

PERFORMANCE ANALYSIS OF A TWIN-SHAFT GAS TURBINE WITH FAULT IN THE VARIABLE STATOR GUIDE VANE SYSTEM OF THE AXIAL COMPRESSOR

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ABSTRACT

In this study, an analysis of the performance of a twin-shaft industrial gas turbine (IGT) with a fault in the mechanism of the compressor that changes the position of variable stator guide vanes (VSGVs) is carried out. Measured field data of a twin-shaft engine denoting a difference (offset) between the demanded inlet guide vane (IGV) angle and the measured IGV angle in the axial compressor have been considered for the analysis. A validated Simulink model which simulates the performance of the twin-shaft engine has been considered for the analysis of the fault in the VSGV system. The Simulink model architecture comprises an axial compressor module and considers a multi-stage compressor performance map at optimal conditions (new & clean). The results demonstrate that it is possible to predict the physical parameters such as pressure and temperature measured across the different stations of the engine during the offset of the IGV angle. The effect of the IGV offset on the compressor performance is discussed as well. The change in compressor air flow and compressor efficiency at different IGV offset is discussed, as during a low power engine operation and fault within the VSGV system, the surge line may drift close to the compressor running operation line.

INTRODUCTION

Industrial gas turbines (IGTs) are widely-used to generate electricity or drive rotating machinery such as pumps and process compressors. Multi-stage axial compressors are commonly used in IGTs and consist of a series of number of stages. Each stage comprises a row of rotor blades followed by a row of stator blades. The kinetic

energy of air is increased by the rotor blades and the stator blades transform the kinetic energy of air into static pressure. A variation of stator vane angles across the different stages of an axial compressor ensures correct air diffusion and satisfactory and safe operation of the compressor, particularly at low speeds, “Razak (2007)”. Fig. 1 shows a simplified mechanism to change the angle of the variable stator guide vanes (VSGVs) using a single actuator. At high engine operation speed, it is required to open the VSGVs to allow high air diffusion through the stages and avoid a compressor stall condition at the back stages in the multi-stage axial compressor.

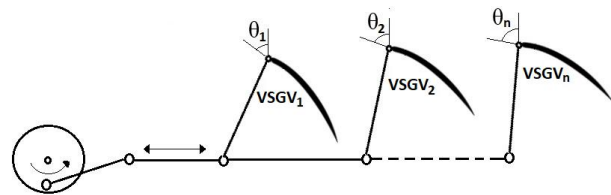


Figure 1. VSGV mechanism in axial compressor

A fault in the VSGV mechanism will change the IGV angle and will also change the VSGV angles across the stages of the axial compressor. “Song et al. (2000)” developed a numerical method to analyze the performance of a multi-stage axial compressor. The method considered the variation of the IGV and VSGV in the compressor performance. The results showed that the closure of vane angles yields a reduction in air flow and pressure ratio. “Muir et al. (1989)” developed a stage-stacking method to estimate the variable geometry effects across the different stages of an axial compressor. The results showed that by increasing in one degree the variable geometry position (closure of VSGV) there is 3 percent reduction in air flow,

4 percent reduction in fuel flow and a power loss of 5 percent. Failures in the VSGV system of a multi-stage axial compressor of an IGT were investigated by “Tsalavoutas et al. (2000)”. The results showed that VSGV faults decrease the engine load and fuel flow for a given controller setpoint. In addition, VSGV faults of the first stages have a greater impact on engine performance. In this study, the performance of a twin-shaft IGT during fault in the VSGV mechanism is studied using a IGT model constructed in Simulink environment “Simulink Release (2015a)”. The Simulink model comprises thermodynamic equations to predict physical parameters such as temperature, pressure, and flow across the different stations of the IGT. Measured field data from a twin-shaft IGT during fault in the VSGV mechanism are considered. The VSGV fault is identified through the difference (offset) between the IGV position demand and the IGV position feedback during engine operation. The Simulink model can predict the measured data such as pressure and temperature at different engine stations and can predict parameters such as compressor discharge air flow and compressor efficiency which are not available in the measured field data. The effect of IGV offset on compressor air flow and compressor efficiency is also discussed.

GAS TURBINE MEASUREMENTS

Measured field data from a twin-shaft IGT denoting fault in the mechanism that changes the position or angle of the VSGV have been considered for the analysis. The demanded IGV angle for air entering the compressor has been scheduled against gas generator speed (GGS). A decrease in the demanded IGV position (degrees) with increasing GGS is related to an opening of the VSGVs to allow high air diffusion through the compressor stages. An increase in the demanded IGV angular position with decreasing GGS is related to a closure of the VSGVs to restrict air flow through the compressor. In the study reported by “Muir et al. (1989)” the angular position of the actuating lever moving the variable vanes on a pipeline compressor unit is scheduled as a function of corrected compressor speed. When the compressor speed is reduced, the stagger of the variable angles is increased to reduce the amount of air flow and avoid unstable compressor performance. The VSGVs can also protect the compressor from surges especially at low power engine operation “Razak (2007)”. The twin-shaft IGT was operated as a power generator at low power operating condition. The fault in the VSGV mechanism was identified by the difference (offset) between the demanded (set-point) IGV position and the feedback measurement of the real IGV position. Fig. 2 shows the measured generated power at low IGV offset ($-0.6 < \text{offset} < 0.6$ degrees). The measured power has been normalized with respect to the maximum achievable generated power during engine operation.

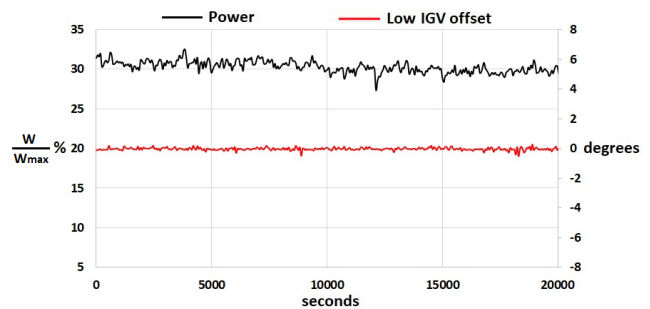


Figure 2. Measured power and at low IGV offset

The small value of the IGV offset, ($-0.6 < \text{offset} < 0.6$ degrees), shown in Fig. 2 can be attributed to noise during the data acquisition; therefore, no fault in the VSGV mechanism is expected. Figure 3 shows an increase in the value of IGV offset ($-6.4 < \text{offset} < 4.1$ degrees) during engine operation. The increase in the value of the IGV offset can be related to a fault in the VSGV mechanism which differs from nominal schedule.

A negative offset (measured IGV angle is higher than set-point IGV angle) is related to a closure of the VSGVs. The positive IGV offset is related to an opening of the VSGVs. The measured data also comprise physical parameters such as pressure and temperature across the different stages of the twin-shaft IGT. The compressor discharge flow and compressor efficiency are not available in the measured data.

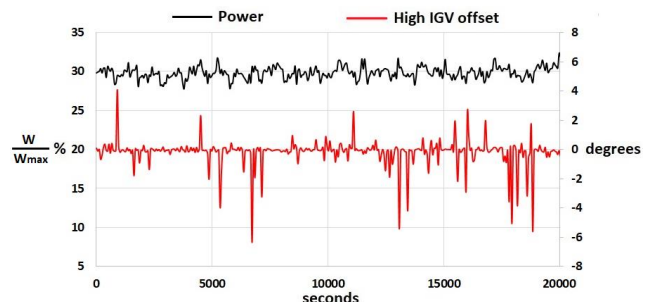


Figure 3. Measured power and at high IGV offset

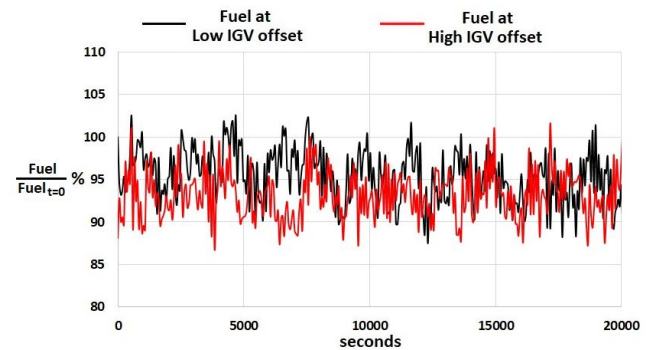


Figure 4. Fuel demand for low and high IGV

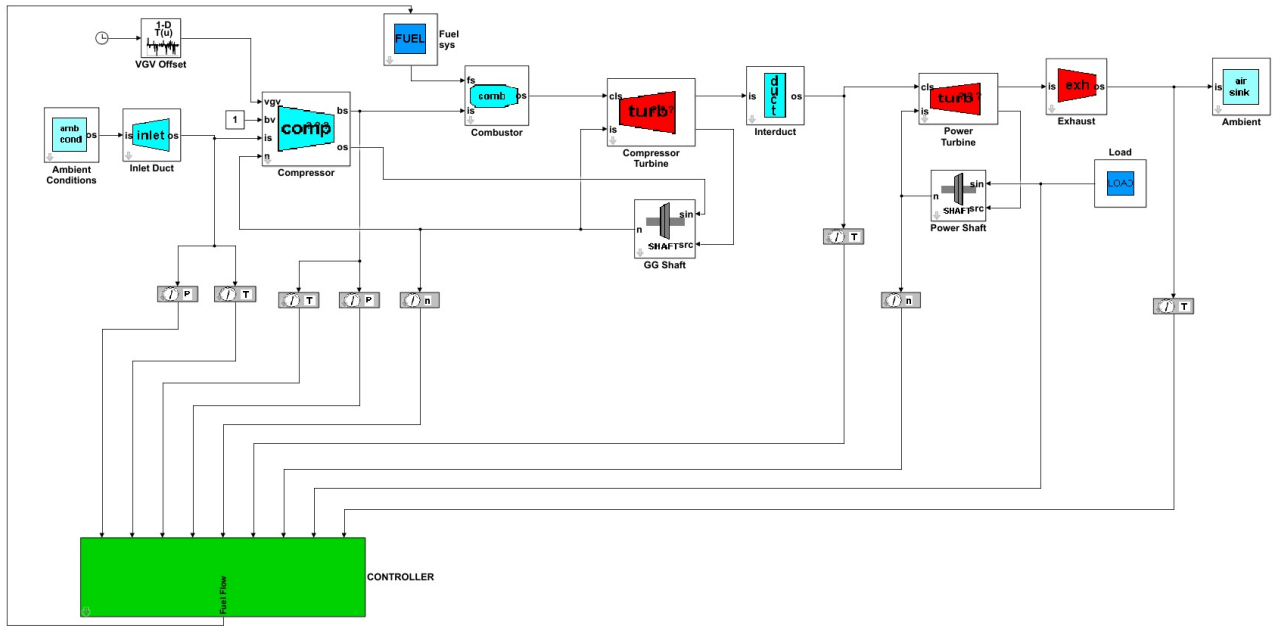


Figure 5. Simulink model architecture, Panov (2009), for IGV offset analysis

The measured generated power slightly reduces more for the high IGV offset condition compared to the case with low IGV offset. The effect of IGV offset on IGT performance could be more noticeable on the fuel demand. The required fuel demand for the generation of power is regulated through a controller that receives as inputs the measured temperature, pressure and speed signals from the sensors located across the IGT system. Fig. 4 shows the measured fuel demand during low and high IGV offset conditions. The fuel demand has been normalized with respect to the data at low IGV offset condition and at $t=0$. The measured fuel demand slightly decreases during high IGV offset conditions. The reduction in fuel demand can be attributed to reduction in air discharged by the compressor during the closure of the VSGVs, “Muir et al. (1989)”, as the negative IGV offset (closure) dominates more over the positive IGV offset (opening) as shown in Fig. 3.

GAS TURBINE SIMULINK MODEL

A validated thermodynamic model of a twin-shaft IGT constructed in Simulink environment “Panov (2009), Cruz-Manzo (2018)” has been considered for the analysis of the IGV offset as shown in Fig. 5. The Simulink model considers thermodynamic and differential equations to predict the temperature and pressure across the different stations of the IGT. The twin-shaft IGT Simulink model is comprised of two main groups named as gas generator group and power turbine group as shown in Fig. 6.

Gas generator group comprises the compressor, combustor and gas generator turbine (GGT). The power turbine group comprises the inter-duct connecting the GGT and power turbine, and the load.

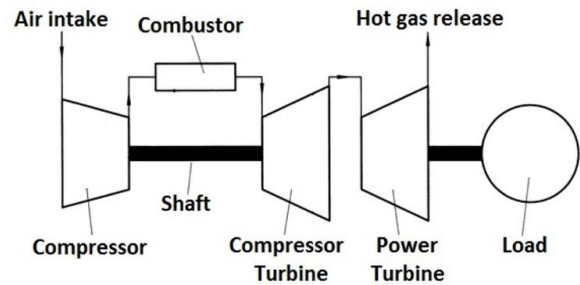


Figure 6. Twin-shaft industrial gas turbine

A mechanical shaft bearing system, connecting the compressor with the GGT and connecting the power turbine with the driven load, has been considered in the Simulink model as well. Each component of the IGT model comprises performance maps at optimal conditions (new & clean). The Simulink model requires as inputs the ambient temperature and the load for different operating conditions. A controller regulates the amount of fuel supplied to the combustor based on the engine load and the temperature, pressure and speed measured across the twin-shaft IGT. The IGV position which is scheduled against actual and corrected GGS is considered as an input in the Simulink model as well. The profile of IGV offset shown in Figs. 2 and 3 is implemented into the compressor module using a 0-D map from Simulink environment, as shown in Fig. 5. In addition, the compressor module considers correction maps to increase or reduce the flow and efficiency when an offset from nominal schedule in the IGV angle is present.

VALIDATION

A comparison between measured data from the IGT and simulated data from the Simulink model is carried out.

The measured data are recorded by sensors located across the different stations of the engine. The IGV offset shown in Figs. 2 and 3 is implemented into the compressor module from the overall Simulink model architecture. The measured load shown in Figs. 2 and 3 was considered as an input as well. Two conditions are considered for the validation: low IGV offset condition attributed to noise during the data acquisition, as shown in Fig. 2; high IGV offset condition attributed to the faulty VSGV mechanism, as shown in Fig. 3. The measured temperature and pressure discharged by the compressor as well as the measured temperature discharged by the power turbine are considered for the validation. The measured and simulated data are normalized with respect to the measured data at $t=0$ with Celsius degree for temperature and Bar absolute for pressure.

Low IGV Offset

Figure 7 shows the comparison between measured and simulated compressor discharge temperature at low IGV offset condition.

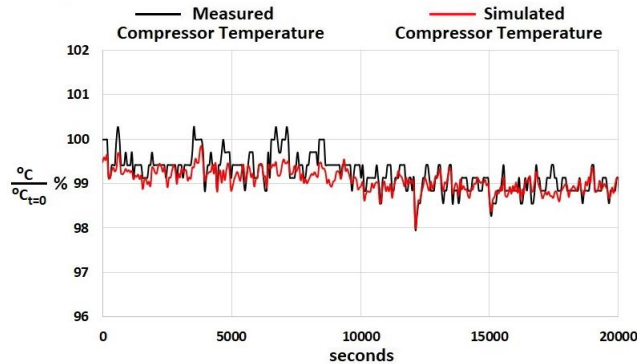


Figure 7. Comparison between measured and simulated compressor discharge temperature at low IGV offset

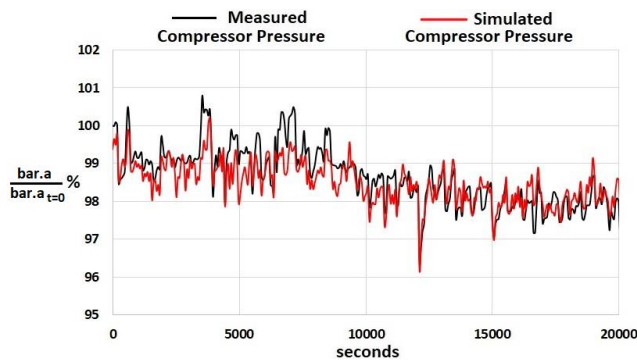


Figure 8. Comparison between measured and simulated compressor discharge pressure at low IGV offset

The comparison between measured and simulated compressor discharge pressure at low IGV offset condition is shown in Fig. 8.

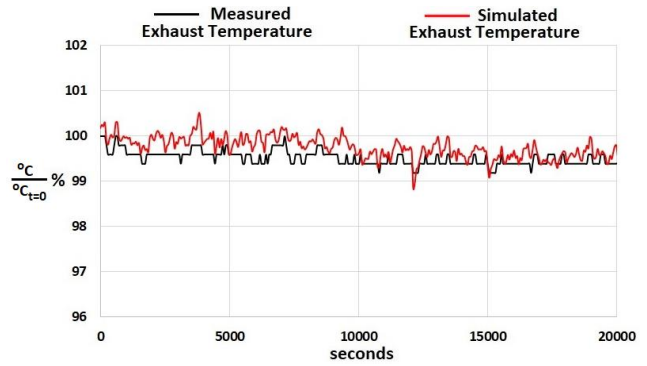


Figure 9. Comparison between measured and simulated power turbine exhaust temperature at low IGV offset.

The Simulink model can predict the measured temperature and pressure discharged by the compressor at low IGV offset conditions as shown in Figs. 7 and 8. Fig. 9 shows the comparison between measured and simulated temperature discharged by the power turbine at low IGV offset condition. The model can predict the measured exhaust temperature discharged by the power turbine.

High IGV Offset

Fig. 10 shows the comparison between measured and simulated compressor discharge temperature at high IGV offset condition.

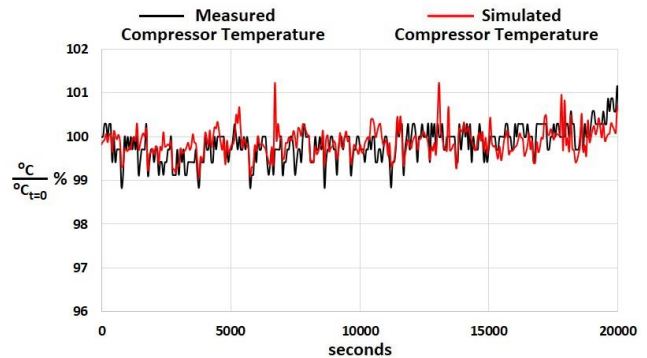


Figure 10. Comparison between measured and simulated compressor discharge temperature at high IGV offset.

The comparison between measured and simulated compressor discharge pressure at high IGV offset condition is shown in Fig. 11. It can be observed that the magnitude of the oscillations in the measured and simulated pressure increases with increasing IGV offset, as shown in Figs. 8 and 11 respectively. The comparison between measured and simulated exhaust temperature at high IGV offset conditions is shown in Fig. 12. The increase in the simulated exhaust temperature 101.4 % at $t=6700$ and at $t=13000$ seconds is attributed to a negative IGV offset (real IGV angle is 6 degrees higher than demanded IGV angle). A negative IGV offset value is related to a closure of VSGVs which restricts the air flow through the compressor. The increase in simulated exhaust temperature for negative IGV offset shown in Fig. 12 could be attributed to this air flow reduction.

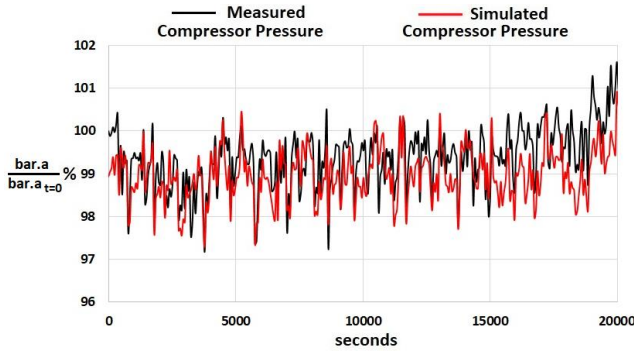


Figure 11. Comparison between measured and simulated compressor discharge pressure at high IGV offset.

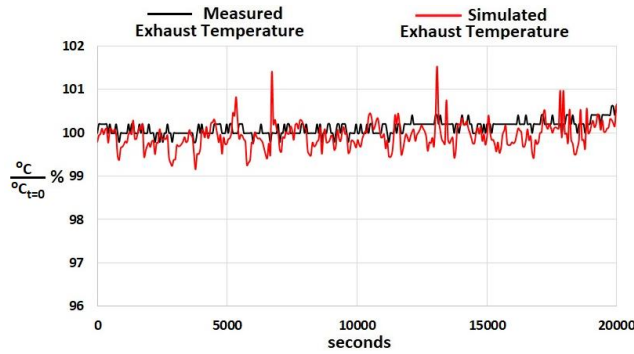


Figure 12. Comparison between measured and simulated compressor exhaust temperature at high IGV offset.

ANALYSIS OF RESULTS

The air flow discharged by the compressor and compressor efficiency are not available in the measured data. The IGT Simulink model can predict the effect of IGV offset on compressor performance. The compressor module from the Simulink IGT architecture can predict the compressor flow and compressor efficiency at different operating conditions.

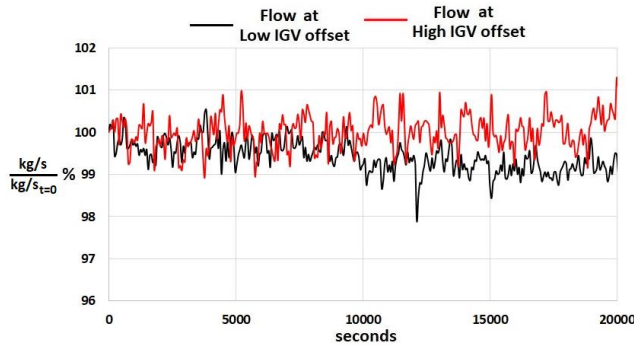


Figure 13. Simulated flow discharged by compressor at low and high IGV offset conditions.

Figure 13 shows the predicted air flow discharged by the compressor at low and high IGV offset conditions. The simulated data have been normalized with respect to the simulated data at $t=0$. There is a difference between the simulated compressor flow at low and high IGV offset

conditions, and the difference is more noticeable after $t=10000$ seconds as shown in Fig. 13. This difference can be attributed to a change in operating condition (load reduction) which could be independent from the IGV offset. This can be corroborated through the difference in measured load for $t>10000$ seconds shown in Figs. 2 and 3 for low and high IGV conditions respectively. Figure 14 shows the compressor efficiency predicted by the Simulink model at low and high IGV offset conditions. There is a difference in compressor efficiency for $t>10000$ seconds at low and high IGV offset. As previously discussed in the compressor flow results shown in Fig. 13, this difference can be associated to a change in load condition.

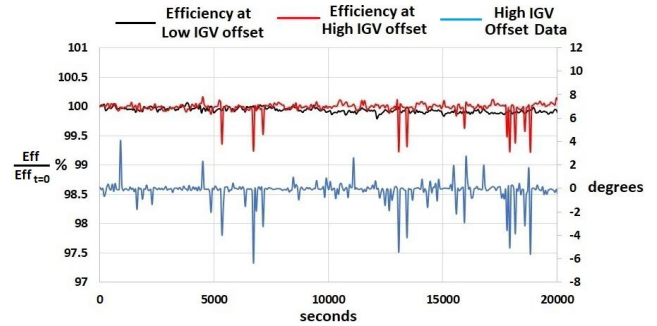


Figure 14. Simulated compressor efficiency at low and high IGV offset conditions

In addition, it can be observed that there is a reduction in efficiency when the IGV offset is negative. A negative IGV offset is regarded as a closure of the VSGVs as the measured IGV angle is higher than the demanded IGV angle. Excessive closure of the VSGVs will result in reduction in compressor performance as if it is fouled “Razak (2007)”; hence the reduction in compressor efficiency as shown in Fig. 14. “Song et al. (2000)” developed a multi-stage axial compressor model and demonstrated a reduction in compressor performance with increasing IGV angle (closure of VSGVs).

Four IGV offset values from Fig. 3 have been considered to compare measured and simulated data. The considered positive IGV offset values are 4.1 degrees at 900 seconds and 2.3 degrees at 4500 seconds. The considered negative IGV offset values are -3.98 degrees at 5340 seconds and -6.4 degrees at 6720 seconds. The error between measured and simulated GGS, compressor discharge temperature (CDT), compressor discharge pressure (CDP), and exhaust temperature (ET) is estimated as shown in Table I. The error between measured and simulated data increased when the IGV offset becomes more negative. A negative value of the IGV offset is related to a closure of the VSGVs limiting the air flow through the compressor.

IGV Offset	% GGS	% CDT	% CDP	% ET
4.1	0.298	0.299	0.663	0.351
2.3	0.079	0.342	0.052	0.102
-3.98	0.700	0.673	0.527	0.816
-6.4	0.739	1.506	0.322	1.387

Table I. Error between measured and simulated data for different IGV offset values.

DISCUSSION

The effect of IGV offset on compressor performance is shown in Figs. 13 and 14. For this operating condition 30% of the maximum achievable generated power, the IGV offset has a more overriding effect on the compressor efficiency than the flow. But this could be invalid at lower GGS and at lower load demand. From Fig. 14 it can be demonstrated that a negative IGV offset (closure of VSGVs) reduces the compressor efficiency. The IGV offset could impact the diffusion of air passing through the different stages in the axial compressor. At low power engine operation, the IGV offset could lead to compressor instability during transient excursions as the running line may get closer to the surge limit. In future work, the effect of IGV offset on the dynamic compressor performance will be analyzed through a validated multi-stage axial compressor model. This can also be important for studying the change of IGV position at different compressor operating conditions.

CONCLUSIONS

In this study, the performance of a twin-shaft IGT during fault in the VSGV mechanism has been analyzed through a Simulink model. Measurements such as temperature, pressure, and speed across a twin-shaft IGT were considered to validate this study. The fault in the VSGV mechanism from measured data was identified by the difference (offset) between the IGV position demand and feedback measurement of the real IGV position during engine operation. The Simulink model can predict the compressor discharge temperature and pressure and exhaust temperature for different IGV offsets. The effect of IGV offset on compressor performance revealed that during closure of the VSGVs (negative offset) at part load conditions, an overriding effect on the compressor efficiency than the flow is present.

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