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EFFECTS OF PERFORMANCE DETERIORATION ON GAS PATH MEASUREMENTS IN AN INDUSTRIAL GAS TURBINE

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ABSTRACT

Studying gas turbine degradation causes and their consequences helps to obtain profound comprehension in how performance deterioration affects the dependent parameters and to explore relevant information about the nature of the fault signatures for fault diagnostics purpose. In this paper, the effects of compressor fouling, gas generator turbine erosion, and power turbine erosion on the engine dependent parameters were considered separately and together. In this regard, firstly, performance prediction model was developed to LM2500 engine using gas turbine simulation program. It was then used to simulate the deterioration effects by means of artificially implanted fault case patterns. Comparison of the clean and deteriorated measurement gives the deviation due to performance degradation. Accordingly, sensitivity order of the gas path parameters to the corresponding performance deterioration was assessed. This helps to select the key parameters, which are crucial in the process of fault detection and isolation. The results showed that, in most of the cases, air mass flow rate, compressor delivery pressure and temperature, gas generator rotational speed, power turbine inlet pressure, and exhaust gas temperature showed significant deviations. Particularly, the compressor delivery pressure and exhaust gas temperature were the parameters highly influenced by all the fault cases. Moreover, faults that have similar impacts are identified, in order to show the difficulty of gas turbine health assessment through direct observation to the measurement deviations.

Keywords: gas turbine, component degradation, performance deterioration, measurement deviation.

INTRODUCTION

Gas turbines have several applications including power generation and driving different compressors in oil and gas industries. As time goes on, faults such as fouling, erosion, corrosion, blade tip clearance, object damage and thermal distortion can cause performance degradation. This may result high energy consumption, high operation and maintenance costs, major damage to gas path components, and environmental pollution. Degradations are manifested by gas path measurement variations. The challenge on engine health assessment based on the history of measurement discrepancies is that the performance can be changed due to ambient condition, load and fuel delivery changes and/or due to component performance degradation(s). Regardless of the other effects, the investigation on the impacts of engine component performance degradation on measurement deviations provides relevant information about the nature of the fault signatures in fault diagnostics.

Over the years, gas turbine performance degradation has been studied by several scholars. For instance some authors in [1-3] and others in [4-5] focused on the assessment of compressor and turbine degradation effects, separately. Kurz *et al.* [6], Morini *et al.* [7], Lakshminarasimha *et al.* [8], and recently Campora *et al.* [9] evaluated the effects of compressor and gas generator turbine degradations separately and together on single shaft gas turbine overall performance. In these papers, the results obtained from the combined effects were the sum of the results of the individual effects. Moreover, Zwebek and Pilidis [10] also investigated the impacts of gas turbine degradation on combined cycle gas turbine (CCGT) power plant performance. In this work, on the gas turbine side, compressor and turbine fouling, compressor and turbine erosion and their combination were considered. In nowadays more attention is given to further studies on compressor fouling causes, their effects on performance deterioration, and cleaning techniques with economic analysis (see, [11-13]). Recently, Mohamedi [14] studied the influence of compressor, compressor turbine and power turbine performance deteriorations, assumed to be happened separately, on gas path parameter deviations at full load and part load conditions using computer simulation.

In the field of engine diagnosis, an optimal parameter selection is very important. Concerning this, many researchers including Ogaji *et al.* [15], Ganguli *et al.* [16] and recently Chen *et al.* [17] proposed different techniques. In these studies, compressor discharge pressure (CDP), compressor discharge temperature (CDT), gas generator shaft speed (NGG), power turbine (PT) inlet pressure, fuel flow rate (Wf) and exhaust gas temperature (EGT) for twin shaft gas turbines, low pressure compressor discharge temperature, high pressure compressor discharge pressure and temperature, high pressure and low pressure compressors' shaft speeds, Wf, and EGT on double spool gas turbines and air mass flow rate (Ma), fan delivery temperature, high pressure compressor discharge pressure and temperature, high pressure turbine outlet pressure and temperature, high pressure compressor rotational speed, and Wf on double spool turbofan engines are suggested as crucial fault diagnosis parameters, respectively.

Although the issue how and in what extent the gas turbine cycle performance affected by the compressor and GG turbine degradations have been addressed, the impact of PT degradation and concurrent component degradations are not considered. Recently, the PT degradation effect has been addressed by Mohamedi *et al.* [14]. They evaluated the effects of compressor fouling (CF), gas generator turbine erosion (GGTE), and power turbine erosion (PTE) taking in to account only one fault at a time. Hence, there is a room to evaluate the degree of sensitivity of measurement variations and cycle performance changes to multiple component faults.

Thus the fundamental motivation behind this work was to give a better comprehension in how a gas turbine engine multiple component degradation affects the measurement variations. Specifically: to assess the response of the measurements to component(s) degradation; to identify key parameters which are highly influenced by engine degradation; to show the level of the challenge to detect and isolate engine component faults by simply looking in to measurement deviations.

For this purpose, LM2500 engine is considered and the effects of single, double, and triple component faults on the measurements investigated.

GAS TURBINE PERFORMANCE SIMULATION

In this study a double shaft industrial gas turbine engine, LM2500, in oil and gas exploration and production services of Petronas Resak Development Project (PRDP) was considered. It consists of 16-stage axial compressor, 2-stage gas generator turbine and 6-stage power turbine. Figure-1 illustrates the schematic of the basic engine components with the measurement parameters. The design point specifications have also been presented in Table-1. First, the design and off-design performance analysis is performed using a gas turbine modelling scheme, 'Gas turbine Simulation Program' (GSP). For this purpose, generic component maps have been used scaled to the design point data of the engine at ISO conditions. Following that the gas turbine performance deterioration simulation at full load condition is executed to investigate the corresponding effects on the engine measurable parameters.

Table-1. LM2500 design point specifications.

Parameters	Values
Power output (KW)	20163
Mass flow (Kg/s)	66
Compressor pressure ratio	17.5
Cycle efficiency	0.39
Max cycle temperature (K)	1400
Compressor isentropic efficiency	0.88
Gas turbine isentropic efficiency	0.915
Power turbine isentropic efficiency	0.915

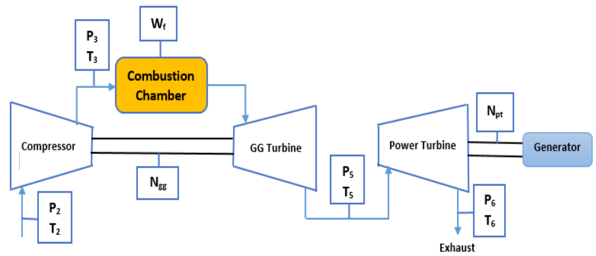

Figure-1. Two-shaft gas turbine engine gas-path measurements.

EFFECT OF COMPONENT DEGRADATION ON THE ENGINE MEASUREMENTS AT FULL LOAD

Gas turbine performance can be degraded temporarily or permanently. The former can be partially recovered during operation and/or engine overhaul while the latter requires replacement [18]. Fouling, erosion, corrosion and blade tip clearance are among temporary degradation causes. Whereas, airfoil untwist and platform distortions lead to permanent deterioration. Climate conditions, engine operating conditions, and maintenance practice are considered as usual sources of these faults. Some studies stated that more than 80% of the engine degradation is subjected to compressor fouling and turbine erosion [8,19]. The exposure of the power turbine in favor of its location and physical design is lower than the compressor and gas generator turbine [15]. In this paper, based on Zwebek and Pilidis [10], equal severity ranges have been considered (see Table-2). Accordingly, for each fault type listed in Table-3, ten fault patterns are generated. According to Saravanamuttoo and Lakshminarasimha [20], to simulate compressor fouling, for each 0.5% flow capacity loss, its isentropic efficiency is assumed to be reduced by 0.25%. Likewise, as per [10], to simulate turbine erosion, for each 0.5% flow capacity increase, isentropic efficiency is assumed to be decreased by 0.25%. This has been done for the progressive degradation with steps of 0.5% starting from the healthy condition to the maximum deterioration. Then, the measurement deviation has been determined using Equation. (1).

$$\Delta Z_e = \left(\frac{Z_d - Z_c}{Z_c}\right) \times 100 \quad (1)$$

Where Z_c and Z_d are the measurement values at clean and deteriorated conditions, respectively.

Table-2. Assumed fault severity ranges.

Fault Type	Flow capacity change	Efficiency Change	Deterioration Range (%)	
CF	$\downarrow \Delta\Gamma_C$	$\downarrow \Delta\eta_C$	0→-5.0	0→-2.5
GGTE	$\downarrow \Delta\Gamma_{GGT}$	$\downarrow \Delta\eta_{GGT}$	0→5.0	0→-2.5
PTE	$\downarrow \Delta\Gamma_{PT}$	$\downarrow \Delta\eta_{PT}$	0→5.0	0→-2.5

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Table-3. Implanted fault cases.

Fault Types	Fault Category
CF	Single
GGTE	
PTE	
CF + GGTE	Double
CF + PTE	
GGTE + PTE	
CF + GGTE + PTE	Triple

RESULTS AND DISCUSSION

Case 1: Single component degradation

This section presents the effects of single gas turbine engine component faults on dependent parameter deviations. This helps to realize the nature of the measurement variations associated with single component faults. As shown in Figures-(2-4), it has been clear to understand that whenever fault severity increases, in all the cases, measurement variation increases. The measurements variation trends obtained from the simulation agreed with the literature [10,14]. As far as compressor fouling is considered, at 100% severity EGT, (CDP, PT inlet pressures, Ma, and Wf) and NGG showed 5%, 4% and 1.3% delta, respectively. Whereas, the impact on CDT and PT inlet temperature is negligible. When the GGTE is introduced to the engine NGG, CDP, CDT & Ma, PT inlet pressure and temperature, and PT outlet temperature changed by 10%, 9%, 4.6%, 3% and 2.7%, respectively. The maximum variations for all the measurements, except for NGG, due to PT degradation ranges are under 4%. In general, in this work, according to their sensitivity to single component degradation, the engine measurements can be categorized as NGG, CDP, Ma and EGT as first class key parameters and CDT, P4 and T4 as second class key parameters to identify faults.

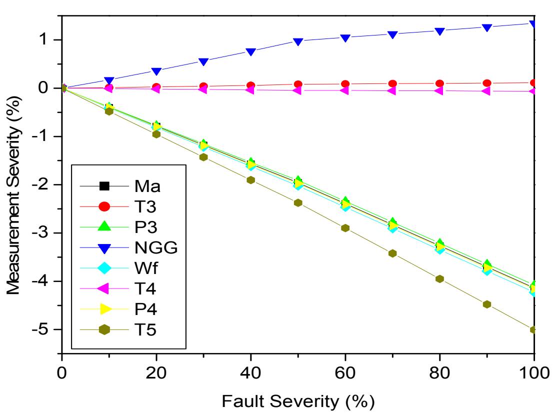

Figure-2. Engine measurement variations vs CF (%).

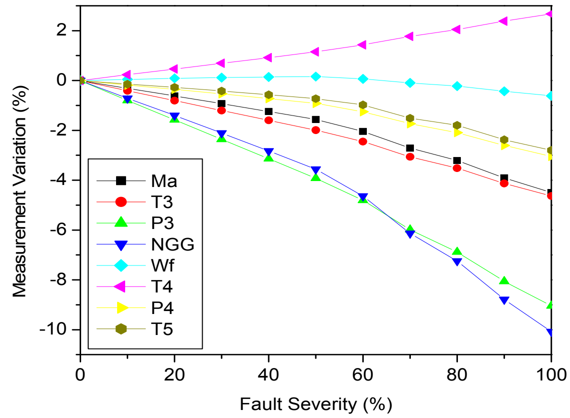

Figure-3. Engine measurement variations vs GGTE severity (%).

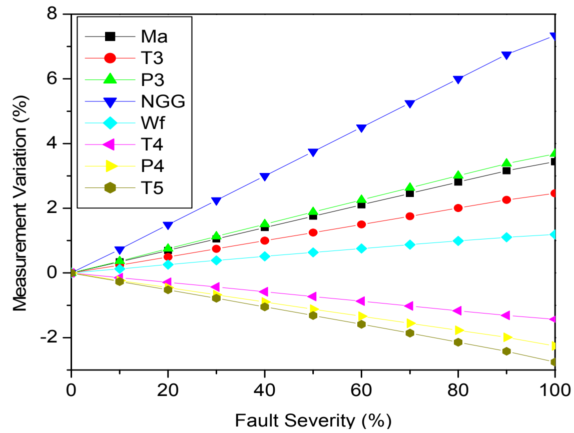

Figure-4. Engine measurement variations vs PTE severity (%).

Case 2: Double components degradation

In this case, the impacts of two component faults implanted at the same time has been evaluated. For this purpose, concurrent fault patterns, i.e., CF and GGTE, CF and PTE, and GGTE and PTE are considered. Figure-(5-7) show the impacts of these faults on measurements' variations. In the case of CF+GGTE all the parameters except P3 and Ma changes significantly. On the other hand, the effect of CF+PTE on NGG and Ma is negligible. When GGT+PTE exists all the measurements change significantly. In general, the influence of dual faults on measurements is not similar.

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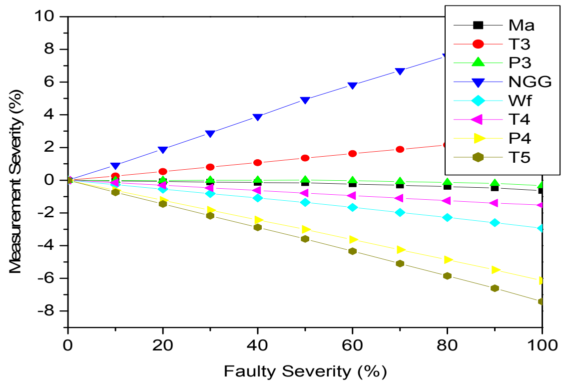

Figure-5. Engine measurement variations vs CF and GGTE exist simultaneously (%).

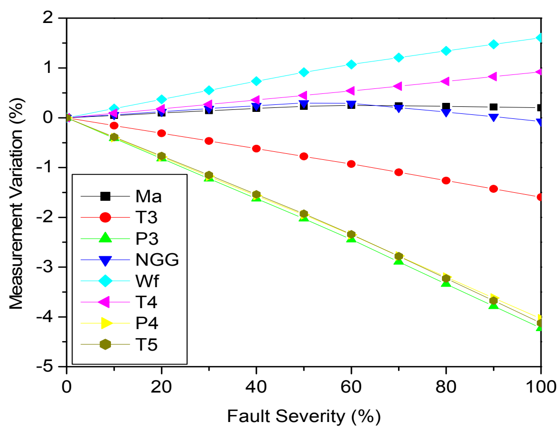

Figure-6. Engine measurement variations vs CF and PTE exist simultaneously (%).

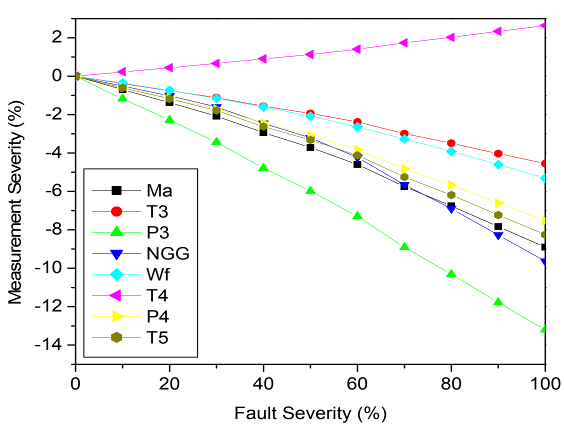

Figure-7. Engine measurement variations vs GGTE and PTE exist simultaneously (%).

Case 3: Three components degradation

In this case, the effects of simultaneous triple component faults namely CF, GGTE and PTE on the engine measurement have been evaluated (see Figure-8). It is found that EGT, CDP, and PT inlet pressure are the first three key parameters in triple fault diagnosis. On the other hand, the gas turbine simulation for three components degradation effects on NGG and PT inlet pressure showed negligible deviation.

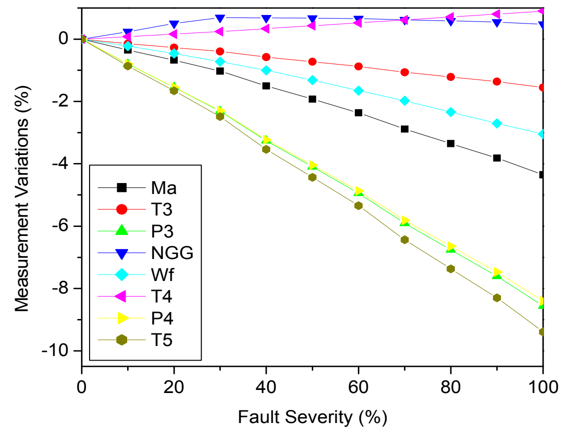

Figure-8. Engine measurement variations vs CF, GGTE, and PTE exist simultaneously (%).

Comparison between the effects of component faults on measurements

This section aims to compare the responses of engine measurements on component degradations, which exist(s) one at a time or concurrently. For this purpose, the engine model is simulated at maximum severity of all fault types considered in this work. Figure-9 illustrates the measurement responses to each fault types. The measurement variations due to double and triple component faults are the sum of the deltas due to the faults when they exist separately. For example, Ma decreased by 4.14% and 4.5% owing to CF and GGTE, respectively, and increased by 3.44% due to PTE. Consequently, when double faults such as CF & GGTE and CF & PTE occur at the same time, the Ma reduced by 8.54% and increased by 0.7%, respectively. In the same manner, when all the three faults occur simultaneously, the Ma decreased by about 4.5%. This works for all of the measurement variations. Thus, it can be concluded that, as also proved by Zwebek [10], the combined effects are additive. Moreover, during compressor fouling Ma, CDP, Wf, PT inlet pressure and EGT showed similar variation (about 4%) whereas CDT and PT inlet temperature changed insignificantly.

The percentage change in P3 and NGG due to GGTE reached 10% and 9%, respectively, which is two times of Ma and T3 changes. P4, T4, and EGT changed by 3%. On the other hand, the GGTE has the least effect on

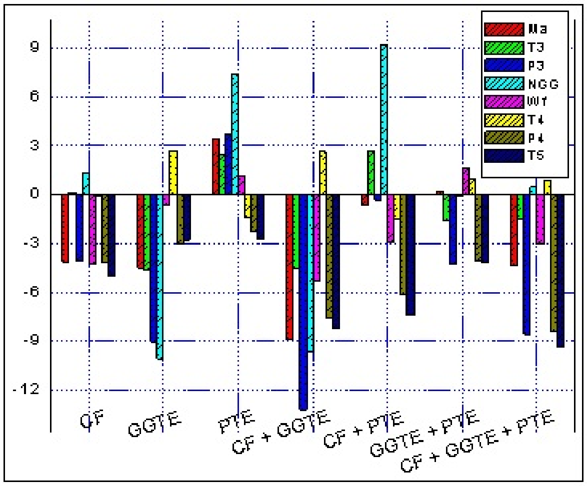

Figure-9. Gas turbine measurement variations vs single double and triple component faults at 100% severity.

Wf. Likewise, the highest effect has been shown on NGG (i.e. 7%). Air mass flow rate and CDP changed by 3.5%, CDT, PT inlet presser shows similar variation more than 2%. The remaining two parameters, fuel mass flow rate and PT inlet temperature changes by 1%.

For more clarity, the comparative evaluation of the parameters' sensitivity order is given in Table-4. For the most part, the EGT and P3 responds were similar. P3 showed an insignificant change only under the CF & PTE. Moreover, NGG was very sensitive to single and double faults than triple faults. Under all the fault cases T4 slightly changed at high severity. Furthermore, the sensitivity of Wf was good in multiple faults than single faults. In general, NGG, CDP, EGT, mass flow rate and P4 are the key parameters for all fault types.

Table-4. Order of sensitivity of measurement variations to performance deterioration.

	CF	GGTE	PTE	CF+GGTE	CF+PTE	GGTE+PTE	CF+GGTE+PTE
Decreasing sensitivity ↓	T5	NGG	NGG	P3	NGG	P3	T5
	Wf	P3	P3	NGG	T5	T5	P3
	P4	T3	Ma	Ma	P4	P4	P4
	Ma	Ma	T5	T5	Wf	Wf	Ma
	P3	P4	T3	P4	T3	T3	Wf
	NGG	T5	P4	Wf	T4	T4	T3
	T3	T4	T4	T3	Ma	Ma	T4
	T4	Wf	Wf	T4	P3	NGG	NGG

CONCLUSIONS

In this paper, a gas turbine simulation program (GSP) is utilized to model and simulate a two-shaft stationary gas turbine engine (LM2500) in order to evaluate the effect of performance deterioration on gas path measurements. The effects of the most common gas turbine faults namely, compressor fouling and turbine erosion on engine measurements such as Ma, CDP, CDT, NGG, Wf, PT inlet pressure and temperature and EGT are investigated. For this purpose, CF, GGTE and PTE as a single component faults, CF & GGTE, CF & PTE and GGTE & PTE as double component faults, and CF, GGTE and PTE as triple component faults are considered. In general, in most of the cases, Ma, CDP, CDT, NGG, PT inlet pressure, and EGT showed significant deviation. Particularly, the EGT and CDP are highly influenced by all the fault cases.

On the other hand, Wf and NGG showed less sensitivity to single faults and triple faults, respectively. P3 showed an insignificant change only under the CF & PTE. Moreover, when two or more components degrade together, some of the measurements change insignificantly due to the additive nature of the faults' effects.

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