Показано, що в сучасних напівпровідникових апаратах постійного струму для обмеження комутаційних перенапруг до встановленого рівня доцільно запасену в індуктивності мережі енергію розсіювати за допомогою обмежувача перенапруг, виконаного на послідовно-паралельно увімкнених енергоємних варисторах. Розроблена методика розрахунку його параметрів та наведені приклади розрахунку

Ключові слова: комутаційна перенапруга, обмежувач перенапруг, варистор, напівпровідниковий апарат, напівпровідниковий прилад

Показано, что в современных полупроводниковых аппаратах постоянного тока для ограничения коммутационных перенапряжений до установленного уровня целесообразно запасённую в индуктивности сети энергию рассеивать с помощью ограничителя перенапряжений, выполненного на последовательно-параллельно включенных энергоёмких варисторах. Разработана методика расчёта его параметров, приведены примеры расчёта

Ключевые слова: коммутационное перенапряжение, ограничитель перенапряжений, варистор, полупроводниковый аппарат, полупроводниковый прибор

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METHODS OF OVERVOLTAGE LIMITATION IN MODERN DC SEMICONDUCTOR SWITCHING APPARATUS AND THEIR CALCULATION

A. Soskov
Doctor of Technical Sciences, Professor*
E-mail: ansoskov@gmail.com
N. Sabalaeva
PhD, Associate Professor*
E-mail: natalysub@mail.ru
Y. Forkun
PhD, Associate Professor*
E-mail: yana_forkun@mail.ru
M. Glebova
PhD, Associate Professor*
E-mail: glebova_marina@mail.ru
*Department of Theoretical and General Electrical Engineering
O. M. Beketov National University of Urban Economy in Kharkiv
Revolutsiy str., 12, Kharkiv, Ukraine, 61002

1. Introduction

In the 1980s, a new stage began in the development of power electronics associated with the creation of powerful fully controlled semiconductor devices (SDs), primarily including a double-gate turn-off (D-GTO) thyristor, a GCT-thyristor (gate communicated turn-off thyristor) and, especially, a high-speed power insulated gate bipolar transistor (IGBT-transistor). The high level of modern electronic technology has made it possible to organize mass production of these devices in the form of compact integrated module structures such as IGCTs (GCT-based thyristors) and IGBTs (BTIZ-based thyristors), which are characterized by high reliability and reasonable price. The combination of power devices and circuits for their control in a single package with different degrees of integration has created favourable conditions to implement various laws of controlling superpower electricity flows [1, 2].

The aforementioned devices have given a powerful impetus for further improvement of the previously developed hybrid and contactless switching power semiconductor devices (SDs) for the direct current (DC) by applying in their main circle new fully manageable semiconductor transformers (STs) as switches. The advanced devices have such operational qualities as high switching durability (up to several million cycles), an extremely high speed of performance (only several microseconds), absence of highly expensive and unreliable systems of forced switching, improved functional features, and convenience of combinability with microprocessor devices, which make them really competitive on the world market despite their high cost [3, 4].

These improved semiconductor apparatus (SA) of the DC, both contactless [5, 6] and hybrid [7, 8], have switching surges continuously caused by energy stored in the inductance of the circuit and the load at the time of switching. However, due to the fact that the circuits at switched off at a significant load almost instantly, the stored energy will be much higher, and dampening it will be much more difficult than in previously developed devices with the capacitive switching of the semiconductor switch where the switching capacitor combines its main function with the role of a voltage regulator [9].

Therefore, it is expedient to research the methods of limiting switch surges in these devices and to make relevant calculations. The study is likely to be of indispensable interest to professionals working in the field of electromechanical engineering.

2. Analysis of previous studies and statement of the problem

In semiconductor apparatus of the direct current, damping of the switching surge caused by stored energy in the inductance of the circuit and the load at the switch-off time can be practically performed in the following ways:

– by applying switching capacitors (condensers) [10];

– by using the same capacitors but shunted with linear resistors (condenser-resistive) [10];

– by using energy-intensive variable resistors (varistors) [11, 12].

In all the above-listed methods for scattering the energy stored in the inductive load, it is traditional to use either a reverse diode or a reverse thyristor (in the case of a reverse execution system) that are switched on simultaneously with the load [13]. Transient electromagnetic processes taking place along have been studied in sufficient detail [11]. Moreover, it should be noted that, due to high energy stored in the inductive load at the time of switching, other methods are unsuitable because of impossibility to implement them (usually the energy stored in the inductive load is much higher than the energy stored in the circuit inductance) [14]. Thus below we shall analyse the above methods, provided that it is necessary to dampen only the energy stored in the circuit inductance.

The use of capacitors to limit switching surges by transferring the energy stored in the circuit inductance into potential energy of the charged capacitors is a classic method used in SA of the direct current with compulsory capacitive switching of the primary semiconductor switch of the SA made on the basis of thyristors [10]. To obtain an admissible level of surge, it was necessary to use bulky, unreliable and expensive special impulse capacitors, with a limited temperature operating range (it especially concerns electrolytic pulse capacitors). This method can be justified when SA already have capacitive compulsory switching; however, in modern SA, which are constructed using fully controlled STs, the use of this method would not be expedient [15].

The use of protective capacitors with linear resistors that are enabled by a special scheme in parallel to the capacitors has allowed significant reduction of their size. However, in addition to the problems connected with deficiencies of the special capacitors, there have appeared difficulties involving the need to create special schemes for switching linear resistors that would allow their switching on and off at the right time [10]. Therefore, this method is also impractical to use for reducing switching surges in modern SA.

Voltage regulators that are made on the basis of the two discussed principles are fully analysed in [10]. The study considers the methods of their calculation subject to constraining switching surges to a level acceptable for SA of the direct current.

At present, due to the development of energy-intensive varistors that allow dissipating the energy of several hundred kJ and that are suitable in size and cost, sufficiently favourable conditions have been created for their use in modern switching SA for the dissipation of stored energy in the circuit inductance at switching off the device [11, 16].

The above-disclosed critical analysis of the various methods of damping switching surges in the circles of power switching devices of the direct current shows that while using SA of the direct current in which STs are fully controlled it is expedient to limit voltage surge to the level established for this class of devices (down to 2.5U_{nom}) [17] by dissipating the energy stored in the inductive load by means of the voltage regulator (VR) VR1 made on the basis of the feedback diode turned on parallel to the load, and the energy stored in the circuit inductance should be dissipated with the help of the VR2 based on powerful varistors switched on at the apparatus inlet.

Since there are no methods currently used for calculating varistor VRs integrated into the work of SA of the direct current using fully controlled power SA, there is a need for a detailed study of the electromagnetic transient processes that occur in the limiters of these devices while switching the load. Therefore, it is necessary to develop a method of calculating the parameters of varistor VRs that reduce switching surges to the level established for this class of devices.

3. Research aim and objectives

The aim of this study is to develop a method of calculating the parameters of voltage regulators made on the basis of energy-intensive varistors at a given switching surge level in SA of the direct current with fully manageable STs.

Therefore, it is necessary to solve the following problems:

– to study transients that occur in the voltage regulators for SA of the direct current at the load switching;

– to determine the analytical expressions to calculate the basic parameters of VRs and to formulate them as the basis of an engineering method of calculation;

– to provide examples of calculating the parameters of VRs and switching surges for the most common types of SA of the direct current.

4. Research of transients in voltage regulators on semiconductor switches of semiconductor apparatus at switching the load

An equivalent embodiment of switching a VR in the SA power supply circuit is shown in Fig. 1.

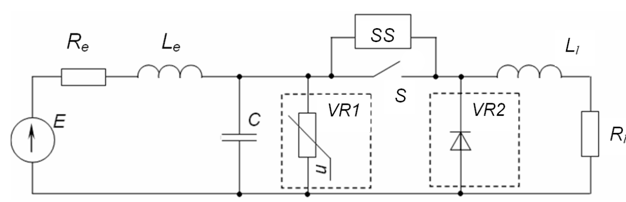

Fig. 1. An equivalent circuit of switching voltage regulators (SS is a semiconductor switch on fully controlled devices, S is a mechanical switch available only in hybrid apparatus, L_l and R_l are load inductance and active load resistance, whereas L_e and R_e are equivalent inductance and resistance in the circuit)

The parameters R_e and L_e are chosen in the mode of a short current (sc) in the apparatus circuit:

$$R_e = \frac{U_{nom} \cdot 1.1}{I_{sc\,max}} \text{ and } L_{sc} = L_e = \tau R_e, \quad (1)$$

where U_{nom} is the nominal voltage in the circuit, $I_{sc\,max}$ is the maximum admissible short circuit current and τ is the time constant of the short circuit current ($\tau = 0.01$ s) [17].

Parallel to the VR1 in this circuit, there is the connected capacitor C that limits the growth rate of the switching surge in STs of semiconductor switches at the break of the load current. The value of this capacitor capacitance is determined by the obvious expression:

$$C=\frac{I_{SI}}{\left(\frac{du_T}{dt}\right)_{crit}}, \qquad (2)$$

where I_{SI} is the maximum admissible switched current of the apparatus, for example, for a contactor and a modern high speed circuit breaker (usually, $I_{SI}=4I_{nom.o}$) [4], $I_{nom.o}$ is a nominal operating current (usually, $I_{nom.o}=0.6I_{nom}$) and $\left(\frac{du_T}{dt}\right)_{crit}$ is a maximum admissible growth rate of the current in power semiconductor devices (PSDs).

The parameters of the varistors used in the VR1 must comply with the inequalities [4]:

$$\begin{cases} W_{c.max}<W_{c.adm}, \\ I_{c.max}<I_{c.adm}, \\ t_c<t_{adm}, \\ U_{cl}\geq\frac{U_{nom}}{0.85}\cdot 1.1, \end{cases} \qquad (3)$$

where t_c is the duration of the varistor current, $I_{c\ adm}$ and t_{adm} are the admissible amplitude and duration of the current impulse of the varistor at which its energy W_c does not exceed the admissible energy $W_{c.adm}$, W_{cmax} is the maximum energy released in the varistor, I_{cmax} is the maximum current in the varistor and U_{cl} is a classified varistor voltage.

For real parameters of the switching circuit of a SA of the direct current, the values of I_c and W_c can be much higher than the admissible $I_{c.adm.}$ and $W_{c.adm.}$. For example, for a contactor for which $I_{nom}=630$ A, the maximum switched current I_{sc} in the circuit in the mode of rare switches is equal to $4I_{nom.r}$; therefore, at $I_{nom.o}=0.6I_{nom}$, $L_e=0.5$ mH, the stored energy of inductance in the electric circuit is $\frac{L_e I_{SI}^2}{2}=571$ J, whereas in varistors CH2-2, $W_{c.adm}\leq 150$ J and in BC2-2 $W_{c.adm.}=350$ J [3].

Therefore, to increase the admissible energy for the VR1, the authors of the study suggest a parallel connection of a varistor series, which is shown in Fig. 2.

Such a VR has n parallel branches, each containing m consecutively connected varistors RU1-RUm and one ballast resistor R_b that aligns the currents in the parallel branches.

Calculation of the maximum energy released in one varistor of the VR in Fig. 2, *a* is done for the limiting case of uneven current distribution in the parallel branches, which corresponds to determining the minimum values of the parameters in an n-th branch while and the maximum values are determined in the other branches.

The current in the n-th branch will be the maximum, and the currents in the other branches will be minimal. It is obvious that the energy released in one varistor proportionally to the square of the current will be maximal for the varistor that is set in the n-th branch with the maximum current.

The calculation diagram of replacing the switching circuit of the VR1 (Fig. 2, *a*), which has a given distribution of the current, at the stage of limiting the surge looks like in Fig. 2, *b* (excluding the capacitor current C of the VR1, which has too small a capacity to have any actual effect on the current distribution in the VR1), where L_e is equivalent inductance in the switching circuit ($L_e=L_{sc}; R_e\approx 0$);

$$R_{emax}=mR_{d.max}+R_{b.max} \text{ and } U_{emax}=mU_{cmax}$$

are equivalent maximum resistance and voltage in an (n-1)-th branch with the minimum currents i_{cmin};

$$R_{emin}=mR_{d.min}+R_{b.min} \text{ and } U_{emin}=mU_{cmin}$$

are equivalent minimal resistance and voltage in stabilizing the n-th branch with the maximum currents i_{cmax}, R_{dmax}, R_{dmin} are the maximum and minimum dynamic resistances of the varistors; U_{cmax}, U_{cmin} are the maximum and minimum voltages in stabilizing the varistors; $R_{b.max}$, $R_{b.min}$ are the maximum and minimum resistances of the ballast resistor; S1 is the switch simulating the operation of the VR1 (it switches off the branches with the currents i_{cmin} at the declining voltage in the VR1 u_{vr} below U_{emax}).

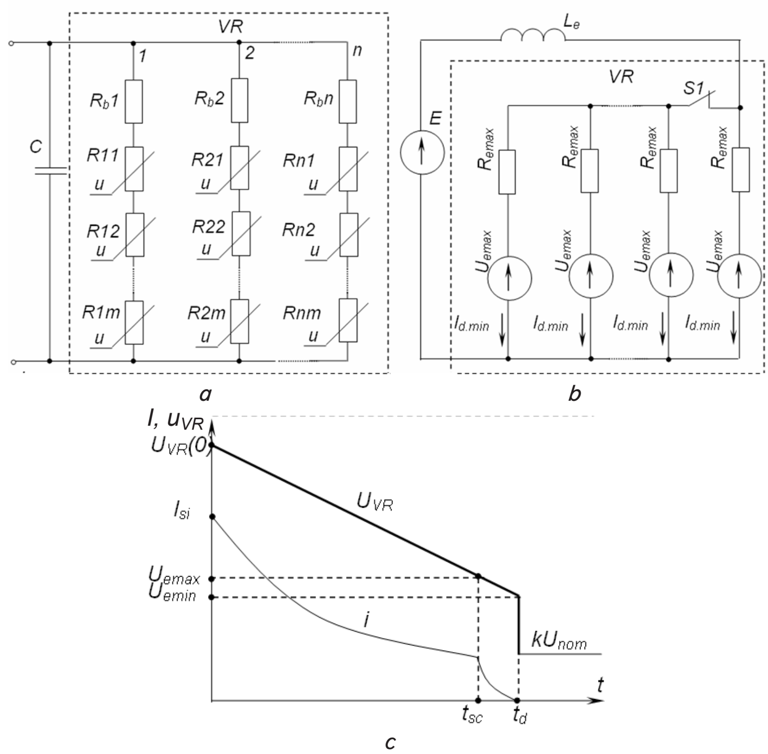

Fig. 2. The voltage regulator: *a* is a diagram of a parallel-serial connection of varistors, *b* is a calculation diagram of an equivalent switching circuit in the VR and *c* is the diagram of the VR operation

For the current to flow in the VR, it is necessary to increase the voltage u_{vr} to the value of U_{emin} and the switch S1 can be locked to allow the current flow in all the n branches if the inequality is the following:

$$I_{SI}>(U_{emax}-U_{emin})/R_{emin}. \qquad (4)$$

The experience of operating varistors CH2-2 for big energy volumes to scatter in them shows that it is advisable to choose the varistor value U_c as its I–V curve at the current of $I_{1.0} = 1$ A, and its dynamic resistance is determined by the expression [4]:

$$R_d = \frac{U_{v100} - U_c}{I_{100}},$$

where U_{v100} is the voltage in the varistor at $I_{100} = 100$ A.

Then the voltage in the varistor U_v is determined by the expression $U_v = U_c + I_v R_d$.

5. Analytical expressions to calculate the basic parameters of the VR and their inclusion into the engineering method of calculation

To fulfil inequality (3), the process in the equivalent circuit (Fig. 2, *a*, $0 \le t \le t_{sc}$) with the locked switch S1 at the time interval of $0 \le t \le t_{sc}$ (Fig. 2, *c*) is described by the following set of equations [18]:

$$\begin{cases} E = L_e \dfrac{di}{dt} + u_{vr}, \\ u_{vr} = U_{emin} + i_{c.max} R_{emin} = U_{emax} + i_{c.min} R_{emax}, \\ i = i_{c.max} + (n-1) i_{c.min}, \end{cases} \quad (5)$$

where u_{vr} is the voltage in the voltage regulator; $E = kU_{nom}$ is the maximum admissible electromotive force (emf) of the circuit (k=1.1).

The calculation of the parameters of the protection circuit is given below.

The solution is subject to the initial condition of $i(0) = I_{SI}$:

$$i_{cmin} = \rho i_{cmax} - I_{imb},$$

$$i = [1 + \rho(n-1)] i_{cmax} - (n-1) I_{imb},$$

$$i_{cmax} = Ae^{-t/\tau_{sc}} - I_*,$$

where

$$\rho = \frac{R_{emin}}{R_{emax}}; \quad I_{imb} = (U_{emax} - U_{emin}) / R_{emax}$$

is an imbalance current;

$$I_* = \frac{U_{emin} - E}{R_{emin}};$$

$$U_{emin} > E;$$

$$A = I_* + \frac{[I_{SI} + I_{imb}(n-1)]}{1 + \rho(n-1)};$$

$$\tau_{sc} = \frac{[1 + \rho(n-1)] L_e}{R_{emin}}.$$

The amplitude of the maximum current in the varistor is:

$$I_{cmax} = i_{cmax}(0) = [I_{SI} + (n-1) I_{imb}] / [1 + \rho(n-1)]. \quad (6)$$

The amplitude of the limited VR voltage at the device input is:

$$U_{vmax} = u_{vr}(0) = R_{emin} I_{cmax} + Ue_{min} \le 2.5 U_{nom}. \quad (7)$$

The duration of the locked state of the switch S can be found by solving the equation $u_{vr} = U_{emax}$

$$t_{sc} = \tau_{sc} \ln \frac{\rho A}{I_{imb} + \rho I_*}. \quad (8)$$

Within the time interval $0 \le t \le t_{sc}$ (Fig. 2, *c*), the switch S1 in the equivalent circuit is unlocked, and the current i declines to zero. Meanwhile, the process in the equivalent circuit can be described through the equations [18]:

$$E = L_e \frac{di}{dt} + u_{vr}, \quad u_{vr} = R_{emin} i + U_{emin}.$$

The solution is subject to the initial condition of

$$i(0) = \frac{I_{imb}}{\rho}: \quad i = -I_* + Be^{-t/\tau_{r.s.}},$$

where

$$B = I_* + \frac{I_{imb}}{\rho}, \quad \tau_{r.s.} = \frac{L_e}{R_{emin}}.$$

The time of the unlocked state of the switch S1 can be determined by solving the equation where i=0:

$$t_{r.s.} = \tau_{r.s.} \ln\left(1 + \frac{I_{imb}}{\rho I_*}\right). \quad (9)$$

The time of the current flow through the VR is:

$$t_d = t_{sc} + t_{r.s.}. \quad (10)$$

The maximum energy W_{cmax} released in one varistor of the n-th branch with the current of $i_{c.max}$ is:

$$W_{c.max} = \int_0^{t_{sc}} i_{c.max}\left(U_{c.min} + R_{d.min} i_{c.max}\right) dt + \int_0^{t_{r.s.}} i\left(U_{c.min} + R_{e.min} i\right) dt,$$

or

$$W_{c.max} = \int_0^{t_{sc}} (Ae^{-t/\tau_{sc}} - I_*)(U_{c.min} + R_{d.min}(Ae^{-t/\tau_{sc}} - I_*)) dt +$$

$$+ \int_0^{t_{r.s.}} (-I_* + Be^{-t/\tau_{r.s.}})(U_{c.min} + R_{e.min}(-I_* + Be^{-t/\tau_{r.s.}})) dt. \quad (11)$$

The maximum energy $W_{b.max}$ released in the ballast resistance of the same branch is:

$$W_{b.max} = \int_0^{t_{sc}} (Ae^{-t/\tau_{sc}} - I_*)^2 R_{b.min} dt +$$

$$+ \int_0^{t_{r.s.}} (-I_* + Be^{-t/\tau_{r.s.}})^2 R_{b.min} dt. \quad (12)$$

The minimal energy $W_{c.min}$ released in the varistor of the (n–1)-th branch with the current of $i_{c.min}$ is:

$$W_{c.min} = \int_0^{t_{sc}} \left[(Ae^{-t/\tau_{sc}} - I_*) \cdot \rho - I_{imb}\right] \times$$

$$\times \left[U_{c.max} + R_{d.max} \cdot (Ae^{-t/\tau_{sc}} - I_*)\right] dt. \quad (13)$$

On the basis of the above-obtained expressions, we suggest the following engineering method of calculation.

1. It is initially necessary to select from the VR varistors the type whose main parameters correspond to restriction (3) and then to apply expression (2) to determine the value of the capacitor capacitance that shunts the VR.

2. The parameters are determined to calculate the VR operation, provided that the deviation in the parameters U_c, R_d and R_b is within the range of ±5 %, and $R_b \approx R_d$.

3. Expression (7) helps to determine $I_{c.max} \leq I_{c.adm.}$ (for the varistor CH2-2 $I_{c.adm} \leq 120$ A, $W_{c.adm} \leq 150$ J).

4. Expression (6) on the basis of the known $I_{c.max}$ and I_{SI} helps to find out the number of the parallel-connected varistors n; the n is rounded up to the next whole number. The values of $I_{c.max}$ and $U_{v.max}$ are specified.

5. Expressions (8)–(10) determine the time of the current flow through the varistor (the decline time) t_d.

6. Expression (11) determines the maximum energy released in the varistor.

7. If at least one of the varistor parameters does not meet the accepted restrictions, the calculation is repeated until all varistor settings satisfy the specified restrictions (3) and (7).

Below are the results of calculations on a varistor VR and the switching surges determined by the developed method for the case of using the specified VR in hybrid DC contactors for a voltage of 220 V, which are the most common power switching SA.

Calculations were made in an environment Mathcad on the basis of such output data: $I_{nom.r.} = 0.6 I_{nom.}$, $I_{nom.} = 4 I_{nom.r.}$ (the maximum current switched by the device in the mode of rare switching), and $I_{scmax} = 10$ kA. In this case, the basic voltage regulating element of the VR is the varistor of the type CH2-2, 330 V.

Table 1 contains the basic calculation parameters for this type of the VR.

The analysis of the calculation parameters listed in Table 1 shows that the use of inexpensive and compact energy-intensive varistors CH2-2 in creating a VR can limit the level of switching surges to below 2.5 U_{nom} while using hybrid DC contactors to switch boundary currents that are equal to 4 $I_{nom.\ r.}$. In this case, even in the loaded contactor (with the effect of the stored circuit energy on the VR) when $I_{nom} = 630$ A, the maximum energy released in the loaded varistor is three times less than the admissible level, and the weight of the components that are part of the VR is less than 0.1 kg at their price of about 10 USD [4].

Table 1

The main calculation parameters of the VR

The nominal contractor current I_{nom}, A	The number of the parallel varistors enable, items	The maximum current of the varistor $I_{c.\ max}$, A	The duration of the current flow through the varistor t_d, ms	The maximum switching surge $\frac{U_{v\max}}{U_{nom}}$	The energy in the varistor		C, µF	R_b, Om
					$W_{c.min}$, J	$W_{c.max}$, J		
100	3	103.60	0.32	2.22	3.71	6.94	1.0	0.68
160	5	105.32	0.50	2.23	6.33	11.56	1.6	
250	7	117.21	0.75	2.30	11.38	19.43	2.2	
400	12	113.37	1.20	2.07	17.90	30.97	3.0	
630	18	118.81	1.85	2.31	29.90	50.34	3.9	

In comparison, for example, in the previously developed hybrid contactor KP81-39 (I_{nom}=630 A), the resistive-capacitive VR has 14 enabled parallel capacitors of the type K75-17 (1000 V, 50 µF, and the weight of 1.25 kg) [1]. Accordingly, the weight of the VR is at least 17.5 kg, which is much bigger than the considered varistor VR. It should be added that the level of restricting voltage surges by this VR amounts to 4.5 U_{nom}, which means that it exceeds the admissible level for the existing switching devices.

Certainly, a varistor VR can be based not only on varistors CH2-2; varistors of other types and companies can be used if they comply with the requirements (2.24): for example, promising in this regard are the varistor types SKP6.5.110SA and BYZ50A22.50K39 produced by Semicron. Since they are designed for $U_{cl} = 6.5-110$ V, they should be enabled in the VR as in a parallel series connection, and the varistor, operating in the most adverse working conditions, must conform to the restrictions (3).

6. Analysis of the research results on switching surges in power SA of the direct current

The main advantage of the study is that it has resulted in developing an engineering method of calculating the parameters of varistor voltage regulators for hybrid and contactless SA of the direct current at a given for this class of devices admissible surge levels. It should also be noted that the results of this study, as well as previous studies of the thermal mode of power circuits working in SA [19], facilitate high accuracy at a small amount of time in choosing fully controlled STs with regard to the current and voltage when designing modern switching SA that work with the direct current. This helps solve the basic tasks of planning.

However, the research findings concern only low-voltage SA (up to 1000 V), so it is difficult to extrapolate them onto SA that are designed for higher voltage, which have been made possible with the development of high-voltage STs based on silicon carbide [8]. It is expedient to continue research on this issue in order to eliminate this shortcoming.

The practical recommendations arising from the results of this study and the suggested calculation methods are being used by the joint stock company ENAS, Kharkiv, Ukraine, to modernize hybrid DC contactors of the KP81 series so that the size and cost can be significantly reduced. This study refers to the stage of developing design documentation.

7. Conclusion

1. The suggested VR with a series of parallel-connected varistors is a highly reliable device that effectively limits switching surges in the circuits of power SA of the direct current to below 2.5 U_{nom}. It significantly surpasses such parameters as the dimensions, weight and cost of resistive-capacitive surge limiters previously used in semiconductor contactors. Moreover, it can reduce the class level of fully controlled PSDs that are used in switches of semiconductor devices for the voltage of 220 V from class 10, previously common, down to class 6.

2. An engineering method has been developed to calculate the VR parameters of a parallel-connected series of varistors. Unlike the previously researched cases, the present study has considered calculation for only the worst case of distributing varistors on the branches with various deviations of their parameters from the nominal ones. This allows creating VRs on the basis of quite simple calculations to provide a suitable level of switching surges in SA of the direct current at different operation modes, which is quite useful for technical professionals.

3. The method of calculation that has been developed in the study can be further used in calculating surges in fully controlled PSDs that work in an impulse mode within power electronic devices.

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