РАДІОТЕХНІКА, ЕЛЕКТРОНІКА ТА ТЕЛЕКОМУНІКАЦІЇ

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SUPERCAPACITOR QUALITY CONTROL

The paper deals with the peculiarities of supercapacitor quality control, which are based on the use of nonlinear characteristics of transient resistance and transient conductance of supercapacitors. The procedure for increasing the reliability of supercapacitor control has been suggested on the basis of minimizing the average supercapacitor control risks that do not depend on the probability densities of probe effects of supercapacitor voltage and current. The manuscript contains a methodological approach to increasing the reliability of the supercapacitor, which has been proposed in the context of a multi-parameter supercapacitor control by applying nonlinear, frequency dependent mathematical models of supercapacitors that take into account the nonlinearity, frequency dispersion of parameters and the effect of transient processes in supercapacitors. The article states that increase in the reliability of the supercapacitor control, and hence the quality of control, is possible when using supercapacitor characteristics, which contain information on the nominal values of the technical condition of supercapacitors in the range of changes in nominal voltages in the operating frequency range or in the operating time range. Results of the conducted experimental researches of supercapacitors show that their parameters are nonlinear and depend on the value of charge-discharge voltages and currents, as well as the speed of charge-discharge processes. Proven the nonlinear mathematical model of supercapacitors and the non-linearity of parameters of the elements included into the supercapacitor equivalent circuit. Development of mathematical models of supercapacitors that most accurately describe their parameters and characteristics is extremely important for reducing the average supercapacitor control risks.

Keywords: supercapacitor, quality control, transient resistance, transient conductance, average quality control risk.

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КОНТРОЛЬ ЯКОСТІ СУПЕРКОНДЕНСАТОРІВ

В статті розглянуті особливості контролю якості суперконденсаторів, які базуються на використанні нелінійних характеристик його опору та провідності. Пропонується процедура підвищення надійності контролю суперконденсаторів. Рукопис містить методологічний підхід до підвищення надійності суперконденсатора, запропонований у контексті багатопараметричного суперконденсаторного регулювання шляхом врахування нелінійних, частотнозалежних математичних моделей суперконденсаторів, що враховують нелінійність, частотну дисперсію параметрів і ефект перехідних процесів у суперконденсаторах. Підвищення надійності контролю суперконденсаторів можливе при використанні характеристик суперконденсатора, що містять інформацію про номінальні значення технічного стану суперконденсаторів в діапазоні зміни номінальної напруги і робочому діапазоні частот. Результати проведених експериментальних досліджень суперконденсаторів показують, що їх параметри нелінійні і залежать від величини напруг і струмів заряду-розряду, а також від швидкості процесів заряду-розряду. Приведено нелінійну математичну модель суперконденсаторів та описано нелінійність параметрів елементів, що входять в еквівалентну схему заміщення суперконденсатора. Основою підвищення ефективності виробництва суперконденсаторів та забезпечення їх високої якості є вдосконалення методів та засобів контролю параметрів суперконденсаторів у процесі їх розробки, виробництва та експлуатації.

Ключові слова: суперконденсатор, контроль якості, перехідний опір, перехідна провідність, середній ризик контролю якості.

Introduction

Supercapacitors are polar electrochemical devices that are capable of storing and releasing electrical energy by internal redistribution of electrolyte ions. According to their electrical parameters, supercapacitors occupy an intermediate position between electrolytic capacitors of high capacitance and batteries, but according to the principle of operation differ from both of them [1, 2].

The low operating voltages of supercapacitors limit their range of applications, so separate supercapacitors are combined into blocks, connecting them serially. With such a connection, it is possible to get the required operating voltages of the block, maintaining the required capacitance values.

However, in case of a serial connection, the voltage between individual supercapacitors will not be equally distributed. It is conditioned by the technological dispersion of the capacitance and self-discharge current values of the individual supercapacitors. As a consequence, individual supercapacitors in the block may have uncontrolled overvoltage values at their outputs, which will result in their failure, and then the failure of the entire block of supercapacitors.

Also, experimental researches of supercapacitors show that their parameters are nonlinear and depend on the value of charge-discharge voltages and currents, as well as the speed of charge-discharge processes. This gives grounds to prove the nonlinear mathematical model of supercapacitors and the non-linearity of parameters of the elements included into the supercapacitor equivalent circuit.

The basis of increasing the efficiency of supercapacitor production and ensuring their high quality is the improvement of methods and means of controlling the parameters of supercapacitors in the process of their development, production and operation. The notion of supercapacitor parameter control will be considered as verifying compliance of supercapacitor parameter values with the requirements of technical documentation and determining on this basis one of the specified types of supercapacitor technical condition: either working or defective.

When constructing devices for controlling the parameters of supercapacitors, it is necessary to take into account the properties that reflect their technical state.

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In addition to the nominal technical condition values of supercapacitors, such as capacitance *C*, active resistance *R* and self-discharge current I_{sd}, their quality is influenced by the change in these technical condition values due to frequency dispersion and nonlinearity: $R(\omega,u)$, $C(\omega,u)$, $I_{sd}(t,u)$.

Analysis of the latest researches and publications

In accordance with international documents and current state standards, a supercapacitor will be considered to be working, when all its parameters meet the requirements of the technical documentation for this supercapacitor, and if at least one of the parameters of a supercapacitor does not meet these requirements, then a supercapacitor will be considered to be defective [3].

In the process of development, production and operation of supercapacitors, the measurement control of their parameters is applied, which determines the values of supercapacitor parameters in relation to their permissible limit values by carrying out a measurement procedure.

Reliability of control is the degree of objective conformity of the result of control to the actual technical condition of the object, which is estimated by the probability of making the correct decision about the condition of the object of control [4]. The components of the general reliability of control are methodological and instrumental reliabilities of control [5]:

$$D_G = D_M \cdot D_I, \qquad (1)$$

where D_M is methodological reliability of control; D_I is instrumental reliability of control.

Methodological reliability of control is calculated by the following formula [5]:

$$D_M = \frac{N_1}{N}; \qquad (2)$$

where N_I is the number of exponents which characterize the technical condition of the object of control and are included into the mathematical model of control;

N is total number of exponents which characterize the technical condition of the object of control.

Instrumental reliability of control is defined by the probabilities of errors of the first and second kind respectively α i β [5]:

$$D_I = 1 - \alpha - \beta, \qquad (3)$$

where α is probability of errors of the first kind; β is probability of errors of the second kind.

Mathematical model for electromechanical supercapacitor parameter control

Let's consider a simplified mathematical model for controlling supercapacitor parameters in the stationary mode, which is based on a one-time measurement of capacitance *C*, active resistance *R* and self-discharge current I_{sd} of supercapacitors.

Depending on the measurement method, capacitance *C* and active resistance *R* of supercapacitors are measured either at the alternating current at one probe effect frequency ω_0 with one nominal constant voltage at the supercapacitor outputs U_{nom} or at the direct charge (discharge) current of supercapacitors I_0. Self-discharge current I_{sd} of supercapacitors is also measured at one nominal constant voltage at the supercapacitor outputs U_{nom}. As a result of such measurements, we get three measured values: *r*, *c* and i_{sd}.

Next, two hypotheses are put forward.

1. The basic hypothesis H_0 (the supercapacitor is working):

$$H_0: r \in [R_{\min}, R_{\max}] \cap c \in [C_{\min}, C_{\max}] \cap i_{cp} \in [Isd_{\min}, Isd_{\max}], \qquad (4)$$

where R_{min}, R_{max}; C_{min}, C_{max} and Isd_{min}, Isd_{max} are limits of permissible interval for *r*, *c* and i_{sd} respectively.

2. Alternative hypothesis H_1 (the supercapacitor is defective):

$$H_1: r \notin [R_{\min}, R_{\max}] \cap c \notin [C_{\min}, C_{\max}] \cap i_{cp} \notin [Isd_{\min}, Isd_{\max}]. \qquad (5)$$

The reliability of supercapacitor parameter control is defined as the product of the methodological and the instrumental reliabilities of supercapacitor parameter control (1). In its turn, the methodological reliability of supercapacitor parameter control is defined by the ratio between the number of exponents characterizing the technical condition of the object of control and included to the mathematical model of control and the total number of exponents characterizing the technical condition of the object of control.

From this we can conclude that the simplified mathematical model for controlling the parameters of supercapacitors, which is based on the one-time measurement of capacitance *C*, active resistance *R* and self-discharge current I_{sd} of supercapacitors, is characterized by low methodological reliability of control.

It can be explained by the fact that for supercapacitors capacitance C≠const, active resistance R≠const and self-discharge current I_{sd}≠const.

In case of a simplified model of supercapacitor parameter control, the number of exponents characterizing the technical condition of supercapacitors N_1=3 (capacitance, active resistance and self-discharge current). As for the total number of exponents characterizing the technical condition of supercapacitors, frequency dispersion and non-linearity of supercapacitor parameters ($R(\omega,u)$, $C(\omega,u)$, $I_{sd}(t,u)$) are equivalent to the increase in the total number of exponents characterizing the technical condition of supercapacitors. Hence, we can conclude that $N \neq N_1$ і $N >> N_1$, and the methodological reliability of supercapacitor parameter control for a simplified model of supercapacitor parameter control is much smaller than one.

$$D_M = \frac{3}{N} << 1 . \tag{6}$$

The instrumental reliability of supercapacitor parameter control is defined by the expression (3), which includes the probabilities of errors of the first and second kind, α and β respectively. The probabilities of errors of the first and second kind are defined separately for the capacitance C, active resistance R and self-discharge current I_{cp} of supercapacitors according to the expressions:

$$\alpha_C = \int_{C_{\min}}^{C_{\max}} f(C)\left(\int_{-\infty}^{C_{\min}-C} f(\delta_C)d\delta_C\right)dC + \int_{C_{\min}}^{C_{\max}} f(C)\left(\int_{C_{\max}-C}^{\infty} f(\delta_C)d\delta_C\right)dC ; \tag{7}$$

$$\beta_C = \int_{-\infty}^{C_{\min}} f(C)\left(\int_{C_{\min}-C}^{C_{\max}-C} f(\delta_C)d\delta_C\right)dC + \int_{C_{\max}}^{\infty} f(C)\left(\int_{C_{\min}-C}^{C_{\max}-C} f(\delta_C)d\delta_C\right)dC , \tag{8}$$

where $C_{\max}$, $C_{\min}$ are permissible maximal and minimal capacitance values for supercapacitors; $f(C)$ is density of probability of supercapacitor capacitance; $f(\delta_C)$ is density of probability of supercapacitor capacitance measurement error.

$$\alpha_R = \int_{R_{\min}}^{R_{\max}} f(R)\left(\int_{-\infty}^{R_{\min}-R} f(\delta_R)d\delta_R\right)dR + \int_{R_{\min}}^{R_{\max}} f(C)\left(\int_{R_{\max}-R}^{\infty} f(\delta_R)d\delta_R\right)dR ; \tag{9}$$

$$\beta_R = \int_{-\infty}^{R_{\max}} f(R)\left(\int_{R_{\min}-R}^{R_{\max}-R} f(\delta_R)d\delta_R\right)dR + \int_{R_{\max}}^{\infty} f(R)\left(\int_{R_{\min}-R}^{R_{\max}-R} f(\delta_R)d\delta_R\right)dR , \tag{10}$$

where $R_{\max}$, $R_{\min}$ is permissible maximal and minimal active resistance values for supercapacitors; $f(R)$ is density of probability of supercapacitor active resistance; $f(\delta_R)$ is density of probability of supercapacitor active resistance measurement error.

$$\begin{aligned}\alpha_{Isd} = &\int_{Isd_{\min}}^{Isd_{\max}} f(Icp)\left(\int_{-\infty}^{Isd_{\min}-Isd} f(\delta_{Isd})d\delta_{Isd}\right)dIsd + \\ &+\int_{Isd_{\min}}^{Isd_{\max}} f(Icp)\left(\int_{Isd_{\max}-Isd}^{\infty} f(\delta_{Isd})d\delta_{Isd}\right)dIsd\end{aligned} ; \tag{11}$$

$$\begin{aligned}\beta_{Isd} = &\int_{-\infty}^{Isd_{\min}} f(R)\left(\int_{Isd_{\max}-Isd}^{Isd_{\max}-Isd} f(\delta_{Isd})d\delta_{Isd}\right)dIsd + \\ &+\int_{Isd_{\max}}^{\infty} f(Isd)\left(\int_{Isd_{\min}-Isd}^{Isd_{\max}-Isd} f(\delta_{Isd})d\delta_{Isd}\right)dIsd\end{aligned} , \tag{12}$$

where $Isd_{\max}$, $Isd_{\min}$ are permissible maximal and minimal self-discharge current values for supercapacitors; $f(Isd)$ is density of probability of supercapacitor self-discharge current; $f(\delta_{Isd})$ is density of probability of supercapacitor self-discharge current measurement error.

The general probabilities of errors of the first and second kind, α and β respectively, are defined by the expressions:

$$\alpha = 1-(1-\alpha_C)(1-\alpha_R)(1-\alpha_{Isd}) ; \tag{13}$$

$$\beta = 1-(1-\beta_C)(1-\beta_R)(1-\beta_{Isd}) . \tag{14}$$

Then, the general reliability of supercapacitor parameter control for a simplified model of parameter control is defined by the expression:

$$D_G = D_M \cdot D_I = \frac{3}{N}\cdot\left(1-\alpha-\beta\right) << 1 . \tag{15}$$

Assessment of supercapacitor control quality for a simplified model can also be performed using the formula of average control risk:

$$\Psi \approx W_{1R}\alpha_R + W_{2R}\beta_R + W_{1C}\alpha_C + W_{2C}\beta_C + W_{1Isd}\alpha_{Isd} + W_{2Isd}\beta_{Isd}\,, \tag{16}$$

where W_{1R}, W_{1C} and W_{1Isd} are losses due to errors of the first kind for each parameter r, c and i_{sd} respectively;
W_{2R}, W_{2C} and W_{2Isd} are due to errors of the second kind for each parameter r, c and i_{sd} respectively;
α_R, α_C and α_{Isd} are probabilities of errors of the first kind for each parameter r, c and i_{sd} respectively;
β_R, β_C and β_{Isd} are probabilities of errors of the second kind for each parameter r, c and i_{sd} respectively.

Increase in the reliability of supercapacitor control, and hence the quality of control, is possible when using supercapacitor characteristics that contain information on the nominal values of technical condition of supercapacitors in the range of changes in nominal voltages in the operation frequency range or in the operation time range. Such characteristics include nonlinear complex resistance $Z(j\omega, u)$ (or nonlinear resistance $Z(s,u)$ and nonlinear transient resistance $z(t,u)$ of supercapacitors, related to each other by inverse and direct Laplace transforms:

$$Z(s,u) = L^{-1}\left[z(t,u)\right]; \tag{17}$$

$$z(t,u) = L\left[Z(s,u)\right], \tag{18}$$

where $s = j\omega$ is complex frequency.

The supercapacitor's input is supplied with either the probe voltage $u_p(t)$ or probe current $i_p(t)$, and either the current $i_m(t)$ through the supercapacitor or the voltage $u_m(t)$ at the supercapacitor is measured. Operators Z or Y determine the complex of mathematical operations over $u_p(t)$ or $i_p(t)$ which allow obtaining $i_m(t)$ or $u_m(t)$ respectively:

$$i_m(t) = Z\left[u_p(t)\right]; \tag{19}$$

$$u_m(t) = Y\left[i_p(t)\right]. \tag{20}$$

Let's consider that the probe voltage $u_p(t)$ and the probe current $i_p(t)$ are observed without an error, and the measured voltage $u_m(t)$ and the measured current $i_m(t)$ are observed with errors

$$i_m^*(t) = i_m(t) + \Delta i_m(t)\,; \tag{21}$$

$$u_m^*(t) = u_m(t) + \Delta u_m(t)\,. \tag{22}$$

where $\Delta i_m(t)$ and $\Delta u_m(t)$ are stationary random processes with known characteristics.

Hence, we can conclude that in the process of supercapacitor control it is necessary to obtain a rating of the defined operators Z_m and Y_m approaching the operators Z and Y which describe the properties of supercapacitors. Taking into account the fact that operators Z or Y are in most cases unknown, to describe supercapacitors their mathematical models characterized by operators $Z_м$ or $Y_м$ are used [6-8].

The criterion for estimating the proximity of operators Z_m, Y_m, and $Z_м$, $Y_м$ is approximation of the measured voltage $u_m(t)$ and the measured current $i_m(t)$ to the voltage $u_м(t)$ and current $i_м(t)$ of the model at the similar probe effects of $i_p(t)$ and $u_p(t)$ respectively. Let's introduce positive functions of losses $\eta_u\left[u_m(t), u_м(t)\right]$ or $\eta_i\left[i_m(t), i_м(t)\right]$ which depend on the measured voltage and current of an supercapacitor and its model, and also determine the amount of losses connected with different combinations of $u_m(t)$, $u_м(t)$ and $i_m(t)$, $i_м(t)$. Average loss or average risk is defined by the mathematical expectations of loss functions $\eta_u\left[u_m(t), u_м(t)\right]$ or $\eta_i\left[i_m(t), i_м(t)\right]$:

$$\bar{\Psi}_u = M\left\{\eta_u\left[u_m(t), u_м(t)\right]\right\}; \tag{23}$$

$$\bar{\Psi}_i = M\left\{\eta_i\left[i_m(t), i_м(t)\right]\right\}. \tag{24}$$

On the other hand, average risks are defined by expressions:

$$\bar{\Psi}_u = \iint \eta_u(u_m, u_м) f_u(u_m, u_м)\, du_m du_м\,; \tag{25}$$

$$\bar{\Psi}_i = \iint \eta_i(i_m, i_м) f_i(i_m, i_м)\, di_m di_м\,, \tag{26}$$

where $f_u(u_m, u_м)$ and $f_i(i_m, i_м)$ are voltage and current probability functionals.

Expressions (25) and (26) can be simplified, if the nonlinear transient resistance $z(t,u)$ and nonlinear transient conductance $y(t,i)$ of supercapacitors are monotone functions, and probe signals $u(t)$ and $i(t)$ are stationary:

$$\bar{\Psi}_u = \int_{u \in U} \eta_u\left[z_m(t,u), z_м(t,u)\right] f_u(u)\, du\,; \tag{27}$$

$$\bar{\Psi}_i = \int_{i \in I} \eta_i\left[y_m(t,i), y_м(t,i)\right] f_i(i)\, di\,, \tag{28}$$

where U is definition domain of u;

I is definition domain of i.

Deviation of the defined nonlinear transient resistance $z_m(t,u)$ from the nonlinear transient resistance of the model $z_м(u)$, as well as deviation of the defined nonlinear transient conductance $y_m(t,i)$ from the nonlinear transient conductance of the model $y_м(t,i)$ may be estimated by the criterion of regular approximation (maximum deviation of characteristics):

$$m_u = \max_{u \in U} \left| z_m(t,u) - z_м(t,u) \right| ; \quad (29)$$

$$m_i = \max_{i \in I} \left| y_m(t,i) - y_м(t,i) \right| . \quad (30)$$

Let's choose such mathematical models of supercapacitors $z_м(t,u)$ and $y_м(t,i)$ which will satisfy the criteria of regular approximation in the ranges of change in the probe voltage $u_з(t)$ and current $i_з(t)$ of supercapacitors.

Let's define the average risk of supercapacitor control for the following loss functions $\eta_u = \left| z_m(t,u) - z_м(t,u) \right|^k$ and $\eta_i = \left| y_m(t,i) - y_м(t,i) \right|^k$:

$$\bar{\Psi}_u = \int_{u \in U} \left| z_m(t,u) - z_м(t,u) \right|^k f_u(u) du \le \int_{u \in U} m_u^k f_u(u) du = m_u^k ; \quad (31)$$

$$\bar{\Psi}_i = \int_{i \in I} \left| y_m(t,i) - y_м(t,i) \right|^k f_i(i) di \le \int_{i \in I} m_i^k f_i(i) di = m_i^k . \quad (32)$$

The advantage of the obtained expressions of the average supercapacitor control risks (31) and (32) in comparison with the expressions (25) and (26) is the possibility of calculating the maximum values of the average supercapacitor control risks that do not depend on the probability densities $f_u(u)$ and $f_i(i)$ of EC voltage and current probe effects [9].

Conclusions

1. Analysis of the expressions of the average supercapacitor control risks (31) and (32) shows that development of mathematical models of supercapacitors that most accurately describe their parameters and characteristics is extremely important for reducing the average supercapacitor control risks.

2. The methodological approach to increasing the reliability of supercapacitor electrical parameter control has been proposed, in terms of multi-parameter supercapacitor control by applying nonlinear, frequency dependent mathematical models of supercapacitors that take into account nonlinearity, frequency dispersion of parameters and the effect of transient processes in supercapacitors.

3. The procedure for increasing the reliability of supercapacitor control has been suggested on the basis of minimizing the average supercapacitor control risks that do not depend on the probability densities of probe effects of supercapacitor voltage and current.

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