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Reliability evaluation of a Gas Turbine Water Wash System — A case study

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ABSTRACT

In this article, a reliability analysis was carried out on a Gas Turbine Water Wash System used for washing the compressors of three (3) GE Frame 7 EA Gas Turbines using Weibull Distribution. Note that availability of this system is crucial to recovering compressor efficiency and by extension generation capability that has been lost due to contaminants on the compressor blades. This system therefore, helps maintain and improve the reliability of the turbine and of plant-wide generation. The reliability analysis covered two failure modes for each piece of equipment and took into account the reliability of the system in two operational modes, off-line washing cycle and online washing cycle for a 300 h operational time. Based on the results obtained it can be concluded that the entire water wash system can be taken as 76% reliable based on a 300 h running time. It is more reliable to perform an online water wash than an off-line water wash by at least 4% based on a 300 h operating time. This increased reliability of the water wash system to perform an online water wash is due to an off-line water wash requiring additional equipment which must be run in series.

In addition to the aforementioned analysis fault trees were created to model two scenarios which relate directly to the efficiency of the gas turbine compressors and the generation capability of the turbine: (1) the likelihood of no water being present when conducting a water wash; and (2) the likelihood of cold water being sent to the water wash manifold. Based on the estimated reliabilities, the likelihood of no water being present when conducting a water wash was found to be 3.7% and the likelihood of cold water being sent to the water wash manifold is 1.6%.

1. Introduction

Reliability engineering involves the use of a wide variety of analytical techniques for predicting the probability of satisfactory operation of an item under specified conditions over a known time period (Nourai et al., 2002; Lecchi, 2011; Daejun-Chang and Seong-Yeob, 2015). These techniques provide the means to aid one in the understanding of the failure modes and patterns of these parts, products and systems. To conduct reliability analyses, quantitative reliability measurements are required (Rudd, 1962). These measurements are used for defining the rate of failure relative to time and are subsequently used to model the failure rate in a mathematical distribution which can be used for analysis (Troyer, 2014) and (Ataoui and Ermini, 2014).

There exists many mathematical distributions for reliability engineering purposes which include: (1) the Gaussian (normal) distribution; (2) the Log-normal distribution; (3) the Rayleigh distribution; (4) the exponential distribution and others. This report will be limited to the use of one of the more popular types of distributions in reliability engineering, the *Weibull distribution*. The exponential distribution models machines with the constant failure rate, or the flat section of the *bathtub curve*, see Fig. 1. The Weibull distribution has the ability to characterize failure data as exhibiting early life, constant (exponential) or wear out failures (Troyer, 2014). Most industrial machines occupy the constant failure rate for the bulk of their lifetimes making these distributions widely applicable (Nourai et al., 2002). After the reliability of components or machines have been evaluated relative to the operating context and required run time, the overall system/process reliability can then be assessed.

The system to be assessed for this report is the Gas Turbine Water Wash System used for washing the compressors of three (3)

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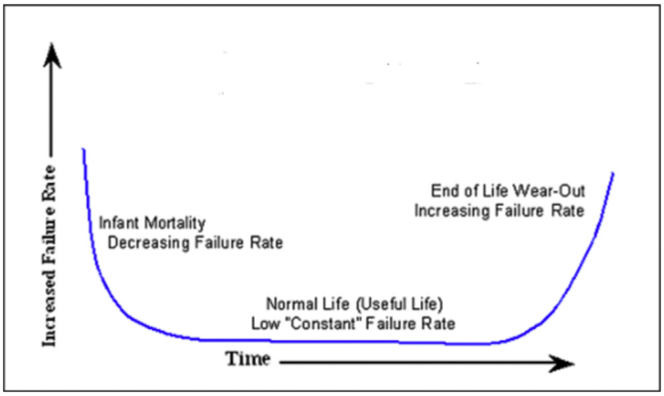

Fig. 1. The "Bathtub" curve.

GE Frame 7 EA Gas Turbines (see Fig. 2). Pollutants in the air that pass through the filtration process can deposit on the internal components of a gas turbine which can lead to a loss of performance during operation. This loss of performance can be indicated by a decrease in power output and an increase in heat rate. The contaminants must be removed from the compressor by washing with a water-detergent solution followed by a water rinse to rejuvenate compressor performance (General Electric, 2008), (Wood et al., 2012) and (Liao and Guam, 2012). A good paper about degradation of gas turbine was written by (Kurz and Brun, 2009).

During operation of the system, water or wash solution is sent through piping to the gas turbine in the proper mix ratio. The water wash solution is delivered to the turbine unit at the proper pressure, temperature and flow rate to wash the gas turbine compressor. The water wash system is capable of performing both an online and an offline water wash. The online water wash allows an operator to water wash the turbine without having to shut down the turbine whilst the offline water wash requires the internal machine temperature to be significantly lower and is therefore usually scheduled during a normal shutdown. It must be noted that wash solution is not used during an online water wash.

The reliability analysis of the water wash system will allow for estimation of a frequency at which preventative maintenance should be conducted for best system performance through analyzing the effects of operating time and the type of operation on system reliability. It is also sought through this report to identify weaknesses within the water wash system to allow for recommendations to be made for improving overall system reliability. In addition, water wash system fault trees leading up to specified fault events that pose significant risks to safety and gas turbine availability are to be developed. It is hoped that this method will allow better understanding of the causes of major failure events that may otherwise be overlooked through other means.

2. Methodology

Development of the reliability analysis of the water wash system involves the following stages: (1) Creating a block flow diagram of the process see Fig. 3; (2) Identifying the failure modes of the equipment; (3) Acquiring reliability data (Failure Rates for equipment, Weibull Shape Factor $\boldsymbol{\beta}$ and Weibull Characteristic Life $\boldsymbol{\eta}$); (4) Calculating the Mean Time Between Failure/Mean Time To Failure (MTBF/MTTF), $\boldsymbol{\theta}$; (5) Calculating the reliability, **R** and the probability of failure, **P**; (6) Calculating the system reliability for all possible combination of failure modes; (7) Evaluating how system reliability for all combinations of failure modes behave with increasing run time both types of operation (online and offline water wash); and finally (8) Developing fault trees for the water wash system.

This process involves representing the water wash system as a series of interconnected blocks that have been arranged in combinations of series and/or parallel configurations. Series systems refer to those that cause system failure do to the failure of any one component while parallel systems (or redundant systems) fail only if all components fail. This involves identifying the relevant pieces of equipment and assigning to them possible ways that they can fail. The equipment pieces and failure modes identified in this report are shown in Table 1.

2.1. Acquiring reliability data

To perform reliability calculations some estimates and assumptions are required. The MTBF/MTTF, β and η values all need to be defined before further calculations can be done. The MTBF/MTTF, β and η values for most of the system equipment were obtained using estimations made by standard systems (Lewis, 1994) and (Riverol and Pilipovik, 2014). For equipment that could not be obtained using the latter, the failure rate, λ was obtained for the particular pieces of equipment and the MTBF/MTTF calculated using Equation (1).

$$\mathrm{MTBF/MTTF}(\theta) = \frac{1}{\lambda} \tag{1}$$

The Weibull shape factor was estimated as being 1.0 for the MTBF/MTTF values obtained via the failure rate calculation due to the system still being relatively young with respect to its plant life and it is assumed that the system has already passed its infant mortality stage. This means the equipment's failure rate lies within the constant region of the bathtub curve where failures are random.

Using the retrieved reliability data the reliability $R_{(t)}$ and probability $P_{(t)}$ of failure for each piece of equipment for each component mode can be calculated using equation (2):

$$\begin{aligned} R_{(t)} &= e^{-\left(\frac{t}{\theta}\right)^{\beta}} \\ P_{(t)} &= 1 - R_{(t)} \end{aligned} \tag{2}$$

To calculate the system reliability we first determine all possible combination of failures during operation based on the failure modes identified for each piece of equipment. Following the block flow diagram and calculate the reliability of the system and the probability of failure for each possible failure combination. The reliability for both parallel and series subsystems as follows:

For a series subsystem (with n subsystems in series)

$$Rs_{(t)} = R1_{(t)} \times R2_{(t)} \times \ldots \times Rn_{(t)} \tag{3}$$

For a parallel subsystem (with n subsystems in parallel)

$$Rs_{(t)} = 1 - \left[\left(1 - R1_{(t)}\right) \times \left(1 - R2_{(t)}\right) \times \ldots \times \left(1 - Rn_{(t)}\right)\right] \tag{4}$$

The system reliability will be evaluated based on how the system reliability behaves with different operation conditions: (1) for different run times (up to 400 h of operation) and (2) for different types of operation (online and offline). It is important to distinguish between the two types of operation because the entire system is not required for performing an online water wash (no detergent is required). It can therefore be shown that the system can more reliably perform an online water wash rather than an offline one. Or, in other words, the probability of failure when performing an offline water wash is more than that of an online water wash for the