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Performance and Condition Assessment of Slip-Ring and Carbon-Brush Systems in Wound-Rotor Synchronous Generators

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ABSTRACT

This review examines the sliding electrical contact formed by carbon brushes and slip rings in externally excited, wound-rotor synchronous generators. The interface must transmit direct current while accommodating rotation, vibration, surface films, frictional heating, and environmental contamination. Rather than treating current density, contact drop, brush pressure, temperature, or surface roughness as universal constants, the paper organizes them as interacting, grade- and machine-specific variables. It first summarizes asperity-scale current transfer and the role of the collector film, then compares brush-grade families and ring materials, identifies measurable performance indicators, and links common surface symptoms to electrical, mechanical, thermal, and environmental causes. A condition-based maintenance framework is proposed that combines per-brush current measurements, temperature trending, visual film assessment, geometry and pressure checks, and contamination control. The principal conclusion is that reliable operation depends less on a single alarm threshold than on maintaining stable contact conditions relative to an established machine baseline and to the limits specified by the original-equipment manufacturer and brush supplier.

1. Introduction

In a wound-rotor synchronous generator, direct current is supplied to the rotor field winding to establish the air-gap magnetic field. Where the excitation source is stationary, a pair of rotating slip rings and stationary brushes provides the current-transfer path. Brushless exciters eliminate this sliding interface, but slip-ring excitation remains relevant where plant design, retrofit constraints, field forcing requirements, or maintainability favor direct access to the field circuit [1]-[3].

The brush-ring system is a coupled electrical and tribological contact. Its behavior is governed simultaneously by brush grade, ring material and finish, current density, sliding speed, normal force, holder geometry, ventilation, humidity, contamination, and vibration. Because these variables interact, a symptom such as sparking or high temperature rarely identifies a unique root cause. For example, a hot brush may reflect high current, elevated contact resistance, excessive friction, inadequate cooling, poor seating, or a combination of these factors.

The submitted manuscript correctly identified the collector film, current sharing, brush pressure, ring geometry, and environmental control as important topics. However, many numerical values were stated as universal limits even though brush manufacturers and standards treat them as test- or application-dependent. This revision therefore emphasizes mechanisms, measurable trends, and evidence-based interpretation. Its goals are to: (i) define a physically consistent contact model; (ii) distinguish material families without assigning unsupported generic ratings; (iii) organize failure modes by causal pathway; and (iv) translate the analysis into a condition-based maintenance workflow.

2. System Function and Analytical Scope

2.1 Excitation-current path

The collector assembly comprises the excitation source, flexible conductors and terminals, brush holders and pressure systems, carbon brushes, two slip rings, and the rotor field winding. Each component contributes resistance and may influence current sharing. The electrical path should therefore be evaluated as a system rather than by inspecting the brush face alone.

Excitation source -> Brush set -> Slip rings -> Rotor field winding

Figure 1. Simplified current-transfer path in a slip-ring excitation system.

2.2 Operating variables

The main independent variables are field current, number and dimensions of brushes, ring diameter and rotational speed, brush pressure, brush grade, ring material, surface condition, and the collector-compartment environment. Key responses include contact voltage, temperature, wear rate, current distribution, friction, vibration, sparking, dust generation, and changes in ring profile. IEC standards define terminology, brush dimensions and test methods, but they do not convert these responses into one universal operating envelope for every generator [3]-[6].

Domain	Primary variables	Observed responses
Electrical	Field current; brush current density; contact voltage; excitation ripple	Electrical loss; current sharing; arcing propensity
Mechanical	Sliding speed; brush force; holder clearance; ring runout and roughness	Contact continuity; friction; wear; vibration
Thermal	Ambient and inlet-air temperature; ventilation; contact and friction losses	Brush, holder, pigtail, and ring temperature
Environmental	Absolute humidity; dust; oil mist; corrosive gases; silicone vapors	Film formation; contamination; insulation risk

Table 1. Coupled variable groups at the brush-ring interface.

3. Contact Mechanics and Current Transfer

3.1 Real contact area and constriction resistance

Machined brush and ring surfaces touch at a population of microscopic asperities rather than over the full apparent area. Holm termed the conducting microcontacts a-spots [1]. Under the simplifying assumption that the softer asperities deform predominantly plastically, the total real area of contact can be approximated by

$$Ar \sim F / H \tag{1}$$

where Ar is the real contact area, F is the total normal force, and H is the indentation hardness of the softer contact body. Equation (1) is a scaling relation, not a complete model: elastic deformation, roughness statistics, film layers, brush porosity, and dynamic load modulation can all alter the effective area.

Current lines converge into the a-spots, producing constriction resistance. For one ideal circular contact spot joining two semi-infinite conductors, a first-order expression is

$$Rc \sim (rhob + rhor) / 4a \tag{2}$$

where rhob and rhor are the bulk resistivities and a is the spot radius. A real brush contains many transient spots connected through a heterogeneous surface film, so measured contact resistance should be interpreted as the aggregate response of the entire interface [1], [2].

3.2 Collector film and dynamic conduction

During service, the ring develops a transfer film-often called the collector film or patina-containing carbonaceous material, metallic oxides, adsorbed species, and wear debris. Its composition and continuity depend on the brush/ring material pair, current, speed, temperature, humidity, and contaminants. The film is neither purely insulating nor purely lubricating; it participates in both current transfer and friction control. Experimental studies on electrographite/copper systems show that humidity and current alter film morphology, composition, resistance, and wear [8], [9].

CARBON-BRUSH BODY

Asperity contacts and wear particles

Dynamic collector film: carbon + oxides + adsorbed species

METALLIC SLIP RING

Figure 2. Conceptual layers in a filmed brush-ring contact; thicknesses are not to scale.

Current can pass through direct microcontacts, conductive constituents within the film, and localized electrical breakdown of high-resistance regions. The relative importance of these mechanisms varies with contact state; assigning one fixed film thickness or one dominant conduction mechanism to all generator collectors is therefore not justified. Practically, a stable and visually uniform film is desirable, but film appearance must be interpreted together with current, temperature, pressure, and geometry.

3.3 Coupled electrical and frictional heating

A useful first-order heat-generation model separates electrical and mechanical losses:

$$Ploss \sim IVc + muFv \quad (3)$$

Where, I is brush current, V_c is the measured contact voltage, mu is the coefficient of friction, F is normal force, and v is sliding speed. The first term captures aggregate electrical loss without requiring the contact to be purely ohmic; the second estimates frictional power. Temperature is then governed by heat capacity, conduction into the holder and ring, convection, and radiation. This formulation avoids the misleading inference that a decrease in brush bulk resistance alone necessarily causes thermal runaway. Instability can occur, but it is driven by the complete parallel-contact network and by temperature-dependent changes in film, pressure, seating, and current distribution.

4. Materials and Interface Matching

4.1 Brush-grade families

Carbon brushes are engineered materials rather than interchangeable blocks of graphite. IEC 60413 specifies procedures for measuring material properties such as density, porosity, resistivity, flexural strength, hardness, and ash content, while IEC 60773 addresses operating-characteristic tests [5], [6]. The most useful selection distinction is qualitative: each grade family trades electrical conductivity, friction behavior, film-forming tendency, mechanical strength, and permissible speed against one another.

Grade family	General tendency	Typical selection rationale
Carbon-graphite / carbographitic	Relatively hard; useful cleaning action; higher resistivity	Contaminated or difficult filming duties; selection is grade-specific
Electrographite	Graphitized at high temperature; generally stable at higher speed and temperature	Common in industrial machines and generator collectors
Natural graphite / soft graphite	Low friction and good lubricity; lower mechanical strength	Duties where gentle ring action is important
Metal-graphite	Graphite with copper, silver, or other metal; low resistivity and high current capability	Low-voltage, high-current contacts; speed and ring wear must be checked

Grade family	General tendency	Typical selection rationale
Resin-bonded or impregnated grades	Properties tailored by binder or impregnation	Special environments, commutation, or mechanical requirements

Table 2. Qualitative brush-grade comparison; supplier data for the exact grade governs final selection.

The original manuscript assigned fixed current densities, contact drops, friction coefficients, and maximum speeds to broad families. Such values are not portable across grades or machines. Manufacturer guides explicitly note that current density limits vary with machine characteristics and ventilation, and that friction has no single fixed value because it depends on grade, speed, load, surface condition, and environment [7].

4.2 Slip-ring materials and surface condition

Slip rings may be made from steels, copper alloys, or other application-specific materials. High-speed rotor design may favor mechanically strong steel rings, whereas copper-alloy rings offer higher electrical and thermal conductivity. Material selection cannot be separated from ring stress, rotor design, brush grade, cooling, corrosion exposure, and the supplier's intended film system. The relevant engineering objective is not simply maximum hardness or conductivity, but a stable material pair with acceptable ring wear, brush wear, contact loss, and film behavior.

Surface finish and geometry are equally important. A ring that is too smooth may glaze and provide unstable seating; one that is too rough accelerates abrasive wear. Runout, waviness, local high spots, groove geometry, and tool marks can excite brush motion. Because acceptable roughness and runout depend on ring diameter, speed, brush grade, and holder dynamics, these values should be taken from the OEM drawing or maintenance manual rather than from a generic review [7].

5. Performance Indicators and Measurement

A defensible assessment combines electrical, thermal, mechanical, and visual indicators. Single measurements are less informative than normalized trends taken at comparable field current, speed, cooling state, and ambient conditions.

5.1 Current distribution

For N brushes operating in parallel on one ring, define the mean brush current and each brush's normalized deviation as

$$I\_avg = (1/N)\ sum\ Ij \tag{4}$$

$$deltaj = (Ij - I\_avg) / I\_avg \tag{5}$$

A positive deltaj identifies an overloaded brush and a negative value an underloaded one. The standard deviation or coefficient of variation can summarize the set. No universal percentage should be used without validation: the alarm should reflect sensor uncertainty, normal machine-to-machine spread, field-current dependence, and the persistence of the deviation. A sustained outlier that is also hotter than neighboring brushes is more actionable than a transient current difference alone.

5.2 Contact voltage and temperature

Contact voltage should be measured with a defined probe location and polarity, preferably under repeatable load. Its absolute value is grade- and film-dependent, so the strongest indicators are step changes, increased scatter, polarity asymmetry, and divergence among nominally identical brushes. Temperature should be trended at the brush, pigtail terminal, holder, and ring when practicable. Infrared measurements require controlled emissivity assumptions and a clear line of sight; shiny ring surfaces can produce misleading apparent temperatures. Comparison with neighboring components and with prior load-matched data is usually more reliable than a generic camera threshold.

5.3 Wear, film appearance, vibration, and geometry

Brush wear rate should be expressed as length loss per operating hour or per unit of sliding distance, with load history recorded. Visual inspection should document film color and uniformity, streaking, patchiness, pitting, burning, dust accumulation, and brush-face contact pattern. Ring runout and profile should be measured with a method whose bandwidth and reference are stated. Vibration data from holders can help distinguish once-per-revolution geometry effects from broadband chatter, but frequency bands must be established from the actual structure rather than assumed generically.

Indicator	Method	Preferred metric	Diagnostic value
Per-brush current	Shunt or Hall-effect transducer	Mean, deviation, coefficient of variation	Loose connection, sticking brush, pressure or film inequality
Contact voltage	Differential voltage measurement	Load-matched level and variability	Film/contact change, poor seating, arcing
Temperature	Contact sensor or calibrated IR	Rise above ambient; neighbor comparison; trend	Electrical loss, friction, cooling, terminal resistance
Brush wear	Length gauge or wear sensor	mm/1000 h or mm per sliding distance	Grade mismatch, pressure, contamination, arcing
Film/surface	Visual/stroboscopic inspection	Uniformity, streaks, pits, deposits	Mechanical, electrical, or environmental disturbance
Pressure/holder	Force gauge; dimensional check	Force spread; free movement; clearance	Spring degradation, binding, rattle
Ring geometry	Probe, profilometer, or runout gauge	Runout, waviness, grooves, roughness	Machining, thermal distortion, abrasive wear
Environment	Temperature, absolute humidity, particle/oil monitoring	Condition versus baseline	Dry-film wear, corrosion, contamination

Table 3. Core condition indicators and their interpretation.

6. Degradation Mechanisms and Failure Modes

6.1 Loss of contact and arcing

When a current-carrying brush separates from the ring, the field circuit's inductance opposes an instantaneous change in current. Voltage can rise across the opening contact and produce an arc. Repeated arcing erodes the brush and ring, disrupts the film, generates conductive debris, and can damage nearby insulation. Common initiating mechanisms include ring runout, holder vibration, inadequate or unequal pressure, brush binding, poor seating, and surface contamination. The term ghosting should not be used as a synonym for sparking: supplier literature uses ghosting or ghost marking for a distinct ring-marking phenomenon on synchronous-machine collectors [7].

6.2 Current crowding and thermal instability

Unequal pressure, terminal resistance, holder friction, surface-film differences, and brush geometry can concentrate current in a subset of brushes. Local electrical and frictional losses then raise temperature, which may further alter the film and contact state. In a parallel brush set, this feedback can produce an unstable current distribution even though the bulk resistivity of graphite alone does not determine the outcome. The appropriate diagnostic signature is therefore the joint evolution of current, contact voltage, and temperature, not a single assumed temperature coefficient.

6.3 Polarity-dependent wear

Direct-current direction can influence tribochemical reactions, material transfer, arc behavior, and wear. Laboratory studies confirm that polarity effects depend strongly on the material pairing and operating conditions [11]. It is therefore unsafe to assert that one ring polarity always wears faster or that periodic polarity reversal is universally beneficial. Any polarity-reversal practice must be authorized by the generator and excitation-system OEM and should consider rotor-winding insulation, protection, and established plant experience.

6.4 Mechanical wear and surface damage

Abrasive particles embedded in the brush face can machine circumferential grooves into the ring. Excessive roughness, hard debris, high pressure, poor alignment, or unsuitable brush grade can accelerate this process. Helical or screw-thread patterns may originate from machining marks, groove geometry, or dynamic tracking; their interpretation should be based on the actual surface profile and maintenance history rather than attributed automatically to underloading. Spring pressure also has a non-monotonic effect: too little pressure promotes separation and arcing, while too much increases friction and wear. Controlled tests on copper-graphite contacts demonstrate distinct wear regimes as pressure changes [10].

6.5 Environmental degradation

Water vapor participates in normal film formation, but relative humidity alone is an incomplete descriptor because the available water content changes strongly with temperature. One manufacturer guide expresses the preferred range as 8-15 g/m^3 absolute humidity and identifies very dry conditions below about 2 g/m^3 as critical for many conventional grades; these are supplier guidance values, not universal generator limits [7].

Oil mist, grease, dust, and silicone products can produce deposits, impede brush movement, and destabilize the film. Corrosive gases such as chlorine compounds, ammonia, hydrogen sulfide, and sulfur dioxide can damage the film and ring surface, especially in humid conditions [7].

7. Diagnostic and Condition-Monitoring Strategy

7.1 Online monitoring

Per-brush current monitoring is the most direct method for identifying load imbalance. Sensors should be installed and calibrated so that their resistance, bandwidth, and wiring do not materially alter current sharing. Data should be normalized by total field current and synchronized with generator load, cooling state, and excitation mode.

Thermal monitoring should emphasize repeatability. Fixed sensors provide the strongest long-term trends, while infrared surveys are valuable for spatial screening when emissivity and reflections are controlled. A pigtail terminal hotter than the brush body suggests a different fault path from a hot contact face.

Visual or video inspection can capture sparking, brush motion, dusting, and film condition. Stroboscopic techniques can freeze the apparent ring surface during operation, but safe viewing arrangements and arc-flash controls are essential.

Vibration and acoustic emission may provide early indication of chatter or intermittent contact. Their use is most effective when spectra are compared with shaft speed, ring runout, and known structural resonances; broad generic frequency bands are not sufficiently specific for diagnosis.

7.2 Offline inspection

- Verify brush grade, dimensions, orientation, seating pattern, remaining length, and pigtail condition.
- Measure spring force on every holder using a calibrated force gauge; compare like-for-like mechanisms at the same brush length.
- Confirm that each brush moves freely without binding or excessive rattle and that holder clearances conform to the applicable drawing or IEC dimensional requirements.
- Measure ring runout, profile, groove condition, and surface roughness using a documented reference and sampling method.
- Inspect terminals, insulation, ventilation paths, dust extraction, seals, and evidence of oil or chemical contamination.
- After a grade change or ring resurfacing, follow the supplier's seating and film-development procedure rather than returning immediately to unrestricted loading.

7.3 Alarm philosophy

Alarm limits should be layered. A first level identifies statistically unusual deviation from a load-matched baseline; a second requires persistence or corroboration by another indicator; a trip or immediate maintenance threshold should remain tied to OEM protection criteria and observed risk. This approach reduces false alarms from normal operating transitions while still detecting compound faults.

Level	Trigger logic	Response
Advisory	One indicator departs from baseline	Check data quality; increase sampling; inspect at next safe opportunity
Action	Deviation persists or two indicators corroborate	Plan controlled load reduction or maintenance; perform root-cause checks
Urgent	Sustained severe sparking, rapid temperature rise, insulation risk, or protection operation	Follow plant emergency procedure and OEM limits; remove from service if required

Table 4. Example layered alarm philosophy; plant procedures and OEM criteria take precedence.

8. Condition-Based Maintenance Framework

A practical program can be implemented in six steps. The objective is to create a traceable relationship between operating condition, observed symptom, confirmed cause, and corrective action.

1. Establish configuration control. Record ring material and dimensions, brush grade and geometry, holder type, spring mechanism, number of brushes, excitation rating, and ventilation arrangement.
2. Create a reference baseline. Collect per-brush current, contact voltage, temperature, vibration, environmental data, and visual records at defined field-current and speed points after verified healthy operation.
3. Normalize and trend. Express brush current as a fraction of total field current, temperature as rise above ambient or neighbor difference, and wear against operating hours or sliding distance.
4. Use corroborating evidence. Do not diagnose a root cause from surface appearance or temperature alone; combine at least two independent indicators whenever feasible.
5. Apply a cause-directed correction. Examples include restoring free brush movement, correcting terminals, equalizing pressure, controlling contamination, resurfacing within OEM limits, or changing to a supplier-approved grade.
6. Verify the intervention. Repeat the same load-matched measurements and document whether current balance, temperature, sparking, and wear returned to baseline.

8.1 Troubleshooting matrix

Observed condition	Plausible causes	Confirmatory checks	Corrective direction
One brush carries high current and is hotter	Binding, low contact resistance, unequal pressure, terminal configuration	Check free movement, force, contact voltage, sensor calibration, terminal resistance	Correct holder/spring/terminal; replace damaged brush; verify balance under load

Observed condition	Plausible causes	Confirmatory checks	Corrective direction
Brush is hot but current is normal	High friction, poor seating, restricted cooling, IR emissivity error	Inspect face pattern, pressure, ring finish, airflow; confirm with contact sensor	Reseat or replace brush; correct pressure/finish/cooling; recalibrate measurement
Dense intermittent sparking	Runout, vibration, low pressure, sticking brush, contamination	Correlate video with shaft phase; measure runout and holder motion	Restore contact mechanics; clean contamination; machine only to approved limits
Rapid dusting and wear	Dry air, abrasive contamination, unsuitable grade, excess pressure, rough ring	Measure absolute humidity, particle/oil contamination, pressure, roughness	Control environment; correct pressure; use supplier-approved grade; clean/resurface
Circumferential grooves	Embedded debris, roughness, high pressure, hard grade, poor filtration	Analyze brush face and debris; profile ring; inspect filtration	Remove source; renew brushes; resurface as approved; improve filtration
Patchy or streaked film	Load cycling, contamination, pressure inequality, ring deformation	Compare current/temperature by brush; inspect runout and environment	Correct underlying cause; allow controlled film stabilization

Table 5. Cause-directed troubleshooting matrix.

8.2 Spring pressure as an example of qualified guidance

Spring pressure illustrates why generic limits must be qualified. A current Mersen data sheet recommends approximately 18-20 kPa for several electrographitic and carbographitic grade families on slip rings under normal operating conditions, with different ranges for other families and duties [7]. The same source calls for periodic force measurement. This value is useful as an example, but it does not override a specific brush drawing, supplier instruction, or generator manual. Pressure should also be assessed as a distribution across the brush set, not only as an average.

9. Discussion and Limitations

First, laboratory tribometers and commutator studies provide valuable mechanisms but do not reproduce every feature of a large synchronous-generator collector. Ring diameter, speed, ventilation, field-current dynamics, holder structure, and maintenance history affect transferability.

Second, the term carbon brush covers a wide range of formulations. Values measured for one electrographite or copper-graphite grade should not be assigned to an entire family. Supplier qualification data for the exact brush grade are essential.

Third, a review cannot establish machine-specific alarm thresholds without operating data. A robust maintenance program should therefore preserve raw measurements, load state, environmental conditions, calibration records, and photographic evidence so that thresholds can be refined empirically.

Finally, standards primarily provide definitions, dimensions, and test methods. Safe operating and outage decisions remain governed by the plant's approved procedures, generator OEM instructions, excitation-system protection, and brush supplier recommendations.

10. Conclusion

Slip-ring and carbon-brush performance in wound-rotor synchronous generators is controlled by a dynamic, multi-asperity electrical contact whose behavior cannot be reduced to one current-density, temperature, roughness, humidity, or pressure limit. Reliable operation requires a compatible brush-ring material pair, stable collector film, adequate and uniform pressure, controlled geometry and vibration, clean ventilation, and balanced current distribution. The most effective condition assessment therefore integrates per-brush current, contact voltage, temperature, wear, film appearance, holder mechanics, ring profile, and environmental data.

The recommended maintenance principle is baseline-centered and evidence-based: establish healthy load-matched signatures; trend normalized deviations; require corroboration before assigning a root cause; and use OEM- and supplier-specific limits for intervention. This approach is more defensible than universal threshold tables and provides a clearer path from observed symptom to verified corrective action.

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