Contacting Stability of Sliding Electrical Contacts

Igor Plokhov[1,*], *Igor* Savraev[1], *Alexander* Ilyin[1], *Oksana* Kozyreva[1], *and Sergei* Loginov[1]

[1]Department of Electric Power Engineering, Electric Drive and Automation Systems, Pskov State University, 180000 Pskov, Lenin Square, 2, Russia

Abstract. It is stated that the operation of the sliding contact unit is accompanied by vibrations of the brushes that occur as a result of internal and external mechanical influences. The resulting violations of the sliding contact (SC) and the instability of contacting lead to a deterioration in the quality of current transmission, increased sparking, accelerated wear of the SC. The article is devoted to the derivation and verification of universal formulas for calculating the relative instability factor (RIF) of the SC. Derived formulas allow calculating the RIF of any SC compounds. Mathematical expressions are obtained to determine the distributions of instability in the tangential and axial directions of the transition layer of the SC. An experimental stand for studying the instability of various SC compounds at idle and in the rated load mode is described. The contacting cycle, which establishes a correspondence between the instantaneous value of the length of the measuring platform and the movement of the collector is described. Expressions for determining the equivalent length of the measuring area for different cases of placing the measuring brush relative to the zone of the main sliding contact are derived. These formulas allow us to find the RIF of various SC regions on experimental data based.

1 Introduction

Sliding electrical contacts are used widely in electrical machines of various types as part of sliding contact unit (SCU). We will further consider the operation of SCU with slip rings, which are equipped, for example, with turbogenerators (TG). Nowadays despite the use of contactless current transmission SCU, consisting of slip rings and brushes sliding along them, are widely used. Such nodes are used [1]:

- in turbo- and hydrogenerators,
- in synchronous motors and DC motors,
- in asynchronous motors with a wound rotor;
- in urban railway transport (electric locomotives, electric rolling stock of the subway, electric trains);
- in the anti-icing system of helicopter rotor blades;
- in power plants of sea vessels.

In synchronous turbo- and hydrogenerators, SCU are used to supply direct current to the field winding, as well as for other purposes. The current supply system to the exciting winding of the turbogenerator is carried out through a sliding contact formed by brushes located on a stationary brush crosshead and two slip rings fixed on a rotating rotor [2]. The rings operate at high angular speeds, so the material for them is high-strength structural steel. For modern turbogenerators with excitation currents of 3500–5000 A the permissible current density under the brushes is 8–9 A/cm2. The dimensions of the slip rings are 450–500 mm in diameter and 150–200 mm in width [3], the number of SCU of TG brushes can reach several hundred.

The work of the SCU is accompanied by mechanical vibrations of the brushes arising from their interaction with the moving irregularities of the contact surface. This causes dynamic efforts reaching values at which contact disturbances with short-term no-current pauses are observed [4–7]. The quality contacting of SC is evaluated by measuring of RIF [2, 8]. As a result of unstable contacting short-term violations of electrical contact occur. It breaks the power electrical circuit of SCU. This leads to sparking in the transition layer of SC, especially at the running edge of the brush. Sparking causes increased wear of the contacting surfaces, overheating of the SC, in some cases it can lead to an all-round fire in the SCU and the failure of the entire electrical machine. For collector electric machines, the main cause of sparking is the commutation process. For brush apparatus with slip rings (SR) the reasons for sparking have not been satisfactorily explained until recently. At present it is established that the main cause of sparking in the SCU with SR is the mechanical instability of the contact. As a result breaks of the power current of the brushes lead to the occurrence of parametric electromagnetic oscillations of high amplitude and frequency in the resonant electromagnetic circuits of SCU.

Analysing processes in the SCU of turbogenerators there is no problem of ensuring sparkless commutation of windings, however the problem of ensuring reliable current collection on slip rings of turbo generators is no less complicated than the problem of providing sparkless commutation of DC machines. It is much more difficult to ensure the mechanical stability of the brush contact

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[*] Corresponding author: igor_plohov@list.ru

when working with turbogenerators. The main material of the collectors is copper or its alloys, while for the slip rings it is necessary to use steel, which has the worst contact properties. The peripheral speed on the working surface of slip rings due to the large diameters of the rings is 70–90 m/s. Therefore, ensuring the stability of current transmission in the SCU of turbogenerators is a very important and difficult task. This implies the relevance of work on the research of the mechanics of contact interaction in the SCU.

2 Relative instability factor

The work of sliding contact unit is accompanied by mechanical vibrations of the brushes resulting from their interaction with the contact surface. The presence of irregularities on the surface causes dynamic forces reaching values at which disturbance of contact with short pauses, during which there is no current, are observed [9–15]. This causes parametric instability of the brush-contact. In this case, there is a parametric instability of the brush-contact device [4, 9, 16–20].

The quality of contacting is evaluated traditionally by measuring of relative instability factor [7, 14]:

$$K = \frac{1}{T}\sum_{i=1}^{n} \Delta\tau_i \tag{1}$$

where τ_i is the duration of the i-th interval of time of disturbance of contact, T is the total measurement time,

$$T = \sum_{i=1}^{n} \Delta\tau_i + \sum_{j=1}^{m} \Delta t_j \tag{2}$$

where $\Delta\tau_i$ is the duration of the j-th interval of time of stable contact.

We introduce the random event A, which consists in the disturbance of contact during an infinitely small interval of time $d\tau$, then

$$K = n/N \tag{3}$$

where n is the number of elementary disturbances of contact; $N = n + m$ is the total number of elementary acts of contacting; m is the number of acts of successful contacting.

Thus we represent the relative instability factor as the probability of disturbances of contact during the electro-frictional interaction [20]

$$K = P(A) = \lim_{N\to\infty}\left(\frac{n}{N}\right) \tag{4}$$

We define by the methods of the probability theory of the RIF of various connections of sliding electrical contacts under the condition of mutual independence of random events A_j consisting in an elementary disturbances of the j-th sliding contact. In parallel connection, the break of the electrical circuit occurs when the contact is disturbed in all parallel branches. Therefore, the RIF of the group M of parallel connected contacts K_{DIZ} is defined as follows:

$$K_{DIZ} = P\left(\prod_{j=1}^{M} A_j\right) = \prod_{j=1}^{M} P(A_j) = \prod_{j=1}^{M} K_j \tag{5}$$

where K_j is the relative instability factor of the j-th sliding contact; M is the number of sliding contact.

For the serial connection of sliding contact we get

$$K_{KON} = 1 - P\left(\prod_{j=1}^{M} \overline{A}\right) = 1 - \prod_{j=1}^{M}\left[1 - P(A_j)\right] \tag{6}$$

$$K_{KON} = 1 - \prod_{j=1}^{M}\left(1 - K_j\right) \tag{7}$$

Equations (5, 7) allow to get the formulas for any combined connections of the sliding contacts. However, more often there is a need to determine the individual RIF indirectly through the instability of readily available combined connections. This corresponds to the solution of the inverse problem. To do this, we compose the following system of linear equations

$$K_j = \frac{K_{1,j} - K_1}{1 - K_1} \tag{8}$$

where K_j is the sought for RIF; K_1 is the measured RIF of the 1st sliding contact; $K_{1,j}$ is the RIF of the serial connection of the 1st and j-th sliding contact.

In parallel connection of contacts, we take the probability of simultaneous occurrence of events A_j for the number of brushes $S \geq N$ as a generalized criterion of instability of contacting of the whole set of brushes.

The probability of the event B consisting in synchronous separation of S brushes from N:

$$P(B) = \frac{N! \cdot k^S \cdot (1-k)^{N-S}}{S! \cdot (N-S)!} \cdot 100\,\% \tag{9}$$

where k is the average value of RIF of the contacting of the individual brush.

The probability P_S of a contact disturbance of at least S brushes from N we find by determining the sum of the probabilities $P(B)$ on the set $S \subseteq N$:

$$P_S = 100\,\% \cdot \sum_{i=S}^{N} \frac{N! \cdot k^i \cdot (1-k)^{N-i}}{i! \cdot (N-i)!}. \tag{10}$$

We call the value of $P(B)$ sectional instability factor (SIF), and the value P_S is operational instability factor (OIF) of contacting of the sliding contact unit. We denote: $P(B) = K_G$, $P_S = K_O$. We represent the formulas K_G and K_O in relative units

$$K_G(S^*) = \frac{N! \cdot k^{S^*N} \cdot (1-k)^{N(1-S^*)}}{S^* \cdot N! \cdot Int!\left[(1-S^*) \cdot N\right]} \cdot 100\,\% \qquad (11)$$

$$K_O(S^*) = 100\,\% \cdot \sum_{i=Int(100s^*)}^{100} \frac{100N!k^{\frac{i}{100}}(1-k)^{N(1-\frac{i}{100})}}{i\,N!\,Int!\left[(1-\frac{i}{100})N\right]} \qquad (12)$$

where $S^* = S/N$ is the relative number of brushes in the group with disturbance contact.

In the process of experimental studies two more practically valuable quality factors of brush contacting were identified [14].

1) Current transmission instability factor (CIF)

$$K_{CIF} = \frac{1}{T}\sum_{i=1}^{n} \Delta\tau_i\,, \qquad (13)$$

where $\Delta\tau_i$ is the period of the termination of the power current flow through the sliding contact.

Similarly to RIF, CIF is the probability of the termination of the power current flow through the sliding contact for $n \to \infty$.

2) Brush current ripple factor (CRF)

$$K_{CRF} = \frac{I_{\approx}}{I_{=}} 100\,\%\,, \qquad (14)$$

where $I_{\approx}, I_{=}$ is variable and constant brush current components.

These indicators make it possible to evaluate the quality of the sliding contact by the stability criterion in real operating modes of the sliding contact block. This distinguishes K_{CIF} and K_{CRF} from RIF, SIF and OIF which have been introduced for evaluating the mechanical stability of brush contacting without taking into account the processes of forming the contact layer conductivity.

3 Dynamics and topology of contact instability

Let the contact surface of the current collector (of SCU) consists of n sections of different lengths Δl_i and the periods of time of moving under the brush are set as Δt_i. Then RIF for the separate section of sliding $K_i = \Delta\tau_i / \Delta t_i$, where $\Delta\tau_i$ is the time interval of the absence of the contact at the period of moving the section Δl_i during Δt_i.

RIF defined for the period of time $T = \sum\limits_{i=1}^{n} \Delta t_i$ is calculated as:

$$K = \frac{1}{T}\sum_{i=1}^{n} \Delta\tau_i = \frac{1}{T}\sum_{i=1}^{n}\sum_{j=1}^{m_i} \Delta\tau_j\,,\ \Delta\tau_i = \sum_{j=1}^{m_i} \Delta\tau_j \qquad (15)$$

$$K = \frac{1}{T}\sum_{i=1}^{n}\frac{1}{\Delta t_i}\sum_{j=1}^{m_i} \Delta t_i \Delta\tau_j = \frac{1}{T}\sum_{i=1}^{n}\frac{\Delta\tau_i}{\Delta t_i} = \frac{1}{T}\sum_{i}^{n} K_i \Delta t_i \qquad (16)$$

where T is the measurement period of instability of the sliding contact; m_i is the number of contact losses occasions during the period of time Δt_i; $\Delta\tau_i$ is the time interval of the j-th absence of the contact at the period of moving the i-th section ($j = 1 \ldots m_i$)

$$K = \frac{1}{L}\sum_{i=1}^{N} K_i \Delta l_i\,, \qquad (17)$$

where $L = \sum\limits_{i=1}^{N} \Delta l_i$ is the total path length of the brush during the period of time T.

Since different brushes contact with different degree of instability it may be said that there is a distribution of instability in the SCU in tangential and axial directions. The tangential distribution is caused mainly by the different settings of the brush holders and the variation in the mechanical properties of the brushes, and therefore it is random. The axial distribution is caused also by the different quality of the contact surface and may be regular.

According to the experimental studies the instability of contacting is different in the different sections of the sliding contact. Consequently there is a distribution of RIF under the brush surface, and this distribution is two-dimensional and continuous.

Let the sliding contact surface consists of m equally small sections, provided that the instability is equally distributed over the contact area. Accepting RIF of the sections given K_Δ equal, one may present the sliding contact of sections S_1 and S_2 as a parallel connection of n_1 and n_2 elementary contacts accordingly. For the sections given in accordance with (5):

$$K_{S_1} = K_\Delta^{n_1}, \quad K_{S_2} = K_\Delta^{n_2}, \qquad (18)$$

where K_{S_1}, K_{S_2} are RIF of the sliding contact sections having surface areas S_1 and S_2 accordingly.

It follows from the system of equations (18) that:

$$K_{S_1}^{1/n_1} = K_{S_2}^{1/n_2}, \quad K_{S_2} = K_{S_1}^{n_2/n_1}, \qquad (19)$$

As the sizes of the sections ΔS are small enough, one may turn to considering the surface areas S_1 and S_2 instead of considering the number of sections:

$$\frac{n_1}{n_2} = \frac{S_1}{S_2}, \qquad K_{S_2} = K_{S_1}^{S_2/S_1}. \qquad (20)$$

Thus mathematical expressions for determining the main indicators by calculation have been derived. The indicators given describe the stability of contacting and current transmission in the sliding contact unit. Brief comments for the formulas are given in the table 1.

Table 1. Mathematical expressions for determining the main indicators of SC.

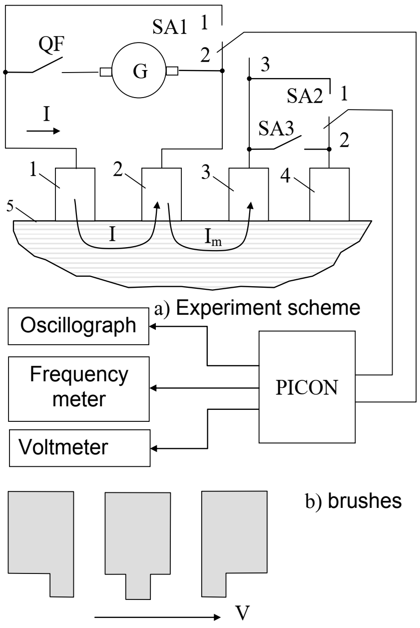
№	Formula	Name	Functiona-lity
1	2	3	4
1.	$K_{DIZ} = \prod_{j=1}^{M} K_j$	RIF of parallel SC	For practical evaluation CRI of parallel brush groups
2.	$K_{KON} = 1 - \prod_{j=1}^{M} (1 - K_j)$	RIF of series SC	For evaluation RIF of series brush groups
3.	$K_j = \frac{K_{1,j} - K_1}{1 - K_1}$	RIF of single SC	For evaluation RIF of single brush using CRI of other brushes
4.	$P(B) = \frac{N! \cdot k^S \cdot (1-k)^{N-S}}{S! \cdot (N-S)!}$	Sectional instability factor (SIF)	For general estimating quality of parallel brushes contact
5.	$P_S = 100 \cdot \sum_{i=S}^{N} \frac{N! \cdot k^i \cdot (1-k)^{N-i}}{i! \cdot (N-i)!}$	Operatio-nal instability factor (OIF)	For general estimating quality of brush contacts
6.	$K_{CIF} = \frac{1}{T} \sum_{i=1}^{n} \Delta \tau_i$	Current transmis-sion instability factor (CTIF)	For experimental studies of sliding contact gears
7.	$K_{CRF} = \frac{I_{\approx}}{I_{=}}$	Brush current ripple factor (CRF)	For practical evaluation of RIF and CIF of electrical machine
8.	$K = \frac{1}{T} \sum_{i=1}^{N} K_i \Delta t_i$	RIF of sliding contact for a cycle. Cycle RIF	For calculation of cycle RIF using known RIF of the intervals
9.	$K_{S_2} = K_{S_1}^{S_2 / S_1}$	RIF of single pad	For calculation RIF of the contact pad using RIF of other contact pad

The instability of the contact interaction of brushes leads to the electromagnetic transient processes in the electrodynamic system of "brush-contact surface", as well as in the power circuits of the group sliding contact. These processes can take a resonant behavior, intensifying the arcing and being the cause of the "breakdown of commutation" on the contact rings of turbogenerators.

4 Experimental studies of electrical brushes contact instability

The aim of the experiments was to test the theory based on the concept of the statistical nature of RIF, as well as to study the distribution of instability over the brush width and the influence of various factors on RIF.

The experiments were carried out on a stand containing two power units with DC generators (I_{nom} = 90 and 450 A) and a pilot plant designed and manufactured at "AO Electrosila" (now "Power Machines"). The unit is a collector (diameter 500 mm) with electrically unbound segments, placed on bearings in a steel housing. In the body is fixed insulated brush traverse with brush holders. The collector shaft is connected to the DC motor, which is connected to the generator by the Ward-Leonard drive system. The stand allows smoothly adjust the engine speed and power current through the brushes of the pilot plant.



a) Experiment scheme

b) brushes

Fig. 1. Experimental studies of the contact stability.

Fig. 1a shows the scheme of experimental studies. On the brush traverse of the plant, four isolated brush holders are fixed, in which the test brushes 1, 2 and measuring brushes 3, 4 with a reduced contact pad are placed, pressed against the collector 5. There are two sets of measuring brushes (Fig. 1b): a pair of brushes with a contact pad on the leading edge of the test brush and two other pairs with contact pads on the trailing edge and in the middle. For a specific test, the brush holders are equipped with a pair of identical brushes 3, 4, which allows to measure the CRI in a given zone of sliding contact of the tested brushes. The DC generator G is connected to the brushes by a QF switch. The SA1 switch is intended for connection of the PICON device (for measuring of the relative instability factor of brushes) either to one, or to other tested brushes, and also to measuring. The SA2 switch is designed to connect the instrument to different measuring brushes. The SA3 switch allows the measuring brushes to be connected in parallel.

Before carrying out the main measurements, we check the RIF of the serial connection of the brushes 3, 4, achieving stable (continuous) operation in the full frequency range of the collector (SA1 in position 3, SA2 in position 2). Then SA1 is switched to position 1 or 2 and SA3 is closed, which further reduces the probability of accidental contact losses of the SC.

Using the oscillograph, we control the signal waveform of the voltage on the brushes and the packets of filling pulses at the output of the logic block of the PIKON device. Using the frequency meter we control the correctness of the decimal counter and produce a refined determination of the number of pulses filling the clock generator at the output of the logic block. Using the voltmeter, we adjust the device to a given value of the comparator offset voltage and the voltage of the internal source.

Commutator 1 with electrically unbound commutator segments (Fig. 1) and measuring brushes are used in experimental investigation of relative instability factor RIF in different zones of sliding contact. Measuring brushes should be installed on the side of diagnosable brush 2, first of all, on the leading edge, then under the middle, and only then on the trailing edge. On Fig. 1 measuring brush 3 is situated on the side of leading edge of the diagnosable brush 2.

To calculate RIF of local zones of sliding contact one should define equivalent length of measuring square per contacting cycle. Let us assume that contact between measuring brush and commutator is stable ($K = 0$). At start connection between main brush and measuring brush is carried out by commutator segment 1, so RIF of square of commutator segment 1 with length l_L and contact surface of brush 2 should be calculated. Then commutator segment 2 starts to contact with brushes 2 and 3, and while commutator move over a distance of l_L increasing of commutator segment's length, enveloped with measurement from l_L to $l_L + l_2$ takes place. Then commutator segment 1 is losing it's contact with measuring brush and square's length decreasing to l_2 step-wise. After this moment length of measuring square linearly increasing to l_L while commutator segment 2 is moving under the leading edge of the brushes, and then it remains constant while commutator is moving over a distance of l_P. This process has a cyclical pattern, where X is the commutator shift, l is the tangential size of measuring square.

Equivalent length of measuring square in a single cycle:

$$l_{e\_inc} \cdot t_k = \frac{2 \cdot l_L + l_2}{2} \cdot l_2 - \frac{l_2 + l_L}{2} \cdot (l_L - l_2) + l_L l_P, \quad (21)$$

$$l_{e\_inc} = \frac{l_{L2}}{t_k}\left(l_M + \frac{l_L}{2}\right). \quad (22)$$

Equivalent square l_{e_inc} for trailing edge is defined likewise, and for same with l_M for leading and trailing edge measuring current of measuring brushes will be:

$$l_{e\_inc} = l_{e\_esc} \quad (23)$$

Let's deduce mathematical expression for measuring square's equivalent length calculation when measuring brush installed symmetrically in the middle of contact zone.

Main diagnosable brush 1 and measuring brush 2, which pinned to commutator 3, that moves with velocity V are schematically illustrated on Fig. 2. Typical positions of commutator, that register borders of the basic phases of contacting cycle between main brush and measuring brush through commutator segments are shown on this picture.

Contacting cycle that set up correspondence between instantaneous length of measuring square l and commutator shift X is illustrated in Fig. 3. Let's deduce mathematical expression for measuring square's equivalent length l_{e_mid} the case when measuring brush installed in the middle of the zone of main sliding contact.

$$l_{e\_mid} = \frac{1}{t_k} \cdot \begin{pmatrix} \frac{1}{2} \cdot \left(3 \cdot l_L + \frac{l_b - l_м}{2}\right) \times \\ \times \left(l_L - l_n + l_м - \frac{l_b}{2}\right) + \\ + l_L \cdot \left(\frac{l_b}{2} - l_м\right) + 3 \cdot l_L \cdot l_n \end{pmatrix} \quad (24)$$

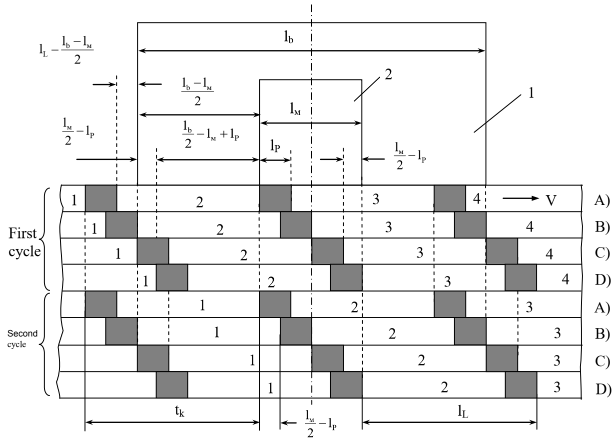


Fig. 2. Schema to contacting of a brushes.

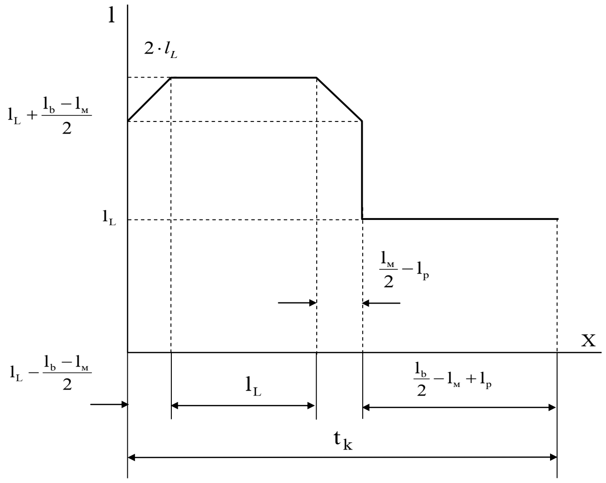


Fig. 3. Contact cycle for the middle position of the measuring brush.

Formulas (21) and (24) helps to calculate CRI of different zones of sliding contact with the use of experimental data. They were used for experimental testing of theoretical expressions, that link space and time relationship of contacting instability.

5 Conclusions

Maksym, as a national Kyrgyz and Kazakh drink, is Formulas for determining the relative instability factor of contact of various compounds and areas of sliding electrical contact are derived from experimental data. Experimental verification established the validity of theoretical expressions establishing the spatial and temporal relationship of contact instabilities.

Practical methods for determining the relative instability factor of contact of various connections and areas of sliding electrical contact, designed for use in the diagnosis of sliding contact units of electrical machines and apparatus.

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