Carbon Brushes for Electrical Machines

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I. Introduction

.1 Carbon the element

Carbon is an element with unique properties that can be found practically everywhere. Carbon, the element C, can be found in a variety of forms such as the extreme hard clear diamond, or the soft graphite used for pencils. Graphite can be mined or produced out of different organic or mineral materials.

Chemically carbon is quite inactive and can withstand most acids, gasses and other corrosives. At high temperature carbon will oxidize relatively slowly and does not melt.

The mechanical properties of carbon are equally interesting. In graphite form it has low friction and can be used as lubricant at high temperature applications.

Carbon is a better thermal conductor than most non-metallic materials, and in graphite form even better than most metals.

The electrical resistivity of carbon is high compared with metal, but in combination with some of its other unique properties it finds many applications as conductor of electrical current.

Carbon is the base material for various industrial products and plays an important role in the generation and application of electrical energy.

.2 History of the carbon brush

The first recorded electrical application of carbon was an experiment by Sir Humphry Davy in the V.K. In the beginning of the 19th century he experimented with electric arcs between carbon electrodes using galvanic cells on the power source.

The electrodes were made out of a mixture of ground charcoal and molten pitch, molded under pressure and baked to give amorphous carbon rods. In the following years experiments with carbon for are light applications increased.

Increased use of electricity as an energy source for lighting and the rapid growth of industrial activities caused an increased need for generators. The d.c. generators or motors of those days used brushes made of copper or brass to make the electrical connection with the rotating commutator. This method caused heavy sparking and very short commutator life.

In spite of their poor performance they formed the power source enabling the are lamp to become the replacement of gaslight. In 1876 Charles Brush used are lamps to light the Cleveland U.SW main square, proving that electricity was indeed a better power source for lighting purposes.

The carbon electrodes that were used in those days were made from gas coke, a by-product from the production of gas. However this material showed big differences in wear, mainly caused by impurities.

Charles Brush searched for a source for more pure carbon. The answer was found at an oil refinery where carbon residue from the distillation process. This product, called petroleum coke is nowadays one of the most important base materials for the carbon industry.

The use of carbon for electric motors in fact started with the Scottish professor George Forbes who experimented with different methods to improve the contact with a rotating commutator. In 1885 he patented a method that used copper strips on which thin layers of carbon were glued. As happened in other fields, it was quite impossible to find any really interested companies that would like to use his invention. Finally he sold his patent to Westinghouse for £2000. Westinghouse made little or no use of the idea.

Thomas Edison had built the first electric tram and proved that electricity is an excellent power source for traction. Those early traction motors used brushes made out of copper wire. The commutator wear, caused by these brushes made use of electric traction practically impossible. One of his collaborators, Charles van de Poele, started an experiment with pieces of carbon while trying to find a solution for this problem. The results showed a major improvement, compared with the copper wire brush.

Soon after these experiments, carbon became the replacement for the copper brush. The name carbon brush however still reminds us of the old days when a (copper wire) brush was still a real brush.

With an acceptable commutator life the d.c. generator and motor rapidly found their way into a variety of industrial applications and still today form an important element in the generation of electricity, traction, automotive, household appliances and other applications.

II. Fabrication of carbon

The methods used today for the fabrication of carbon do not have much in common with the methods of the early days. A lot of research into the base materials, process and process control has made this technology into a real science.

Measurement of properties at every step of the process ensures that the final product has the required mechanical and electrical properties within the narrowest possible limits.

.1 Basematerials

As basis for most industrial carbon applications the following products are used:

.a Petroleum coke

Petroleum coke is a by-product from the oil refineries and contains traces of oil and other volatile substances. Before use it is calcined at high temperature to drive out all those volatile elements. It is then crushed and milled to flours of definite particle sizes.

.b Lampblack

Lampblack is one of the most important ingredients in carbon brushes. It is produced from oil that is burned in a special furnace under carefully controlled temperature conditions and with accurately restricted supply of air. Like the flame of a kerosene lamp, when the wick is turned too high, the flame in the burner of these furnaces is very sooty. The soot is practically pure carbon which deposits on the ceilings, walls and floor of huge settling chambers through which the products of combustion pass.

.c Graphite

Graphite used in brush materials includes a wide range of mined graphite from all over the world and artificial graphite. Artificial graphite is produced by high temperature treatment of carbon materials.

.d Pitch

It is necessary to bind the ingredients with a binder that further in the process can be reduced to carbon.Pitch is a very good binder and will reduce to carbon at high temperatures.

.2 Mixing

All the raw materials, having gone through their respective process of

preparation, have to be mixed. Accurate quantities of lampblack, coke and graphite or possibly just one or two of these ingredients are weighed out in amounts specified for the product to be manufactured. These are put into the mixer and thoroughly mixed with the required amount of binder. This is one of the most important steps in the whole manufacturing process. To insure uniform and consistent quality it is of utmost importance that materials are homogeneously mixed. The carbon mixing is then pressed in blocks. During this step in the process the pressure of the press has to be monitored carefully, as it influences the properties of the final product. For carbon brushes for some applications such as certain types of household appliances and automotive alternators the carbon mixing is directly pressed to its final shape.
After all properties of the pressed material have been checked, the blocks are then baked.

.3 Baking

During the baking process the bonding material is carbonized by driving off all the volatiles to give the whole composition a rigid structure. This process is done in specially designed furnaces at high temperatures for a period of several days. The temperature cycle, as well as the ultimate temperature, is subject to very accurate control.

.4 Graphitisation

Most of the carbon grades that are used in industrial direct current applications are known under the name electro-graphite. The blocks that come out of the baking process are given another heat treatment in special electric furnaces where the temperature is carried to a point far beyond that is possible to obtain in the preceding bake. At this tremendous heat (greater than 2500ºC) practically all elements other than carbon, which might have escaped earlier purifying stages and remained in the block, are volatilized and driven off. Carbon from the original mix and the carbonized bond are changed from the amorphous form into the crystalline structure of graphite. This gives the process its name of graphitisation and the material is called electro graphite. Its effect on the performance characteristics of a brush material is very marked. The electrical conductivity is increased and the friction lowered. Abrasivness is reduced and commutating properties are improved.

.5 Other types of brush material

Besides carbon, the product from the baking process, and electrographite, there are some more types of brush materials used in the industry, such as:

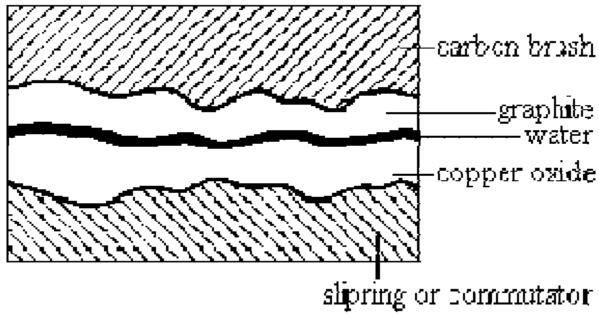
- Resin bonded material
  The ingredients such as graphite are milled and bonded with a resin instead of pitch or tar. The mixed ingredients are pressed to size or in the form of blocks that are cut to the requested dimensions afterwards. The pressure and temperature during the press operation are very important factors determining the electrical and mechanical properties of the final grade. Resin bonded graphite is often used for smaller household appliances, small difficult commutating industrial machines, or a.c. commutator motors.
- Metal graphite
  There are two different ways to manufacture metal graphite grades, which are:
  - Metal impregnated grades
    Carbon is a porous material. In autoclaves the material is impregnated with molten metal, filling the pores of the carbon structure. Material, thus obtained has lower electrical resistance than carbon and better thermal conductivity. These grades are often used for contacts or brushes for low voltage d.c. motors or sliprings.
  - Metal powder mixed grades
    Graphite and metal powder are mixed and pressed under high pressure. After sintering a material is created with low electrical resistance and high strength. Applications are: slipring brushes, starter motors and alternators for cars, low voltage d.c. motors and electrolytic tinning lines.

III. Commutator film and carbon brush performance

In the next paragraphs a theory of brush performance will be explained based on oxide, water, commutation and contact. The first two are essential to the commutator film. This film is automatically formed on a copper ring or commutators under normal working conditions. Without this film the friction would be extremely high, causing very short brush-life. The film, which is very thin, is built up from the following elements:

.1 Copper oxide

Copper oxide is the most important part of the film.

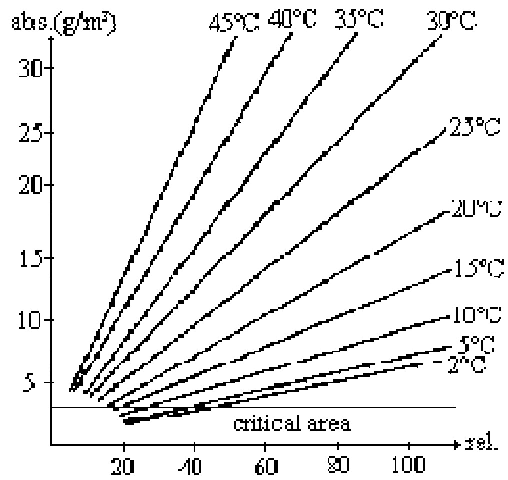


The following influences formation of the oxide layer:

- Temperature
  On a copper ring or commutator an oxide layer is quickly formed at a temperature of 80 - 100ºC, even without an electric current.
- Electric current
  The flow of current from carbon brush to ring or commutator is not through a very large number of contact spots as in the case of normal electrical contacts. Only a limited number of conducting spots carries the total current load. This means that at these points the current density is extremely high. So high that at these points a very little amount of copper will ionize. After a short while the conducting spot stops performing and others take over that task. Thus we can say that the current flow between a brush and commutator or ring occurs through a constantly changing, small number of high current, point contacts. After a point stops conducting, a little bit of copper oxide remains. This explains why electric current through the brush helps to form the oxide part of the film.

.2 Water

Another very important part of the film is water. The humidity in the air normally provides the water needed to reduce the friction to an acceptable low level.
In very low temperature conditions, the absolute humidity of the air will be too low. This can cause high brush wear. The absolute humidity can be calculated from the relative humidity and the temperature by using the graph on this page.



If the absolute humidity drops under 2,5 g/m³ brush problems may occur.
In those cases where the humidity is always extremely low, such as in air-crafts at high altitude, brush grades with additives are used that can substitute for the water in the film and reduce friction to an acceptable level.

.3 Graphite

Little particles of graphite from the brush face form a part of the film. It also helps to keep the friction low. This does not mean however that a thick black film is a sign for good brush performance. A too heavy film can disturb the current flow causing sparking, pitting and could be the beginning of a very unstable situation such as film stripping and flash-overs.

.4 Filmforming and practical problems

As described before, the film contains oxide, water and graphite. Factors that influence the filmforming are:

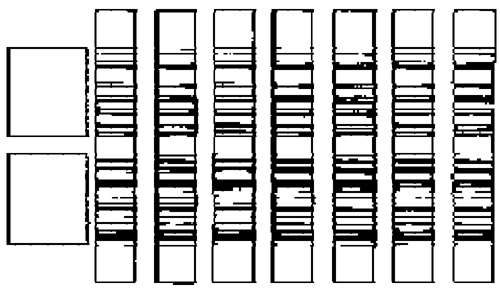
- Ring or commutator temperature.
- Electrical current.
- Humidity.
- Graphite particles.

During operation the above mentioned filmforming factors built up the film and at the same time the rubbing effect of the brush and possible pollution are trying to remove the film.
Under good operating conditions a stable situation will be reached in which the

rate of build up and break down of the film are equal.
Disturbance of the stable situation will cause problems.
Following are some typical practical cases that will be explained using the theory of filmforming as described above.

.a Threading under low load

At very low loaded machines, such as continuously running generators, threading is a well-known phenomena. The commutator (or slipring) shows fine grooves over the total brush path.



This threading is likely to be found at too low electric loads typically less than 6 A/cm² on the brush face and at too low commutator temperatures (less than 40ºC). These factors reduce the formation of oxide, and too thin a film is the result. As friction will be higher, small particles of copper are removed from the commutator. Embedded in the brush face these copper particles can cause scratches on the commutator, the beginning of threading.

Improving the film formation can stop threading. This can be done in a number of ways.

- Increase oxidation by reducing the number of brushes the current density per brush increases, which cause more oxide to be formed. When removing brushes it is important to keep an equal number of positive and negative brushes on each track.
- Increase the commutator temperature, for instance by reduction of the amount of cooling air.

- Use a specially treated brush grade that helps to increase the formation of oxide.
- Increase the graphite part of the film by using a more graphitic type of brush grade.

.b High wear without sparking, normally in combination with highly polished commutator surface

In cases like this, the brush surface is normally also highly polished and tight textured. These signs indicate high friction. Reasons for this high friction can be:

- Too low humidity.
- Too low temperature.
- Wrong brush grade.

If humidity and temperature cannot be changed to levels where brush performance is satisfactory, the brush grade must be changed.

In a number of locations in the world, the humidity can become low during winters (Canada, Northern Europe). In those areas there is often poor brush performance due to low humidity.

Humidity can be improved as follows:

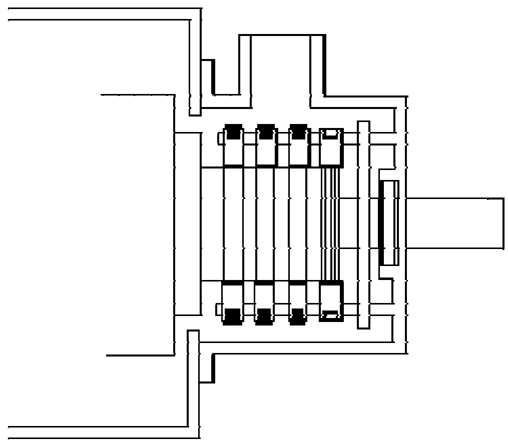
- Installation of an industrial humidifier in the cooling air system.
- To bring the cooling air from a place where the humidity is higher.

In practice a lot of simple and inexpensive techniques to increase the humidity were developed that may work quite well. Two of them are:

- In the air intake of a cooling system of a turbo alternator a little bit of steam was injected, just enough to increase the humidity to a workable level. The result was a significant increase in brush life. Under conditions where the humidity of the air was sufficient the steam injection was stopped.
- A small tray filled with water was placed inside a totally enclosed motor. After this, brushlife was improved considerably.

.c Different film at different brush tracks

If the brush pressure and mechanical contact is within limits, the cooling air likely causes this phenomena. One track can be cooled different from an other, for instance due to the design of the air inlet in the motor.



The brushes with less cooling (right) will have the highest current due to the negative temperature coefficient of total contact resistance. The oxidation rate of the commutator will be higher because of higher current and higher temperature. If the oxide film becomes somewhat thicker than the other tracks, causing friction to be less, the result is lower brush wear. If overfilming occurs in that one track, brush wear can become much higher than on the other tracks.

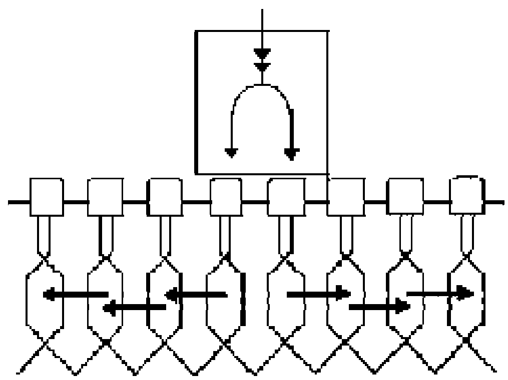
IV. Carbon brushes and commutation

.1 Commutation

For our theory of brush performance we explained the importance of oxide and water. Both effect the performance of brushes on slip rings as well as commutators.

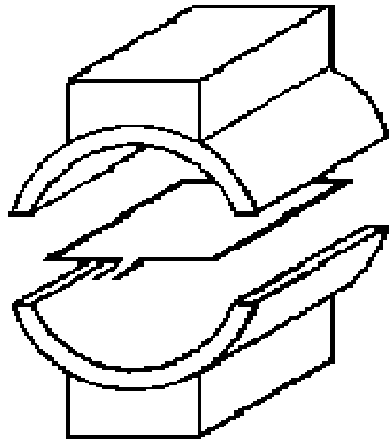
In commutator motors or generators there is another element that plays an important role in the performance of carbon brushes, the commutation process.

A commutator could be defined as a rotating switch that changes the direction of the current in an armature coil. The electrical effects that are found during changing of the direction of the current are known as commutation. The following drawing illustrates this.



Every armature coil is connected to the two adjacent commutator bars. The electrical current flows through the brush via the bars in two directions into the armature. In the coil that is short-circuited by the brush, there is theoretically no current. When the commutator turns, compared to the fix position of the brush, a certain coil will first be part of one circuit of armature windings, then short circuited by the brush, and finally be part of the other chain of armature windings. This coil is called the commutating coil. So, during commutation the direction of the current in the coil is reversed.

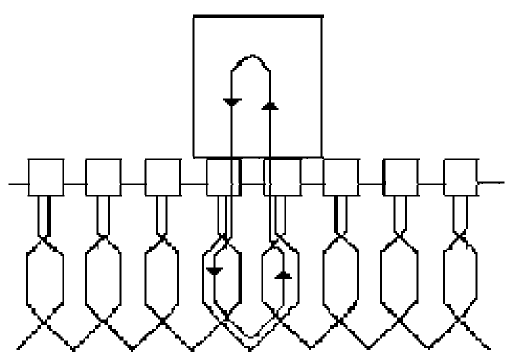
The magnetic field of the main poles of a d.c. motor or generator induces a voltage in the rotating coils. Theoretically this voltage is zero when a coil is in a position 90° to the magnetic field. This is also the position where the brush short-circuits the coil.



In practice the magnetic field is never in a position exactly 90° to the coil that is short-circuited by the brush. Design limitations of the motor, tolerances in the magnetic circuit, adjustments of air gaps and brush holders can all influence the direction of the magnetic field compared to the position of the commutating coil.

This implicates that there will be a voltage induced in the coil that during commutation is short-circuited by the brush.

As a result, a current will flow, called the circulating current. Circulating current is caused by the voltage induced in the commutating coil and flows within one coil, through two bars and one brush.



.2 Circulating currents

Too high commutation currents will cause the brushes to spark, the brushes and commutator to wear faster or worse, may cause flash-overs.

The circulating current follows Ohm's law, and is therefore dependent of:

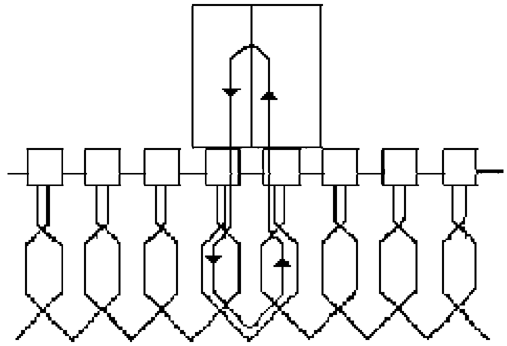
- The voltage induced in the commutating coil. Most important factors that influence the voltage induced in the commutating coil are:
    - Neutral zone.
      The neutral zone is the position of the brush compared to the total magnetic field. As described before this must be set in such a way, that at the moment the brush shortens a winding, it makes an angle of 90° to the total field. At this position the induced voltage is minimum.
    - Strength of the interpoles
      The main armature current of a d.c. motor or generator induces a magnetic field at a 90° angle to the main field. The interpoles should compensate this field completely. If required the interpole field can be adjusted by means of shims, which are placed between the stator and interpole base. By using metallic or non metallic shims the airgap of the interpole magnetic circuit is changed, influencing the total magnetic resistance and the magnetic flux. The motor manufacturer adjusts Interpoles at an optimum. When severe sparking occurs, even with the correct brush grade and correct neutral setting, the interpoles may have to be adjusted.
- Resistance of the closed circuit.
  The resistance of the brush coil circuit is determined by the resistivity in the path of short circuit current in the brush. The higher resistance, the lower the circulating currents. The current through a carbon brush on a commutator is always a combination of main current and circulating current. The position of the brush holders (neutral zone), the strength of the interpoles and the resistivity of the brush influence the circulating current on a given machine. In practice two of those can be changed rather easy by means of:
    - Setting of the neutral zone.
    - Choice of the brush grade with the appropriate resistivity.

.3 Brushes and commutation factor

The commutation factor of a carbon brush is its ability to handle the electrical effects during commutation. This factor is influenced by:

- The resistivity of the brush material.
  As discussed before, the resistivity of the material in the path of the circulating currents is of great importance. This means that the resistance in the path depends on the resistivity of the brush material, the contact resistance and the brush design.
- Elasticity
  An equally important factor determining the commutation abilities of a brush grade is the elasticity of the brush material. A material with high elasticity (low Young modulus of elasticity) is better capable to follow each bar on a commutator and therefore is capable of making a better and longer electrical contact.

The commutation abilities of a given brush grade can be improved by changing the brush design. For instance, if the brush is split up in two wafers (thickness) a contact surface between the two halves is formed with higher cross resistance than that achieved with a single wafer brush.

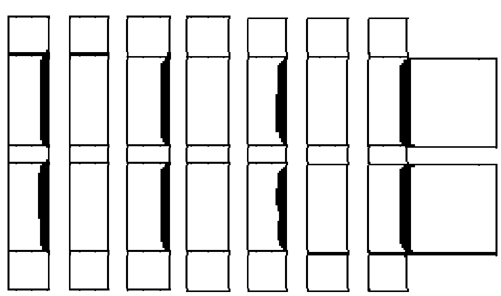


This split design increases the resistance of the short circuit path, thereby reducing the circulating currents. Using a brush with 3 or 4 wafers will increase the commutation ability.

Mechanical strength limits the number of wafers that can be used. Too thin wafers easily brake under mechanical stresses.

.4 Commutator appearance and commutation problems

In chapter 6 we will introduce the expression, language of the commutator, an expression that is very much true when commutation problems are the case. Even in an early stage of commutation problems, the commutator clearly indicates this phenomena to us. Besides sparking under load, which might not always be seen, the commutator shows a regular pattern of dark and light bars. In a later stage this can develop in a regular pattern of bars with bar edge burns. If neglected this problem can develop in a regular pattern of totally burned bars, causing exceptionally high brush-wear, heavy sparking and finally flash-overs. A situation requiring immediate action.



The reason of the regular pattern of different colored bars is found in the design of the d.c. motor or generator. Windings connected to a number of adjacent commutator bars come together in one armature slot (the number of commutator bars is not the same as the number of slots). If for instance 3 windings of adjacent commutator bars use the same armature slot, two windings might be positioned in such a way that the induced voltage during commutation is low. The third winding will be in a worse position to the magnetic field, causing higher commutation currents. This effect itself cannot be changed. The results, bar marking, bar edge burning or bar burning can be reduced by:

- Choice of a brush grade with better commutation properties.
- Better adjustment of the neutral.
- Adjustment of the airgap (inter-pole strength).

V. Electrical contact

In our theory of brush performance we so far discussed the elements oxide, water and commutation.

Electrical contact, is equally important. Problems with electrical contact may occur on commutators as well as on a slipring.

It is essential that the brush must make a good contact with the commutator or ring. A bad contact condition will cause sparking and burning marks. The places of burning marks form spots of high friction, causing the brushes to jump. The result is an even worse contact, giving more sparking and heavier burning. This shows that, once problems with the contact have started, they never stabilize but always get worse, eventually causing flash-overs and severe machine damage.

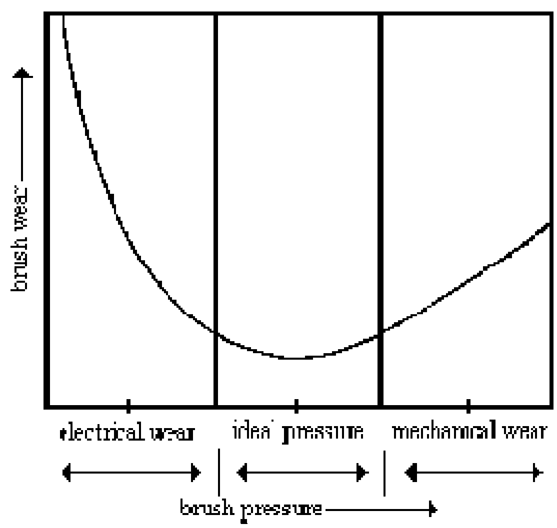
The parts of the electric machine that influence the contact are:

.1 The brush holder

It is important that the brush holders are equipped with springs with the same pressure.

For industrial applications, a brush pressure of 140 to 360 g/cm² brush surface must be chosen. This depends on the selected brush grade and the application.

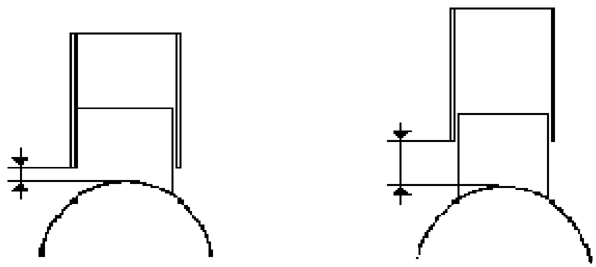
Heavy vibrations with an external cause require higher pressures; sliprings in a smooth running alternator require a lower pressure. Too high brush pressure gives higher mechanical wear. Too low brush pressure gives sparking thus electrical wear. Also important is to have uniform pressure.



If the brush holder is damaged on the inside, the brush will stick in the holder. The effective pressure will, in that case, be much less, causing electrical wear. It is important to periodically check the brush pressures and the free movement of the brushes in the holders.

Loose holders, brush arms or rockers will obviously give the same bad effect to the electrical contact.

The clearance between slipring or commutator and brush pocket is also important. Ideally this should be between 2 and 3 mm. Too large clearance makes a worn brush unstable in the holder.

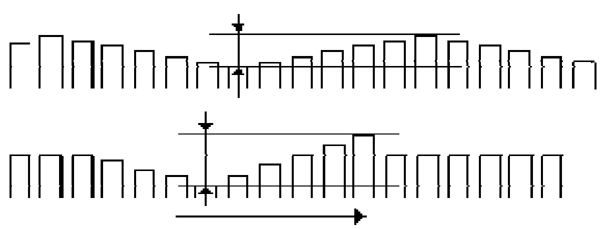


.2 The slipring and the commutator

The condition of the slipring or commutator also effects the contact of the brush.

Some examples:

- Commutator construction.
  The centrifugal force sometimes causes the commutator to deform to an unacceptable level. This deformation is unacceptable if some bars or groups of bars move into a higher position than the others do. High bars act like a cutting tool, causing high brush wear and sparking.
- Out of round commutator or slip-ring.
  An unround commutator or slipring gives the same effect as an unstable commutator. In this case the profile of the commutator does not change back to its original shape when the machine is stopped. Typical limits of commutator and slipring unroundness, however depending on the speed, are:
    - 0,08 mm total out of roundness.
    - 0,02 bar to bar.



If values are found higher than these limits, the commutator has to be resurfaced.

- Burned spots.
  Burned spots on the ring or commutator can be caused by various reasons. Some of them are:
    - local overload
    - out of roundness
    - unstable commutator
    - vibration.

At the burned spots the brushes will have a tendency to jump.

- Scoring of the commutator.
  Undercutting the slots between the bars of a commutator is a precise job. It can happen that the tool for undercutting or the scraper that is used to bevel the sharp copper edges, damages the bar surface. In that case the high edges of the score have to be removed with sand paper. It is important that grinding with sand paper is performed in the direction of rotation (tangential) and not in the axial direction.
- High mica.
  If the mica is not undercut in the proper way, some mica will be higher than the adjacent bars. It is therefore important to insure that fins of mica do not remain in the slots. Heavy sparking and high brush wear will be the result.

VI. "Language" of the commutator

During the many years of experience with carbon brushes engineers have found hundreds of different causes that effect the performance of carbon brushes. We have described four important elements, which are:

- oxide
- water
- commutation
- contact.

Using those four components as a checklist most of the problems with brush performance can be explained and counter active measures taken. In fact, with these components given it must be possible to understand the language of the commutator.
Using the four components theory, an explanation can be given for most problem situations, making the corrections a logical step. After all, the black magic is only clear logic.

VII. Typical problem situations

.1 Heavy sparking under load

- Oxide.

Is there enough film built up? The brushes could vibrate due to high friction, causing them to spark.

- Water.
  Too low humidity gives the same effect as described under oxide.
- Commutation.
  Inspect the commutator and look for a regular pattern of discolored or burned bars.
- Contact.
  Check the following:
  - Do the brushes freely move in the holders?
  - What is the variation in brush pressure?
  - Mechanical connections brush holders, arms rockers are they tight?
  - Commutator roundness.
  - High mica.
  - Unstable commutator (spin the motor at full speed and feel the vibrations of the brush with an non conducting thin rod).
  - Rough spots.
  - Disconnected or short circuited windings (badly burned bar or group of bars)?

.2 Broken or chipped brushes

- Oxide.
  Is there enough film and is therefore the friction low enough.
- Water.
  Is there enough moisture to keep the friction low.
- Commutation
  Only in a later stage of heavy bar edge or bar face burn the brushes may break.
- Contact.
  - Too weak springs.
  - Unround commutator or slipring.
  - High mica.
  - Loose mechanical connections.
  - Strong vibrations from outside.

.3 Broken flexibles

Near the connection with the brush.

- Oxide.
  The vibrations that are caused by high friction cause vibration of the cables. The result is metal fatigue and broken flexibles.
- Water.
  Too low humidity also causes high friction.
- Commutation
  No relation.
- Contact.
  Vibrations caused by unround commutator or ring, bad pressure fingers, high mica or loose holders may cause the brushes and cables to vibrate. Metal fatigue then can cause the flexibles to brake.

Some times broken flexibles can also be found at other places, for instance at a point half way between brush and terminal.

The cooling air can cause this, as the air stream makes the cables to vibrate. At the places where the cables touch each other or the holder pressure finger, the rubbing effect damage the flexible. An easy cure for this problem is to insulate the flexibles or to hold them together with a metal band.

.4 Discolored or burned cables

- Oxide.
  High friction cause extra heat dissipation. Cables will be heated to a point where they discolor. Differences in cooling air cause different film built up at different brush tracks and different current densities. The brushes with the highest current will show discolored cables.
- Water.
  Increased friction causes an increased temperature.
- Commutation
  On d.c. motors or generators with bad commutation that use a split brush design it can happen that the cables of one part of the split brush are discolored or burned. The circulating current causes this effect.In a split design brush a large part of the circulating current will flow into one brush part, through the flexible(s) into the terminal, and then back through the flexible of the second brush half into the brush path and commutator. The main current flows from the terminal through the cables into both brush parts. This means that in one set of cables and one brush half the commutation current and main current are in opposite direction, and in the other half in the same direction. As a result the total current in one brush half and its connecting cable(s) is much higher than in the other half. The current densities can become so high that the cables of the brush wafer with high current may discolor or burn.
- Contact.
  Bad contact may cause some brushes to carry much less current. Others have to share this extra current that could lead to overheating of the cable. Unequal spring-pressure is a typical cause.

.5 Unequal brush-wear on different brush tracks

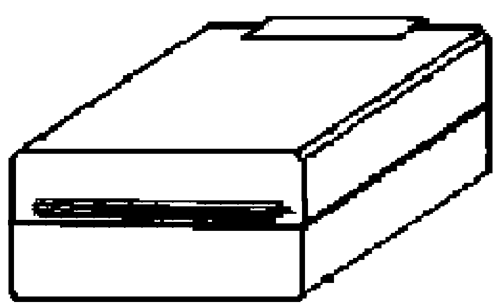
- Oxide.
  The built up of oxide between brush tracks could be unequal, likely to be caused by unequal cooling. A film will be built up of unequal thickness with different friction per brush track and therefore different brush wear.
- Water.
  No direct relation.
- Commutation
  No direct relation.
- Contact.
  If the commutator has been damaged under one specific brush track, the brush wear is obviously higher at this brush track than at the others. Heavy vibrations of brush holder assemblies could also cause extra wear. Unstable brush holder assemblies normally show a pattern of increasing wear from one side of the commutator to the other. Brushes close to the rocker show the lowest wear (more stable).

.6 Different brush-wear between brush arms

- Oxide.
  Besides the fact that a brush with negative polarity wears less than the one with a positive polarity (flow of electrons) there is no connection.
- Water.
  No relation.
- Commutation
  If the airgaps between interpoles or main poles and rotor are different (4 poles or more), some brush arms will see heavier commutation currents than others. Bad equipotential connections in the motor can also cause differences in brush currents.
- Contact.
  Loose or damaged brush arms, bad electrical connections between brush arms and main cables also may cause unequal currents between brush arms.

.7 High brush-wear without serious sparking

- Oxide.
  Not enough film will give too high friction. This can give more brush wear. A highly polished commutator is normally an indicator of high friction. The brush face will be closed and polished, also the brush sides may be polished.
- Water.
  There is also a clear connection between low humidity and high brush wear, having the same effects as described for the oxide film.
- Commutation
  Very good commutating brush grades do not show much sparking. However, at bad commutation conditions wear is expected to be higher than when commutation is good. A dark stripe on one brush wafer, or traces of burning on the brush face are signs of poor commutation.



- Contact.
  Normally would be in combination with sparking.

.8 Dark commutator with pin point size pitting

- Oxide.
  The circumstances are such that a heavy film is formed. Possible reasons are high load, high temperature or a brush grade that tends to overfilm under those conditions.The thick film makes current flow difficult. The current punches through the film, forming pin point size spots through which the current can flow. This situation can happen after a relatively short period of heavy load.

If the spots are shiny (pure copper) the situation may be more serious. If the spots are covered with film (dull) the situation is stabilized, for instance because the load is back to normal again. Pitting will, in a later stage develop into film stripping, high friction, severe sparking and finally flash-overs.

- Water.
  No relation.
- Commutation
  Heavy circulating currents can also cause the pitting effect under overfilming conditions.
- Contact.
  Only in a later stage the film stripping can cause the brushes to loose contact with the commutator.

.9 Copper dragging

Copper particles are pulled from the bar face to the bar edge, forming a rim of copper, that in a later stage can cause a short circuit between bars.

Copper dragging can be caused by:

- High friction.
  Mostly detected in combination with polished sides of the brush and closed brush face. The high friction cause the brush to vibrate in the holder. This hammering effect cause the copper to be pushed to the edge and into the slot. By reducing the friction this problem will be solved (higher current density, higher temperature, brush grade with better filming properties). It is necessary to carefully clean copper drag from the commutator slots after copper drag is found.
- Pick-up of copper particles in the brush face.
  Under specific conditions and the use of porous brush grades, copper particles get into the brush face. The circulating current at the bar edge sinters these particles back on the commutator. Usually the cure will be a change of brush grade.

.10 Threading

The depth of the grooves will increase with time.

- Oxide.
  Not enough oxide. Metal particles are picked up from the ring or commutator surface and embedded into the brush face. These particles have at least the same hardness as the ring or commutator and will therefore cause the threading. By increasing the temperature or the current density (remove brushes) oxidation is improved and threading stopped. A brush grade with better film forming properties is another solution.
- Water.
  No relation
- Commutation
  No relation
- Contact.
  No relation

.11 Commutator wear (ridging or grooving)

- Oxide.
  Ridging, commutator wear on the brush paths can be the result of a long period of threading (see 10). Other cause can be abrasive dust, corrosive gas or oil in the cooling air, usually with high brush wear. Ridging is sometimes also caused by too abrasive brush grades.
- Water.
  No relation
- Commutation
  No relation
- Contact.
  No relation

.12 Regular pattern of discolored or burned bars

- Oxide.
  No relation
- Water.
  No relation
- Commutation
  As described in paragraph IV, carbon brushes and commutators, the bars that are connected to bad commutating coils can become darker than the other bars. A light discoloration is quite acceptable.
  A situation with burning marks is more serious and steps have to be taken to improve the commutation of the motor or to change the brush grade or brush design. To identify traces of burning, the black deposit on the bar edge is carefully removed with a pencil eraser. If underneath no burning marks are found, the situation is stable.
- Contact.
  Only when the bar edge burning becomes severe, the contact will be poor, causing extra sparking and commutator damage.

.13 Dull black film

- Oxide.
  It is obvious that the film is too thick. The situation can be improved by increasing the cooling or reducing the current density, or to change the brush grade to one with less film forming properties (clean running).
  Pollution of the cooling air with chemicals that help oxide formation, also quite often cause the film to become too thick. In that case the best solution is to get cleaner cooling air. A change to a clean running brush grade might also help.
- Water.
  No relation.
- Commutation
  Strong circulating currents also contribute to more filmforming. If the machine is correctly adjusted, the solution can be a change of brush grade.
- Contact.
  No direct relation.

VIII. Inspection procedures

The relationship between commutator or ring appearance and the four different components oxide, water, commutation and current have been described.

During an inspection all four components have to be checked carefully. Not only the commutator or ring has to be inspected, but also all parts of the collecting mechanism.

The following list provides a number of checkpoints that together will help you to form your opinion about the condition of motor or generator.

1. Mechanical damage on the outside of the machine.
2. Vibrations of the machine near the bearings under working condition.
3. Temperature of the machine near the bearings under working condition.
4. Air inlet or filter.
5. Commutator area.
    a. Carbon dust, sand, etc.
    b. Oil or grease from the bearing.
    c. Water.
    d. Copper dust.
6. Commutator.
    a. Mechanical damage.
    b. Threading, grooving, ridging.
    c. Bar face or bar edge burn.
    d. Color of the film and discoloration of the copper.
7. Commutator slots.
    a. Dust.
    b. Other types of deposits.
    c. Copper dragging.
    d. Depth.
    e. High mica
    f. No sharp edges.
8. Brush holders.
    a. Correct force of pressure fingers (tolerances of ±10% are acceptable)
    b. Easy radial movement of brush in holder without pressure finger in place.
    c. Distance between holder pocket and commutator (2-3 mm).
    d. Correct angel of brush-holders.
    e. Signs of flash-overs.
9. Riser bars.
    a. Connections.
    b. Signs of flash-overs.
    c. Carbon dust.
10. Brush arms.
    a. Fixing bolts.
    b. Electrical connections.
    c. Distortion
11. Brushes.

a. Differences in wear between the brushes.
b. Discoloration or damage of the flexibles.
c. Brush face burning, traces of commutation, porosity.
d. Sides of the brush, polished surfaces indicate high friction or out of round commutators.

12. Load connections.

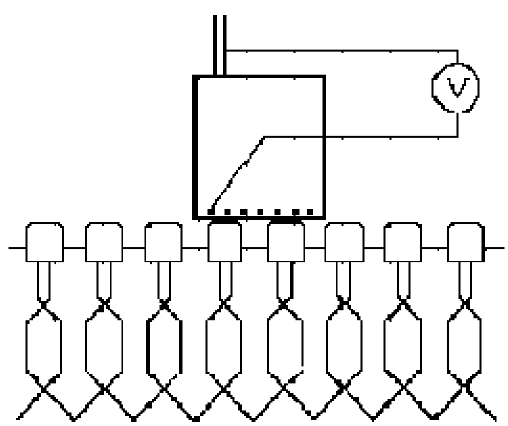
a. Check the current density and calculate the current density in the brushes.

IX. Adjustments and checks of d.c. machines.

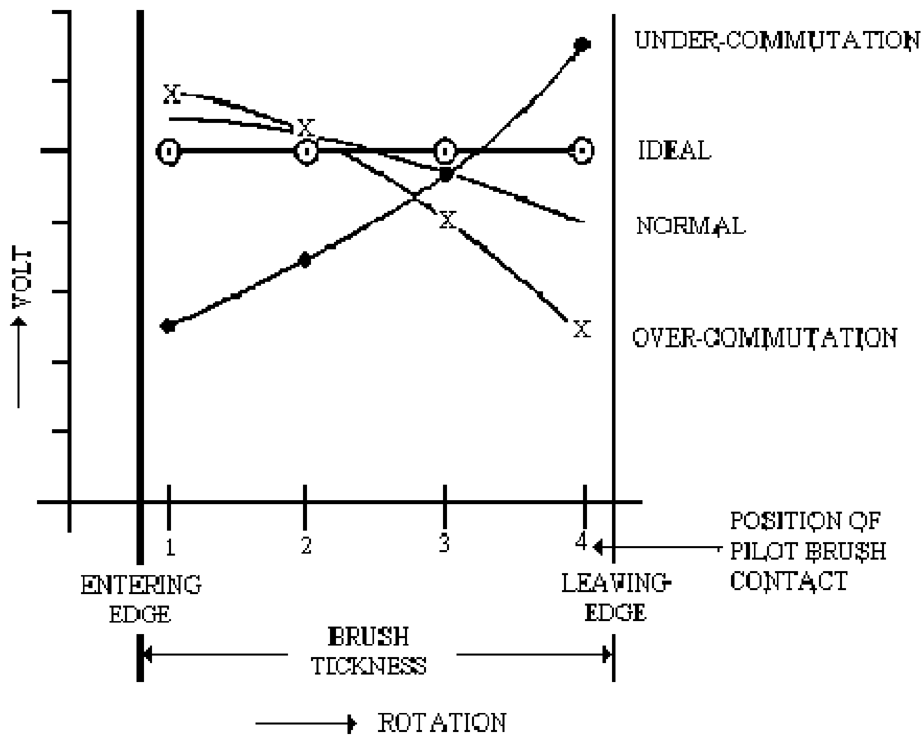
.1 Neutral zone

The neutral zone of a d.c. machine can be set in various ways. Three of them will be described.

1. The no load speed method.
   At a given field and armature voltage the speed is measured in both directions of rotation. In the neutral position both speeds must be the same.
   This technique cannot be used if the brushes are in a non radial position (trailing or reaction), as friction will be different in both directions.
2. The AC power-source method.
   The main field of the d.c. machine is connected to a AC power-source. This AC voltage induces a changing magnetic flux. This flux induces a voltage in the armature coils. Theoretically the total voltage induced in all coils between two brushes of different polarity have to be zero. If the brush-rocker are not in a neutral position the induced voltage can be measured on two brushes of different polarity. The brush-rocker must then be turned to find a position of minimum reading on the meter. This is the neutral position.
3. Brush potential method.
   With the D.C. machine under nominal load the voltage at a number of points over the brush surface close to the commutator is measured.



The results, plotted on a graph give an indication about the commutation and can help to set the neutral (see graph).

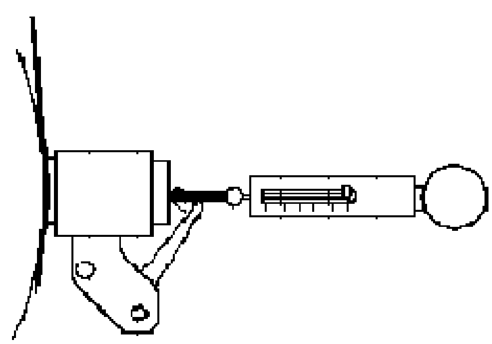


The advantage of this method is its accuracy; the disadvantage is that it is time consuming.

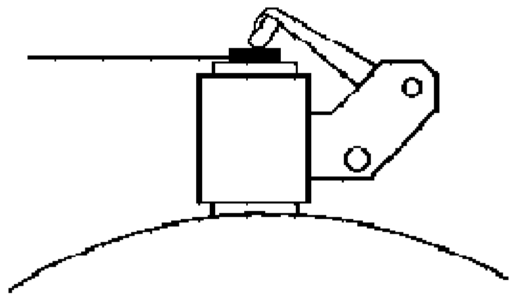
.2 Brush pressure

Brush pressures have to be checked regularly. Two types of instruments can be used.

1. Tension scale.
   The tension scale is connected to the pressure finger by means of a strap. A strip of writing paper is placed between commutator and brush. The pulling force on the tension scale must be increased gently to the point where the piece of paper slips free. At that point the scale indicates the actual pressure.



2. Digital brush pressure meter.
   Instruments specially designed for accurate brush pressure (force) measurement are available. A miniature load cell is placed between pressure finger and brush. The digital read-out gives an accurate reading of the pressure.



The required brush pressure is normally given in grams/cm² brush surface. The brush pressure that was found with the tension scale or brush pressure meter has to be divided by the surface of the brush (cm²) to get the value. The table gives some guidelines with respect to brush pressure (grams/cm²) and application.

Machine	min.	nom.	max
Sliprings asynchronous machines	140	200	300
Sliprings synchronous machines	120	160	225
Sliprings turbo alternators	90	140	180
Industrial d.c. drives	140	225	360
Rapid transit/tramway	225	300	450
Locomotives	285	350	600

The right pressure for the application is important. More important however is that all brushes have the same pressure ±10%.

.3 Brush holder position

The brush holders have to be positioned approx. 2-3 mm from the commutator or ring. A practical way of doing this is with the help of a plastic strip of the correct thickness. This strip is placed under the holders on the ring or commutator while the holders are fitted. Make sure that all brush-holders have the same angle relative to the commutator or slipring.

X. Maintenance

In this section some brush related maintenance jobs are described that have to be carried out on a regular basis.

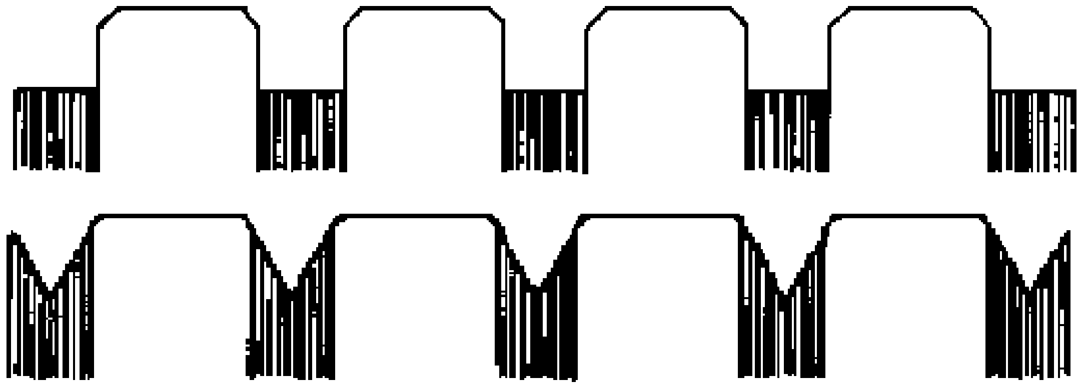
.1 Seating of the brushes

When a complete set of brushes has to be replaced, brushes have to be properly seated to ensure full brush face contact with the ring or commutator.

- Using sandpaper.
  A piece of sandpaper, that has to be wider than the width of the brush, is placed between the brush and the ring or commutator, with the abrasive side towards the brush. Draw the sandpaper a number of times in the direction of rotation until the brush-face is properly shaped. Note that the sandpaper completely follows the ring or commutator curve. After grinding the brushes must be removed from the holders and commutator or ring and holders properly cleaned with compressed air and brush.
- Using seating stone.
  Seating stones are made of a soft abrasive material. The stones has to be gently held against the rotating commutator. Note that depending on the motor voltage, the stone has to be clamped in an insulating holder. Particles of the stone get between brush and commutator and grind the brush surface to a perfect fit. After seating all brushes have to be removed and the holders and the commutator properly cleaned.

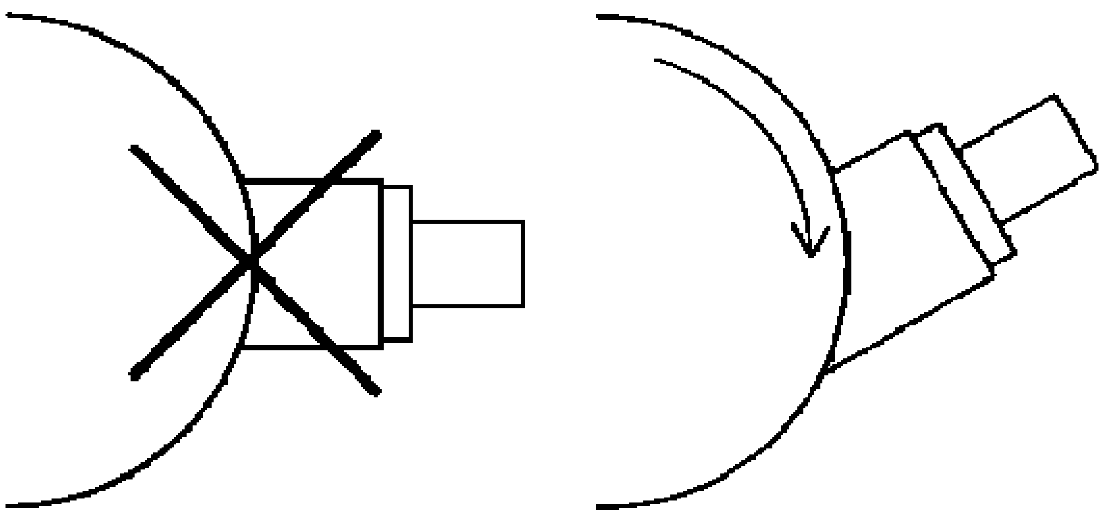
.2 Slotting

The mica between the commutator bars has to be removed (slotting). For this purpose special slotters (fine pitch saw-blades of special shape) are available. First all slots are undercut to the required depth (as a rule the depth is equal to the width of the slot). After slotting the bar edges have to be chamfered, typically 0,5mm/45°.



.3 Grinding

Based on my experience I strongly advise to only grind the commutator by hand if no support can be mounted in the motor or the complete rotor cannot be removed. For hand grinding the surface speed of the commutator should be approx. 10 m/sec. The grinding stone is gently held on the commutator surface and slowly moved in axial direction. Out of roundness will hardly be reduced. Roughness will be reduced. Notice that the grinding stone is not pressed in radial position on the commutator, but always trailing (see drawing).



It is always preferred to have the stone fitted in a special support, a method that gives perfect round commutators. Experienced motor repair shops normally carry out this job.

Renown Electric's Guide to Carbon Brushes for Motors & Generators

Table Of Contents

Introduction

What is A Carbon Brush?

Also known as a motor brush, a carbon brush is a sliding contact that is used to transmit an electrical current from a static to a rotating part in a generator or motor. In DC machines, a carbon brush ensures a spark-free commutation.

They can be made of one or more carbon blocks, and come equipped with one or more shunts or terminals. In brush manufacturing, five brush-grade families are used, each of which has its own production process and corresponds with its own specific requirements.

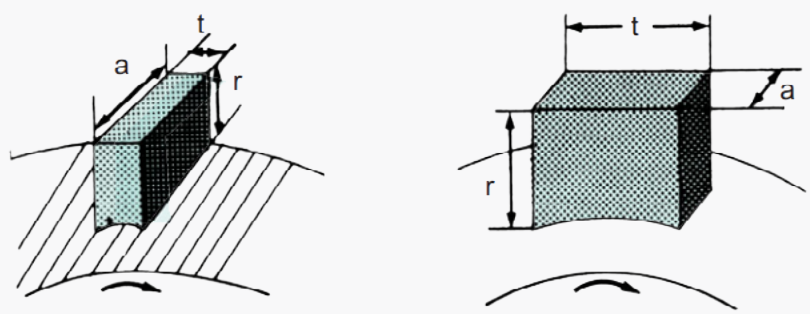
Carbon Brush Operation

As an essential part of the operation of electric motors, a carbon brush has three operating parameters: **mechanical**, **electrical** and **physical/chemical (a.k.a. environment)**. The selection of the right carbon brush grade for a specific application will depend on these parameters and ensure the best performance.

MECHANICAL

Slip Ring and Commutator Surface Conditions (Roughness) *(Fig. 1)*
Using the right slip ring or commutator provides an adequate seating base and good current transmission for the carbon brush. They should not be too smooth/glossy, nor too rough, in order to ensure the best carbon brush performance. Commutators must be checked for proper mica undercutting and the absence of burrs along the edges, and the bar edges must be properly chamfered. Also be sure the slip ring or commutator run out does not exceed acceptable limits.

Figure 1



NORMAL ORIENTATION OF A CARBON BRUSH ON A COMMUTATOR

NORMAL ORIENTATION OF A CARBON BRUSH ON A SLIP RING

Friction Coefficient
The friction coefficient of a carbon brush must be low and stable over time in order to prevent overheating. The friction coefficient ("μ") is the relationship between tangential force due to friction (T) and normal force (N), and depends on many factors, including the carbon brush's speed, grade, load, commutator/slip ring condition, and environment.

Vibration
Vibration can be caused by a number of factors, including incorrect balancing/alignment, deformed commutators, the machine's external components, moving machinery, and high or fluctuating friction (from a number of factors). Excessive vibration can damage the carbon brush as well as the brush holder and commutator/slip ring. Choosing the right brush and regularly maintaining it will help prevent this.

Carbon Brush Pressure on a Slip Ring or Commutator

No matter the machine speed, the spring pressure must ensure proper contact between the slip ring/commutator and the carbon brush. The spring pressure must remain equal for current distribution, which can be aided by regular pressure measurements with a scale or load cell. Recommended spring pressure is:

- For stationary electrical machines: 180 - 250 g/cm² (2.56 - 3.56 psi)
- For electrical machines under heavy vibration (e.g. traction motors): 350 - 500 g/cm² (5.00 - 7.11 psi)

Brush Holders

In order to avoid the brush getting stuck or rattling in the holder, it's necessary for the brush to be guided by a brush holder with the right height and clearance. The International Electrotechnical Committee (I.E.C.) sets tolerances and clearances.

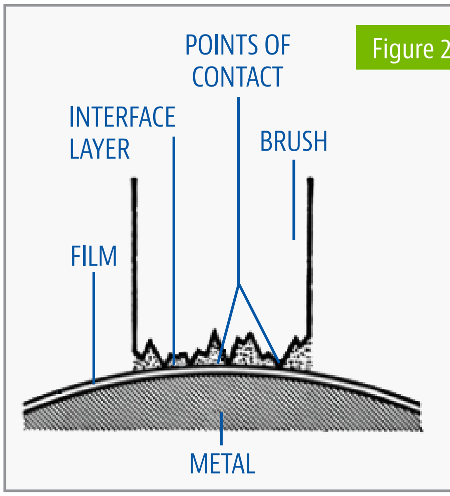
ELECTRICAL

Voltage or Contact Drop *(Fig. 2)*

To avoid overheating or electrical loss, which will damage the sliding contact, voltage drop must remain moderate. This also affects commutation and current distribution between the carbon brushes. This will depend on the carbon brush grade, electrical contact, and film (a mix of metal oxides, carbon and water, deposited on the slip ring or commutator).

Factors that affect the film include room temperature, pressure, and humidity; environmental impurities, pressure on the carbon brush; commutator/slip ring speed; and transverse current.

Figure 2



Commutation (DC Machines)

Commutation is the reversing of the direction of the flow of current in the armature coils located under the brush of an AC/DC commutator motor or generator.

Commutation sparking can occur due to incorrect adjustment of the brush position or asymmetrical brush arm adjustment. Commutation can be improved by a number of factors, including multi wafer carbon brushes, sandwich brushes, staggering carbon brushes, and more.

Distribution of Current in Brush Contact Surface

Current flows through a varying number of contact spots, which are very small areas of the brush that come in contact with the surface of the commutator or slip ring. These contact spots should be evenly distributed. If contact spots decrease or concentrate, balance could be disrupted and the film will show signs of bar marking, streaking, grooving, erosion and deterioration.

Current Density

Current density (JBrush) is the ratio of the current to the cross-sectional area of the brush, and significantly influences every aspect of the brush performance. Maximum densities vary based on the machine's characteristics and the ventilation method, and as a general rule, a low current density is more harmful to the carbon brush than a high current density.

Introduction *(Continued)*

Resistivity

Resistivity (rho (ρ)) refers to the resistance of a material to the flow of electrical current, and higher resistivity material improves commutation. It's an important factor in the choice of a carbon brush grade.

PHYSICAL/CHEMICAL (ENVIRONMENT)

Humidity

Water is a critical component of commutator/slip ring films, and is supplied by ambient air. For best performance, a humidity range of 8 to 15 g / m3 (0.008 to 0.015 oz/ft3) of air should exist. Therefore, dry air is unfavorable, and in applications such as aerospace/space, totally enclosed motors, desert/arctic environments, and machines in dry-gas enclosures, special treatments are recommended.

Corrosive Vapors or Gases

Corrosive vapors (whether in low concentration or in humid conditions) can damage and destroy the commutator and contact film, and therefore the brush itself. These gases include, but are not limited to, chlorine, ammonia, sulphur dioxide, and hydrogen sulphide. In these cases a protective surface on the brush can help prevent their effects on the brush.

Oils and Hydrocarbons

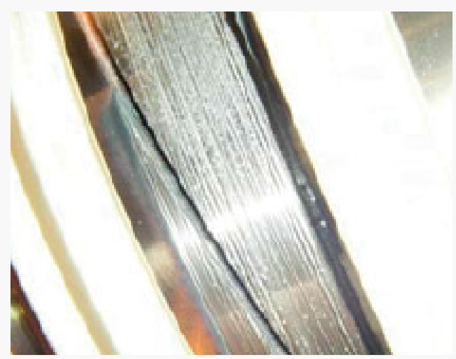
Leaks, vapor condensation, and drops of mist can contaminate carbon brushes and their commutators/slip rings. They lead to deterioration or immobilization of the brushes.

Dust

Dust leads to high brush wear, machine pollution, grooving of commutators/slip rings, and brush side gulling. The best way to prevent this is through the use of clean, filtered air and cleaning motors regularly.

P1

P2



P2a

P1 is a good example of streaky film, which contains lines of varying widths, alternating light and dark, without copper wear. Frequent causes include excessive humidity, aggressive gases or oil vapors in the atmosphere, underloaded carbon brushes.

P2 and P2a depict raw grooved film. This is a result of excessive exposure to humidity, aggressive gases or oil vapors in the atmosphere, for long periods of time. Additionally, the carbon brush grade may not be suitable.

The 5 Main Carbon Brush Grades

The choice of the right brush grade largely depends on the motor itself and the environment. There are five main brush grades, and working with an expert can help determine which is right for you.

The grades are broken down as follows:

1. Electrographitic Brushes (EG)

These are made of carbographitic materials that have been graphitized, transforming them into artificial graphite. These brushes have a medium contact drop and low to medium friction coefficient. They have low electrical loss and are well suited for high peripheral speeds. Characteristics include high strength, low resistance material, and resistance to high temperatures.

Applications include DC stationary or traction industrial motors operating with low, medium, or high voltage and constant or variable loads. Additionally, AC synchronous and asynchronous slip ring applications.

2. Carbographitic Brushes (A)

Made from a mixture of coke and graphite powders, these materials are not graphitic. These brushes commutate well as a result of their high resistance. They provide good polishing action and can withstand high temperatures and variable loads.

Applications include older motors (characterized by slow speed, low voltage, lack of interpoles), modern small motors (operating with permanent magnets, servomotors, and universal motors), and low-voltage battery-powered motors.

3. Soft Graphite Brushes (LFC)

Made of purified natural graphite and artificial graphite mixed with additives, these brushes have excellent shock absorption and low shore hardness. They are particularly well suited for high peripheral speeds.

Applications include steel and stainless steel slip rings for synchronous motors.

4. Resin-Bonded (Bakelite Graphite) Brushes (BG)

Made from either natural or artificial graphite that is mixed with thermo-setting resin, these brushes have high to very high electrical resistance, contact drop, mechanical strength, and electrical loss. This translates to good cleaning and commutating properties. They work at very low current densities.

Applications include AC Schrage-type commutator motors and medium-speed DC motors at medium voltage.

5. Metal Graphite Brushes (CG, MG, or CA)

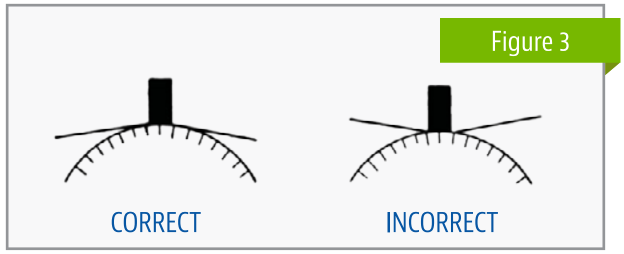
Made from either natural or artificial graphite mixed with a thermo-setting resin, copper powder, and/or other metal powders, these brushes are dense to very dense with low friction and low contact drop. They operate with low losses and high currents. These brushes also include EG and A carbon brushes that are metal-impregnated.

Applications for copper-based brushes include low-speed, low-voltage DC motors; medium-speed, highly-loaded AC asynchronous motors (e.g. wind turbine generators); medium-speed AC synchronous motors slip rings; high-current collection systems; low-voltage current collection; special motors; and slip ring assemblies in rotary joints.

Applications for silver-based brushes include signal current transmission; pulse transmission to rotating devices; tachometer generators; aerospace and space applications; and shaft grounding in a dual-grade construction.

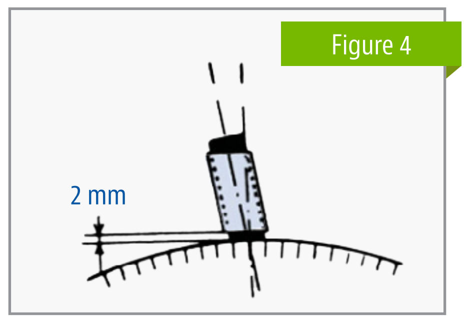
Installing Carbon Brushes in Motors

Installation Tips:



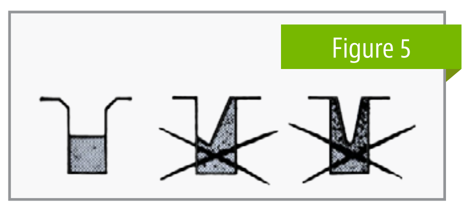
- In order to avoid serious problems, never mix different carbon brush grades on a motor.
- Be sure to remove the existing film before any carbon brush grade change.
- Check that the carbon brushes slide freely in their brush-holders without excess clearance.
- Always check that the carbon brushes were not fitted (or re-fitted) in the wrong direction in the brush-holders. This is especially important for carbon brushes with a beveled contact surface or split brushes with a metal plate.
- Use brush-seating stones (pumice stones) while running at low or no load in order to precisely match the carbon brush contact surface to the slip ring/commutator radius. Always use the medium grade (M) grinding stone again after this operation. When removing carbon brush material, first rough-grind the surface with sandpaper by inserting the abrasive face up between the contact surface and the commutator and moving it back and forth (*Fig. 3*). Thoroughly clean the contact surface after brush seating.

For Brush-holders:



- Make sure that the brush-holder is in working condition and check the interior surface condition.
- Adjust the distance between the brush-holder and commutator to range from 2.5 to 3 mm (*Fig. 4*).
- Align the carbon brushes parallel to the commutator bars.
- Check with an appropriate gauge that the pressures are equal on all of the carbon brushes.

For Commutators and Slip Rings:



- Be sure there is no out-of-round above 3 mils or any surface defects. Grind or machine if necessary (*Fig. 5*).
- Chamfer the bar edges.
- Clean the surface with an "M" grade grinding stone, and do not use abrasive paper/cloth. Sufficient roughness is critical.

Putting the Motor into Service:

Make sure that all carbon brushes slide freely within the brush-holders and that the shunts are correctly routed and the terminals are tightened. Then start the motor at a low load, slowly increasing until the full load is reached.

Installing Carbon Brushes in Motors *(Cont.)*

Film Monitoring:

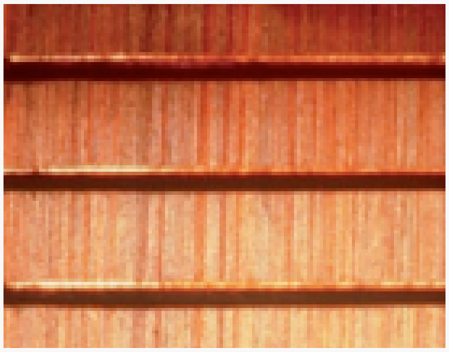
Look out for:

- Film deposits (streaky, patchy, and/or raw grooved film).
- Patchiness from mechanical causes (uneven film, dark patches in middle or edges, park patches followed by lighter fading, etc.).
- Bar marking from electrical causes (alternate bars of light and dark, pitting/spark marks, etc.).
- Oil/grease deposits from pollution/contamination.
- Burning (spark burns, burning at center or edges, pitted film).
- Marking (brush images on commutator/slip ring, dark fringes.
- Commutator bar faults.
- Commutator bar wear.

Normal Films:

Uniform, light brown (P3) to dark browner (P5). These images show normal films, where the machine and carbon brushes work well.

P3



P4

P5

Carbon Brush Maintenance

In general, always be aware of vibration or noise on the motor frame, on the bearings or bearing housings, or on the carbon brushes themselves. Once the motor has stopped, measure the commutator/slip ring temperature.

Checklist for carbon brush maintenance includes:

- ☐ Be sure to check for carbon brush stability, checking the clearance between brush holders and carbon brushes.
- ☐ If the carbon brush does not slide properly, check the brush-holder interior surface condition.
- ☐ Check the distance between the brush-holder and the commutator/slip ring, making sure it's adjusted correctly.
- ☐ Check spring pressure with a spring scale, making sure pressures are the same on all carbon brushes.
- ☐ Be sure brush-holders are adjusted at the correct angle.
- ☐ Check for signs of commutator wear and for the presence of copper dust.
- ☐ Measure/compare lengths of all brushes for any abnormal wear.
- ☐ Be sure brush edges are intact and have no chips or burn marks, and there are no signs of vibration, sparking, or sticking.
- ☐ Check that shunts are not oxidized, loose, frayed, or discolored.
- ☐ Following re-installation, be sure carbon brushes slide freely, their pressure devices are correctly centered, shock absorber pads are in good condition, and shunts are correctly located for minimal interference.
- ☐ Be sure carbon brushes are installed in the right direction in the brush-holders (especially important for carbon brushes with a beveled contact surface or split brushes with a metal plate).
- ☐ Remove the existing film before changing carbon brushes.
- ☐ Never mix different carbon brushes or brush grades on the same motor.
- ☐ Always maintain an equal number of positive and negative brushes per track.
- ☐ Be sure brush arm spacing is equidistant around the commutator.

Commutators/slips rings must be maintained/checked for:

- ☐ Degreasing
- ☐ Run-out
- ☐ Surface roughness
- ☐ Control of commutator bars
- ☐ Cleaning: Remove dust with a vacuum cleaner and blow dry air through the rotor and stator in both directions, blowing the dust out of the machine, no through it. Maintain filters regularly.

Precautions to take include:

- ☐ Protect commutators/slip rings against oil and dust using non-porous insulating materials.
- ☐ Lift all carbon brushes or insert a sheet of non-porous insulating material between carbon brushes and commutators/slip rings.

Troubleshooting & Repair Guide

SYMPTOMS

A=Sparking at the Leaving Edge
B=Sparking at the Entering Edge
C=Excessive Brush Vibration
D=Sparking Vicious and Trailing Around Commutator
E=Commutator - Slip Ring - Too Hot
F=Brushes and Brush Holders Too Hot
G=Shunts Burned Out or Discolored
H=Rapid Brush Wear - While Commutation Good
I=Unequal Brush Wear
J=Excessive Commutator or Slip Ring Wear - Bright Surface / Film Stripping
K=Cooper Dragging
L=Excessive Commutator or Slip Ring Wear - Bright Surface / Film Stripping
M=Threading and Grooving of Commutator or Slip Ring

PROBABLE CAUSE OF TROUBLE	A	B	C	D	E	F	G	H	I	J	K	L	M
Interpole Field Too Strong		●	●				●						
Interpole Field Too Weak	●		●				●				●		
Interpole Air Gap Too Small		●	●				●						
Interpole Air Gap Too Large	●		●				●				●		
Air Gaps Uneven (Bearings Worn)	●	●							●				
Overload Of Machine	●				●	●	●		●	●			
Vibration From External Causes, i.e., Prime Mover: Nearby Forge Hammer, etc.	●								●		●		
Vibration From Internal Causes, i.e., Out Of Balance, Poor Alignment, etc.	●								●		●		
Oil and Dirt on Commutator or Slip Ring	●							●	●				●
Resistance Between Brushes And Brush Arms Not Uniform						●	●		●				
Grains of Abrasive in the Brush Contact Face									●	●			●
Faults in Armature Winding or Equalizer Connections	●			●		●							
High MICA	●		●	●								●	
Commutator or Slip Ring Eccentric	●	●	●	●				●				●	
Commutator Riser Connections Open Circuited	●	●											
High or Low Commutator Segments	●		●	●								●	
Commutator Loose	●		●	●								●	
Flats on Commutator or Slip Ring	●		●	●								●	
Brush Pressure Too Low	●				●	●	●	●	●	●	●	●	●
Brush Pressure Too High					●	●		●		●	●		●

NOTE: The time factor is important. If consulting a National Application Engineer, state whether the trouble is new, or of long standing.

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PROBABLE CAUSE OF TROUBLE	A	B	C	D	E	F	G	H	I	J	K	L	M
Spring Pressure Unequal	●					●	●						
Brush Grade Unsuitable for Machine and Duty	●			●	●	●		●	●	●	●	●	●
Brush Arc of Contact Excessive	●	●	●										
Brush Arc of Contact Insufficient	●	●	●										
Brush Shunt Connection Faulty							●		●				
Brush Shunt Too Short or Too Stiff	●				●		●		●				
Imperfect Brush Bedding	●	●			●				●				
Radial Brush Holders Mounted At Small Reaction Angle	●				●				●		●		
Brush Sticking or Sluggish in Brush Holder	●				●		●	●	●			●	
Brushes Too Loose in Brush Holder (Holders Worn)	●					●			●				
Terminal Connections Loose or Dirty					●	●	●		●				
Brush Holder Mounted Too Far From Commutator or Slip Ring	●								●				
Incorrect Brush Position	●	●	●									●	
Unequal Brush Holder Spacing or Alignment	●	●	●	●			●		●				
Humidity of Atmosphere Low								●		●			
Humidity of Atmosphere Excessive											●		●
Dusty Atmosphere								●		●			●
Gas or Acid Fumes in Atmosphere	●						●	●					●
Long Periods at Low or Steady Loads											●		●
Silicone Contamination								●					
Fumes From Oils with High Pressure Additives											●		

Troubleshooting & Repair Guide

REMEDY	SYMPTOMS **N**=Wear of Slip Ring on One Polarity **O**=Copper Picking in Brush Face **P**=Brush Chatter **Q**=Commutator Surface Streaky **R**=Commutator Has Unsymmetrical Burn Marks **S**=Commutator Has Symmetrical Burn Marks **T**=Commutator Has Wavy Pattern **U**=Ghost Marks on Steel Still Rings **V**=Pitted Contact Surface of Brush **W**=Chipping of Brush Edges or Brush Breakage **X**=Failure to Develop A Protective Skin									
	N	O	P	Q	R	S	T	U	V	W	X
Weaken Interpole Fields by Diverting or by Increasing Gap		●				●			●		
Strengthen Interpole Fields by Reducing Air Gap		●				●			●		
Enlarge Air Gap to Decrease Effective Interpole Flux		●				●			●		
Reduce Air Gap to Increase Effective Interpole Flux		●				●			●		
Renew Bearings and Realign Machine		●				●			●		
Reduce Limit Load on Machine		●					●		●		
Locate and Remove Cause of Vibration	●	●	●			●	●	●	●	●	●
Balance Armature and Check for Bearing Wear	●	●				●	●	●	●		●
Reverse the Polarity of Rings Periodically	●							●			
Clean Commutator or Slip Ring				●	●						●
Clean and Tighten the Connections						●			●		
Rebed and Clean the Brush Face											●
Locate and Cure Fault or Consult Manufacturer					●	●			●		
Recess MICA, or Use More Abrasive Brush		●	●		●				●	●	●
Turn or Regrind Preferably at Near Rated Speed	●	●		●	●		●		●		
Repair Riser and Equalizer Connection						●					
Tighten Commutator, Turn, or Regrind			●		●				●		
Rebuild or Replace Commutator if Necessary		●	●	●	●		●			●	
Locate and Remove Cause of Flatting, Turn or Regrind		●	●						●	●	
Adjust Brush Pressure (For Spring Force) To that Recommended for the Machine	●	●	●	●	●	●		●	●	●	●

Troubleshooting & Repair Guide

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X=Failure to Develop A Protective Skin

REMEDY	N	O	P	Q	R	S	T	U	V	W	X
Select One of Our Alternative Grades or Ask for Our Recommendation	•		•			•			•	•	•
Apply A Suitable Circumferential Stagger, Preferably Consult Manufacturer		•				•					
Fit A New Brush With A Sound Flexible Connection											
Use Brushes With Flexible of Correct Length and Flexibility						•					
Bed Brushes by Our Recommended Method				•							•
Adjust Holders To A Radial Position, and Correct Distance From Commutators See * Below	•		•		•	•			•		•
Reverse Holders or Direction of Rotation	•		•		•	•			•		
Check that Brush Size is Correct, Clean Brushes and Holders, Remove Any Burrs		•		•	•		•			•	
If Holders Worn, Replace with New Ones, Order brushes of Correct Dimensions			•			•			•		•
Clean Terminal and Terminal Block, Tighten Screws			•								
*Adjust Holder to be 3/32 in. or 2m.m From Commutator	•		•	•	•	•			•		•
Adjust Holders to Correct Position		•				•		•		•	
Correct Spacing and Alignment of Holders		•				•				•	
Humidify the Cooling Air or Draw Air From Normal Humidity Source			•						•		•
Enclose Machine or Draw Cooling Air From Normal Humidity Source				•				•			
Remove Cause if Possible or Install Filter											•
Arrange Clean Air Cooling				•	•			•		•	•
Change Brush Grade, Ask for Our Recommendation		•	•						•		•

About Renown Electric

Renown Electric is a privately-owned company based out of Concord, Ontario specializing in motor management and supply. Founded in 1984, all aspects of electric motor repair, re-manufacture, overhaul, field service, and engineering support are provided by experts 24 hours a day, 7 days a week, 365 day a year.

Renown is an authorized dealer and service representative of most major manufacturers, and can re-manufacture all major AC and DC motors up to 5000 hp. Renown has CSA qualification for the repair and service of motors and generators in hazardous locations as well as ISO 9001 certification. All repairs use the latest computerized testing techniques, and the service offerings include predictive maintenance, vibration analysis, infrared thermography, oil analysis, and non destructive testing.

Visit our website at www.renown-electric.com, or contact us with any questions or for more information any time.

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CSA QUALIFIED ISO 9001

ALL REPAIRS USE THE LATEST COMPUTERIZED TESTING TECHNIQUES

SOURCES
1. Mersen. Technical Guide: Carbon Brushes for Motors and Generators.
2. Mersen. Maintenance of Carbon Brushes, Brush-Holders, Commutators and Slip Rings.

White Paper: DC Motor Brush Life

DC Motors

DC Motor Brush Life

Abstract

This paper looks at brush life, why brushes wear and what can be done to achieve longer brush life. It is meant to provide one with an understanding of the factors and conditions that contribute to brush wear in order that problem areas can be avoided and existing problems identified and resolved. This however, is not an instruction manual on how to fix problems. The motor manufacturer should be contacted for help in resolving brush and commutation problems. The following applies to medium and large horsepower industrial DC motors and generators.

I. Why Brushes Wear

DC brush wear is the result of mechanical friction and electrical erosion. Friction produces carbon dust; the result of electrical erosion is the vaporization of carbon with little physical residue.

A. Friction

Carbon rubbing on bare copper has a rather high coefficient of friction. A low coefficient of friction is achieved when the commutator has good film. With good film the coefficient of friction can be reduced to 10% of the original bare copper value.

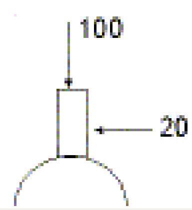
Friction changes with commutator temperature. The coefficient of friction decreases to some point, with increases in commutator temperature and then increases again as the commutator temperature increases. For example, a given brush might have a coefficient of friction of 0.15 running on a commutator with a surface temperature of 140?F, 60?C. When running on a commutator with a surface temperature of 220?F, 104?C the coefficient of friction could be 0.08. Yet higher temperatures can result in an increase in the coefficient of friction. Standard brushes on warm commutators at medium speeds will typically have a coefficient of friction of 0.13 to 0.19. This is considered to be a low coefficient of friction. The coefficient of friction, to a large degree is a result of the film produced on the commutator which is dependent on commutator surface temperature and the other factors which influence film.

Table I. Brush Coefficient of Friction

Very low	Less than 0.10
Low	0.10 to 0.19
Medium	0.20 to 0.29
High	0.30 and higher

Fig. 1. Friction

Friction is the resistance that opposes the force to slide one object over another. If the vertical brush force on the commutator is 100 and the horizontal force required for the commutator to move under the brush is 20, then the coefficient of friction is 20100 or 0.20.



Some brushes with low coefficients of friction are not as hard as brushes with higher coefficients of friction. There are however, a number of hard grades that have low coefficients of friction. A hard brush with a medium or high coefficient of friction may provide long life but could be noisy. Due to noise considerations, it sometimes becomes necessary to trade some brush life for quiet operation. A hotel elevator motor for example, would need to be quiet.

Friction can also be caused by mechanical problems such as high mica, high brush spring pressure, a feather edge on a copper bar or other imperfections on the commutator surface. Brush wear on an unpowered motor in a tandem motor-motor set or on an unloaded generator in a motor-generator set, is due to friction. Friction is a function of the atmosphere, temperature, current loading and the mechanical characteristics of the motor.

B. Erosion

Erosion can be the result of improper film on the commutator or a wear condition such as threading.

Sparking and erosion can also be caused by other motor set up conditions or mechanical problems such as the brush neutral setting, interpole strength, low brush spring pressure, poor brush seating, high mica, commutator eccentricity etc. Sparking increases with current loading and motor speed. Brush life decreases with increased sparking.

The condition of the commutator film directly affects friction and erosion and thus brush life. In order to achieve good brush life, the commutator must have good film.

II. What Is Good Commutator Film

When electric current is passed between the carbon and copper in the presence of water vapor, a microscopic layer of copper carbon composite or film, is formed. Good film is chocolate brown or burnished bronze to dark brown or black and uniform in color. It is not bright copper or burnt black copper. Consult a commutator color and appearance picture chart to determine the condition of the commutator. There is a condition known as false filming in which brush graphite deposits become cooked on the commutator resulting in an appearance similar to dark film. Oil can also leave a coating which resembles film. If this film can be easily wiped away, it's not the desired good commutator film!

Commutator filming is a continuous process. That is, the film is continuously being formed and stripped away. A good film is only 200 nano inch thick (0.000,000,2 inch or 0.000,005,08 mm). Thus the conditions required to build good film must always be present. Changes in current, humidity, etc. will affect the commutator film.

III. Requirements For Good Film

Good commutator film is dependent on the fulfillment of certain requirements for each of the following items:

- Brush Current Density
- Commutator Surface Temperature
- Water Vapor
- Brush Pressure
- Commutator Surface Speed
- Brush Material or Grade
- Lack of Contamination
- Mechanical Integrity And Setup

A. Brush Current Density

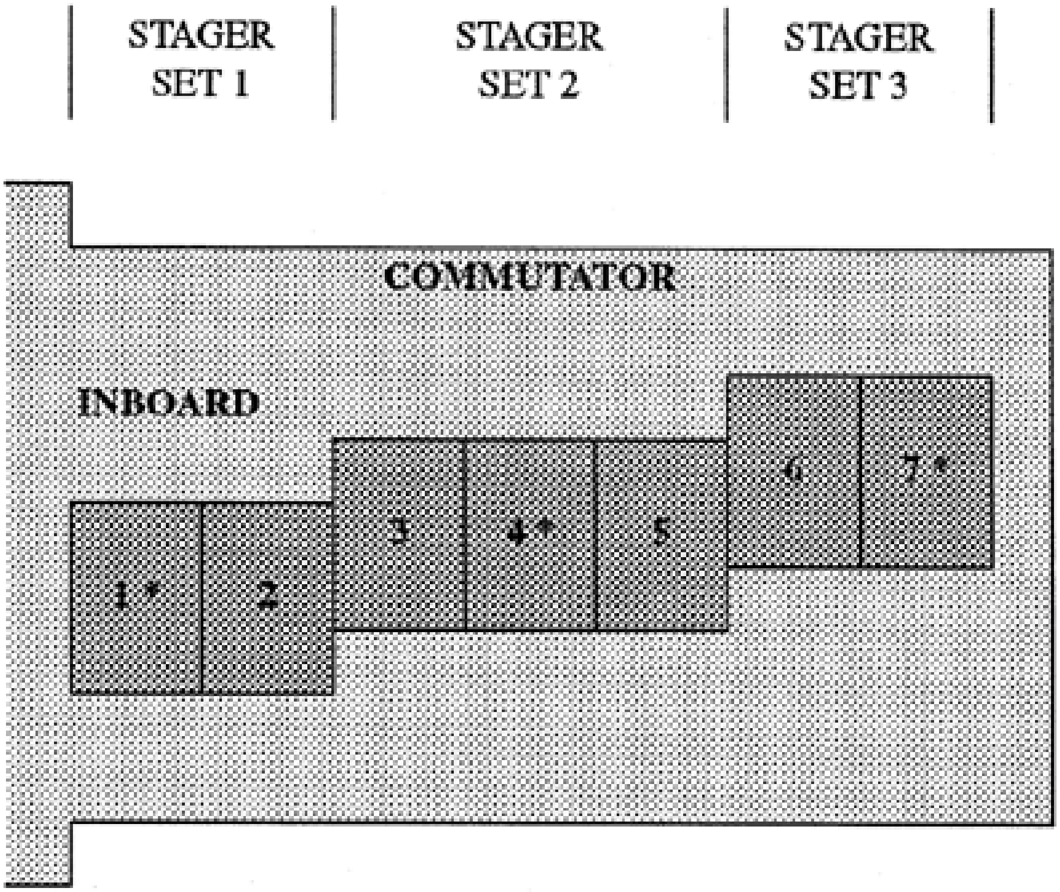
A majority of the operating time must be within the designed brush current density range. For SA45 or like grade brushes on warm commutators, this range is generally stated as 55 to 85 amps per square inch. If the current density exceeds this for long periods, the commutator will run hot, blacken and brush life will be reduced. If the current density is too low, the film will be striped from the commutator and the commutator will begin to thread. If allowed to continue, sparking and threading will increase, brushes will wear rapidly and the commutator will require resurfacing.

Often motors are run continuously at light loads where brush current density is always below the minimum. In such cases, a change in brush grade to something that will film at lower current densities, may solve the light loading problem. Many times the best solution is to remove a row or more of brushes to bring the current density back into the acceptable range. Before brushes are removed or changed, be sure that the new arrangement of brushes and brush shunts have sufficient capacity to handle the overload requirements of the motor. When removing brushes from machines with staggered brush sets, the remaining brushes on each stud must cover the same commutator surface arc as was covered prior to the removal of the brushes. This means that the brushes from the center stager set on each stud are removed first. When wear indicator brushes are used, be sure that some remain. Usually this is not a problem since the wear indicator brushes are most often the inboard and outboard brushes on the stud as well as the middle brush. The motor manufacturer can advise the order in which the brushes are to be removed. Some system must be in place to insure that the removed brushes are put back in place if the load conditions increase to near motor nameplated load.

Brush Current Density, amps/in^2 = Motor Current, amps divided by Total No. Brushes x .5 x Brush Surface Area, in^2

Fig 2. Brush Removal

Brush removal for light load example

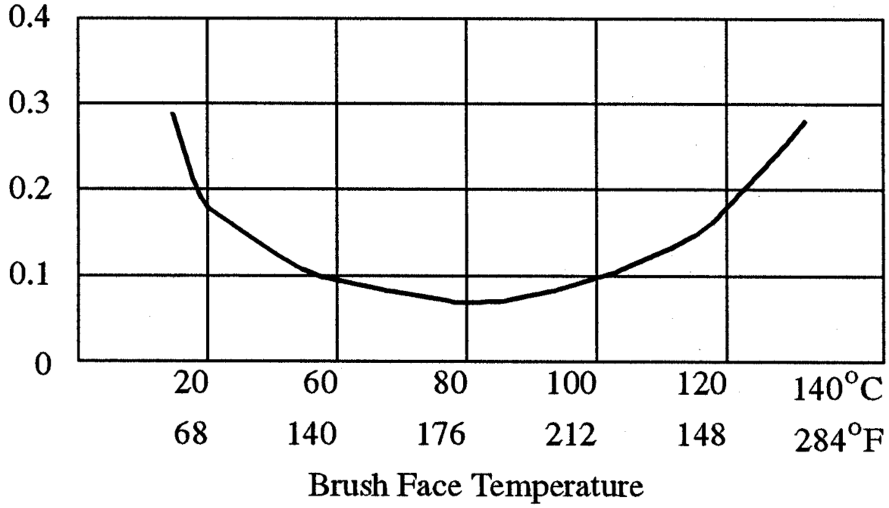


Pictured is one stud with 3 stager brush sets, 7 brushes per stud. When removing brushes due to a light load, remove the same brushes from each stud as follows:

No. Per Stud Removed	Brush No.
1	4
2	3,5
3	3,4,5

* Wear indicator brushes are numbers 1, 4 and 7.

Fig. 3. Coefficient of Friction and Temperature



B. Commutator Surface Temperature

It is generally accepted that the commutator temperature at the face of the brush should not be less than 60?C, 140?F. A sufficient layer of copper oxide will not form if the commutator runs cold. The commutator surface temperature should be between 60?C, 140?F and 115?C, 239?F for the majority of the running time with 100?C, 212?F about right for the best film building with standard brush grades. The graph in Fig. 3 is an example of how the coefficient of friction changes with brush face temperature. This is an example only, values change with brush grade, commutator film, brush pressure etc.

Hot commutators due to high ambient temperatures, overloads, or loss of coolant not only result in increased brush wear but reduced insulation life as well. The motor thermal protection is designed to help guard against this condition.

C. Water Vapor

An Absolute Humidity of 2 to 7 grains of water per cubic foot of air is required to build good film with SA45 or like grade brushes. When the Absolute Humidity is less than 2 grains (about 0.004,57 oz.) of water per cubic foot (about 20% Relative Humidity at 75?F, 24?C or 40% Relative Humidity at 55?F, 13?C), brushes will wear rapidly. High humidity can cause over filming or even more of a problem, low insulation megohm readings or ground faults.

There are several digital meters on the market that can be used to quickly measure Temperature and Relative Humidity. Measurements should be taken where the air enters the motor and at several points around the motor. The readings should be in the same range. Motors some distance away may be in ambients that give different results. Expect summer readings to differ from winter readings. On the enclosed Humidity Chart, read the Absolute Humidity on the horizontal line at the point of intersection of the diagonal Temperature line and the vertical Relative Humidity line.

D. Brush Pressure

It is running brush pressure, not spring pressure, that concerns us. Brush pressure is dependent on spring pressure and the position of the brush. It is also affected by the friction between the brush and holder. The coefficient of friction of the brush and holder is affected by commutator speed, brush grade, brush holder finish and brush clearance in the holder. It thus becomes difficult to measure brush pressure in the field, so spring pressure is measured. If the springs are weak, spring pressure being light, the brush will spark. If the pressure is too great, friction and wear increase. Good brush life and performance is usually achieved with brush spring pressures of 2 to 8 lbs per square inch (1.38 to 5.52 Newtons per square centimeter or 0.14 to 0.56 kilogram per square centimeter). This number varies with manufacturer, motor size and motor application. Spring pressure should be as recommended by the motor manufacturer.

$lb/in^2 = N/cm^2 \times 1.45$

$lb/in^2 = kg/cm^2 \times 14.21$

The best laboratory brush life is achieved with brush pressures of 2 to 4 lbs per square inch with filmed commutators running at speeds below 8,000 fpm. Typical brush pressures for integral horsepower industrial motors is in the range of 3 to 6 lbs per square inch. When a brush is at some angle to the commutator, as opposed to radial, there is a loss in the spring's force due to the brush angle. This loss is about 6.0% with a 20?angle and 9.4% with a 25?angle. Today most manufacturers supply brush springs that provide constant pressure throughout the life of the brush.

E. Commutator Surface Speed

The coefficient of friction between the brush and commutator increases approximately as the speed. Brush wear is proportional to the coefficient of friction. At higher speeds, above 5,000 or 6,000 fpm, greater brush pressure may be required, resulting in decreased brush life. At high field weakened speeds, commutation deteriorates, that is sparking increases. At higher speeds the film can be stripped from the commutators faster than it is being formed. If the motor runs at high speeds for only short periods of time, film can still be maintained.

For a given motor rpm, the smaller the commutator diameter, the lower the surface speed and the greater the brush life. In general, the commutator surface speed of industrial motors limited to 8,000 fpm.

Commutator Surface Speed, fpm = Commutator Diameter, in divided by 12 x 3.1416 x Motor Speed, rpm

F. Brush Material or Grade

With the above conditions met, SA45 or like grade brushes produce good commutator film on most integral horsepower DC motors. Special brush grades are available that will help compensate for certain undesirable conditions. Keep in mind that every brush fix is a compromise. That is, the fix is to compensate for something that in field operation, differs from the primary motor design mission. Thus new problems can sometimes be introduced as a result of the fix.

There is no magic brush that will give good life with a variety of loads, humidity, commutator conditions, etc. The magic is in controlling the conditions so that they all work together to provide the best brush life.

G. Lack of Contamination

Other chemical ingredients present in the air will become part of, or influence the composite that is film. So we can say that an absence of foreign chemicals is required to produce good film. Silicone vapors, chlorine, sulfur, PVCs, dirt such as carbon black, and oil are some of the industrial contaminants that are particularly harmful to commutator film.

Silicone based sealants must not be used in sealing motor air duct work, hand hole covers or any mating surfaces on or near the motor. Acetic acid vapors from silicone sealants will destroy commutator film. Other types of sealants also give off vapors when curing, that can be harmful to commutator film. Non-silicone Permatex sealants can be used without harm.

H. Mechanical Integrity And Setup

The commutator must be concentric and the surface free of imperfections. The brush rigging needs to be sound and properly aligned. Springs must be checked for proper tension. Brush holders and brushes must be checked to assure that brush side to side movement in the holder is not excessive. Brushes must be free to travel in their holders and seated to the commutator. Brush shunts or pig tails, must be tight in the brush and of sufficient size to handle overload current requirements when they are in excess of the standard 150%. The brushes must be on electrical neutral. Interpoles need to be properly adjusted, shimmed and secure.

Replace springs that measure outside of the recommended range. If the brush is sloppy in the holder, compare the manufacturer's dimensions to the measured brush and holder dimensions to determine if the problem is with the brush or the holder. Replace worn parts as required. Failure to seat brushes results in sparking and can cause brushes to chip. Seat brushes with sandpaper; never use emery cloth since the grit is conductive and can lodge between commutator bars. Rough seating can be done with 60 or 100 grit sandpaper. Final seating should be done with fine sandpaper.

The surface finish of new or turned commutators should be in the range of 40 to 70 micro inches (0.000,040 to 0.000,070 inch). On new commutators, the mica is undercut approximately 1/16 inch, 1.59 mm. Brush holders should be adjusted for approximately 3/32 inch, 2.38 mm commutator clearance.

IV. Commutation And Brush Life

The above paragraph lists the mechanical and setup considerations necessary to achieve good commutation. But what is commutation and how does it affect brush life?

In a DC motor, commutation is the process of periodically reversing the current flowing in individual armature coils in order to maintain unidirectional torque as the armature coils move under alternate field poles. The commutator must reverse current through armature coils which left the influence of one field pole and are approaching the influence of an alternate field pole. The motor brush then contacts more than one commutator segment and an armature loop is momentarily shorted. If the short has a difference of potential across it's ends, severe sparking can occur between the brush and the commutator. The commutator then can burn and pit and brush life is reduced. It is thus necessary to insure that voltage is not induced in the commutator loop at the time of the momentary short. If the short occurs when the active conductors in the armature loop are moving in parallel to the field, magnetic lines of force will not be cut and voltage will not be induced in the armature loop. This vertical axis occupied by the shorted armature loop is the geometric neutral plane. In theory, this is where sparkles or black commutation takes place. But life is not that simple! Due to the self induced e. m.f. and changes in load, the situation is somewhat more involved and beyond the scope of this article. In the end however, electrical neutral must be properly set to assure good commutation and good brush life.

Table II. Commutator In Service Limits

Maximum allowable commutator eccentricity varies with motor design, the following limits in inches are typical for standard industrial motors:

	Medium hp	Large hp
Max Total Indicated Runout in 360?	0.001,5	0.003
Max Total Indicated Runout in any 90?	0.001	0.001,5
Max Bar to Bar Runout	0.000,5	0.000,5
Max Taper, inches per foot	0.002	0.002

When we talk of a motor's ability to commutate we are also referring to the motor's armature current handling capability. Standard industrial DC motors are required to successfully commutate 150% of the nameplate full load current for one minute at any speed within the motor's nameplate speed range. There is no exact definition of successful commutation and commutation can be considered successful even if sparking occurs provided that it does not result in excessive maintenance. Intermittent sparking due to overloads or a slight amount of sparking does not necessarily indicate poor commutation. The cause of excessive sparking should be determined and the problem corrected. It is common to refer to the amount of sparking as the degree of sparking along with a reference number such as 1, 1 1/4, 1 1/2, 2 etc. The enclosed drawing SK-10817 is an example of a degree of sparking numbering system. Numbering systems vary with motor manufacturers. The lower numbers represent a few small sparks. The higher numbers indicate more sparks and larger sparks which do the most damage to the brushes and commutator. Desirable is black commutation in which there is no visible sparking. The degree of sparking drawing is somewhat misleading in that both the small or pin point sparks and the large sparks are smaller than shown on the drawing.

A wear rate factor is sometimes assigned to the degree of sparking reference number. The wear rate factor would be 1.00 for a given motor on a given application when commutation is in the black. If this condition provides 7,000 hours brush life for example, and a change in the degree of sparking occurs such that the degree of sparking reference number is now 2 with a 1.75 wear rate factor, the new expected brush life would be 7,000 hours1.75 or 4,000 hours. The following degree of sparking guide can be used with drawing SK-10817 to determine the degree of sparking and to provide an insight to brush life.

Table III. Degree of Sparking Guide

No.	Description	Wear Rate Factor
1	Black with no visible sparking	1.00
1 1/4	Light intermittent sparking	>1.00
1 1/2	Light continuous sparking over half of the brush length	>1.00
2	Light continuous sparking over the entire brush length	1.75
3	Light continuous sparking with one or two heavy sparks	2.50
4	Light continuous sparking with three heavy sparks	5.00
5	Heavy continuous sparking with few small sparks	12.50
6	Heavy continuous sparking with glowing spots; approaching flash-over	50.00

Table IV. Brush Life Example

Load Type	Amps/in²	Hours, Life
Intermittent, Light	down to 30	750 - 2,000
Within Rated Load	45 to 85	3,000 - 7,500
Intermittent, Heavy	up to 125	1,000 - 4,000

Table V. Factors That Affect Brush Life

Application and duty cycle
Atmospheric conditions
Commutator condition which includes film, runout, quality of the undercut, etc.
Brush assembly design which includes brush grade, brush length, holder design, spring pressure, etc.
Motor building practices including the accuracy to which neutral is set
Power supply and motor design

V. What Is Normal Brush Life

As an estimate, 7,500 hours brush life could be considered normal for general purpose, medium horsepower DC motors with good commutator film operating with commutator surface speeds in the range of 2,500 to 4,000 fpm. The minimum life might be 2,000 to 5,000 hours with 10,000 hours being about maximum. It is not uncommon however, for motors with light or variable loads, such as machine tool motors, to have brush life that is less than 2,000 hours. Brush life is even further reduced at higher commutator surface speeds. As a rule of thumb, brush life at 3,600 rpm is half that at 1,800 rpm. Brush life is also affected by load. The brush life of a 50 hp, 1,750 rpm, motor with a commutator surface speed of 2,620 fpm, could vary with load as shown in Table IV.

VI. When To Replace Brushes

Brushes should be replaced before the tamped shunt or pigtail lead has a chance to score the commutator and before the brush is at the end of the spring travel. Some brushes have three wear lines so that brush life can be monitored. When the brushes wear to the third line, the brushes should be replaced. Brush probes that contact the commutator and provide a voltage signal equal to the armature voltage and mechanical devices that move with the brush spring and close a contact are also available on some motors to tell you that it is time to change brushes.

VII. What We Can Do To Achieve Longer Brush Life

To identify all of the variables and then determine brush life gets to be quite a job, especially when the variables are changing. What we can do is identify the current problems and take corrective action. By monitoring the conditions that affect brush life, along with or as part of a maintenance program, we will have information that can alert us to potential or developing brush and commutator problems. Just as commutator filming is a continuous process, so is the monitoring and corrective action process continuous. Through monitoring and corrective action, down time may be reduced and longer, trouble free motor life achieved.

References

This paper is a compilation of my written responses over the past twenty years, to numerous brush and commutator questions.

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Note: This material is not intended to provide operational instructions. Appropriate Reliance Industrial Company instruction manuals and precautions should be studied prior to installation, operation, or maintenance of equipment.

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