Failure of 9FA Gas Turbine Compressor – A Unique Experience.

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Dhabol power project of RGPPL, a Joint Venture of NTPC, GAIL & MSEB, consist of 6 numbers of GE make gas turbines and 3 number of GE make steam turbines with module configuration of 2 GT + 1 ST. Hence, there are 3 module and known as block -I, block -II and block -III.

Though there are 6 numbers of GE make gas turbines but all 6 gas turbines are not identical so far the capacity, TIT and heat rate are concerned. As per the data available at site and Tractable (Consultant to Indian lenders) report, the gas turbine of block -I is suppose to be PG 9331 and gas turbine of block -II and block- III are PG 9351 version. As per GE technical literature PG 9331 is known as 9FA+ and PG 9351 is known as 9FA+e model. From the technical literature available in internet, the technical specifications of 9FA+ & 9FA+e are as follows:

<table>
<thead>
<tr>
<th>S.N</th>
<th>DESCRIPTION</th>
<th>9FA+</th>
<th>9FA+e</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Capacity at ISO</td>
<td>226.5 MW</td>
<td>255.6 MW</td>
</tr>
<tr>
<td>2.</td>
<td>TIT</td>
<td>1288 deg. C</td>
<td>1326 deg. C</td>
</tr>
<tr>
<td>3.</td>
<td>H.Rate on OC basis</td>
<td>10308 Btu/Kwh</td>
<td>9757 Btu/Kwh</td>
</tr>
<tr>
<td></td>
<td></td>
<td>i.e. 2597 Kcal/Kwh</td>
<td>i.e. 2459 Kcal/Kwh</td>
</tr>
<tr>
<td>4.</td>
<td>Efficiency on OC basis based on H.Rate (calculated)</td>
<td>33.1%</td>
<td>35.0%</td>
</tr>
<tr>
<td>5.</td>
<td>Fuel Flow with 8500 Kcal/SCM LCV &amp; 0.8 gm/cc Density (calculated)</td>
<td>55.33 T/Hr</td>
<td>59.1 T/Hr</td>
</tr>
<tr>
<td>6.</td>
<td>Pressure Ratio</td>
<td>15.1</td>
<td>15.4</td>
</tr>
<tr>
<td>7.</td>
<td>Discharge Pres assuming 90 mm of WC pres drop at bell mouth of Compressor. (calculated)</td>
<td>14.43 Kg/Cm²</td>
<td>14.74 Kg/Cm²</td>
</tr>
</tbody>
</table>

It can be seen from the technical specifications mentioned above in the table that technically there is substantial difference between PG 9351 and PG 9331.

Though Block- II and Block- III gas turbines of Dabhol Power Project are suppose to be PG 9351 but due to failure of compressor of GT 2B and failure of tie rod of GT#3A, gas turbine rotor of GT#2B has been replaced with spare refurbished rotor of block - I and GT#3A rotor has been replaced with GT-1B/1A used rotor. Therefore, with the present configuration, block - II and block-III consists of one GT of PG 9351 and one GT of PG 9331 version.
The entire plant has been revived by GE experts and under their supervision. Not only this, before starting revival activities, GE carried out condition assessment of all 6 Gas Turbines and based on assessment result GE recommended spares to be replaced for healthy running of the plant and all the spares recommended by GE have been replaced during the restoration of respective Gas Turbine.

But in spite of this, RGPPL – Dabhol has faced three catastrophic failure of 9 FA Gas Turbine Compressor with in a span of two years. And all three failures are of same nature that is High Cycle Fatigue.

It started with the failure of GT#2B on 05th Jan-2007, GT#2A on 19th Jan-2008 and GT#3A on 8th Nov-2008. And failure of GT#3B avoided due to premature unscheduled inspection.

In all three happenings, machines were running absolutely normal. In spite of all normal running parameters, stable grid frequency and at steady load, all on a sudden, Gas Turbines have tripped on Hi-Vibration Protection on auto with very high sound, Abnormal sound was coming from the compressor side and rotor stopped rotating did not come on turning gear. On cooling, Compressor rotor inspected from compressor IGV end and damage of compressor moving blades & vanes observed.

**Compressor Section**

On opening the compressor mid casing (Stage 2 to 12) upper half, catastrophic failure of Compressor Moving & Stationary blades from Row #2 to Last Stage in case of GT#2A& 3A and from R3 to Last Stage in case of GT#2B observed. The failure is so massive that failed moving & stationary blades have got melted and molten metallic debris(slag) deposited on compressor outlet area, air extraction lines and in blades/vanes cooling air duct as well as on entire the casing inner surface in case of GT#2A& 3A..

On close observation, it is found that the failures are due to impact and on further examining it has been found that all moving Blades and stationary vanes failed from...
root and all failed surface are so badly deformed that it is very difficult to identify the primary failed blade. In case of GT#2A, on further observation, it was noticed that 2 nos. of moving blade of Row#2 failed from the platform but the failure pattern are different from the rest. Out of this two moving blades of row#2, one has failed from just above the platform and one piece has failed 5-8 mm below the platform and failed surfaces were found to be less deformed. Similarly in case of GT#3A, 8 nos. of moving blades of row#2, have failed 5-8 mm below the platform and failed surfaces were found to be less deformed. But in case of GT#2B, one no. of moving blades of row#3, one has failed from just above the platform.

![Images of GT#2A, GT#3A, and GT#2B]

Gas Turbine

On opening the Turbine casing no major physical damage was found in the moving blade/ Vanes. But very huge metallic molten debris found in the cooling passage of vanes & blades of row#1 & Row#2. This is due the fact that the cooling air is extracted from the discharge of compressor and with the damage of compressor blades & vanes, very fine debris, have been carried by the cooling air, have entered in to cooling passages of blades and vanes and got deposited.

![Images of cooling holes blocked and debris]

Root Cause Analysis of Failures
On visual inspection of failed surface and material flow on the damage surface of the moving blades & vanes, it appeared that the blades and vanes of the compressor have failed due to impact. For impact failure, the components have to be hit with an object. The object may come from outside and hit the component causing damage to the components and this type of damage is popularly known as Foreign Object damage (FOD). Or the object may be generated within the turbine and may hit the component causing damage to the components and this type of damage is known as Domestic Object damage (DOD). This is most common type of failure in gas turbine and takes place due to premature failure of gas turbine components. As mentioned above that the failure is due to impact and for impact failure, the material is to be hit by an object and this object may be external or internal, hence further investigation done on each and every stages of moving and stationary blades of compressor to identify the source of object.

**Damage due to Foreign Object**

If the damage was due to foreign object, then the material has to travel from outside the Gas Turbine, and it has to be entered in to the Gas turbine Compressor through Compressor inlet air plenum air flow path only.

If the material entered through this path, then the object should have hit the IGV and 1st row i.e. R0 of compressor moving & stationary blades and those components would have damaged. But in all cases the IGV, Compressor moving blades of row#0 and stationary vanes of row#0 have been found to be OK (minute dent mark at trailing edge). FOD damage can not start from intermediate stage, hence the damage of compressor moving blades and vanes can not be due to the FOD.

**Damage due to Domestic Object**

As the probability of damage due to FOD has already been ruled out therefore, the damage has to be due to DOD, in order to find the source of Domestic Object, when the compressor mid casing was opened, it was found that all most all moving & stationary blades have failed from the root just above platform with massive deformations and failed surface are totally distorted (clockwise). Therefore, though a nos. of moving & stationary blades have failed still question arises which has/have failed first and whether they have failed of their own (due to any reason) or they have also been hit by an object and this object has be generated with in compressor. Now Domestic Object will generate only because of any one or combination of the following:-

1. Something left during last inspection
2. Failure of fixing material and hitting the other components
3. Dislodging of metallic piece from stationary blade and hitting the other components.
4. Dislodging of metallic piece from moving blades and hitting the other components.

5. Dislodging of metallic piece from moving and stationary blades and hitting the other components.

In order to find the root cause, the factors mentioned above, theory of elimination have been applied to come to the final cause of failure.

- **Failure due Something left during last inspection:** - Inspection was carried out under the supervision of GE & BHEL hence chances of leaving some object inside the compressor is very remote, besides if some thing was left then the damages would have occurred during re commissioning itself when the machine was started & stopped for a number of times. Therefore the probability of damage of compressor blades due to left over material is very remote and can be ruled out.

- **Failure of fixing material:** - If the source of DOD is due to the failure or dislodging of fixing material, then missing of fixing material would have observed but on physical inspection of compressor no fixing material was found to be missing. Hence the failure of compressor blades due to Failure of fixing material is ruled out.

- **Failure due to dislodging of metallic piece from moving/ stationary blade:** A number of moving as well as Stationary blades have been found to be uprooted from the platform. And this failure is sufficient to cause extensive damage. Now the question is why this component has failed. The component will fail due to the following reason :-

  a) **Fatigue**

     - **HCF**
       i. Resonance during critical Speed,
       ii. Flow induced vibration- Flutter.
       iii. Rotating Stall.

     - **LCF not applicable for compressor**

     - **Thermo mechanical Fatigue crack (TMF) is very rare for initial 5 stages of compressor blades.**

  b) **Metallurgical Non Conformity.**

  c) **Bending over load (Impact).**
d) Machining Defect (Notch, Tool mark)

e) Forging Defect

f) Over Load

g) Corrosion/Erosion.

By doing the *fractographic* analysis of the failure surface of the failed component it is possible to know the exact cause of failure. But the fracture surface of the damaged uprooted stationary as well as moving blades are so badly *deformed* that *fractographic* analysis will not give any useful information.

In all cases the failed surface, the failed surface is having different colour (dark as well as bright)

From the preliminary study and the failure pattern, cause of failure of GT#2B, 2A & 3A appears to be same.
ne hot path components are very prone to high temperature Creep, Thermo mechanical fatigue and Low Cycle fatigue failure. Designers, depending upon duty condition (Cyclic Load), design hot path components, considering Creep life/ fatigue life of almost 90% of the life of material after which development of these type of defect i.e. Creep Crack / fatigue crack is expected.

Depending upon the amplitude and frequency of cyclic load, cyclic fatigue is again classified in to Low cycle fatigue failure (LCF) where the amplitude of cyclic load is such that it reaches up to yield stress but the frequency of cyclic load is less. Where as in case of High cycle fatigue failure (HCF), the amplitude of cyclic load is much below the yield stress but the frequency of cyclic load is more.

In any fatigue failure, the failed surface will have the following indications:-

- Beach mark in some cases Beach Marks is visible even with naked eye.
- Thump Nail Shape, this is also visible with naked eye.
- Striations this requires high resolution Microscope.

When the cleaned failed surface is seen with high resolution microscope e.g. with Scanning Electron Microscope (SEM), then the presence of those indications are evidenced as shown below.
Presence of Thump Nail Shape, Beach mark with naked eye indicates that the failure mode is due to fatigue, obviously this is to be confirmed with Fractographic analysis and the cause of fatigue most likely will be due to flow induced vibrations coupled with rotating stall /resonance/ Flutter because of modulation of IGV with frequency. As a result of IGV modulation, change in GT load with change in frequency is more compare to change in GT load without IGV modulation.

This additional fluctuation of load due to modulation of IGV is creating more flow induced vibration which is pulsating in nature due to aerodynamic flow instabilities. This aerodynamic flow instabilities (separation of flow on both leading and trailing edges), tend to formation of vortex. The vortex Shedding frequency is determined by STROUHAL NUMBER($S_t$). The Strouhal number is named after Vincenc Strouhal & is an integral part of fundamentals of fluid mechanics.

**Vortex Shedding Frequency** ($F_v$) = Strouhal No.($S_t$) X Flow Velocity ($V_f$) / Vortex Shedder Width($W_v$) which is a Hydraulic parameter and depends upon the angle of inlet and exit.

$$F_v = S_t \times \frac{V_f}{W_v} = \frac{(S_t \times Q)}{(A \times W_v)} \text{ Where Q is the flow & A is the area of flow}$$

Since for a particular, compressor $S_t$, $Q$, $A$, $W_v$ are assumed to be constant, but in actual working condition $S_t$, $Q$, $A$ remain constant but Vortex Shedder Width ($W_v$) varies with IGV position & fouling on compressor blades, as a result, Vortex Shedding Frequency changes. Since maximum fouling takes place in the initial stages of stationary & moving blades of compressor, hence even for a very less change in IGV angle, separation of flow takes place resulting in formation of vortex shedding. For Reynolds number in the range of 800 – 200,000 there exist two values of Strouhal number. The lower frequency is attributed to the large scale instability of the wake and is independent of Reynolds number. The higher frequency Strouhal number is caused by small scale instabilities from the separation of shear layer. If this Vortex Shedding Frequency coincides with natural frequency of Blade, the Blade will oscillate in harmony with the Vortex Shedding and begin to FLUTTER. FLUTTER imposes significant aerodynamic lateral and torsional forces on the blade, resulting in more than expected stress concentration just above the platform of the blade, at subsynchronous frequency that can have a detrimental effect on blade life.

As already mentioned above, fouling is more in the initial stages of compressor, therefore, initial stages are subjected to flutter induced vibration more compare to other stages because of flow separation. This is why the initial stages of compressor blades and vanes fail due to flutter. In case of RGPPL- Dabhol, the failures took place in $R_3$ & $R_1$; therefore, the following can be concluded:-
1. Presence of primary & secondary failed surfaces indicate that the crack developed much earlier and propagated gradually with loading cycle and finally the component has failed due is Tensile over load. **Fractographic Analysis will confirm this observation**

2. Presence of Thump nail shape & Beach mark on the failed surface of the failed component, indicate that the failure mode of GT#2B, 2A&3A are due to High Cycle Fatigue.

3. High Cycle fatigue is due to flow induced vibration called “Flutter”.

4. Flutter is due to higher frequency Strouhal number **which is a design Criteria**.

5. Higher frequency Strouhal number is due to small scale instabilities from the separation of shear layer.

6. Small scale instabilities from the separation of shear layer are due to modulation of IGV with frequency coupled with fouling & fluctuation in GT load. This can be confirmed by putting sensitive probe on casing just above the blades and if any side band frequency is observed and if this side band frequency is not a multiplication of Natural frequency then it can be concluded that this side band is not due to Resonance but because of Flutter.

But it is to be kept in mind that fatigue is not the root cause. Root cause is the factor caused the material to go under fatigue. By Fractographic analysis it is also possible to identify which factor/factors caused the material to be fatigue e.g. machining defect (Notch/Tool Mark), Design deficiency, forging defect, Metallurgical defect, Corrosion, Oxidation etc.

The study of failure surface with the help of high resolution microscope is known as fractigraphic analysis and this is a pure NDT Test and test specimen is not / should not be disturbed during the study. If the failed surface is even minutely disturbed, then the fractographic analysis will not give fruitful result.

**Corrective Measures in absence of Fractographic Result.**

1. **Increase in Frequency of Inspection**: On fractographic analysis, if it is found that the primary cause of failure is HCF (most likely, obviously with visual inspection but actual failure can only be confirmed after fractographic analysis) If on analysis, it is established that the failure is due to fatigue, then this is due to design deficiency and can not be rectified in situ until and unless these blades are replaced with modified blades. Under this circumstances, to avoid premature failure of the components, the machines are to be opened frequently for proper inspection so that the premature
damage can be detected before reaching critical value/failure and GE, most likely recommended more inspection compare to inspection interval mentioned in GER 3620K for other utilities.

2. **Vibration Measurement**: It is pertinent to mention here that the vibrations of Gas turbine bearings are monitored judiciously but the existing vibration monitoring system mounted on bearings of turbines can not detect this type of problem, however, if any increasing trend is observed then the vibration spectrum is to be analysed with a potable FFT analyzer. If on FFT analysis, the peak value is found to be corresponding to a blade pass frequency then the machine is to be stopped for inspection. **Existing On line vibration monitoring system can not detect this problem.** If special vibration pick up is directly mounted on the casing on stage from row#R0 to Row#4 (failure prone zone) and data is collected on continuous at various load and frequency. After carrying out FFT analysis, load/ Grid frequency at which the peak value is appearing, that particular load/ Frequency is to be avoided. The amplitude of peak value is to be monitored strictly. If any increase in amplitude is observed then the machine is to be stopped and after stopping, blade/vanes of stage corresponding to a blade pass frequency is to be thoroughly checked for development of Crack.

3. **Monitoring of Compressor Efficiency**: Failure of Gas Turbine Compressor takes place mainly because of Rotating Stall / Surging and this takes place due to fouling. With the fouling, compressor efficiency decreases resulting reduction of air flow and the compressor operation regime is shifted towards the Surging. All OEM supplies the Compressor efficiency curve for different ambient temperature. If the measured efficiency value is close to the recommended value mentioned in the curve then compressor should be washed immediately either by On Line, if facility is there, or by OFF Line otherwise surging will take place which will cause huge damage to the Compressor, Gas turbine may also damage.

4. **Stopping of IGV Modulating at base load**: Normally GT is started with IGV in minimum position and after synchronizing of GT, as the GT load is increased IGV started opening at 60 to 65% of the base load. On load Control mode, IGV full opens when the load is ~ 80 to 85% of the base load. After this with further increase in load on load control mode, GT exhaust temperature increases and finally GT control changed over to Temperature control mode from load control mode. And on temperature control mode since IGV remains full open so on temperature control, IGV has no control on quantity of air therefore, it regulates fuel flow to maintain the designed TIT hence IGV normally does not modulate. But in case of Dabhol, it has been noticed that though the GT is running at base load on temperature control mode, still IGV is modulating with frequency and the frequent modulation of IGV is causing flow induced vibration owing to fluctuation in air flow, matter is be taken up with OEM for such behavior of IGV.