QUARTZELEC WHITE PAPER

Damaged generator rotors: the economic and logistical benefits of repair over scrappage. New advances in repair techniques and stress analysis extend the feasibility of a repair further than traditionally thought.

Authors:

Wojciech Betlej | Tony Croucher
Bernhard Fruth | Dominic Buse

Quartzelec Ltd, United Kingdom

HOW

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ABSTRACT

Many would agree that one of the worst possible electrical failure mechanisms on a generator rotor is a motoring event while the rotor is at standstill. The resulting damage can be extremely severe – including a melted rotor body and double earth faults. In many cases, this renders salvage impossible and the rotor has to be scrapped.

This paper describes extensive repairs recently carried out by Quartzelec to a generator rotor following such an occurrence whilst the rotor was at standstill. The failure resulted in a double earth fault and severe arcing damage, which included deep excavations within the forging slots, almost 20% of the copper winding on the rotor melting away or becoming severely distorted, and severe damage to the retaining rings, snap rings and wedges.

It is believed that the repairs carried out by Quartzelec to save the rotor rather than scrapping it, were a first and that they could well replace current practice: rotor bodies which would normally be condemned can now be successfully repaired.

INTRODUCTION

During steady-state condition, the main magnetic field set up by a generator's rotor winding and that produced by the current flow in the stator winding are aligned, so no unwanted voltages are induced in the rotor. During transient conditions, however, the magnitude of both magnetic fields changes causing negative sequence currents to flow in rotor components such as the body, damper cage and field winding.

International standards for new generators specify requirements which must be met whilst in the transient state, including the ability to sustain certain abnormal conditions such as external faults in the transmission system, or minor voltage and frequency variations which would induce negative-sequence currents on the rotor surface. Most new units incorporate leading edge protection systems to guard against most major faults. Unfortunately, however, neither malfunction of these protection systems nor human error can be fully controlled.

The objective of this article is to reveal the consequences of a motoring incident, and the repair methods used by Quartzelec to tackle the resulting severe rotor damage, including weld repairing the melted rotor forging and altering the geometry of the slot dovetails section supported by precedent stress analysis.

Can a synchronous generator work as an induction motor?

Loss of excitation whilst a generator is under full load effectively turns a synchronous generator into an induction motor. The rotor speed rises until the prime mover governor reduces the steam input to inhibit the speed increase. This induces low frequency currents in all conductive components such as the rotor body, wedges, damper cage and winding. The time for which the rotor can sustain this asynchronous condition depends on many considerations – but principally upon the induced currents flowing through rotor components that have not been designed to sustain them for prolonged periods.

Due to centrifugal force present whilst the generator is under load, contact between all of these components is very good, resulting in low resistance. So normally, no harm is done to the rotor before the generator trips. This phenomenon – known as reverse current, reverse power or motoring, is not normally allowed to persist for any period of time. However, until the generator breaker is opened, the generator will act as a motor with current from the grid, keeping the prime mover spinning at slip frequency. This can be very destructive to rotor wedges and rotor-retaining ring contact areas if allowed to continue for any length of time. Most generator units are protected from this by reverse power relays or loss of excitation protection.

The situation changes dramatically if the generator rotor is running at low speed or standstill and the main circuit breaker has been inadvertently closed. Under such conditions, the generator attempts to run as a squirrel-cage motor, using a damper circuit (Figure 1). High currents flowing through the stator winding induce a 50Hz current flowing in the rotor components. Due to lack of centrifugal force, high resistance is created between squirrel-cage components, generating excessive heat. The rotor will try to accelerate, but the presence of rectification diodes within the excitation system will allow only half cycle current to flow through the damper circuit, successfully reducing the rotor speed. Bitter experience shows that generators exposed to this condition can be permanently damaged in a matter of seconds.

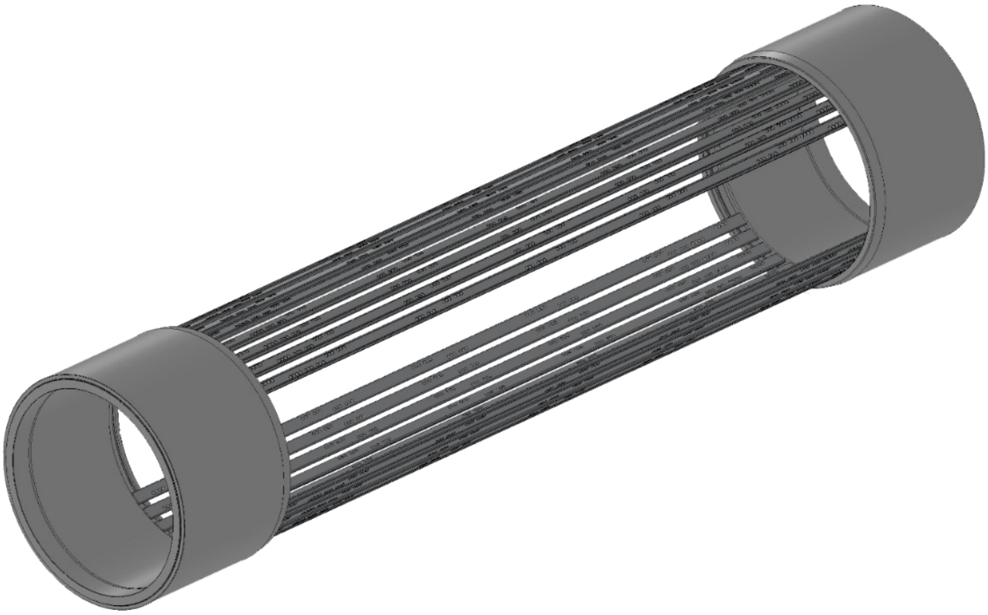

Figure 1. Rotor damper circuit made from wedges and retaining ring

CASE STUDY

Repair time: < 5 months

Repair cost: 50% lower than replacement

The following scenario occurred on a 155 MVA generator in a Ghanaian power station, causing severe damage to several rotor components. The customer report confirmed that undefined issues with one of the circuit breakers may have occurred, tripping the generator during run-up. Subsequent attempts to start the machine were unsuccessful and the decision was made to remove the rotor and conduct the appropriate investigation.

Investigative findings

Investigation revealed damage consistent with a motoring incident. The damper circuit on the Ghanaian generator rotor was comprised of aluminium wedges shorted by retaining rings shrunk onto both sides of the rotor. By design, the circuit does not become fully active until the rotor's speed exceeds 2000 rpm, when the damper components create a low resistance path, preventing negative sequence currents induced from causing any damage.

Figure 2 & Figure 3 (overleaf) clearly show severe damage caused by high currents flowing in the damper circuit during the motoring incident. When the rotor is stationary, there are no centrifugal forces to load the slot content against the rotor to cause full contact between the ends of the rotor slot wedges and the end winding retaining rings. Full contact between the slot wedge flanks and wedge slot flanks also becomes intermittent.

The majority of induced currents flow through the aluminum wedges and rotor body surface, causing substantial heat to be produced when a high resistance joint occurs between two damper circuit components. This explains the severe arcing damage on wedge tips, flanks and retaining rings. Similar damage was found in every slot dovetail.

Figure 2. Molten retaining ring fit area

Figure 3. Molten wedges

In addition, almost 20% of the copper winding on the rotor had either been melted away or suffered severe distortion. See Figure 4 & Figure 5 below.

Figure 4. Molten copper from slot 24

Figure 5. Molten copper from slot 11

Later investigation confirmed the presence of a double earth fault, resulting in severe arcing damage. Two deep excavations (250mm and 300mm axially, up to 20mm deep) were found within two of the forging slots where material had vaporized at the site of the earth faults. It is believed that an earth fault had occurred during attempts to run the generator after the motoring incident. See Figure 6 & Figure 7 below.

Figure 6. Molten tooth in slot 11

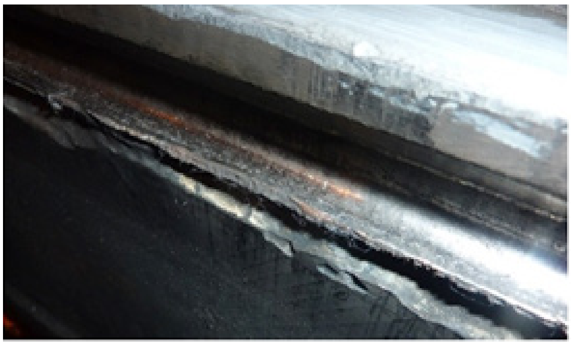

Figure 7. Molten tooth in slot 24

Quartzelec's solution

The component with potentially the longest lead time and highest cost to replace was the rotor forging; preliminary engineering work was focused here to make sure that it was salvageable. This involved the following:

STEP 1: Rotor body inertial slots

- During the motoring incident, the highest currents flowed through the wedges as well as the rotor body, with the highest density around the inertial slot teardrops.
- A hardness test was conducted to confirm that heat damage had not occurred in those locations.

STEP 2: Rotor slot dovetails

- Severe arcing damage was confirmed in all rotor dovetails.
- The depth of the most severe damage was measured.
- It was identified that it was necessary to open every slot by 1mm in order to remove all damage.
- Stress analysis of the rotor teeth was conducted to prove the mechanical integrity of the new dovetail and wedge design (see Figure 8 overleaf).

STEP 3: Deep excavations in slot 11 and 24

- The locations of the earth fault on the rotor body were dressed out.
- Metallographic replicas to make sure that the heat affected zone was completely removed.
- Additional hardness tests were conducted in multiple locations around the damaged area.
- A weld repair to the rotor body was subsequently carried out (See Figure 8 overleaf).

Original damage

Dressed out excavation

Material replica

Figure 8. Earth fault location recovery process

STEP 4: Rotor body

- The forging itself required the standard set of non destructive tests (NDT) including dye penetration test, magnetic particle test and ultrasonic test to all high stress locations.
- On confirmation that the rotor body could be salvaged, all remaining components were checked and revalidated.

STEP 5: Rotor wedges

- All aluminium wedges showed evidence of severe arcing damage along their entire length and were deemed unfit for use.
- Because the rotor slot dovetails were opened to remove arcing damage, new wedges were required.
- Existing aluminium wedges were reverse engineered.
- New wedges were manufactured to incorporate new modified shape and original vent hole configuration.

STEP 6: Rotor retaining rings

- Both retaining rings showed evidence of severe arcing damage and were scrapped.
- Existing retaining rings were reverse engineered. New retaining rings were manufactured from 18/18 material to ASTM A289.

STEP 7: Rotor snap rings

- Both snap rings showed evidence of severe arcing damage and were scrapped.
- Existing snap rings were reverse engineered to enable new ones to be manufactured.

STEP 8: Rotor copper

- The rotor copper was thoroughly inspected to identify damaged turns.
- Hardness tests were conducted to review the condition of coils affected by high temperatures.
- Collapsed copper corners were found on every top turn, prompting the decision to replace every coil.
- Approximately 20% of the winding was deemed unsuitable for re-use.
- New copper turns were manufactured using silver bearing copper, drawn to incorporate the contraflow cooling system.

STEP 9: Rotor field lead

- The field lead wedges were NDT tested and passed acceptable.
- The field lead dovetail was NDT tested and passed acceptable.
- The existing field lead wedge insulation was replaced.

STEP 10: Radial stalks and upshaft

- Radial stalks were cleaned and replaced.
- The connection was removed, cleaned and HV tested to ascertain the electrical integrity of the upshaft.
- The existing upshaft was found to be acceptable, and reused.

Following the rewind, the rotor was tested at 120% overspeed for two minutes to confirm mechanical and electrical integrity. Insulation resistance, RSO, search coil and HV testing were carried out at 3000 rpm. A heat stability run was also carried out at a mean winding temperature of 80 C to ensure acceptable rotor vibration response at temperature.

Rotor teeth stress analysis

The rotor is machined from a low alloy steel Ni, Cr, M having 0.2% proof stress of 600-700MPa. The rotor has longitudinal slots to give the correct location for the copper stack to be positioned as Figure 9 below.

The copper coil group is made up from a series of copper turns in an ‘E’ cross section, separated from the forging by an insulated slot liner and placed together to form cooling air passages with alternate turns electrically isolated by an insulation layer. A final top packer provides the final barrier between the current carrying conductors and the wedges.

The forces generated by rotation are restrained against radial movement by the aluminium wedge that locates in the dovetail profile of each rotor slot, see Figure 9.

To determine if machining the profile to remove the damaged material was a viable option, an FEA study was undertaken of the original profile and of the new profile, see Figure 10.

The rotor had not been damaged by a failure with the slot profile, the exact material properties were not known, therefore, the change in stress level was of more interest. This contrasts with the approach used for new designs of rotor where the mechanical properties are known and the stress level is of paramount importance.

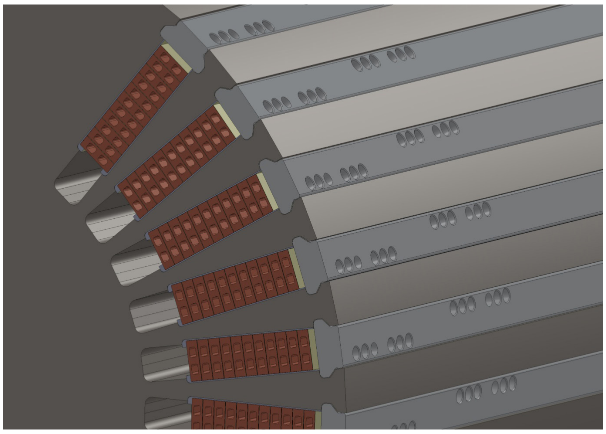

Figure 9. Rotor slot content

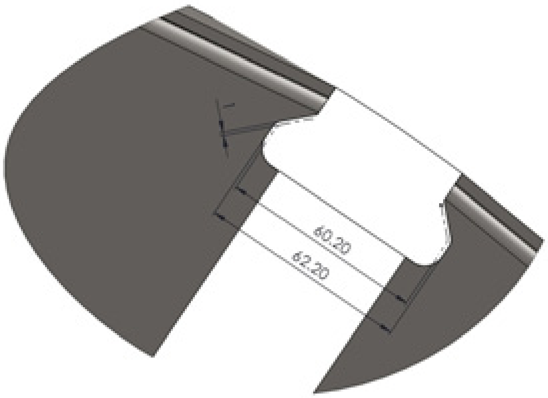

Figure 10. New profile dimensions and the old in chain dotted

The rotor slots are distributed symmetrically about the rotor's Z axis – a feature used to reduce the FEA model down to two slots. The slot was also loaded uniformly along the length of the wedge due to the mass of the copper and the aluminium wedge acting on the dovetail profile. This enabled a 100mm section to be taken to represent the rotor length, see Figure 11 & Figure 12.

Figure 11. Rotor forging – general view

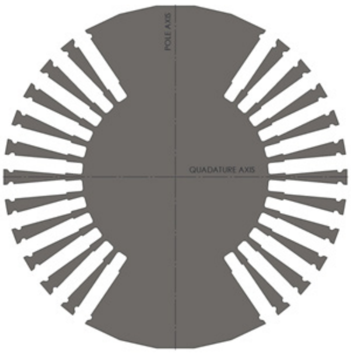

Figure 12. Rotor forging cross section through rotor body

The model was restrained against movement in the Z axis (axis of rotation) on the faces – and normal to the radial faces – leaving the section free to move in the radial directions.

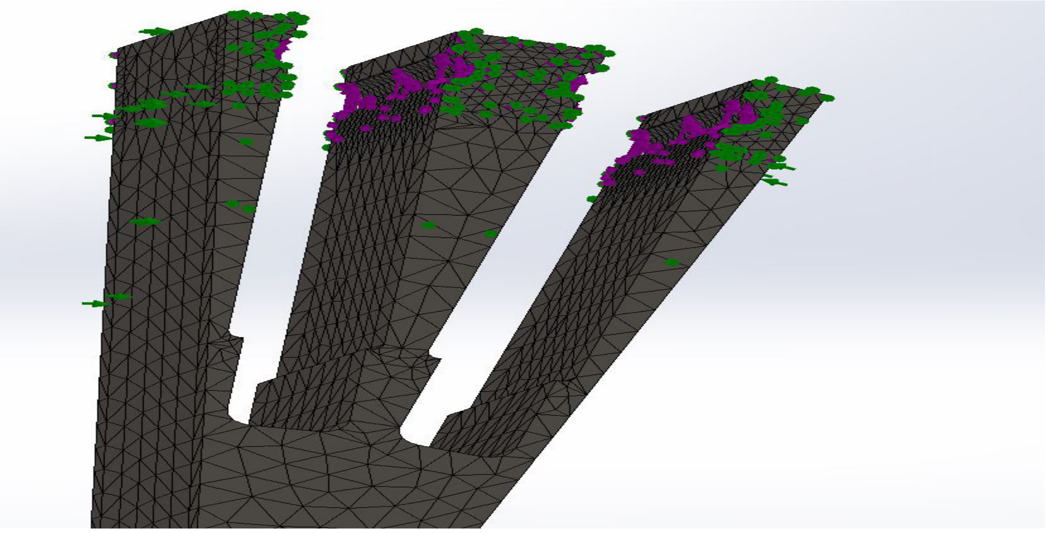

Figure 13. Restraints and applied load to profile flanks

Loads representing the copper and aluminium mass were applied to the dovetail flanks, orientated normally to a plane in the centre of the slot and reducing the FEA model to a single component. The applied centrifugal force was calculated using the restrained masses, their centre of gravity and the rotor speed, thus:

Where,

m = (Cu) 3.67 + 0.402 (Al) = 4.075kg

^{2} = 3600rpm 120% overspeed, = 388 radians/sec

R = 0.4m

CF = m ^{2} R= 4.075 x 388^2 x 0.4 = 245,206N

In additional to this load a centrifugal load was applied to the rotor segment along the Z axis, using a speed factor of 120% of the running speed to simulate the centrifugal loads from the rotor's mass.

The overspeed value (3600rpm) was used because the centrifugal force increases with the square of the speed. If the change in stress is low at overspeed levels, it follows that it will be even lower at normal running speed.

The FEA model was run for both slot profiles in a basic mesh configuration, then with successive mesh refinement around the dovetail profile to increase the accuracy in the relevant area and demonstrate convergence in the stress level as required by NAFEMS (the International Association of the Engineering Modelling, Analysis and Simulation Community). Also, following the association's guidance on convergence to determine whether a good quality mesh had been designed, the displacement for all meshes was checked and found to be independent of the mesh quality.

The results shown in Table 1 (overleaf) show a converging solution for all simulations, other than the final refinement for the original profile where there is a divergent. For comparison the medium mesh refinement is used as a convergent point on all simulations.

The Von Mises stress between the two profiles changes by only 8.7% for the increase in width.

FEA profile	Mesh size	Von Mises stress (MPa)	Deflection (mm)
Original	8mm	516	0.331
	5mm	**516**	**0.331**
	2mm	548	0.331
New	8mm	533	0.318
	5mm	**565**	**0.318**
	2mm	564	0.310
New profile, with wedge surface contact	8mm	281	0.230
	5mm	**361**	**0.236**
	2mm	339	0.233

Table 1. Simulation results summary

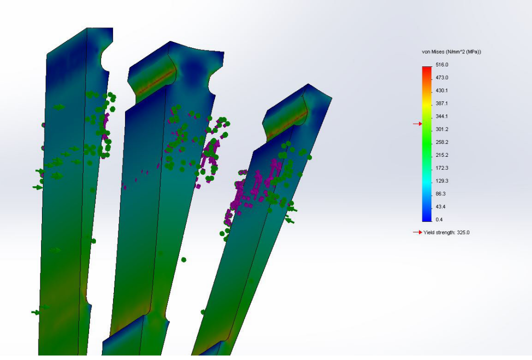

Figure 14. Stress pattern, original slot profile

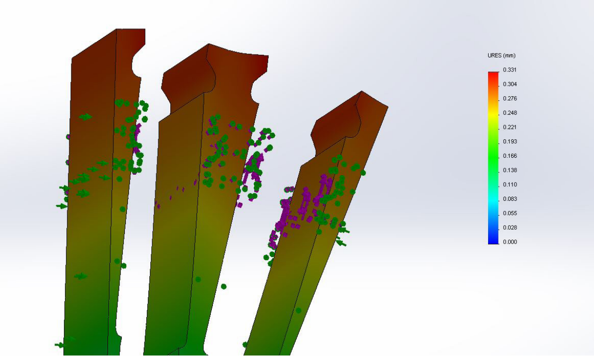

Figure 15. Displacement pattern, original slot profile

Whilst not the deciding factor, the predicted stress for the groove was higher than expected, for both profiles. To check that the FEA model had not been over simplified, an additional simulation was conducted with the wedge included in the model and loaded against the slot flank profile.

The meshing and restraints used the same symmetry principle as for the simple FEA model, with the contacting flanks of the wedge mated to the rotor slot profile for a no penetration contact. This contact allows for sliding motion between the two faces and more realistic simulation; NB the figures overleaf show the model in an exploded view.

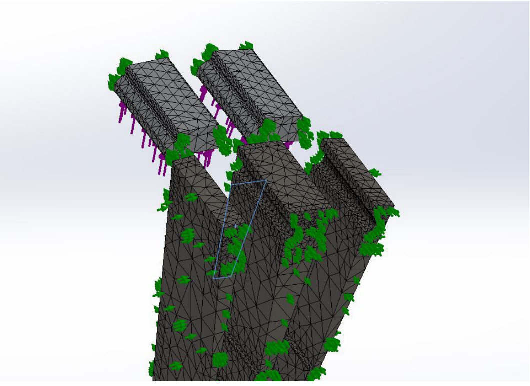

Figure 16. Medium mesh with wedges in exploded view

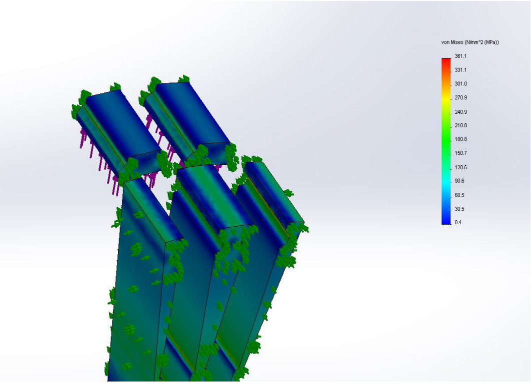

Figure 17. Stress pattern

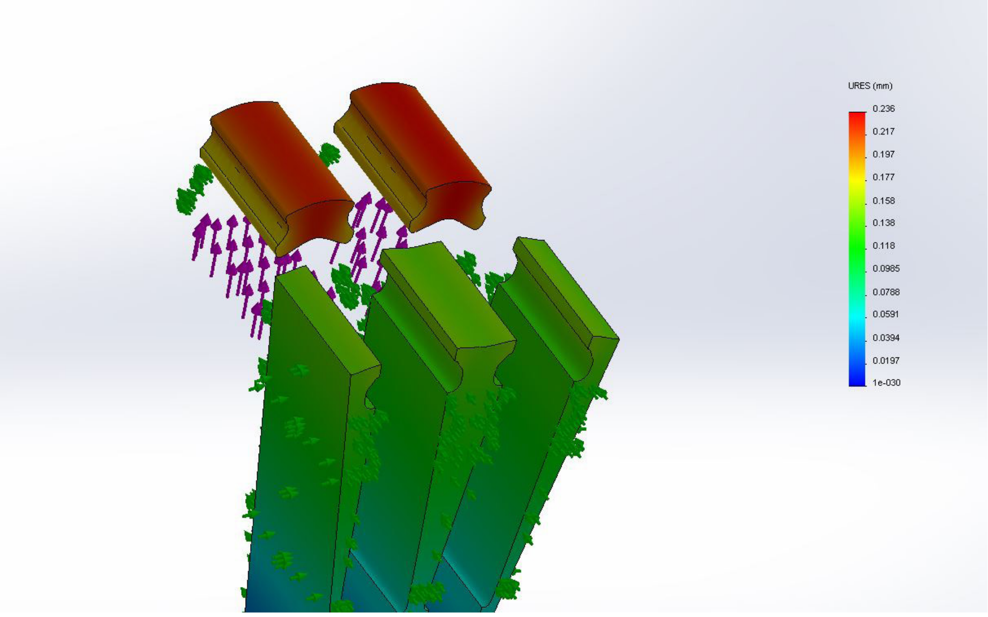

Figure 18. Displacement pattern

This also confirmed that the bending stress on the aluminium wedge remained within a reasonable level, despite the slight increase in span.

All the simulations confirm that an increase in profile results in a minor increase in stress, but would not be detrimental to the rotor stress, or wedge, even at overspeed.

Rotor weld repair

Once the excavations had been prepared by the removal of heat-affected areas – confirmed by performing a set of material replicas and additional hardness tests – preparation for TIG welding commenced. The rotor forging was preheated to increase the strength of the weld and provide finer weld structure by full martensite transformation using highly accurate temperatures. The welding was then carried out in accordance with internal processes at previously agreed parameters by highly experienced welders specialising in this procedure. The welding locations were then carefully dressed to allow NDT inspection. Both magnetic particle and ultrasonic tests were carried out by a specialist NDT technician with over 35 years experience to confirm effective fusion between materials. Finally, both weld locations were hand-polished and the forging stress relieved in accordance with company internal specifications.


Figure 19. Slot 24 ready for weld repair


Figure 20. Slot 11 ready for weld repair

Rotor body stress relief

The elevated temperatures generated during the welding process leave high residual stresses in the welded location, potentially causing unacceptable metallurgical changes in the alloy and in turn, stress corrosion cracking and increased risk of brittle fracture. To minimise the risk of this happening, high temperature was applied to the affected location, reducing proof strength and allowing deformation to take place and residual stresses to fall, until the required level was achieved. This in itself is a stringently controlled process, as relief time and temperature level are dependent on the alloy in question.

Conclusion

With today’s power generation sector under intense pressure to reduce maintenance costs and times, the question of component repair verses replacement has become crucial to economic viability. Quartzelec has effectively demonstrated that a severely damaged rotor with vaporised forging and molten components can be recovered if bold engineering solutions are applied and skillful craftsmen deployed.

In this case, the severely damaged rotor was repaired in less than five months, and at a cost 50% lower than the cost of a new rotor.

24 Hr Support
+44 (0) 8705 002 003

Tel: +44 (0) 1788 512512

info.uk@quartzelec.com
www.quartzelec.com