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Design Plant-wide Control to Waste Heat Recovery Generation on Cement Industry Based HYSYS

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Abstract
Waste heat recovery generation (WHRG) is a power plant system that utilizes the flue gas to generate an electrical power in cement industry. This plant has various unit operations, such as economizer, evaporator, superheater, steam drum, and turbine. To design WHRG plant, steam drum needs to be controlled in the first place, for the reason that this unit operation will affect steam quality utilized to drive the turbine. There are three finest control elements which can be applied on steam drum; they are level control, pressure control, and mass flow rate control. The control structure on steam drum has deficiency on overcoming the load change value. To handle this problem, WHRG plant needs the other control structure. Plantwide control (PWC) is one of control method to handle the default load changes value. There are two kinds of design methods part based on PWC, the first part is top-down and the second part is bottom-up. Top-down part is a method used to optimize a particular process by determining the advantageous function, while bottom-up part is a method used to maintain the stability rate of the system. Since this study was aimed to control WHRG plant by considering the stability rate, bottom-up part was utilized. The stages used in designing the research based on bottom-up part are determining the operational objectives and limitations, analyzing the degree of freedom in the form of degree of freedom value used to calculate the total of manipulated variable (MV), determining variable process needs controlling, determining the manipulator of production rate, determining the structure of regulatory control layer, determining the adjustment of controller based on Relative Gain Array (RGA) method, and administering open loop test derived from the resulted system’s responses. Based on PWC method, there are three kinds of control structures; they are boiler follow (BFC), turbines follow (TFC), and coordinate controller (CC). The output response resulted by this simulation show that CC is the most precise control structure to handle the load changes on WHRG plant. It can analyze with low value of IAE, settling time, and maximum overshoot of the control result. The IAE value of CC is 857.3439, BFC = 1182.895, while TFC = 887.1246. CC control structure produces IAE better than BFC and TFC. Hence, the precise control structure for WHRG plant is CC.

Keywords : Plantwide control, Three control elements, Tuning, Waste Heat Recovery Generation (WHRG).
1. Introduction

Currently, energy is still one of the basic needs that should be fulfilled for human. This issue happened, because the whole human activity is never separated from energy consumption [1]. Energy usage which rises continuously initiates energy crisis [2]. Based on data taken from Ministry of Energy, electricity consumption during the first half of 2013 increased by 7.2% compared to the same period last year. Total electricity consumption in first half of 2013 is 90.48 TWh and in first half year of 2012 is 84.43 TWh. Based on statistical tables taken from Indonesia National Electricity Company (PLN), the electrical energy consumption is divided into various sectors, including the sectors of household, commercial, industrial, lightning, social, and government. The percentage of energy consumption that occurred with the last 9 years, in 2006 to 2014, is as follows, 39.7% for household sector, 17.1% for commercial sector, 37% for industrial sector, 2% for lightning, 2.4% for social sector, and 2% for government sector. From these data, the level of energy usage in the industrial sector is the second highest level after the household sector.

Flue gas on industry can be utilized for power plant system, that is called Waste Heat Recovery Generation (WHRG) [3]. Because designing this plant is expensive, checking the performance of WHRG plant design is done via simulation [4]. Stimulating this plant needs the right control system to produce proper performance.

There are several kinds of operating units to design WHRG plant, such as economizer, superheater, evaporator, steam drum, and turbine [5]. Because this power plant has wide operating units, an appropriate control system that is used in the plant model is required to design WHRG. Many varieties of control techniques are applied to power plant. PID control techniques are a control technique that is used in many plants, because PID control technique is easy to use and it can produce rapid response system [6]. However, PID control can only be used for linear. Due to complex design of power plant, the response system generated by power plant is in the form of non-linear equation [7]. Therefore, it cannot be controlled using PID. Emerging techniques IMC-PID controller is capable of controlling non-linear response [8]. IMC-PID is a control structure that utilizes feedback and feedforward controller to create stable responses as desired by setpoint and disturbance change [9].

Steam drum is a unit operation affecting steam quality produced. To overcome this problem, this unit operating will pair three types of controller; they are mass flow controller, pressure controller, and liquid percent level controller [10]. Three control elements in steam drum will be tested by using set point and disturbance change. Set point tuning is used to know the system performance. It is used to increase production with revamp set point value. Meanwhile, the tuning based disturbance change is used to control response system if disturbance happens from outside environment. This research conducted two kinds of test by disturbance tuning: the first is test with disturbance input value +5% and the second is disturbance input value -5%. Temperature on flue gas will be set as disturbance in this research, because temperature of flue gas always changes over time. The control structure in steam drum has a weakness; it cannot be used to control electricity rate based on load demand [11].

Plantwide control is one of the methods used to determine appropriate control strategy on the WHRG plant [12]. The function of plantwide control is to relieve interaction of all operating units for safety and to increase output responses. This method is used to set the most appropriate control section so that the response on WHRG plant will robust against for disturbances change [12]. It not only produces robust response to various types of the given interference, but also controls the use of plantwide control method which is capable of controlling the desired electrical rate of load demand.

2. Waste Heat Recovery Generation Plant

Waste Heat Recovery Generation (WHRG) is a power generation system that utilizes exhaust gas still has high energy value [13]. There are two kinds of input variables used; they are flow of exhaust gas which has a high calorific value and feedwater which is used as a producer of steam. Flue gas is a waste gas that is used to heat water that will produce steam to rotate turbines. The rotation of turbines will change the thermodynamic energy into electrical energy. Designing WHRG plant needs huge investment
costs. Therefore, in designing WHRG plant must be done a simulation in first to determine the value of its performance [14].

There are three steps to simulate the plant design of WHRG. First, determine the overall unit operation. Second, determine the type of unit operations used. Third, describe the process flow of the WHRG plant. WHRG plant simulation software can make use of HYSYS. There are four steps that must be utilized. First, determine the composition of the whole stream. Second, determine the thermodynamic equations. Third, determine the overall unit operation. Fourth, enter parameters such as stream name, composition, temperature, pressure, and mass flow rate.

3. **Plantwide Control**

Plantwide control is one of the types of control strategies that are used to consider the overall operation of existing units in a plant, such as the interaction between the unit operation to determine the optimal operating system and security of the whole plant [15]. There are two kinds of part used in plantwide control method [12]. Top-down part is a method used to optimize a particular process by determining the advantageous function, while bottom-up part is a method used to maintain the stability rate of the system. Since this study was aimed to control WHRG plant by considering the stability rate, bottom-up part was utilized.

The stages used in designing the research based on bottom-up part are:
- determining the operational objectives and limitations
- analyzing the degree of freedom in the form of degree of freedom value used to calculate the total of manipulated variable (MV)
- determining variable process needs controlling, determining the manipulator of production rate
- determining the manipulator of production rate
- determining the structure of regulatory control layer
- determining the adjustment of controller based on Relative Gain Array (RGA) method
- administering open loop test derived from the resulted system’s responses.

| No | Name of unit operation | Name of variable | Symbol | Amount |
|----|------------------------|-----------------|--------|--------|
| 1. | Steam Drum             | Liquid fraction | $X_L$  | 1      |
|    |                        | Vapour fraction | $X_V$  | 1      |
|    |                        | Flow liquid     | $F_L$  | 1      |
|    |                        | Flow vapour     | $F_V$  | 1      |
|    |                        | Pressure on steam drum | $P$ | 1      |
| 2. | Economizer             | Mass balance flowrate in | $m_{in}$ | 1  |
|    |                        | Mass balance flowrate out | $m_{out}$ | 1  |
|    |                        | Energy balance  | $-$    | 1      |
|    |                        | Component       | $-$    | 1      |
| 3. | Evaporator             | Mass balance flowrate in | $m_{in}$ | 1  |
|    |                        | Mass balance flowrate out | $m_{out}$ | 1  |
|    |                        | Energy balance  | $-$    | 1      |
|    |                        | Component       | $-$    | 1      |
| 4. | Superheater            | Mass balance flowrate in | $m_{in}$ | 1  |
|    |                        | Mass balance flowrate out | $m_{out}$ | 1  |
|    |                        | Energy balance  | $-$    | 1      |
|    |                        | Component       | $-$    | 1      |
| 5. | Turbin                 | Energy balance  | $-$    | 1      |
|    |                        | Mass balance    | $-$    | 1      |
| **TOTAL** |             |                 |         | 19     |
Figure 1. Design WHRG plant uses software HYSYS.
To determine the appropriate design of control system derived from plantwide control method, DOF value is required to determine MV and PV values which are going to be utilized. To calculate DOF value can be used by reducing the total number of variable and total number of equation \[16\]. Total number of variables and equations number can be determined by looking at the model of a mathematical equation for each unit operation. Table 1 shows the variables used in this study to calculate the amount of valve that is used as manipulated variable.

While the equations used to determine DOF value in WHRG plant, there are four kinds of equations; they are equilibrium components, mass balance, vapor liquid equilibrium, and energy balance. Table 2 shows the equations used by each unit operation constituent of WHRG plant to determine the DOF value that is used to calculate the number of valves.

| No | Name of equation          | Unit operation | Amount |
|----|---------------------------|----------------|--------|
| 1. | Component balance         | Steam drum     | 1      |
| 2. | Mass balance              | Superheater    | 1      |
|    |                            | Evaporator     | 1      |
|    |                            | Economizer     | 1      |
|    |                            | Steam Drum     | 1      |
|    |                            | Turbine        | 1      |
| 3. | Vapor liquid equilibrium  | Superheater    | 4      |
|    |                            | Evaporator     | 1      |
|    |                            | Economizer     | 1      |
|    | TOTAL                      |                | 13     |

Based on the equation determining DOF value, DOF value obtained from the reduction of the number of variables with number equation variable is 6. DOF is used to determine the number of valves that is used to design WHRG plant. Figure 2 below is a picture of streams contained process in the WHRG plant based on the determination of the amount of DOF earned.

**Figure 2.** Design WHRG plant with using value calculation DOF
While to determine of mounting between the PV and MV that is appropriate, we can use relative gain array (RGA) method \[17\]. Before installing the PV and MV using this method, the inventory control structures should be done first. Inventory control structure at this WHRG plant is a control system on steam drums unit operation. There are three kinds of controls on steam drum unit operations namely the level control, pressure control, and mass flow rate control. The equation below is the RGA matrix equation used to determine the appropriate controller installation to be given:

\[
\begin{bmatrix}
MV1 \\
MV2
\end{bmatrix} = \begin{bmatrix}
22 & -24 \\
24.75s + 1 & 28.47s + 1 \\
103.8 & -260.2 \\
27.22s + 1 & 27s + 1
\end{bmatrix} \begin{bmatrix}
R \\
Q_r
\end{bmatrix}
\]

RGA matrix above is a matrix that describes the effect of changes in PV and MV against PV and MV others \[17\]. As for getting the determination of the installation of the best control parameters, it needs evaluation of steady-state gain matrix RGA that can be written as follows:

\[
K_p = \begin{bmatrix}
22 & -24 \\
103.8 & -260.2
\end{bmatrix}
\]

\[
\lambda_{11} = \frac{1}{1-K_{12}K_{21}/K_{11}K_{22}} = \frac{1}{(103.8)(-24)/(22)(-260.2)} = 1.77
\]

\[
RGA = \begin{bmatrix}
\lambda_{11} & 1-\lambda_{11} \\
1-\lambda_{11} & \lambda_{11}
\end{bmatrix} = \begin{bmatrix}
1.77 & -0.77 \\
-0.77 & 1.77
\end{bmatrix}
\]

From steady state gain RGA matrix above, the results can be written in Table 3 to clarify the relationship between PV and MV against PV and MV the other with RGA method.

| Table 3. RGA Value between PV and MV against PV and MV the other |
|-----------------|-----------------|-----------------|
| MV1             | MV2             |
| CV1             | 1.77            | -0.77           |
| CV2             | -0.77           | 1.77            |

Based on Table 3, the installation of precise controller (best pairing) is MV1 likes inlet flue gas will be paired with PV1 likes steam out HRSG, while MV2 likes inlet turbine will be paired with PV2 likes electric power generated. Based on plantwide control analysis, there are three types of control strategies produced, it is boiler controller (BFC), turbine follow controller (TFC), and coordinate control (CC) which has been applied in power plant industry.

4. Results and Discussion

In this section, test and analysis are going to be administered to design WHRG plant. There are three kinds of control systems; namely tuning based on set point, disturbance, and load changes.

4.1 Closed loop test based on set point change

The first control system in WHRG plant is control based on set point change. There are three kinds of control systems in the steam drum; they are level control, pressure control, and mass flow rate control. Figure 3 represents closed loop responses controlling the flow rate of FIC-100 derived from tuning set point with 5% increase within steam drum operational unit.

4.2 Closed loop test based on disturbance change
Closed loop test based on disturbance change is used in WHRG plant by determining the disturbance value. The variable that is used as the disturbance variable is temperature change at flue gas from the rotary kiln and the AQC. The large of temperature served as the disturbance parameter is ± 5% from 325 °C. Table 4 shows the analysis disturbance test

![Figure 3. Closed Loop Test of FIC within tuning set point with 5% set point increase of steam drum](image)

Table 4. Closed loop test based on disturbance change in LIC, PIC, and FIC with increasing of ±5% from the desired value.

| No | closed loop test of parameter | Increasing disturbance + 5% | Decreasing disturbance - 5% |
|----|-------------------------------|-----------------------------|-----------------------------|
|    | LIC-100| PIC-100| FIC-100| LIC-100| PIC-100| FIC-100|
| 1. | IAE    | 7,0723 | 361,639 | 1353,5 | 7,2789 | 476,66 | 1556,43 |
| 2. | MO (%)  | 0,9884 | 1,00817 | 0,9866 | 0,98804| 1,0077 | 1,00687 |
| 3. | ST (second) | 63 | 61,5 | 111,45 | 60 | 66,78 | 137 |

4.3 Closed loop test based on electrical load change use plantwide control method

Closed loop test analysis based on changes in electrical load change use BFC, TFC, and CC control strategy with load changes +5%, +10%, and +15%. Table 5 shows the results of analysis of the closed loop test based on load demand +5%, +10%, and +15% with a variety of control structures.

Table 5. Analysis of closed loop parameters with electrical power increment by +5%, +10%, and +10%

| No | Characteristics of Closed Loop | Type Control Strategy |
|----|--------------------------------|-----------------------|
|    |                                | BFC | TFC | CC |
|    |                                | +5% | +10%| +15%| +5% | +10%| +15%|
| 1. | IAE                           | 1182| 2742| 5609| 887 | 2685| 5315| 857 | 2446| 5152|
| 2. | MO (%)                        | 1,02| 1,05| 1,09| 1,01| 1,01| 1,02| 1,01| 1,00| 1,01|
| 3. | ST (second)                   | 440 | 455 | 460 | 360 | 377,8| 387 | 300 | 332 | 341 |

To analyze the control results in the form of load changes given, we will analyze the output responses based on IAE, settling time, and maximum overshoot. The precise performance is shown by small IAE values obtained, the small value of settling time generated, and the small value of maximum overshoot generated.
5. Conclusion

Based on experiments that have been done, some conclusions can be drawn as follows:

1. The inventory control variables should be determined first. The inventory control in the steam drum i.e. level control, pressure control, and mass flow rate control. Therefore, to determine another pairing of PV and MV the relative gain array (RGA) method. RGA method produces several types of control strategies like boiler follow (BFC), turbine follow (TFC), and coordinate control (CC) which has been applied to industrial power systems.

2. Based on electrical load changes on WHRG plant, CC is the most precise control structure to apply WHRG plant. By changing in electrical load + 5%, the CC control strategy resulted IAE value of 857.3439, BFC = 1182.895, while TFC = 887.1246. The settling time of CC, BFC and TFC are 300, 440 and 360 seconds, respectively. The CC also resulted lowest maximum overshoot compare to BCC and FCC that amounted to 1.009959, 1.022232 and 1.014929, respectively

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