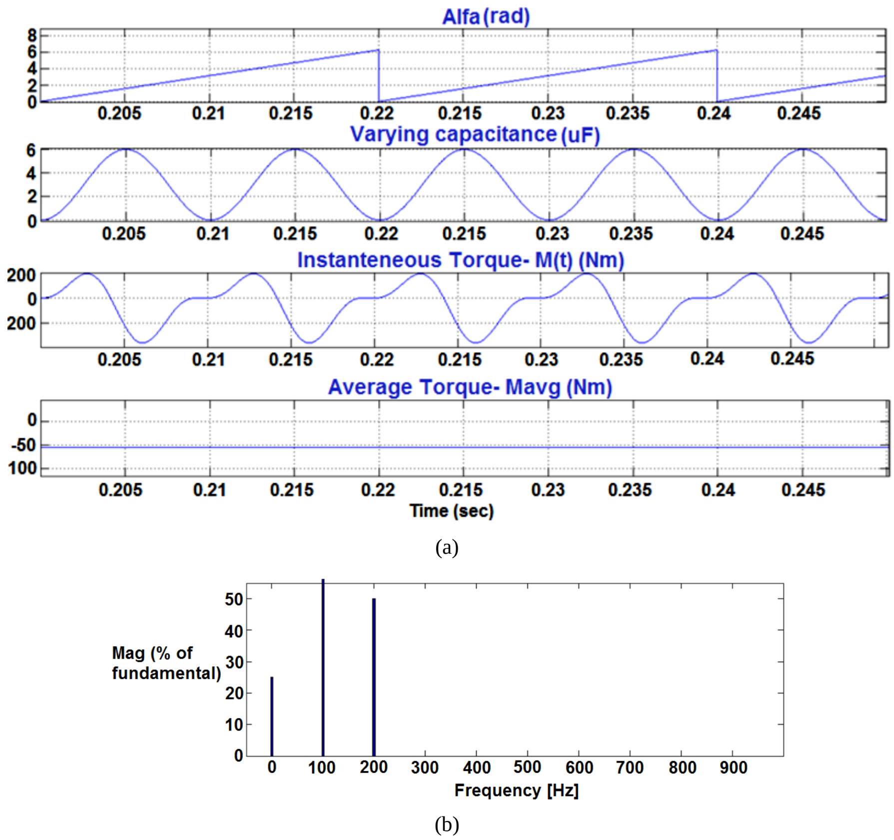
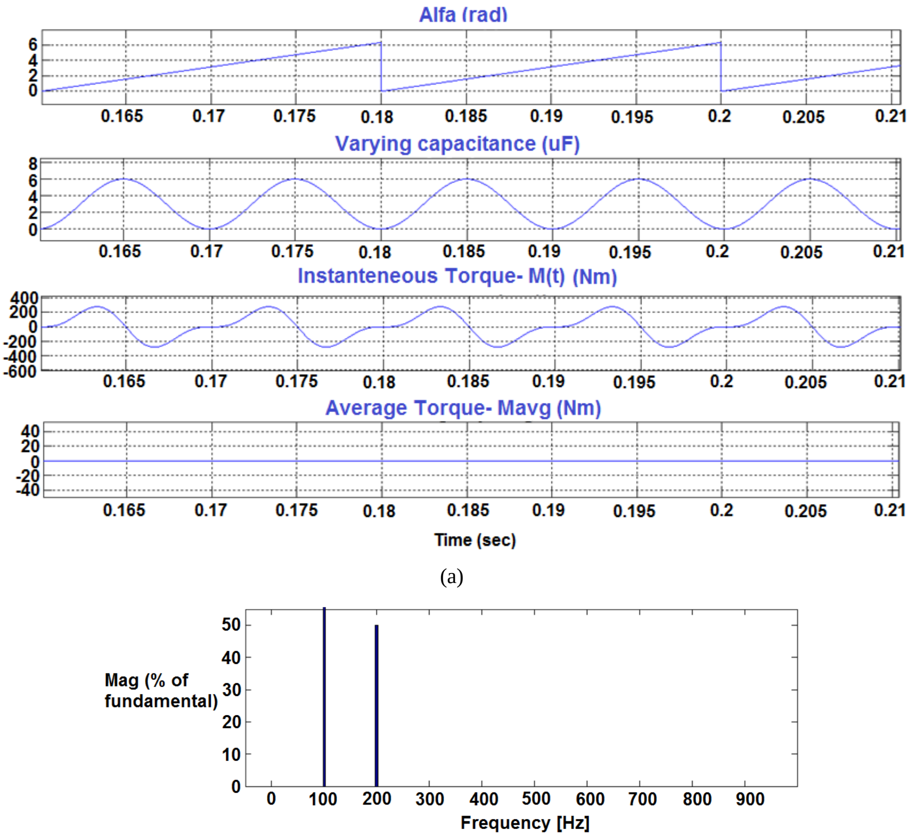



**Figure 5.** The angle $\delta = 30^\circ$ (generator mode). (a) The simulated rotating rotor angle $\alpha$ (varies from zero to 2π), varying capacitance $C(\alpha)$, instantaneous torque of the machine $M(t)$ and the average torque $M_{avg}$. (b) The spectrum of the instantaneous torque.




(a)

(b)

**Figure 6.** The angle $\delta = 0^\circ$ (boundary between the generator and motor modes). (a) The simulated rotating rotor angle $\alpha$ (varies from zero to 2π), varying capacitance $C(\alpha)$, instantaneous torque of the machine $M(t)$ and the average torque $M_{avg}$; (b) The spectrum of the instantaneous torque.

For the case of $\delta = 30^\circ$, the calculated average torque would be:

$$M_{avg} = -\frac{C_m U_m^2}{2}\sin\delta = -\frac{\left(6\times10^{-6}\right)\times\left(6\times10^{3}\right)^2}{2}\times0.5 = -54\text{ Nm}$$

For the case of $\delta = -30^\circ$, the calculated average torque would be:

$$M_{avg} = -\frac{C_m U_m^2}{2}\sin\delta = -\frac{\left(6\times10^{-6}\right)\times\left(6\times10^{3}\right)^2(-0.5)}{2} = 54\text{ Nm}$$

In this case, the motor output power would be:

$$P_{out} = M_{avg}\times\omega_r = M_{avg}\times\frac{\omega}{k} = \frac{54\times314}{4} = 4239\text{ W}$$

The calculations show that the presented simulation results are correct.

## 5. Conclusions

The novel capacitive synchronous machine is proposed. The machine is operating on the principle of the electric field. By using new materials with high electric permittivity $\varepsilon$, the proposed machine is feasible from the theoretical and the practical points of view. The machine design is based on the sinusoidal capacitor whose capacitance varies according to a sinusoidal function. The proposed machine is actually electrical synchronous machine with characteristics similar to those of the magnetic synchronous machines.

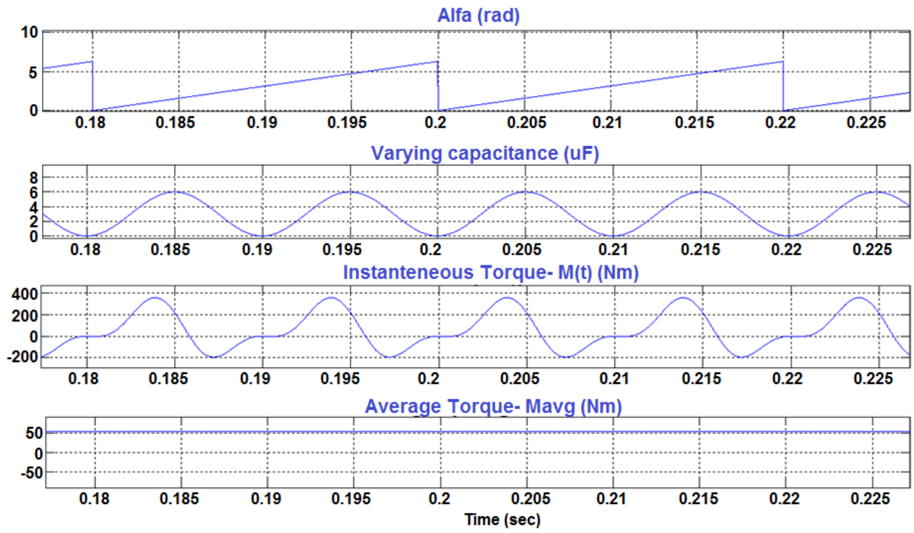



**Figure 7.** The angle $\delta = -30^\circ$ (motor modes). The simulated rotating rotor angle $\alpha$ (varies from zero to $2\pi$), varying capacitance $C(\alpha)$, instantaneous torque of the machine $M(t)$ and the average torque $M_{\text{avg}}$.

Extensive simulation results of the machine operated in the motor and the generator modes validate the theoretical analysis and show the practical feasibility of the proposed machine.

The proposed machine has a number of advantages upon the conventional electric machines based on the magnetic interaction. The main advantage is that the electric field machines are much smaller in size and lighter in weight than the electromagnetic machines with the same output parameters. Furthermore, the capacitor motor has very low inertial torque due to the low weight of the rotor. This fact allows rapid starting and stopping of the machine, as well as other variations during operation. This feature could be highly important in control systems. Another advantage is the simple structure of a single-phase capacitor motor.

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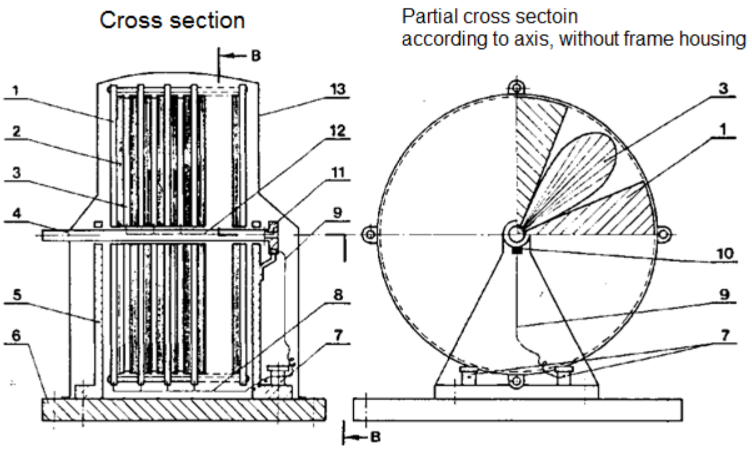
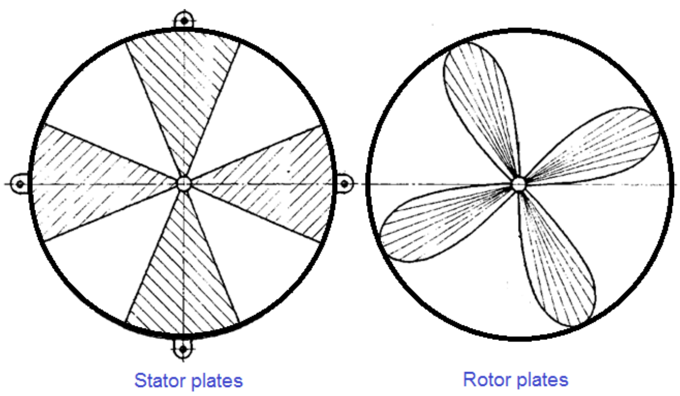
## Appendix: Example of Design of the Capacitive Motor

The proposed capacitive machine and the shape of the plates of both stator and rotor are shown in **Figure 8**. In order to increase the overall capacity of the motor, it is made of a large number of plates, and the insulation between the plates is of a material with a high $\varepsilon$ value. This material takes the form of insulation washers. In order to ensure a good contact between the plates of the rotating rotor and the insulation washers, idling together with the stator plate, and in order to reduce friction, the lubricant should have also high $\varepsilon$ value.




1—Stator plates; 2—Insulating washer; 3—Rotor plates; 4—Motor shaft; 5—Supports; 6—Bed plate; 7—Terminals; 8—Connecting lead of stator; 9, 12—Connecting lead of rotor; 10—Brush; 11—Slip rings; 12—Frame housing.

(a)




(b)

**Figure 8.** The proposed capacitive motor.