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BLADE DAMAGE IN POWERGEN TURBINE LOSSES AND BLADE HEALTH MONITORING

Bin Zhou
FM Global Research
Norwood, MA, USA

ABSTRACT

Losses of gas turbines and steam turbines in the power generation industry are often due to mechanical breakdowns associated with flow-path component damage, especially on rotating blades. Advanced condition monitoring technologies, such as Noncontact Blade Vibration Monitoring (NBVM), have been shown to effectively detect abnormal behaviors of blades during turbine operation, and thus help to mitigate the turbine loss. Following a brief review of the technology, this paper focuses on results of analyses performed using FM Global's turbine loss data. Loss events were categorized according to different blade damage mechanisms, turbine types and damage locations; and analyzed in order to identify the realizable benefits through noncontact blade monitoring. Based on the results of the analysis, field applications of the technology for improvement of long-term turbine condition monitoring are discussed.

Keywords: PowerGen, turbine blades, loss investigation, condition monitoring, NBVM, risk mitigation.

1. INTRODUCTION

Rows of rotating blades are the core components in turbo-machines such as gas turbines, steam turbines and stand-alone compressors. Increasing loads, harsh environment and off-design operations have continued to challenge the durability of these components.

Analyses performed using FM Global turbine loss data over a recent 10-year period indicated that large fractions of all loss events (hundreds) and the total loss value were originated or associated with damage of rotating blades in the turbine flow-path. For PowerGen gas turbines, roughly 90% of the total loss value or 75% of loss events involved blade damage. These loss events included: i) blade/dovetail cracking initiated loss that usually resulted in severe collateral damage, ii) loss due to significant rubbing and clashing, and iii) loss due to impact damage from foreign/unknown or domestic objects (FOD/DOD). In fact, the cost of turbine losses induced by blade and dovetail cracking alone was more than 40% of the total turbine loss value based on an earlier FM Global study [1], consistent with the "Handbook of Loss Prevention" [2]. For PowerGen steam turbines, about 59% of the total loss value and 62% of loss events were associated with significant blade damage due to similar damage mechanisms.

Noncontact Blade Vibration Monitoring (NBVM) systems monitor vibration and static position of the rotating blades through sensors mounted on the turbine casing. Abnormal blade vibration provides indications of any existing or imminent blade material damage. A change of blade static positions commonly indicates undesired clearance reduction, blade movement or permanent deformation.

Installation of NBVM as a condition monitoring system would enable early warning or detection of damage on rotating blades. With proper and in-time corrective actions, risk of turbine breakdown could be mitigated. The presence of such risk-reducing condition monitoring systems also allows equipment insurers to take a more positive view on the insured hardware [3].

Section 2 of the paper briefly reviews the background, working principles, general capability and durability of NBVM systems, followed by detectable blade damage mechanisms. Section 3 presents the evaluation of FM Global's turbine loss data during the 10-year period and classifications of the loss events based on damage mechanisms, turbine types and damage locations in the turbine. Finally, recommendations are proposed in Section 4 regarding field applications of NBVM technology as a method for long-term turbine condition monitoring.

2. NBVM TECHNOLOGY REVIEW

2.1 Background

During gas turbine design and validation, surface mounted strain gages and NBVM systems are routinely utilized to measure blade vibration and induced alternating stress/strain to verify design intent at various operating conditions. In post-commission operations however, external factors such as hostile working environment, FOD/DOD, and off-design operations further challenge the durability of the instrumentation and preclude the use of surface mounted strain gages on rotating blades due to their poor durability and high cost for an extensive coverage. Compared to strain gages, certain NBVM systems have higher durability, while covering all blades in any given blade row on a per-stage installation basis. Therefore, they become a good choice for long-term health monitoring.

2.2 Working principles of NBVM failure detection

2.2.1 Monitoring parameters

NBVM systems monitor vibration and/or position of the tip of a rotating blade.

Any changes of blade vibration characteristics, including natural frequencies and vibration amplitude can potentially be detected by a properly set up NBVM system. The explicit change of blade geometry, mass and stiffness as a result of cracking, rubbing and impact damage will change the blade vibration. An abnormal blade vibration may also indicate imminent cracking. The status of blade supports or attachments for example, can be altered by corrosion, wear, looseness or a missing part, and cause excessive blade vibration beyond the design intent through the change of system stiffness and damping. On the other hand, mechanical and aerodynamic loading such as any synchronous stimuli, flow instabilities introduced by stall, surge, flutter and off-design operation, may force high vibratory response of the blades, leading to ultimate cracking.

In addition to the vibration signatures, the blade static positions are observable to NBVM system. The original positional signature can be altered by undesired clearance reduction, blade movement or permanent deformation due to rubbing, unsecured attachment, cracking, impact, and violent surge, etc.

2.2.2 Measurement method

A case-mounted sensor can pick up a signal as each blade passes by and the time of arrivals (TOAs) of blade tips relative to a once-per-revolution signal is measured. The time when the blade actually passes the sensor is converted to a deflected blade position, which is then compared to a precisely calculated un-deflected blade position to yield a deflection. Such measured deflection represents either a vibration amplitude or permanent change of position (i.e., deformation). Stress-deflection ratios can be subsequently used to infer corresponding stress levels experienced in the blades. (Note: The conversion, however, is not generally required in field monitoring applications, because the *change* of vibration amplitude, frequency and blade static positions can directly reflect the blade health condition.)

Axial and circumferential locations of multiple sensors need to be carefully decided to cover rows of blades. As a general practice, two to four sensors are required for each blade row depending on requirements of the accuracy and the nature of the vibration to be detected.

2.3 Sensing technologies

Sensing technologies largely determine the capability and limitations of an NBVM system. There are mainly four types of sensors that have been used for NBVM systems: optical sensors, eddy-current sensors, capacitive sensors and microwave sensors. In this section, systems with the four types of sensors are described in terms of detection principle, capability, relative cost level, and durability or environmental limitations.

2.3.1 Optical sensors

Optical sensors generate signals when their light path is blocked by the passing blade tip. These sensors are widely used in turbine development and validation because they have the best resolution, can accurately measure the blade deflection and convert measurements to stresses, at a reasonable cost. However, the durability and maintainability of these sensors may become an issue when they are used in the field for long-term monitoring. Specifically, these sensors are sensitive to dirt and water droplets, which could deflect/reflect the light beam and skew the results. In addition, optical sensors have lower temperature capabilities and require substantial cooling when deployed in the hot section of the turbine. As a result, they are not well suited to long-term condition monitoring where durability is critical.

2.3.2 Eddy current sensors

Eddy current sensors (ECS) are the most popular sensors used in blade health monitoring. These sensors generate a magnetic field as alternating current flows through a coil. When a conductive object such as a metal blade passes below the sensor, an eddy current will be induced in the sensor, altering the magnetic field. By monitoring the change in the magnetic field, averaged (over a region and in time) blade tip deflection can be measured. Because ECSs have a relatively larger spot[1] size and average signal, their resolution is relatively low and is suitable for measurement with longer distance to target. Eddy current sensors are generally of lower upfront cost, very tolerant to harsh and dirty environment and therefore often incur a lower maintenance cost as well. The temperature capability of ECSs is similar to that of optical sensors. These features make ECSs ideal for permanent installation for health monitoring in the low temperature sections of turbines.

2.3.3 Capacitive sensors

Capacitive sensors work based on the change of capacitance of an electric field between two surfaces. They work on both metallic and non-metallic targets. The target distance and measurement range suitable for measurement are smaller and therefore these sensors are suitable to measure smaller and closer targets. Capacitive sensors can also measure accurately the blade tip clearance; thus, they are often used as proximity probes as well. Capacitive sensors generally have a similar or better resolution than eddy current sensors but the cost is higher. While the temperature capability of some capacitive sensors could be very high and suitable for the turbine hot section, a low tolerance

[1] Target area that are detectable to the sensor.

to other environmental factors such as contaminants and moisture still challenges their applications in dirty environments over longer time periods.

2.3.4 Microwave sensors

Microwave sensors work according to the Doppler effect of microwaves sent from the sensor to the target to determine the positions of targets. These sensors can accurately measure blade deflection and tip clearance with a larger measurement range, and are of relatively high cost. Microwave sensors are also resistant to contamination and electric interference in the environment. The high temperature version of the sensor can withstand temperatures similar to those of capacitive sensors, allowing for permanent installation in the hot turbine section. However, microwave sensors have not yet been applied widely for long-term turbine monitoring and some further development is still on-going.

2.4 Detectable blade damage mechanisms

Blade damage that is detectable by NBVM can be classified into three major groups based on the nature of the damage. There have been field examples where blade existing or imminent damage was captured by NBVM systems.

2.4.1 Blade and dovetail cracking

Cracking can be initiated on the blade assembly due to various material failure mechanisms. Released blade material usually triggers severe collateral DOD damage.

High cycle fatigue (HCF) is the leading cause of catastrophic blade cracking. The US Air Force for example reported that 56% of its “Class A” gas turbine engine related mishaps between 1982 and 1996 were due to HCF [4]. In-service damage such as corrosion, erosion and FOD/DOD often times creates local material defects that degrade the HCF resistance of the material. At the blade root or attachment, static mechanical loads induced low cycle fatigue (LCF) and/or fretting fatigue can work in conjunction with HCF resulting in cracks. In addition, hot corrosion, thermo-mechanical fatigue (TMF) and creep contribute significantly to the damage of turbine blades in the hot gas path or the turbine section. In steam turbines, a majority of blade failures occur on the large low pressure turbine blades that are susceptible to stress corrosion cracking (SCC), LCF and HCF.

NBVM monitors the changes of blade vibration signatures and blade positions due to cracking or imminent cracking, and is by far the only effective long-term monitoring method that is backed by substantial successful field experience.

2.4.2 Rubbing

Rubbing occurs in the radial direction between rotating blade tips and casing, or axially between stationary vanes and rotating blades (a.k.a. clashing). Deformation of the casing and the blade, rotor movement, eccentricity or run-out, and compressor surge, etc., can all result in rubbing. Severe rubbing will abrade, warp and break blade tips and possibly cause a rotor seizure.

As rubbing involves damage on both rotating and stationary components, multiple methods of detection can be applied. NBVM, among these methods, can detect rubbing by monitoring blade movement and changes of radial clearance.

2.4.3 Impact (FOD/DOD)

Domestic impact damage can come not only from released mass of cracked blades, but also from broken stationary vanes, or any attachments or fasteners that break or detach from working locations. Small parts causing impact to the blades include but are not limited to blade locks, bolts, pins, shroud plates, shims, gaskets, probes, and actuation parts, etc. In addition, foreign impacting objects such as debris or left-over maintenance equipment/material may come from the external environment. Sometimes, the impacting objects are simply unknown.

The changes of the vibration signature and possibly the position of affected blades can trigger the NBVM system, which then provides opportunities for corrective actions to avoid further damage.

3. CLASSIFICATION OF TURBINE LOSS DATA

Classification of turbine loss data based on damage mechanisms, turbine type (gas or steam turbine) and damaged section of turbines helps to further determine the functional applicability of an NBVM system in preventing or reducing turbine loss.

As discussed in Section 2.4, blade/vane and dovetail cracking, rubbing/clashing, and impact damage are the three major damage mechanisms of turbine flow-path components, and they can all be detected by NBVM systems. The impact of loss reduction, however, could be different based on the stage of the scenario when the incident is detected.

Loss data were grouped by turbine type and sections, where the initiating or major damage occurred, to develop insights on installation locations of the NBVM systems. For example, frequent losses in a certain section of the compressor would imply that deployment of the system in that section brings more cost-effective results. On the other hand, high temperature in the gas turbine high pressure turbine section and high moisture environment in a steam turbine low pressure section may prohibit the use of certain monitoring systems due to their environmental limitations.

In the following sections, results of the analyses performed using turbine loss data are presented for PowerGen gas turbines and steam turbines, considering the mechanisms and the locations of damage.

3.1 Gas turbine loss with blade damage

3.1.1 Damage mechanisms

As seen in Figure 3-1, cracking of a gas turbine blade and its attachment including dovetail (DV) or slot has been the most frequently occurring damage mechanism and had the largest loss exposure in dollars. This type of damage includes cracking of blade base metal or coating that results in material loss. The pieces of material broken off the blade assembly would subsequently impact the downstream blades and vanes resulting in severe collateral DOD damage. NBVM can detect such blade problems before crack initiation or at an early stage of crack propagation before the material loss occurs.

Loss events due to impact damage were categorized separately into two groups[2]. The group "Vane DOD" represents a significant number of loss events that were found to have originated from stator vane cracking, material loss and subsequent DOD. The two groups, "Vane DOD" and "Other FOD/DOD" combined represent the second largest loss category by loss value. NBVM remains an effective detection tool for impact damaged blades, regardless of whether the incipient component damage (in case of DOD) is detectable or not.

As shown in the same figure, rubbing damage resulted in the third and the smallest group of loss events[3]. While some rubbing events occurred following earlier detectable rotor vibration, blade clearance and vibration monitoring by NBVM provides an additional device to reduce or prevent turbine loss.

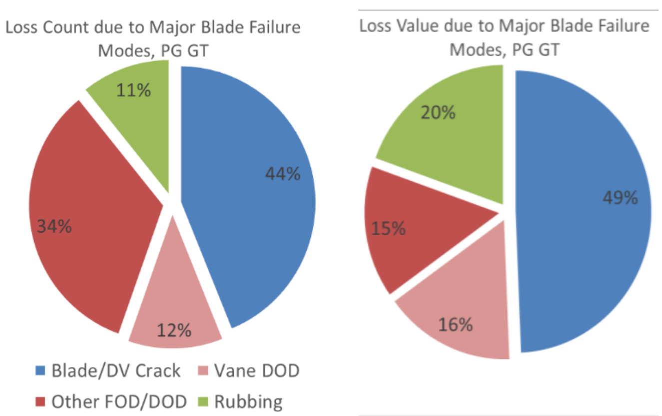

Figure 3-1: Distribution of gas turbine loss by count and value, per major blade damage mechanisms

3.1.2 Damage locations

The loss data classified by gas turbine sections with primary damage are shown in Figure 3-2[4]. In determining the damaged section of a particular loss event, blade and dovetail cracking induced losses and impact losses were classified based on the originating or initial damage; while rubbing induced losses were classified based on the primary site of damage[5].

The blade loss data were divided into four groups based on turbine section, i.e., forward compressor section or low pressure compressor (LPC)[6], aft (or rear) compressor section or high pressure compressor (HPC), forward turbine section or high pressure turbine (HPT), and aft turbine section or low pressure turbine (LPT). Each of the turbine sections is unique in design and operating conditions, which not only results in a different nature or pattern of blade damage, but also poses different challenges to NBVM condition monitoring. For example, modern gas turbines may have turbine inlet temperatures up to 2600-2900°F (1430-1590°C), beyond the temperature capabilities of most currently mature NBVM technologies. While active cooling is an effective method to keep the sensor working in a high temperature environment, it is in general not suitable for long-term monitoring due to potential durability issues of the cooling system itself.

Figure 3-2 clearly shows that damage to the low compressor (LPC) was dominant in the loss value, followed by the damage to the high pressure turbine (HPT), while the loss count associated with HPT blade damage was actually larger than that of LPC. This indicates a higher average cost of loss events due to LPC damage. Aft sections in both compressor and turbine had smaller number of loss events and associated cost.

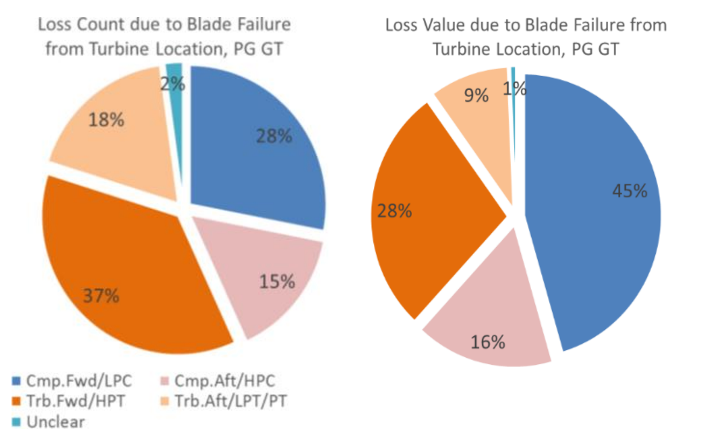

Figure 3-2: Distribution of gas turbine loss by count and value, per blade damage locations

3.1.3 Combined evaluations

Figure 3-3 shows the percentage of loss count and loss value for different blade damage mechanisms and turbine sections, as percentages of *all* gas turbine loss events considered (including those without blade damage). It can be observed that the largest portion of loss value (more than 40% of the total loss value) actually was due to blade damage in the forward compressor or LPC, and the biggest loss driver there was blade and dovetail cracking, followed by compressor rubbing. Further, it was also found that (though not shown in the figure), out of the all LPC blade damage induced losses, 85% of events or 84% of the total

[2] Losses due to impact damage as a result of blade cracking and broken-off material were represented by the blade/DV cracking group.

[3] This group excludes the losses due to broken blade induced rotor imbalance and rubbing, which are again represented by the blade/DV cracking group.

[4] For legends in the figures, Cmp.Fwd/LPC is forward compressor or LPC; Cmp.Aft/HPC is aft compressor or HPC; Trb.Fwd/HPT is forward turbine or HPT; Trb.Aft/LPT is aft turbine or LPT.

[5] Rubbing in particular is a system level problem and may on some occasions involve multiple stages across different turbine sections.

[6] For single spool heavy duty platform gas turbines, forward compressor section normally refers to the first several stages of the compressor, up to stage #4 or #5 depending on different designs. Forward turbine section typically refers to the first one or two stages of the turbine. For multi-spool aero-derivative machines and some single-spool turbines, both compressor and turbine have structurally separated low pressure, i.e., forward; and high pressure, i.e., aft, sections respectively.

loss value involved blade damage at the first three LPC stages; nearly 100% of the total LPC loss value was from the first four stages of LPC. Loss events due to damage on HPT, on the other hand, occurred most frequently (driven primarily by blade/dovetail cracking and impact damage), but were second in terms of loss value. The loss count and value associated with blade damage in the aft section of compressor and turbine (HPC and LPT) were more moderate.

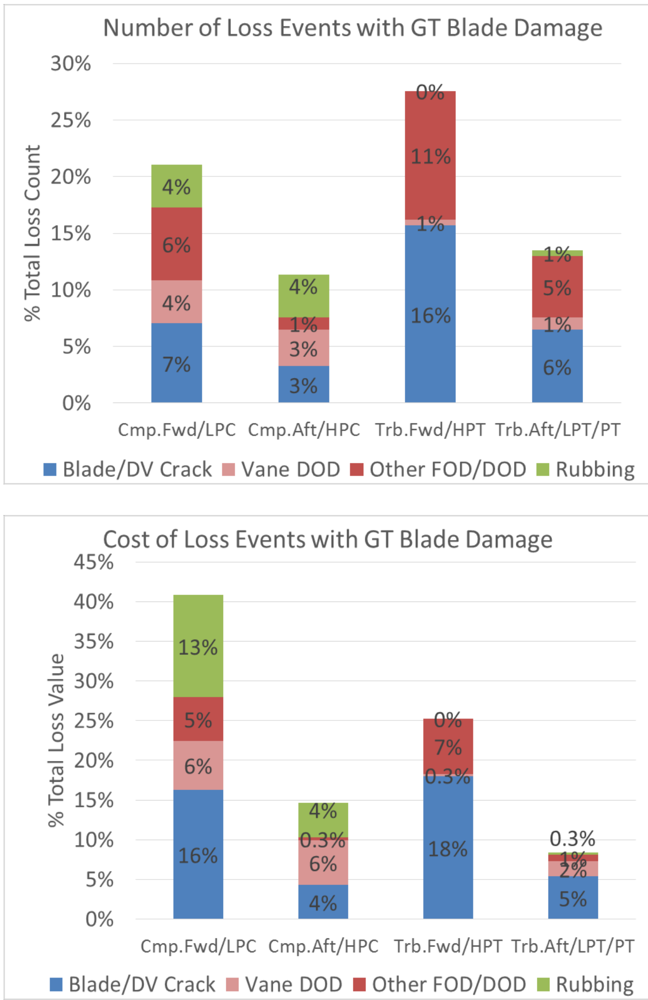

Figure 3-3: Distribution of gas turbine loss with blade damage by count and value, per turbine sections and damage mechanisms

Blade and dovetail cracking was in general the most significant damage mechanism across all compressor and turbine sections. Components such as highly stressed large low compressor (LPC) blades, and forward turbine (HPT) blades with complex design for temperature resistance can pose a high challenge to design for durability. Fatigue and thermo-mechanical damage particularly drove a large number and high value losses in the LPC and HPT sections respectively.

Rubbing was more of an issue in the compressor, especially in the LPC. Thinner compressor blades in a large number and under tight clearance with the casing would be more susceptible to massive rubbing damage.

Impact damage appeared to be quite significant in the LPC, where damage due to foreign objects from the environment would be an apparent concern. Similarly, considerable damage in the forward turbine stages (HPT) was possibly a results of high exposure to frequent impact damage from domestic components that failed and broke off from the combustion system. In addition, the damage due to broken stationary vanes was a major loss driver in the entire compressor section, both LPC and HPC.

Figure 3-4 presents normalized average loss value per event related to blade damage in different gas turbine sections and caused by different damage mechanisms. Loss with blade/dovetail cracking or rubbing in the LPC appeared to be most severe. Broken blades and vanes in other sections also caused a significant average cost per event due to considerable collateral damage.

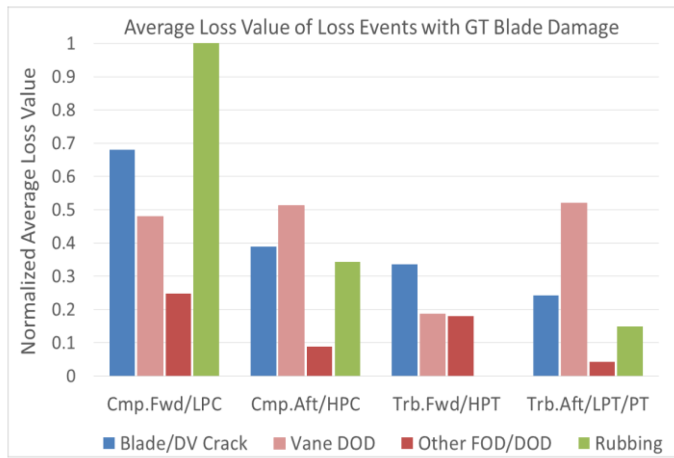

Figure 3-4: Average value of gas turbine loss with blade damage per turbine sections and damage mechanisms

3.2 Steam turbine loss with blade damage

Steam turbine loss data were analyzed using the same approaches that were applied for the gas turbine loss data.

3.2.1 Damage mechanisms

Figure 3-5 shows the contributions of three major blade damage mechanisms to the total number and value of all steam turbine loss events. It can be noted that blade and dovetail cracking was also clearly the dominant damage mechanism in PowerGen steam turbines. Blade cracking in steam turbines was largely due to HCF, commonly initiated at corrosion or erosion pitting sites, and LCF or SCC often occurred at the blade attachment. Rubbing damage induced loss events formed the second largest group in total loss value and count, a more significant share compared to rubbing in the gas turbine (Section 3.1). Loss events due to impact damage on turbine blades formed the smallest group in terms of both loss count and loss value, in major contrast with gas turbines. The DOD events in this group also included only a small number of loss events, where broken stationary vanes collided with the downstream blades and vanes.

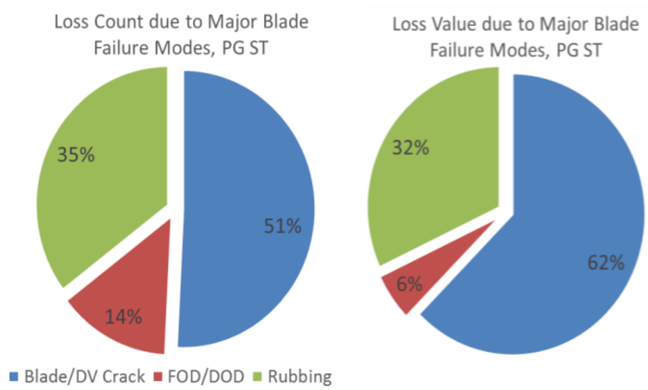

Figure 3-5: Distribution of steam turbine loss by count and value, per blade damage mechanisms

3.2.2 Damage locations

Steam turbine loss data were also divided based on damage locations into two major turbine sections in Figure 3-6, i.e. the low pressure turbine section (LP) and the combined high and intermediate pressure turbine section (HP/IP)[7]. LP turbine blades are exposed to a high moisture environment and a higher static and aerodynamic load, and therefore are more susceptible to SCC, water droplet erosion and HCF. NBVM system in the LP section hence should have sufficient corrosion and erosion resistance and should be able to detect signals in the high moisture environment. HP/IP blades, on the other hand, are susceptible to creep and oxidation due to the relatively high working temperature. Therefore, NBVM in the HP/IP sections should have a sufficient high temperature capability. Figure 3-6 shows that, while there are more loss events due to HP/IP blade damage, the total value of losses associated with LP blade damage was actually greater than that of the HP/IP blades.

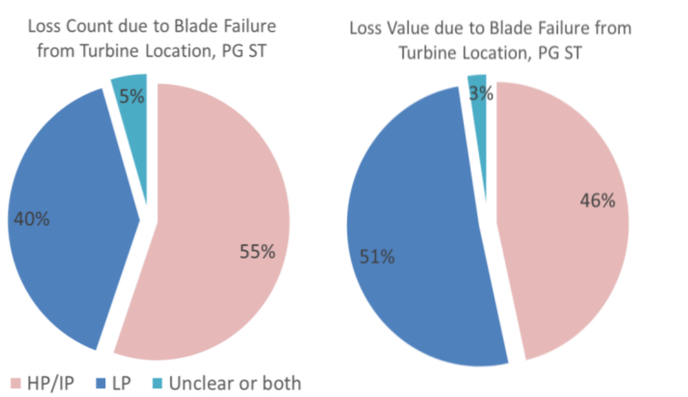

Figure 3-6: Distribution of steam turbine loss by count and value, per blade damage locations

3.2.3 Combined evaluations

Figure 3-7 exhibits the percentage of loss count and loss value for different steam turbine blade damage mechanisms and locations. It can be noted that LP blade and dovetail cracking led to the largest share of loss value and event count. In the LP section, however, rubbing damage was a small portion of the total loss, possibly due to the larger radial clearance by design. There was also no event of major impact damage in LP turbines during the10-year period considered in this study. The HP/IP turbines, on the other hand, saw significant rubbing damage and resulting losses, some blade or dovetail cracking and only a small amount of impact damage. Comparing the LP turbines with the HP/IP turbines, blade cracking induced loss value in LP was about three times of that in HP/IP, at a significant 28% of the total loss value.

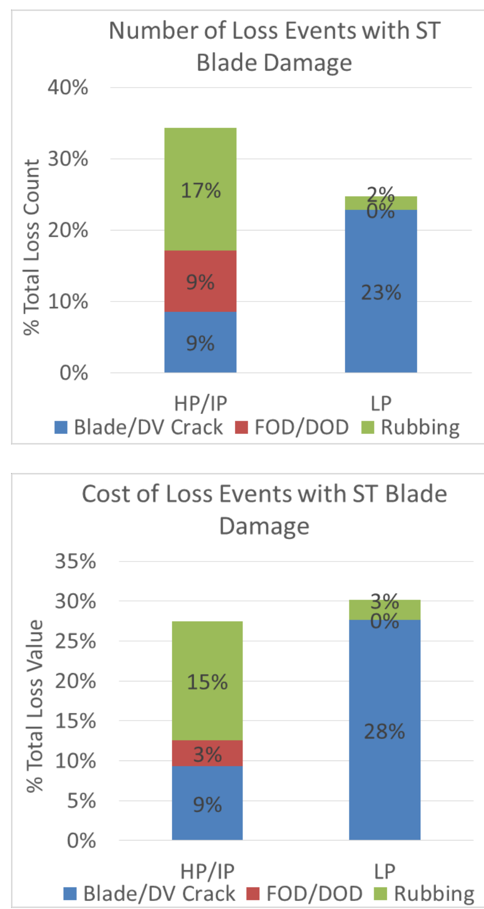

Figure 3-7: Steam turbine loss with blade damage by count and value, per sections and damage mechanisms

Figure 3-8 presents the normalized average loss value per event related to blade damage. Blade cracking and rubbing both resulted in a significant per-event loss. Loss due to impact damage in HP/IP had relatively low cost, including that from broken vanes.

[7] While HP and IP sections of steam turbines are often physically separated, their respective loss data were combined in this study due to similar nature of blade damage.

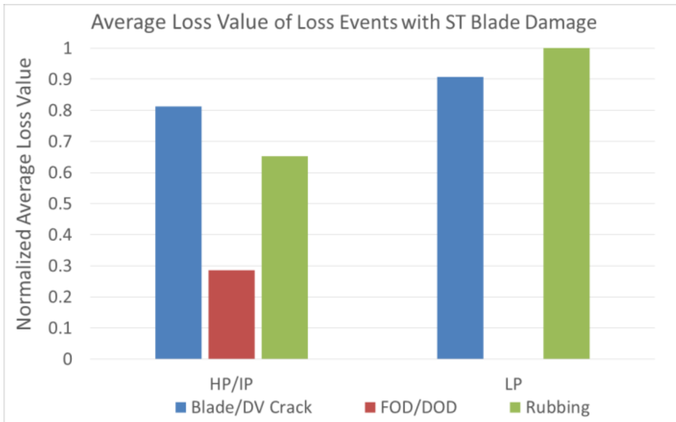

Figure 3-8 Steam turbine loss with blade damage per sections and damage mechanisms

4. NBVM APPLICATIONS

Based on the loss data analyses, it was found that for PowerGen gas turbines the dominant loss event count and associated loss value originated from or involved significant blade damage. These events include losses initiated by blade/dovetail cracking (mostly with severe collateral damage due to DOD), losses with significant rubbing and clashing, and losses due to impact damage from foreign/unknown or domestic objects. Loss events associated with blade damage, excluding those that occurred in the gas turbine HPT section (considering the temperature limitation of current NBVM technologies), still represented 64% of the total loss value or 48% of loss events. For PowerGen steam turbines, 59% of the total loss value or 62% of the loss events were associated with significant blade and vane damage.

NBVM condition monitoring methods can significantly mitigate turbine losses with blade damage. Based on the evaluations undertaken on capability and durability of existing NBVM systems, as well as the analysis on turbine loss data, potential field applications of NBVM are discussed below.

- Eddy current sensors are very robust, low cost and maintenance free for years. They are suitable to use in harsh and low-to-medium temperature environments, and particularly for larger blades, on a long-term monitoring basis. Eddy current sensor based NBVM systems can potentially be applied to gas turbine forward compressor/LPC, aft compressor/HPC and low pressure turbine/LPT, as well as any stages of a steam turbine.

- Based on FM Global data over a recent 10-year period, damage of the gas turbine LPC section has contributed to the largest amount of turbine loss. The average loss value was also relatively high for LPC damage induced loss events. Further, blade damage at the first three or four stages of the low pressure compressor was the dominant cause of LPC induced loss. Accordingly, application of NBVM systems could be focused on a handful gas turbine forward compressor stages (LPC). The larger blades and the exposure to lower temperatures but more contaminants at the LPC stages are suitable for the application of eddy current sensor based systems.

- In steam turbines, damage of the low pressure (LP) blades resulted in larger loss value and higher average cost per event. Blade and dovetail cracking was the dominant damage mechanism for LP blades. Application of NBVM systems in steam turbine could therefore be focused on the LP section, which also shares some common characteristics (lower temperature, larger blades) with the forward low pressure compressor and low pressure/power turbine in gas turbines. Eddy current sensor based systems are moisture and contaminant resistant, and should serve as a good choice for NBVM application in the steam turbine LP section.

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