Transient Processes in High Power Discharge of Electrochemical Capacitors

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INTRODUCTION

Electrochemical capacitors (EC) (Super capacitors, Ultra capacitors, Double Layer capacitors) are widely used in different spheres of application, where discharge time lasts at the range from tens of millisecond to minutes. At the same time one of the most significant spheres of application – power quality – requires special knowledge about EC behavior during more shorter discharges with maximum power. It is very important to know, for example what will happen when energy consumer is switched over from the main supply line to the auxiliary one, or how short (milliseconds) interruption of energy supply will effect on the state of local grid, equipped with short duration UPS system. Traditionally pulse discharge systems (milliseconds) market is occupied by aluminum electrolytic capacitors, which, however, have very low energy density and they cannot be applied in powerful industrial systems. In addition, capacity unit cost of traditional capacitors is significantly higher, than of EC.

There are many estimation means to determine the steady-state (constant) power of power source. For example, multilevel RC model for capacitor [1, 2] and correlation between RC-time constant and capacitor power [3] are used. However these methods do not describe rate of system response during first microseconds of discharge. It would be interesting to investigate reaching the steady-state power, i.e. *transient process of EC power, increasing from "Zero" during its connection into powerful discharging condition* including short circuit mode.

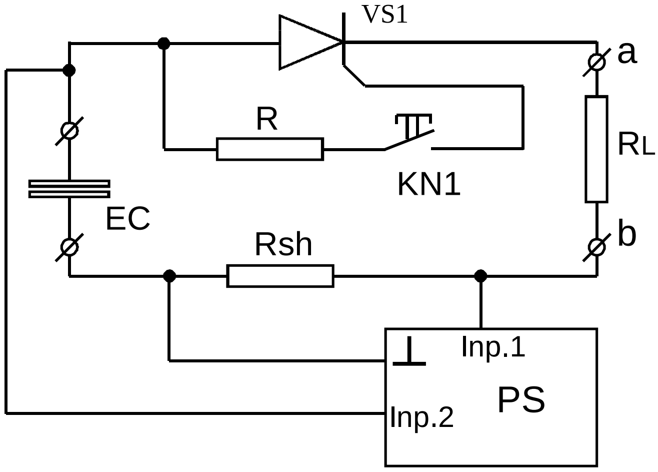
In present article, for investigation of transient processes the method of direct current and voltage recording during load switching was used. Such method was used previously for preliminary estimation of the initial capacitor's power [4, 5].

Now equipment with highest resolution is used, which makes it possible to register very precisely current and voltage changing in within the range of 0 → 1000 microsecond.

The obtained data make it possible to estimate opportunity to use different capacitors in power quality systems for power drops compensation during transient periods. The results of direct current and voltage measurement will be very useful for designers of short duration UPS/bridge systems on the basis of electrochemical capacitors.

1. EXPERIMENTAL

During testing, electric circuit according to Figure 1 had been made for determining of EC performances in transient period of powerful discharge.



EC – electrochemical capacitor
R_N – load resistor
R_{sh} – shunt (75 мV)
VS1 – thyristor switch

KN1 – start button
PS – oscillograph
R – resistor to open VS1

Fig. 1 Scheme of measurements

ELIT Co's production-run EC were used while measuring characteristics. Parameters are shown in Table 1.

Table 1

EC type	**U_o, V**	**C_N, F**	**W, KJ**	**ESR, mOhm**
14PP-0,5/0,015	12,0	5	0,36	10,1
15PP-1/0,025	12,0	15,4	1,11	14,8
18PP-6/0,006	12,0	50,5	3,63	6,0

As active loads resistors with nominal impedance of 10 mOhm and 47 mOhm and power of 5 KW were used. For experiment purity in the circuit high rate thyristor (2000 A, 400 V) was used with switching time less then 0,3 mcsec. It allowed to register the front of current growth without distortion. Copper wire with section of 70 mm^2 was used for connecting conductors.

Digital double-channel memory oscillograph TDS-3032 Tecktronix was used for recording of discharge performances.

In the course of tests each of the above mentioned capacitors was charged from the laboratory power source up to 13V and then it was discharged through thyristor switch VS.

The first discharge was "short-circuited"(in this case points "a" and "b", Fig.1 were connected together) and then it was carried out to each of the mentioned resistors. Oscillograph recorded up to 500 000 points per second during process registration, and then the obtained data processing was carried out.

2. RESULTS AND DISCUSSION

Initially it was planned to study transient processes using active and active-inductive loads. But the first experiments showed at once significant process delay at the beginning of discharge for mixed load (Fig.2) compared with pure active load (Fig.3).

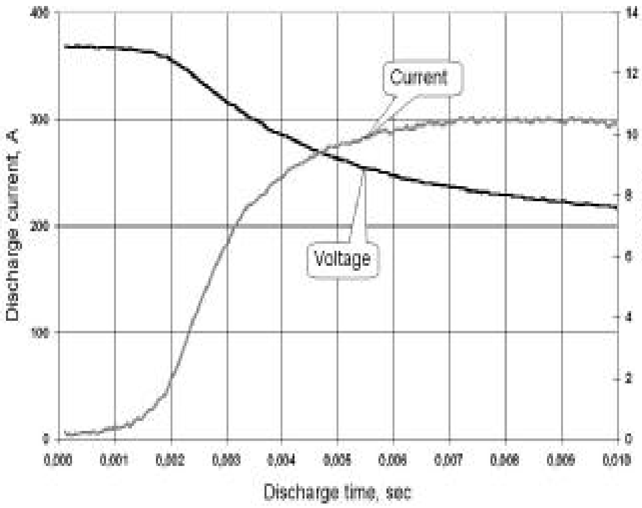


Fig.2 Typical Current/Voltage Profile at discharge on mixed load: Inductive-active (29 mOhm – 50 mc Henry). Capacitor 5 F, 14 V (RC 50 msec.)

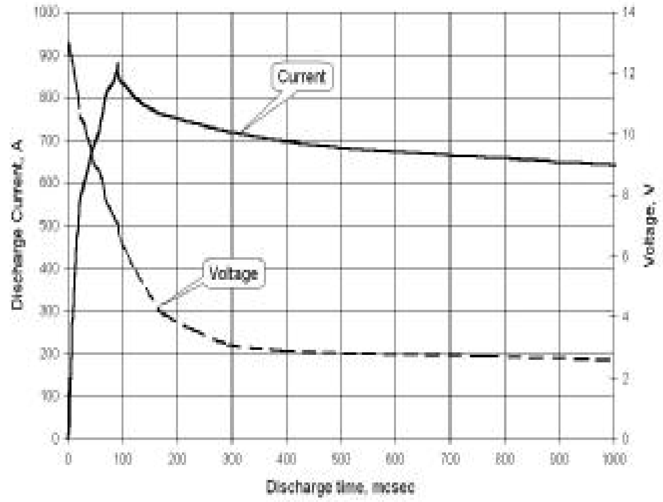


Fig. 3 Current/Voltage Profile during 1 msec. Short circuit Mode. Capacitor 5 F, 14 V (RC 50 msec.)

Comparing C/V profiles on Fig.2 and Fig.3 one can see, that process changings for mixed load begin only after 1500 mcsec, as distinct from pure active load, less then 100 mcsec. That is why further experiments with inductive load were not carried out.

Typical view of discharge curve for devices with higher values of RC-time constant in short –circuit condition is shown in Fig.4 and Fig.5.

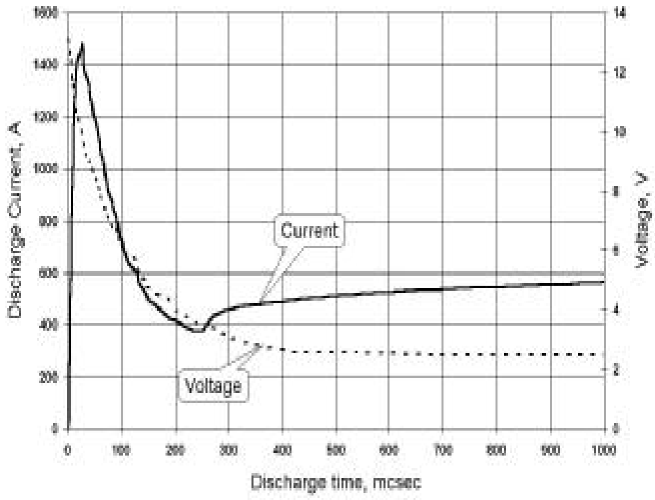


Fig.4 Current/Voltage Profile during 1 msec. Short circuit Mode. Capacitor 15 F, 14 V (RC 220 msec.)

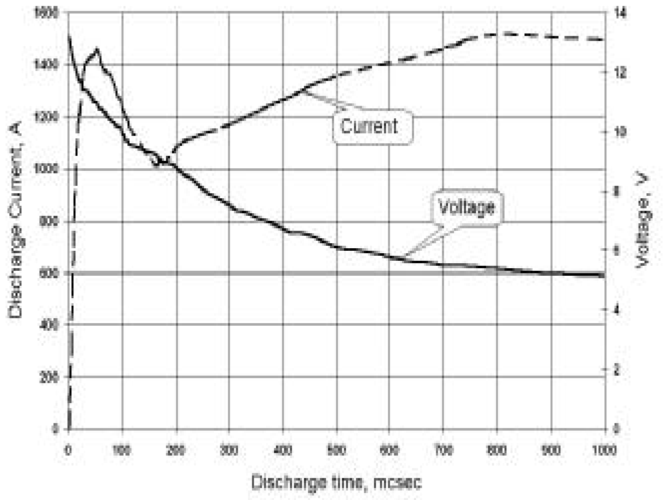


Fig.5 Current/Voltage Profile during 1 msec. Short circuit Mode. Capacitor 50 F, 18 V (RC 300 msec.)

As compared with discharge profile of device with lower RC-time constant (Fig.3), for these two capacitors untypical shape of discharge current curve is observed, and local minimum between 100 mcsec and 300 mcsec appears. Comparing design features of different unit cells, one may suppose, that the reason of this minimum appearance lies in the kinetic difficulty for current by electrolyte. Capacitors with RC-time constant of 220 msec and 300 msec have electrodes and separator the thickness of which is twice more than that of capacitor with RC ≈ 50 msec.

For estimation of inertia of electrochemical system carbon-carbon with aqueous electrolyte, analysis of reaching the peak of maximum current for different types of active loads, including short circuit**,** was carried out (Fig.6, Fig.7, Fig.8).

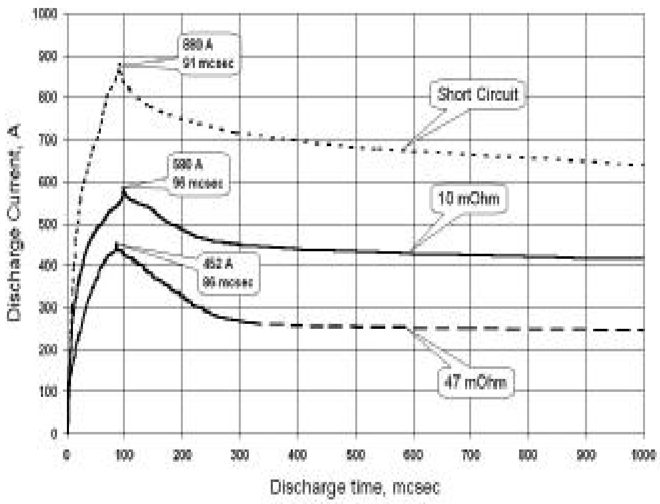


Fig. 6 Current Profiles on Different Discharge Loads.
Capacitor 5 F, 14 V (RC 50 msec.)

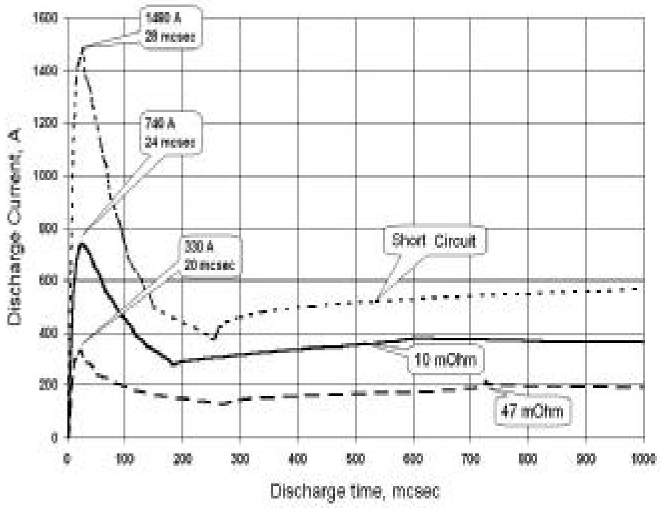


Fig. 7 Current Profiles on Different Discharge Loads.
Capacitor 15 F, 14 V (RC 220 msec.)

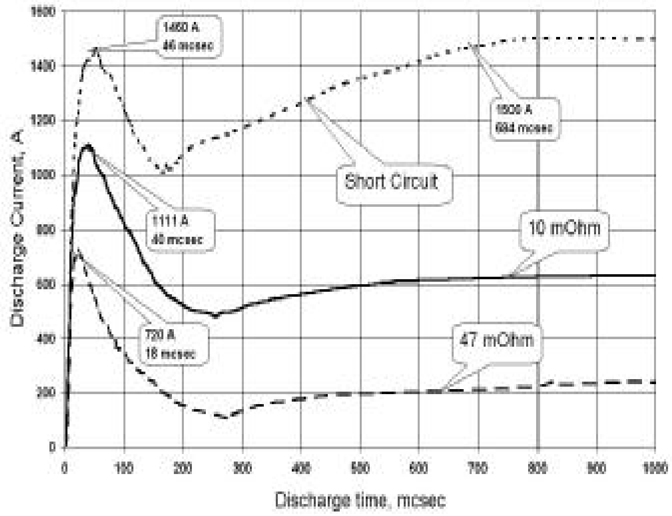


Fig. 8 Current Profiles on Different Discharge Loads.
Capacitor 50 F, 18 V (RC 300 msec.)

First of all, peak of maximum current for all the devices with RC-time constant of 50-300 msec is to the left of the 100 mcsec point and that shows the low inertia of DLC capacitors in powerful discharge conditions.

It is interesting to mention, that the time of maximum current reaching as a rule, does not depend upon active load value. Thus, for capacitors of 5F, 14V it is: 91 mcsec – for short-circuit mode, 96 mcsec – for 10 mOhm load and 86 mcsec – for 47 mOhm load. It should be noted, that for capacitors with RC-time constant of 220 msec and 300 msec current peak shifting to the left takes place during discharge load increasing: 28 → 24 → 20 mcsec and 46-48-18 mcsec.

Kinetic difficulty of discharge influences shape of the current curve. As it is seen in Fig.8, initial peak current for capacitor of 50F, 18V is even lower, than the current, that was reached at the point of 1000 mcsec: 1460A (46 mcsec) vs 1540A (1000 mcsec).

Discharge power changing during transient process are shown in Fig.9, Fig.10, Fig.11.

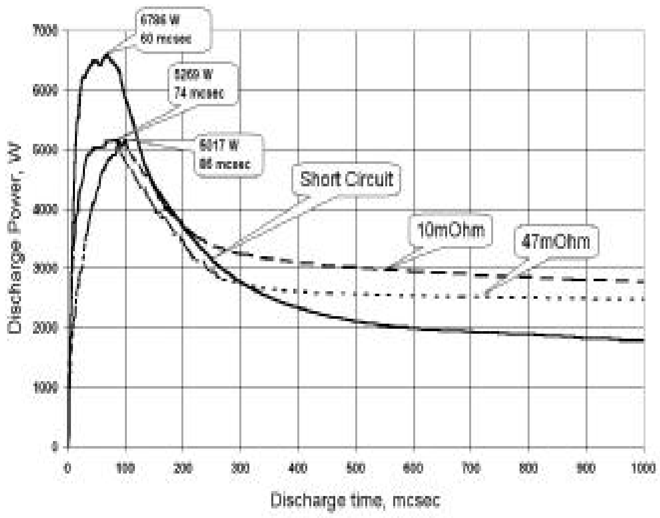


Fig. 9 Power VS. Time on different Discharge Loads.
Capacitor 5 F, 14 V (RC 50 msec.)

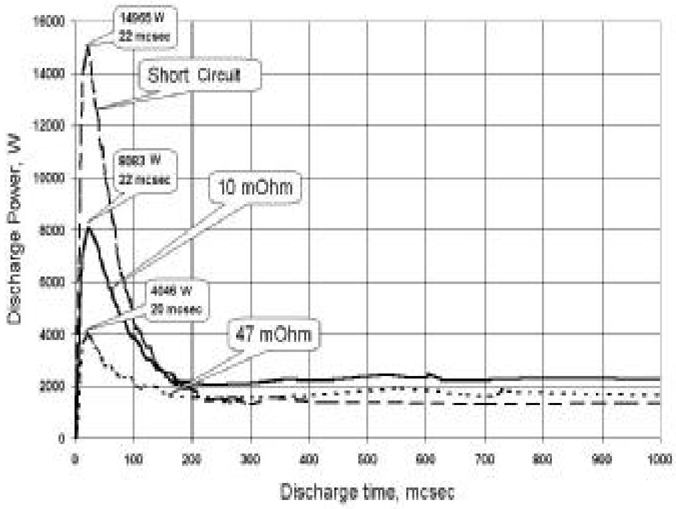


Fig. 10 Power VS. Time on different Discharge Loads.
Capacitor 15 F, 14 V (RC 220 msec.)

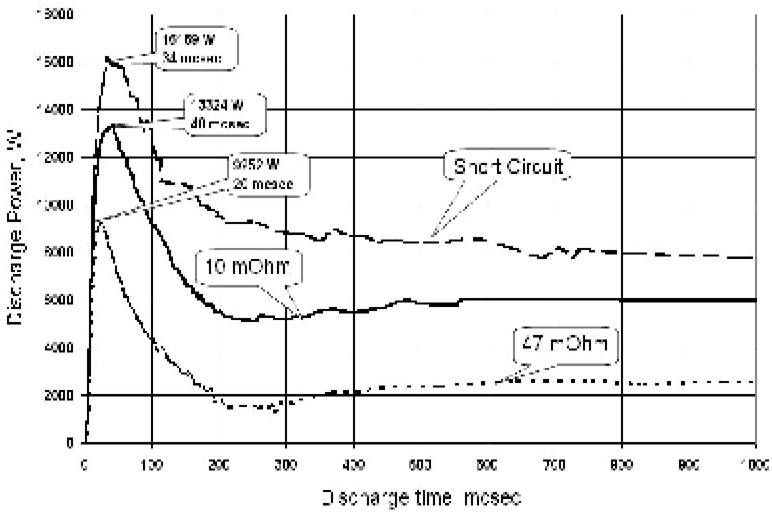


Fig. 11 Power VS. Time on different Discharge Loads.
Capacitor 50 F, 18 V (RC 300 msec.)

It is necessary to note high absolute values of peak power and power density of the tested capacitors. Thus, for device of 15F, 14V it is more than 7000 W/kg. Maximum peak power for capacitors with RC-time constant of 220 msec and 300 msec practically coincides with maximum peak current over the full range of discharge loads. The exception is capacitor with RC of 50 msec, where maximum power is to the left of the maximum current for short-circuit condition and 10 mOhm load.

Kinetic difficulties of discharge for capacitor with higher RC are revealed also on the curve of power changings, Fig.11, discharges on 10 mOhm and 47 mOhm.

As the investigated capacitors consist of different number of cells in series circuit and different number of parallel connected blocks it was impossible to carry out comparative analysis of discharge efficiency during transient period.

For this purpose the obtained data were then referred to the to the stored capacity. Typical view of changing the specific current curve for different capacitors in short-circuit mode is shown in Fig.12.

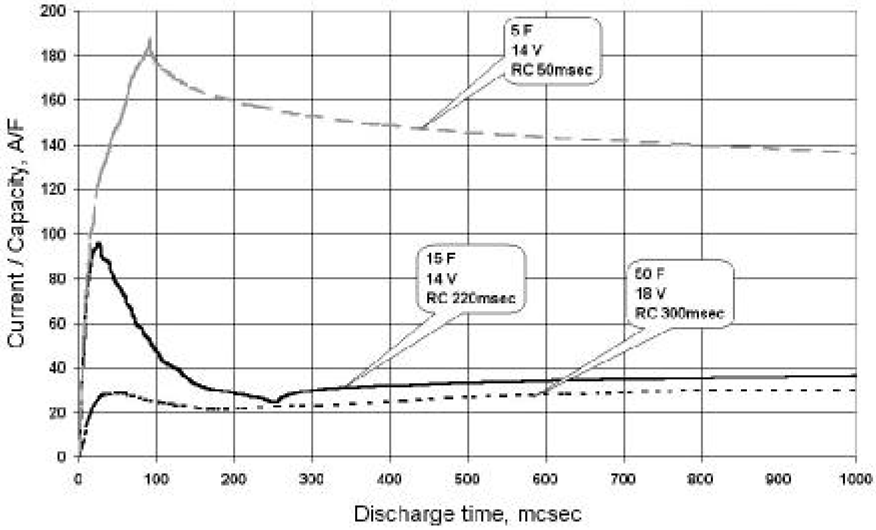


Fig. 12   Specific Current (A/F) during short Circuit Discharge

One can see more than three-fold increasing of specific current (A/F) for the capacitor with lowest RC value in comparison with capacitor with 220 and 300 msec RC values.

It proves more effective usage of stored capacity in the initial period of powerful discharge.

There were given calculations of maximum specific current dependence on discharge load value. Generalized dependences are shown in Fig.13.

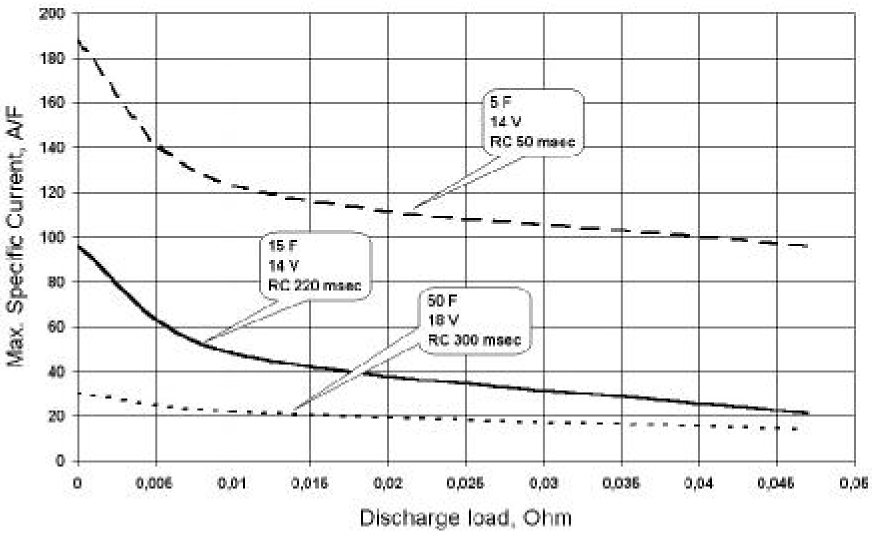


Fig. 13   Maximal Specific Current (A/F) VS. Discharge load for different Capacitors

It is noted that maximum specific current is not sufficiently changed within the active loads range of 10-47 mOhm, but it significantly differs from the loads within the range: short-circuit – 10 mOhm. This difference is especially noticeable for capacitors with lower value of RC-time constant (50 msec and 220 msec).

Changing of specific power (W/F) during transient process for different capacitor types is shown in Fig.14.

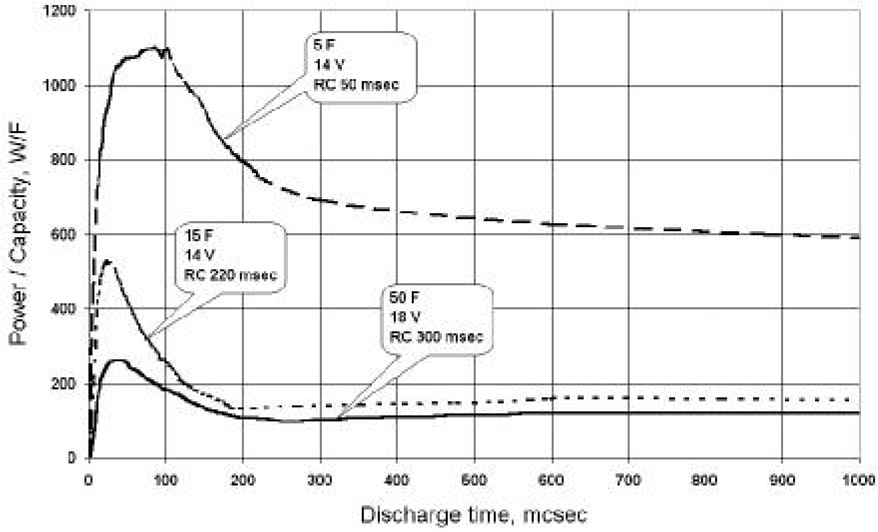


Fig. 14 Specific Power (W/F) during discharge on 10 mOhm of active load

Here, as well, higher effective power for capacitor with lower RC-time constant should be mentioned. Dependence of maximum specific power vs. different values of active loads is shown in Fig.15.

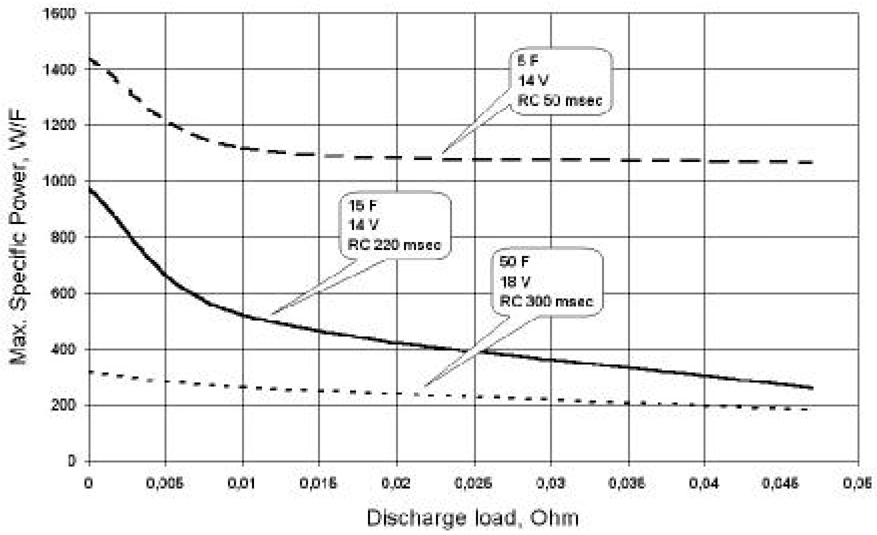


Fig. 15 Maximum Specific Power (W/F) VS. Discharge load for different capacitors.

Changings of maximum specific power are analogous to that of the maximum current (Fig.13).

The majority of UPS systems users are interested in *Energy Delivery Rate* of auxiliary power in the moment of switching over from the main supply line to the auxiliary source.

We have derived the following index: *joule (delivered)/discharge time, sec/stored capacity, F.*

Dependence of specific rate of energy delivering during transient process is shown in Fig.16.

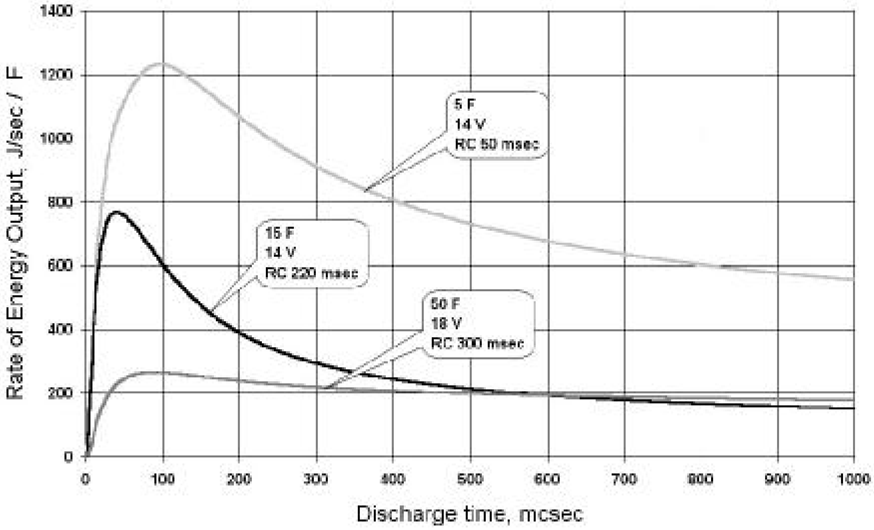


Fig. 16 Specific rate of energy delivering (J/sec/F) during short circuit discharge.

It should be noted that rate of energy delivering is not power. Functional curves for these indexes have different shape than those in Fig.14 (Power) and different parameter values.

Maximum specific rate as a function of discharge load value is shown in Fig 17.

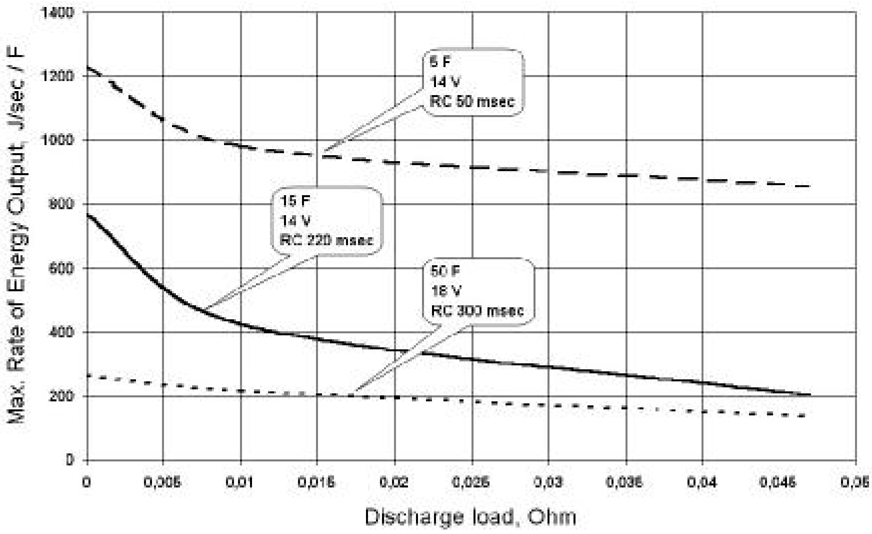


Fig. 17 Maximum Specific rate of Energy delivering (J/sec./F) VS. discharge load for different capacitors.

Character of curves is analogous to those of the maximum specific current (Fig 13) and maximum specific power (Fig 15).

Changings of specific delivered energy during transient process are shown in Fig.18.

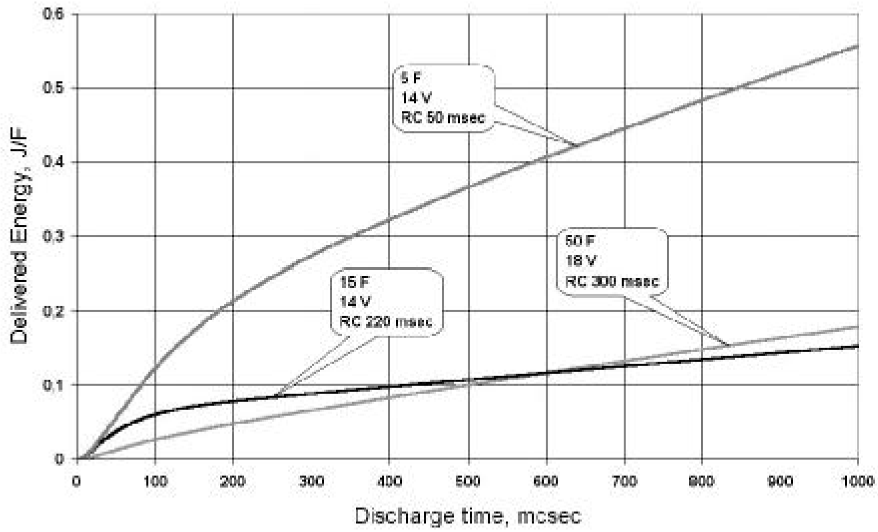


Fig. 18 Specific delivered energy (j/F) during short circuit discharge.

Here also more than three-fold excess of delivered energy in capacitor with low RC over capacitors, having higher stored energy and higher value of RC-time constant takes place.

It should be noted that relatively small values of delivered energy: 0,56 J/F to 1 msec actually point to large potential possibilities of capacitor system carbon/carbon with aqueous electrolyte. Thus, capacitor with 1000 F capacitance (it is easy achieved for practical realization) will deliver 500 joules! during 1 msec.

3. CONCLUSIONS

Investigation of transient processes of powerful discharge within the range 0 - 1000 mcsec by direct current and voltage recording showed the following:

- electrochemical capacitor of carbon/carbon system with aqueous electrolyte are low inertial devices and may successfully compete with aluminum electrolytic capacitors in pulse discharge modes within the range from 0 to 1000 mcsec from discharge beginning;
- shapes of discharge curve depend upon load type (active, active-inductive), but time of reaching of maximum peak current (power) does not depend on active load value;
- generalized RC-time constant value cannot characterize EC speed of response during transient period , but demonstrates efficiency of stored capacity usage - the less RC values characterizes higher rate of energy delivery.

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