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Thirty Year Operational Experience of the JET Flywheel Generators

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The JET flywheel generator converters have operated since 1983 and for over 85 000 pulses. Problems with this plant are discussed, including corrosion, unbalanced flow and arcing within the liquid resistors; starting difficulties on both machines; and failure of the plug-braking transformers at energisiation. In 2012/13 two sets of thrust bearing pads have required refurbishment, a process which highlighted the importance of their profile. Extensive *half-life* inspections have shown that there are no serious problems with either generator.

Keywords: Energy Storage Systems, JET Tokamak.

1. Introduction

The JET Pulsed Power Supply System employs two identical vertical Flywheel Generator Converters (FGCs) which can each supply 2600MJ to their respective magnet load coils to supplement the 575MW (pulsed) grid supply [1]. One of these, the poloidal-field (PF) generator is connected to the tokamak central solenoid through the ohmic heating network, and the other, the toroidal-field (TF) generator, is connected in series with the TF static units, to the TF coil. Since these generators entered service in 1983 they have both operated for approximately 85 000 JET pulses, and this paper is intended to highlight some of the main issues which have arisen since that time, and to build on the report given in 1994 [2].

2. Liquid-Resistor

2.1 Background

Control of each generator's 8.8MW, 11kV pony motor employs a purpose built liquid resistor in the rotor circuit. Rotational speed is regulated by adjusting the position of three electrodes connected by tie rods and driven hydraulically by a ram to alter the resistance. An electrolyte comprising demineralised water dosed with sodium carbonate is contained within a steel tank and pipework. The electrodes are positioned on rollers in the tank, immersed in the electrolyte which is pumped at a constant rate across them to remove excess heat. The heat is extracted from the electrolyte via a heat exchanger coupled to the site cooling system.

2.2 Operational Issues

Due to the coarse nature of the control valves and the variable flow characteristics of the electrolyte from aeration and temperature fluctuations, equalisation of flow in each of the three phases can prove problematic. Weirs have been fitted to help balance these flows and to reduce arcing at low flow rates. In addition limits have been placed on the ram speed to reduce splashing within the tank which has the potential to cause flashovers between the phases.

Other improvements have included the addition of strengthening struts to stiffen the back box covers where the electrolyte enters and a programme of upgrading all the fasteners to stainless steel.

Due to the harsh environmental corrosive conditions the tanks require periodic cleaning and repainting. For the same reason problem have occurred with rollers sticking, which can lead to imbalance between the phase resistances, and they too require frequent maintenance.

Regular maintenance of seals, electrolyte levels and concentration, pumps and hydraulic oil levels have been key to ensuring reliable operation of the liquid resistors. In addition the hydraulic rams and servos were completely refurbished in 2007.

3. Generator Starting Difficulties

3.1 Symptoms

From 2004 the PF Flywheel Generator periodically failed to start when the pony motor was energised – the machine appeared to be physically stuck. There were many of these events over the next few years, eventually becoming as frequent as a couple of times each week which began to impact the JET scientific programme. It was observed that waiting a few hours whilst cycling the cooling and oil systems would eventually free the rotor, but clearly there was an underlying issue that needed to be addressed.

A similar situation also occurred on the TF generator in December 2011 but in this case the machine was solidly stuck for several weeks and the techniques which had been used to free the PF machine were not effective.

3.2 PF Generator Investigation and Refurbishment

The JET shutdown which began in October 2009 provided the opportunity to carry out a thorough investigation to identify the cause of the starting difficulty on the PF generator. The approach adopted was to identify anything that could stop, or provide resistance to starting the machine and then thoroughly investigate each of these areas.

Of the twelve areas identified, two were quickly eliminated following testing – poor quality of the thrust pad lubricating oil and low starting torque. The remaining candidates for failure were grouped as summarised below and a combination of dismantling, inspection and testing undertaken.

3.2.1 Machine Alignment

The machine was precisely centred on the vertical axis by setting-up the top and bottom guide bearings to a radial precision of 150µm. Care was taken not to 'pinch' the guide bearings in the process. There was no evidence of wear or burring on the guide bearings which would have suggested 'pinching' or 'wedging'.

3.2.2 Oil Supply to Thrust Pads

The pressure relief valve on the oil supply to the thrust pads was replaced to ensure full pressure was available to lift the rotor. Experiments were also performed which confirmed the lift was acceptable by varying the thrust pad oil pressure between 110bar and 130bar. Oil flow to each pad was measured with a temporary flow meter. The variation of oil flow to each of the twelve pads was found to be less than 15%, thus eliminating oil starvation to a thrust pad as a cause.

3.2.3 Thrust Pads

The thrust pads, which had 24 years of service in the PF generator, were removed and replaced with the spare set. This spare set of thrust pad had only been in service for around 18 months in the early 1980s before being removed as part of modifications to include a low pressure oil feed to improve thrust bearing cooling [2].

3.2.4 Mechanical Fouling

The labyrinth seals prevent oil to the guide bearings escaping by providing a tortuous, slightly depressurised leak-path. These seals were inspected and evidence of rubbing against the generator's shaft observed. The position of the seal plates were adjusted to ensure adequate clearance.

In addition, there was visual evidence that one or more of the six mechanical brakes were not fully releasing during the start-up sequence. All the brakes on both generators were removed for inspection and sent away for refurbishment with the original manufacturer.

3.2.5 Outcome of Investigation and Refurbishment

Following the completion of the work listed above, the PF generator was returned to service in 2011 and has not suffered any starting difficulties since.

3.3 TF Generator Thrust Bearings

Inspection of the TF generator's thrust bearing pads after it stuck for several weeks in 2011 showed an area of white metal that had melted on one pad, and evidence of rubbing between the running disk and the pad trailing corners (figure 1). This damaged pad set, as well as the set removed from the PF generator (3.2.3) were refurbished using the available manufacturer's drawing and specification data.

In the process of fitting a refurbished set of thrust pads to the TF generator, higher than normal break-out torque was observed during manual test pulls. An investigation into possible causes was undertaken which identified that the white metal surface profile itself could be a major contributor to excessive friction.

Fig 1. Pad 12 removed from the TF generator in 2012

Key points of the investigation were:

- Deposition of white metal had been observed on the surface of the running disc
- As noted above, the white metal surfaces of the thrust pads from the TF generator were found to have wear marks at their corners, especially so at their outer trailing edges.
- Theoretical finite-element analysis indicated pad shape to be influenced by temperature differential (into a convex profile) and load (into a concave profile)
- Drawings, specifications and interrogation of previous suppliers enabled a different decision on white metal profile originally used
- Measure the thrust pad support springs (75 for each pad) to check for plastic deformation; they were found to be in good condition
- Running disc and thrust pad surface profile measurements

It was concluded that it is desirable for the pads to have a "crowned" (spherical) profile at ambient temperature.

3.3.1 Refurbishment Process #1

A process was developed in conjunction with a sub-contract supplier expert in the design and manufacture of white metal bearings. This attempted to produce a spherical profile by machining several concentric rings and hand-lapping. This process was applied to one set of pads, during which the pad-to-pad variation in the amount of white metal removed was greater than expected.

3.3.2 Refurbishment Process #2

For the second of pads which were reprofiled the same manufacturer proposed a simplified process intended to result in better dimensional control. In this, a single machining operation producing a truncated cone was followed by hand-lapping.

3.3.3 Results and Operational Experience

Due to the very small amount of material being removed, control of the machining fixtures and process is critical. In anticipation of that, tests were made on trial pads, and although these were smaller than the thrust pads they demonstrated that consistent results could be obtained.

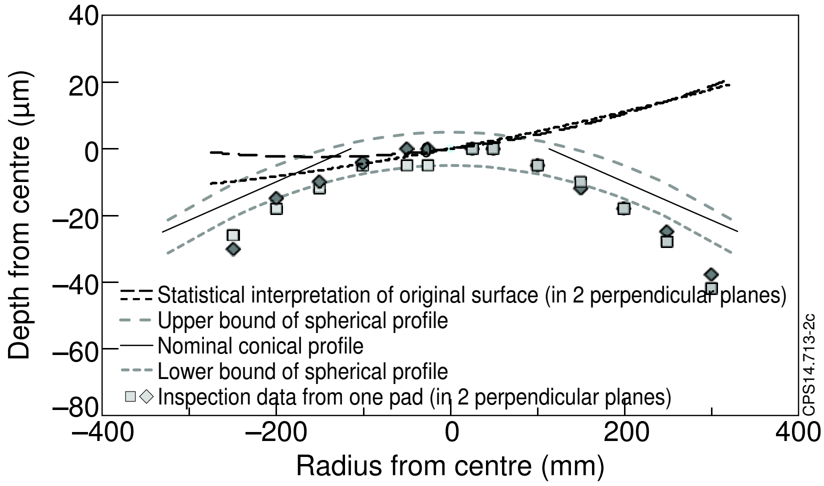

Fig.2 A comparison of pad profiles before and after refurbishment process #1

Similarly, inspection was challenging, necessitating development of techniques and tooling to ensure accuracy and repeatability.

Figure 2 compares the shape of one pad after conical machining with the generalised profile from before machining, and the target spherical profile.

The set refurbished by cutting concentric rings has been refitted to TF generator. Commissioning tests gave acceptable results for break-out torque during manual test pulls which were an improvement over the pads which were known to be concave, and the machine has operated without apparent problem or any starting difficulty.

The set refurbished with as a truncated cone has yet to be installed and is available as the spare set.

4. Plug Braking Circuit

4.1 History of Flywheel Braking

A braking system is required to slow and then stop the generators at the end of each operational day or in case of an emergency. The mechanical brakes are only able to operate below 35 rpm, therefore an electric braking system is used above this speed. The flywheel generators were originally designed with ”dynamic" braking to dissipate the stored kinetic energy in the pony motor’s rotor circuit by passing 500A dc through a pair of stator windings. In 1982 this system was changed to a plug braking circuit because the original system suffered from an unbalanced load which caused excessive deflection of the pony motor's cantilevered rotor.

Plug braking employs switchgear to reverse a pair of stator phase connections to operate the pony motor with slip in the range 2 to 1, but requires a transformer to reduce the stator voltage from 11kV to 5.5kV to avoid excessive voltage stress on the rotor circuit’s insulation at high rotor speeds. These dry-type, plug braking step-down transformers (one for each machine) were placed close to the machines inside the generator building.

4.2 Transformer Failures

In March 2006 the TF generator’s plug braking transformer suffered significant damage when a primary winding shifted during energization, causing a flashover on the 11kV supply. JET operations were able to continue by operating the TF coils exclusively with the static unit transformer rectifiers. The damaged transformer was repaired by fitting a spare winding which had been purchased with the transformers, and the TF generator brought back into service in May 2006.

The TF generator’s plug braking transformer then suffered a second 11kV flashover when another primary winding shifted in July 2011. This was then followed in May 2012 by a failure of the PF generator’s plug braking transformer. On both these occasions the generators were brought back into service with temporary, oil filled transformers located outside the generator hall whilst suitable permanent replacements were purchased.

4.3 Transformer Replacement

Two replacement 3.7MVA dry-type transformers were sourced with a voltage ratio of 11/5.5kV and primary taps from 11.55kV to 10.45kV. As the previous failures presented a risk to personnel in the generator hall, the replacements were located outside in dedicated, heated shelters.

Both transformers were delivered in July 2012 after successful routine tests were completed at the supplier’s factory. Mechanical key interlocking, plant protection and monitoring were commissioned, and the power circuit insulation tested before each transformer was energised for a 24 hour ‘soak’ (no load) test.

When the generators were available the plug braking circuit was tested with a series of braking cycles, from increasing speeds up to 200rpm to test the thermal performance of the transformers. Finally, five braking cycles from 180rpm within 5 hours were completed. The maximum winding temperature observed was 62°C; significantly below the 130°C maximum rating of the new transformers.

The PF generator was returned to service with the new plug braking transformer in March 2013, and the TF six months later in September 2013 because of the thrust pad issues discussed in 3.3.

5 TF Generator Balancing- 2013/14

It was recognised in 2013 that the vibration levels of the TF generator were larger than historically reported values and those seen in the PF generator (circa 40-50µm). In November 2013 an unsuccessful attempt was made to balance this machine using a single-plane technique and the existing vibration instrumentation.

It was felt that a better result could be obtained using two-plane balancing and more up to date data logging. A balancing specialist was engaged to develop a suitable balancing process and apply it to the TF generator in April 2014. The results of this balancing process are shown in table 1.

Table 1 - Measured Vibrations for TF Generator (µm)

Date	Top vibration	Bottom vibration
June 2012	62	52
October 2013	28	82
November 2013	66	81
March 2014	82	34
May 2014	62	42
August 2014	54	48

Compared with the readings taken at the start of this exercise, the magnitude of the greatest vibration has been reduced by two-plane balancing, but this has been accompanied by an increase in the bottom vibration values. It has not been possible to reduce the magnitudes to those of the PF generator.

Both top and bottom vibration values are within the acceptance standard based on the bottom limit of Class B of BS ISO 7919-5 Figure A.2 (Class B is the zone in which long-term operation is permissible), which approximates to the trip levels at which the daily operational alarms are set.

5.1 Issues Identified by Two-Plane Balancing

Using the more sophisticated equipment and analysis tools now available, it has been possible to use the 2014 balancing recordings to identify some other associated areas of TF generator performance. For example it has been found that:

- There is a change in vibration over time which is largely a change in couple balance, likely due to a change in the mass distribution of the shaft due to thermal growth. As the machine has to operate under different temperature conditions, compensation for this is of necessity a compromise.
- Vibration changes with machine speed, and differs whether accelerating or decelerating. The rotor is effectively stiffer at high speeds, likely due to gyroscopic moments becoming more significant. As the machine has to operate at different speeds, compensation for this is a compromise.
- The 2 x speed vibration component found indicates an effect magnified by misalignment: this is unlikely to be improved by balancing.
- The 100Hz vibrations greatly reduce when the pony-motor is de-energised, and their modulation by running speed suggests these forces are uneven over one rotation.

A possible cause is uneven flux distribution in the pony-motor windings' air-gap. This will not be improved by balancing of the mechanical components and is the subject of ongoing investigations.

5.2 Conclusions Drawn from Balancing Exercise

While the TFGC vibration levels are not as low as those of the PFGC, they are acceptable for continued use.

6 *Half-Life* Inspection

During the 2009/10 JET shutdown, a *half-life* inspection of the PF and TF generators was undertaken to determine their remaining life and the extent of any wear or deterioration. Some of this work was combined with the work described in section 3.2 to investigate the PF generator starting difficulties, but also included the following:

- Remove and inspect guide bearings
- Measure and setup machine air-gaps and guide bearing clearances
- Inspect generator windings and lamination cores
- Remove, inspect and pressure test an oil cooler
- Carry out magnetic particle inspection of critical welds on the rotors
- Perform partial discharge and tan delta tests on each machine winding to determine the health of the winding insulation
- Perform EL-CID tests on the PF generator to determine the condition of the inter-lamination insulation; this required the removal of two rotor magnet coils

This set of tests and inspections identified a loose finger plate on the PF generator's stator winding which required the fitting of a retaining box. No major issues were identified.

7. Conclusions

The JET flywheel generators have proved to be effective well beyond their expected life. Regular maintenance and refurbishment has minimised the impact of faults on operations. Whilst the balancing process has identified areas for further investigation, the set of *half-life* inspections has shown that there has been no significant deterioration of the machine's major components.

Acknowledgments

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