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RESEARCH

A Method of Assessing the Service Life and Reliability of Motor Brushes Based on Wear Under Variable Current and Environmental Conditions

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A B S T R A C T

Wear behaviour determines the service life and reliability of the motor's commutator and Brush, including mechanical and electrical wear. The temperature and relative humidity, especially humid tropical climate conditions, significantly affect the wear behaviour of commutator brushes. The traditional life tests are often manual and time-consuming due to a long expected life. This paper presents study results on the service life and reliability of graphite brushes when the temperature, relative humidity, and current change. The calculation method of service life and reliability depending on wear testing was used to evaluate the service life characteristics. The experimental results, service life, and reliability calculations showed that the service life and reliability of the graphite brushes were influenced clearly by current, temperature, relative humidity, and the probability of failure-free operation. It depends on the current more than relative humidity and temperature. In the range of changing current in this study, the service life: $T_P(99\%) \sim 0.54*T_P(50\%)$, $T_P(95\%) \sim 0.62*T_P(50\%)$, and $T_P(90\%) \sim 0.68*T_P(50\%)$.

1. INTRODUCTION

The service life and reliability of commutators and brushes have an important influence on the performance of electric motors. The tropical monsoon climate has high relative humidity (RH) and the average temperature (T) is from 15^0C to ~ 49^0C, with marked seasonal variations [1]. It influenced of wear of the commutator-brushes pairs of the motor. Therefore, the electrical sliding contact between the commutator and brushes is degraded in quality when the motor works in humid tropical climates. The service life and reliability of the electric motor are also the life and reliability of the carbon copper or graphite copper material pair in the commutator and brush pair. The wear surfaces of the commutator and brush pair can be the third layer in tribology. It consists of an oxide layer, a mix of brush and copper elements, or a wet film.

It's changed very much under the influence of a humid tropical climate. The third object was directly influenced by wear and was born friction. Many studies indicated [2-4] a mechanism for forming a layer (third object) between the moving objects. It was a new method of wear prediction and analysis of the properties of sliding contact between commutator brush surfaces of the electrical motor. According to many studies [5–8], the commutator and brush pair was also the mechanism of third object wear in tribology. Vera Deeva et al. have analyzed the third layer model and stochastic simulations. It has explained the causes of non-equilibrium behavior and the correlation parameters of sliding contact [9]. Duffy O et al. indicated shown that the electro-mechanical contact between the brush and the slip-ring influence the lifetime of alternators [10]. Slade P. found that the electro-mechanical contact of the slip-ring and brush depended on the graphite brush dynamics: The rotational speed, the vibrations, the spring force, the friction coefficient, the wear rate, the current density, and the ambient parameters (including temperature and humidity) [11]. Senouci et al. studied the wear mechanisms of electrical sliding contacts of graphite brush on copper. They found that the wear behavior can be correlated with the surface morphology of the graphite orientation in the contact [12]. Wae-Gyeong Shin et al. have studied the wear characteristic of copper-graphite brushes pairs in a small brush-type DC motor. They found that: the sliding speed and contact pressure of graphite brush depend on current density, and the brush wears greatly varied with current density. The Joule heating was added because the current increased in voltage drops [13]. Many studies found that thermal field arcing, and electrical discharge affect the wear rate of graphite brush surfaces. Electrical wear for about 1/2 to 2/3 of the total wear of the brushes [14-20].

When conducting a study on copper-graphite composites in reciprocating sliding against copper with current density M. Grandin et al. found that the friction coefficient was higher, and the wear rate was lower. The wear rate reduces due to the increase of metal amount in the graphite composite [21]. Jau-Wen Lin et al. studied the contact friction temperature of a carbon graphite brush, which slides over a copper ring without current. The study result showed a relationship between friction, temperature, and wear rate. The debris of wear particles softens under high temperatures, it adheres and forms flattened regions [22]. Wae-Gyeong Shin et al. indicated that changing temperature and the direction of current flow at the brush contact site affect the brush wear. It tends to increase rapidly because the temperature rises with the current. The contact resistance and voltage drop in the contact site lead to temperature changes. [23]. When the electric current increase, the friction coefficient increases and makes the wear of the friction pair will be aggravated [24, 25]. Slavicˇ et al. studied the effect of brush stiffness on brush wear and studied the dynamic stability of an electrical motor's Brush using numerical simulations [26]. Slavicˇ J et al. have studied a wear model on the local loss of mechanical energy under dynamic loads. The result has shown the dynamic relationship of the brush with the rough contact surface and determined the coefficient of friction for different temperatures and currents [27,28]. Alesˇ Turel et al, have studied the wear and contact resistance of sliding contacts and are typically researched with a pin-on-disk experiment that prevents dynamic excitation. They showed that: The contact resistance decreased with an increased ambient temperature, electrical current, and rotating speed, whereas the wear rate increased with the rotating speed at low current density and low ambient temperature [29]. Du Sanming et al, showed that the wear rate of copper-graphite composite increases in the high-speed dry sliding against GCr15 steel while increasing current [30]. Hao Zhao found that: contact voltage drop and wear rate augment while current density increases; The wear rate first reduces then increases while the contact pressure rises; The lubricating film on the contact surfaces depended on the test conditional, it improves the tribological characteristics of the sliding pair [31]. AlesˇTurel et al, [32] have studied the electrical contact resistance and wear of a dynamically excited metal–graphite brush and showed that contact resistance decreased with an increased ambient temperature, electrical current, and rotating speed. In contrast, the wear rate increased with the rotating speed at low current density and low ambient temperature. Nguyen Anh Tuan et al. have researched the effect of the Vietnam climate on the wear of the material pair. The result shows that the amount of wear varies depending on the change in the relative humidity, and the wear amount increases rapidly as the relative humidity increases [33]. Z.L. Hu et al. found that the thickness of the oxide layer and the wear rate on the sliding surface of brushes increases with current density. The wear rate of the brush decrease when humidity increases by 10-50%. This can be explained by the oxide film's ability to act as a lubricant [34]. The specific wear rate (Ws) of the brush in the motor increase when relative humidity, temperature, and the current increase has been studied by Hung et al [35, 36]. Fakih and Dienwiebel found that forming a thick layer on the commutator and the brush surface was the main reason for the motor's failure [37]. Barnawi et al. have studied the contact resistance of sliding contact. The results showed that the wear rate increased when the atmospheric temperature decreased. The contact-voltage drop is reduced when ambient temperatures increase [38]. Shin and Lee proposed the reliability analysis of small DC motors for automobiles with accelerated life testing. The application of the inverse-power law model indicates its main failure mechanism—performance degradation by graphite brush wearing out. The accelerated Shin and Lee have studied the reliability analysis of small DC motors with accelerated life testing. The result show that indicates its main failure mechanism—is performance degradation by graphite brush wearing out. The accelerated destructive degradation test (ADDT) is a method for making reliable inferences and predictions of products with limited testing times and resources [39]. Chinuk Lee et al proposed the step-by-step procedure of an ADDT analysis for the return springs in a bi-functional DC motor system in this work. They only considered one degradation mechanism. However, there may be more than one degradation mechanism, which can cause the observations to be right-censored [40].

Research on the wear characteristic, service life, and reliability of the commutator brush pairs has been mentioned through many studies. The result shows that brush lifetime and reliability depend on the main factors velocity, spring pressure, current density, temperature, material properties, and environmental conditions. Not many studies were realized about the influence of temperature and relative humidity environments on brush wear, life, and reliability. There are several studies on the influence of the environment on the wear of carbon brushes, which can be mentioned [34, 35, 36]. Some studies about the service life, reliability calculation, and the accelerated destructive degradation test were realized.

This paper presents a method of assessing motor brushes' service life and reliability based on wear under variable current and environmental conditions. This method is based on rapid experimental results of graphite brush wear under varying currents, temperatures and relative humidity conditions.

2. METHOD AND EXPERIMENTAL

2.1 Calculation of service life, reliability of motor brushes on a wear amount basis

The calculated scheme of service life and reliability dependent on wear amount is shown in Fig 1.

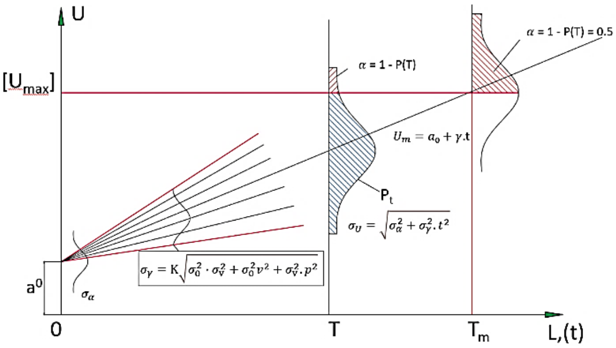


Fig. 1. The calculated scheme of service life and reliability is dependent on wear amount [41]

The average wear rate of graphite brush γ_{mu} can be determined experimentally or calculated using the formula:

$$\gamma_{mu} = k_J . p_m . v_m \rightarrow \gamma_{mu} = k . p_m . n_m \quad (1)$$

where:

p_m – Average load,

v_m – Average speed,

n_m – Average rotational speed,

k_j – and k are the coefficients that can be determined experimentally.

The wear amount of graphite brush U over time (t). It is assumed to obey the linear law and is expressed by the following equation:

$$U_m = a_{ou} + \gamma_{mu} . t \quad (2)$$

where:

U_m- Average wear amount of graphite brush over time,

a_{ou} – Initial wear amount of graphite brush, Under normal operating conditions, it can be assumed that the load P and the speed *v* are two random variables with standard deviations σ_p (N) and σ_v (m/s). Thus, the average wear rate is also a random variable that obeys the law of large numbers, which has an expected and standard deviation of with the density function f(γ) calculated by the formula:

$$f(\gamma) = \frac{1}{\sigma_\gamma \sqrt{2\pi}} exp\left\{-\frac{[\gamma - \gamma_{mu}]^2}{2{\sigma_\gamma}^2}\right\} \qquad (3)$$

where:

$$\sigma_\gamma = \sqrt{D(kpn)} = k\sqrt{\sigma_p^2\sigma_n^2 + \sigma_p^2 n_m^2 + \sigma_n^2 p_m^2} \qquad (4)$$

$$\gamma_{mu} = \frac{U_m}{T} \qquad (5)$$

T - expected lifespan,

D - variance.

The standard deviation of Um is calculated:

$$\sigma_u = \sqrt{\sigma_{aou}^2 + \sigma_\gamma^2 T^2} \qquad (6)$$

The probability of failure-free operation of the graphite brush P(t) is calculated according to wear amount U, at the time t = T. It corresponds to the area under the probability density curve of U: f(U) and lies in the interval $a_{ou} \leq U \leq [U]$ (Figure 1). The probability of working without failure P(t) – characterizing the ability to work continuously, is calculated through the Laplace operator [41] as follows:

$$P(t) = 0{,}5 + \phi\left[\frac{[U] - a_{0u} - \gamma_{mu}.T}{\sqrt{\sigma_{aou}^2 + \sigma_\gamma^2 T^2}}\right] \qquad (7)$$

Where:

Φ – Laplace operator,

σ_{aou} – Standard deviation of initial wear amount,

σ_γ - Standard deviation of wear rate,

[U] – allowable limit wear amount.

The life equation T depends on the reliability based on wear amount will be:

$$U_\alpha\left(\sqrt{\sigma_{aou}^2 + \sigma_\gamma^2.T^2}\right) = [U] - a_{ou} - \gamma_{mu}.T \qquad (8)$$

where:

[U] – Allowable limit wear amount,

Uα – The argument of the Laplace function, whose value depends on the confidence P(t).

Equation (8) in principle, has two solutions T_{1u} and T_{2u}, but the confidence level of 50% is the smallest, so the solution of this equation must be in the range $T_r < T < T_m$. The average lifetime Tm of the graphite brush, when the allowable limit wear amount is [U], will be determined by the formula:

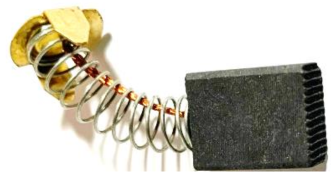
$$T_m = \frac{[U] - a_{ou}}{\gamma_{mu}} \qquad (9)$$

In this study, the average wear rate of graphite brush γ_{mu} was determined from these experiments.

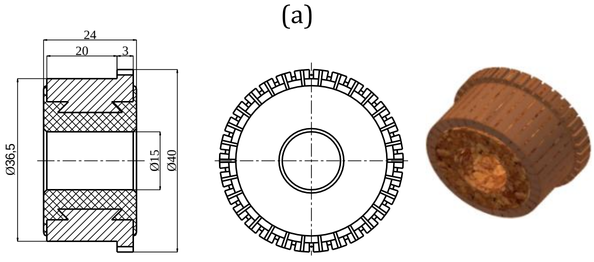
2.2. Materials

Fig. 2a depicts the size of the graphite brush. Its dimensions are 13.8mm, 6.8mm, and 17.8mm (width, height and length, respectively), and the contact surface is somewhat curved. 72% flake graphite, 8% carbon black, and 20% pitch make up the electrographite brushes' composition. At 2200°C, they were graphitized.

The cylindrical rotating body of the copper commutator depicted in Fig. 2b is made up of 32 bars, each measuring 36.5 mm in diameter and 24 mm in length. The copper substance is made up of 99% Cu and 0.1% impurities. The average roughness (Ra) value of the copper commutator is around 0.16 μm, and its micro-hardness is 130 HV. The brushes used in DC motors are usually the equivalent of 417A type.



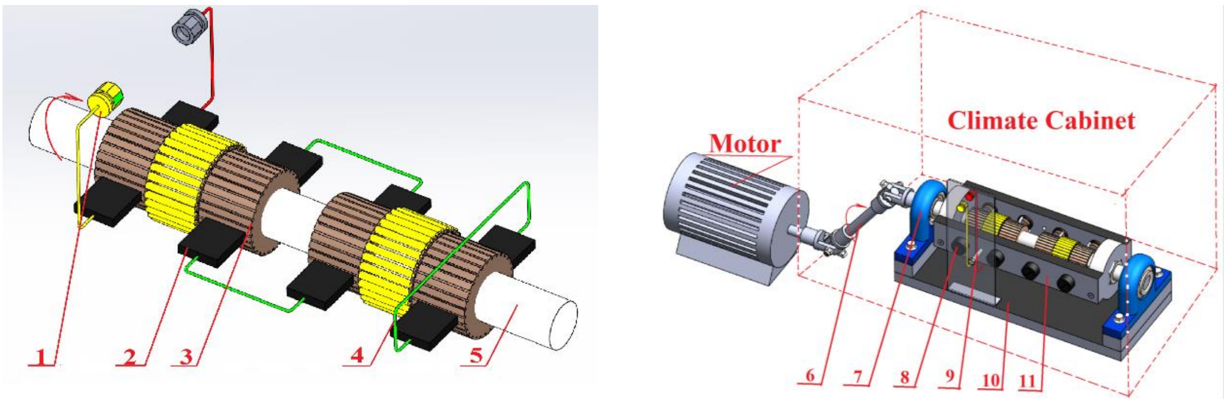
(a)



(b)

Fig. 2. Shape and size of the pair of commutator brushes.

Wear testing machine of commutator brushes pairs is performed using a self-made environment tribometer. The schematic diagram of the wear-testing machine is shown in Figure 3. The wear-testing machine is driven by a motor with n = 1450 rpm and N = 0.27 kW. On the main shaft, four commutators are working at the same time. It is assumed that the surface quality of these new graphite brushes is the same. These commutators are always in contact with the brush using a constant spring force of 2N. The commutator's constant velocity is 2.77 m/s. The mechanical system of the wear testing machine is placed in a climate cabinet and the motor is placed outside the chamber in Fig 3b. The climate cabinet is controlled humidity from 51% - 99% ± 2% and temperature from 15^0C-55^0C ± 1^0C. The electrical circuit is used for the commutator brushes pairs in Fig 3a. It uses a power rheostat to vary the current passing through the contact surfaces between the brushes and the commutator. The wear amount of the brush is measured as mass loss ΔM under testing conditions after 10 hours of operation. Using an electronic micro-scale with an accuracy of 1/1000 to measure the mass of the brush.



(a) (b)

Fig. 3. (a)- Electrical circuit applied, (b)- Experimental setup, 1 - Connector, 2 - Brush, 3 - commutator, 4 - line connection, 5 - Main shaft, 6 -universal joint; 7 - bearing; 8 - brush holder; 9 - anti-rotation mechanisms; 10 -system base; 11 brush locating frame.

2.3 The main experimental parameters

The main experimental parameters of the study of the wear amount under the simultaneous influence of current, temperature, and relative humidity of the ambient in constant speed conditions are shown in Table 1.

The objective function of experiments is brushed mass loss ΔM. The input influencing factors are temperature, relative humidity, and current. Experimental organization according to 3 input factors. Each factor has 3 levels and the number of experiments is 3^k = 27. It is presented in Table 2.

Table 1. Main experimental parameters.

Main experimental parameters	Variation of parameters	Constant parameters
Speed of comuntator n(rpm)		1450 rpm
Temperature T (^{0}C)	25^0C, 40^0C, 55^0C	
Relative humidity RH (%):	51%, 75%, 99%	
current I (A)	5 A, 7.5 A, 10 A	
Spring force (N)		2 N
Time trials t (h)		10 N
Mass loss of Wear amount ΔM(g)		M_{Before}– M_{End}

Table 2. Experimental parameters and variation range.

Experimental parameters	Encoding variable	Encryption level			Variation range Δ
	X_i	+ 1	0	-1	
Temperature (^{0}C)	X_1	55	40	25	15
Humidity (%)	X_2	99	75	51	24
Current (A)	X_3	10	7,5	5	2,5

3. RESULTS AND DISCUSSIONS

After 10 hours of operation for every test, the mass loss of the graphite brush ΔM_i is measured. The average of the mass loss ΔM, the variance, the wear amount U, the initial wear amount, and the wear rate of the graphite brush are calculated. These experimental results and calculations are presented in Tables 4, 5, and 6.

The run-in is within the overall life of the brush. Usually, the running time is about 3 hours. During this period, the wear rate is high and tends to decrease gradually to a stable value, assuming the wear amount of graphite brush after run-in U_r = $0.5U_{10h}$. Therefore, the initial wear amount of graphite brush a_o and wear rate γ is calculated from wear amount graphs over time. Selecting the allowable wear amount of a graphite brush [U] based on the remaining brush length required for them to be stable during service: Length (L) ≥ 1.2 height (H) = 8.16 mm. So the allowable wear amount of a graphite brush [U] = 9.64 mm.

Considering the case of 5A current, the temperature change range from 25°C to 55°C, and the relative humidity change range from 51% to 99%. The wear amount U_5, initial wear amount a_{ouav_5}, and wear rate γ_{mav_5} after 10 hours of operation are presented in Table 3.

Table 3. Experimental array and wear amount U, initial wear amount, and wear rate after 10 hours of operation with 5A current.

No	RH (%)	T (^{0}C)	I (A)	X_1	X_2	X_3	Average ΔM (g)	Variance $\sigma^2_{\Delta M}$	Wear amount U_5 (mm)	$a_{o\text{-}5}$	γ_5
1	51	25	5.0	-1	-1	-1	0.01725	1.583E-06	0.096605	0.0276	0.0069
2	75	25	5.0	0	-1	-1	0.02450	3.333E-07	0.137207	0.0392	0.0098
3	99	25	5.0	+1	-1	-1	0.03250	1.667E-06	0.18201	0.052	0.013
4	51	40	5.0	-1	0	-1	0.02550	3.333E-07	0.142808	0.0408	0.0102
5	75	40	5.0	0	0	-1	0.03575	9.167E-07	0.200211	0.0572	0.0143
6	99	40	5.0	+1	0	-1	0.04650	3.333E-07	0.260414	0.0744	0.0186
7	51	55	5.0	-1	+1	-1	0.02875	2.500E-07	0.161009	0.046	0.0115
8	75	55	5.0	0	+1	-1	0.04750	3.333E-07	0.266014	0.076	0.019
9	99	55	5.0	+1	+1	-1	0.05550	3.333E-07	0.310816	0.0888	0.0222

The parameters are determined from the experimental data and equations of wear amount over time with current density I=5A: The average initial wear amount of graphite brush a_{ouav5} = 0.027889, standard deviation s_{ao} = 0.01008, s^2_{ao}= 0.0001016. The average wear rate of graphite brush γ_{mav5} = 0.006972, standard deviation s_γ = 0.00252, s^2_γ= 0.00000635.

Calculate the average life of the graphite brush according to the wear criterion with the formula (10):

$$T_{mu} = \frac{[U]-a_{ou}}{\gamma_{mu}} = 32.1h \sim 1378.673 \text{ h}$$

The probability of failure-free operation of the graphite brush is P(t) = 90 %, 95 %, and 99 %. The argument of the Laplace function, whose value depends on the confidence P(t) so that U_α = 1,28; 1.64; 2.33. Substituting Uα values into equation (8), The service life of the graphite brush under laboratory conditions is as follows: $T_{P(90\%)} \sim 942$ h, $T_{P(95\%)} \sim 861$h, and $T_{P(99\%)} \sim 748$ h.

Considering the case of 7.5 A current, the temperature change range from 25°C to 55°C, and the relative humidity change range from 51% to 99%. The wear amount $U_{7.5}$, initial wear amount $a_{ou7.5}$, and wear rate $\gamma_{7.5}$ after 10 hours of operation are presented in Table 4.

The parameters are determined from the experimental data and equations of wear amount over time with current I=7.5 A: The average initial wear amount of graphite brush $a_{ouav\_7.5}$ = 0.031022, standard deviation s_{ao} = 0.012251, s^2_{ao} = 0.0001501. The average wear rate of graphite brush $\gamma_{mav\_7.5}$ = 0.007756, standard deviation s_γ = 0.003063, s^2_γ = 0.00000938.

Calculate the average life of the graphite brush according to the wear criterion with the formula:

$$T_{mu} = \frac{[U]-a_{ou}}{\gamma_{mu}} = 32.1h \sim 1238.909 \text{ h}$$

The probability of failure-free operation of the graphite brush is P(t) = 90%; 95%; 99% then the service life of the graphite brush under laboratory conditions is as follows: $T_{P(90\%)}$ ~ 822h, $T_{P(95\%)}$ ~ 751h and $T_{P(99\%)}$ ~ 645 h.

Table 4. The **e**xperimental array and wear amount U, initial wear amount, and wear rate after 10 hours of operation with 7.5A current.

No	RH (%)	T (⁰C)	I (A)	X_1	X_2	X_3	Average ΔM(g)	Variance $\sigma^2_{\Delta M}$	Wear amount $U_{7.5}$ (mm)	$a_{o7.5}$	$\gamma_{7.5}$
10	51	25	7.5	-1	-1	0	0.01875	2.500E-07	0.105006	0.03	0.0075
11	75	25	7.5	0	-1	0	0.02850	3.333E-07	0.159608	0.0456	0.0114
12	99	25	7.5	+1	-1	0	0.03650	3.333E-07	0.204411	0.0584	0.0146
13	51	40	7.5	-1	0	0	0.02575	2.500E-07	0.144208	0.0412	0.0103
14	75	40	7.5	0	0	0	0.03825	2.500E-07	0.214211	0.0612	0.0153
15	99	40	7.5	+1	0	0	0.05150	3.333E-07	0.288415	0.0824	0.0206
16	51	55	7.5	-1	+1	0	0.03050	3.333E-07	0.170809	0.0488	0.0122
17	75	55	7.5	0	+1	0	0.05275	2.500E-07	0.295416	0.0844	0.0211
18	99	55	7.5	+1	+1	0	0.06650	3.333E-07	0.37242	0.1064	0.0266

Considering the case of 10A current, the temperature change range from 25°C to 55°C, and the relative humidity change range from 51% to 99%. The wear amount U_{10}, initial wear amount a_{ouav_10}, and wear rate γ_{mav_10} after 10 hours of operation are presented in Table 5.

Table 5. Experimental array and wear amount U, initial wear amount, and wear rate after 10 hours of operation with 10A current.

No	RH (%)	T (⁰C)	I (A)	X_1	X_2	X_3	Average ΔM(g)	Variance $\sigma^2_{\Delta M}$	Wear amount U_{10} (mm)	a_{o10}	γ_{10}
19	51	25	10.0	-1	-1	+1	0.03175	2.500E-07	0.177809	0.0508	0.0127
20	75	25	10.0	0	-1	+1	0.05150	3.333E-07	0.288415	0.0824	0.0206
21	99	25	10.0	+1	-1	+1	0.06450	3.333E-07	0.361219	0.1032	0.0258
22	51	40	10.0	-1	0	+1	0.03825	2.500E-07	0.214211	0.0612	0.0153
23	75	40	10.0	0	0	+1	0.06250	3.333E-07	0.350018	0.1000	0.025
24	99	40	10.0	+1	0	+1	0.07350	3.333E-07	0.411622	0.1176	0.0294
25	51	55	10.0	-1	+1	+1	0.04275	2.500E-07	0.239413	0.0684	0.0171
26	75	55	10.0	0	+1	+1	0.07575	2.500E-07	0.424222	0.1212	0.0303
27	99	55	10.0	+1	+1	+1	0.09175	2.500E-07	0.513827	0.1468	0.0367

Table 6. Service life T depends on the probability of failure-free operation and current.

Probability of failure-free	ServiceLife_5A	ServiceLife_7.5A	ServiceLife_10A
50%	1378.673h	1238.909h	811.015h
90%	942.538h	822.842h	570.333h
95%	861.895h	751.956h	524.69h
99%	748.372h	645.226h	456.817h

The parameters are determined from the experimental data and equations of wear amount over time with current I=10 A: The average initial wear amount of graphite brush a_{ouav_10} = 0.047311, standard deviation s_{ao} = 0.015746, s^2_{ao} = 0.0002479. The average wear rate of graphite brush γ_{mav_10} = 0.011828, standard deviation s_γ = 0.003936, s^2_γ = 0.00001549.

Calculate the average life of the graphite brush according to the wear criterion with the formula:

$$T_{mu} = \frac{[U] - a_{ou}}{\gamma_{mu}} = 32.1h \sim 811.015 \text{ h}$$

The probability of failure-free operation of the graphite brush is P(t) = 90%; 95%; 99% then the service life of the graphite brush under laboratory conditions is as follows: $T_{P(90\%)}$ ~ 570 h, $T_{P(95\%)}$ ~ 524 h and $T_{P(99\%)}$ ~ 457 h.

In this study, when the temperature and humidity are variable, the service life of the Brush at the currents changes by 50%, 90%, 95%, and 99% failure-free operation probability as shown in Figure 4.

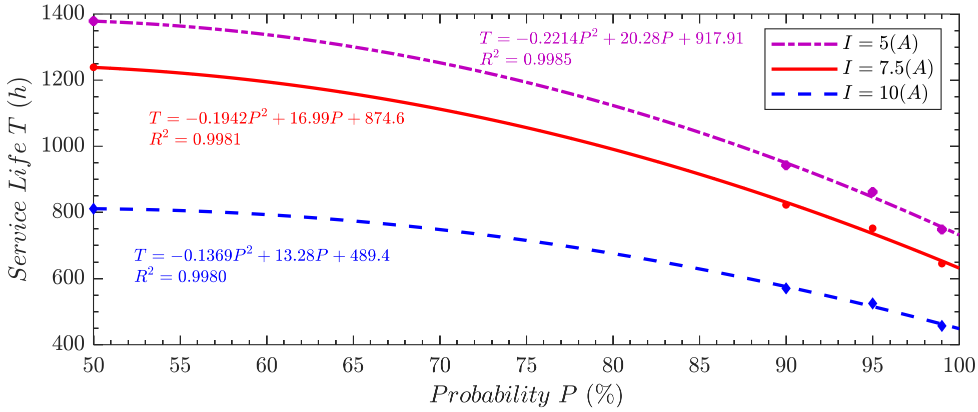


Fig. 4. The service life of graphite brush depends on the probability of failure-free operation at current 5A, 7.5A, and 10A when the temperature and humidity are variable random.

In a humid tropical climate environment: the temperature is from 25°C to 55°C, and relative humidity is from 51% to 99%; when the current increases then, the life of the Brush is rapidly reduced. The current increases to the upper limit value, and the life reduces more sharply. When humidity and temperature are high, electrical wear increases rapidly due to the interaction of the electric current with the moisture film existing between the friction surface of the brush commutator to generate sparks. This is similar to the published research results of scientists, but the level is higher in the presence of moisture. Service life when 10A current compare to 5A: $T_{10A\_P(50\%)} = 0.59*T_{5A\_P(50\%)}$; service life when 7.5A current compare to 5A: $T_{7.5A\_P(50\%)} = 0.89*T_{5A\_P(50\%)}$.

The dependence of service life on reliability has been specifically calculated with different reliability levels, showing that: In tropical climate conditions, the service life varies very strongly with the probability of failure-free operation. This shows that the failure-free operation probability of the brushes decreases rapidly when working in high temperatures and humid conditions. In the range of changed current by this study, the service life: $T_{P(99\%)} \sim 0.54\ T_{P(50\%)}$, $T_{P(95\%)} \sim 0.62\ T_{P(50\%)}$, and $T_{P(90\%)} \sim 0.68\ T_{P(50\%)}$.

The appearance of a third object between the friction surfaces of graphite brushes and the commutator can explain the variation of service life T in these experiments. It often acts as a lubricant and reduces mechanical wear. However, the electrical wear of brushes is associated with current and contact voltage drop. The interaction between these two types of wear will directly affect service life and reliability especially when the ambient humidity is high, it will increase the adhesion of the graphite to the commutator surface and increase the thickness of the third object. As the thickness of the third layer rises, the contact voltage drop will increase, causing electric arcs to appear. Such electrical wear increases. When the relative humidity, ambient temperature, and current increase, the total wear of the brush, including electrical and mechanical wear, still increase, but the speed tends to decrease. Therefore, the service life reduces. At certain thermal and humid conditions, the effect of current on wear is similar to the result of published studies.

The service life graph T in Figure 5 depends on two parameters: The failure-free operation probability (under the random influence of relative humidity and ambient temperature) and current. The graph's density of contour lines shows the parameters' influence level. As the current increases, the density of the contour lines T increases rapidly, in the current range from 9A to 10A, the density of the contour lines is more than in the range of 7A to 8A twice. Thus, the service life T reduces ~1.4 times. As the probability of failure-free operation increases, the density of contour lines T gradually increases about ~ 1.15 to 1.25 times. So, the service life T reduces about ~1.1 to 1.15 times.

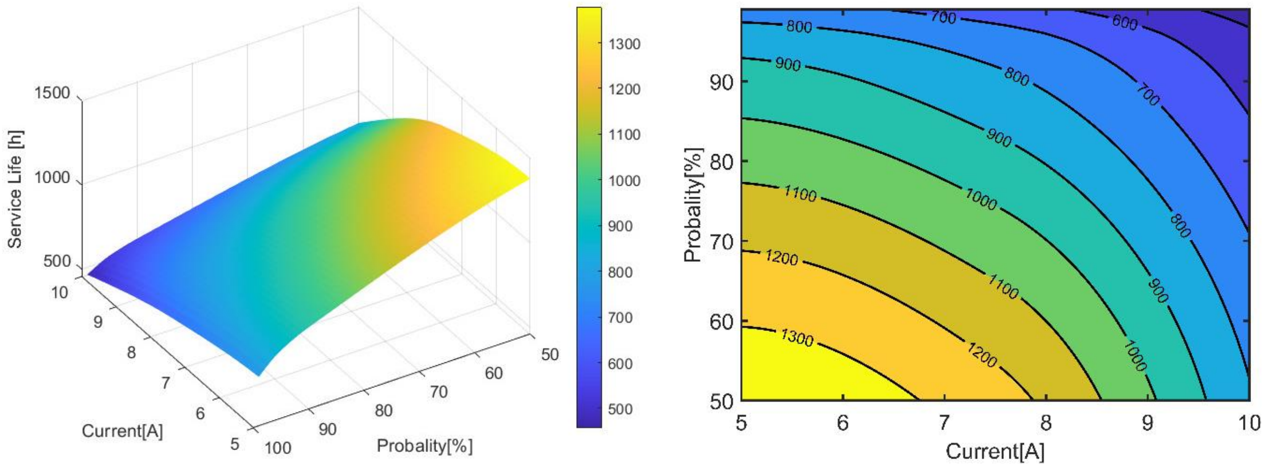


Fig. 5. Dependence of service life T on the probability of failure-free and current when the temperature and humidity are variable random.

The contour density increases rapidly when current I > 7.5 A and P(t) > 75%, In this region, the graphite brush has a large wear amount and a low life. The insulation between bars is decreased when graphite adhesion increases due to high relative humidity. It causes an electric arc, increases current wear, and leads to damage which does not allow the commutator - brushes to pair.

4. CONCLUSION

Research on the simultaneous influence of current and two characteristic parameters of the humid tropical environment on wear, service life, and reliability of DC motor brushes has been performed. The method of assessing the service life and reliability is based on a calculated scheme of the linear wear rate. It depends on the allowable limit wear and the probability of failure-free operation of DC motor brushes. The study results make the following conclusions:

The service life, reliability evaluation research method, and graphite brush wear experiments in the laboratory are consistent with the operating condition of the commutator and brushes pair.

The lubricated condition is greatly improved when relative humidity and temperature environment are high and the rate of third body formation is large to reduce mechanical wear. While electrical wear greatly increases at all currents due to the thickness of the third layer and the contact voltage drop is increased. It causes generates arcing between the brush and the commutator. So graphite brush wear still increases.

When the relative humidity, ambient temperature, and current increase, the service life of graphite brushes reduce due to the total wear, including electrical and mechanical wear still increasing, but the speed tends to decrease. In published studies, the effect of current on wear is confirmed in certain thermal and humid conditions.

In a humid tropical climate environment, when the current increases from 5A to 7.5A and from 5A to 10A, the service life of DC motor graphite brushes decreases by 1.11 and 1.69 times. The service life of DC motor graphite brushes varies very strongly with the probability of failure-free operation. when the reliability increases from 50% to 90%, from 50% to 95%, and from 50% to 99% then the lifetime decreases 1.46, 1.6, and 1.84 times, respectively.

Based on the contour lines of the service life graph, it is possible to determine the service life of the brush according to the electrical current and failure-free operation probability when working in conditional relative humidity, ambient temperature and current vary. This value ensures the brushes work stably and without problems.

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