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Optimization of Combined-Cycle Power Plant Operating Pattern

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Abstract

The economic and industrial growth in Indonesia has an impact for electricity demand, but the availability of electricity is still limited. Along with the government's efforts to increase energy intake with a 35,000 MW power project, it will require efforts to generate more energy-efficient electricity, especially for fossil fuel power plants. One effort to improve efficiency is to operate a gas turbine into a Combined Cycle Power Plant (CCPP), in which the exhaust from gas turbine is utilized to produce steam through the Heat Recovery Steam Generator (HRSG) as Steam turbine drives . The Combined Cycle Power Plant can be operated in various configurations, including 2-2-1 (2 Gas turbine, 2 HRSG, 1 Steam turbine) and 3-3-1 (3 Gas turbine, 3 HRSG, 1 Steam turbine) The efficiency of each combined cycle depends on how the load arrangements in each of the Gas turbine affect the efficiency of the plant and affect the cost of production in power plant and with changing the operating pattern with start/stop unit can provide cost of production savings of 3.1% / Month

Keyword: Combined Cycle Power Plant, Gas turbine, efficiency, cost production

INTRODUCTION

Recent economic and industrial growth in Indonesia has led to increased need for electric power[5]. The Indonesian electric power community estimates that the need for electric power will grow rapidly in a couple of years.

Electric power is the primary need in the modern era, and it is needed in adequate quantity and quality.

The electric power in Indonesia grows rapidly. This is in line with the government project to attain 35,000 MW power by 2019, which aims to satisfy the electrical power need of Indonesian people from Sabang to Merauke[7] and give a significant impact on the economic growth in Indonesia, especially outside Java Island.

One of the power plants common in Indonesia is combined-cycle power plant, which is a combination of gas power plant and steam power plant, in which the exhaust of gas turbine combustion is routed through Heat Recovery Steam Generator (HRSG) to produce steam used as the driver of steam turbine.

Turbine gas can be operated first, and the gas exhaust resulted can be used to produce steam through a process in the HRSG, and subsequently, the steam is routed to the steam turbine. Generally, it 50% power is obtained from Gas Power Plant.[2]

PT.X is one of Independent Power Plants in Indonesia.In the operation, the load arrangement of each unit is found to be not optimum, which will lead to high cost of production

This research aims to generate an operating pattern that is optimum and efficient in terms of cost of production.

THEORETICAL FRAMEWORK

1. Combined-cycle power plant definition

Combined-cycle power plant basically consists of two main cycles, namely Brayton cycle (gas) and Rankine cycle.

2. Gas turbine

Gas turbine is a driving machine that uses gas fuel as the working fluid. The compressed air input mixed with gas in the combustor causes combustion, which will produce heat. The heat is converted into mechanical energy to spin the turbine blades, and eventually drive the generator to produce power.

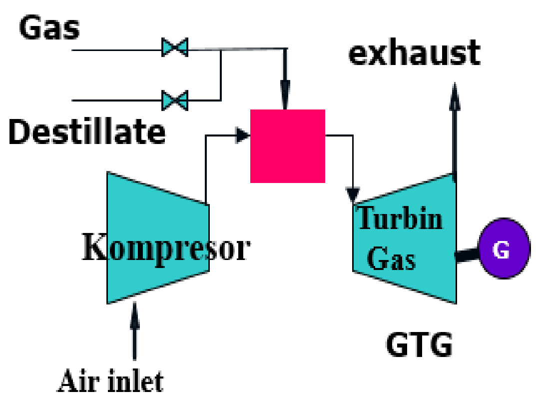


Figure 2.1: Gas turbine

Gas turbine cycle

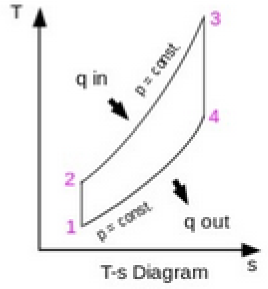


Figure 2.2: Brayton cycle

The cycle commonly used in gas turbine is Brayton cycle. This cycle consists of 2 isentropic processes and 2 isobaric processes (constant pressure).

- 1-2 The air is compressed in an isentropic manner in the compressor
- 2-3 The compressed air is combusted in the combustor in an isobaric manner with fuel inserted into combustor
- 3-4 The heated gas is expanded to the turbine in an isentropic manner to spin the gas turbine blades
- 4-1 The heat of the gas exhaust is released to the atmosphere/ environment in an isobaric manner

Steam Turbine

Basically, the working principle of steam power plant is using Rankine cycle below:

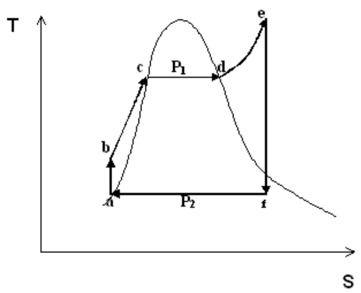


Figure 2.3: Theoretical Rankine cycle (Dietzel,Fritz,1990)

The processes taking place in the Rankine cycle are as follows:

- a-b Isentropic compression takes place in the feed water pump.
- b-c Water heating at a constant pressure in the economizer.
- c-d Water is evaporated into saturated steam at a constant pressure and temperature in the evaporator.
- d-e The saturated steam is dried into further hot steam at a constant pressure in the superheater.
- e-f Isentropic expansion takes place in the steam turbine, where the steam drives the turbine blades.
- f-a Steam condensation at a constant pressure and temperature in the condenser.

Calculation of heat rate

Heat rate is the amount of heat added, usually in Btu, to generate work/energy amount (usually in kWh). Heat rate is expressed in Btu/kWh. In a power plant system, heat rate is calculated as follows:

$$NetStation\ HR: \frac{\text{rate of heat added to generator}}{\text{Net station power}}$$

where,

- *Rate of heat added to generator* = the heat energy used for generating electrical energy (Btu)
- *Net station power* is the electrical energy generated, reduced by electrical energy to be used for auxiliary equipment (house load) (kWh).

Heat rate is inversely proportional to efficiency, thus the lower the value, the better.

Since 1 kWh equals to 3,412 Btu, the calculation of the plant efficiency in relation to the heat rate is as follows

$$\eta = \frac{3412\ \text{Btu/kWh}}{\text{Net Station Heatrate Btu/kWh}}$$

RESEARCH METHOD

This research was conducted using observation and experiment.

The data were collected by:

1. Collecting the data of operating pattern in January 2017
2. Changing the load of every turbine gas unit to obtain data of fuel use of variable loads.
3. Obtaining the characteristics of the load of steam turbine in each block combined cycle
4. Calculating the heat rate of each block combined cycle and station heat rate

ANALYSIS AND CALCULATION

The gas power plant and steam power plant of PT. X has 3 blocks operating in combined cycle operation and 2 units of gas turbine that standby as peaker load operating in simple cycle operation, as follows:

a. Block#1 in the 3-3-1 configuration (3 GTGs, 3 HRSGs, 1 STG) = 3 x 31 MW + 1 x 55 MW

b. Block#2 in the 3-3-1 configuration (3 GTGs, 3 HRSGs, 1 STG) = 3 x 31 MW + 1 x 55 MW

c. Block#3 in the 2-2-1 configuration (2 GTGs, 2 HRSGs, 1 STG) = 2 x 108 MW + 1 x 116 MW

d. 2 units of GTG = 2 x 108 MW (operating in simple cycle)

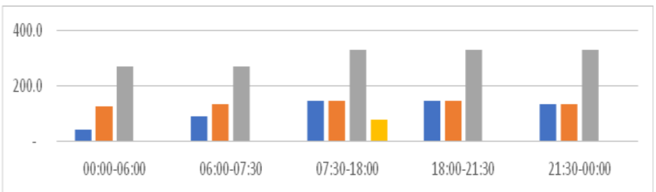
COLLECTION OF OPERATING DATA IN JANUARY 2017

Table and chart of operating pattern of the units in January 2017:

1. The units in simple cycle operation on working days are operated from 07.30 to 18.00.
2. On Saturdays and Sundays, the block 1 unit operates using the 1-1-1 configuration, block 2 units operates using the 3-3-1 configuration and block 3 unit operates in the 2-2-1 configuration.

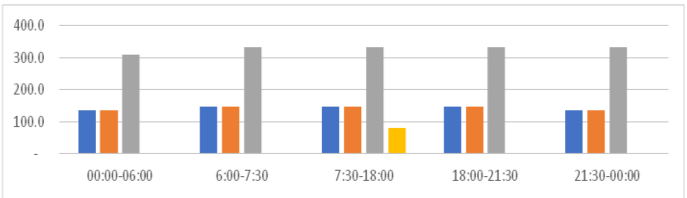
Monday

Time	Block 1 (MW)	Block 2 (MW)	Block 3 (MW)	SC (MW)
00:00-06:00	41.8	128.4	270.3	-
06:00-07:30	91.0	136.4	270.3	-
07:30-18:00	147.6	148.0	332.9	80.0
18:00-21:30	147.6	148.0	332.9	-
21:30-00:00	136.2	136.4	332.9	-



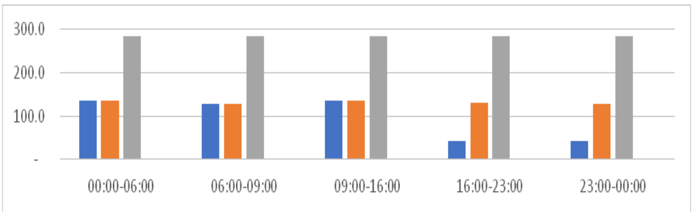
Tuesday-Friday

Time	Block 1 (MW)	Block 2 (MW)	Block 3 (MW)	SC (MW)
00:00-06:00	136.2	136.4	310.2	-
6:00-7:30	147.6	146.8	332.9	-
7:30-18:00	147.6	148.0	332.9	80.0
18:00-21:30	147.6	148.0	332.9	-
21:30-00:00	136.2	136.4	332.9	-



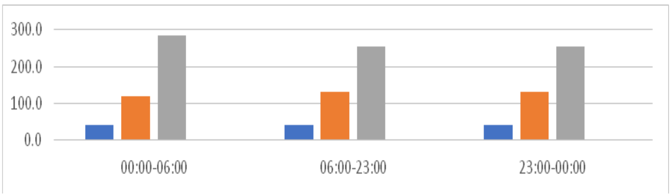
Saturday

Time	Block 1 (MW)	Block 2 (MW)	Block 3 (MW)	SC (MW)
00:00-06:00	136.2	136.4	283.9	-
06:00-09:00	128.2	128.4	283.9	-
09:00-16:00	136.2	136.4	283.9	-
16:00-23:00	41.8	131.1	283.9	-
23:00-00:00	41.8	128.4	283.9	-



Sunday

Time	Block 1 (MW)	Block 2 (MW)	Block 3 (MW)	SC (MW)
00:00-06:00	41.8	120.0	283.9	-
06:00-23:00	41.8	131.1	254.7	-
23:00-00:00	41.8	131.1	254.7	-



The data above are the loading pattern of the units in January 2017 before the improvement of operating pattern. From the power plant operating pattern, the cost of production is obtained as follows:

1. Net Station Heat rate Plant
   a. Total Production : 443,516,538 kWh
   b. Total Fuel : 3,662,000 MMBtu
   c. Total House load : 11,643,600 kWh

Hence, the values of Net Station Heat rate and Plant efficiency can be calculated as follows:

$$Net\ Station\ HR: \frac{\text{rate of heat added to generator}}{\text{Net station power}}$$

$$Net\ Station\ HR: \frac{3{,}662{,}000\ \text{MMBtu} \times 1{,}000{,}000}{(443{,}516{,}538 - 166{,}463{,}413)\text{kWh}}$$

$$Net\ Station\ HR: 8{,}386\ Btu/kWh$$

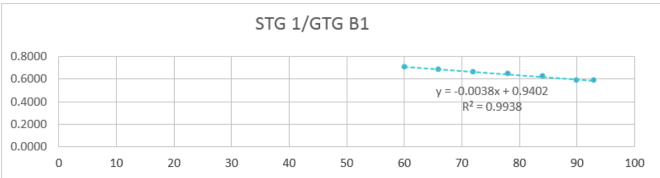
$$\eta = \frac{3412\ \text{Btu/kWh}}{8{,}386\ \text{Btu/kWh}} = 40.6\%$$

Obtaining Steam Turbine Load Characteristics

BLOCK 1 (3-3-1)

Load GTG (MW)	TOTAL GTG B1 (MW)	STG 1/GTG B1
20	60	0.7129
22	66	0.6842
24	72	0.6622
26	78	0.6448
28	84	0.6208
30	90	0.5897
31	93	0.5873

y = -0.0038x + 0.9402

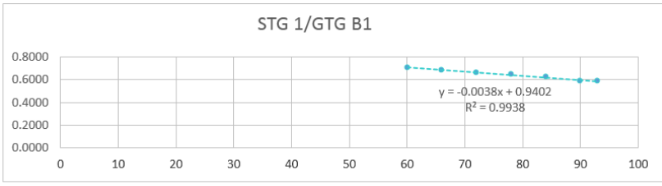


From the data above, the ratio of steam turbine load based on gas turbine load is obtained. When the gas turbine works on the maximum load, which is 31 MW x 3 units of GTG (in one block), the steam turbine load generated is 93 MW x 0.5873 = 54.6 MW.

BLOCK2

Load GTG (MW)	TOTAL GTG B2 (MW)	STG 2/GTG B2
20	60	0.7080
22	66	0.6859
24	72	0.6679
26	78	0.6539
28	84	0.6244
30	90	0.5993
31	93	0.5887

y = -0.0036x + 0.9265

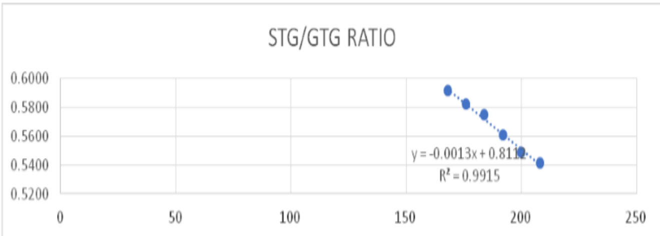


1 Wc or $x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$

From the data above, the ratio of steam turbine load based on gas turbine load is obtained. When the gas turbine works on the maximum load, which is 31 MW x 3 units of GTG (in one block), the steam turbine load generated is 93 MW x 0.5887 = 54.7 MW.

BLOCK 3 (2-2-1)

Load GTG (MW)	GTG 8+9 (MW)	STG 3 (MW)	STG/GTG RATIO
108	216	116.9	0.5412
100	200	109.79	0.5490
96	192	107.7	0.5609
92	184	105.8	0.5750
88	176	102.4	0.5818



From the above data obtained the ratio of Turbine load based on turbine gas load, when the load

The gas turbine is at a maximum load of 108 MW x 2 GTG units (in 1 block), then

The resulting steam turbine load is 216 MW x 0.5412 = 116.9 MW

Obtaining Heat Rate of Combined Cycle Unit

This testing was conducted to obtain the heat rate of each combined cycle unit.

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Block 1 & 2 (operating in 3-3-1)

Load GTG (MW)	TOTAL Load GTG (MW)	STG load (MW)
20	60	42.8
22	66	45.2
24	72	47.7
26	78	50.3
28	84	52.1
30	90	53.1
31	93	54.6

Hence, the heat rate of unit load of 30 MW in simple cycle (SC), in which the exhaust is released to the atmosphere, is calculated as follows:

$$\textit{Heat Rate}: \frac{9{,}500 \text{ MMBtu x } 1{,}000{,}000}{(30 \text{ x } 24\text{x } 1000\ )\text{kWh}} = 13{,}194\ BTU/kWh$$

The efficiency is calculated as follows:

$$\eta = \frac{3412 \text{ BTU/kWh}}{13{,}194 \text{ BTU/kWh}} = 26\%$$

Meanwhile, the heat rate in combined cycle (CC) of unit load of 30 MW is calculated as follows:

$$\textit{Heat Rate}: \frac{9{,}500 \text{ MMBtu x } 1{,}000{,}000}{((30 + 17.2) \text{ x } 24\text{x } 1000\ )\text{kWh}} = 8{,}386\ BTU/kWh$$

The efficiency is calculated as follows:

$$\eta = \frac{3412 \text{ Btu/kWh}}{8{,}386 \text{ Btu/kWh}} = 41\%$$

MWh GTG	BBTU Fuel	BTU/kWh SC Heatrate	Eff. (η)	BTU/kWh CC heatrate	Eff. (η)
30	9.5	13194	26%	8386	41%
28	9.1	13614	25%	8577	40%
26	8.7	13970	24%	8683	39%
24	8.3	14325	24%	8786	39%
22	7.8	14681	23%	8887	38%
20	7.2	15036	23%	8985	38%

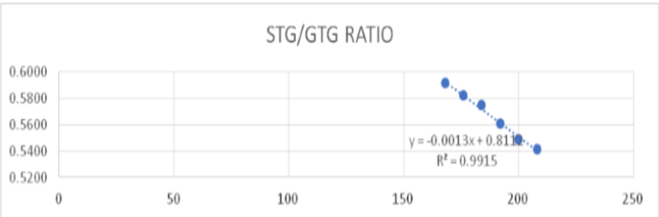


Figure 4.6: Table and graph of total combined cycle load and heat rate values of block 1 and 2

According to the data above, it is found out that a power plant system will be more efficient if it is operated in combined cycle (the exhaust is used to produce the steam for driving the steam turbine) as compared to the simple cycle (the exhaust is released to the atmosphere). The best heat rate of combined cycle blocks 1 and 2 are 8.386 Btu/kWh, or equal to an efficiency of 41%.

Block 3

Load GTG	Total Load GTG	STG 3
108	216	112.6
100	200	109.79
96	192	107.7
92	184	105.8
88	176	102.4

Therefore, the heat rate for the unit load of 108 MW in simple cycle operation (the exhaust is released to the atmosphere) is calculated as follows:

$$\textit{Heat Rate}: \frac{30{,}400 \text{ MMBtu x } 1{,}000{,}000}{(108 \text{ x } 24\text{x } 1000\ )\text{kWh}} = 11{,}728\ BTU/kWh$$

The efficiency is calculated as follows:

$$\eta = \frac{3412 \text{ Btu/kWh}}{11{,}728 \text{ Btu/kWh}} = 29\%$$

Meanwhile, the hate rate in the combined cycle operation with unit load of 108 MW is calculated as follows:

$$\textit{Heat Rate}: \frac{30{,}400 \text{ MMBtu x } 1{,}000{,}000}{((108 + 58.5) \text{ x } 24\text{x } 1000\ )\text{kWh}} = 7{,}607\ BTU/kWh$$

With efficiency value of:

$$\eta = \frac{3412 \text{ Btu/kWh}}{7{,}607 \text{ Btu/kWh}} = 45\%$$

MWh GTG	BBTU Fuel	BTU/kWh SC Heatrate	Eff. (η)	BTU/kWh CC heatrate	Eff. (η)
108	30.35615	11728	29%	7607	45%
104	29.51292	11824	29%	7674	44%
100	28.64808	11937	29%	7695	44%
96	27.76161	12049	28%	7716	44%
92	26.85353	12162	28%	7737	44%
88	25.92382	12275	28%	7757	44%
84	24.97249	12387	28%	7777	44%

From the data above, the best heat rate of combined cycle block 3 obtained is 7.607 Btu/kWh, or equal to an efficiency of 45%.

It can be concluded that the combined cycle block 3 has better efficiency than the combined cycle blocks 1 and 2.

Steps of Improvement of Operating Pattern

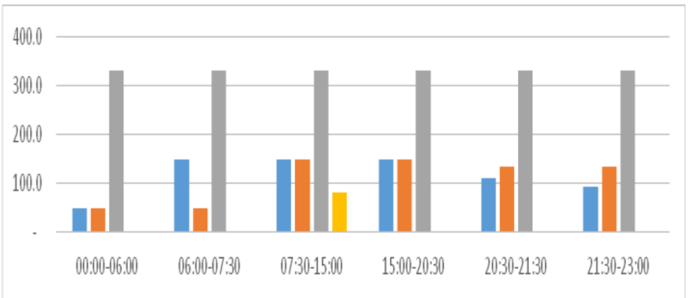
The steps that can be taken are as follows:

a. Making a loading configuration according to the Industrial Need by operating combined cycle Block 3 in the Baseload condition at all time (conducted in March 2017)

b. Setting up the simple cycle start/stop unit on Monday-Friday and combined cycle blocks 1 and 2 on Saturday-Sunday, where the simple cycle units are operated from 07.30 to 15.00, and on Saturdays and Sundays, combined cycle blocks 1 and 2 are operated in the 1-1-1 configuration, while block 3 remains in the 2-2-1 configuration.

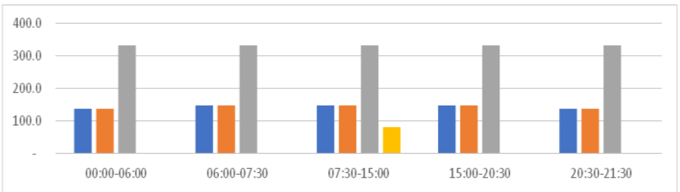
Monday

Time	Block 1 (MW)	Block 2 (MW)	Block 3 (MW)	SC (MW)
00:00-06:00	48.2	48.4	332.9	-
06:00-07:30	147.6	48.4	332.9	-
07:30-15:00	147.6	148.0	332.9	80.0
15:00-20:30	147.6	148.0	332.9	-
20:30-21:30	111.5	135.1	332.9	-
21:30-23:00	92.5	135.1	332.9	-



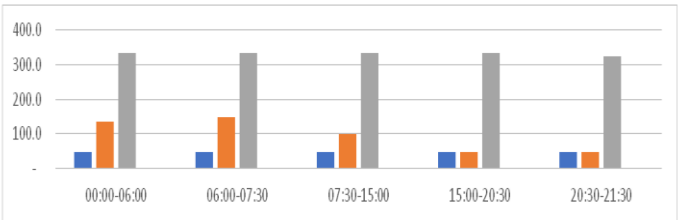
Tuesday-Friday

Time	Block 1	Block 2	Block 3	SC
00:00-06:00	136.2	136.4	332.9	-
6:00-7:30	147.6	148.0	332.9	-
7:30-15:00	147.6	148.0	332.9	80.0
15:00-21:30	147.6	148.0	332.9	-
21:30-00:00	136.2	136.4	332.9	-



Saturday-Sunday

Time	Block 1	Block 2	Block 3	SC
00:00-06:00	48.2	136.4	332.9	-
06:00-09:00	48.2	148.0	332.9	-
09:00-16:00	48.2	99.3	332.9	-
16:00-23:00	48.2	48.4	332.9	-
23:00-00:00	48.2	48.4	323.7	-



From the research data that were collected in March 2017, the heat rate and plant efficiency after some changes in the operating pattern were made are:

- Total Station Production : 440,513,049 kWh
- Fuel Total Energy : 3,548,000 MMBtu
- Station House load : 11,643,400 kWh

The Nett Heat rate was calculated as follows;

$$Net\ Station\ HR: \frac{\text{rate of heat added to generator}}{\text{Net station power}}$$

$$Net\ Station\ HR: \frac{3{,}548{,}000\ \text{MMBtu} \times 1{,}000{,}000}{(440{,}513{,}049 - 11{,}643{,}400)\text{kWh}}$$

$$Net\ Station\ HR: 8{,}274\ Btu/kWh$$

$$\eta = \frac{3412\ \text{Btu/kWh}}{8{,}274\ \text{Btu/kWh}} = 41.2\%$$

From the change in the operating pattern, it can be seen that the heat rate and plant efficiency changed from 8,386 Btu/kWh and 40.6%, respectively, into 8,274 Btu/kWh and 41.2%. Hence, the saving of the cost of production can be calculated as follows:

Saving in gas usage could be calculated as follows:

January 2017
3,662,000 MMBtu

March 2017
3,548,000 MMBtu

Saving = 3,662,000 – 3,548,000

= 114,000 MMBtu or 3.1% saving/Month

CONCLUSIONS

In the research of combined-cycle power plant unit conducted, some conclusions were drawn, namely:

1. In the collection of unit data, the characteristics of combined-cycle block 3 has a better efficiency as compared to combined-cycle blocks 1 and 2. Thus, to achieve optimum operation, combined cycle block 3 must always work on maximum load.
2. According to the research analysis results, it was found out that the simple-cycle unit start/stop is scheduled to operate on work days from 7:30 to 15:00, while the combined-cycle unit stop is scheduled on Saturday-Sunday, with block 1 and block 2 only operating using the 1-1-1 configuration (1 gas turbine – 1 HRSG – 1 steam turbine) as the load need of the industry is too high.
3. The arrangement of load and unit start/stop lead to saving of cost of production 3.1% per month as compared to the previous operating pattern.

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