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HIGH-EFFICIENT SOURCES FOR ARC WELDING ON THE BASE OF CAPACITIVE ENERGY STORAGE SYSTEMS

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A new class of high-efficient arc welding equipment is proposed, which is based on wide application of capacitive energy storage systems, in which high-capacity capacitors with a double electric layer are used as such storages. The paper is a study of the structure of sources, which are based on switching-modulation conversion of welding current. Procedures of signal conversion in the proposed sources, using the charge transfer method are analyzed in detail. Analysis of dynamic characteristics of this type of sources was performed, and basic equations were derived, which characterize different types of capacitive welding current converters. 13 Ref., 1 Table, 4 Figures.

Keywords: arc welding, capacitive energy storage system, double electric layer capacitor, charge transfer method, topological structures of the sources, step-down type converter

Modern approaches in designing of welding power sources are based on the following requirements to their parameters: high energy efficiency of welding current conversion, required level of operational reliability, increased generated specific capacity (determined in relation to weight or volume), power factor of not lower than 0.9, high dynamic parameters in the mode of current/voltage stabilization. It is naturally, that the abovementioned requirements can be satisfied only by high-frequency welding converters [1]. But transfer to the conversion of welding current energy at a high frequency raises the problem of electromagnetic compatibility (EMC) [2]. Meeting all these requirements leads to additional costs on hardware, which to some extent reduce the economic efficiency of high-frequency welding equipment.

Basically, modern welding inverters are designed according to the double conversion circuit, when the mains voltage is rectified, smoothed by a capacitive filter and then supplied to the input of the DC/DC converter unit. In capacity of the latter, three types of circuits are mainly used: full-bridge, half-bridge inverters, and most often in the sources of up to 200 A – a single-step bridge inverter, which in the technical literature is often called an «oblique» bridge (OB). The prospects of this structure of welding inverter are indisputable. That is why a number of works [3] devoted to the search for new circuit solutions, as well as to increase the parameters of energy efficiency are devoted to its further investigations and improvement. A particular interest of the works in this area is paid to the dual OB [4], which in terms of technical and economic indices competes even among bridge converters with a phase control.

An important role in welding inverters is played by dynamic parameters of power keys, which mainly determine the losses on switching. Namely these losses limit the switching frequency, to increase which it is necessary to use resonant or «softly» switched technologies [5].

One of the ways to increase the energy efficiency of inverter welding equipment is elimination of a high-capacity filter capacitor in the rectifier circuit and transfer from a double energy conversion to a direct one. As is shown in [6], in case of excluding the function of input voltage rectification, it is possible to obtain high parameters of efficiency (EF) and power factors (PF) of the welding inverter. However, it will not be possible to get rid of a low-frequency transformer. And this causes deterioration of mass and size parameters of the device.

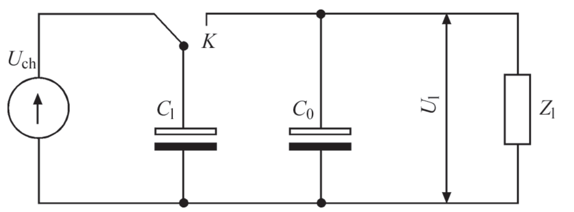
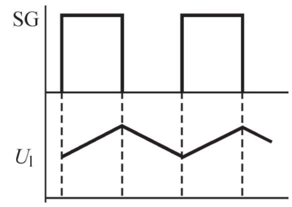
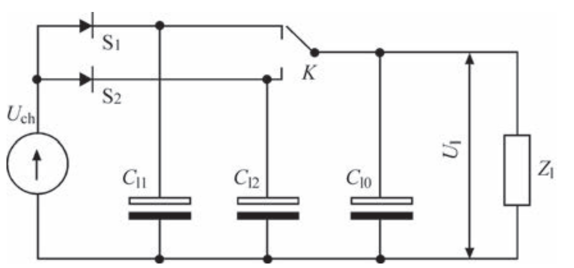
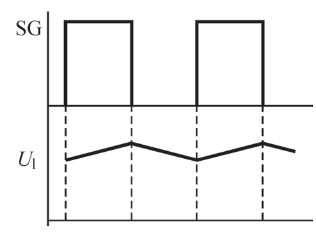
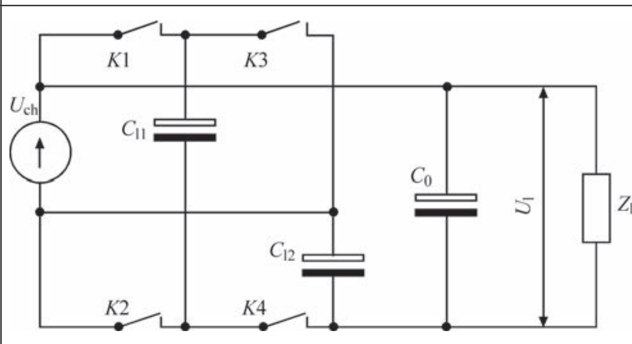
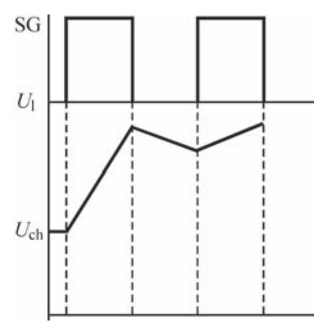
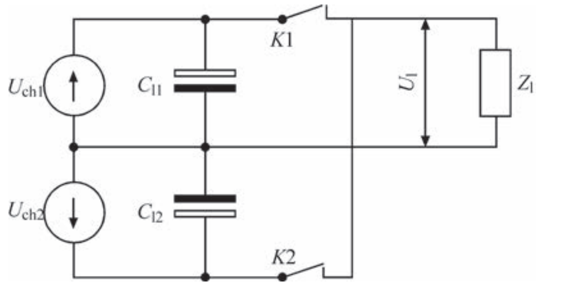
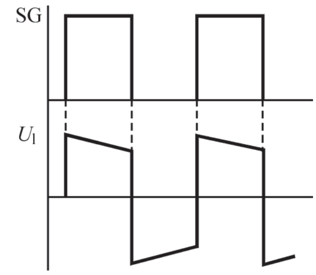
The authors of [7] showed that elimination of this drawback is possible by transfer to sources with a three-phase input. Here the principle of direct conversion of a three-phase voltage of industrial frequency into a high-frequency voltage is realized, which will then be converted in the same way as it is realized in the circuits of conventional welding inverters. However, here additional difficulties associated with the need in using bidirectional keys arise. And this leads to doubling a number of switching elements and circuits of their control, which ultimately reduces the economic indices of such sources.

One more direction in the creation of high-efficient welding equipment is resonance technologies [8]. They are based on a wide range of different types of inductive-capacitive converters (ICC), the circuitry of which is based on a wide range of elements of power electronics. These can be simply resonant LC circuits [9], inducons [10] operating in a wide range of frequencies. It is also necessary to note high-frequency welding converters designed on the base of artificial long lines (ALL) [11], in which EF of up to 90 % is achieved.

Despite such a large number of technical solutions in the field of welding current converters, the search for new methods of manufacturing sources continues. One of the prospective areas is creation of sources, in which inductive energy storages are replaced by capacitive ones. Naturally, a simple replacement is impossible here: it is necessary to develop new circuit solutions that would allow using the functionality of capacitive energy storages (CES) in a full extent. This class of noninductive converters should have the following properties:

- change the polarity of the input voltage;
- increase or decrease its level in accordance with the specified conversion factor;
- carry out the mode of galvanic isolation if necessary.

All these procedures can be realized in switching-modulation devices, when the accumulated charge in accordance with the conversion determined by the law (inversion, summation, multiplication, etc.) is transferred from one capacitor to another. Therefore, this type of sources can be called converters with charge transfer (CCT). The success of their practical realization is primarily associated with achievements in the field of creating powerful electric energy storage devices — supercapacitors (SC) [12], which are characterized by a high quality factor. This provides their increased energy efficiency. In this regard, the

Number	Circuit schemes of switching-modulation converters	Time diagrams
1		
2		
3		
4		

1 — switching-modulation converter (SMC) on the base of conventional circuit of a «flying» capacitor; 2 — SMC on the base of circuit of a two-step «flying» capacitor; 3 — SMC in the mode of voltage doubling; 4 — SMC in the mode of alternating voltage formation.

problem of using capacitive storage systems in creation of sources for arc welding is certainly relevant.

Until now, in welding SC have been used exclusively for pulsed technologies such as resistance spot welding, welding of studs, press welding using magnetically-impelled arc [13], etc. Here, SC was functionally used to form a powerful current pulse in the range of 0.5–10 kA in a single cycle of welding. At present, the experience of using SC in continuous arc welding modes is currently absent. The proposed work is the first attempt to implement this idea in relation to arc welding processes.

Let us consider some of the possible variants of CCT circuits given in Table, on the base of which it is possible to design equipment for arc welding. The circuit 1 represents a converter of type «flying» capacitor, where the storage capacitor [14], preliminary charged to the voltage U_{ch} is discharged with a help of the key K to the capacitor C_0. The latter is used as a power source of the load Z_l. As follows from the time diagram, the voltage on the load U_l is ripple, the level of which is determined by the frequency of the step generator (SG).

A significant reducing of their value is possible by using the circuit 2, which represents a double-step «flying» capacitor. In this circuit, the charge-discharge processes occur in an antiphase. Therefore, the value of voltage ripple on the load can be easily reduced to 1 %. However, the price for this advantage will be installation of additional capacitor C_{l2}.

The converter, designed in accordance with the circuit 3, provides a mode of doubling the voltage on the load. This occurs as follows: in the first step (keys $K1$, $K2$ are closed, and $K3$, $K4$ are open), the charge C_{l1} occurs to the voltage U_{ch}. Then, in the second step (keys $K1$, $K2$ are open, and $K3$, $K4$ are closed), the voltage is transferred to the storage system C_l with a change in polarity. Since the device is designed in such a way that this voltage and U_{ch} are summed, then on the load a double voltage ($U_l = 2U_{ch}$) will act. It is easy to see that the device designed according to this circuit is advisable to be used to create battery welding sources. This is especially prospective for military transport systems, where 24 V batteries are used.

The circuit 4 can be recommended for creating alternating current welding sources on its base. It consists of two charging devices, which form the voltages U_{ch1}, and U_{ch2} equal in amplitude, but opposite in sign, two storage systems C_{l1} and C_{l2}, as well as two keys $K1$, $K2$, which are switched on in an antiphase. When the key $K1$ is closed, a positive half-wave is formed, and when the key $K2$ is closed, a negative half-wave is formed. A distinctive feature of such drivers is the fact that without changing the circuit elements at all

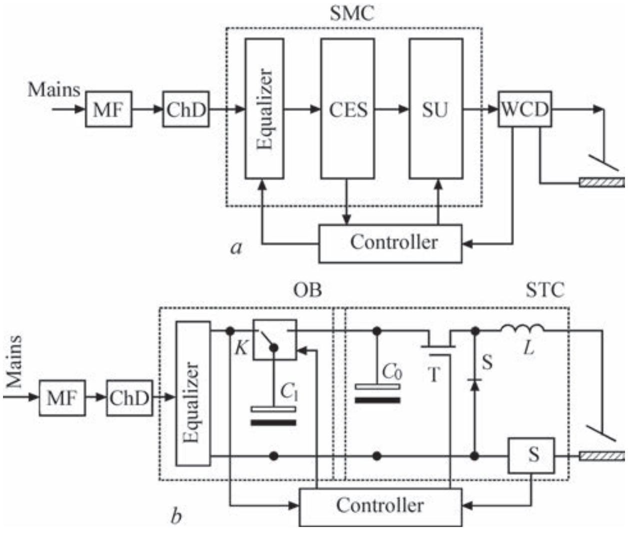


Figure 1. Circuit scheme of the source, that realizes the method of charge transfer (*a*), example of circuit realization of the source, based on a «flying» capacitor and SMC (*b*)

it is possible to adjust the frequency of the voltage supplying the arc in a wide range.

The structural and functional circuit of the source with the energy storage system on SC is shown in Figure 1, *a*. It consists of mains filter (MF), the primary purpose of which is to reduce the level of interferences generated in the mains. The MF output is connected to the charging device (ChD), as any type of direct current converter and also an autonomous power sources, such as batteries, flywheel capacitors, mini-power plants, etc. can be used. The voltage from the output of ChD is then supplied to SMC, which includes an equalizer. Its main purpose is to optimize the charge of CES elements. The switching unit (SU) performs the necessary procedures of an energy flow conversion in accordance with the algorithms specified by the controller. Thus, the obtained voltage is supplied to the input of the welding current driver (WCD), which provides the required volt-ampere characteristic (VAC) for the selected welding method.

An example of practical implementation of the described approach in creation of welding source is shown in Figure 1, *b*. In this device, as SMC, the circuit 1 (mode of «flying» capacitor), designed on the key K and the storage capacitor C_l is used. Then the charge accumulated on it is partially transferred to the capacitor C_0, which is a part of WCD, designed on the base of a step-down type converter (STC), which is known to be one of the most energy-efficient units in the field of power conversion technology.

The formation of the required VAC in accordance with the selected welding method is carried out due to the action of the feedback circuit, which is set by the signals of the current sensor (CS). As a result of action of these signals two control commands are synchro-

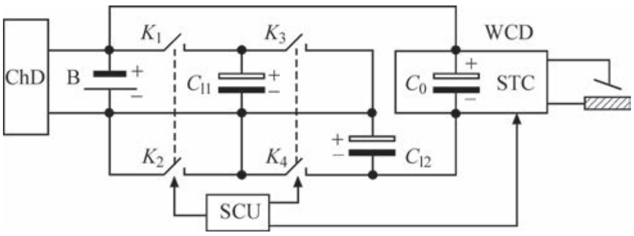


Figure 2. Battery power source

nously formed, which determine the time modes of operation of the key K and the transistor switch (TS) of the converter.

To create battery welding sources, the use of SMC is quite prospective. One of the possible variants of such a device is shown in Figure 2.

Procedurally, the conversion of energy flow occurs in the following order. In the first cycle, with the help of the closed keys $K1$ and $K2$, the storage system C_{l1} is charged from the battery (B). Then in the second phase, the keys $K1$ and $K2$ are opened and the keys $K3$ and $K4$ are closed. In this case, a part of the charge is transferred to the storage system C_{l2}, charging it to the voltage of the battery (B), but of a reverse polarity. As a result, this voltage is summed with the voltage of the battery and we obtain its double value. When the battery with $U = 24$ V is used, the total voltage acting on the storage systems C_0, amounts to 48 V. This is absolutely sufficient to power the STC converter, which is included in the WCD unit. All the described procedures of welding current conversion are realized by the switching control unit (SCU) of the keys, which are a part of SMC, and also the STC switch.

The advantage of this circuit of the battery source as compared to the known [15] is that due to the key decoupling of the battery circuit and the welding circuit, short-circuit currents in the arc do not lead to degradation of the battery, which took place during a direct switching into the welding circuit.

One more interesting technical solution in this class of devices is a source of alternating current for arc welding, in which it is simply enough to change the frequency in a very wide range. And most importantly, in this case the mode of frequency modulation (FM) of the welding current can be applied, which is almost impossible to realize in the conventional circuits of sources. Therefore, the technological properties associated with such a mode of FM have not been studied before.

The circuit scheme of such a source is shown in Figure 3, *a*. It consists of two charging devices ChD1 and ChD2, which form the voltage of positive and negative polarity U_1 and U_2. Therefore, the storage systems C_{l1} and C_{l2} are in the mode of a continuous charge. The voltage on them is periodically connected to WCD, which represents an inductive-capacitive converter (series resonant circuit), which, as is known [8], provides a high stability of welding arc burning.

The frequency of welding current is determined by the frequency selection switch (FSS). Depending on different settings of the circuit L_1, C_1 or L_2, C_2, it is set by the controller software, which controls the switching modes of the keys K_1, K_2 and FSS. The results of the experiments of the source verification in the mode $f = 1.41$ kHz are shown in Figure 3, *b*. The curve *1* is the arc voltage, the curve *2* is the welding current, the amplitude of which $I_w = 180$ A.

Let us consider the energy issues that arise when designing CCT sources. We shall assume that the state of the circuit before closing the key K (Figure 4, *a*) is as follows: C_1 and C_0 are charged. Moreover, $U_m > U_d$. Then at the moment of switching, it is possible to write down:

$$U_m = I(t)r + U_d. \tag{1}$$

If we pass to the charge shape, then (1) can be represented as:

$$-\frac{q_1}{C_1} + \frac{q_0}{C_0} + I(t)r = 0, \tag{2}$$

where $I(t)$ is the current in the circuit; q_1 and q_0 are the charges of the storage systems C_1 and C_0.

If we differentiate (2) in time, we obtain:

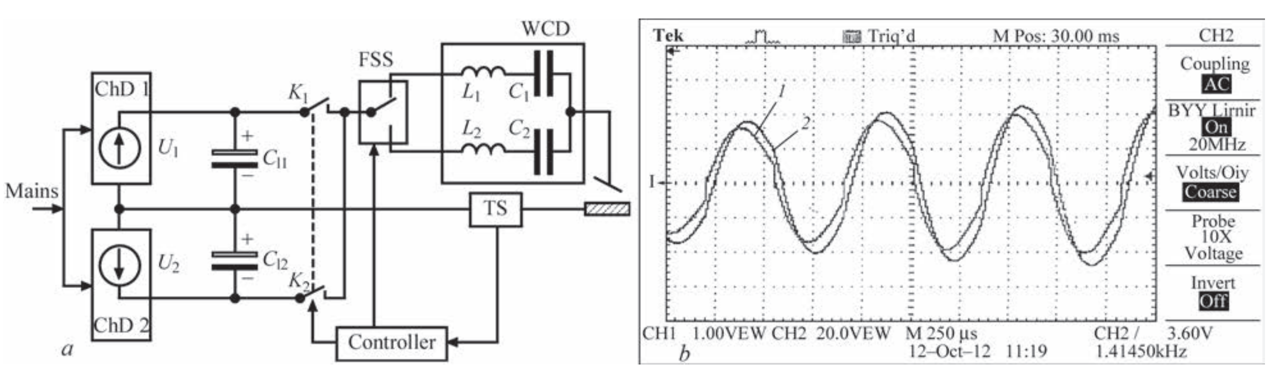


Figure 3. Circuit scheme of ac source (*a*), oscillogram of voltage (*1*) and current (*2*) (*b*)

$$-\frac{1}{C_1}\frac{dq_1}{dt}+\frac{1}{C_0}\frac{dq_0}{dt}+r\frac{dI(t)}{dt}=0. \quad (3)$$

Taken into account the fact that based on the law of charge conservation, current in the circuit is equal to:

$$I(t)=-\frac{1}{C_1}\frac{dq_1}{dt}=\frac{1}{C_0}\frac{dq_0}{dt},$$

(3) can be represented as:

$$\left(\frac{1}{C_1}+\frac{1}{C_0}\right)I(t)+r\frac{dI(t)}{dt}=0. \quad (4)$$

As is known from [16], the solution of equation (4) will be the function

$$I(t)=I(0)\exp\left(-\frac{t}{\tau}\right), \quad (5)$$

where $I(t)$ is the current at the moment of switching; $\tau=r\frac{C_1C_0}{C_1+C_0}$ is the time constant of the discharge circuit.

If we determine $I(t)$ according to the initial values of $U_m(0)$ and $U_d(0)$, it can be written:

$$I(t)=\frac{U_m(0)-U_d(0)}{R}\exp\left(-\frac{t}{\tau}\right). \quad (6)$$

As we agreed, $U_m > U_d$. Therefore, the equations of the discharge C_1 and the charge C_0 in time can be represented by the following equations:

$$U_m(t)=U_m(0)-\frac{1}{C_1}\int_0^t I(t)\,dt= =U_m(0)-\frac{I(0)}{C_1}\int_0^t \exp\left(-\frac{t}{\tau}\right)dt. \quad (7)$$

Taken into account the fact that

$$I(0)=\frac{[U_m(0)-U_d(0)]}{};$$

$$U_m(t)=U_m(0)-\frac{\left[U_m(0)-U_d(0)\right]C_0}{C_1+C_0}\times \left[1-\exp\left(-\frac{t}{\tau}\right)\right] \quad (8)$$

similarly, the expression for the voltage on $C_0-U_d(t)$ can be represented

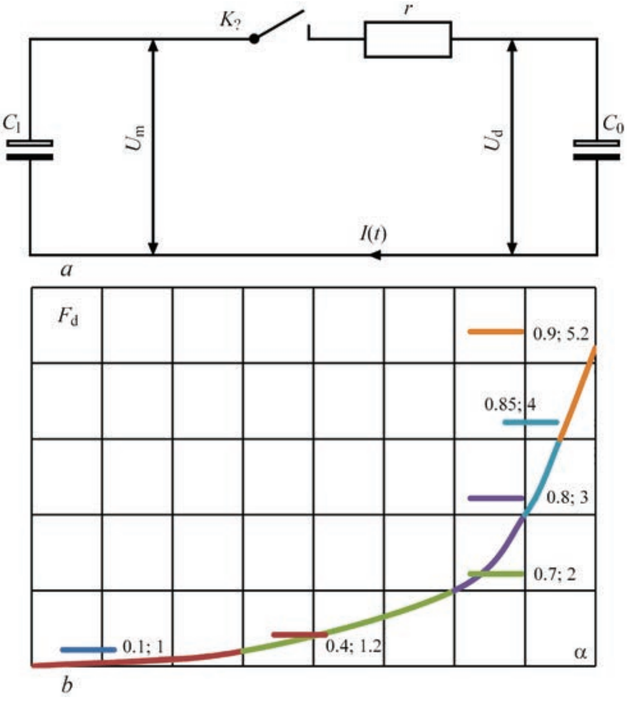


Figure 4. Circuit scheme of storage system discharge (*a*) and function of discharge F_d (*b*)

$$U_d(t)=U_d(0)-\frac{\left[U_m(0)-U_d(0)\right]C_0}{C_1+C_0}\times \left[1-\exp\left(\frac{t}{\tau}\right)\right]. \quad (9)$$

The abovementioned formulas (6–9) fully describe the processes of the charge transfer in the sources with SMC.

The subsequent transfer of energy to the load (arc) occurs by the transfer of the charge, which is formed by the storage system C_0 during some time Δt. In terms of power, this can be described by the following formula:

$$\Delta P(t)=C_0/2\left(U_1^2-U_2^2\right), \quad (10)$$

where U_1 and U_2 are the voltage of the charged and partially discharged C_0.

Let us denote $U_2=\alpha U_1$ where α is the coefficient that characterizes the degree of discharge of the storage system C_0. Then (10) can be represented by the following expression:

$$\Delta P(t)=\frac{C_0}{2}U_1\left(1-\alpha^2\right). \quad (11)$$

From (11) the value of the storage system C_0 capacity can be determined as:

$$C_0=\frac{2\Delta P(t)}{U_1^2}\frac{1}{1-\alpha^2}=\frac{2\Delta P(t)}{U_1^2}F_d, \quad (12)$$

where $F_{\mathrm{d}} = \frac{1}{(1-\alpha^2)}$ will be called a discharge function. It describes the degree of the charge transfer into the welding circuit. Its diagram is shown in Figure 4, *b*. Using the formula (12), it is possible to determine the storage system capacity for a set power of the welding current source.

In order to functionally link all the processes that take place in the sources with the charge transfer, we will use the following considerations. As is known, on the one hand the charge can be represented by the formula $q = C_1U$, on the other hand $q = It$, therefore:

$$C_1U = It. \quad (13)$$

Assuming that the process of energy flow conversion occurs every period, i.e. $t = 1/t$, then (13) can be converted to the form:

$$I / UC_1 f = 1. \quad (14)$$

The expression (14) describes the basic regularities, occurring in this class of sources for arc welding. It links the electrical (U, I) and time (t) characteristics with the storage system (C_1) capacity, and can serve as a base for calculating the parameters of CCT.

Further, the calculations performed in accordance with (14) will be adapted for different topological structures of inverter welding current converters, in which it is rational to use storage systems for realization of the charge transfer method. In our opinion, such an approach is especially prospective for calculations of step-down type converters.

Conclusions

New topological structures of power sources for arc welding, designed on the base of capacitive energy storages, are proposed.

Using the methods of the theory of switching-modulation converters, the theoretical substantiation of the work of this class of sources was carried out, and also the basic analytical expressions, describing the operation of such structures were obtained.

Based on the offered approaches, the working model of an alternating current source, providing a wide range of frequencies of output voltage regulation, was created and experimentally investigated.

It is shown, that an increase in energy efficiency of this class of equipment is achieved due to a high quality factor of capacitive energy storage systems, designed on the base of capacitors with a double electric layer.

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