THE OPTIMUM DESIGN OF FUNCTIONAL COMPOSITE MATERIALS FOR ELECTRICAL BRUSHES IN DC MACHINES

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SUMMARY: The designability of composite materials is a big advantage over other even structured materials. In this work, a CAD program had been developed to design Carbon fiber/Graphite composite brushes to take advantages of both of the designability of composite materials and the commutation equations of DC machines for the best commutation performance. The electrical properties of both the carbon fiber and the graphite had been measured and the commutation curve under different fiber distribution had been calculated. The design scheme of the composite brush which meet the best commutation performance was given by the program and also several factors which had effects on the commutation had been discussed according to the results of computer simulation. The results given by the computer meet the real application and theoretical analysis quite well.

KEYWORDS: optimum design, brush, DC machines, carbon fiber

INTRODUCTION

The bad commutation performance of DC machines is one of the key factors that hindered machines' development. So, how to improve the commutation performance had always been the hot topic among people who are engaged in the design and use of DC machines.

Electrical brush is the main part used for current transmission in DC machines, its performance has a direct effect on the commutation. According to the commutation principle of DC machines, the existence of the commutation current makes the current distribution uneven on the contact face between brush and commutator. In other words, during the commutation period, the current flowing through the different parts of brush's working face is different. So it is apparently that the even structure of the conventional brush can not meet the need of current variation during the commutation period.

Carbon fiber/Graphite composite brush is an uneven structure brush made from carbon fiber and graphite matrix. The big advantage of the composite brush is that the amount and the distribution of the fiber can be varied on the brush surface to meet the need of the electrical machine to achieve the best performance. Fig.1 is the draft of such composite brush.

The purpose of this work is to complete a CAD program, with the specified properties of the DC machine, the carbon fiber and the graphite matrix, a design scheme of the distribution of the carbon fiber on graphite matrix will be given to meet the best commutation performance of the DC machine.

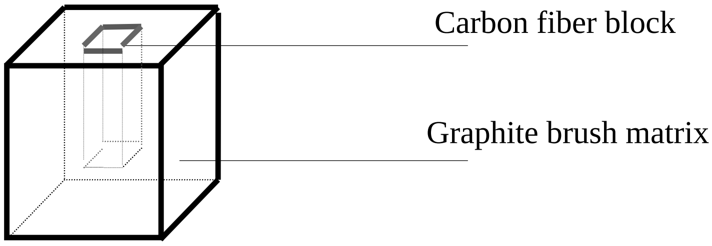


Fig.1 Draft of Carbon Fiber/Graphite Brush

DESIGN PRINCIPLE

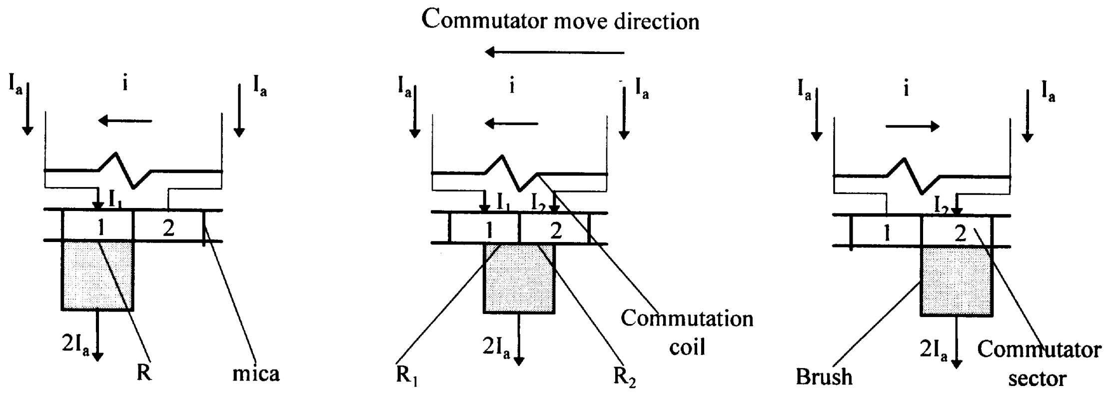


Fig. 2 Illustration of commutation

Commutation procedure is such a period that during a short time interval, the current in commutation coil reversed. As shown in Fig.2, the current in commutation coil(bold line) reversed when brush had moved from position 1 to position 2. According to the commutation principle of DC machines, we got the following equations.[1][2]

$$\begin{aligned}
&\Delta U_1 - \Delta U_2 = \Sigma e \\
&\Delta U_1 = I_1 R_1 \\
&\Delta U_2 = I_2 R_2 \\
&I_1 = I_a + i \\
&I_2 = I_a - i
\end{aligned} \tag{1}$$

ΔU_1 , ΔU_2 — Contact voltage drops between brush and sector 1, brush and sector 2.
I_1 , I_2 — Current flowing through sector 1 or sector 2.
R_1 , R_2 — Contact resistance between brush and sector 1, brush and sector 2.
I_a — Current in normal coil.
i — Commutation current.

If it is assumed that the contact resistance is inversely proportional to the contact area between the brush and the sector, from Eqn 1, the commutation current i at time t.

$$i_t = i_a(1-\frac{2t}{T_K}) + \frac{\Sigma e}{R} \tag{2}$$

t — commutation time, Σe — composed e.m.f.(electromotive force)
T_k — commutation period, R — contact resistance between brush and commutator sector.

Eqn 2 is discussed as shown in Fig.3.

When Σe =0, i is linear with t, it is called linear resistance commutation.

When Σe <0, commutation current changes earlier than that of the resistance commutation, it is so called over commutation.

When Σe >0, commutation current changes later than that of the resistance commutation, it is so called under commutation.

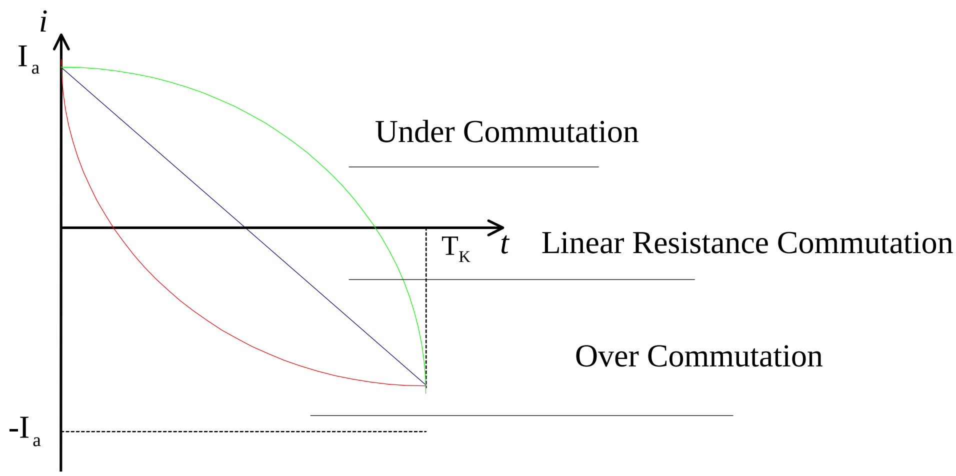


Fig. 3 Illustration of three commutation models

The most serious problem during commutation is commutation sparking which will seriously affect the normal operation of DC machines. Linear resistance commutation, which is the perfect commutation, has no sparking, while serious over and under commutation will lead to sparking. The physical cause for sparking is that at the end of the commutation, the current in commutation coil does not reach the value in other normal coil. As shown in Fig.4, the remaining current difference i_K will lead to the energy releasing(sparking) to complete the commutation. The reason of the existence of remaining current difference is as following. During practical commutation, the actual contact between brush and commutator sectors occurs only at relatively few discrete points, the remaining areas is separated by gaps of the order of 0.5×10^{-6} m. Passage of current through limited points develops high intensity electric field between the non-contact areas. Such electric field initiates field emission, which makes the contact resistance not increase with the decrease of the contact area during the end period of commutation[3][4]. It means the assumption of "contact resistance is inversely proportional to the contact area between the brush and the sector" can not be taken as we discussed in Fig.3. The low resistance at the end of commutation causes the finishing commutation current in brush different than that in normal coil, thus leads to the energy releasing of the sparking.

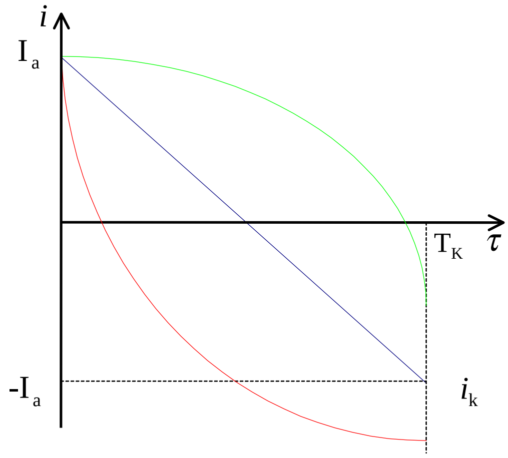


Fig.4 Practical Commutation Curve

As discussed above, there will be two ways to prevent the bad commutation sparking. One is to modify the contact performance of the brush and commutator, prevent the field emission which will leads to resistance decrease. The other is to modify the commutation current, makes it change smoothly to prevent the energy release due to sudden change of the current. As proved in real practice, the linear resistance commutation is the perfect commutation with no sparking.

The use of Carbon fiber/Graphite composite brush can meet the above two requirements. First, the excellent contact and conductivity performance of carbon fibers greatly improves the contact performance between brush and commutator, reduces the possibility of field emission. Second, the designability of the composite materials makes it possible to change the distribution of the fibers on graphite brush surface to modify the commutation curve to be closed to the linear commutation.

DESIGN PROCEDURE

From Eqn 1, commutation current

$$i = \frac{\Sigma e - I_a R_1 + I_a R_2}{R_1 + R_2} \tag{3}$$

To a specified DC machine, Σe and I_a are constant. So the commutation current i is changed with the change of R_1 and R_2. Thus, to design the commutation current variation with the requirement is just to design a proper variation of the contact resistance between brush and commutator. For composite brushes, such design requirement is technically realized by varying the amount and the distribution of carbon fibers on the surface of the graphite brush matrix. So it is necessary to know the electrical contact properties of both the graphite and the fiber.

Electrical Contact Properties of the Components

Fig.5 is the V-A property of the D172 graphite which is used as brush matrix.

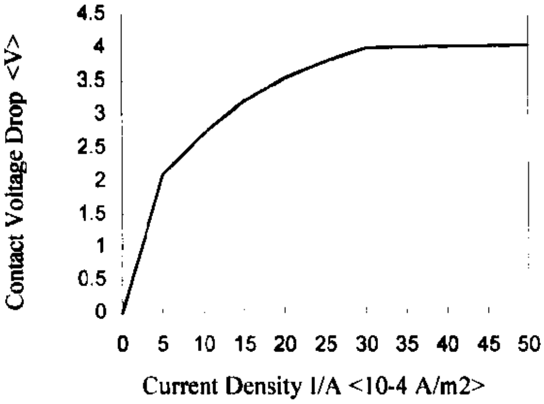


Fig.5 V-A curve of the** D172 **graphite

Fig.5 is regressed to get the V-A equation of the D172 graphite,

$$\Delta U_G = a_G(\frac{I_G}{S_G})^3 + b_G(\frac{I_G}{S_G})^2 + c_G(\frac{I_G}{S_G}) + d_G \tag{4}$$

ΔU_G — Contact voltage drop of the graphite
I_G — The current flowing through the graphite, S_G — The contact area of the graphite,
$a_G = 4.67\times10^{-17}$, $b_G = -5.62\times10^{-11}$, $c_G = 2.25\times10^{-5}$, $d_G = 1.05$

Use the same method, the V-A equation of the carbon fiber used in composite brush is,

$$\Delta U_F = a_F(\frac{I_F}{S_F})^3 + b_F(\frac{I_F}{S_F})^2 + c_F(\frac{I_F}{S_F}) + d_F \tag{5}$$

ΔU_F — Contact voltage drop of the carbon fiber
I_F — The current flowing through the fiber, S_F — The contact area of the fiber,
$a_F = 2.36\times10^{-19}$, $b_F = -8.89\times10^{-13}$, $c_G = 1.28\times10^{-6}$, $d_G = 1.81$

Find the Result of the Commutation Current

In a same contact face of the brush and the commutator, the contact voltage drop of the fiber part is equal to that of the graphite part, so

$$\Delta U_F = \Delta U_G \tag{6}$$

From Eqn 1, 4, 5, 6, we got

$$a_G(\frac{I_{1G}}{S_{1G}})^3 + b_G(\frac{I_{1G}}{S_{1G}})^2 + c_G(\frac{I_{1G}}{S_{1G}}) + d_G \quad = \quad a_F(\frac{I_{1F}}{S_{1F}})^3 + b_F(\frac{I_{1F}}{S_{1F}})^2 + c_F(\frac{I_{1F}}{S_{1F}}) + d_F$$
$$I_{1G} + I_{1F} = I_1 \,,\ I_1 = I_a + i_t \tag{7}$$
$$a_G(\frac{I_{2G}}{S_{2G}})^3 + b_G(\frac{I_{2G}}{S_{2G}})^2 + c_G(\frac{I_{2G}}{S_{2G}}) + d_G \quad = \quad a_F(\frac{I_{2F}}{S_{2F}})^3 + b_F(\frac{I_{2F}}{S_{2F}})^2 + c_F(\frac{I_{2F}}{S_{2F}}) + d_F$$
$$I_{2G} + I_{2F} = I_2 \,,\ I_2 = I_a - i_t$$

S_{1G} , S_{1F} — The contact area between sector 1 and graphite, sector 1 and fiber.
S_{2G} , S_{2F} — The contact area between sector 2 and graphite, sector 2 and fiber.
I_{1G} , I_{1F} — Current flowing through sector 1 and graphite, sector 1 and fiber.
I_{2G} , I_{2F} — Current flowing through sector 2 and graphite, sector 2 and fiber.
i_t — Commutation current at time t.

The Newton method is used to find the result of the commutation current i. An assumed value of commutation current i' is assigned to i_t. From Eqn 7, we got the result of

I_{1G}, I_{2G}, I_{1F}, I_{2F}

Use them in Eqn 4,5, we got the result of

ΔU_{1G}, ΔU_{2G}, ΔU_{1F}, ΔU_{2F}

From the equation $R=\Delta U/I$, we got the value of

R_{1G}, R_{2G}, R_{1F}, R_{2F}

From the parallel connection law of the resistance, we got the value of

R_1, R_2,

Use them in Eqn 3, we got the commutation current i.

A threshold ξ is assigned, when $|i - i'|<\xi$, value i' can be taken as the solution of the commutation current i. Otherwise, $i_t = (i + i')/2$ is taken and the above procedure is repeated. Since practically, i_t should have a solution, so this equation should be restraint.

Realization of the Optimization

Different distributions of fibers on brush surface will result in different commutation curves. Since the linear resistance commutation is the best one, the difference to the linear one is chosen as the criterion to find the best commutation. The computer realization is as following. The commutation period is divided into *k* time interval. At moment *t*, the current on linear commutation curve is i_{0t}, the current on real commutation curve is i_t, the mean square of the errors for totally *k* moments is

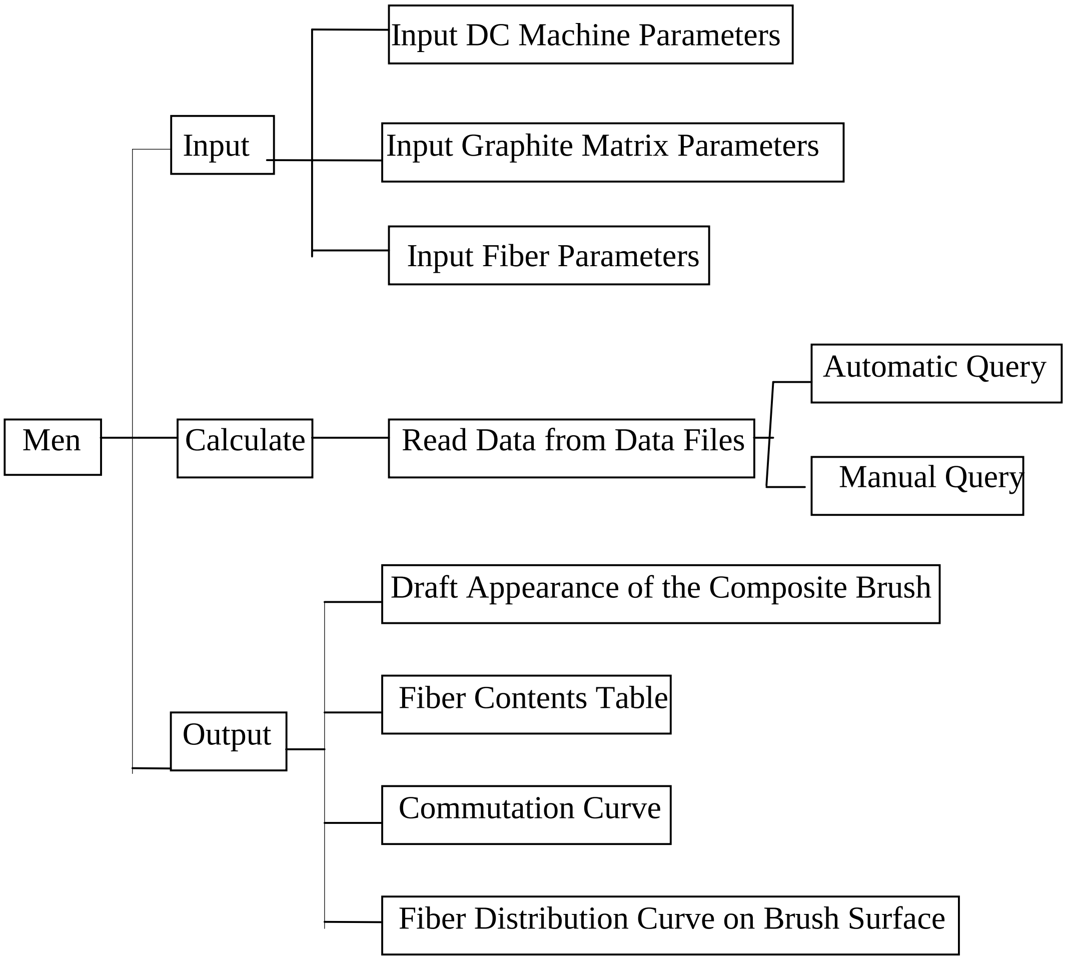
$$W = \sum_{t=1}^{k}(i_t - i_{0t})^2$$

Virtually, the surface of the brush is divided into *n* even parts, the proportions of the fibers on each part can be varied from 1/m , 2/m to m/m. The value of *n* and *m* can be assigned by the user. So there is totally m^n different distributions for a specified composite brush. The commutation curve of each fiber distribution is calculated and the one with the minimized W is chosen as the best commutation, the corresponding fiber distribution is also given out.

INTRODUCTION TO THE CAD PROGRAM

The program is developed with C language on IBM PC platform.

Program Module



Program Explanation

Four types of parameters should be input to complete the design. They are parameters of electrical machines, graphite brush matrix, carbon fibers and parameters used for calculation.
Automatic query and manual query are used in this program. In automatic query, the commutation curve of every different fiber distribution on graphite matrix are calculated and the one which is most close to the perfect liner commutation will be found out, also the design

scheme of such composite brush will be given. In manual query, the commutation curve will be given by the program with the fiber distribution input by user.

The Characteristic of the CAD Program.

Good Modular Structure and User Interface

Every module is independent to each other which makes the further modification and maintenance easy. The large amount of parameters of DC machines, graphite matrices and carbon fibers, once input, they will be stored in the computer with different names and ready for use in the further calculation. Also, each design scheme is stored in the computer and can be read when needed. Meanwhile, the friendly user interface is specially designed to those customers without computer background. It is easy to learn and use.
Double Functions on Both Design and Simulation

This CAD program, not only can be used to give out the optimum design scheme according to different DC machines, also, it can simulate the commutation curve with different brush materials, different brush current densities and different commutation conditions. It gives us big flexibility during brush design.

THE RESULTS OF THE COMPUTER DESIGN

Required Parameters

The parameters of the DC machine used in design is shown in Table 1.

Table 1: DC machine parameters

I_a(A)	Σe(V)	Mica width(m)	Sector width(m)	Commutator speed(m/s)	Winding	Number of the sectors one brush covers
288	7	0.004	0.016	30.4	Single lap	1

The graphite matrix used in composite brush is D172, its electrical property is given by Eqn 4. The electrical property of the carbon fiber used in composite brush is given by Eqn 5. During calculation, we choose the virtually brush division n=4, the number of the different fiber distribution in one part m=4, the number of the time interval in one commutation period k=15.

Design Result

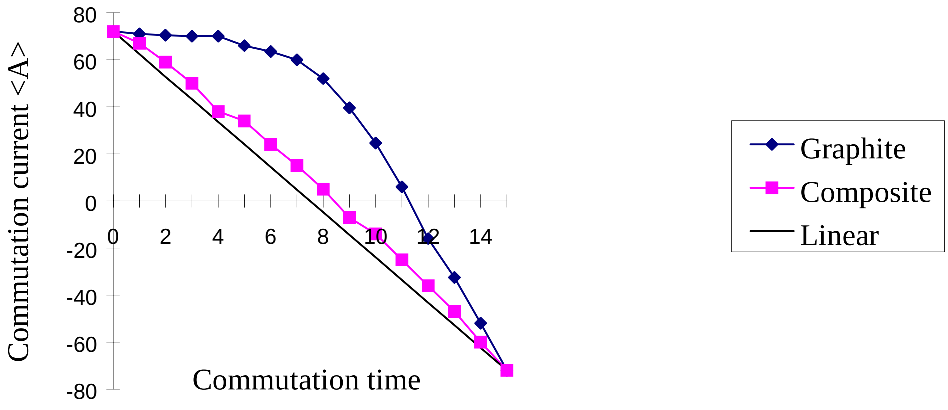


Fig.6 Comparison between theoretical perfect liner commutation, computer designed composite brush commutation and graphite brush commutation

Fig.6 shows the comparison between the commutation curve of the optimum designed composite brush and that of the pure graphite brush. The brush current density is 0.36MA/m^2. It is apparently that the use of computer designed composite brush significantly improved the commutation performance compared to the use of pure graphite brush. The design scheme can be given by several ways. Fig.7 shows the draft of the composite brush with the best commutation performance. Table 2 gives the design scheme by the fiber distribution value.

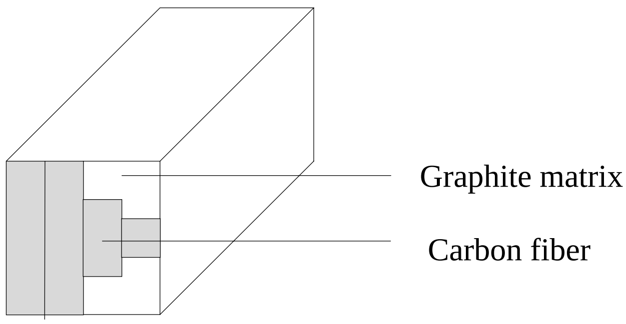


Fig.7 Draft of the optimal designed composite brush

Table 2 The fiber distribution of the optimal designed composite brush

Block	**1**	**2**	**3**	**4**
Fiber contents	100%	100%	50%	25%

DISCUSSION ON THE SIMULATION RESULTS

Factors Affect the Commutation

Brush Current Density

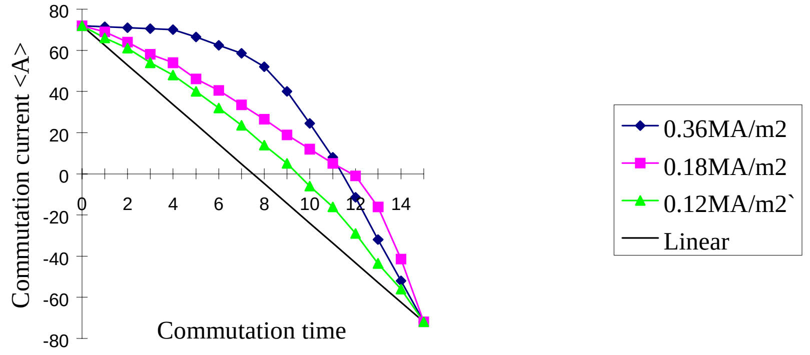


Fig.8 Commutation curves under different brush current densities

Fig.8 shows the simulation result of the commutation curves for a same graphite brush under different current densities. It is apparently that with the decrease of the current density, the curve is going close to the linear commutation. The simulation results can be explained physically that under high current density, the field emission in the contact face of the brush and the commutator is quite serious and results in sparking. While if the current density is low, such field emission will not be activated and the commutation performance will be better. So, reduce the brush current density is good to commutation.

Contact Resistance

Fig.9 shows the simulation result of the commutation curves of two graphite brush with different contact resistance. The brush with high contact resistance has a better commutation. Theoretically, it can be explained that high contact resistance is good to reduce the commutation current, thus good to commutation. While the increment of the contact resistance will also result in the increment of the contact voltage drop, and this will lead to the loss of the DC machine's output power. So, although increase the contact resistance is good to commutation, it will reduce the output power.

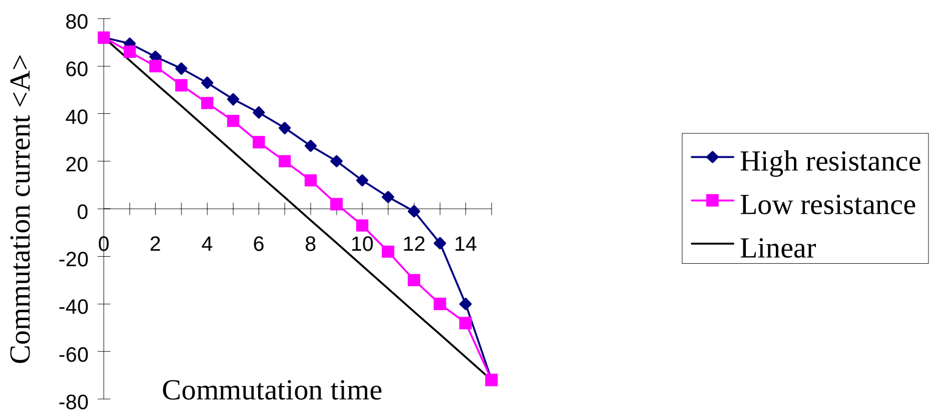


Fig.9 Commutation curves under different contact resistance

Composed e.m.f.

Fig.10 shows the simulation result of the commutation curves of two DC machines with different composed e.m.f. The brush in use is same. The composed e.m.f. of one machine is 7 times higher than that of another machine. It is apparently that reduce the composed e.m.f. is good to commutation, in practical use, reduce the e.m.f. is done by add a pair of commutation poles.

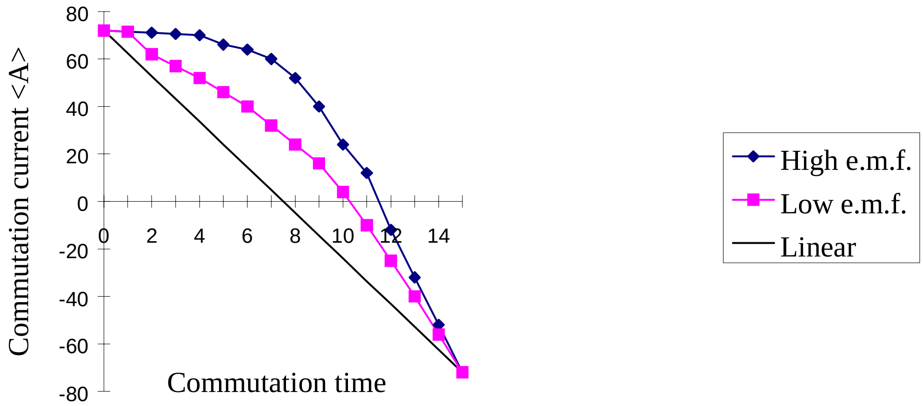


Fig.10 Commutation curves of the DC machines with different composed e.m.f.

Comparison between the Simulation Results and the Practical Use

Brush Current Density

From Fig.8, we got the commutation curves of the D172 graphite brush under different current densities. When the current density is $0.18MA/m^2$ or $0.36MA/m^2$, the simulated curve is far from the linear commutation. In real application, graphite brushes working under such high current density results in serious sparking. When current density is $0.12MA/m^2$, the simulated commutation curve is close to the linear commutation. And actually, $0.12MA/m^2$ is just the normal working current density for D172 graphite brush.

The Composite Brush Real In Use

Fig.11 shows the simulation result of the commutation curves of the real in use composite brush, computer designed composite brush and the graphite brush. Although the commutation curve of the real in use composite brush is worse than that of the computer designed one, it is still better than that of the conventional graphite brush. And in real application, the use of our current available composite brush significantly improved the DC machine’s commutation performance. Brush current carrying capacity increased by 3-4 times, the wearing resistance improved by 20%-50%, and the no-sparking zone (a strong indicator of commutation performance) enlarged by 5-7 times.

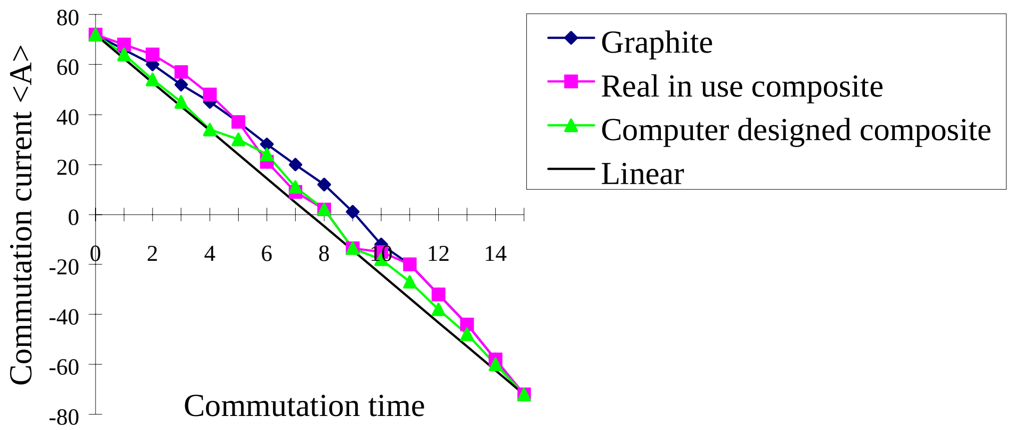


Fig.11 Commutation curves of the real in use composite brush and computer designed brush

CONCLUSION

According to the discussion of the above sections, we found that reduce the brush current density, increase the contact resistance and reduce the composed e.m.f. are good to improve the commutation performance of DC machines. Once the proper physical models and mathematical methods were chosen, the optimum design of the composite brush can be realized by the computer program with the different DC machines, brush matrices and carbon fibers. The use of such composite brush will result in the best commutation performance.

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