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# 2 Guidelines for Successful Commutator and Brush Operation

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## Abstract

The production of mechanical or electrical energy using motors and generators is a common practice throughout industry. Successful operation of many of these machines depends on the satisfactory performance of carbon brushes riding on commutators. Unfortunately, there appears to be a considerable amount of confusion and controversy surrounding the criteria used to judge satisfactory brush and commutator performance. Examples of acceptable commutator conditions that may appear unattractive at first glance are provided. The primary impetus of this paper then focuses on a discussion of various destructive commutator conditions with related causes. Pictorial views of commutators are included to help relate word descriptions to actual operating conditions. Both engineering and maintenance personnel who work with commutators and brushes should benefit from the information contained herein.


## Introduction

A carbon brush riding on a commutator conducts current from a stationary member to rotating collector. It is the responsibility of the brush to form the necessary interface at the brush/commutator junction to enable current to be conducted successfully. Therefore, the brush must properly lubricate the sliding contact by establishing the commutator film necessary to insure a smooth ride and uninterrupted current flow. In addition, a brush must aid in the commutation process to keep circulating currents and associated sparking and heating minimal.

A collector system that is functioning properly results in satisfactory performance characterized by the following interrelated criteria:

1. Nondestructive sparking
2. Satisfactory brush life
3. Acceptable commutator life

These three qualities are used to establish guidelines for judging satisfactory brush and commutator performance.

Nondestructive sparking is classified as "black commutation" or fine pinpoint sparking that does not cause brush and commutator deterioration. Destructive sparking will electrically erode both the brush and commutator surfaces, which can eventually lead to equipment failure if not corrected.

Satisfactory brush life is a comparative index usually established by comparing past and present performance on a particular machine or by comparing similar machines. Unsatisfactory life may not be caused by the brush itself, for there are many factors that can have a negative influence on brush life. High brush temperatures, low humidity, excessive sparking, destructive vibration and abrasives are the most common factors that contribute to a reduction in brush life. It must be remembered that the brush is replaceable item that will eventually wear out, by it is important that life be reasonably predictable to avoid unexpected and expensive shutdowns.

Acceptable commutator life is another comparative index established through experience with a particular machine or by a comparison with similar machines. Commutator bar burning grooving and general deterioration must be nonexistent or controlled within satisfactory levels before acceptable or commutator life is attained. Some commutator wear is expected and most designs enable resurfacing when necessary with stones or other appropriate tools.

## Acceptable Commutator Conditions

Most people are familiar with the textbook description of what a normal and healthy commutator should look like. This leads to classifying every commutator that is not "chocolate brown in color with a medium polish" as unfit for service. This is simply not an accurate assumption, for there are many commutators in service throughout industry that do not comply with the textbook definition but have been successfully performing their duties for many years. The three previously mentioned qualities; nondestructive sparking, satisfactory brush life and acceptable commutator life, should be the primary criteria in determining satisfactory performance. Successful operation can and does occur on commutator films that are not pleasing to the eye. For example, the brush face is constantly changing during commutator rotation, which may produce uniform circumferential streaks in the film as shown in Figure 1. Streaking is not harmful to the operation if this is a surface condition in the film only and the commutator is not being damaged.

**Figure 1**
**Streaking – Not harmful if there are just streaks in the film and the commutator is not damaged.**

Film color is an appearance factor that is quite often discussed at great length. Dark or light film colors can be caused by the type of brush being used or by atmospheric contamination. Some brush materials produce dark films while others provide satisfactory performance with a much lighter color. Both are acceptable if the equipment is functioning properly and commutator and brush distress is not detected. Contamination can cause the film to be very non-uniform in color, such as that shown in Figure 2. Oil contamination can cause this mottled appearance, in which random dark and light colored areas are observed on the commutator surface.

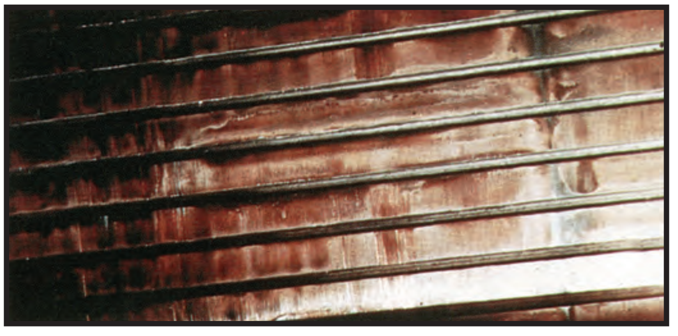

**Figure 2**
**Mottled – Satisfactory operation can result with a film color that is not uniform.**

The number of conductors in the armature slot can influence commutator bar coloration resulting in a keyboard appearance or pattern. This is commonly referred to as a slot bar pattern and is characterized by every second, third or fourth bar being of a darker color than the others. Figure 3 illustrates a two-bar pattern where every second bar is darker in color. This pattern occurs in regular intervals around the commutator circumference. Slot bar patterns are related to the electrical design of the machine and are not considered harmful if the commutator has not been damaged. This is readily determined by erasing the film on darker colored bars with a pencil eraser and looking for burned or etched areas on the trailing edges.

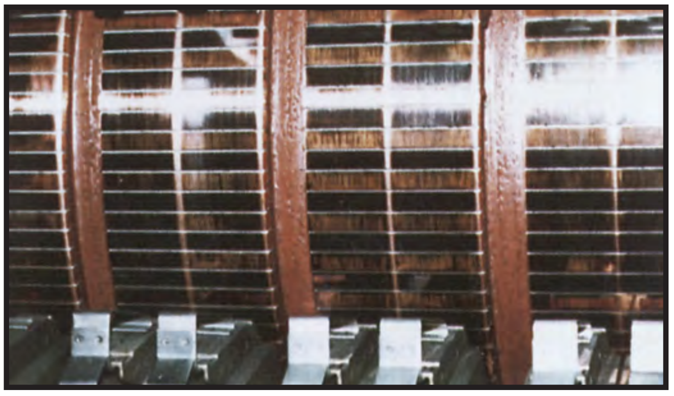

**Figure 3**
**Nondestructive Slot Bar Pattern. Darker film color pattern related to the number of conductors per slot.**

## Destructive Commutator Conditions

Destructive commutator conditions must be avoided if possible to extend equipment life and to prevent unnecessary shutdowns. Unfortunately, this is not always possible, for both brushes and commutators experience distress on occasion, leading to an increase in operational expense. Therefore, it is import to recognize commutator distress symptoms and to take corrective action as soon as possible. Listed in Table 1 are the most common destructive commutator conditions observed in a variety of industries. They are not necessarily listed in order on importance to any particular industry, for they represent common complaints registered in the operation of direct current motors and generators worldwide. Each condition will be defined and examined for its respective causes.

**Table 1**

**Destructive Commutator Conditions**

- **Slot Bar Burning**
- **Pitch Bar Burning**
- **Threading**
- **Copper Drag**
- **Grooving**
- **Selectivity, Stripping and Grooving**
- **Nonconductive Filming**

## Slot Bar Burning

Both the nondestructive slot bar pattern described earlier and destructive slot bar burning are influenced by the number of conductors in the armature slot. Also, both are characterized by second, third or fourth bar discoloration in regular intervals around the commutator circumference. However, slot bar burning is more than just an integral part of the film. Sparking levels have become high enough to remove metal from the trailing edges of the commutator bars, which will appear burned or etched when the film is removed. These electrically eroded areas usually enlarge with continued operation and become readily detectable without film removal if the destructive process is allowed to continue. This situation is analogous to a pothole in a road progressively increasing in size with the continuing passage of traffic. The commutator illustrated in Figure 4 has experienced slot bar burning on two of every three bars in a repeating pattern around the commutator surface.

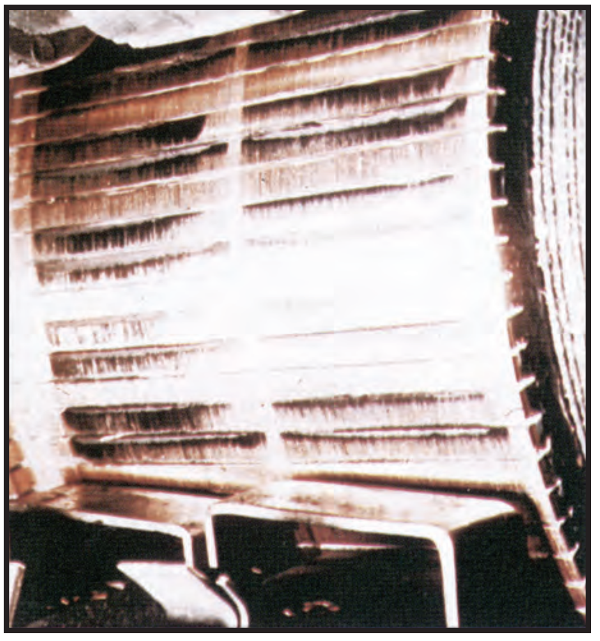

**Figure 4**
**Slot Bar Burning – Etching on the trailing edges in a regular pattern.**

Slot bar burning is influenced by factors that reduce the commutating ability of a dc motor or generator. These factors are numerous, but the most common ones can be grouped in the following three categories:

1. Use of a carbon brush material or brush design with insufficient commutating ability.
2. Improper electrical adjustment of the machine.
3. Exceeding the machine load or transient load design limits.

An electromotive force (EMF) of self and mutual induction is induced in an armature coil undergoing commutation when current reversal occurs. This induced EMF, commonly called the reactance voltage, acts to oppose current reversal and can be expressed in its simplest form by the following equation:

$$e_R = (L + M)\, di / dt$$

Where the eR is the reactance voltage, L is the coefficient of self induction, M is the coefficient of mutual induction and di / dt is the rate of change of current with time in the short-circuited coil. High reactance voltage values increase brush circulating currents, temperatures and sparking, which can lead to slot bar burning and flashovers.

It is very important to have the correct brush material and brush design at higher reactance voltages (eR) to maintain lower levels of brush circulating currents and associated sparking. The simplified drawing shown in Figure 5 illustrates the importance of brush resistivity in reducing circulating currents. Higher resistivities reduce circulating currents (iC) by increasing brush cross resistance (RB) and increasing contact drop volts (VC1 and VC2) since contact drop usually increases as brush resistivity increases. These are reasons why higher resistivity brushes are used on the more difficult to commutate motors and generators that have elevated sparking levels that cannot be neutralized by the generated commutating pole flux voltage (VØ) alone.

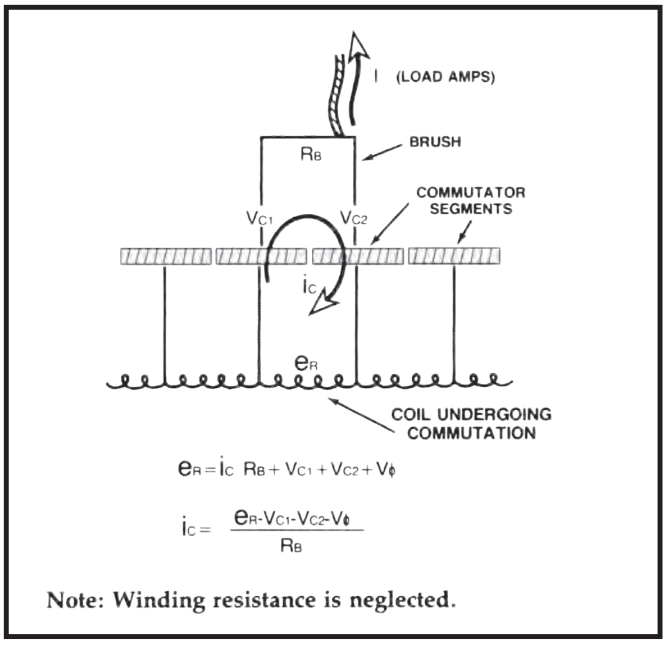


**Figure 5**
**High resistivity brush materials reduce circulating currents.**

The drawing shown in Figure 6 is similar to that in Figure 5 except that a three wafer brush design is shown instead of a single thick wafer. The additional increase in cross resistance between the wafers (RW) also helps to reduce circulating currents. In addition, a multi-wafer brush generally has a better opportunity to follow irregular commutator contours, accounting for a further decrease in sparking and associated bar burning.

Correct circumferential brush positions and commutating pole air gaps are essential to the proper electrical adjustment of dc machines. Misadjustment of either can lead to higher reactance voltages in the coil undergoing commutation. Some machines have narrow commutating zones which make proper electrical adjustment paramount to successful operations.

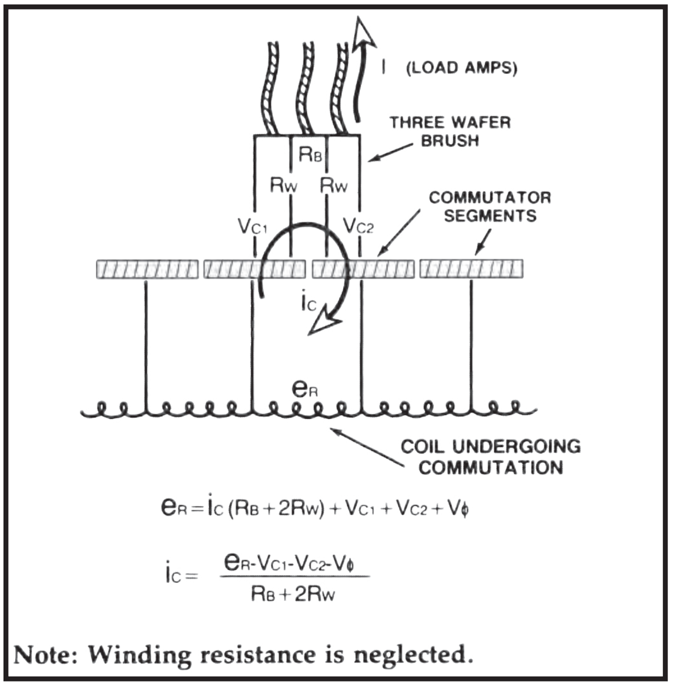


**Figure 6**
**Multiple wafer brushes aid in improving commutation.**

Exceeding the machine load design limits can create higher than normal reactance voltages because commutating pole magnetic saturation and insufficient neutralizing flux can result. The commutating pole flux can also lag the armature reactive flux under severe transient loads, leading to severe sparking at the brushes and to slot bar burning and flashovers.

## Pitch Bar Burning

Pitch bar burning starts under the cathode brush when certain mechanical or electrical disturbances are in phase with armature rotation. Excessive arcing, metal transfer and associated burning occur every time the same commutator bars pass under the cathode brushes. Usually, the burned bars will initially be spaced at distances equal to half the number of main poles, i.e., 180° on a four pole machine, 120°on a six pole machine, etc. The commutator will develop burned areas related to the total number of poles if operation continues. Each burned area may contain one or more bars, such as shown in Figure 7, which cause the brush to bounce and eventually break if the commutator is not resurfaced.

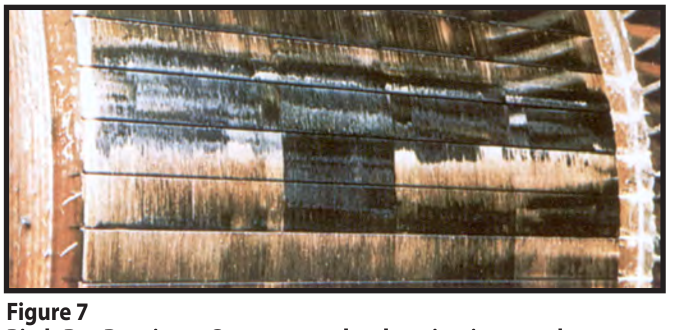

**Figure 7**
**Pitch Bar Burning – Commutator bar burning is a regular pattern caused by a cyclical mechanical or electrical disturbance.**

At times, it is difficult to determine the cause of pitch bar burning since there are a number of possible electrical and mechanical contributing factors. Open circuit and high resistance connections in the armature circuit are leading electrical contributors. This applies to the equalizer circuit in addition to the riser/armature conductor connections. Another electrical contributor in the presence of vibration is an unbalanced main field magnetic circuit caused by shorted turns or unequal pole gaps.

Sources of vibration such as armature unbalance, worn bearings misalignment and rough or eccentric commutators are leading mechanical conditions to be considered. Insufficient brush pressure and poor riding brushes have tendency to aggravate the overall problem.

## Threading

A threaded commutator is characterized by fine machined lines around the circumference that appear similar to screw threads. Threading is caused by metal transfer from the commutator to the brush face. The metal particles lodge in a porous brush material and eventually become harder (through work hardening) than the original commutator surface. The brush then acts like a cutting tool on a lathe, machine the screw-like, threaded appearance shown in Figure 8.

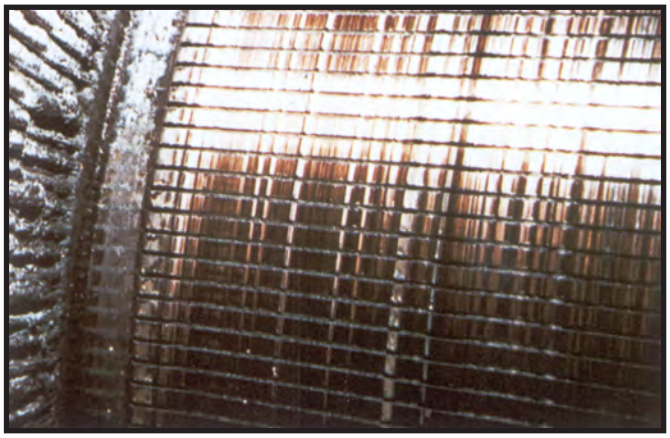

**Figure 8**
**Threading – Fine machined lines in the commutator.**

It is normal to experience some metal transfer to the brush face during current collection; however, most of the metal is vaporized at the higher energy levels produced when operating close to rated current loads. Operation at reduced loads lowers energy levels and allows for an excessive metal buildup in the brush face. Some corrective measures that can be taken are:

1. Remove some brushes to increase current density to reasonable levels in the remaining brushes
2. Use a graphite brush with less "holes" or "anchoring points" instead of porous electrographitic material
3. Use a treated electrographitic material
4. Maintain spring pressure within recommended limits.

Recommended safety and operational precautions must be followed when taking corrective action.

It is common to find a considerable amount of threading on commutators operating in the presence of acids, bases and some oils. Metal accumulation in the brush face is accelerated by either (1) less vaporization of contaminated metal particles because of their protective outer coating or (2) more metal being transferred because of the contaminant creating a better conductive path. Use of some graphite brush materials and treated electrographitics can help reduce metal transfer by forming a protective coating on the commutator surface. Porosity is reduced in treated electrographitic materials, but they are still prone to threading at current densities less than 45 A/in2.

It is important to note that while threading is unsightly, it usually does not prohibit equipment operation since substantial operating time is normally required before detrimental limits are reached. It is beneficial to lower threading levels as much as possible; however, be careful that a more serious problem, such as copper drag, does not develop when brush grades are changed.

## Copper Drag

Copper drag is buildup of conductive material between commutator bars that can cause sparking and lead to flashovers when bar-to-bar voltages are significant. Copper drag is quite often associated with a combination of excessive metal transfer to the brush and environmental contamination that reduces metal vaporization. Excessive metal transfer can occur when electrical or mechanical disturbances stimulate increased sparking at the brush/commutator contact. The molten metal is formed into thin sheets by commutator rotation and brush pressure which eventually forces the flattened particles into the commutator slots. They normally adhere to the trailing edge of the commutator bar, where they build up in layers similar to that shown in Figure 9.

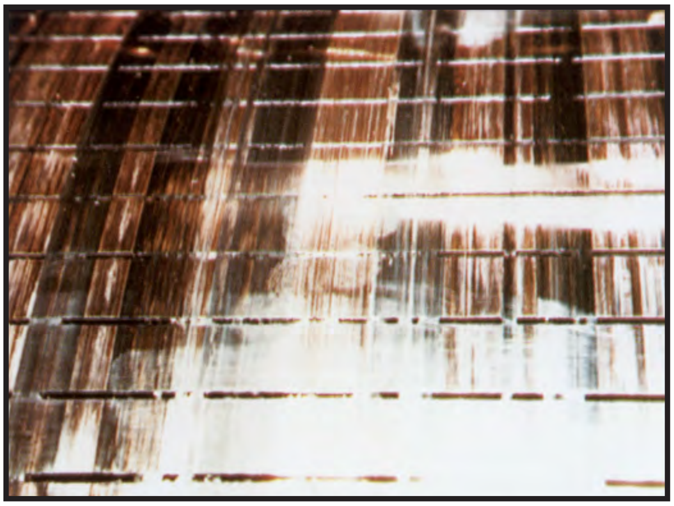

**Figure 9**
**Copper Drag – Accumulation of conductive material on the trailing edges.**

Some brush materials can operate satisfactorily in the presence of atmospheric contamination, such as oxygen inhibiting lubricants, while other brushes will promote the growth of copper drag. Simply changing the treatment in an electrographic brush material has eliminated copper drag on excavator shovel generators operating near the use of cable lubricants. This is also true in oily steel mill atmospheres and contaminated paper mill areas.

In general, reducing the causes for sparking and removing the contaminant will usually alleviate the copper drag. But, this is not practical in all cases and the simplest solution is to periodically clean the slots. Fortunately, copper drag is not tightly bonded to the bar edges and can easily be removed if there is sufficient access to the commutator.

Copper drag has also been known to occur on machines that are not normally heavily loaded and where contamination does not appear to be a major factor. Selective copper drag or copper drag that may not develop on all brush paths is common on these types of applications. Commutator grooving and rapid brush wear has also been observed on the brush path(s) experiencing copper drag. A considerable amount of copper has been found in brush faces removed from the grooved paths, indicating that the brush face copper is acting like a cutting tool to machine the commutator. Changing brush grades has been found to minimize or eliminate this problem since some grades have a tendency to be more selective than others.

Grooving

Commutator grooving usually occurs completely across the brush paths as shown in Figure 10. Groove depth may vary from path to path; however, depth in a particular path is fairly uniform around the commutator. This type of grooving is caused by either an abrasive brush or by abrasives in the atmosphere. A brush that is hard will not necessarily cause more grooving than a softer brush.

**Figure 10**
**Grooving – Metal machined from across the brush paths.**

Usually the opposite is true, for many softer brushes are made from natural graphites that inherently contain ash. Sometimes ash is added to artificial graphite brushes to control filming properties in contaminated atmospheres. Both of these natural and artificial graphite materials are soft and have a tendency toward commutator grooving. Many harder brushes (electrographitic) are baked at temperatures well over 2000°C which removes most of the abrasives that would cause commutator grooving. These electrographitic brush materials are often treated with additives that protect the commutator by promoting the establishment of a film which reduces the chemical reactions between the contaminants and commutator copper. Much of the grooving and costly periodic maintenance is thereby eliminated by the use of treated electrographitic brushes instead of the softer graphite variety that contain ash.

On some applications, grooving caused by atmospheric abrasives can be controlled with filters or by changing equipment ventilation systems to receive cleaner air. Brush wear usually is also greater in the presence of atmospheric abrasives since both members of the rotating contact are exposed.

Selectivity, Film Stripping and Grooving

Selectivity, film stripping and grooving are three interrelated distress signals that have plagued a number of applications. Less is known about the exact physical phenomenon that triggers these events; however, certain environmental and/or operating conditions are usually present which suggest possible reasons for their occurrence.

Selectivity is the unequal distribution of current between brushes operating in parallel.. Heavily loaded machines with numerous brush paths are more prone to be selective since there are more opportunities for variations in resistance between brushes. Resistance variations can be caused by a number of factors that include: mixed grades on the same machines, poor electrical connections between the brush shunts and brush, inadequate fastening of brush terminals to the holder, paint on the holder / brush terminal connection, differences in spring pressures, variations in commutator film thickness between brush paths, temperature differences across the commutator and sparking caused by mechanical or electrical disturbances.

Selectivity is a condition that usually continues once initiated since carbon electrical resistance decreases as temperature increases. Excessive brush currents, temperature and sparking can develop to the point of burning brush shunt connections and even flashing over. Brushes carrying the extra current usually wear much faster than other brushes on the same support arm.

Some brush materials have a tendency to be more selective than others. This is true for graphite brush materials that produce commutator films of varying thicknesses, creating major differences in path-to-path resistivity. Therefore, graphite materials are not normally used on commutators that have more than four brush paths. Certain electrographitic brush treatments can also contribute to the formation of unequal current distributions through adjacent brushes of the same polarity. It is important to recognize the symptoms of potentially destructive conditions and to take appropriate action if problems arise. Reducing the causes of resistance variations mentioned earlier should be initiated as a first step. Sometimes removing a contaminant, such as oil, can correct the problem. Changing brush grades to a more compatible material can be done if the problem persists. Spiral grooving the commutator surface to reduce brush "hot spots" is a technique that has proven worthwhile on a number of applications.

Commutator film stripping, as shown on the fourth brush path from the left in Figure 11, is quite often associated with selectivity on machines that are subjected to heavy transient loads. Film stripping promotes additional selectivity since the contact drop between brush and commutator is less on the stripped paths, resulting in a further decrease in resistivity. Brush temperatures, currents and sparking can the reach extremely high levels on the stripped paths. For example, excavator generator brush temperatures of over 200°C were recorded on stripped paths while adjacent brushes on filmed paths were operating at less than 150°C. Sparking levels had reached the "streamer" stage on stripped path brushes. Cold air flow on the commutator and low humidity can further aggravate an already poor situation.

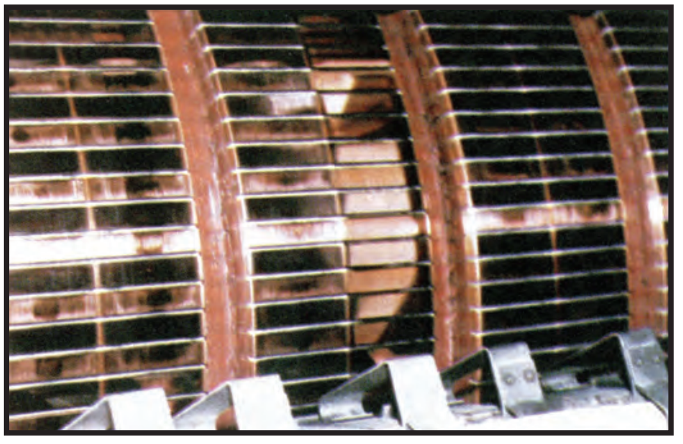

**Figure 11**
**Stripping – Less film on the fourth brush path is a destructive condition. The slot bar pattern is acceptable since the bars are not etched.**

Selective grooving can result if film stripping is not corrected. Very high current and sparking levels on heavily loaded machines are thought to vaporize the commutator copper during periods of excessive metal transfer. This differs from the selective grooving caused by machining on lighter loaded machines described in the section, "Copper Drag".

## Nonconductive Filming

Nonconductive filming is an expression that is synonymous with the "over-filming" phrase heard quite often. Sparking and bar burning usually accompany this condition since high resistance areas in the film can be found when the commutator is probed. Nonconductive films can be formed from contamination, certain types of brush materials and sparking. Sometimes a combination of these three factors creates the unattractive commutator appearance shown in Figure 12.

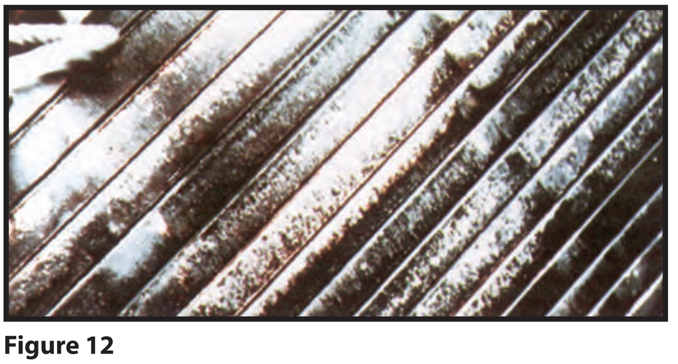

**Figure 12**
**Nonconductive Filming – Brush sparking usually results from this condition.**

It is important to note that commutator film color should not be used to determine if the film is nonconductive. It is not uncommon to see very dark films on paper mill commutators that are performing quite well. This applies to other industries as well. The correct brush grade in the presence of contaminants can help provide for a successful application without costly maintenance.

## Conclusion

Satisfactory brush and commutator performance is characterized by:

1. Nondestructive sparking
2. Satisfactory brush life
3. Acceptable commutator life

These three interrelated criteria can occur on attractive commutators as well as on those considered not pleasing to the eye.

There are times when machine problems develop that emerge as distress signals at the brushes or commutator. The collector system acts like a thermometer in revealing equipment problems even it the cause originated elsewhere. It is important to locate the problem source and take corrective action quickly to prevent additional machine damage. The destructive commutator conditions discussed in this paper should help engineering and maintenance personnel determine whether the source of a particular problem is machine or brush related.

## Reference Note

The subject matter contained herein was acquired by the author through years of experience as an electrical design engineer in the motor/generator field and through years of investigating and resolving commutator and brush related problems. Much of the information presented is based on the combined experiences of other experts in this field in addition to those of the author himself. Therefore, it is difficult to designate specific individuals, books or periodicals for detailed references.

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