Journal of Engineering Science and Technology
Vol. 12, No. 2 (2017) 333 - 348

STUDY OF PLANT-WIDE CONTROL IMPLEMENTATION IN PRODUCTION PROCESS OF GEOTHERMAL POWER PLANT

KATHERIN INDRIAWATI, GUNAWAN NUGROHO,
BAMBANG L. WIDJIANTORO, TOTOK R. BIYANTO*

Department of Engineering Physics, Institut Teknologi Sepuluh Nopember,
Jl. Arief Rahman Hakim, Sukolilo, Surabaya, Indonesia (60111)
*Corresponding Author: trbiyanto@gmail.com

Abstract

The design of plant-wide control system to optimize electricity production in geothermal power plant is proposed in this research. The objective is to overcome the deficiency due to changes in the characteristics of production well and fluctuation in electricity demand load. The proposed plant-wide control system has two main tasks; to maintain production process at optimum value and to increase efficiency. The pressure in separator and condenser is maintained at the respective set points under electrical load fluctuations in order to ensure optimum efficiency. The control system also reduce the usage of auxialiary electrical power and increase efficiency. The task was performed by controlling inlet cooling water temperatures to the condenser. It was concluded that the proposed control structure was able to increase efficiency and maintain production.

Keywords: Geothermal power plant, Single flash, Optimization, Plant-wide control.

1. Introduction

The potential of geothermal energy in Indonesia is up to 30 to 40% of total geothermal energy available worldwide [1]. Based on the 2010 data from Geological Agency, Ministry of Energy and Mineral Resources (ESDM), the total potential in Indonesia is up to 29.038 GWe in 276 locations. This large energy potential becomes one of the critical natural resources for future energy development.

Nomenclatures

A	Heat transfer area, m^2
c_p	Spesific heat of water, kJ/kgK
c_{pa}	Specific heat of dry air, kJ/kgK
c_{pv}	Specific heat of steam, kJ/kgK
$c_{p,w}$	Heat capacity of cooling water, kJ/kgK
D	Absorbtion constant
dF_{cw}	Changes of mass flow rate leaving condenser, kg/s
F	Conversion factor
F_c	Mass flow rate of condensate, kg/s
F_{cw}	Incoming cooling water flow rate, kg/s
F_s	Steam mass flow rate entering condenser, kg/s
h_1	Enthalpy of dry steam entering turbine, kJ/kg
h_{2s}	Enthalpy of dry steam leaving turbine at ideal condition, kJ/kg
h_{fg}	Laten heat of evaporation, kJ/kg
Le_f	Lewis number
M	Inertia constant
$m_{a,in}$	Air flow rate entering cooling tower, kg/s
M_{cw}	Mass of water in condenser, kg/s
m_{evap}	Mass flow rate of evaporated water, kg/s
m_w	Mass flow rate in cooling tower, kg/s
$m_{w,in}$	Water mass flow rate entering cooling tower, kg/s
p_c	Condenser pressure, Pa
p_{dem}	Vapor pressure in demister, Pa
p_{sep}	Vapor pressure at separator, Pa
q_{ins}	Inlet flow rate to separator, kg/s
q_{outs}	Outlet flow rate from separator, kg/s
Q	Heat load of condenser, kW
R	Spesific gas constant, kJ/kgK
T_c	Condenser temperature, K
T_w	Water temperature in cooling tower, K
T_{win}	Hot water temperature entering cooling tower, K
u	Control signal
U	Overall heat transfer coefficient, kW/m^{2}K
V_c	Condenser volume, m^3
$V_{effective}$	Effective volume, m^3

Greek Symbols

$\Delta\omega$	Frequency changes from normal load position, rad/s
ΔP_{mot_ref}	Canges of reference power motor of generator, kW
ΔY	Changes of opening control valve fom normal position, %
ΔT_m	Logarithmic mean temperature difference, K
λ	Laten heat of steam, kJ/kg
ω_a	Humidity ratio of incoming air

Abbreviation

NTU	Number of transfer unit

Considering the resources, a few selected engineering applications in the field have been highlighted. Several important developments in production technologies are expected in the future. From an economic viewpoints, maximizing withdrawal of geothermal fluids over a 10-20 year period is a more attractive option than operating at a lower electrical or heating capacity for longer productions [2]. In this case, whether geothermal is a sustainable energy source is also depends on the extraction rate and utilization chosen for each resource. The geothermal exploration generates a perturbation of temperature and pressure field. At shallow level (0-100 m) the explorations will not produce any significant disturbances, and can be made compatible with other applications. The results are important for the evaluation of volcanological processes and for the general assessment of geothermal resource sustainability [3].

The evaluation of geothermal power plant using the energy and exergy analyses based on the actual data was also conducted [4]. Eight performance parameters; the total exergy destruction ratio, component exergy destruction ratio, dimensionless exergy destruction, energetic renewability ratio, exergetic renewability ratio, energetic reinjection ratio, exergetic reinjection ratio and improvement potential were investigated. Energy and exergy losses/destructions for the plant and its units are determined and illustrated using flow diagrams. It is found that the largest energy and exergy losses are occur in brine reinjection unit. It is concluded that the variation of the energy efficiency is between 6% and 12%, while the exergy efficiency vary between 35 and 49%. For the case of implementation using regenerative organic Rankine cycle (ORC) with R-123 working fluid, the maximum efficiency is 15.35% [5]. Similarly, many have been done to evaluate the performance of geothermal power plant, either in Indonesia [6, 7] and worldwide [8, 9]. The performance investigations also utilize energy and exergy analyses of the considered systems.

More technically, dry steam plant, flash steam plant, and binary cycle plants are common energy conversion system for geothermal power plant. Operating parameters from energy conversion system is crucial and dictate the efficiency of the electricity production. Efficiency could be maintained at its optimum value only if operating conditions of the system are controlled at its optimum. Thus, the investigation of the modeling of the electrical production in geothermal power plant plays a crucial role. The model may be illustrated by the thermodynamical steam power cycle theory using directed graphs or structural models for considering different types [10].

Moreover, a control system with ability to maintain operating conditions at its optimum is also required to ensure optimum electricity production. Researches in the control of production process of geothermal power plant are expanding. Some were focusing on control system in steam flash plant [11, 12], control system in binary plant system [13] and control system in dry steam plant [14]. The technology to increase performance and reliability of geothermal power plant was also discussed [15]. It can be concluded that the plant optimization may be performed by considering three strategies; selection of energy conversion cycle, primary vapor pressure and condenser pressure.

Considering the case, the plant-wide control and optimization has been widely used in many industrial processes including thermal power plant [16]. Optimization on supervisory level has been investigated by Saez et al. [17] with the use of predictive control theory to get set points for regulatory level. Supervisory control takes into account the economic and management criteria so that the trade-off between those two criteria is determined. The proposed control strategy is compared with control under constant optimum set points. The comparison shows that the proposed control strategy could bring advantages in a range between 2.4% to 4.4%. The method is useful since the procedure is also similar for other application [18, 19].

As other example, Skoric et al. [13] proposed integrated control system (ICS) for geothermal power plant in Wayang Windu which integrates the steam field with power station and operations. The case of Kawerau's geothermal power plant in which the control station is connected to generation area and steam field is discussed in [20] which also employ supervisory and integrated control.

In this paper, a plant-wide control approach is performed on a geothermal power plant, since according to the previous studies [16-20], it was able to maintain optimum operating conditions of electricity production. The main objective was to overcome fluctuation on electrical power demand or production rate due to disturbance in production well and distribution system. One of the known strategies was to maintain the related process variables at their optimum with or without disturbance (known as 'homeostatis' control). The option of reducing steam exhaust rate on vent valve and auxiliary power diminution was also considered.

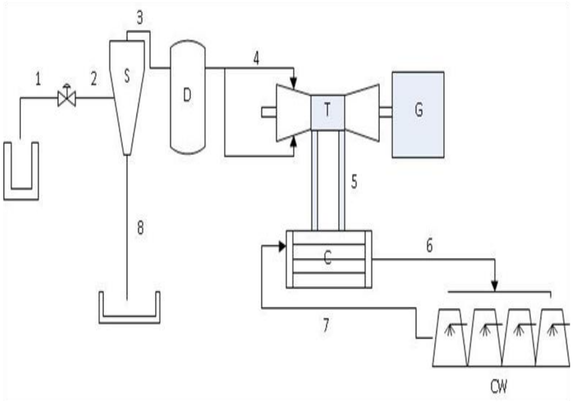
2. Dynamic Modelling of a Single Flash Power Plant

Production process in a single flash power plant consist of three stages; steam production, electricity generation and final cooling. The flow scheme in the plant is presented in Fig. 1. Geothermal fluid is separated into vapor and liquid, and the process is assumed to be isobaric. From the separator, the vapor travel to a demister to eliminate any condensate to ensure only dry steam enters the turbine. Under the normal operation, turbine inlet flow rate and turbine exhaust pressure have been set. The maximum possible work would be generated if the turbine operated adiabatically and reversibly, i.e., at constant entropy or isentropically**.** Thus the process happen in turbine is assumed as the ideal process [21]. Exhaust steam leaving the turbine is condensed in a surface-type condenser. Water condensate from hot well condenser is then sprayed to the cooling tower. It has a direct contact with the air which is supplied by a fan on the top. Cooled water from the tower is re-used back in the condenser.

The pressure of exhaust vapor from separator is assumed equal to the vapor pressure in the separator, which only dry vapor enter the separator, hence, no water is formed in the separator. Under this assumption, the dynamic model is,

$$\frac{dp_{sep}}{dt} = \frac{RT}{V}(q_{ins} - q_{outs}) \tag{1}$$

where p_{sep} is vapor pressure in separator (pa), R is the specific gas constant of water vapor (0.461526 kJ/(kg.K)), T is vapor temperature in separator (K), V is separator volume (m^3), q_{ins} is inlet flow rate to separator (kg/s), and q_{outs} is outlet flow rate from separator (kg/s).



S : separator
D : demister
T : turbine
G : generator
C : condenser
CW : cooling tower
1 : throttle valve inlet
2: separator inlet
3 : separator steam outlet
4 : turbine steam inlet
5 : turbine outlet
6 : condenser outlet
7 : condenser water inlet
8 : separator brine outlet

Fig. 1. Schematic diagram of production process of a single flash geothermal power plant (GPP).

The demister is expressed in a static condition, which there is no leakage on the vapor flow line (no mass lost) through demister and only pressure drop existed.

$$p_{dem} = p_{sep} - 0.1 \qquad (2)$$

where p_{dem} is a vapor pressure in demister (Pa).

The scheme of steam turbine and governor system is described in Fig. 2, which consists of governor valve, steam turbine and shaft modeling. The model is based on input-output balance equation in the form of first order transfer function. For governor valve,

$$\frac{output}{input} = \frac{\Delta Y}{u} = \frac{1}{\tau_{gov} s + 1} \qquad (3)$$

where ΔY is changes of opening control valve from normal position, u is control signal which is an error function,

$$error = \Delta P_{mot\_ref} - \Delta\omega / R_g \qquad (4)$$

with ΔP_{mot_ref} is changes of reference power motor from generator and $\Delta\omega$ is frequency changes of reference and generator from normal load condition.

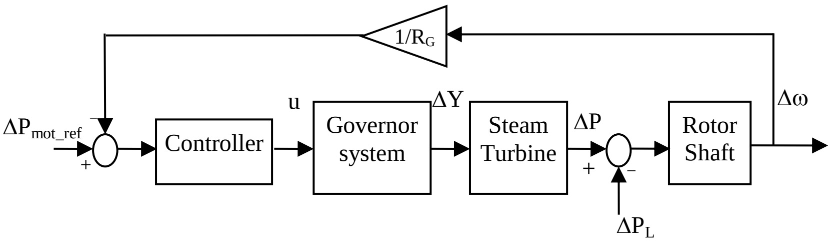


Fig. 2. Block diagram of turbine-generator.

For steam turbine, the transfer function equation can be written as below:

$$\frac{output}{input}=\frac{\Delta P_m}{\Delta Y}=\frac{1}{\tau_{tur}s+1}F\,\dot{m} \tag{5}$$

where F is a conversion factor to convert steam flow rate into mechanical torque. F value is calculated from energy conversion equation in the turbine, that is;

$$F=\eta_{tur-gen}\left(h_1-h_{2s}\right) \tag{6}$$

where h_1 is enthalpy of dry steam entering turbine (kJ/kg) and h_{2s} is enthalpy of dry steam leaving turbine at ideal condition (kJ/kg) in which the condition is the same with the inlet condition of condenser.

Output from the shaft is speed changes on motor due to changes on the mechanical power ($\Delta P_m - \Delta P_L$). The transfer function from the motor inertia and load is,

$$G_{shaft}(s)=\frac{\Delta\omega}{\Delta P_m-\Delta P_L}=\frac{1}{D+sM} \tag{7}$$

with D is absorption constant and M is inertia constant

Dynamic modeling for condenser is referred to mass and energy balance with the assumptions that there is full condensation and inlet and outlet fluid is in saturation. Heat transfer from cooling water to steam is equal to latent heat of the steam and can be written as,

$$Q = F_c\,\lambda \tag{8}$$

where Q is heat load of condenser (kW), F_c is mass flow rate of condensate (kg/s), and λ is latent heat of the steam.

Heat transfer rate between incoming steam with cooling water can be approximated with equation as below,

$$Q = UA\,\Delta T_m \tag{9}$$

where UA is overall and area heat transfer coefficients and ΔT_m is logarithmic mean temperature difference.

Moreover, the energy balance equation for the cooling water can be described as,

$$\frac{dT_{cw}}{dt}=\frac{F_{cw}}{M_{cw}}\left(T_{cw_{in}}-T_{cw}\right)+\frac{Q}{M_{cw}c_p} \tag{10}$$

where F_{cw} is incoming cooling water flow rate (kg/s), M_{cw} is mass of water in condenser (kg), c_p is heat capacity of cooling water (kJ/kg.K).

Mass balance in condenser is assumed that steam volume and condensate in condenser is constant. In this case, the condensate output is controlled to keep condensate level to be constant. For a model simplification, it is also supposed that both incoming steam and exhaust condensate are saturated. Finally, based on the ideal gas equation, the dynamic equation for pressure in condenser can be determined as,

$$\frac{dp_c}{dt} = \frac{RT_c}{V_c}\left(F_s - F_c - dF_{cw}\right) \tag{11}$$

where p_c is pressure in condenser (kPa), T_c is condensate temperature (C), V_c is condenser volume (m^3), F_s is steam mass flow rate entering condenser (kg/s), F_c is condensate mass flow rate (kg/s) and dF_{cw} is changes on water mass flow rate leaving condenser (kg/s).

Energy balance of water in cooling tower is,

$$m_w c_{p,w} \frac{dT_w}{dt} = \dot{m}_{w,in} c_{p,w}\left(T_{w,in} - T_w\right) - \dot{q} \tag{12}$$

where m_w is mass of water in cooling tower (kg/s), $c_{p,w}$ is specific heat of water (kJ/kg.K), $m_{w,in}$ is water mass flow rate entering cooling tower (kg/s), T_w is water temperature in cooling tower (^{o}C), T_{win} is hot water temperature entering cooling tower (^{o}C).

Any changes on water temperature would lead to evaporation so that it would change the water volume in cooling tower. The changes is expressed as,

$$\frac{dm_w}{dt} = \dot{m}_{w,in} - \dot{m}_{w,out} - \dot{m}_{evap} = -V_{e\,ffective}\beta_w \rho_w \frac{dT_w}{dt} \tag{13}$$

where m_{evap} is mass flow rate of evaporated water, $V_{effective}$ is effective volume heat and mass transfer, β_w and ρ_w can be determined from thermodynamic table at temperature T_w.

On the air side, transient mass and energy storage can be neglected, thus, it is observed only at steady condition. Based on Braun equation, it would be,

$$\dot{q} = \dot{q}_{sen} + \dot{q}_{lat} \tag{14}$$

Sensible heat, $\dot{q}_{sen}$, can be determined with equation as,

$$\dot{q}_{sen} = Le_f.NTU.(c_{pa} + \omega_a c_{pv}).\dot{m}_{a,in}(T_w - T_a) \tag{15}$$

where NTU (number of transfer unit) is numerical heat transfer unit, Le_f if Lewis number, c_{pa} is specific heat of dry air, c_{pv} is specific heat of steam, and ω_a is humidity ration of incoming air.

Latent heat, $\dot{q}_{lat}$, can be calculated from equation as in the following,

$$\dot{q}_{lat} = h_{fg}.\dot{m}_{evap} = h_{fg}.NTU.\dot{m}_{a,in}(\omega_{s,w} - \omega_a) \tag{16}$$

where h_{fg} is latent heat of evaporation which depends on water temperature, and $\dot{m}_{a,in}$ is air flow rate entering cooling tower.

3. Plant-wide Control Implementation

Optimization of production process in geothermal power plant was conducted by determining optimum values from operating condition in separator, turbine and condenser. The three main components in the geothermal power plant are interacting to each other such that the required control system must accommodate these problems. Multivariable control system approach is one of the alternative solutions. However, this control system does not guarantee the production optimization, which in this case is a balance between maximizing electrical power and minimizing power load. Thus the plant-wide control approach was performed in order to keep optimum production of electrical power.

Determination of which variables should be controlled, measured, and manipulated together with correlation among the variables are problem that was discussed in plant-wide control [21]. There are two approaches, which are mathematical oriented (control structure design) and process oriented. The design of control structure includes determination of three variables as mention above and configuration with the control system. In this procedure, plant-wide control structure was divided into several layers; regulatory control, supervisory control and optimization (which consist of local optimization, site-wide, and scheduling).

The term supervisory controller was used to define a plant-wide control system and supervision referred to observer of the whole operation, planning and scheduling, coordination and execution actions which increase the reliable performance economically.

Dynamic control is a dynamic regulation of system variables which is not the task of supervisory controller. On the highest level, the main purpose of supervisory controller is to optimize electrical supply. Two main tasks should be fulfilled to achieve these objectives; to increase system performance and to keep operating parameters within the limit. The control actions are changing the model of system operation and set points from several components.

More formal approach is proposed by Downs and Skogestad [22] in order to help procedure regulation of plant-wide control design. The current investigation utilizes the same approach, with details as in the following;

3.1. Top-down analysis

Determination of operational objectives and the constraint

The focus of operational objective is to produce electrical power at its optimum operating condition. On the other hand, constraint is related to physical condition from equipments and the assumption.

Degree of freedom and operation optimization analysis under disturbance

Main inlet steam pressure entering turbine and condenser pressure affect electrical power production produced by geothermal power plant. When there are changes on geothermal fluid conditions, there are two optimum values on the two variables in order to achieve optimal power.

Determination of controlled variables

The inlet steam pressure and condenser pressure are the kept constant variables. Besides these variables, there are turbine speed variable which should be controlled to fulfill consumer requirements. The fluctuation of turbine speed might be resolved. However, it could bring additional work load more than 10% even though still profitable.

The three control variables are related with objective function to maximize the rate of production. This work will also discuss the problem on how to maximize efficiency of production process that has been set. It is related to minimizing utilities usage, maximizing usage of raw material and minimizing waste treatment cost. For these purposes, additional control variable (which is cooling water temperature entering condenser) were proposed. It is expected that auxiliary power utilized for fan cooling tower could be minimized by controlling the variable.

Determination of production rate manipulator

Based on the equation of the controlled variables, the variable manipulation was then selected to regulate variable control condition based on desired set point. Variable manipulation to control main steam pressure can be an exhaust steam rate on vent valve. From the production efficiency viewpoint, this method could reduce the efficiency. Therefore, this work will propose other manipulation variable - steam flow rate entering separator. The governor valve and main condensate pump are used for turbine frequency regulation and condenser pressure. While for controlling cooling water temperature, manipulation variable - air flow rate entering cooling tower is utilized.

3.2. Bottom-up design

Structure determination of regulatory control layer

On this layer, the derived dynamical model from previous research was implemented. The four local controlled were designed according to top-down analysis as explained above. The implemented control algorithm was PI with feedback structure (feedback controller).

Structure determination of supervisory control layer

On this layer, the action was changing set point on two local controller (regulatory controller), which are pressure regulation of receiving header and condenser. The determined set point was based on changes on geothermal fluid and the environment. In this case, the optimum value from main steam pressure and condenser pressure variables was used as the new set points. This action was applied only under full-load condition (100%). Therefore, the action on this layer must be initially started with selection of operating condition. The algorithm was on/off-algorithm, namely the supervisory control is on when the plant operates full load and it is off when the plant was not operating at full load.

Structure determination of optimization layer

On this layer, optimization procedure was applied in order to give optimum value from main steam pressure and condenser pressure variables.

Based on plant-wide control approach, the structure of control system was shown in Fig. 3. There are three layers in this structure; regulatory control (consist of four local controllers), supervisory control layer and site-wide optimization layer [23].

4. Result and Discusion

In order to describe the performance of proposed plant-wide control system, numerical simulation was performed. The simulation is built under Simulink MATLAB for testing purpose under load fluctuation and disturbance. Before doing the test, simulation on normal condition was firstly performed. This result was an initial value of the testing of control system.

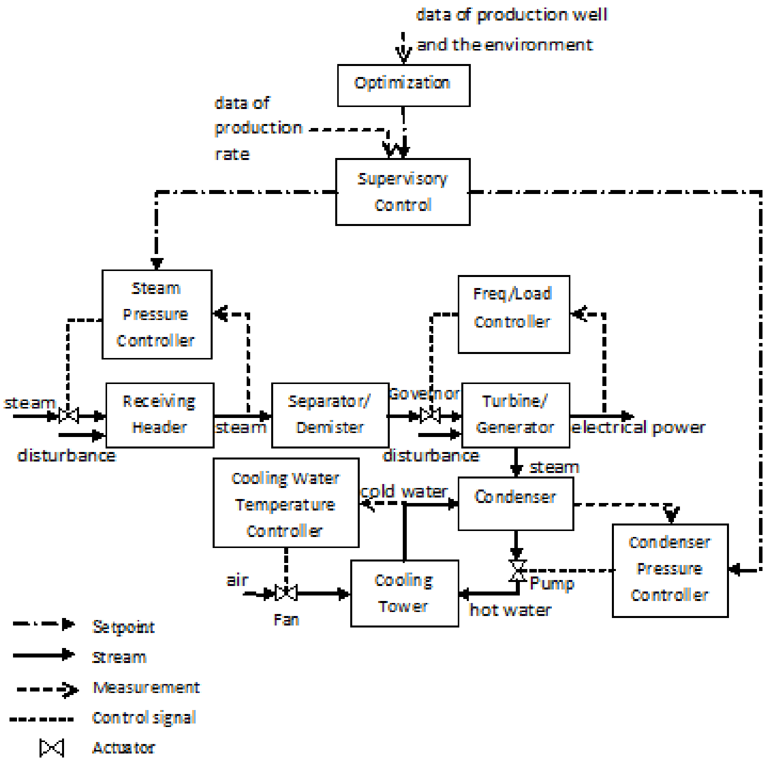


Fig. 3. The structure of control system with plant-wide control approach.

4.1. System response of cooling water controller

Set point value of cooling water temperature is 30°C. Testing on cooling load changes is conducted by changing the environment temperature from 18°C to 20°C. Respond of cooling water temperature with and without control is shown in Fig. 4. This is obtained from Eq. (12) and other related equations. The size of the cooling tower simulated is 11,033 m^3. The result shows that without control, cooling water temperature leaving the cooling tower is smaller than cooling water temperature with applied control (constant at 30°C according to the set point). This is because the fan is working equal from time to time when without control, i.e. at 600 kW. On the other hand, the fan work load is reduced when the controller is used as presented in Fig. 5. This is related to the decreasing of air flow rate used in cooling tower, $\dot{m}_{a,in}$ that affect $\dot{q}$ in Eq. (12) as described in

Eqs. (14)-(16). Therefore, the energy usage can be reduced up to 35 kW if cooling load fluctuations exist.

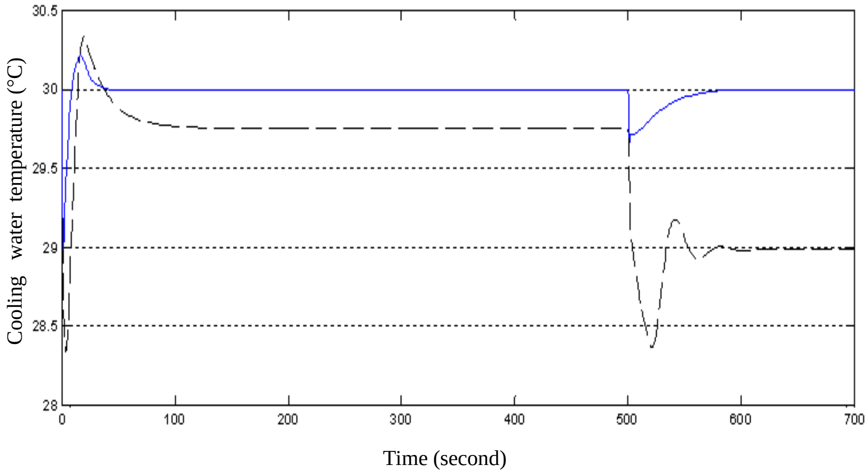


Fig. 4. The respond of cooling water temperature with (solid line) and without (dashed line) control.

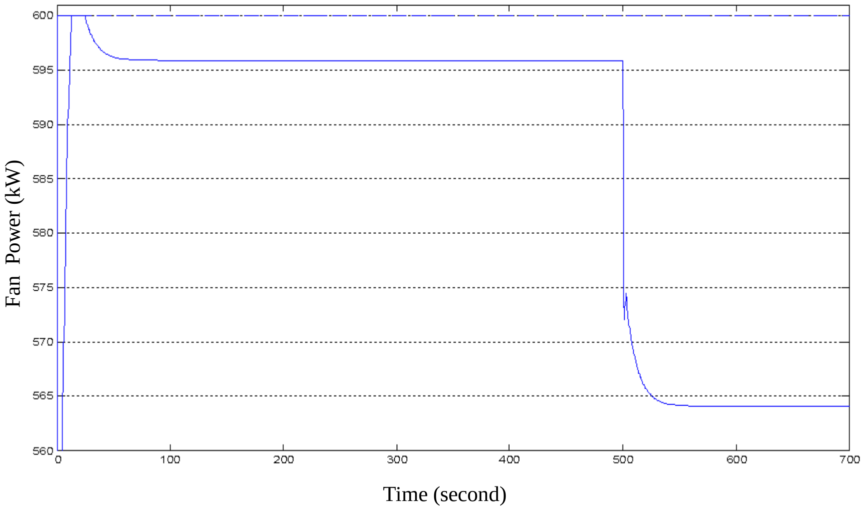


Fig. 5. The fan power with (solid line) and without (dashed line) control.

Pump power under the proposed control is constant at 1,600.5 kW under no change in condenser cooling load, *Q*, as the cooling water temperature is maintained at the setpoint. It is inferred from Eq. (10). On the contrary, pump power is not constant if the cooling water is not controlled. However, the pump power reduction in this case is only 2 kW which is significantly smaller compare to fan power reduction with control, as shown in Fig. 6. Therefore, it is confirmed that adding cooling water temperature control system, under decreasing cooling load, reduced auxiliary power on electrical production process of the geothermal power plant as much as 35 kW compare to that without control which only give 2 kW reduction.

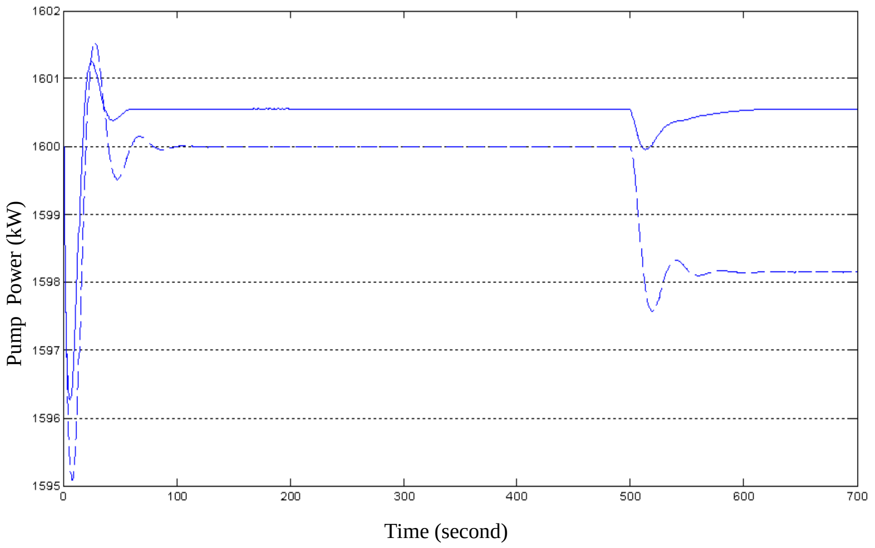


Fig. 6. The pump power with (solid line) and without (dashed line) control.

4.2. Results of supervisory control implementation

Implementation of supervisory control was performed when there were changes on conditions of geothermal fluid such that new set points are generated for steam and condenser pressure. This implementation was simulated with set points changes at *t* = 200 second where separator pressure became 6.15 bara and condenser pressure became 0.125 bara, where bara is bar absolute. Results on responds of the control system for these cases are presented in Figs. 7 and 8. These are obtained from the simulation of Eqs. (1) and (11) as well as other related equations.

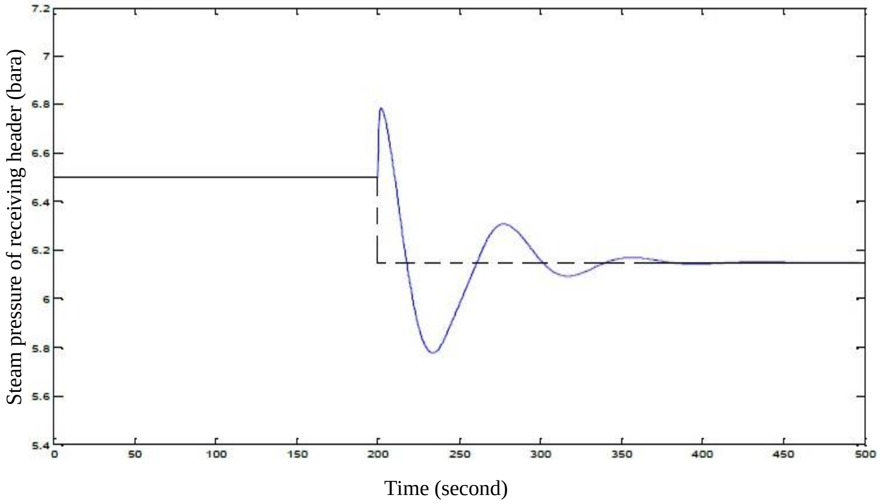


Fig. 7. The respond of steam pressure of receiving header (solid line) during set point tracking (dashed line).

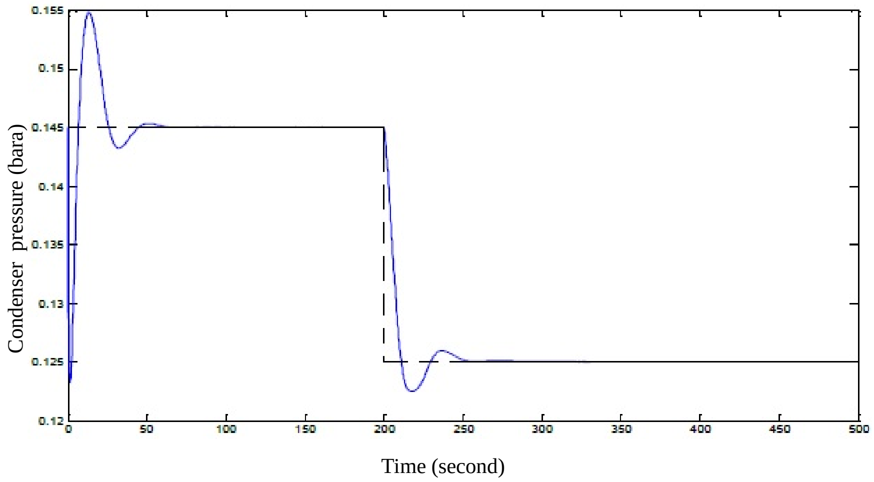


Fig. 8. The respond of condenser pressure (solid line) during set point tracking (dashed line).

It can be confirmed that pressure control system in the two inter-connected unit could carry out the task as a set point tracker. With the new set points changes, according to Eq. (6) the turbine output power increase to 54.3 MW at steam flow rate 390 ton/hr as seen in Fig. 9. It means that the desired output power is increased up to that value after set point changes on separator and condenser pressure.

Changes on reference the turbine output power was conducted on operation control mode during set point tracking. During load fluctuation, operation mode must be changed back to load control operation mode. The changes of operation mode are applied on supervisory control layer.

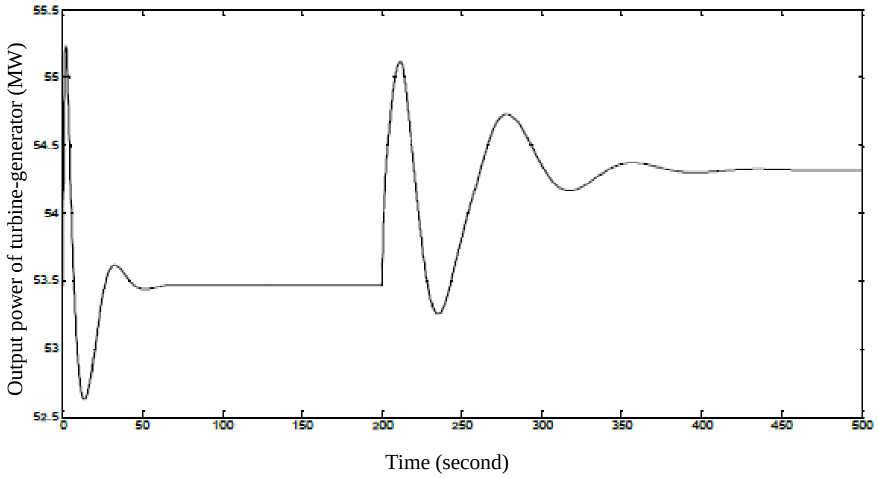


Fig. 9. The output power responds of turbine-generator during tracking set point.

Under condition where the steam and condenser pressure are controlled, the respond of output power of turbine-generator during load fluctuation, ΔP_L, was as shown in Fig. 10. It is shown that the electrical production process provides expected load demand by consumer, either when the load drop to 42.8 MW (80% capacity) or when the load increased back to 47.8 MW. It is proved that the turbine load controller whose the dynamic is described through Eqs. (3)-(7) performs well. This controller runs by using the governor valve which regulates the utilization of steam.

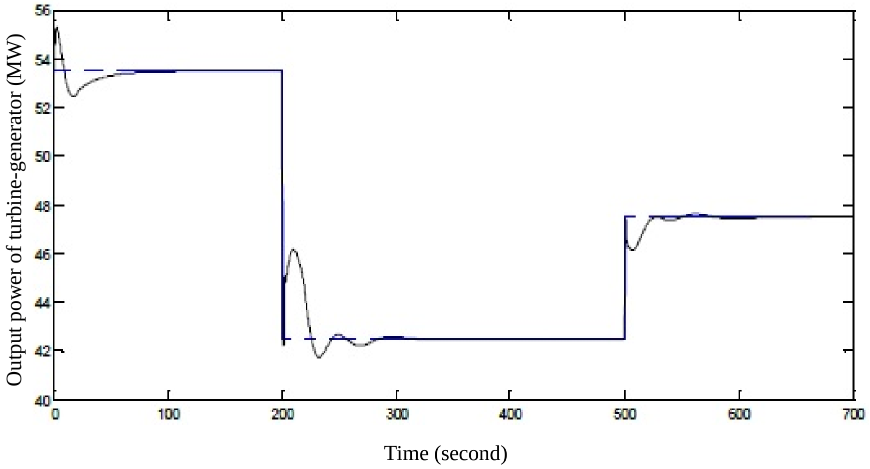


Fig. 10. The output power responds of turbine-generator under load testing.

5. Conclusions

The design of plant-wide control system to get the optimum electricity production in geothermal power plant was conducted in this work. There are four local controllers in the proposed system: the main steam pressure controller, the frequency/load controller, the condenser pressure controller, and the cooling water temperature controller. Thus the concerned manipulated variables are the production well steam flow rate, the turbine inlet steam flow rate, the condenser outlet hot water flow rate and the cooling tower inlet air flow rate respectively. The results showed that the proposed control system was able to achieve the expected objective. The system efficiency was increased by zero venting action and auxiliary power reduction on the fan. Under implementation of supervisory control, the output power of turbine-generator can be maintained or even increased. The electrical production process could accommodate and adapt the load changes.

References

1. Saptadji, N.M. (2010). *Energi panas bumi: status saat ini*. Downloaded on 21-02-2012 <http://majalahenergi.com/status/energi-panas-bumi-status-saat-ini-2010>.
2. Gallup, D.L. (2009). Production engineering in geothermal technology: a review. *Geothermics*, 38(3), 326-334.

3. Carlino, S.; Somma, R.; Troiano, A.; Di Giuseppe, M.G.; Troise, C.; and De Natale G. (2014). The geothermal system of Ischia island (southern Italy): critical review and sustainability analysis of geothermal resource for electricity generation. *Renewable Energy*, 62, 177-196.
4. Coskun, C.; Oktay, Z.; and Dincer, I. (2011). Performance evaluations of a geothermal power plant. *Applied Thermal Engineering*, 31(17), 4047-4082.
5. Yari, M. (2010). Exergetic analysis of various types of geothermal power plants. *Renewable Energy*, 35(1), 112-121.
6. Bertani, R. (2010). Geothermal power generation in the world 2005–2010 update report. *Proc. World Geothermal Congress 2010*, Bali, Indonesia, 25-29 April 2010.
7. Pambudi, N.A.; Itoi, R.; Jalilinasrabady, S.; and Jaelani, K. (2014). Exergy analysis and optimization of Dieng single-flash geothermal power plant. *Energy Conversion and Management*, 78, 405-411.
8. Poletti, V.; Langella, G.; Di Napoli, R.; Amoresano, A.; Meo, S.; Pecoraino, G.; and Aiuppa, A. (2014). A tool for evaluating geothermal power exploitability and its application to Ischia, Southern Italy. *Applied Energy*, 2014, http://dx.doi.org/10.1016/j.apenergy.2014.11.009.
9. Jalilinasrabady, S.; Itoi, R.; Valdimarsson, P.; Saevarsdottir, G.; and Fujii, H. (2012). Flash cycle optimization of Sabalan geothermal power plant employing energy concept. *Geothermics*, 43, 75-82.
10. Sanchez, E.; Torres, C.F.; Guillen, P.; and Larrazabal, G. (2013). Modeling and simulation of the production process of electrical energy in a geothermal power plant. *Mathematical and Computer Modelling*, 57(9), 2140-2148.
11. Dagdas, A.; Ozturk, R.; and Bekdemir, S. (2005). Thermodynamic evaluation of Denizli Kizildere geothermal power plant and its performance improvement. *Energy Conversion and Management*, 46(2), 245-256.
12. Clark, J.; McLay, L.; and McLeskey Jr, L. (2014). Comparison of genetic algorithm to particle swarm for constrained simulation-based optimization of a geothermal power plant. *Advanced Engineering Informatics*, 28(1), 81-90.
13. Skoric, P.; Boutot, R.; Scott, J.; and Iwata, A. (2000). Wayang windu integrated control system - the control concept for modern geothermal power plant. *Proc. World Geothermal Congress*, Kyushu-Tohoku, Japan, May 28-June 10, 2000.
14. Gabor, G.; and Zmaranda, D. (2005). Techniques used to design reliable control systems, a case study: electrical geothermal plant from the University of Oradea, Romania. *Proceedings of World Geothermal Congress*, Antalya, Turkey, 24-29 April 2005.
15. Mulyana, T. (2001). Optimalisasi sistem kontrol pada fasilitas produksi uap panas bumi Kamojang. *Proc. of the 5th INAGA Annual Scientific Conference & Exhibitions*, Yogyakarta, 7-10 Maret 2001.
16. Skogestad, S.; and Govatsmark, M. (2003). A plantwide control procedure with application to control structure design for a gas power plant. *AiChe Annual Meeting, Indianapolis*, USA, 2003.
17. Saez, D.; Ordys, A.; and Grimble, M. (2005). Design of supervisory predictive controller and its application to thermal power plants. *Optimal Control Application and Method*, 26(4), 169-198.

18. Yabanova, I.; and Kaceba, A. (2013). Development of ANN model for geothermal heating system and a novel PID-based control strategy. *Applied Thermal Engineering*, 51(1), 908-916.
19. Garduno-Ramirez, R.; and Lee, K.Y. (2005). Compensation of control-loop interaction for power plant wide-range operation. *Control Engineering Practice*, 13(12), 1475-1487.
20. Funaba, H.; Muto, T.; and Stabler, I. (2010). Features of Kawerau geothermal power plant control system. *Proc. World Geothermal Congress*, Bali, Indonesia, 25-29 April 2010.
21. DiPippo, R.; (2008). G*eothermal power plants: principle, applications, case studies and environmental impact, 2nd ed.* Elsevier, Oxford.
22. Downs, J.J.; and Skogestad, S. (2011). An industrial and academic perspective on plantwide control. *Annual Reviews in Control*, 35(1), 99-110.
23. Larsson, T.; and Skogestad, S. (2000). Plantwide control: a review and a new design procedure. *Modeling, Identification and Control*, 21(4), 209-240.