Kurzfassung

Erfahrungen der EDF mit Erosionen an Endschaufelabrisskanten von Niederdruckturbinen im flexiblen Betrieb

In Frankreich, wie in den meisten europäischen Ländern, unterstützen fossile befeuerte Kraftwerke beim Ausgleich der Elektrizitätsproduktion und -nachfrage. Die schwankende Produktionsauslastung wird in erneuerbaren Energien erweitert. Die Kostendruckregulierung ist äußerst wichtig. Kann man nicht die Tatsache, dass der Energiebedarf der Gesamtheit der Welt nicht ausreichend ist für die Energieproduktion, durch Schaufelvibrationsmessungen abgeglichen werden. Dieser Ansatz wurde entscheidend für die Erosion an Endschaufelabrisskanten. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravierender, als ein Erosionsvorgang in einem Fall die norskei gen. Das Problem wurde umso gravie


How flexible operation could bring new issues on old and well-proven units

The EDF thermal fleet in France has been significantly renewed during the past 10 years, to provide flexible operation capability. Very modern plants like the new generation combined cycle gas turbine plant in Bouchain which demonstrate a very high efficiency, more than 62%, have been built. However, old units like fuel oil units with only a few years remaining before the end of life are still in operation. These old fuel oil power plants were built in the late sixties, early seventies when fuel oil was cheap. They were originally designed for base or semi-base load operation, and they have been operating like that for years.

In France, where electricity generation comes for a very large part from nuclear power plants, the thermal plants duty is to ensure the balance between generation and consumption with enough flexibility, especially during peak periods. Nowadays, the old fuel units are facing these new operating constraints, with the request for very high flexibility. As a consequence, new issues have been raised, like the last LP stage blade trailing edge erosion, which is the purpose of this paper. We could see this erosion in the Figure 1 where we have a view on the last LP stage blade, from the exhaust. The erosion zone encompasses about one third of the blades on the lower part near the root. The unit has operated during more than 30 years without facing this erosion, but with new operating conditions, it was observed within a few years only!

These steam turbines were built in the 1970ties, see Figure 2. These steam turbines (600 MW class) have 1 HP, 1 IP casing and 2 or 3 LP casing. The last LP stage blades are 42 inches long, free standing and have four tree roots. One unit of this type faced a major accident in the seventies coming from a blade rupture near the root. Since this accident, the blade design has been modified and the last stage blades have been regularly controlled. From these periodic inspections, we have the opportunity to get a good follow-up on the shape of the blades; we have then clearly seen how fast the trailing edge erosion was coming. All blades are not affected to the same extent. On the Figure 3, we could see one blade with a strong erosion and one with a very light erosion. Among the differences between blades, two parameters appear to have a significant influence on the phenomenon:

- Shapes are not strictly identical
- Axial locations are slightly different

What could cause such erosion?

In order to assess the issue, we carried out at first a root cause investigation on the erosion phenomenon. Erosion in a steam turbine is a very well-known phenomenon, but not on the LP last stage blade trailing edge. Erosion can be caused either by solid particles or by water droplet. Solid particle erosion affects mainly HP or IP turbine, and in such a case all steam path (all stages) is concerned. It is not our case where only last stage blades are damaged.
Last stage blade trailing edge erosion feedback in EDF LP turbines with flexible operation

Water droplet erosion affects LP turbine: there is a percentage of wetness in the last LP stages, which depends on the steam expansion. The possible origins of droplets are:

- Droplet nucleation during condensation gives droplets of very small size (a few microns)
- Water can also come from liquid film on upstream stator blade. This “coarse water” (droplets up to 100 microns) is carried by steam flow to the blades: this water is well known to cause the blade leading edge erosion
- Water is also injected for desuperheating purpose at start-up and low load: This is done with nozzles spraying small size droplets (nearly 100 microns). However spray operates when heating is suspected, and then droplets should evaporate

Fig 2. LP turbine.

In order to compare order of magnitude of kinetic (impact) energy (E), we can calculate the ratio of impact energy of droplet on rotating blade.

Assuming for this calculation that droplets have the same velocity, we can compare the influence of droplet diameter: \( \frac{E(100 \text{ microns})}{E(1 \text{ micron})} = 1,000,000 \). So, the influence of droplet dimensions is huge. Only large size droplet could cause the erosion.

We can also compare the impact energy at the root and the top of the LP blade: \( \frac{E(\text{at top})}{E(\text{at root})} = 4.5 \), that is only a small difference. As we have no erosion visible at the top, that means no droplets are present on the upper part of the blades trailing edge.

As a first conclusion, only large size water droplet can cause such erosion.

Fig 3. The erosion depends on the blade shape.

To have erosion at the trailing edge, it is necessary to have flow coming back to the blades. That could happen in specific conditions like at start-up, at low load or with bad condenser vacuum, when a vortex brings flow to the lower part of the LP blade. See Figure 4

From this short order of magnitude analysis we can say that erosion may be caused by water droplets of large size to have enough momentum to cause the damage, when operating conditions create desadaptation of the flow and when a vortex bring the droplet to blades.

Then the blades which have high velocity, strike the droplets. We could assume that the effect on the blade starts with probably a period of nucleation (a light change of the blade surface), and then a period of growth of the scars.

We have seen that large size droplets may come from two origins. However it is very improbable that they come from upstream as far as the vortex occurs mainly at low load. In addition, at low load, wetness in the steam is very low if we look at the steam expansion.

At the opposite, it is very probable that droplets come from the LP exhaust desuperheating system. The system operates at low load and at start-up, when vortex do exist. But the design is done to cool steam flow and nozzles spray small water droplet which should evaporate. Off-design conditions should exist to explain the erosion.

When we analyzed the recent operating conditions of these steam turbines on site, we observed:

- at start-up, there was sometimes anticipation of the starting sequence to be sure to be on time at full load. So the LP exhaust desuperheating system can be opened a longer time
- Moreover, the LP exhaust desuperheating system was sometimes manually opened to optimize the differential expansion of the steam turbine… Then, it was possible to let it open for hours without any alarm to warn the operator (with the risk to forget it)

Why was this erosion never seen during 30 years? As already said here above, more hours with spray in operation is a part of the answer.

Another specificity was the presence of corrosion in the LP exhaust desuperheating circuit which is in carbon steel. This corrosion could develop during shutdown time, more frequent with new operating conditions. The corrosion debris could then move in the circuit toward the filter or the nozzles. According to the nozzle design, the droplet size is larger when nozzles are damaged or when water pressure is lower.

By design in these units, the water spray flowrate is constant, at a maximum flow...
required for the maximum desuperheating case. This flow is too much for most of cases. So far, water is in excess most of the time and doesn’t evaporate. In addition, coalescence of the small droplets could happen to create larger ones.

All these facts lead to conditions where large size water droplets are present close to the blades.

Finally, we could highlight that steam velocity and direction in the vortex depend on the condenser vacuum. In the historical data, we could see that vacuum is often poor in these plants where the priority is the availability and not the thermodynamical performance.

How could we manage the case?

For these power plants, which are not far from the end of life, the challenge is to find a solution to continue to operate with the minimum of expenses. If not possible, blades replacement would be costly (at least to open casings if we have blades in spare) and could need time to procure new spare blades.

For this last stage blade, we had the opportunity that many studies have already been done in the past. Among them, on-site measurements by BVM (blade vibrations monitoring) were available. These results let us know flow-induced vibrations in the various operating conditions.

To assess the consequences of the erosion, we decided then to perform a mechanical study in order to estimate the stress in the blade.

We applied 3D FEM (Finite Element Method) to calculate stresses due to centrifugal force, eigenvalues and then stresses due to high cycle vibration using as input data the BVM results.

Maximum stress was found near the root and this area was notably affected by the erosion as it could be seen in the Figure 5.

From what we have seen on blades, the erosion could be significant. However, no crack was detected. In order to avoid confusion, we decided to call the damages “erosion scars”. But to evaluate the consequence of the presence of erosion scar, even if erosion scar is not a crack, we simplified our study assuming we have a crack at this location.

If so, could we have propagation? For a crack, it depends on its location, its depth, the rotation speed (centrifugal force), the dynamic stress (flow induced vibration) from our mechanical study, we reached the following main conclusion:

– Keeping margin, we could define a criteria of maximum depth for the scars

– It is important to avoid overspeed

Now that we have a criterion, how can we apply it? We were looking for an enough practical, cheap and accurate method to compare with our criteria.

We decided to develop our own methodology, combination of modern tools and heuristic approach (see Figure 6).

When we have access to the LP turbine through the manhole, we need only 1 day on site to collect data for 1 LP casing (2 flows). Then from the raw data, we have developed a post-treatment (less than 1 week for 50 blades).

**BVM techniques**

BVM (Blade Vibration Monitoring), also called Tip Timing or NSMS (Non-intrusive Stress Measurement System), is a method of blade vibrations measurement without any contact. The principle is to measure the blade transit time in front of one or several fixed sensors, mounted at the bladed row rim. Then, we can compare this measured transit time with theoretical transit time of blades assumed rigid. Time differences allow to calculate blades vibration frequency and amplitude.
Finally what have we decided?

In the specific context of these power plants (not far from the end of life), all collected information and analysis allow us taking the following decisions:

- Act on the root causes
- Limit time with water spray in operation. We modify a few logic in the DCS to avoid inappropriate use of water spray and put in place additional monitoring to optimize its use. We raise awareness among operators.
- Check and modify water spray system: we decided to replace all parts in carbon steel by stainless steel from filter to nozzles
- Monitor the water spray pressure
- Improve condenser vacuum
- Compare erosion scars to our criterion: The chosen criteria of erosion scars maximum depth can be easily applied thanks to our own-developed methodology. This methodology being practical, cheap could be regularly used to monitor the erosion scars future evolution.
- Restart the power plant if erosion is below the criteria

We also decided the alternative strategy in case erosion scars come beyond the criteria in the following priority order

- Grinding the blade near the root when possible: We find it possible as affected blade are the largest
- Replace the blade if the previous repair is not possible and if we have a spare blade. However, such replacement needs to open the casing, so it needs time and is far more expensive
- If too many blades are damaged, cut all blades of the row (and also those of the equivalent row in the opposite flow) -> This action has an impact on the maximum load achievable by the plant in order to avoid overload on the L-1 LP stage

Conclusion and lessons learnt

Where blades were damaged beyond a certain limit, blades are replaced... but because of a limited number of blades in spare, we also had blade cutting. As shown on Figure 7, we let blade roots in place. It was done on only 1 casing (2 flows). Due to the overload on the L-1 stage, the max allowed load of the power plant decreased to 90%. In both cases, we have to open the casing.

We also apply blade grinding. It was done only near the root in the radius area. Shown in Figure 8 is the blade used for validation. Then it was applied on a selection of blades (often proud), after a dimensional check to confirm that this process could be acceptable. This grinding operation can be done without casing opening.

As a conclusion, we would like to highlight some lessons learnt from this case

- New type of operation may cause new problems
- LSB trailing edge erosion may potentially affect any unit operating with not adapted flow (vortex)
- To limit the erosion, we could remind the following good practices
- For the spray water system: stainless steel at least between filter and nozzles, pressure monitoring to check the good operation of the nozzle
- Control spray water flowrate at low load operation, in order to adjust flow at what is needed only
- Coating not only at leading edge but also at trailing edge should help?
- New methods could bring high added value: in our case, our methodology for erosion monitoring is efficient, accurate and limited in cost!
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