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Comparison of lifing results of gas turbine operated in base load and as a back up to wind turbine.

* Saleh, Mohamed; [2]Ali, Ezeddin; [3]Pilidis, Pericles; [4]Sampath, Suresh;
Cranfield University, Power and Propulsion
Cranfield University, Power and Propulsion
Cranfield University, Power and Propulsion
Cranfield University, Power and Propulsion
Corresponding Author: Saleh Mohamed

ABSTRACT: *When operating the gas turbine in a flexible mode as a back up to renewable energy sources such as wind, solar, tidal and so on. A fluctuation of power produced by the GT will be apparent which in turn will cause low cycle fatigue in the high-pressure turbine blades. The drive behind this study is to estimate the life of a 100 MW GT operated in a baseload scenario and compare the lifing results with two different scenarios of operating the GT as a back up to a wind turbine operated in the UK in 2016.*
For the estimation of the GT lifing, some performance parameters are essential such as turbine entry temperature (TET), blade cooling temperature (Tc), and the shaft rotational speed (PCN). All these parameters are obtained from running the in-house TURBOMATCH model, which was developed in Cranfield University, under certain operating conditions (temperature and pressure). These values are used with other parameters as input to a FORTRAN code to estimate the lifing and lifing consumption of the GT. In comparison, it was found that the base load scenario has the highest value of creep while in the backup scenarios the LCF was higher due to the power fluctuation.
KEYWORDS: *Gas Turbines; Flexibility;Wind Energy; Creep; Fatigue; lifing.*

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I. INTRODUCTION

Power plants are considered one of the sources of pollutant gases, such as CO, CO2, and SO2. To reduce CO2 emission, significant amendments have been made in power production, renewable energy sources (RES) have been introduced ,nevertheless using the RES has some cons accompanying with its pros, these cons are the unpredicted nature of power generated by the RES because it mainly depends on the weather conditions like sunshine and wind speed. Moreover, the variation in the power demand throughout the day and different seasons of the year necessitates backup source of energy to fill the shortage in energy production, because of that, Gas turbine power plants were used for compensating the energy demand at peak times of the day and the year[1] [2][3]

Operating the industrial gas turbines as a back up to RES will lead to a variation in the power settings, during the day according to the production and demand. Likewise, the number of daily start-ups and shutdowns will increase, which consequently will affect the gas turbine performance parameters such as, (TET), (Tc), and the shaft rotational speed (PCN), these changes will, therefore, cause a variation in centrifugal stress affecting the high-pressure turbine blades. So the blades will not be subjected to the only creep due to operating in very high temperature but also to fatigue loading due to the cyclic operation of the gas turbines used as a back up to RES. The estimation of lifing and the lifing consumption for the GT operated in three different scenarios is presented using developed tools.

II. METHODOLOGY

The methodology as presented in figure (1) comprises three different elements: input data stage, processing data stage, and output results stage.

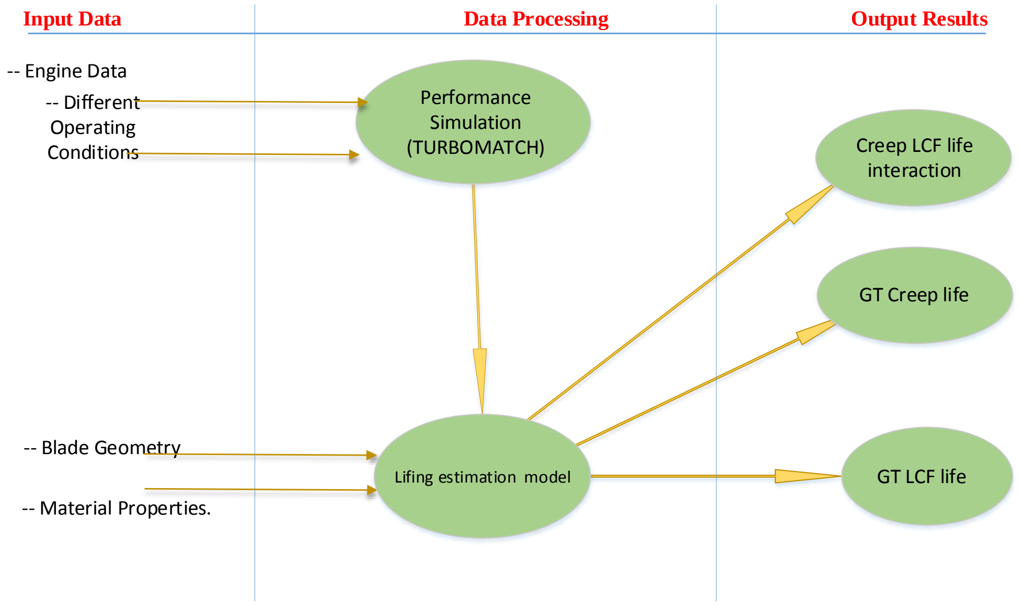

Figure1: Gas turbine lifing estimation model

2.1 Input data stage

In this stage, the power produced by the wind turbine is downloaded from the UK National Grid Status website (http://www.gridwatch.templar.co.uk ((accessed in 17/02/2016)). A graphical representation of the power produced in the UK is as shown in figure (2). It can be observed from the graph the distribution of wind power throughout the year in the four seasons. The highest values were noted in winter and autumn respectively, while in summer and spring it was at the lowest rate. These values were used to represent the gas turbine operating scenarios in the four seasons of the year as shown in figures (2-5).

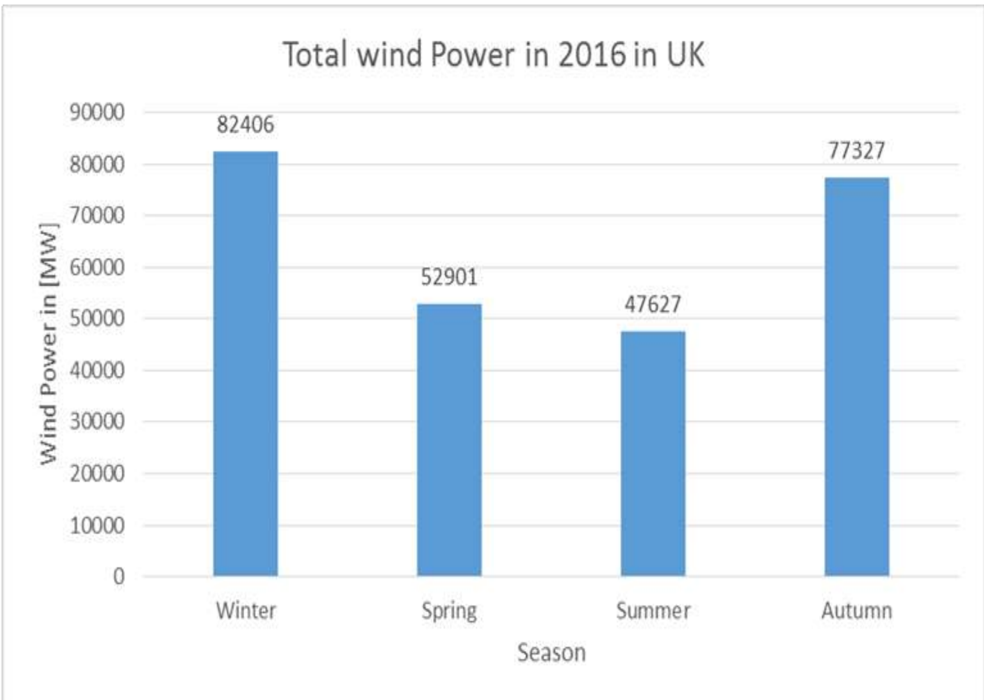

Figure 2: Wind power produced in 2016 in the UK.[4]

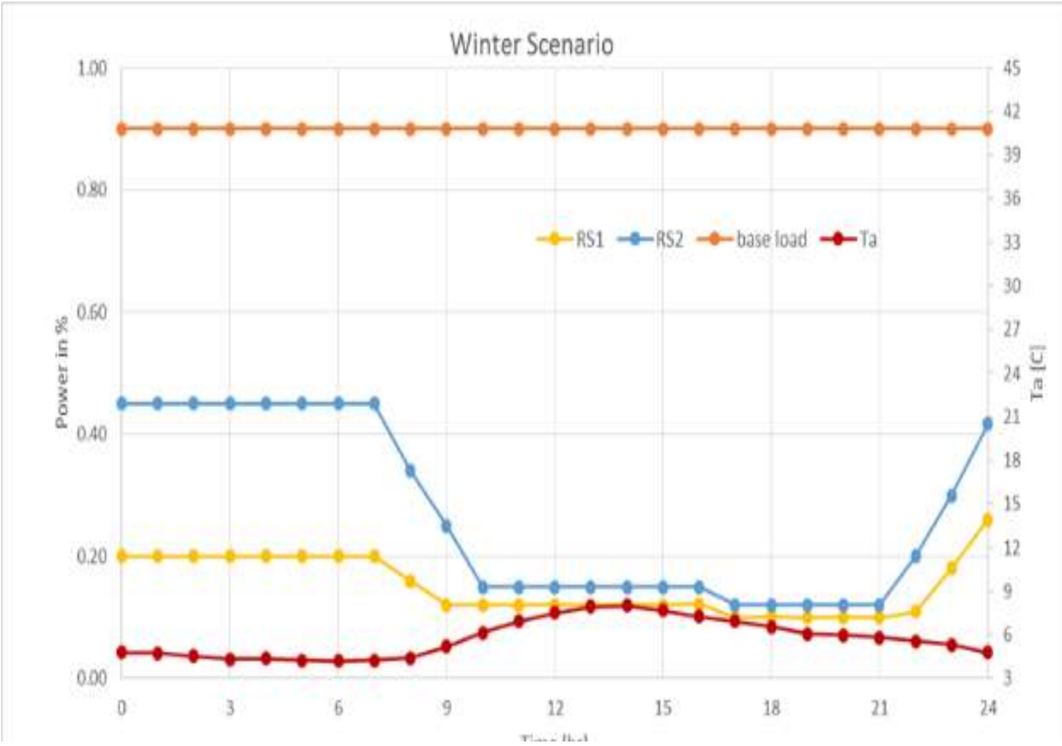

Figure3: Winter scenarios and Ta vs time.

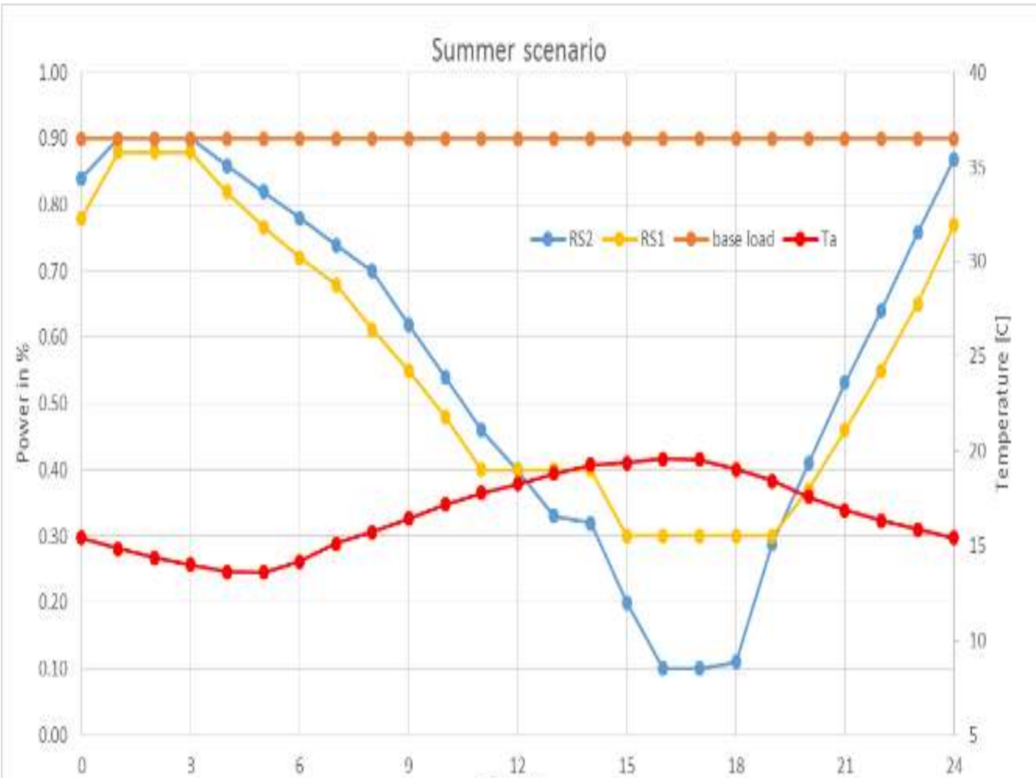

Figure4:Summer scenarios and Ta vs time.

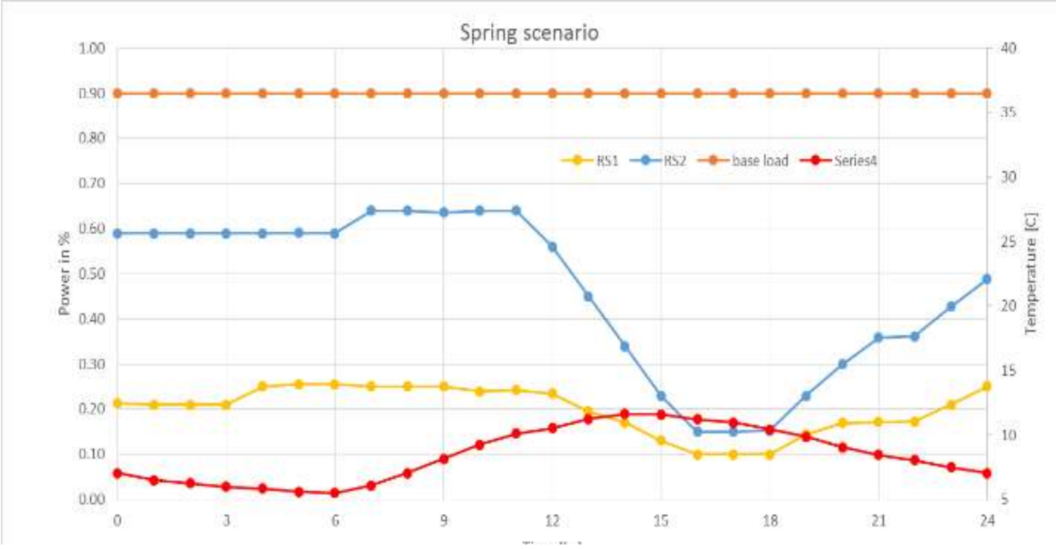

Figure5: Spring scenarios and Ta vs time.

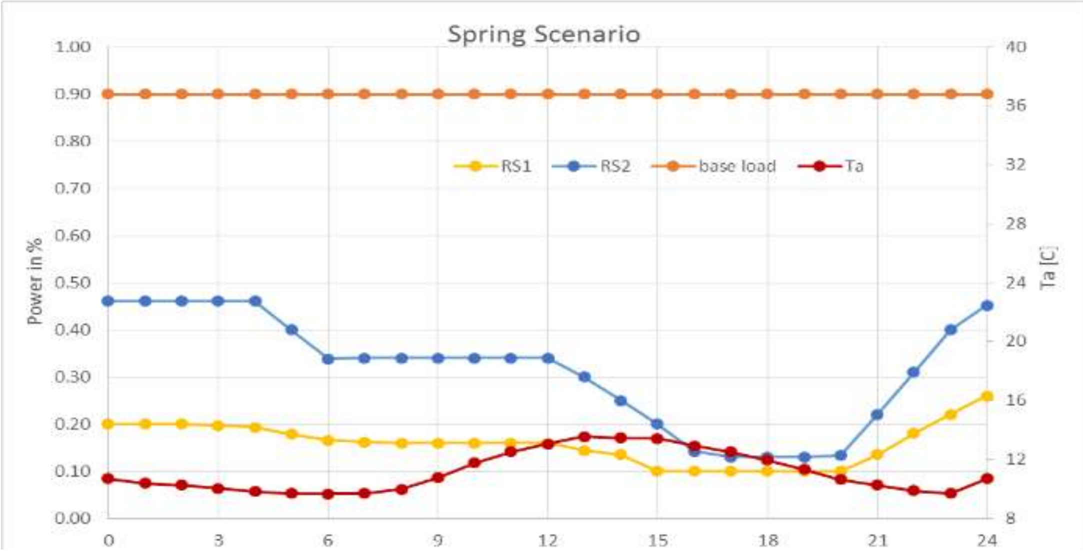

Figure6: Autumn scenarios and Ta vs time.

In the operating scenario figures (3-6) it is evident in the four different seasons the output power is constant in the base load scenario at 90 MW with a correspondent variation in ambient temperature through all the day. This scenario will be used for the comparison with the other two hypothetical scenarios, focusing at the ambient conditions, which has a significant influence on GT performance where the temperature varies from a minimum of around 4C° in winter to a maximum of around 19C° in summer. Autumn has a minimum of 10 C° while the ceiling is 14 C°, whereas in spring the minimum was 5C° and the peak was 12C°.

It is apparent that there is a variation in the wind power produced through all the year and during the day as well, which will necessitate the GT to operate in a flexible mode to back up the wind power shortage. Relatively autumn has the highest variation in the power in both the scenarios ranges between (10MW) and (90MW) minimum and maximum respectively, whereas the change in the other three seasons is limited between (10 MW) as minimum and (65MW) as a maximum in the summertime.

2.1.1 Ambient conditions

The ambient conditions (Ta) are likewise presented in figure (7) for the year 2016 in the UK, which has a significant influence on engine performance.

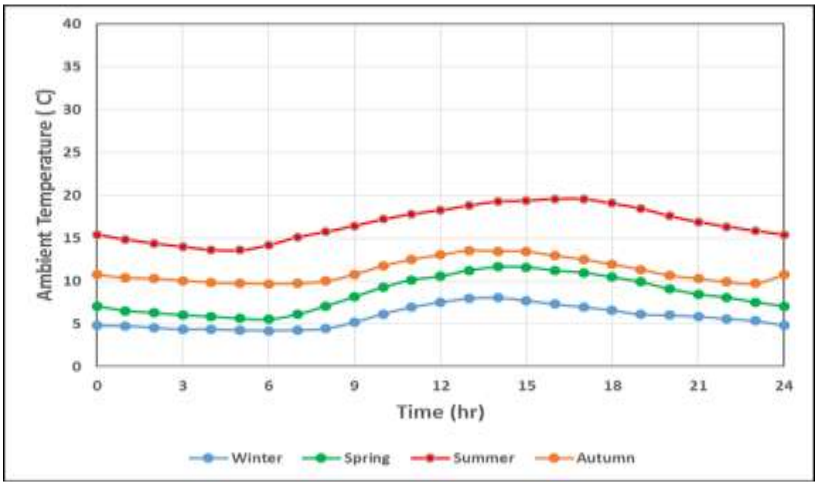

Figure 7:The average ambient temperature in 2016 in the UK.[5]

From the figure, it is apparent that the highest value of Ta is 20°C in summer, while the lowest one is around 5°C in winter. The highest values of (Ta) are recorded between 12 and 18 hrs, while the lowest was recorded between 3 and 6 hrs. These values of the (Ta) and the corresponding values of power are used as inputs to the performance model (TURBOMATCH) to estimate the engine performances changes in 24 hours'. The Ta values with the corresponding power produced and material properties will be the input data of the lifing estimation model.

2.1.2 Material property

The most important material properties are density, young modulus, and tensile strength. All these properties are highly dependent on temperature. A curve fitting method was used to define an expression for estimating these properties as a function of temperature, which then will be used in the lifing model to estimate the HPT blade lifing. The material used here in this analysis is Nimonic 105 with the specific mechanical properties as a function of temperature as follows. [6][7]

I. Young Modulus (E):

variation of Young modulus with temperature is obvious in figure(8), which proves that there is an inverse proportional relationship between the material Young's modulus and the temperature.

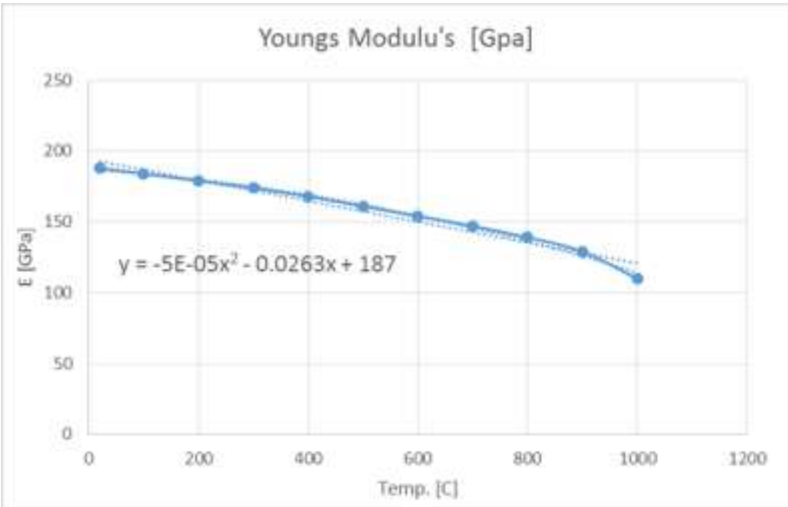

Figure8: Young modulus relation with temperature.

II. Tensile Strength:

The tensile strength is profoundly affected by the temperature, which in turn will influence the low cycle fatigue life estimation.; this variation is presented graphically in fig. (9) In three different sectors to attain more precise equations expressing the tensile strength temperature relation. It can be noticed that at temperatures from 0 to 750 °C there is no significant change in the tensile strength, whereas there is a steep relation in the range from above 750°C up to 1000 °C.

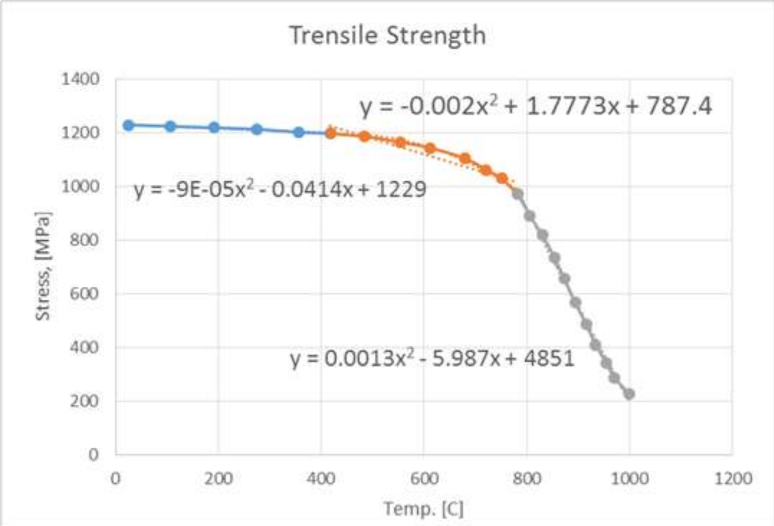

Figure9: Tensile strength variation with material temperature

2.2 Data processing stage

This stage of the lifing estimation methodology can be split into two main models one for the engine performance simulation, while the other is a lifing estimation model.

2.2.1 The performance model

Gas turbine performance TURBOMATCH model, which is a component developed in Cranfield University to simulate varieties of gas turbines is used. The following parameters TET, Tc, and PCN. Will be essential to estimate the life of the component.[8]

2.2.2 Lifing estimation model

This model determines the creep, low cycle fatigue (LCF) life and also the superposition between both of them. This model gets input data from the performance simulation model (TURBOMATCH). A FORTRAN code was developed which can estimate the lifing of the GT based on the ambient conditions, operating scenario, shape, and material used in high-pressure turbine blade design.

2.2.2.1 Low cycle fatigue life

The low cycle fatigue life is mainly estimated by the number of cycles (Nf) to failure; there are different approaches to do so. The widely used one is the Coffin-Manson approach and the Neuber's constant for stress calculation [9]. [10]

Neuber's constant = σ x ε. (1)

The total strain in cyclic loading involves both the plastic and elastic strain

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \frac{1}{2}\left(\frac{\Delta\sigma}{K'}\right)^{\frac{1}{n'}} \quad (2)$$

Based on Coffin Manson the total strain amplitude can be estimated based on the following formula, where

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E}(2N_f)^b + \varepsilon'_f(2N_f)^C \quad (3)$$

For the vast majority of materials, b varies from (-0.5 to -0.12), and c varies from (-0.5 to -0.7). [11][12]
Solving the equations (2) and (3) the LCF life is estimated for the 100MW gas turbine operated as a back up to RES.

2.2.2.2 Creep life estimation

Creep is mainly slow stress occurring in a material when it is subjected to high temperatures for a prolonged period. For creep to take place, it will pass through three different phases, primary phase, secondary phase, and then the tertiary creep phase, where creep accelerates quickly until a material fracture happens. These three phases are illustrated in fig(10). [13]

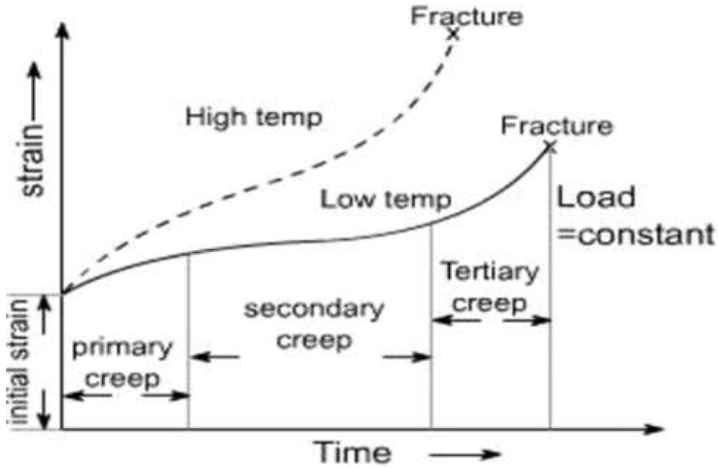

Figure 10: Three different phases of creep. [12]

Creep life can be estimated using different approaches, in this study the Larson-Miller parameter approach is implemented to determine the creep life of the HTP blade.
The Larson-Miller parameter correlates the rupture data, where it combines the material temperature T in C° and time to rupture t in hours. [14][15]

$$p = \frac{(\Theta + 273)}{1000}(C + \log_{10} t) \quad (4)$$

Where:

P --- Larson-Miller Parameter.

Θ --- Temperature, C°

C --- Constant, usually assumed to be 20

T --- Time in hours to rupture or to reach a specified value of creep strain.

The approach of the Larson-Miller parameter was the core of the FORTRAN 90 code to estimate the creep life for the 100MW gas turbine.

2.2.2.3 Creep LCF interaction life estimation

In industrial gas turbines which are operated in a load base mode the problem of interaction is not of great importance, whereas when operating the gas turbine as a back up to RES this problem appears and has a significant effect on the life of gas turbines. The creep-fatigue interaction appears in case of both creep and fatigue act at the same time. Creep appears because of severing temperature while fatigue appears due to load changing or cycling. These two damage mechanisms develop consequently or simultaneously resulting in accelerated crack initiation and propagation, the phenomena of these two failure mechanisms is shown in figure (11).[16][17]

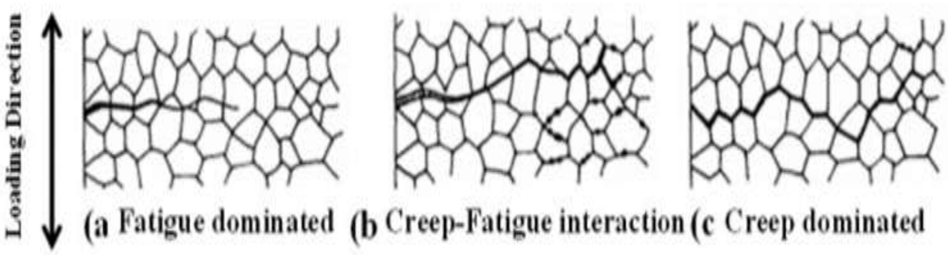

Figure 11: Creep-fatigue interaction phenomena [17][18]

There are different approaches to estimate the lifing of the HPT blade due to the interaction between the creep and the LCF, the widely used approach is the Linear Damage Summation (LDS) method due it is simplicity, this approach is the one implemented in the lifing FORTRAN code to estimate the life of the 100 MW GT. This approach considers the idea of fatigue damage is arising in the surface, while creep is initiated internally between the grains. And the total damage is the total sum of life fraction for LCF (Df) and the life fraction of the creep damage (Dc).

Dcf = Dc+ Df (5)

Where $D_f = \sum \frac{N_i}{N_f}$ and $D_c = \sum \frac{t_i}{t_f}$ and it is expressed as:

$$\sum \frac{t_i}{t_f} + \sum \frac{N_i}{N_f} = D_{c+f}$$

The damage level is presented by the value of the parameter Dc+f when the value is equal to one it is supposed that the failure will take place. The lifetime of creep-fatigue is estimated based on the reciprocals of the creep and fatigue lifing results.

$$\frac{1}{\mathrm{Np}} = \frac{1}{\mathrm{Nc}} + \frac{1}{\mathrm{Nf}} \qquad (6)$$

III. RESULTS AND DISCUSSION

Electric power generated from wind turbines in the UK for the four seasons in 2016 hasbeen downloaded from the UK National Grid Status website for electricity produced. These data have been used to develop three different scenarios for operating the 100MW gas turbine (figures 3-6). The first one is the base load scenario, where the power produced is fixed at 90MW through all the day in the four seasons with a corresponding alteration in ambient temperature. In the other two hypothetical scenarios, the fluctuation of the power produced is evident during the 24 hour time. Summer has got the highest power generated by the 100MW, wherein some points the GT has to produce 90MW because wind power is at the lowermost level at that period. Besides spring has got the second highest power generated and the fluctuation is between 10MW and 65MW through all day. Furthermore, autumn and winter both have reached the lowest powermade by the GT ranging from 10MW as a minimum to 45MW as maximum, that's due to the high level of electricitygenerated by the wind turbine.

3.1 Performance simulation results

The In-House TURBOMATCH software is used to estimate the 100MW GT performance in the four different seasons, The most critical parameters affecting the LCF and Creep life are the TET, Tc and the PCN, these values are presented in figures (12-15), which show how they vary through all the day in the four different seasons.

The summer season has the highest values of TET, Tc, and PCN due to high power produced by GT and high ambient temperature as well, which has a significant influence in the GT creep life. Spring also has got a high value of TET, Tc, and PCN due to high power capacity produced by GT. whereas winter and autumn bothhave reached a low power capacity, which reflected on the values of TET, Tc, and PCN. These valuesaffect significantly creep life and slightly LCF life. The variation in PCN profoundly influences LCF life while it is somewhat affected by TET and Tc variation.

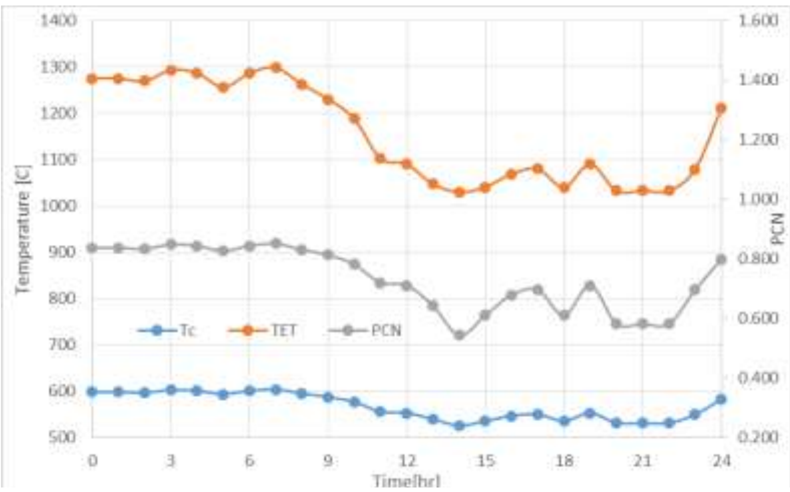

Figure 12: TET, Tc and PCN versus time in winter.

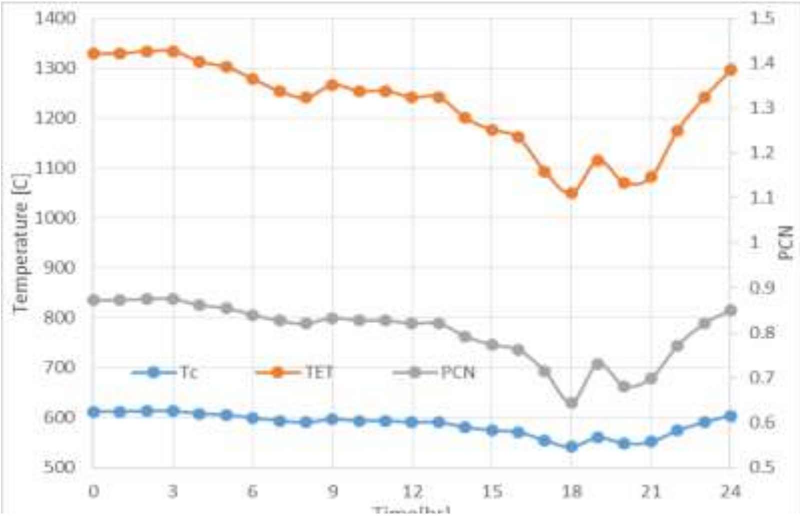

Figure 13: TET, Tc and PCN versus time in autumn.

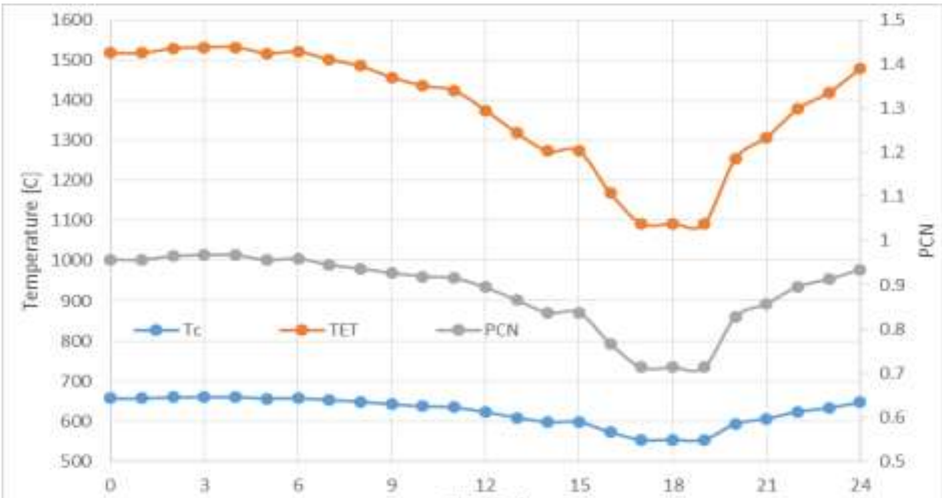

Figure 14: TET, Tc and PCN versus time in summer.

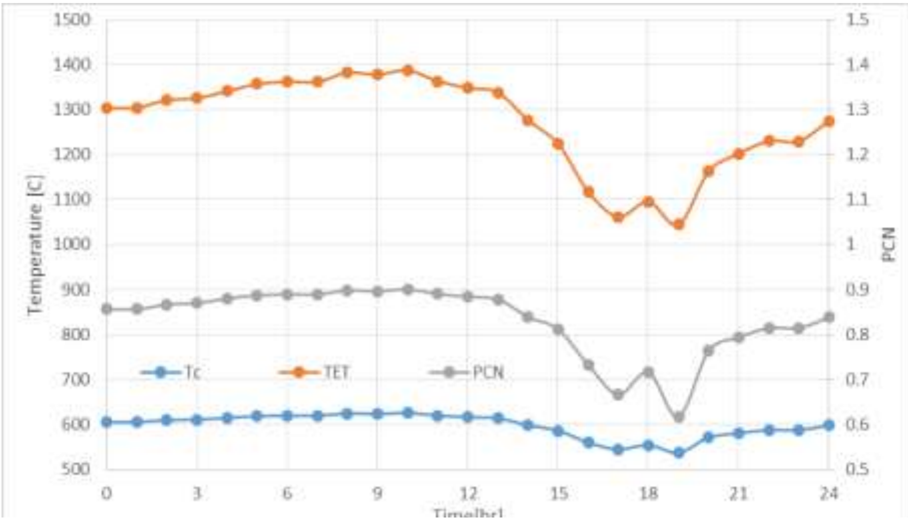

Figure 15: TET, Tc and PCN versus time in spring.

3.2 Lifing results

Based on the performance simulations outputs (TET, Tc, PCN) the FORTRAN lifing code has been run different times to reach an estimation of the GT lifing. Results of these runs for LCF, creep and interaction of lifing are listed in the table (1) for the three different scenarios in the year 2016 in the UK.

Figures 16 and 17 illustrate the lifing and lifing consumption in the three different scenarios (Baseload, RS1, and RS2).

Table (1) lifing results for the three different scenarios.

	Base load	RS2 **4	RS1 **2
yearly LCF life consumption=	0.015749351	0.042259071	0.049911
yearly creep life consumption=	1.246554885	0.01756263	0.036197
yearly LCF-Creep life consumption=	1.262304246	0.043395666	0.069681126
LCF life in years=	63.49467867	23.66355847	20.03581146
Creep life in years=	0.802210967	56.93908099	27.62695999
Creep_Fatigue Life in years =	0.792202041	23.04377563	14.3510885

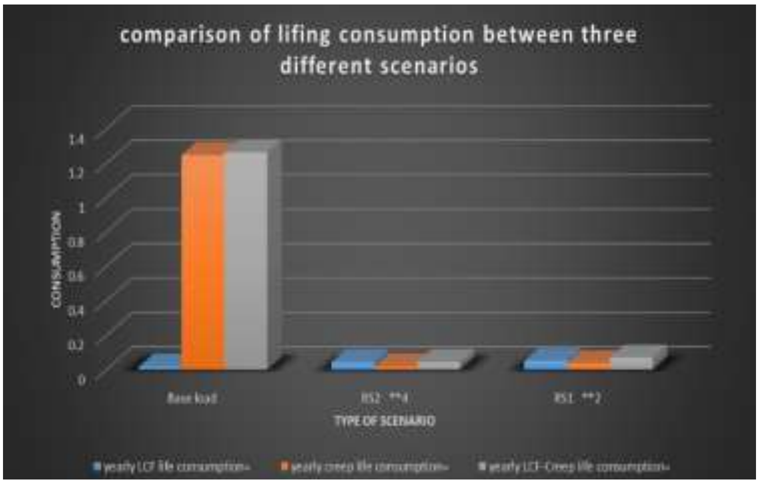

Figure16: GT Lifing consumptions

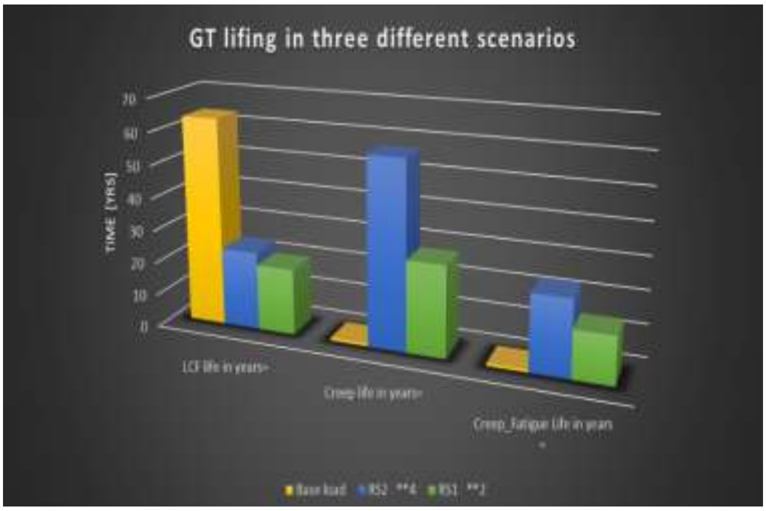

Figure17: Gas Turbine lifing results

IV. CONCLUSION

- The ambient conditionis altering through all the year and daytime, which has a significant influence on GT lifing.
- Due to the low level of wind power produced in summer, the GT has to operate at 90MW, which makes the use of 100MW GT reasonable.
- Young modulus and tensile strengthare temperature dependent, so estimation of the variations during the day is essential for LCF and creep life estimation.
- TURBOMATCH performance results show the highest values of TET, Tc, and PCN are in summer, due to the low wind power produced which enforced the GT to operate at a high rate.

- Daily LCF consumption is affected by the number of cycles per day and year.
- In the base load scenario, the creep life consumption is the highest due to operating at high capacity for a long time, while the LCF life consumption is very low due to no power fluctuation.
- In the case of LCF life, the GT life is reduced to around 33% compared to the base load life in the backup scenarios due to power fluctuation.
- In a comparison between the three scenarios, it is evident that the RS2 scenario has the highest LCF, creep and the interaction lifing results.

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