WOUND ROTOR REPAIR TIPS: TESTING, APPLICATION AND FAILURE ANALYSIS

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Wound rotor (WR) motors represent only a small fraction of all electric motors in service. Reviewing the Technical Support call logs, one might conclude that the proportion of wound rotor motors in service is far greater. Because many of us do not work on wound rotor motors very often, it is understandable that not everyone has a clear understanding of how they differ from a squirrel cage motor. The purpose of this article is to dispel some misconceptions about how they work, and to offer valuable tips for failure analysis, repair and testing.

Conveyors, ball mills and crane hoists are common applications for wound rotor motors, because of their varying speed-torque requirements. The benefit of a wound rotor motor is that the resistance of the rotor circuit can be externally varied, to provide either variable resistance (in the case of a liquid rheostat) or steps (when a series of external resistors of fixed resistance are used), to maximize the torque to suit a particular application.

HOW DOES A WOUND ROTOR MOTOR WORK?
In Figure 1, the highlighted path along the several torque curves illustrates this advantage. Beginning with torque curve C, then stepping to curve B, and on to curve A allows the motor to produce the maximum possible torque as it accelerates along those torque curves. Depending on the external resistance added to that of the rotor, torque curves D through G could result. None of those would be a good choice for an application requiring a large amount of torque to start or accelerate a load. Each might offer benefits if increased slip / reduced speed were desired. For example, although uncommon, a wound rotor motor can be used in a pumping application to reduce speed and, therefor flow.

WHAT ABOUT THE SECONDARY VOLTAGE?
One of the first differences noted, before even dismantling a wound rotor machine, is the “secondary voltage” (and secondary current) reported on the nameplate. That label leads to understandable confusion about how a wound rotor motor actually works.

Misconception #1: “They energize the rotor too.”
Contrary to the nameplate marking, the rotor is not energized by an external power source during service. As with a squirrel cage induction motor, the rotor is the secondary winding to the primary stator winding. The secondary voltage on the nameplate indicates the transformer ratio between the stator and rotor windings. This is used to calculate the external resistance required to obtain the desired torque for each step.

In operation, the stator is energized just as a squirrel cage induction motor (SCIM), but the rotor leads are connected to variable external resistance. This often takes the form of a series of contactors to a resistor grid, with multiple steps to provide different resistance at each step. Figure 1, from the EASA Technical Manual, illustrates the torque curves that result for each specific rotor circuit resistance. More specifically, the external resistance in series with the rotor leads changes at each step to provide maximum torque. Visualize the torque curve of the motor as following the highlighted portion of those different torque curves. When set up correctly, just as the torque of one step falls off, the operator steps to the next resistance.

Because of the high-torque capability, the wound rotor motor is popular for crane applications. Pay attention the next time someone in your service center is assembling a large vertical motor. It’s likely they will tap-tap-tap on the down button to gingerly lower the stator over the rotor. Each “tap” has the potential to cause a rapid restrike failure of the windings (see EASA’s Root Cause Failure Analysis, Page 3-20). Predictably, this causes a failure at the weak link—in a wound rotor motor this would be...
the rotor lead connection to a slip ring.

When inspecting a wound rotor motor and the rotor lead is the point of failure, the transient caused by a rapid restrike is a strong contender for the root cause of the failure. If it was not caused by an operator tapping the button, it could be a weak magnetic holding coil allowing a contactor to chatter, damaged contacts on one of those contactors, or even a damaged resistor grid.

Larger machines sometimes use a saltwater rheostat; with fixed contacts immersed to varying depths in a conductive liquid such as a brine solution. Some controls manually raise and lower the contact tong into the solution, but most raise and lower the level of the solution around the fixed tongs.

The stator and rotor are rewound just like any three-phase winding, with the added consideration of securing the rotor windings against centrifugal forces. EASA Tech Note 36 can help you calculate the amount of banding required to withstand those forces.

The more circuits a rotor has, the more it tries to behave like a SCIM. If a 4-pole rotor has a 4-delta connection, consider reducing the circuits and turns in proportion (and increasing the wire area in inverse proportion). The motor’s speed control will improve, and the volts/coil stresses will be reduced. (See Figure 2.)

**Misconception #2: “We can’t have the same number of circuits on the rotor as on the stator.” Or “If the rotor is wye, the stator needs to be delta.”**

The number of circuits for the stator and rotor, and the selection of wye or delta connection (as well as the jumper arrangement in most cases), are independent of each other. In other words, it does not matter if the stator and rotor have the same circuits, or a different number of circuits. Either (or both) stator and/or rotor can be connected wye or delta.

Both stator and rotor should pass a surge test. Just as you can apply 15% of rated stator voltage to perform an open stator ball test, you can apply 15% of secondary voltage to “ball test” the rotor.

**Bonus tip:** Use a replacement garage door roller as a dummy rotor. Use acrylic sleeving or electrical tape on the shank to insulate the handle. Keep a finger on the roller as it turns, so you can detect a dead spot or reversed coil.

**TESTING TIPS, AFTER ASSEMBLY**

After assembling the wound rotor motor, some technicians discover another anomaly unique to the wound rotor motor. Because the stator and rotor each contain a 3-phase winding, the number of slots must be divisible by three (3 phases). The slot count also has to be compatible with the number of poles. That means that there is inherently a “bad” stator slot—rotor slot combination (Table 1). Two common concerns, when trying to run a wound rotor motor in the service center, are cusp and cogging. Without the external resistance in the rotor circuit, cogging or a cusp is likely. Electrical noise is another possibility. The two probable explanations for electrical noise are:

- a bad stator slot-rotor slot combination
- an eccentric air gap

To rule out the eccentric air gap, run the motor at half rated voltage. If the air gap is not uniform within 10% of the average, the motor will be very noisy at rated voltage. The magnetic flux varies as the square of the voltage, and the decibel scale is a logarithmic scale, so a motor with an eccentric air gap will not be noisy at half of rated voltage.

Before running the motor, with the rotor leads open, apply rated voltage to the stator leads and measure the voltage between slip rings. It should be balanced, and within 10% of the secondary voltage reported on the nameplate. For larger machines, or those rated above 2 kV, it is acceptable to apply a fraction of rated voltage,
and compare the ratio of applied primary to secondary voltage to that of the nameplate.

Assuming the results are as expected, we now know that the turn ratio between stator and rotor is correct. Therefore, the turns and connection of both rotor and stator are correct. The rotor should not rotate during this test, but the more parallel circuits the rotor has, the more likely it will do so. In most cases, very little torque develops under “open rotor” conditions. Because this is a transformer test, if the rotor was spinning the secondary voltage (and frequency) would decrease. To obtain accurate values, the shaft must be stationary.

Next connect the rotor leads together, and run the motor as a SCIM. The magnetizing current should follow the expected norms. (See “No-Load Current Basics: Practical Guidelines for Assessment,” Currents, February 2005).

**Bonus tip:** Be sure the brushes are fully seated. If you run a wound rotor motor with brushes that are barely contacting the slip rings, the motor may draw high current.

An optional test is to connect the stator leads together, and run the motor by energizing the rotor leads at the rated secondary voltage. One benefit to doing so is that, if an eccentric air gap is suspected, the electrical noise will still be present. As with the stator test, above, operation at half of the secondary voltage should greatly reduce or eliminate the noise. The ratio of magnetizing current (i.e., no-load amps) for the rotor and stator should be similar. In other words, for as low-speed wound rotor motor, if the NLA of the stator is 70% of FLA the ratio of rotor NLA/FLA should also be approximately 70%.

If the motor runs correctly on one winding but not the other, that indicates a connection error in the winding that does not run properly. Such an error should also be detected by the secondary voltage test.

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**TABLE 1: STATOR-ROTOR SLOT COMBINATIONS**

<table>
<thead>
<tr>
<th>Poles</th>
<th>Noise</th>
<th>Cogging</th>
<th>Cusp</th>
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<td>±2, -4, -10</td>
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<td></td>
<td></td>
<td></td>
<td>±48, -96</td>
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**TROUBLESHOOTING ROOT CAUSE FAILURE ANALYSIS**

When a wound rotor motor fails, there are several things to check to determine the underlying root cause of the failure. First, the entire rotor circuit must be considered. An interruption of the rotor circuit can result in a voltage transient (e.g., “rapid restrike” or “reclosure”) failure mode. Most wound rotor motor rotor circuits use a series of fixed resistors, with contactors used to close each subsequent step. Each contactor, each resistor, and the associated wiring must be checked. The simplest way to go about this is to connect ohmmeters to the leads at the rotor terminal box, and observe the resistance as each step of the controls is closed. All three phases should be balanced, for every step. A broken resistor, a badly burned contact, or a weak magnetic holding coil allowing the contactor to chatter – any of these can cause rotor failure, often at a rotor lead from the slip rings.

Next examine the contacts themselves (Are they burned? Do they meet simultaneously when the contactor operates?), and the holding coil (Is it weak, perhaps not pulling in strongly?) for each contactor. Physically examine the power supply to the crane. Not only the trolley, but also the bridge are mobile, so at any point along the path of each there might be a kinked power wire, or a damaged “shoe” used for energy transfer. Check the rails as well. A misaligned rail, or uneven support beneath the track rail could cause a sharp jolt when the crane is traveling—especially at higher speeds.

**IDENTIFYING WOUND ROTOR CONNECTIONS**

When preparing to rewind a wound rotor, the first step is to make sure you can correctly identify and duplicate the connection. Larger rotors, and most vintage rotors, are wave wound. That means the coils, rather than clos-
ing in a diamond configuration like most of the coils we use these days, form a pattern that resembles a path zig-zagging up a ladder (Figure 3).

If you trace the connection, the pattern has a logical progression to it. Divide the number of slots by the number of poles to obtain the back pitch. The path around the rotor forms one side of each pole, alternating from end-to-end, then moves into the next slot to repeat the path until all the half-coil paths are formed. Then the path follows a reversing jumper, which (as the name implies) reverses the path through the other half of each phase, with the same number of trips around the rotor.

Start by sketching the connection end, drawing each clip (Figure 4), and then trace each lead, reversing jumper and wye back from the connection to the slot it exits. Stamp identifying numbers on those slots, so that the connection can be duplicated exactly.

If the connection is beyond interpretation due to the failure mode, use EASA’s **AC Motor Verification & Redesign** program as a diagnostic tool. The air gap density of the stator and rotor should be similar—often the rotor air gap density is slightly higher. Because EASA’s **AC Motor Verification & Redesign** program is designed for stators, ignore the backiron and tooth densities calculations of the program—they will be incorrect. However, the air gap density calculation will be correct and is useful for determining the connection. Current density for the rotor, is typically lower than for the stator because the rotor is moving through air and cooling is better than for the stationary stator windings.

To interpret the partially developed rotor winding shown in Figure 5, the relationship between the top and bottom coil sides and their leads can be difficult to interpret the first time. The top and bottom clips are arranged in a circle, and when facing the connection end of the rotor that

By sketching the clips, relative position of jumpers and clips, the original winding can be duplicated.

Reference: Liwshitz-Garik; the partly developed winding diagram gives the key positions of the connection.
much is intuitive. Number the slots, in the CW direction of the coils are “top left” as shown in the Liwschitz-Garik diagrams (Figure 5). Identify the bottom coil side from slot 1, and mark it (a temporary flag of masking tape works well for this) as A1. Count over the slot #16, and position the top lead from slot 16 to align with the bottom lead from slot #2. Setting the relationship between the top and bottom clips is just that simple.

(Note: If the rotor coils are “top right” instead of “top left”, trace from the back side of the page to create a reverse image. Then number the slots CCW and follow the steps outlined above.) Next, simply count the clips as you bend and pair them, along the way marking the leads, wye and jumpers as appropriate.

The best clips are made from copper strips, and folded over a jig of steel slightly over the thickness of the copper conductor (Figure 6). For convenience, fold the copper strip into a box so the ends meet (on the side of the steel jig), and braze the clip. Then knock it off the jig, and fold the next copper clip.

If the clips are to be TIG-welded, use silphos as feedstock while welding them. The silphos will flow in at temperature below the melting temperature of copper, and penetrate deeper, making for a better electrical connection.

Tip: To facilitate cooling during operation, extend evenly spaced clips a reasonable distance beyond the majority of the clips to function as fan blades. Divide the total number of clips to find a whole number, to establish the uniform spacing. For example, on a rotor with 90 clips you might extend every tenth clip so as to create 9 evenly spaced fan blades.

Debur the clips to remove sharp corners that might puncture insulation. One method for insulating the clips is to use short lengths of acrylic sleeving to insulate every other clip. Allow the sleeving to extend slightly past the clip.

BANDING REQUIREMENTS
The mechanical forces acting on the winding extension of a wound rotor, just as an armature, vary as the square of the speed. It is important to know the following variables, to determine how much banding is necessary to prevent catastrophic failure:

- weight of coil extension (extrapolate this from dimensions and weight of one coil)
- diameter of the rotor, specifically at the area to be banded
- rpm of the rotor; frequency is a factor!

Use the formula from EASA Tech Note 36:

\[ F = 0.000028416 \times W r_n^2 \]

Where:

- \( F \) = force, centrifugal
- \( W \) = weight of coil extension
- \( r \) = radius at the banding
- \( n \) = rpm

In our global economy, be especially cautious when repairing machinery designed for a different operating frequency than that of your own country. A 50 Hz machine operating in a 60 Hz application will experience nearly 150% more centrifugal force (60/50 x 60/50 = 1.44).

OTHER USES FOR WOUND ROTOR MOTORS
The late James Anderson wrote an exceptionally practical EASA article about converting a wound rotor motor for use as a variable voltage transformer (Appendix I, EASA Technical Manual, Section 7.5). By connecting the stator and rotor phases with the stator phases the extension of the rotor, one pole pitch of rotation yields a voltage range that (if the stator and rotor voltages are equal) extends from zero volts up to twice the input voltage. In other words, a service center with only 460v input service can use a wound rotor motor as a 0-920 volt test panel.

A wound rotor motor, with no modification, can be used
as a rotating voltage and frequency converter. By driving a wound rotor against the direction of phase rotation with a DC motor, the range of voltage and frequency is only limited by the construction of the rotor.

UNDERSTANDING ROTATING FREQUENCY CONVERTERS

A wound rotor motor can be driven by another motor, either AC or DC, to obtain non-standard voltage and frequency output. First developed as a way to supply power for higher than synchronous speeds, the same principle can be used to produce sinusoidal 3-phase power at desired frequencies other than that available in the service center. For example, a country with 50 Hz power could test run a motor being shipped to a 60 Hz country at the intended frequency.

Usually the drive motor has fewer poles than the wound-rotor motor, so the wound-rotor motor is driven faster than its synchronous speed to increase the frequency of the output. The poles for the stator and rotor of the wound-rotor motor must be equal. When rewinding any wound-rotor motor, watch for consequent-pole connections. Grouping alone is not a reliable indicator of poles.

The best way to understand the process is to visualize the rotating electrical field in the stator of a wound-rotor motor. The field rotates one direction, so that when the rotor is driven in the opposite direction (Figure 7) the passing frequency is increased. If the speeds are the same (i.e., the same number of poles as the drive motor) the output frequency will double. So a 4-pole wound-rotor motor operating from 60 (50) Hz could be driven ‘backwards’ (against the stator field) at 1800 (1500) rpm to produce 120 (100) Hz power from the output leads. The input leads of the wound-rotor motor are normally energized from the same power supply as the drive motor.

To obtain other frequencies, we can use a variety of combinations of drive motor / wound-rotor motor poles. Since the stator field is rotating at a constant 60 (50) Hz, it is fairly straightforward to calculate the output frequencies that can be obtained. While most frequency converters are direct-coupled (or integral units on a common shaft), the use of pulleys permits almost any reasonable frequency to be produced.

Calculations should be done using the formula below:

\[ F_2 = \frac{(N_1 + N_2) \times F_1}{N_1} \]

Where:
- \( N_1 \) = Original speed of wound-rotor motor
- \( N_2 \) = Driven speed
- \( F_1 \) = Frequency input into the stator
- \( F_2 \) = Frequency output of the frequency converter

For example, if a 2-pole motor is used to drive a 4-pole wound-rotor motor:

**60 Hz example**

\[ \frac{(1800 + 3600) \times 60}{1800} = 180 \text{ Hz} \]

**50 Hz example**

\[ \frac{(1500 + 3000) \times 50}{1500} = 150 \text{ Hz} \]

Tables 3 and 4 offer a quick reference of some of the frequencies that can be obtained by driving a direct-coupled wound-rotor motor at synchronous rpm.

As the Tables 3 and 4 indicate, there are several options to get the same frequency output. If called upon to build a rotating frequency converter, it is more practical to keep the drive motor and wound-rotor motor as close to the same poles as possible. [For example, we could obtain 180 (150) Hz by driving a 16-pole wound rotor motor at 900 (750) rpm, but driving a 4-pole at 3600 (3000) rpm is more practical.]

Since the stator field remains a steady 60 (50) Hz, driving the wound-rotor motor against the direction of the stator field rotation adds the difference in Hz, while driving it with the rotation subtracts the difference (Tables 3 and 4).

When testing a rotary frequency converter: If the output frequency is less than rated, simply reverse any two input leads of the wound rotor motor or of the drive motor (not both).

The mechanical construction of the wound rotor may limit the speed at which it can be driven. For example, a 20-pole wound rotor driven by a 2-pole would probably fail quickly because of centrifugal force. The peripheral speed of the rotor precludes safe operation. A review of EASA’s database of wound-rotor motors suggests that wound-rotor peripheral speed rarely exceeds 7,500 feet (2,286 meters) per minute. That should be a safe guideline when setting up a frequency converter.

Lamination thickness also limits the frequency that
Frequency output of rotary frequency converter, operating on 60 (50) Hz supply.

### TABLE 3: FREQUENCY OUTPUT IF ROTOR IS DRIVEN OPPOSITE THE STATOR FIELD ROTATION

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<thead>
<tr>
<th>Poles</th>
<th>(N1) Speed</th>
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<th>1800</th>
<th>1200</th>
<th>900</th>
<th>720</th>
<th>600</th>
<th>514</th>
<th>450</th>
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### TABLE 4: FREQUENCY OUTPUT IF ROTOR IS DRIVEN WITH THE STATOR FIELD ROTATION

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<tr>
<th>Poles</th>
<th>(N1) Speed</th>
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### DRIVEN SPEED OF WOUND ROTOR (N2) — 50 Hz

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a motor can operate/produce. A typical 60 Hz motor is likely to experience high eddy-current losses above 200 Hz. A 60 Hz machine typically has lamination thickness about .024” while lamination thickness for a 400 Hz unit is approximately .012”.

**Tip:** For a variable-frequency output, a wound-rotor motor can be driven by a variable speed DC motor, or by an induction motor operating from a stock VFD (to obtain frequencies above VFD capabilities).

**TRANSFORMER ACCEPTANCE TESTING**

Certain transformer acceptance tests require a proof voltage to be applied; the higher the test frequency, the shorter may be the duration of the test. By connecting two wound rotor motors in series, it is possible to step up the voltage and frequency to obtain sinusoidal power at much higher frequency.

**SUMMARY**

The wound rotor motor offers some unique challenges, both to the end users and repairers. By applying the same evaluation criteria to each wound rotor motor, we can accomplish the best possible repair, and avoid problems created by someone else.

The secondary voltage “transformer test” is of critical importance. If the windings are intact, the secondary voltage test is a useful incoming test prior to dismantling the motor. No-load operation, to document and evaluate the magnetizing current of both stator and rotor, is useful. By recognizing that the stator-rotor slot combination is inherently “bad”, we can avoid wasted time trying to trouble-shoot a problem that does not exist.
One of the most important pieces of equipment today in an aggressive service center is a means of variable voltage for AC testing. The source should be three phase and have a sizeable amperage rating.

For a service center handling motors in the range of 10 hp and below, the rating should be no less than 20 amperes. From here on in the size of the unit would be according to the size of equipment handled by the service center. The voltage ratings must be 600 volts minimum. (The need for this will be brought out later.)

There are three good means for obtaining a variable AC source. One is variac ganged together for the proper voltage and current requirement. After a 20 amp rating and in voltages above 120 these get very costly unless they can be found on the used market. Even so, they are hard to find above 120 volts.

Another means for an easily adjustable source is a motor-generator set using a regular three-phase alternator, but wound for 600-800 volts. In using a unit like this, the capacity of the motor and generator will run a motor idle equal to about four times the generator's capacity. The voltage adjustment to the alternator field can be done with a rectifier/variac combination. A motor or a transformer can be brought up on test smoothly and easily with this unit.

Another simple means is the use of a slip-ring motor connected and used as an induction voltage regulator. This is one of the best and least expensive ways of getting a variable-voltage source with a large capacity. Slip-ring motors of all capacities are quite plentiful on the used market. A four-pole machine is the best, and only 90 degrees mechanical rotation is used.

The electrical connection used is shown in Figure 1. It is merely a three-phase autotransformer. For best results, the stator-rotor turns ratio should be 1:1. This will give a zero voltage condition in the opposing position, and twice the applied voltage in the additive position.

At this point, refer to Figure 2. Position A shows the stator and rotor voltage in phase opposition. Position B shows the rotor moved 45 degrees and the voltage adds to produce 41 percent more voltage on the load terminals than the applied voltage. Position C shows the rotor moved 90 degrees to where the stator-rotor voltages add to twice the applied voltage. If the turns ratio is not 1:1, a voltage condition of unequal proportions would exist.

As an example, suppose we had a slip-ring motor with a 220-volt stator and a rotor of 330 volts. If we were to use the stator as the exciting winding and the rotor as the load winding (R), we would find that, when the rotor is in Position A, the line or $L_0$ voltage is 330 minus 220,
or 110 volts. This is produced from the rotor. Between Positions A and C we would get various $L_o$ voltages equal to the vector sum (angle of rotation) of 220 and 330 volts. When we reach Position C, we would have $L_o$ voltage equal to the sum of 330 and 220, or 550 volts.

In making a turns ratio of 1:1 with a good slip-ring motor, coils can be cut out of the rotor or the stator to meet the conditions. Even turns can be cut out of coils to get as close to a 1:1 ratio as possible. Either the stator or rotor can be used for the exciting winding. Whichever winding is used for the R or load winding, the phases have to have the six leads brought out for the connection, as shown in Figure 1. The leads have to be phased out with respect to the exciting winding, but this is just a matter of swapping leads of the R winding until all $L_o$ voltages are equal, and of turning the rotor to reach a zero and maximum condition.

A smooth means of turning the rotor for the various voltages can be had by coupling a gear box directly onto the motor shaft. We have found that using a ratio of 720:1 gives a smooth, slow voltage rise. If the maximum voltage output is 900 volts, then for every degree of rotation there are 10 volts. Consequently, the rotor cannot be turned too fast. The motor has an opposing torque to the gear box, so use a strong one, and no flexible coupling between motor shaft and gear box. The input to the gear box can be driven by a brake motor or handwheel, whichever you prefer. On a 500 hp (375 kW) unit we used a 3 hp (2.25 kW) gearbox of 360:1 ratio and belted that to a variable DC motor with a 2:1 ratio. We used only a 1/2 hp (3/8 kW) motor.

If forced-air cooling is employed, the unit can be used to its full rated amperage capacity. If no cooling is used, it should be derated about 50 percent for continuous duty. For intermittent or 10 minute duty, it could be used to rated capacity or even higher: 200 percent duty is no problem for short time tests.

Note: This article is reprinted from the July 1968 issue of Electrical Apparatus Service (now Electrical Apparatus). Copyright 1968, Barks Publications, Inc., Chicago, IL. It may also be found in the EASA’s Technical Manual, Section 7, Electrical Testing.
APPENDIX 2
PHOTO LOG OF FAILURES AND REPAIR TECHNIQUES

Note the few jumpers required in a wave wound 3-phase rotor.

Large conductors may require that both ends be connected by clips. TIG or silver-solder are recommended in either case.

Lead position relative to the slip ring connection points is critical.

This design did not appear to have enough insulation between leads, jumpers and the wye.

Insulation of leads passing through the shaft is a critical task. Sleeving, preferably multiple layers, can be used to protect the leads from chafing.
The bracing is solid, but the aluminum support ring may not be substantial enough.

The failure at the wye resulted from insufficient insulation between the wye, the braces at ground potential, and other components of the connection.

Note the robust bracing of the connection.