Life Analysis of Industrial Gas Turbines Used As a Back-Up to Renewable Energy Sources

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Abstract

The estimated life of gas turbines is expected to diminish over time when compared to the manufacturers’ estimated life, particularly when used as a back-up to Renewable Energy Sources (RES). As RES have been introduced into the grid, the gas turbines used in conjunction with them are operated in “Load-Following” modes to these RES which includes wind, thermal, solar, etc. As back-up plants, the start/stop and power settings are expected to be dictated by the response to grid requirements and need to compensate for the load shortfall attributable to unpredictable nature of RES. This mode of operation results in Gas turbine high pressure turbine blades experiencing low cycle fatigue and creep life failure over time. It is therefore of great importance to estimate the life consumed during this mode of operation to enable appropriate maintenance planning/repair action. In order to estimate the life consumed during adverse/cyclic operating regimes, a tool has been developed wherein different scenarios can be simulated and analyzed to obtain engine life consumption factors. The tool is capable of estimating life consumption based on seasonal power demand. For the purpose of study, an aero derivative power plant of 100MW power output was used as a reference engine. The paper provides an in-depth analysis of the study undertaken and it arrives at the conclusion that the operation of engine during different seasons in the year has a major impact on the estimated life consumption. As a result, it has been a major concern for power plant operators. For the purpose of study, a GT model with 100MW power output was used as a reference engine. The tool has been developed with this in mind. As part of research, a GT model has been developed. This tool has the capability of giving an estimate changes, the plant will have to increase and decrease the amount of generated power throughout the day. As a result, this has been a major concern for power plant operators. Power plants will have to be required to start and stop multiple times during a day’s operation in order to fill in the gaps during low or high power supply from the renewables during different seasons in the year. Also, the GTs will have to cope with the flexibility requirements mainly due to the ‘Start-Stop’ operations based on the highly fluctuating availability of ‘RES’ – wind energy (as considered in this study). The HPT was selected as the life limiting component in this because it experiences high levels of thermal / centrifugal stresses and high temperatures. This forms the basis of this study. As part of research, a tool has been developed. This tool has the capability of giving an estimate
of how much life is being consumed for load-following plants used during seasonal operations.

Nomenclature
CCGT combined cycle Gas turbine
CCPP combined cycle power plants
DP design point
EGT exhaust gas temperature
HCF high cycle fatigue
HPT high pressure turbine
LCF low cycle fatigue
LMP larson-Miller parameter
LPT low pressure turbine
MW mega watt
ODP off design point
OEM original equipment manufacturer
OPR operating pressure ratio
PCN engine rotational speed
RES renewable energy sources
SFC specific fuel consumption
TET turbine entry temperature

1.1. Common failures in Gas turbines
During the service life of an engine, depending on the operation mode, multitude of material damage failure modes such as erosion, high cycle fatigue, low cycle fatigue, hot corrosion/oxidation, thermo-mechanical fatigue and creep amongst others occur. This is induced to the hot gas path components from the compressor to the HPT and LPT sections. The ability of the HPT blades to endure high temperatures is marked by the creep resistance of the HP turbine alloy in the blades.

For the purpose of this study, only LCF and creep failure will be discussed. This is because the LCF failure mode is the most predominant for engines operating in load-following modes. Creep failure also occurs due to the stresses and high temperatures the blade materials. Low cycle fatigue occurs as a result of repeated application of mechanical and thermal loads which eventually results in high magnitudes of temperature and stress cycles which causes initiation and propagation of cracks.

Creep failure on the other hand is the mode of inelastic material deformation that occurs mostly under sustained loading usually at high temperatures [6]. During the operation of load following plants, the gas turbine components usually go through different types of time-dependent degradation as a result of high temperatures and mechanical loading which makes the components susceptible to failures such as Low cycle fatigue, Creep, Creep–Fatigue, thermal fatigue, environmental attach, and high cycle fatigue [7]. Creep failure occurs in different stages before rupture which include: primary stage, secondary stage and tertiary stage.

1.2. Renewable Energy Sources – Wind Energy
Renewable technologies make use of natural energy to produce electricity. It made a total of 7% of the total electricity generated in the UK. World global energy demand began to rise since 2011 and 2012 which supplied a total of 19% of the total world energy consumption [8].

Figures 1 and 2 illustrate the generation profile of the UK peaking power plants for January 2013. Data was collated from BM reports [9]. It is evident that regardless of its negative environmental impact, the coal power plants continue to dominate in the UK energy portfolio. However, this is projected to decrease as the economic and political decisions influenced by public response to climate change make a step forward to decarbonizing UK energy market. As a result, coal power plants will progressively become replaced by other peaking power plants, of which the CCPP are most promising due to their low environmental impact and much better load response characteristics.

As illustrated in figure 2, wind makes a major contribution to the non-peaking energy mix. Consequently, the CCPP are also projected to continue growing to compensate for irregular nature of the renewable sources. Data was collated from BM reports [9] for the month of January, 2013 during winter in the UK.

2. Case study
An intercooled aero-derivative 2-shaft engine of 100MW capacity with an efficiency of 44% was selected as a case study. Fig. 3 shows the configuration of the power plant used as a case study. Figures 4-7 show the performance parameters of the engines as it varies with time over a season in a day.
Fig. 3. Schematic configuration of reference engine

Fig. 4. Spring daily operating scenario and ambient temperatures

Fig. 5. Summer daily operating scenario and ambient temperatures

Fig. 6. Winter daily operating scenario and ambient temperatures

Fig. 7. Winter daily operating scenario and ambient temperatures

Seasonal operating scenarios (figures 4, 5, 6 and 7) for a 100 MW gas turbine have been created according to data collected from BM reports [9]. These scenarios were collated based on 2014 daily data from the UK grid. It is obvious that the highest demand of electricity from CCGT plants occurs in winter and summer due to heating requirements for the first and the shortage of wind energy production for the latter. Furthermore, summer demand is stable during the day time (full capacity), whereas the demand increases daily in spring, autumn and winter because of domestic lighting and heating. The maximum variation in power capacity between the night and day time is noticeable in winter. Seasonal daily ambient temperatures scenarios data have been collected from [10] for Birmingham as an average of the UK weather.

2.1 Performance simulation results

Performance simulation has been carried out using In-House software TURBOMATCH in order to define the main factors affecting creep life and low cycle fatigue (LCF) life. Figure 8 represents daily hour-by-hour turbine entry temperatures TET, cooling air temperatures Tc, and rotational speeds ‘PCN’ for four seasons.

Fig. 8. Seasonal performance simulation results (TET, Tc and PCN).

Summer periods experience the highest values of TET, Tc and PCN due to the high power capacity and high ambient temperatures, which could be reflected in obvious effect on creep life and LCF life. Although power capacity in winter is higher, autumn day values of TET, Tc and PCN are higher
because of the higher ambient temperatures, whereas spring values are the lowest because of the low power capacity. These values have a significant effect on blade creep life and slightly on LCF life. LCF life is significantly affected by the variation in PCN and slightly by TET and Tc variation. The maximum variation in TET, Tc and PCN occurs in winter, which has the highest daily power setting variation. In addition, summer has the minimum values of variation regarding the low variation in power setting during the summer periods.

3. Methodology

The purpose of lifing process is to estimate Creep, LCF and daily life consumption of a power plant. An algorithm has been developed in 'FORTRAN 90/95' according to the lifing methodology in (Fig. 3), which consists of the following modules: Performance simulation module, stress analysis module, thermal module, material properties module, creep life module, and LCF life module. Results of creep life and LCF life estimation can be used to define the period between overhauls, which in turn is used to estimate the maintenance cost of the gas turbine.

Fig. 9. Lifing methodology principle

3.1 Performance simulation module

For the performance simulation module, a software called TURBOMATCH [11] which was developed in Cranfield University is used to simulate an operating scenario for a two-shaft intercooled gas turbine in a certain ambient condition. Its results are used for stress analysis and thermal modules.

3.2. Stress analysis module

Stress analysis module defines stresses on the turbine blade resulted from operating conditions. The main stress on the blade results from centrifugal force due to rotor shaft rotational speed. Gas bending stresses also arise [12].

\[
\sigma = \frac{C_F \times \omega^2 \times R_{cg}}{A \times h \times \rho \times \omega^3 \times R_{cg}}
\]

\[
R_{cg} = R_{rt} - \frac{R_{rt} - R_{rt}}{Z}
\]

\[
\sigma = \frac{C_F \times \omega^2 \times R_{cg}}{A \times h \times \rho \times \omega^3 \times R_{cg}}
\]

where: \(R_{cg}\) = Radius of the blade centre of gravity from the rotation axis; \(\omega\) = Radial rotational speed; \(n\) = Rotor shaft rotational speed; \(h\) = Blade height; \(A\) = Blade cross-sectional area; \(\rho\) = Blade material density.

The centrifugal stress equation becomes:

\[
\sigma_{cen} = \frac{C_F \times \omega^2 (R_{cg}^2 - R_{cg}^2)}{Z}
\]

where: \(R_t\) = Radius of the blade tip from the axis of rotation; Blade tip; \(R_r\) = Radius of the blade root from the rotation axis; \(\sigma\) = Applied stress.

3.3. Blade thermal model

The thermal module has two models for both the cooled and uncooled blades. A decision is made on the type to implement depending on the availability of data. For cooled blade, 1D model can be used if the blade material properties and geometry, and gas properties data are available [4]. Otherwise, a flexible and simple 0D model for uniform temperature distribution on the blade is used, which requires turbine entry gas temperature (TET), cooling air temperature, and blade cooling effectiveness [10]

\[
T_e = T_a - \epsilon (T_e - T_c)
\]

where \(\epsilon\) = Blade cooling Effectiveness; \(T_a\) = Blade material temperature; \(T_e\) = Turbine inlet gas temperature; \(T_c\) = Blade Cooling air temperature.

3.4. Material properties module

The material properties module defines the properties according to material temperature and the applied stress. LMP for creep life calculations is defined according to the applied stress whereas other mechanical properties for LCF are defined according to material temperature. In this module, material properties graphs and tables has been converted into equations to define each property at any temperature, and to define LMP at any applied stress.

3.5. Creep life module

The function of this module is to estimate creep life (Time to rupture) and creep life consumption. Input data is received from the thermal module as hourly material operating temperatures and from the material properties module as hourly LMP values. Estimation of creep life in the creep life module is carried out by Larson-Miller method as follows:

\[
\text{LMP} = \frac{1000}{10^8} (\log(t_c) + C)
\]

Creep life in (hours):

\[
(t_c) = \frac{\text{LMP}}{1000} - C
\]

The Creep life consumption per hour = 1 / \(t_c\).
where \( t_f \) = time to failure (hours); \( T \) = Absolute operating temperature (K); \( C \) = Larson Miller constant.

### 3.6. Low cycle fatigue module

Low-Cycle Life module estimates number of cycles to failure using Coffin-Manson method and Neuber’s constant for stress concentration according to the following equations:

\[
\sigma_a = \text{stress concentration factor} \times \text{maximum stress on the blade.}
\]

\[
\kappa = \frac{\sigma_a}{E}
\]

Nueber’s constant = \( \sigma \times \varepsilon \)

\[
\Delta \sigma = \Delta \varepsilon \times \left( \frac{\sigma}{E} \right)^n
\]

where \( \sigma_a \) = Applied stress at stress concentration zone; \( \varepsilon_a \) = Strain resulted at stress concentration zone; \( E \) = Modulus of elasticity; \( \sigma = \) Cyclic maximum stress; \( \varepsilon = \) Cyclic maximum strain; \( K' = \) Cyclic strength coefficient; \( \sigma_f = \) fatigue strength coefficient; \( \varepsilon_f = \) fatigue ductility coefficient; \( n' = \) Cyclic strain hardening exponent; \( b = \) fatigue strength exponent; \( c = \) fatigue ductility exponent. By solving equations (12) and (13), \( \sigma \) and \( \varepsilon \) values can be defined. The Massing behavior for cyclic unloading becomes:

\[
\Delta \sigma = \Delta \varepsilon \times \left( \frac{\sigma}{E} \right)^n
\]

\[
\Delta \sigma = \Delta \varepsilon \times \left( \frac{\sigma}{E} \right)^n
\]

where \( \sigma_f \) = material strength; \( b \) and \( c \) are constants which is equivalent to -0.12 and -0.6 for majority of materials [12]. By solving equation 16, \( N_f \) can be defined.

Daily LCF consumption = number of cycles per day / \( N_f \) (17)

### 4. Results and Discussions

#### 4.1. Seasonal Creep life for a 100 MW Gas Turbine (Load-Following scenarios)

The results show the variation in creep life (Fig. 9) for different seasons and Base-Load operating scenarios. The value of the shaft rotational speed resulted in a certain value of centrifugal stress on the HPT blade. According to this value, the LMP was defined. Summer operating scenario has the highest creep life consumption (Fig. 10), which resulted in the lowest creep life.

This is because the high values of TET, Tc and PCN resulted from high power setting and high ambient temperatures. The lowest creep life consumption occurs in spring due to low power settings and low ambient temperatures. In spite of having lower ambient temperatures, creep life consumption in winter is higher than in spring due to the higher power setting. Although spring and autumn have similar ambient conditions, spring has significantly greater creep life resulted from smaller values of TET, Tc and PCN regarding the lower power setting.
PCN. The reason is winter has greater variation in power settings which reflected in TET, Tc, and PCN values.

In Start-Stop scenarios, LCF life is affected significantly by the value of maximum power setting and slightly by the ambient temperature, because they are reflected in TET, Tc and PCN maximum values (Fig 11). Summer scenario has the lowest number of cycles to failure because of the high maximum power setting and high ambient temperature. Despite the fact they have similar maximum power setting, number of cycles to failure in winter is higher than it in summer regarding the lower ambient temperatures, which appears in TET, Tc and PCN maximum values. Spring still has the greatest number of cycles to failure resulted from the smallest values of TET, Tc and PCN.

Although ambient temperatures during spring are higher than winter periods, it still has lower daily creep life consumption due to lower power settings.

- Creep life is affected significantly by TET and Tc values, and slightly by PCN values.
- Number of cycles to failure (LCF life) in “Load-Following” scenarios is affected by the maximum value of power setting and the value of variation in power settings. Whereas, in Start-Stop scenarios, it is affected only by the maximum value of power setting.
- Regarding the difference in ambient temperatures, number of cycles to failure (LCF life) for Start-Stop scenario in winter is higher than that of summer, in spite of having the same maximum power setting value.
- Daily LCF life consumption in summer is lower than that of winter and autumn for Start-Stop scenario, although summer has smaller number of cycles to failure. The reason is that summer operating scenario has lower number of cycles per day.
- Daily LCF life consumption is affected by the number of cycles to failure and the number of cycles of operation per day.

References


