

High Voltage, High Power Electrochemical Supercapacitors for Power Quality – Technical Requirements and Application Peculiarities

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INTRODUCTION

The industrial progress is inseparably linked with a great rate of energy intensification. Nevertheless, even new technological processes are very sensitive to the quality of energy they consume.

Under increase of complicated management control electric system's sensitivity, high price of manufacturing and operation, the vulnerability of fluctuations and short-duration switching off are hidden. As a result – the disruption during equipment operation, release of defective products and serious financial losses occur.

Statistic analysis of power supply failures for last 20 years, made by Electric Power Research Institute, reveals that *98% of voltage drops last less than 1 second*. But it's enough to stop pumps for water-preparation and hot water, or ventilated systems and distribution substations of main power supply line and units, critical industrial processes (oil refining, semi-conductor plants). Annual losses in USA is approximately 5...8 billion dollars, in Russia – more than 10 mlrd. rubles.

Application of uninterruptable power supply systems (UPS) on the base of storage batteries for short-period power drop compensation has not led to any significant result. First of all, battery type UPS delivered their full power only in 80-150 milliseconds from the beginning of demand. This is the principle restriction, peculiar to chemical power sources. Power absence or significant fluctuations in frequency and voltage for 150 milliseconds cause stopping of adjustable speed drive and of equipment which operates from that drive. From the other hand, voltage drop of *less than 1 millisecond (1000 microseconds) is acceptable for the majority of power and industrial systems*. Even better - less than 100 microseconds, i.e. at the level of commutating equipment operation.

The second main reason preventing from battery UPS use - impossibility of the battery development for 1000 Volt, 6000 Volt, etc. At the same time, "drop zone" of power supply lies inside of this voltage range. Transformation (increase) of voltage by means of inverters, for example, from 220 Volt up to 1000 Volt (!) is extremely inefficient physically and it increases the cost for the system by order.

Recently developed low inertial high-power UPS start using new kinds of power sources: hybrid of battery-capacitor, supercapacitor, etc. Specific energy of capacitor systems approaches to battery's one, and specific power of capacitor UPS is 4-5 times higher than that of a battery at discharge time (time of circuit failure) less than 1 second.

During last years the problem of creation of stable high-voltage capacitor circuits with operating voltage up to 11 kV was solved. In addition, unlike batteries which should be under constant control during UPS operation, capacitor sets are absolutely sealed and maintenance free for all service life.

Thus, it is required a "non battery" UPS with high power, high-voltage, low response time, maintenance free, stable to abuse situations during operation, environmentally friendly, to avoid many billion dollars losses caused by short-period voltage drops.

All these parameters are met by systems for peak power compensation and uninterruptable power supply on the base of supercapacitors.

1. SOME FIELDS OF APPLICATION

Nowadays, high voltage supercapacitors can be easily adapted, they have already been introduced without practical alteration of the customer equipment in the following fields:

a) *substations of distribution systems.*

The capacitor set serves as a compact power source to realize processes demanding high currents – switching on of power relays. The storage battery, available in any substation, provides only low-current operation needs, and its required capacity can be halved.

b) *Linear "reclosers" (the automatic device for repeated switching of utility grid).*

The capacitor is set instead of storage battery one. It is maintenance free during its operation, automatics of charge control is extremely simplified.

c) *The centralized energy distribution systems.*

The capacitor set is used for power supply of the high voltage electromagnetic switches during voltage drops in main high voltage network. It is a compact, maintenance free, power source.

Some additional works and changes in customer equipment and long arrangement of technical and administrative questions are required in a number of other application fields. These are:

d) *Substations of distribution systems with their own source* for short-period supply during overloads. These are sets with energy storage of tens megajoules. They are industrially available, but the cost of power automatics is still great, and the algorithm of protection switching is not developed in full.

e) *Customers (consumers) substations.*

Capacitor sets with energy storage from ones to tens megajoules buffer the input feeder of plant avoiding fluctuations of power and alternating current frequency, and also failure of power supply line for 100 msec - 1 ... 2 sec.

f) *Small generating systems (gas turbine: 1MW ... 20MW).*

Capacitor energy storage compensates transients in turbine unit, supplying network with stable energy.

2. SPECIFIC TECHNICAL REQUIREMENTS FOR POWER SOURCES IN PQ SYSTEMS

Reliability of PQ systems operation is the factor of economic safety, that's why strict requirements are determined for power sources used in these systems.

2.1. Operation parameters:

Response time. Period of time to reach maximum power should not last more than ≈ 30 microseconds, thus allowing use in perspective STATCOM systems, increase of reliability for relay operation to prevent voltage drops to electric drive.

Compactness. A number of UPS is set at ground level, so weight parameters do not have any importance, but the role of occupied area and volume is increasing. Compactness requirements should be applied to specific power to a greater extent than to specific energy $\approx 10-12$ kW/lit at (2-4 kJ/lit). An important compactness parameter is also "specific" voltage V/lit (20 ... 100).

Efficiency of energy transformation/charge indemnification. Readiness for repeated switching on in short time frames (after snap action) assumes not less than 90 % of system efficiency in charge-discharge mode. Besides, response time can be defined by maximum charge current, which the system can take. It is about 4000 A/F of stored capacity.

2.2. Reliability and safety parameters:

- Shock resistance is not less than 10G on one axis;
- Stability of all operation characteristics after the system being short-circuited and reversed in polarity without damage;

- Keeping operation for a week after emergency cases exceeding 50% operational voltage for 8 hours;
- Fire and explosion safe in above situations, including open flame;
- Guaranteed service life – not less than 5 years, maintenance free.

Ecological requirements:

- Products should be sealed and should not emit any substances to environment for all their service life;
- Products should not contain any toxic components and thus they present no disposal problems at the end of life.

3. DESIGN IDEOLOGY

3.1. Choice of the electrochemical supercapacitor's system

Nowadays the customer can be proposed 3 generations of industrially developed supercapacitors:

- I. Carbon/carbon with aqueous electrolyte;
- II. Carbon/carbon with non aqueous electrolyte;
- III. Carbon/MeOx with aqueous electrolyte.

Let's analyze the opportunity of their application considering these electrochemical systems from the point of view of specific requirements (item 2 of this article). Basing on operation parameters (item 2.1.), only the first generation meets all the requirements. Carbon/carbon supercapacitors with non-aqueous electrolyte (II) do not have acceptable response time. They are also limited by currents of emergency charge because of heating.

The latter also concerns the systems with ideal non-polarizable electrodes (III) where charge current is limited by efficiency of charge of Faradaic electrode.

As for reliability and safety parameters, all electrochemical systems ensure necessary shock resistance and service life. However the generation III is limited stable to short-circuit and not stable to reversed polarity because of uncontrolled hydrogen emission on Faradaic electrode. It can cause supercapacitor module explosion.

Principally systems with non-aqueous electrolyte (II) can be stable to short-circuit but they cannot resist long 50 % over voltage charging. It results either explosive electrolyte vapour emission through emergency valve or explosion of capacitor body.

Serious restriction is the so-called "thermal runaway", i.e. uncontrolled avalanched increase in temperature of the device because of short-circuit, high charge current, overcharge. All the capacitor generations are subjected to it except for generation I (C/C - aqueous).

High power UPS can be set in conservation areas (alternative power engineering) or in big populous industrial centres, so the requirements for their maintenance and possible emissions of any substances are significantly toughened. That's why II generation supercapacitors with "dirty" organics, and sometimes with flammable and highly explosive acetonitrile do not meet ecological requirements in many countries. Supercapacitors with Faradaic electrode (III generation) are more acceptable from ecological point of view, despite of nickel or lead components. Generation I systems with aqueous electrolyte have practically no restrictions for them to be used anywhere.

Summarizing the aforesaid, we should note, that *only one type of electrochemical systems corresponds completely to specific PQ requirements - carbon/carbon supercapacitors with aqueous solution of electrolyte.*

3.2. Choice of supercapacitor design

Let's look at possible types of design as for special requirements (item 2) once again.

Three kinds of construction are widespread among supercapacitor manufacturers:

- a) Single cells of high capacity with rolled electrodes;
- b) Single cells of high capacity with flat electrodes;

c) Bipolar systems with electrodes of low capacity.

The first two types have a separate current circuit: “electrode (block of electrodes) – terminal”, which occupies up to 30 % of capacitor volume. Bipolar systems have no external circuit of cell, the current goes through all electrode cross-section of cells perpendicularly to normal. In addition to decrease of occupied volume, it gives one more advantage – decrease of ESR in circuit “electrode – external terminal”. Thus, bipolar systems are the most *compact* among all the design solutions. Their low ESR provides maximum specific power as for volume (I).

Practical response time for bipolar systems with aqueous electrolyte was developed in early works of ELIT (2). It is less than 40 microseconds at peak of maximum discharge current.

Serially manufactured supercapacitors of a) and b) designs have high enough RC-time constant. For example: 2700F, 0,4 mOhm – 1,08 sec RC. Bipolar systems with aqueous electrolyte: 5F, 8 mOhm – 0,04 sec RC. RC, as average value, can testify to efficiency of charge/discharge process. It can be said, that bipolar systems with aqueous electrolyte are approximately 20-25 times more effective than single cells of high capacity with non-aqueous electrolyte.

As for shock resistance (including vibration loadings in frequency range), all 3 types of designs are practically stable enough. The design, as a rule, does not have a great influence on supercapacitor stability to short circuit, discharge and recharge, fire and explosion safety and ecology, because it concerns specific electrochemistry of supercapacitor.

Thus, *the best way* to realize power quality solutions is *to use supercapacitors with bipolar design*.

3.3. Stability of high-voltage circuit

Power sources with operating voltage up to 11.000Volt are required for PQ. In case of using supercapacitors with non aqueous electrolyte, the number of separate cells connected in series will exceed 5000! The quantity of cells for systems with aqueous electrolyte is equal or exceeds the value of operating voltage, > 11.000!

The parameter deviation of separate cells connected in series can cause either incomplete use of energy store at U_i nom. decrease, or sudden circuit break at high voltage of a single cell (3) (4). Stability of high voltage circuit during operation is influenced by spread of capacity, ESR and leakage current of single cells (5). Influence of each parameter is various and depends on operation mode: cycling, floating, mixed mode. For example, stability of capacity and ESR is more important for cycling, for floating mode - leakage current.

Influence of leakage current of separate cells in circuit prevails for power quality because the number of cycles is insignificant, sometimes it is once a year.

Industrial manufacturers use various kinds of voltage leveling for separate cells in circuit (6). The simplest way - passive regulation by shunting of each cell in circuit by resistor. At the same time the shunting current through resistors should exceed leakage current of this cell. More complicated way – active electronic voltage control of a single cell and energy transfer by a secondary circuit from "strong" cells to "weak" ones. Application of passive regulation by resistor causes "parasitic" energy losses, but in most cases it does not exceed 0,01 from practically used. The value of "adjusting" leakage current has no principal importance in floating mode. It is only limited by heat distribution from parasitic leakage. By the way, it's the cheapest way.

Active regulation with energy “pumping” does not cause "parasitic" losses, but it is more complicated technically and its cost can reach up to ≈ 30 % of supercapacitor one in this circuit.

As applied to supercapacitor designs, active regulation can be successfully used with cells of big capacity, and passive one - with cells of small capacity.

However, difference in single cells temperature in 1000 cells circuit and their various degree of degradation in time show insufficiency of active or passive voltage regulation only. Moreover, active regulation way cannot be embedded into the bipolar system with electrodes thickness of 50 ... 100 micron.

At the same time the use of combined voltage balancing system: shunt + valve is of certain interest. Thus active system operates well in the field of high operation voltage of an individual cell. The role of passive system is that of voltage balancing at all voltage range, but by low currents.

The active control of cell group and passive regulation in an individual cell is preferable for bipolar design.

The notion of *controllable cell group* was established.

The choice of cell number in controllable group depends on the following principal causes:

- Technological range of cell parameters (capacity, ESR, leakage current), confirmed statistically for a certain type of active material and technological process;
- Length of bipolar module and temperature distribution along its length. Compensation of voltage difference: edge – center of the block;
- Degradation rate of cell parameters, change in leakage current during years of operation (on the basis of accelerated testing at high temperature).

Stability in high-voltage circuit is also influenced by the type of the electrolyte used. J.R. Miller researches (7) showed that high-voltage supercapacitor modules with aqueous electrolyte are more stable against long floating operation, than supercapacitor circuit with non-aqueous electrolyte.

4. PRACTICAL REALIZATION

The following concept is accepted for the manufacture of supercapacitor high voltage sets, used in PQ systems:

Electrochemical supercapacitors of bipolar design of carbon-carbon system with aqueous KOH solution, realized in the form of modules for 100 or 200 Volt, with embedded system of combined voltage regulation (shunt in a cell, electronics in controllable group) and valves for oxygen gassing if the operating voltage exceeds 50 % of nominal value for a long time.

4.1. The complete set for autonomous power supply of independent management circuits and for relay switching on.

Set parameters:

1. Operating voltage	1000 +/- 100V
2. ESR	1.5 Ohm
3. Capacity	0.18 F
4. Weight	60 kg
5. Volume	41 liter
– Peak current	600 A
– Peak power	322 kW (8 kW/kg, 4 kW/liter)
– Specific voltage	24 V/liter

The set includes 5 modules x 200 V connected in series (Fig. 1, 2).



*Fig 1. High-voltage supercapacitor set 1000 V,
(1000PP-90.1,5)*



Fig 2. Module 200 V, 18 kOhm. (the ruler on top is given in centimeters)

4.2. Peak loads compensators.

These are ready to use products, consisting of supercapacitor set, commutation equipment, devices for control and regulation; placed on the individual stands. The number of the stands is determined by operation current.

Such compensators are set in substations in active circuit, which have "oil" type switches with electromagnetic drive (on/off) or other high power short-term loads.

The main technical characteristics are given in table 1.

Table 1

№	Parameter	Capacitor Set			
		KTN-100	KTN-250	KTN-500	KTN-750
1.	Nominal voltage (V)	110/220			
2.	Nominal current of drive (A)	100	250	500	750
3.	Capacity (F)	18,8/4,7	47,0/11,7	94,0/23,5	141/35,3
4.	Energy store (kJ)	114	285	569	854
5.	ESR (mOhm)	19/76	8/30	4/15	3/10
6.	Number of stands (pieces)	2	4	6	9

Example of operation.

The complete set KTN 250 is used for the thrice-repeated relay switching on MKP-110M (110 kV, 50 kW, 220V). At the same time the battery in substation is not used in operation. Current relay characteristic at single switching on is given at Fig.3.

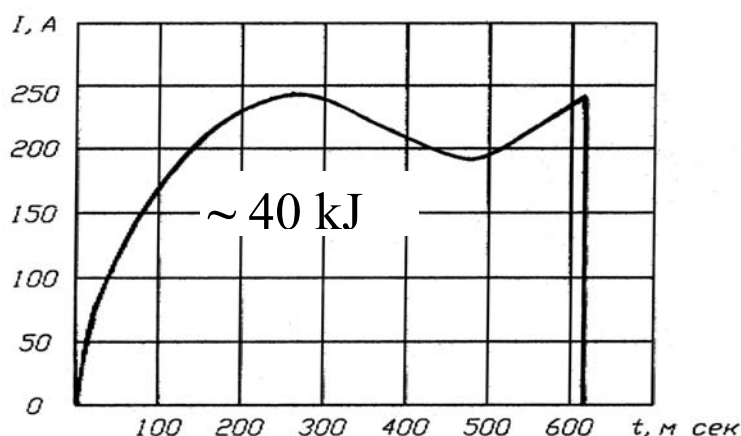


Fig.3. Relay current vs. time at MKP-110M switching on

General view of the stand KTN-100 is given at Fig.4.



Fig 4. KTN-100 (100 A, 220 V)

4.3. Practical advantages of supercapacitor sets and products on their basis:

- 100 % guarantee of relay switching on at any state of storage battery and at any periodicity of on/off relay cycles (*especially important during active current operation from storage battery*);
- Increase in speed of relay snap action (*reduction in time of relay snap action for 0,1-0,2 seconds, decrease in deterioration*);
- Double reduction of capital expenses in case of substations reequipment by storage batteries (*functional separation of power delivery during impulse load (supercapacitor) and of storage (storage battery). The effect is marked stronger at the increase of load power*);
- 5-8 years increase in service life of "old" storage battery:
"old" storage battery - active current, capacitors - pulse mode (*reference in time of reequipment/capital expenses*);
- Reduction of operation costs due to decrease in maintenance (*Supercapacitor use leads to the decrease of weight and dimensions parameters of storage batteries set. Supercapacitors themselves are maintenance free*).

CONCLUSIONS

1. High-voltage and high-power electrochemical supercapacitors can be widely used to solve various problems of power quality and power supply safety in thousand volt networks. Thus we can obtain significant economy due to the absence of switching failure and voltage drop in network. In addition, costs in existing infrastructure of power supply (substation, drives) are removed.
2. The application of supercapacitors with carbon-carbon system with aqueous electrolyte, bipolar design and the active controllable system for cells voltage is considered to be the most effective one. Thus all the customers requirements to PQ equipment are met:
 - High specific power;
 - Compactness;
 - Fire and explosion safety;
 - Maintenance free and long service life;
 - Stability in emergency cases;
 - Economy in operation and utilization.

Practical and technical advantages are confirmed by shipments and by systems operation on the basis of high-voltage supercapacitors.

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