

# **HIGH VOLTAGE ELECTROCHEMICAL CAPACITORS: Problems, Solutions, Applications**

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## **ABSTRACT**

This paper analyzes the causes restricting wide use of electrochemical capacitors in a high voltage DC-sphere. The main cause is insufficient stability of a high voltage circuit consisting of a number of single cells. The authors use simplified mathematics transformations, to show the effect of tolerance spread in performances of separate cells in circuit on stability of the circuit. They are tolerance in capacity, internal resistance (ESR) and leakage current. Analyzing effects of these performances, the authors determine their critical values for diverse modes of use of high voltage electrochemical capacitors. Shown operation modes consider the most interesting existing spheres of application, including hybrid electric vehicle and Power Quality. This paper covers recommendations on practical use of various methods to increase stability of circuit for diverse spheres of application. The authors made the conclusion that existing level of technology allows to produce high voltage electrochemical capacitors with enhanced reliability and service life.

## **1. INTRODUCTION**

This paper concerns high voltage electrochemical capacitors (HVEC). We mean operating voltage window is from 100 to 600 Volts. From the viewpoint of application this voltage window matches requirements to power processes in industry, electricity production and transmission. Power quality problems in industry are also in this sphere of application.

Traditionally electrolytic capacitors are used for these applications, because it is very easy to get a single cell, having needed voltage value. Good frequency performances of electrolytic capacitors allow to use them at AC and high voltage DC.

During last years more markets appear: high voltage traction electric DC drive for hybrid electric transport [1], and Power Quality systems to eliminate sags and interruptions lasting from milliseconds to tens seconds [2]. Typical electrolytic capacitors and similar devices absolutely do not meet these new demands of market. It is caused by their low energy density – lower than 1 kJ/kg (~.28 Wh/kg).

We cannot consider seriously the use of such capacitors as peak load equalizers in electric vehicles, and in power quality systems they are able to support power quality to about 1 second. Systems basing on typical capacitors to support power quality during period from 1 to 10 seconds will be huge and too expensive. Using batteries for the said high voltage spheres is steel more problematic.

Although the Lead/Acid electrochemical system seems to be inexpensive, technology of high voltage battery is very expensive, as it needs to select matching cells by their capacity while manufacturing. During application this circuit will be added to with lots of diverse devices for monitoring and equalizing cells, and this will rise total price of this system. We must not forget extra expenses for service during all service life of such batteries. Besides, no one can expect the battery to normal operation at pulsed discharge with duration from milliseconds to tens seconds.

Analyzing the above we get to conclusion that in these new spheres of application at voltage values of 100 – 600 Volts the electrochemical capacitors might be used properly. Relatively high value of energy density (to 3 Wh/kg), fast response (RC-time constant .05 – 5 sec.) allow to use them in hybrid electric vehicle as well as to solve power quality problems.

The main technical obstacle is lower voltage of a single cell (1, 2 V for aqueous electrolyte, and 2 – 4 V for nonaqueous electrolytes). This results in assembling a line of 100 – 600 series connecting cells. Tolerance values of capacity, leakage current, internal resistance of cells – all these reduce stability of high voltage circuit at continuous use. Active and passive principles of equalizing performances of different items of circuit are widely known today. These principles significantly differ from each other by applied equipment and prices, and they variously influence to retail price for HVEC. This talk should show theoretical aspects of reliability of multi cells circuit and some practical issues of use of equalizing devices. The authors are sure that the existing level of HVEC technology having been developed by today allows to apply them in high voltage circuits, significantly widening spheres of their application.

## 2. INFLUENCE OF HIGH VOLTAGE CIRCUIT SINGLE CELLS PERFORMANCES ON THE CIRCUIT STABILITY.

This item shows simplified mathematics transformations and formulas clearing principal effects of given performances on reliable operation of high voltage circuit including a number of cells. This simplified mathematics is confirmed by results of real operation tests and can be used as estimation method for capacitor development.

Effect of each of these performances is estimated separately, not concerning their joined effect, as this problem is itself hard to do and can be solved when developing specific capacitor and requires appropriate level of the capacitor production technology.

Assessment criteria in all cases is the critical value of voltage of a single cell of circuit, as this value results in disability of the cell. Mostly coming, this is voltage of electrolyte decomposition (upper level) or voltage of reversibility loss at electrode reaction for pseudocapacitive electrode (lower level). A problem for separate estimation is resistance to corrosion of constructive materials used in the capacitor (upper and lower levels) when reversible process on electrodes is still possible, but dissolving or oxidizing of collector systems in given electrolyte begin.

Lost performances of a single cell of circuit: abrupt increasing of ESR, gases output, and others cause failure of entire series circuit, mostly due to high ESR or circuit breakage.

**2.1. Effect Of Variation In Capacities Of Single Cells In Series Circuit.**

To make more clear the effects of cells capacity disbalance, we shall consider the simplest case when circuit of cells is charging (discharging) with constant current. Value of this current does not cause sufficient voltage drop on internal resistance of a cell.

Besides, we consider conventionally that the values of leakage current and ESR of each cell are equal.

In this case charge (discharge) capacity is estimated by the formula:

$$(1) C = \frac{I \cdot t}{|\Delta u|}, \text{ where}$$

C - capacity;  
I - charge (discharge current);  
Δu - difference in initial and end of charge (discharge) voltage

Formula 1 shows that the time of circuit charge can be estimated by the following:

$$(2) t = \frac{C(Ue - Uin)}{Ich}, \text{ where}$$

Ue - end of charge voltage;  
Uin - initial charge voltage;  
Ich - charge current.

In series circuit, the time of charging and charge current of a single cell are equal to values of time and charge current of all cells in the circuit:

$$t = t_1 = t_2 \dots = t_i$$

So, taking into account the expression (2) we can register the following:

$$(3) \frac{C_1(Ue_1 - Uin_1)}{Ich} = \frac{C_2(Ue_2 - Uin_2)}{Ich} = \dots = \frac{C_i(Ue_i - Uin_i)}{Ich}$$

Reducing this expression relative to Ich, we obtain the following:

$$(4) C_1(Ue_1 - Uin_1) = \dots = C_i(Ue_i - Uin_i)$$

Now we shall use the term “average” (estimated) cell. In the series circuit of cells there can appear a cell with voltage equal to average value of this circuit:

$$(5) \bar{U} = \frac{Ue}{n}, \text{ where}$$

Ue - entire voltage of series circuit;  
n - number of cells in series circuit;

We use the same for capacity

$$(6) \bar{C} = Ce \cdot n, \text{ where}$$

Ce - capacity of series circuit with n-cells;  
n - number of cells in circuit.

Transform expression (4) concerning (5) and (6):

(7)  $C_i(U_{ei} - U_{ini}) = \bar{C}(\bar{U}_e - \bar{U}_{in})$  and transfer this again relative to  $U_{ei}-U_{ini}$  of any occasion cell:

$$(8) U_{ei} - U_{ini} = \frac{\bar{C}(\bar{U}_e - \bar{U}_{in})}{C_i}$$

Expression (8) shows that changes in value of voltage of occasional cell is inverse ratio to the cell capacity during charge-discharge process ( $U_{ei}-U_{ini}$ ). In this case, in the series circuit of cells the cell with the higher value of capacity comparing with “average” estimated cell, will have minimum value  $U_{ei}-U_{ini}$ , and vice versa: the cell with minimum capacity comparing with "average" cell will show maximum changes  $U_{ei}-U_{ini}$ . In other words, the "stronger" cell changes its voltage slowly, and the “weak” cell does the same fast. Transforming expression (7) to proportion and adding percents, we obtain other expression (8) which allows us to estimate the values of maximum and minimum voltages of occasional cell dependently on its capacity relative to the “average” one:

$$(9) \frac{U_{ei}^{\max/\min} - U_{ini}^{\max/\min}}{\bar{U}_e - \bar{U}_{in}} = \frac{\bar{C}}{C_{i_{\max/\min}}} \cdot 100\%$$

Now we can estimate the effect of capacity spread of the cells in the circuit on their voltage using real figures.

When initial voltage of charge is 0 V, expression 9 will be as below:

$$(10) \frac{U_{ei}^{\max/\min}}{\bar{U}_e} = \frac{\bar{C}}{C_{i_{\max/\min}}} \cdot 100\%$$

An example of such estimation is in Table 1 below

Table 1

$\bar{U}_e(V)$	Differences in the values of cell capacity relative to average value							
	±1%		±5%		±10%		±20%	
	$Ve^{\max}(V)$	$Ve^{\min}(V)$	$Ve^{\max}(V)$	$Ve^{\min}(V)$	$Ve^{\max}(V)$	$Ve^{\min}(V)$	$Ve^{\max}(V)$	$Ve^{\min}(V)$
0.5	0.505	0.495	0.525	0.475	0.550	0.450	0.600	0.400
0.6	0.606	0.594	0.63	0.57	0.660	0.540	0.720	0.480
0.7	0.707	0.693	0.735	0.665	0.770	0.630	0.840	0.560
0.8	0.808	0.792	0.84	0.76	0.880	0.720	0.960	0.640
0.9	0.909	0.891	0.945	0.855	0.990	0.810	1.080	0.720
1	1.010	0.99	1.05	0.95	1.100	0.900	1.200	0.800
1.1	1.111	1.089	1.155	1.045	1.210	0.990	1.320	0.880
1.2	1.212	1.188	1.26	1.14	1.320	1.080	1.440	0.960
1.3	1.313	1.287	1.365	1.235	1.430	1.170	1.560	1.040
1.5	1.515	1.485	1.575	1.425	1.650	1.350	1.800	1.200
2	2.020	1.98	2.1	1.9	2.200	1.800	2.400	1.600
2.5	2.525	2.475	2.625	2.375	2.750	2.250	3.000	2.000
2.7	2.727	2.673	2.835	2.565	2.970	2.430	3.240	2.160

We split the case where aqueous solution of electrolyte ( $\bar{U} = 1,2V$ ) is used and note that it is impossible to make high voltage circuit stable in other similar conditions if

technological variation of cells is equal or exceeds  $\pm 5\%$  of capacity. Practically, concerning non uniform degradation of discharge capacity of different cells at time, we have to use lower values of operation cell voltage.

### 2.2. Effect Of Differences In Internal Resistance Of single Cells.

Here we used simplification, as well:

Values of capacity and leakage current are equal for all cells of the circuit.

Voltage of a single cell at given time during charge-discharge process was calculated by the formula:

$$(11) U = U_t \pm I \cdot R_o, \text{ where} \quad \begin{array}{ll} U_t & - \text{ difference in potentials of a cell;} \\ I & - \text{ charge (discharge) current;} \\ R_o & - \text{ ESR of cell.} \end{array}$$

Absolute value of voltage difference for two casual cells of series circuit, where one cell has minimum ESR, and the other one has maximum ESR, can be expressed by the formula below:

$$(12) \Delta U = (U_{in}^{\max} + IR_o^{\max}) - (U_{in}^{\min} - IR_o^{\min})$$

If the cells in the circuit have equal capacity and initial voltage of charge, i.e.  $U_{in}^{\max} = U_{in}^{\min}$ , expression (12) will be as following:

$$(13) \Delta U = I(R_o^{\max} - R_o^{\min})$$

Effect of the tolerance spread is obviously seen in Table 2, where results of estimation with exact data of charge-discharge currents are given.

Table 2

Current (A)	Difference in values of internal resistance of cells ( $\Delta R_o$ )		
	1M $\Omega$	10M $\Omega$	100 m $\Omega$
	V (V)	V (V)	V (V)
0.001	0.000001	0.00001	0.001
0.01	0.00001	0.0001	0.01
0.1	0.0001	0.001	0.1
1	0.001	0.01	1
10	0.01	0.1	10
100	0.1	1	100

It is clear, that the value of tolerance spread ESR of different cells effects dramatically on powerful charge-discharge processes. Differences in ESR of separate cells in series high voltage with low resistance circuits must not exceed fractions of m $\Omega$ s.

On the other side, when the charge-discharge processes are going at low current and the window of operating voltage is narrow, wider spread is acceptable: to units and tens m $\Omega$ s per cell.



As it was said, charge current is leakage current when voltage of circuit is constant and equal to voltage of charge device. In this case, to keep constant value of circuit voltage, total discharge voltage of some of cells should be equal to total charge voltage of the rest cells:

$$(18) \quad \sum \Delta V_{dis} = \sum \Delta V_{ch}$$

considering expression (17) we obtain the equation:

$$(19) \quad \sum \frac{t \cdot I_{dis}}{C_i} = \sum \frac{t \cdot I_{ch}}{C_{i+1}}$$

Let's spread this expression for a number of cells, and shorten equal time periods in the both parts of the expression (19) :

$$(20) \quad \frac{I_e^{\max 1} - II}{C_1} + \frac{I_e^{\max 2} - II}{C_2} + \dots + \frac{I_e^{\max i} - II}{C_i} = \frac{II - I_e^{\min 8}}{C_8} + \frac{II - I_e^{\min 9}}{C_9} + \dots + \frac{II - I_e^{\min i+1}}{C_{i+1}}$$

The number of elements in this equation is the same as the number of cells in series circuit.

By rearranging this equation to its formal form and substitute common denominator:

$$(21) \quad \frac{I_e^{\max i}}{C_i} - \frac{II}{C_i} = \frac{II}{C_{i+1}} - \frac{I_e^{\min i+1}}{C_{i+1}};$$

transfer this equation in the form:

$$(22) \quad \frac{II}{C_i} + \frac{II}{C_{i+1}} = \frac{I_e^{\max i}}{C_i} + \frac{I_e^{\min i+1}}{C_{i+1}};$$

We want to remind that:

$II$  - entire leakage current of circuit;

$I_l^{\max i}$  - individual leakage current of the (i) cell, which is higher than entire leakage current of circuit ( $II$ );

$I_l^{\min i+1}$  - individual leakage current of the  $I_{i+1}$  cell which is lower than entire leakage current of circuit ( $II$ );

$C_i, C_{i+1}$  – individual values of cell capacities.

Proceeding from our assumption that values of capacity of different cells in circuit is equal, we reduce  $C$  in equation (22) and divide this by  $n$  – number of cells in circuit. So the equation (22) will be as follows:

$$(23) \quad II = \frac{I_l^{\max i} + I_l^{\min i+1}}{n}$$

This allows us to make the conclusion that the total leakage current of series circuit of cells is equal to the average value of the sum of individual values of leakage current of separate cells at constant voltage on the terminals of capacitor.

This is the important issue that the total leakage current is average. In this case, the cells with higher value of leakage current than the entire leakage current of circuit, do effect on the cells with lower leakage current in the same circuit, by increasing value of the average leakage current of circuit.

In other words, in a cell with lower value of leakage current faster reaching critical value of voltage is possible due to increased value of total leakage current of the circuit.

#### **2.4. Analysis Of Effect Of Difference In Cell Performances In Circuit At Different Operating Modes Of HVEC. Effect Of Accumulating.**

Effect of difference in performances of capacitor at various frequencies of use is adequately described in the work of John R. Miller [3]. In this item we shall try to explain fully the effect of the difference at long dynamic and combined modes of capacitor operating.

a) Continuous cycling with high currents and without long pauses between cycles and between charge and discharge (maximum 2-5 cycles and less a second).

First, it is clear that the difference in the values of leakage current will not effect on the spread of voltage of cells in circuit, because the time of such effect will not come during cycling.

Second, when production technology for capacitors is stable and operation conditions correspond to the specification of manufacturer, the effect of spread of capacities and values of ESR are equal to zero.

That means, the cells are charging and discharging constantly within voltage windows slightly differ from each other; this windows depend on their capacity and ESR and do not reach critical level of voltage.

Effect of difference in ESR can become more sufficient at long cycling at high temperature as heat dissipation is non uniform.

But these are problems of thermal management, which can be solved prior to run production.

Nevertheless, this mode of use can present a hidden danger of appearing new defects which is caused by difference in capacities. We shall make this clear by mathematics.

Transfer the equation (4):  $C_1(U_{e1}-U_{in1}) = \dots C_i(U_{ei}-U_{ini})$  into proportion:

$$(24) \quad \frac{C_1}{C_i} = \dots \frac{(U_{ei} - U_{ini})}{(U_{e1} - U_{in1})} = \frac{\Delta U_{oper_i}}{\Delta U_{oper_1}};$$

where:  $C_1, C_i$  - values of capacity of cells in circuit;  
 $U_{e1}, U_{ei}$  - end charge/discharge voltage;  
 $U_{in1}, U_{ini}$  - initial charge/discharge voltage;  
 $\Delta U_{oper_1}, \Delta U_{oper_i}$  - operation voltage windows of separate cells.

As follows from this reverse proportion, operation voltages window ( $\Delta U_{oper}$ ) for the cells with lower capacity is wider than for the cells with higher capacity. In cycling, that means deeper charge/discharge for the cells with lower capacity, comparing with depth of charge/discharge for the cells with higher capacity.

This is shown in Fig 1 below:

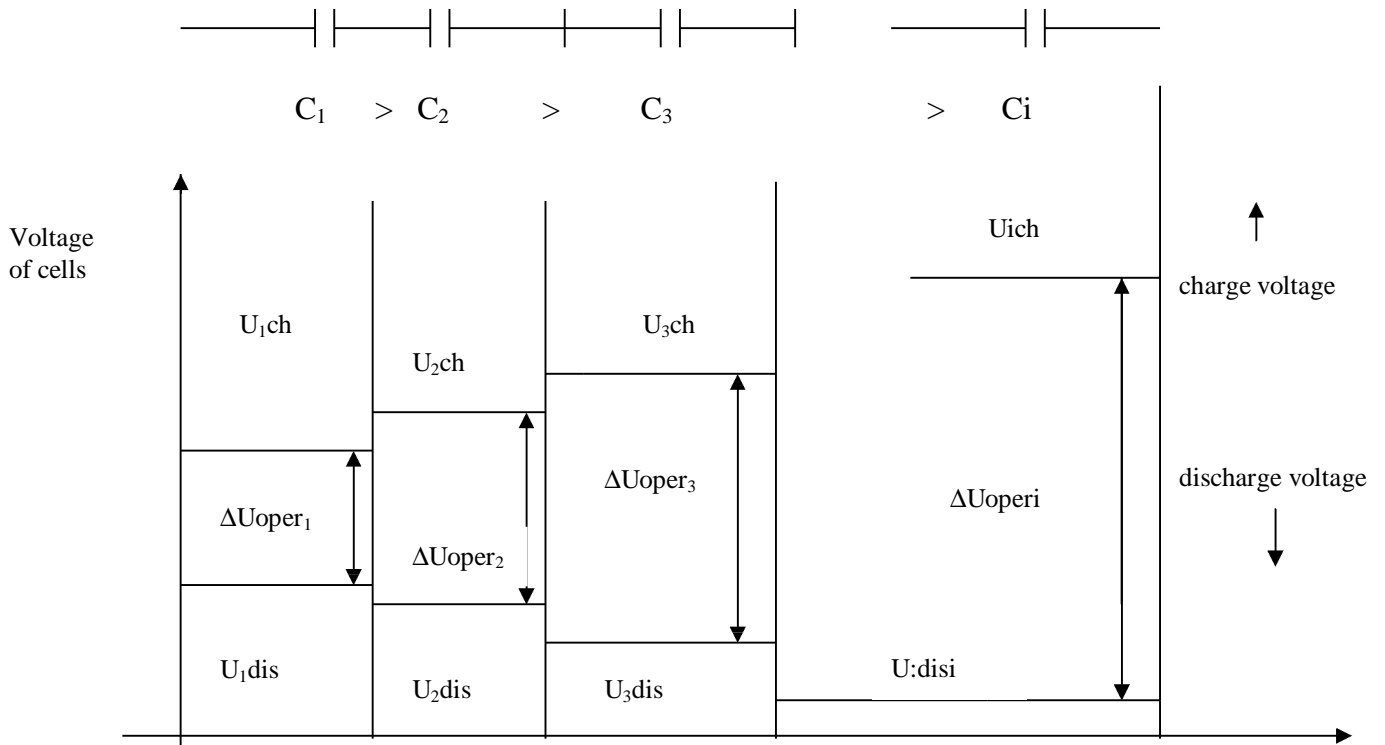


Fig. 1. Depth of charge/discharge processes in cells at cycling a circuit with cells of different capacities.

Thus, series circuit contains the cells charging and discharging for different depth during cycling. Considering the effect of discharge depth on service life and this is mostly coming for pseudocapacitive electrodes, - we can make the conclusion that the rate of cells degradation will be different in time.

That will lead to accelerated aging of deep cycled cells and their premature failure.

b) Floating mode with frequent discharges (maximum several cycles per hour)

It's clear, that the difference in capacities and ESR between cells in circuit will not effect dramatically on steady operation of the circuit. But in this case, the factor of difference in leakage current operates. Its effect directly depends on the duration of pause between charges/discharges, and depends on appropriate technology. The level of technology development can be determined by a number of defects appearing at cycling of high voltage capacitor, and these defects increase leakage current of separate cells.

c) Floating mode with non frequent discharges.  
"Effect of accumulated declines".

This operation mode is represented by non frequent discharges: once a day/week/month. The effect of deference in the values of leakage current of single cells is critical at this mode.

The cells with higher leakage current will constantly reduce their voltage in floating mode. These cells during further deep discharge will have lover values of end voltage,

compared with the other cells. The next charge in normal conditions (before switching to floating mode) is not able to increase the voltages to the values of the other cells.

Furthermore, these cells during floating mode will have lower voltage, and this will slop down as the cells have increased leakage current.

At the same time, the cells with minimal leakage current will have to increase their voltage following the principle of constancy of entire voltage of circuit during the floating mode.

Thus, the cell with increased leakage current will reduce its window of discharge voltage from one discharge to the other, and the cell with lower leakage current will increase such window.

As a result of deep discharge after floating mode, a cell with high leakage current will be reversed in polarity which will result in gassing, cutting line or increasing total resistance of the circuit. If reversed polarity does not cause immediate gassing, then the cell with reversed voltage will increase voltage in the cells with lower leakage current (constancy of total voltage of circuit) to dangerous level. In such case, gassing can appear as voltage of electrolyte decomposition is exceeded.

We can note two causes of circuit failure resulted by difference in values of leakage current:

- reversed polarity and cut line of cells with higher leakage current;
- reaching the voltage of electrolyte decomposition in the cells with lower leakage current.

It is clear that difference in leakage current does not take effect in the first period of a high voltage capacitor operation, and is an "effect of accumulated declines" from one discharge to the other.

Mechanism of "Effect of accumulated declines" can be shown as in Figure 2 below.

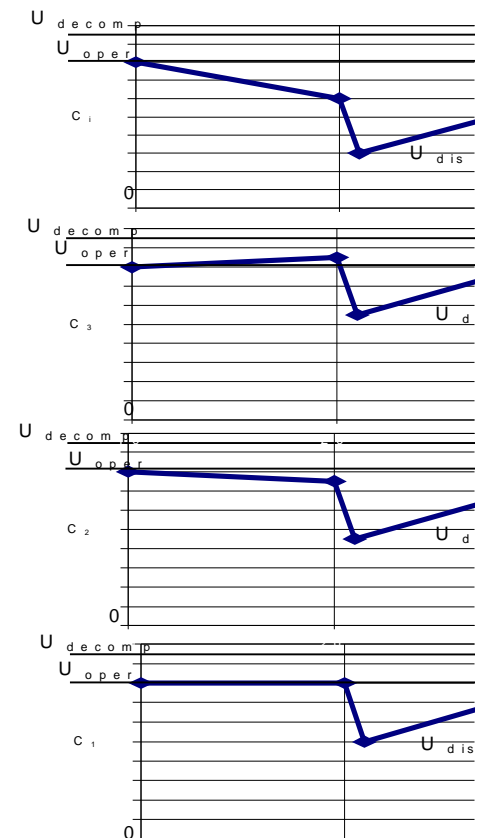


Fig. 2. "Effect of accumulated declines"

Referring to mutually depending combined effect of difference in leakage current and ESR during "accumulation of declines" is in order in this item. Ohmic and polarizing resistance for many types of pseudocapacitive electrodes depends on state of charge of electrodes. Shift of discharge voltage window down results, as a rule, increasing resistance of electrode and entire ESR of a cell. Thus, the cell with higher leakage current obtains additional "acceleration" for sooner failure.

Difference in leakage current takes stronger effect in operation mode, when during floating charge, discharges are needed once a year or less. Changes in time are so sufficient than in practice the high voltage capacitor should be added with auxiliary special equalizing devices.

### 3. WAYS TO IMPROVE STABILITY OF HIGH VOLTAGE CIRCUIT OPERATION

This item is an attempt, without pretension to be comprehensive, to classify and describe the ways widely used and exotic to improve reliability of high voltage circuit operation.

To keep constant voltage of separate cells in high voltage circuit (not to allow achieve critical level), it is necessary to observe the below equations:

$$(25) \quad C_1 = C_2 = \dots C_i \quad \text{where: } C_1 \dots C_i - \text{capacity of cells in circuit;}$$

$$(26) \quad I_l = I_{l1} = I_{l2} = \dots I_{li} \quad \begin{array}{l} I_l \quad - \text{total leakage current of circuit;} \\ I_{l1} \dots I_{li} - \text{individual leakage current of cells in} \\ \quad \text{circuit.} \end{array}$$

It is obvious, these equations may not be realized fully in real production, but they can be a target. The more these equations are realized the more is reliability of circuit, and vice versa.

In principle, individual values of cells capacities might be selected to the utmost during their production. Also it's possible to predict the rate of their degradation and take technological actions beforehand to avoid critical disbalance of voltage during use.

Selecting of cells with closely spaced values of leakage current into series circuit present a real problem.

This requires enlarged production expenses as the production cycle becomes longer to days and weeks. But as a rule, the effects of leakage current (result of "hidden" short circuiting through pinholes, etc.) starts after significant period of operation and technological authenticity of this way decreases.

In this aspect, it is easier to try to adjust (manage) leakage current during operation.

Considering the above, all the ways to improve reliability of high voltage circuit can be divided into two big classes:

- 1. Technological methods;
- 2. Operation methods (determined also by construction of capacitor and maintenance).

The methods of Class 1 is based on improvement of stability of production processes which allow to produce cells with close performances and/or select single cells with closely spaced values from the whole amount. In this case estimated changes of performances in time and matching real performances of capacitor to condition of operation are of importance.

Operation methods are characterized by using of built-in element (device) or material which does not allow to exceed the preset voltage of cells in high voltage circuit of capacitors.

The base of this method is individual exchange current control over of a single cell. Class 2 of the methods incorporates, as well, special maintenance of cells of high voltage circuit during pauses (individual deep discharges or recharges and others).

This classification of the ways to improve reliability of high voltage circuit can be put into more instructive form as in Fig. 3.

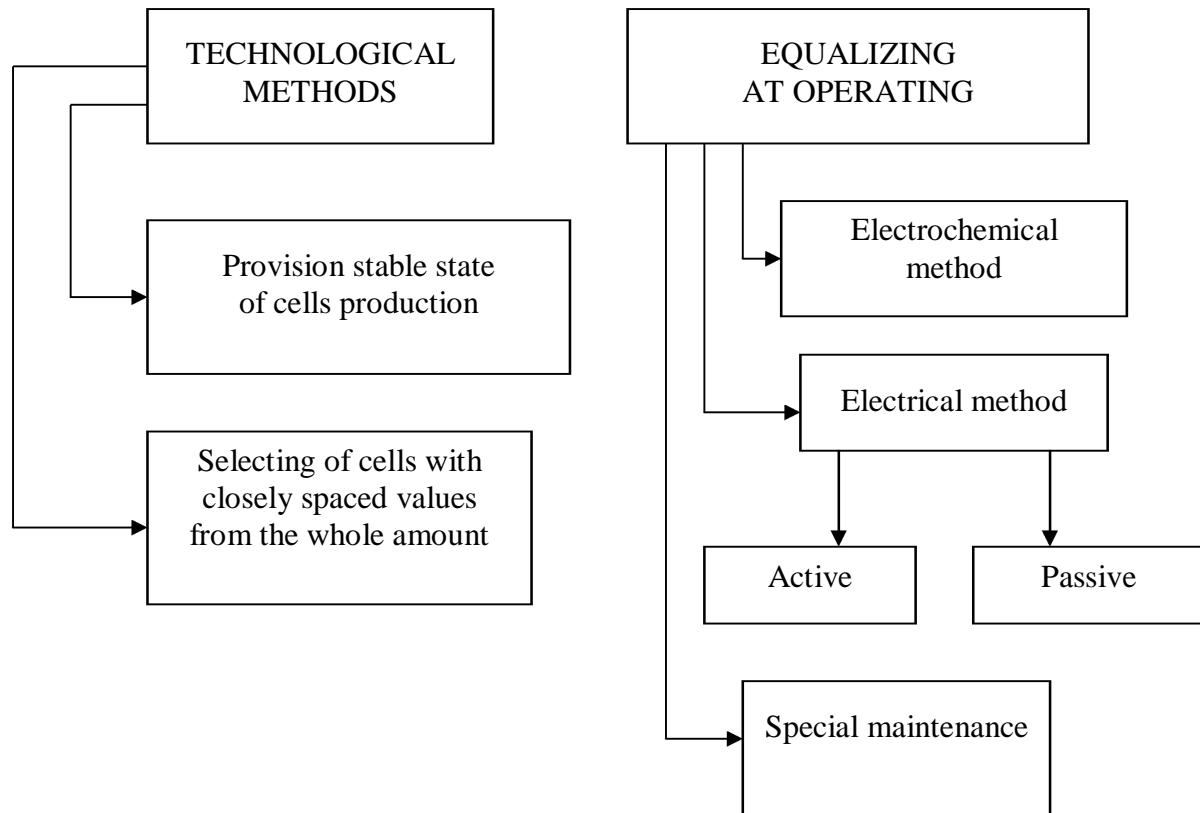


Fig. 3. Ways to improve reliability of high voltage circuit.

We shall consider each of the methods in detail.

a) Technological methods:

Provision stable state of production is based on a stable reproduction of technological requirements for each cell, and includes:

- slightly changeable compound (from a cell to another one) for electrode material, i.e. the ratio of components, including electrolyte, for each electrode;
- stability of electrode material by weight in cells;
- uniformity of physical dimensions of electrodes for cells.

This method is universal for all types of capacitors, including compact capacitors with low capacity and single cells with energy store of tens kJ.

The type of construction (bipolar, single cells) is neither critical for this method.

Selecting of cells into circuit by the minimum of variation can be well realized for capacity and ESR, but this method is very labor-consuming due to selection by the value of leakage current. Besides, this method requires special equipment to sort cells by their performances and software to select them for entire circuit. The way to select by

performances is acceptable for capacitors assembled of separately made cells and cannot be used for bipolar high voltage capacitors, with no separate cells, as technological elements.

In practice of production of high voltage capacitors, these two methods are used often at once.

b) Operation methods

Electrochemical method to control individual voltage of cells is rather exotic way. This method is based on use of special materials – additives to electrolyte or active mass for electrode. Such additive should abruptly increase leakage current of a cell due to side electrochemical reaction, when critical value of voltage is reached. For example, widely used procedure of Ni-Cad batteries production. Active mass NiOOH is added with CdO which prevents hydrogen emission in case when potential of electrode is reversed in polarity. Artificially increased individual leakage current of a cell and its consumption for a side electrochemical reaction return the cell into initial state of non critical value of voltage. In the other case, when voltage has gone over a certain value, there takes place reversible shunting of electrodes through separator. This shunting increases individual leakage current of a cell, too. The main problems of use electrochemical control is unstable reversibility of a side electrochemical reaction at long and frequently employing of this reaction.

Electrical method of control over individual voltage of cells is based on equipping each cell with devices regulating individual current of a cell.

This device can be a resistive shunt, diode, transistor, or other special regulating device. Depending on how this device acts on the current of cell, the electrical method can be divide into active and passive. The passive electrical method is to use individual current of a cell inside this cell without current interchange with other cells of circuit (these are shunt, diode, and others). The Active electrical method is more sophisticated and is based on employing digital comparing of cell voltage with the basic standard and redistribution of equalizing currents into all cells of circuit (so called “Smart” systems). The active method is rather expensive and needs multichannel digital device controlling voltage of each cell in circuit and commutation of interchanging current. That is the reason why in the practice of HVEC the passive methods of equalizing are widely used.

Choosing of the type of electrical control depends, as well, on construction of elements of circuit. The circuits incorporated single low capacitance cells are easy stabilized by shunting resistors and semiconductors. This is determined by low values of individual leakage currents. Controlling the circuits with single cells of higher capacity by means of using resistors-shunts is not very good, because the higher the rate of equalizing is required, the lower the nominal of resistors is, and consequently higher, parasitic current (energy lose on shunting load). That’s why, the active methods of regulation are more acceptable and more often used for cells with higher capacity. An other problem is presented by bipolar construction. This demands special “tricks” either to locate ultra-compact shunts inside cells, or locate wires and equalizing devices outside the HVEC module.

Now we shall try to make some expressions to estimate performances of managing elements. As it was described in item 2, leakage current of cell can be differ from entire leakage current of high voltage circuit. In this case, some cells are charging by the value of difference in currents, and other ones are discharging. Obviously, to make regulating current effective the unequation (27) should be executed:

$$(27) \quad I_{man} > I_l - I_{li}, \text{ where}$$

$I_{man}$	- manage current inside cell;
$I_l$	- entire leakage current of circuit;
$I_{li}$	- individual leakage current of cell.

The values in the right part of the unequation are the measured data of pilot samples of capacitors. And the value of  $I_{m\text{an}}$  exceeding the difference  $I_2 - I_{i2}$  depends on operation conditions specified by customer. Unequation (27) gives us the data needed to select semiconductive devices.

Procedure of control by means of shunting resistor is in Fig4 (wiring)

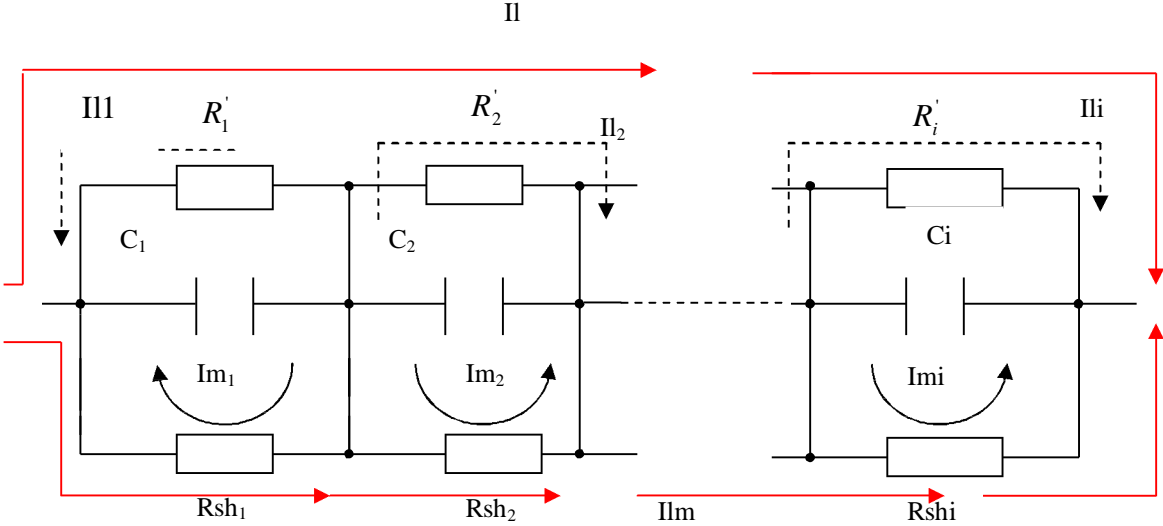


Fig. 4. Wiring for controlling by shunting resistors

- $R'_1, R'_2, R'_i$  - load determined by individual leakage current of a cell.
- $Rsh_1, Rsh_2, Rshi$  - equalizing shunts.
- $Im_1, Im_2, Im_i$  - controlling currents determined by corresponding shunts.

Shunting resistors ( $Rsh$ ) are constantly incorporated into circuit of cells and making their own circuit along all circuit of capacitors.

Stability of voltage of cells connected according to the wiring above can be estimated by the expression:

(28)  $I + I_{lm} = I_{li} + I_{mi}$ ,  
 where:  $I$  - entire leakage current of circuit;  
 $I_{lm}$  - current going through the circuit of shunting resistors;  
 $I_{li}$  - leakage current of  $i$ -cell;  
 $I_{mi}$  - current going through shunting resistor of  $i$ -cell.

For a single cell ( $i$ ) the value of controlling current going through shunting resistor is estimated by the expression:

(29)  $I_{mi} = \frac{U_{i\text{max}}}{Rshi}$ ,  
 where:  
 $U_{i\text{max}}$  - maximum allowable (project) value of voltage of a cell;  
 $Rshi$  - resistance of shunt.

For series circuit of resistors:

$$(30) \quad I_{lm} = \frac{U}{R_{sh_1} + R_{sh_2} + \dots + R_{sh_i}}, \text{ where:}$$

U - total voltage of a high voltage circuit

Since it is hard to select individual shunting resistor for each cell, and such selection is absolutely impossible for bipolar system, we can shunt all the cells of circuit with resistors of same resistance. In principle, this resistor must determine the current which is higher than any value of leakage current of a single cell (see the equation (27)). In this case the expression (30) will transfer to the following:

$$(31) \quad I_{lm} = \frac{U}{n \cdot R_{st}}, \text{ where}$$

U - total voltage of high voltage circuit;

n - number of cells in high voltage circuit;

R<sub>st</sub> - standard shunt with same value for all cells.

But in the expression (31) the quotient of U by n is average charge voltage of cells ( $\bar{U}$ ), thus:

$$(32) \quad I_{lm} = \frac{\bar{U}}{R_{st}}$$

Transfer expressions (29) and (32) into expression (28) and we obtain an equation:

$$(33) \quad I_l + \frac{\bar{U}}{R_{st}} = I_{li} + \frac{U_{i \max}}{R_{st}}$$

Thereafter, we express R<sub>st</sub> considering equation (27):

$$(34) \quad R_{st} < \frac{U_{i \max} - \bar{U}}{I_l - I_{li}}, \text{ where: } R_{st} \text{ - nominal of shunting resistor for each}$$

cell;

U<sub>imax</sub> - preset value of surge voltage of a cell;

$\bar{U}$  - average (estimated) value of voltage of a cell;

I<sub>l</sub> - total leakage current of a circuit;

I<sub>li</sub> - individual leakage current of a cell.

Expression (34) may be used to estimate shunting resistors for the cell of high voltage circuit, as in pilot samples it has statistic values I<sub>l</sub> и I<sub>li</sub>.

In general, the shunting resistors stabilize the circuit by means of time delaying to the moment of reaching critical voltage value in a single cell. When nominal of the shunt is stable, the leakage current of a cell depends on its voltage, and when it increases the leakage current increases too, decreasing thereby the state of charge of this cell.

Nevertheless, resistive shunting is not able to protect a cell with abnormally high leakage current or low capacity, comparing with the other cells in the circuit.

We shall not consider in detail the operation mode of equalizing the performances of single cells by means of a “special maintenance” during scheduled maintenance at use. The only matter we shall mark is that the widely used mode of discharge each cell to zero voltage (or non danger low value) eliminates the “effect of accumulated declines”, and thus equalizes states of charge of the cells. Estimated time to lead such “elimination” is determined by statistics considering the rate of performances degradation at exact level of HVEC production technology.

As for the applications and practical recommendations, one can see that the operation modes in item 2.4. of this paper, cover the main spheres of application for HVEC. They are in Table 3.

Table 3

HVEC Operation Modes And Spheres Of Application	
Operation Modes	Some Spheres Of Application
1. Continuous cycling by high current, without long pauses between cycles and between charges/discharges	HVEC – equalizer for peak loads: in traction electrical drive for hybrid electric vehicles (city driving cycle); in industrial power processes of a cycling type (to enhance efficiency of use energy during cycle); in powerful radio techniques
2. Floating mode with frequent discharges	High-voltage start of internal combustion engines (hybrid electric vehicles, integrated starter-alternator)
3. Floating mode with non frequent discharges	Industrial and Utility Power conditioning (Dynamic Sag Correction 0,0...1 sec; Supporting during interruption: 1 – 10 sec).

We note at once that for all the spheres of application, the lower the value of charge current and the less number of discharges is, the lower current is needed to manage internal exchange current of a cell. In other words, the less the number of cycles, the lower managing action is needed. As it was said in item 2.4., Mode 1 is not so susceptible to leakage current, and depends only on the difference in capacity and ESR. To level the performances of single cells of a circuit at frequent cycling, significantly high equalizing current will be needed. Consequently, lower value of shunting resistor of a cell will be needed, or powerful active equalizing system. From the other side, good thermal management and high stability of HVEC production present the opportunity to use the shunts with medium values of resistance.

Shunting resistors of medium range or semiconductors of low (medium) power easy support stability of high voltage circuit operating in Mode 2, see Table 3.

As for Mode 3 in Table 3 with few discharges, it is easy to stabilize circuit by semiconductors of low power, or by high Ohmic resistors. In some cases, it is economically expedient to use an active system, because exchanging currents are of low value and the

leveling device may be compact and inexpensive. In practice of operation under mode 3, periodical deep discharges of each cell improves performances of such cell. This is released during forced shut-down or specially scheduled maintenance of the main equipment.

#### 4. CONCLUSIONS

The main reason why the high voltage electrochemical capacitors are not widely used for advanced spheres of applications, is instability of series circuit incorporated a number of cells.

Failure of HVEC at use is caused by failure of one or several cells different in their performances from estimated average value.

The value of tolerance spread of the main parameters of a cell: capacity, ESR, leakage current, take various effects on service life of the capacitor in dependence on operation modes.

The most important factors to create reliable HVEC with long service life are:

- Stability of HVEC production, appearing in high reproduction of technological requirements and correct selection of separate cells into circuit by tolerance in performances;
- Usage of circuit managing individual exchanging current in cell, which is worked out at developing of a capacitor and is released at operation.

The problems restricting wide use of HVEC may be solved by means of available existing level of techniques and technologies during developing and manufacturing of capacitors.

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