Inlet Guide Vane Tracking Effectiveness at Various Compressor Efficiency of Gas Turbine

O Purba1, F Zhultriza1

1 Mechanical Maintenance Division, PT. Pembangkitan Jawa Bali UP Muara Karang, North Jakarta, Indonesia

Abstract. The baseload operating patterns in Java-Bali’s system are imposed on coal-fired power plants, the combined cycle power plant (CCPP) is used as a spinning reserve so that the CCPP operates with a small load factor (partial load) to support system reliability. This operation results in a high plant heat rate for the CCPP since it operates more often at minimum loads. To improve the heat rate of CCPP at partial load, inlet guide vane tracking (IGVT) is performed. IGVT alters the opening position of inlet guide vane (IGV) in the partial load operation. The effect of IGVT application in CCPP is analysed with several operating parameters, such as fuel usage, turbine exhaust temperature (TET), the total load generated by the CCPP, and the total of net plant heat rate (NPHR) after IGVT application. The variation on IGV leads TET to increase. A higher TET affects the heat recovery steam generator (HRSG) and causes the load generated by the steam turbine to become larger compared to the load before performing IGVT application. The results show that the combined cycle heat rate drops to 24 kCal/kWh and thus improving the efficiency of the CCPP, up to 1.5% in partial load operation model.

1. Introduction
The demand of electricity is gradually increasing each year. In Indonesia, to reach electricity demand economically, coal-fired power plant becomes the majority source of power. Gas-fired power plants have lower level of pollutant emissions and higher efficiency than coal-fired power plant [1]. However, gas-fired power plant, especially in Combined Cycle Power Plant (CCPP), usually operates with partial load as a support for system reliability. Part-load performance of the CCPP system was analysed to enhance the efficiency of Gas Turbine and to in line with the demand of environmentally friendly and efficient power structure [2].

In Indonesia, Muara Karang CCPP Block 2 has two gas turbines with a capacity of 250MW for each one and three units of 70MW steam. The gas turbine operating pattern relies on the system demand. Due to the operating pattern of Java-Bali system that puts gas turbine plant as a spinning reserve, Muara Karang CCPP block 2 operates in partial load often. Regarding the pattern shown in figure 1 below, it can be observed that that maximum load occurs for 25 percent of the whole operating time, in other words, the gas turbine mostly operates at partial load. To bear peak-shaving tasks frequently, gas turbine should improve its operating efficiency at part-load conditions [3]. Setting the proper position of Inlet Guide Vane (IGV) can maintain the peak efficiency of the system.
The IGV change geometry to adjust the air flow from the compressor and affect the gas turbine dynamics, especially the exhaust temperature, so, the IGV system is critical to keep the function and efficiency of the gas turbine [4]. Optimal IGV state during changes in environmental temperature were studied to optimize power generation and IGV position in part-load performance [5]. More scholars proposed a novel configuration of inlet air heating with constant Turbine Inlet Temperature (TIT) and Turbine Exhaust Temperature (TET) based IGV control to optimize operation strategic of partial load gas turbine [6]. In this paper, to overcome low efficiency at minimum and partial loads, IGV Tracking (IGVT) is applied at minimum and partial loads to improve the efficiency of the system related to quantity of air entering the compressor and fuel consumption. The objective of this study is to evaluate the direct effect of IGVT to raise the efficiency of CCPP.

2. Methodology

2.1. Inlet Guide Vane Tracking (IGVT)

The Inlet Guide Vane (IGV) is located in the compressor inlet of the gas turbine. The IGV varies opening angle to regulate how much air entering the compressor. The air flow rate is increasing when the IGV opens that the engine throttle level is moved to maximum position and it is called acceleration. Otherwise, the IGV in closed position and the air flow rate becomes minimum when the engine throttle level is declined from maximum position to idle position or called deceleration [7]. IGV opening is governed by a lever mechanism that is operated by an actuator [8]. The opening angle of IGV is noted as $\gamma$. Typically, the minimum angle of IGV to open in gas turbine is 23% while the maximum is 100%. In the variation of fuel flow, the opening angle of IGV is varied to obtain the optimum operating point. It also applies for the certain flow rate of air that entering compressor, while the fuel flow is varied to obtain the optimum operating area. The optimum opening of IGV is visualized in Figure 2 as follows.

![Figure 2. The IGV opening angle illustration, (a) Minimum open, (b) Partial open, (c) Maximum open, (d) Minimum open, (e) Maximum open, (f) IGV location at inlet compressor](image-url)
The opening angle values of IGV in a clean existing compressor and in the implemented IGVT compressor are shown in Table 1. The curves of these values are shown in Figure 3. By compare a constant value of air flow and fuel flow, the performance of combined cycle power plant can be evaluated using this method.

Table 1. IGV angle position before and after IGVT

| GT Load (MW) | IGV Position (%) | GT Load (MW) | IGV Position (%) |
|--------------|------------------|--------------|------------------|
| 0            | 23%              | 0            | 23%              |
| 111.7        | 23%              | 110          | 23%              |
| 120          | 25%              | 120          | 23%              |
| 130.3        | 28%              | 130.3        | 23%              |
| 136.3        | 30%              | 136.4        | 23%              |
| 152.4        | 39%              | 152.5        | 31%              |
| 170          | 50%              | 170.1        | 41%              |
| 180          | 57%              | 180          | 49%              |
| 190          | 67%              | 190          | 59%              |
| 200          | 81%              | 200          | 70%              |
| 210          | 96%              | 210          | 83%              |
| 213          | 100%             | 213          | 88%              |
| 220          | 100%             | 220          | 100%             |
| 235          | 100%             | 235          | 100%             |

Figure 3. IGV position curve before and after IGVT

2.2. IGV Tracking Method

In this study, the IGV Tracking was performed by analyze the performance of the CCPP in constant air flow and fuel flow variation until the determination of the optimum operating point. Conversely, the variation of air flow and a constant fuel flow are also analyzed and get the optimum operating point. Then, all the optimum points in these variations plotted in the IGV curve and set as the new opening IGV points.
2.3. Governing Equation in Combined Cycle
As observed in Figure 4, the CCPP typically has certain components, such as, gas turbine, steam turbine, Heat Recovery Steam generator, and compressor of the gas turbine. The equation for these components as follows [9] [10]:

![Schematic diagram of combined cycle power plant](image)

Figure 4. Schematic diagram of combined cycle power plant

a. Compressor
The work of a compressor:

\[
W_C = \frac{C_{pa} \times T_1 \left( \frac{P_2}{P_1} \right)^{\frac{\gamma a - 1}{\gamma a}} - 1}{\eta C}
\]

\[C_{pa} = 1.0189 \times 10^3 - 0.1378 T_a + 1.984 \times 10^{-4} T_a^2 + 4.2399 \times 10^{-7} T_a^3 - 3.7632 \times 10^{-10} T_a^4 (2)\]

\[T_a = \frac{T_2 - T_1}{2} (K)\] (3)

b. Combustion Chamber
\[m_a C_{pa} T_2 + m_f LHV + m_f C_p f T_f = (m_a + m_f) C_p g T_3\] (4)

with
\[C_p g = 1.8083 - 2.3127 \times 10^{-3} T + 4.045 \times 10^{-6} T^2 - 1.7363 \times 10^{-9} T^3\] (5)

Fuel-to-air ratio can be defined as follows:
\[FA = \frac{m_f}{m_a} = \frac{C_{pg} T_3 - C_{pg} T_2}{LHV - C_{pg} T_3 + m_f C_p f T_f}\] (6)

c. Gas Turbine
\[W_T = m_g \cdot C_{pg} \cdot (T_3 - T_4)\] (7)

d. Heat Recovery Steam Generator (HRSG)
\[m_w (h_8 - h_7) = m_g C_{pg} (T_5 - T_6)\] (8)

e. Steam Turbine
\[m_w (h_8 - h_4) = W_{ST}\] (9)

f. Heat rate Calculation
\[Heat rate = \frac{HHV \times m_{fuel}}{P_{Out} \times 1000}\] (10)

\[T = \text{Temperature (K)}\]
\[W_T = \text{Gas turbine power output (MW)}\]
\[ \dot{m} = \text{Mass flow rate} \quad \left( \frac{\text{kg}}{s} \right) \]

\[ P_{\text{Out}} = \text{Power Output} \quad (\text{MW}) \]

\[ C_p = \text{Specific heat capacity in a constant volume} \quad \left( \frac{\text{kJ}}{\text{kgK}} \right) \]

\[ h = \text{Enthalpy rate} \quad \left( \frac{\text{kJ}}{\text{kg}} \right) \]

\[ LHV = \text{Lower heating value of fuel} \quad \left( \frac{\text{kJ}}{\text{kg}} \right) \]

\[ HHV = \text{Higher heating value of fuel} \quad \left( \frac{\text{kJ}}{\text{kg}} \right) \]

3. Results and Discussion

3.1 Analysis of constant air usage

The constant air usage and fuel flow variation formed a new curve of optimum values based on AF values after IGVT was performed and also was shown in Table 5. Figure 5 shows the variation of fuel flow and IGV opening generates the variation of Gas Turbine output power, black line shows the higher limit position of AF and red line shows the lower limit of AF.

Table 2. Data of IGV opening variation at certain airflows

| AF      | GT Load (MW) | AF      | GT Load (MW) | AF      | GT Load (MW) | AF      | GT Load (MW) |
|---------|--------------|---------|--------------|---------|--------------|---------|--------------|
| 42.8092 | 137.8        | 42.37081| 142.8109     | 42.15915| 150.3        | 42.19831| 162.826      |
| 43.02313| 138.7        | 42.51121| 143.2659     | 42.3896 | 150.1        | 42.34912| 162.9218     |
| 43.23705| 139.3        | 42.65161| 143.6622     | 42.82004| 149.9        | 42.4984 | 162.9483     |
| 43.43098| 139.8        | 42.79201| 143.9996     | 42.83049| 149.6        | 42.64769| 162.9507     |
| 43.6649 | 140.0        | 42.93241| 144.2786     | 43.08094| 149.2        | 42.79697| 162.7938     |
| 43.87882| 140.1        | 43.07282| 144.4988     | 43.31138| 148.8        | 42.94626| 162.6128     |
| 44.09275| 139.9        | 43.21322| 144.6602     | 43.54183| 148.3        | 43.09554| 162.3626     |
| 44.30667| 139.4        | 43.35362| 144.7629     | 43.77228| 147.8        | 43.24483| 162.0432     |
| 44.5206 | 138.8        | 43.49402| 144.8089     | 44.00272| 147.2        | 43.39411| 161.0347     |
| 44.73452| 138.0        | 43.63442| 144.7921     | 44.23317| 146.6        | 43.53434| 161.1969     |
| 44.94845| 137.0        | 43.77482| 144.7196     | 44.46362| 145.9        | 43.69268| 160.67       |
| 45.16237| 135.8        | 43.91522| 144.5864     | 44.69406| 145.1        | 43.81197| 160.0739     |
| 45.37629| 134.5        | 44.05562| 144.3935     | 44.92451| 144.3        | 43.99125| 159.4086     |
| 45.59022| 133.1        | 44.19603| 144.1459     | 45.13496| 143.5        | 44.14034| 158.6741     |
| 45.80414| 131.6        | 44.33643| 143.8375     | 45.3854 | 142.6        | 44.28982| 157.8704     |
| 46.01807| 130.1        | 44.47683| 143.4705     | 45.61585| 141.6        | 44.43911| 156.9975     |
| 46.23199| 128.5        | 44.61723| 143.0447     | 45.8463 | 140.6        | 44.58383| 156.0555     |

In figure 5, \( m_{a1} \) indicates a specific IGV position with stable air flow. If the fuel flow increases continuously, the output load power will also increase until reaching the maximum then drop as shown in figure 6. In a more detailed visualization of air flow, \( m_{a1} \), can be seen in figure 6.
Figure 5. Comparison of GT load with AFR at Certain Fuel Flows

Figure 6. (a) Graph of load variation at $m_{a1} = 450 \text{ kg/s}$ (Minimum Opening IGV, 23 %), (b) Variation of AFR towards GT load at certain air flow

The fuel variation characteristic with certain air flow ($m_{a1} = 450 \text{ kg/s}$), maximum load at AF 43.7 can be analysed, as shown in figure 6. If fuel is added more or AF is lesser, load of gas turbine will gradually be decreasing. Thus, $m_{a1}$ with AFR 43.7 as shown in figure 6a will be the optimum point. Moreover, the fuel usage at air $m_{a1} = 450 \text{ kg/s}$ is regulated to get 43.7 AFR or amounting to 10.2 kg/s.

3.2 Analysis of constant fuel flow

As a comparison, the variation of air flow in a specific fuel consumption are also observed as shown in Figure 7. Figure 8 below shows the details of this research. In a constant fuel flow of 10.6 kg/s, the air flow is varied so that the optimum load of gas turbine is obtained at 150MW. This value becomes the new IGV opening points or optimum operating points. These optimum operating points are compared with every constant fuel flow to produce the curve of IGV opening position after IGVT implementation as shown in Figure 7. If Table 3 is plotted to a graph, we can see it in Figure 7. Furthermore, a detailed analysis of $m_{f3}$ yields the following graphs:
Table 3. Variation of IGV opening with certain air flow towards GT load

| Air flow (kg/s) | GT Load (MW) | Air flow (kg/s) | GT Load (MW) | Air flow (kg/s) | GT Load (MW) | Air flow (kg/s) | GT Load (MW) | Air flow (kg/s) | GT Load (MW) |
|----------------|--------------|----------------|--------------|----------------|--------------|----------------|--------------|----------------|--------------|
| 455.00         | 129.06       | 460.00         | 139.78       | 470.00         | 149.83       | 477.00         | 159.83       | 480.00         | 159.33       |
| 456.55         | 129.97       | 462.37         | 139.90       | 472.59         | 149.94       | 480.38         | 159.80       | 483.10         | 159.70       |
| 457.07         | 129.46       | 462.76         | 139.94       | 473.45         | 149.97       | 480.17         | 159.91       | 484.14         | 159.81       |
| 457.59         | 129.54       | 463.45         | 139.97       | 474.31         | 149.99       | 480.97         | 159.92       | 483.17         | 159.90       |
| 459.14         | 129.75       | 465.52         | 140.03       | 476.90         | 150.02       | 483.34         | 159.93       | 488.28         | 160.02       |
| 460.69         | 129.89       | 467.59         | 140.07       | 479.48         | 150.00       | 485.72         | 159.90       | 491.38         | 159.84       |
| 461.21         | 129.93       | 468.28         | 140.07       | 480.34         | 149.96       | 486.52         | 159.89       | 492.41         | 159.73       |
| 462.76         | 129.99       | 470.34         | 140.06       | 482.93         | 149.88       | 488.90         | 159.82       | 495.52         | 159.36       |
| 463.28         | 129.99       | 471.03         | 140.04       | 483.79         | 149.84       | 489.69         | 159.79       | 496.55         | 159.25       |
| 463.79         | 129.99       | 471.72         | 140.03       | 484.66         | 149.79       | 490.48         | 159.76       | 497.59         | 159.15       |
| 464.31         | 129.99       | 472.41         | 140.01       | 485.32         | 149.74       | 491.28         | 159.72       | 498.62         | 159.06       |
| 465.86         | 129.92       | 474.48         | 139.93       | 488.10         | 149.54       | 493.66         | 159.66       | 501.72         | 158.90       |
| 466.38         | 129.89       | 475.17         | 139.89       | 488.97         | 149.46       | 494.45         | 159.54       | 502.76         | 158.87       |
| 466.90         | 129.84       | 475.86         | 139.85       | 489.83         | 149.38       | 495.24         | 159.48       | 503.79         | 158.84       |
| 469.48         | 129.53       | 479.31         | 139.60       | 494.14         | 148.87       | 499.21         | 159.15       | 508.97         | 158.81       |
| 470.00         | 129.45       | 480.00         | 139.54       | 495.00         | 148.75       | 500.00         | 159.08       | 510.00         | 158.81       |

Figure 7. Variation of GT load towards air velocity at certain fuel flow

Figure 8. (a) Variation of GT load towards air low with certain fuel usage $m_{f3} \times 10.6 \text{ kg/s}$. (b) Variation of GT load towards air flow velocity (IGV Velocity) at certain fuel usage.
The variation of IGV opening in several values of specific fuel flow can be observed in figure 8b.

3.3 IGVT characteristics

The decrease of compressor efficiency affects significantly to IGVT effectiveness drop because of the impurities of inlet air that will get in to the combustion chamber. IGVT is implemented to achieve the optimum air supply for combustion process in gas turbine. If the compressor efficiency is disrupted, the air usage for the combustion process is disrupted too.

![Figure 9. (a) Heat rate comparison between CCPP with IGVT implementation and existing, (b) IGV opening curve with IGVT and the efficiency of compressor.](image)

Figure 9a shows the comparison between the CCPP heat rate after and before IGVT. It shows that the heat rates after IGVT implementation are lower than before the implementation. The heat rate reduction begins from 120MW load. The heat rate reduces if the GT load is increasing until it is saturated at loads greater than 210MW (Figure 9a).

Figure 9b shows that IGVT optimum area will be reduced if the efficiency of compressor drops. This occurs when the compressor efficiency drops because of low air compressed. Therefore, to supply enough air usage for the combustion process, the IGV position is set back to the initial position. The decrease of compressor efficiency firstly affects IGVT in the high loads.

4. Conclusion

In this research, the IGVT is implemented in Block 2 Muara Karang Combined Cycle Power Plant. From the field data and analysis, it can be seen that IGVT implemented by finding the optimum operating point in partial loads of CCPP. Optimum operating point increases turbine exhaust temperature that generates greater power in steam turbine, hence it will be decreasing the total heat rate. To overcome the low efficiency of CCPP in partial load, IGVT will operate effectively at partial load (140MW), while it can be observed that the area of heat rate reaches 24 kCal/kWh.

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