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OPTIMIZATION CONTROL SYSTEM IN UNITS 3 AND 4, ULUBELU GEOTHERMAL FIELD, INDONESIA

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ABSTRACT

The control system is the most important part in a geothermal process. To obtain a stable process, it is necessary to tune the process using a method according to the difficulty level of the geothermal system. Currently there are several methods that can be used to perform PID tuning, such as the Ziegler - Nichols, Cohen-Coon, or Internal Model Control (IMC) method.

This study is focused on optimization of the control system in the Ulubelu single flash system geothermal field, Lampung, Indonesia. Optimization is done by determining the response characteristics and control in the Ulubelu plant. Each system of the plant has different response characteristic, fast response, slow response or stabilized response. The results of this study can be applied and used to optimize control loops in a geothermal single flash system.

1. INTRODUCTION

The Ulubelu geothermal field is located 100 km west of Bandar Lampung city, the capital of Lampung province, which is in the Tanggamus regency - Ulubelu district, and covers 5 (five) villages, namely: Datarajan, Karang Rejo, Pagar Alam, Muara Dua, and Ngarip (PGE, 2019). The Ulubelu area is in Way Panas mountain, Lampung province, where four units of power plants have been operating commercially since 2011. The total installed capacity is currently 220 MW (Figure 1). The Ulubelu field is located at 800 - 1500 m a.s.l. (m above sea level) with the production wells being located at higher and the reinjection wells at lower altitudes. Power plant units 1 and 2 are located near units 3 and 4 and are served by the same substation. The electricity output from the Ulubelu power plant is distributed to the city of Lampung and the southern Sumatra regions.

Power plant units 3 and 4 are operated by PT Pertamina Geothermal Energy (PGE). This facility (PGE) also provides steam to power plant units 1 and 2 owned by PLN. The power plant in Ulubelu is using a single flash type with a double-flow turbine (Figure 2).

To generate electricity in the power plant, steam is needed which flows from several remote wells located far apart from each other. In the area around the Ulubelu field are settlements and coffee plantations, oil palms, and a small forest area.

FIGURE 1: The Ulubelu geothermal plant location in Indonesia (PGE, 2019)

FIGURE 2: Ulubelu geothermal power plant units 3 and 4 (PGE, 2019)

There are two sales schemes in the Ulubelu field. For units 1 and 2, PT. PGE sell steam to PT PLN under the steam sales contract (PJBU) scheme, while units 3 and 4 use the electricity sales contract (PJBL) scheme. Consumer in this business scheme is PT. PLN is responsible for receiving and distributing electricity to the public and industry.

Almost all equipment in the Ulubelu field has been integrated with control instrumentation. Operators can operate the steam gathering system (SGS) and power plant manually or automatically. This paper will discuss optimization of control systems in the Ulubelu field using three methods and compare the result to each other.

2. SINGLE-FLASH GEOTHERMAL PROCESS

2.1 Steam gathering system

Two-phase steam from the production wells flows to the pipe header and is separated in a central separator station. Almost all production wells in the Ulubelu field are non-artesian wells (wells that need stimulation in order to operate). The wells in the Ulubelu field have pressures of 7.8 - 44 bar-g and temperatures around 180°C. Each well is equipped with a flow control valve (FCV) and only the largest clusters are installed with a motorized FCV enabling manual or automatic operation from a automation control system.

In the Ulubelu field, there are 8 clusters of production well each cluster consisting of 3-6 wells. Each well is connected to the central separator by carbon steel pipe 16-18” class #300 and combined to a 22” class #300 pipe. Transmitters and gauges are installed to monitor temperature, pressure and flow.

In general, the steam gathering system for the liquid-dominated system is divided into three types: centralized, satellite, and individual wellhead separator (DiPippo, 2012). Each type has its advantages and disadvantages. The centralized separator is joined with several separators located in the same area. Central separators are normally used in geothermal systems with many wells from different clusters. Central separators are characterized by easy maintenance since all production and control equipment such as compressors, pumps, valves, instrumentation etc. is in the same area. The disadvantage of central separators is however the possibility of fluctuations and instability of the liquid level in the separator due to load variations (Figure 3). A steam gathering system that uses a centralized separator requires a shorter pipe connecting the separator station to the injection well.

FIGURE 3: The centralized separator in the Ulubelu units 3 and 4

Satellite separators are used inside a well cluster to separate two-phase fluid from several production wells. The satellite type only requires one separator for each cluster. If many clusters are used to generate electricity in a power plant, supporting equipment is needed at each cluster to monitor and control. The liquid level in satellite separators is easy to control since the fluid comes only from one well. However, this type is costly if used with many wells in one unit for generating electricity. A longer injection pipeline and vast instrumentation in the separator is needed.

The Ulubelu units 1 and 2 use a hybrid separator that is a combination of a satellite and centralized separator. There are three cluster of production wells, clusters B, C, and D. Cluster B and C use a centralized separator located in cluster C while Cluster D uses a satellite separator. The steam line from each separator is joined in a scrubbing line near the power plant. The Ulubelu units 3 and 4 use centralized separators where two-phase fluid from production wells is joined in a pipe header before entering the inlet separator. There are three separators used in Ulubelu units 3 and 4. Each separator is equipped with a level control whose function is to maintain the level of the in the separator vessel. If the level in the separator cannot be controlled due to abnormal conditions, an Emergency Dump Valve (EDV) will open and drain the brine into the pond station. The EDV should only be used in case of an emergency (Figure 4).

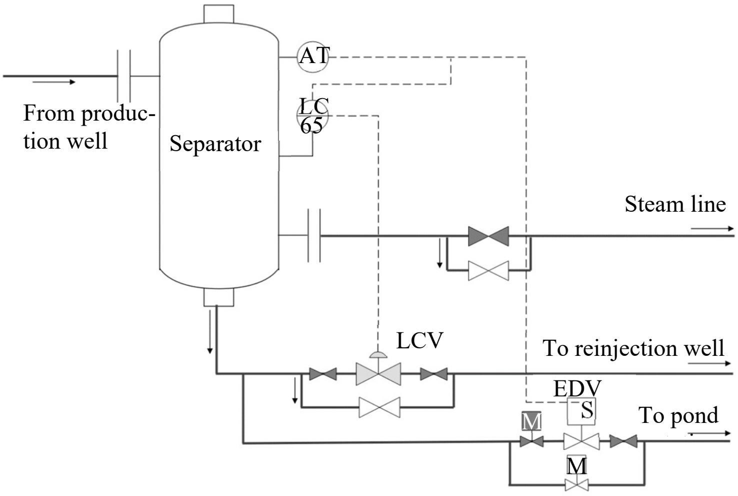

FIGURE 4: Instruments and controls in a separator station

Steam from the separator will flow through the steam pipeline to the power plant. Hot brine is injected back into the ground through a reinjection well. To maintain the reservoir, the hot water (hot brine) and cold water (condensate) flows separately to the hot and cold injection wells. The advantage of using centralized separators is that the injection pipe only uses one lane so that the cost of the reinjection line construction can be reduced.

2.2 Power plant

Steam from the separator is led to the scrubber in the power plant. In the scrubber the moisture is separated from the steam before entering the turbine. The Ulubelu power plant is designed for a certain steam quality (Table 1) which must be achieved when leaving the scrubber to ensure decent performance of power plant. The steam pressure at the turbine main stop valve is designed to be 7.6 bar-a at saturation temperature. To generate 55 MWe of electricity, 375.27 T/h of steam is needed and is controlled by the main control valve.

TABLE 1: Steam quality in Ulubelu power plant

Steam quality at scrubber outlet	Dryness ≥ 99.95% Chloride ≤ 0.3 ppm Silica ≤ 0.3 ppm Total dissolved solids ≤ 5 ppm

Some of the steam from the scrubber flow is led to the gas removal system. Geothermal fluids contain non-condensable gases (NCG) at various amounts. In Ulubelu field NCG concentration is about 1.5 wt % in steam. NCGs should be withdrawn by a gas removal system (GRS) to prevent increase in condenser pressure. If the condenser pressure increases, the performance of the turbine will be decreased.

The main purpose of the condenser especially in the single flash geothermal power plant is to maximize turbine efficiency by maintaining a proper vacuum by condensing steam, removing dissolved NCGs from the condensate and conserving the condensate for re-injection or as feed water for the cooling tower (Najafabadi, 2015). NCG from the condenser will flow to the cooling tower through the gas removal system.

There are three types of gas removal systems that are commonly used in geothermal power plants: all ejector, hybrid, and turbo compressor type. All ejector types usually have two or three ejectors with inter and after condenser. They are easy to operate and maintain and low-cost compared to other types but lead to a higher steam consumption during operation. The hybrid type consists of an ejector, a condenser, and a liquid ring vacuum pump (LRVP). The advantages of the hybrid type are higher efficiency than all other ejector types, but they are more expensive. Turbo compressor types are typically a multi-stage axial machine and are more efficient than the two other types. Turbo compressor types are the highest in initial cost and are more complex in design (Kotaka et al., 2010).

The Ulubelu power plant (Figure 5) is using a hybrid ejector separator type where the ejector and vacuum pump (LRVP) is installed with a pumping capacity of 3x50%. During normal operation, the ejector and LRVP are operated for two units and the other one is for back up.

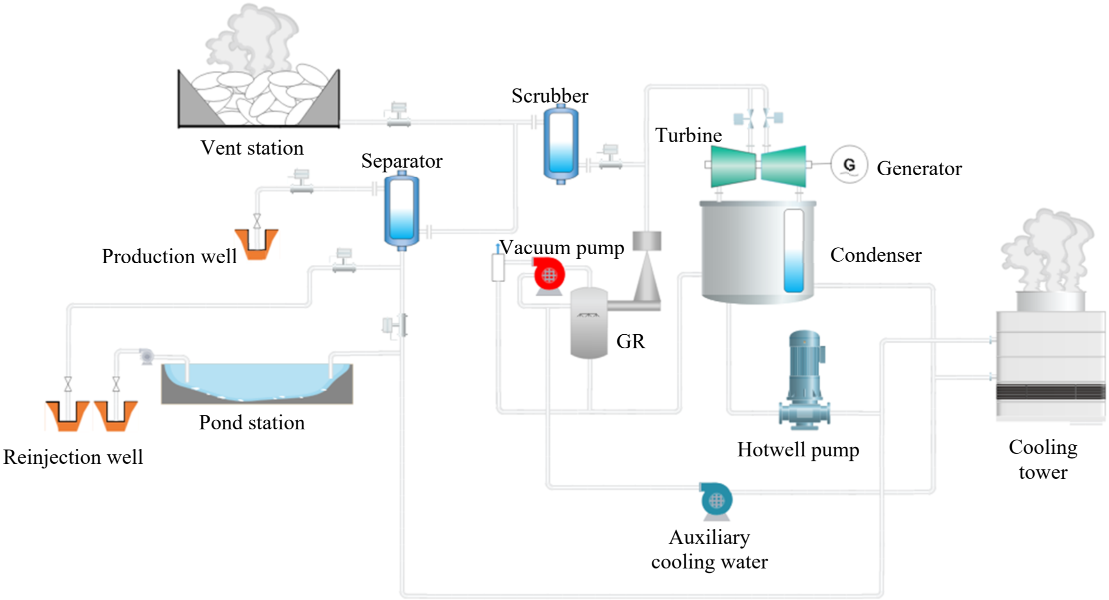

FIGURE 5: Geothermal power plant block diagram of the Ulubelu power plant

NCGs from the ejector flow to the cooling tower to be released into the atmosphere. The Ulubelu power plant units 3 and 4 have two cooling tower packages that are used for each unit. Each cooling tower has six fan stacks (Figure 6). Gas and steam from the ejector are condensed by spraying cold water through the cooling tower nozzle and the is reused for circulation in the cooling system.

FIGURE 6: Cooling tower in Ulubelu power plant units 3 and 4

The condensate from the condenser is partly channelled into the cold injection well as part of the reservoir management. Condensate water is neutralized using pH control by injecting chemicals to avoid scaling inside the pipeline.

Because the operating conditions in a geothermal steam power plant can change over time, instrumentation systems must be installed to continuously monitor and control the performance of the system and equipment. Currently, the technology to operate power plants is getting more advanced. Some of the control instrumentation can be used wireless.

The most important part of instrumentation for monitoring and controlling in a geothermal system includes DCS (Distributed Control System), SCADA (Supervisory Control and Data Acquisition), or PLC (Programmable Logical Controller) as a controller or brain for running the power plant. Field instruments such as control valves, transmitters, and gauges (Figure 7) are also used as tools for monitoring and manipulating processes as required.

FIGURE 7: Field instruments in Ulubelu units 3 and 4 used for monitoring and control

Data from the instrument field (Figure 8 right) is sent to the DCS in real-time and displayed on the monitor screen as a human-machine interface (HMI) to facilitate the operator in reading and executing control processes (Figure 8 left). By using HMI, the operator can manipulate the process both manually and fully automatically so that the process can be optimized. Controllers (DCS, SCADA, and PLC) are made redundant to avoid unwanted conditions due to interference from outside or inside the system.

FIGURE 8: Operators operating power plant in control room for Ulubelu units 3 and 4

3. CONTROL SYSTEM MODELING METHOD

The closed-loop control system is a type of control that adjusts the system input/control input U(s) according to the feedback of the system output (Figure 9). The closed-loop control system is usually used for control of physical parameters such as temperature, pressure, level, position, speed, etc.

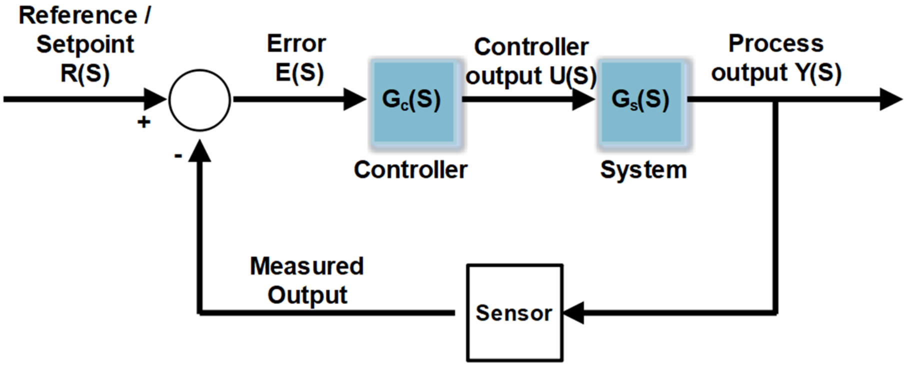

FIGURE 9: Block diagram closed-loop control system

Sensors or transmitters are often referred to as primary and secondary elements, the controller is the "brain" of the control system while the final control element is a control valve. Other examples for final control elements are variable speed pumps, conveyors, and electric motors.

The purpose of the system feedback is to measure the process variable and send the measurement to the controller for comparison to the setpoint. Usually, the setpoint has been determined by the operator. If the process variable is not at the setpoint, control actions are taken to reset the process variable.

Controllers in a control system are devices that receive data from measurement instruments, such as transmitters or sensors. The measured data are compared to the user-set setpoints, and, if necessary, signal control elements take corrective action. Local controllers usually consist of one of the following four types: mechanical actuator, pneumatic, electronic, or programmable. The controller is also usually using digital control systems such as DCS, SCADA, or PLC.

Because the study cannot be done online, open-loop control will be used. Open-loop control processes are like closed-loop but work without feedback. Usually, open-loop tuning is used without interacting with DCS, SCADA, or PLC.

3.1 The characteristics of P_{out}, I_{out} and D_{out} controller

Proportional parameters P_{out} produce output values that are equivalent with proportional controller times the current error value. Equation 1 shows that the proportional response can be adjusted by multiplying the error with the constant K_p. The advantage of using a proportional controller K_p is the reduction in rise time and steady-state errors (defined by Equation 2).

$$P_{out} = K_p \, e(t) \tag{1}$$

$$e = SP - PV \tag{2}$$

where P_{out} = Proportional parameter;
K_p = Proportional gain;
e = error;
SP = Setpoint;
PV = Process variable.

The integral parameter I_{out} in the PID controller is the number of instantaneous errors and can reduce the fixed offset. The total error or integral error over time is then multiplied with the integral gain K_i and added to the controller output (Equation 3). Integral control K_i has the effect of eliminating steady-state errors but can worsen transient responses (Table 2).

$$I_{out} = K_i \int_0^t e(t)dt \tag{3}$$

where I_{out} = Integral parameter;
K_i = Integral gain.

Derivative parameters D_{out} are calculated by determining the slope of the error over time and multiplying the rate of this change with the derivative gain K_d (Equation 4). Improving derivative control K_d has the effect of increasing system stability, reducing overshoot, and increasing transient response. The effects of K_p, K_d, and K_i controller on the closed-loop system are summarized in Table 2.

$$D_{out} = K_d \frac{d}{dx} e(t) \tag{4}$$

where D_{out} = Derivative parameter;
K_d = Derivative gain.

TABLE 2: Comparison of controllers' response to rise time, overshoot, settling time and S-S error

Controller response	Rise time	Overshoot	Settling time	S-S error
K_p	Decrease	Increase	Small change	Decrease
K_i	Decrease	Increase	Increase	Eliminate
K_d	Small change	Decrease	Decrease	Small change

3.2 Interactive, non-interactive and parallel algorithm

In general, there are three types of PID controller algorithms, that is interactive, non-interactive, and parallel controllers. Control systems manufacturers also create their controllers based on these algorithms. The interactive controller is the oldest controller algorithm and is called a series form algorithm. The series nomenclature arises from block diagram notation in which the integral block (Equation 5) is in series with the derivative block (Figure 10). The series controller makes it act like an electronic controller, and some manufacturers still use this algorithm.

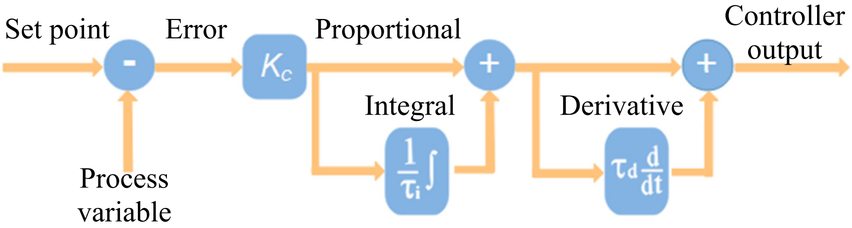

FIGURE 10: Block interactive diagram algorithm (re-drawn and modified from Smuts, 2010a)

$$G(t) = K_c[e + \frac{1}{\tau_i}\int edt]\,[1 + \tau_d \frac{d}{dt}] \tag{5}$$

The non-interactive algorithm is also called an ideal controller. Almost all manufacturers in the industry use this algorithm. If the derivative time constant is not used (τ_d = 0) then this algorithm is like the interactive controller. The ideal controller is not suitable for direct field interaction - therefore it is called a non-interactive controller if we look at Equations 6 and 7, proportional, integral, and derivative influenced by process gain (K_c) and use time constant for integral and derivative (Figure 11).

$$G(t) = K_c[e + \frac{1}{\tau_i}\int edt + \tau_d \frac{d}{dt}] \tag{6}$$

$$G(S) = K_c + \frac{K_c}{\tau_i S} + K_c \tau_d S \tag{7}$$

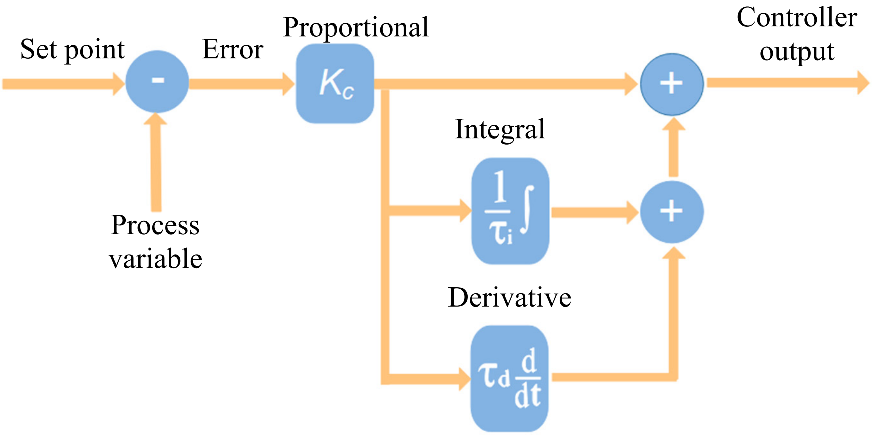

FIGURE 11: Block non-interactive diagram algorithm (re-drawn and modified from Smuts, 2010a)

The final algorithm is a parallel algorithm which is the easiest to understand but not very intuitive to tune. The block diagram of the parallel algorithm is shown in Figure 12. There is no controller gain like in the interactive and non-interactive algorithm but proportional gain for integral and derivative change to integral gain and derivative gain. As we see in the block diagram and Equation 8, a parallel algorithm has a true proportional gain K_p, integral gain K_i, and a derivative gain K_d.

$$G(t) = K_p e + K_i \int edt + K_d \frac{de}{dt} \tag{8}$$

In Laplace transform equation (8) can be re-written as:

$$G(S) = K_p + \frac{Ki}{S} + K_d S \tag{9}$$

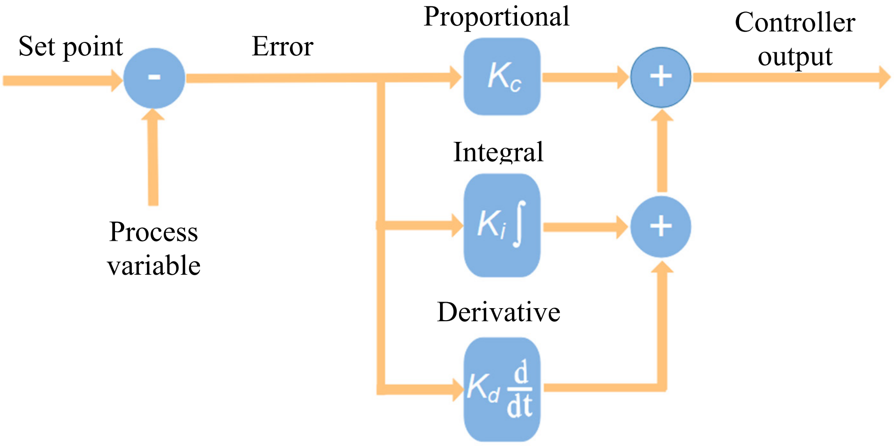

FIGURE 12: Block parallel diagram algorithm (re-drawn and modified from Smuts, 2010a)

3.3 Self-regulating process

In the geothermal process, there are two types of process control systems, that is self-regulating and non-self-regulating (integrating). Self-regulating systems adjust themselves if the set point given by the user changes. The system will be at a steady state at a certain time. Not all processes are categorized as self-regulating. Some examples of methods that have self-regulating properties include pressure, temperature, flow, pH, etc.

In the tuning process, the parameters that play an important part in determining the system performance is the dead time t_d, the time constant τ, and the process gain g_p. The dead time is the delay from the change in the controller output until the process variable (PV) changes (Figure 13). If the operator in the power plant changes the setpoint, the controller changes the output to the final element, which will result in a change of the process variable. Figure 13 shows the process model and the gain has been determined using Equation 10:

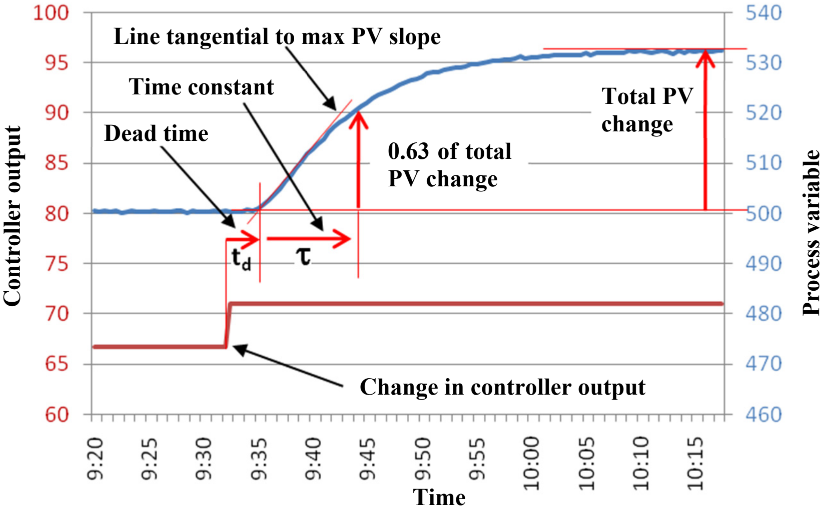

FIGURE 13: Self-regulating process (Smuts, 2010b)

$$g_p = \frac{\Delta PV}{\Delta CO} \tag{10}$$

The process variable will change and adjust to the new setpoint. A good controller will provide a process variable value that follows the change in setpoint without overshoot while having a short rise time and settling time.

Overshoot occurs when the process variable rises above the new setpoint value and oscillates until a steady-state is reached after the settling time. Rise time is the time it takes for the process variable to change from 10% to 90% of the final value. Cooper (2006) states that the process is steady state if the oscillation is not more than 5% of the change in setpoint (Figure 14).

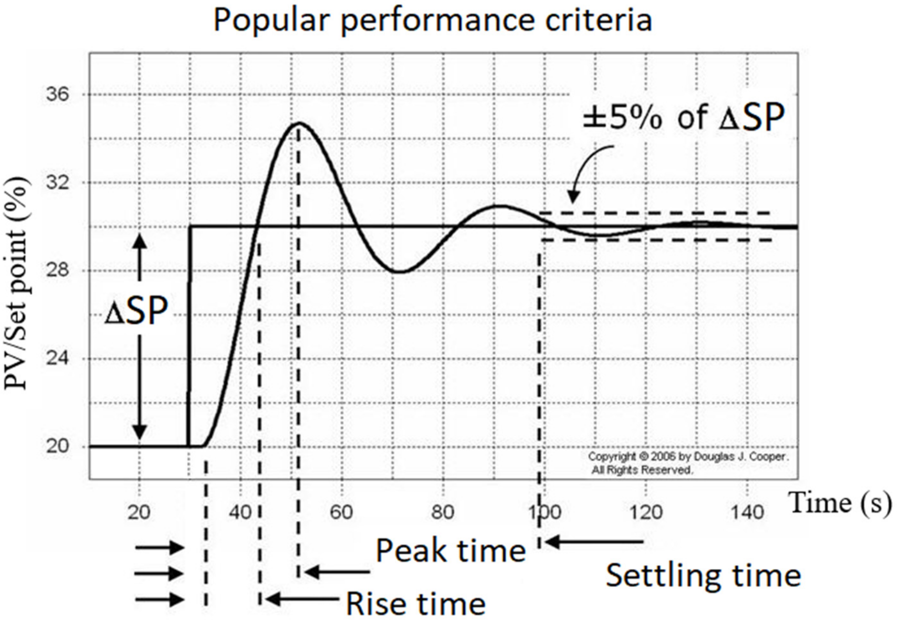

FIGURE 14: Process response to a setpoint with label indication (Cooper, 2006, modified by Controlguru, 2015)

The oscillation that occurs in the process response is also called the quarter amplitude damping response (Figure 15). The first oscillation has a higher peak time than the next amplitude. The amplitude shrinks until it approaches the setpoint value. A quarter amplitude damping response will often be found in process tuning using the Ziegler-Nichols or the Cohen-Coon method.

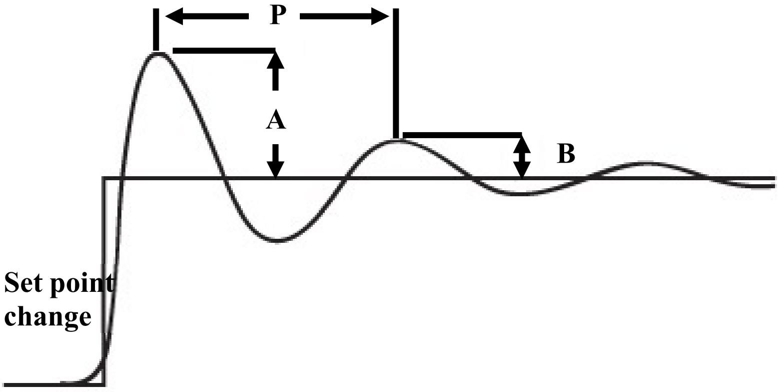

FIGURE 15: Quarter amplitude damping response (ISA, 2005)

Here: A = Deviation of the first peak above (below) set point;
B = Deviation of second peak above (below) set point;
DR = Decay ratio, or $\frac{B}{A}$; and
P = Period or time between two successive peaks (or valleys)

3.4 Ziegler - Nichols method

The Ziegler - Nichols technique is one of the oldest methods for online tuning. Currently, this method is still widely used by manufacturers and industrial companies. The Nichols – Ziegler method gives approximate values of the tuning parameters proportional K_c, integral τ_i, and derivative τ_d to obtain am approximately one fourth decay ratio response (Smith, 2002).

The Ziegler - Nichols tuning rules were designed for controllers with the interactive controller algorithm (Smuts, 2010b). If not using the derivative control mode (i.e., using *P* or *PI* control), the rules will also work for the noninteractive algorithm. However, if applying the derivative (i.e., PID control) and a noninteractive controller or if the controller has a parallel algorithm, the calculated tuning settings are converted to work on the controller.

Ziegler - Nichols divides his method into two parts, the first and the second method (Tables 3 and 4). The first method is used for the open-loop (Figure 16) and the second method is used for the closed-loop self-regulating controllers. Some authors have modified this method to get a better controller response. The Ziegler-Nichols method tuning rules were designed for a ¼-amplitude decay response.

TABLE 3: Ziegler - Nichols first method for open loop (Ziegler and Nichols, 1942)

PID Type	K_p	T_i	T_d
P	$\frac{T}{L}$	∞	0
PI	$0.9\frac{T}{L}$	$\frac{L}{0.3}$	0
PID	$1.2\frac{T}{L}$	$2L$	$0.5L$

where L = Deadtime and T = Time constant

TABLE 4: Ziegler – Nichols second method for closed loop self-regulating (Ziegler and Nichols, 1942)

PID Type	K_p	T_i	T_d
P	$0.5\,K_{cr}$	∞	0
PI	$0.45\,K_{cr}$	$\frac{P_{cr}}{1.2}$	0
PID	$0.6\,K_{cr}$	$\frac{P_{cr}}{2}$	$\frac{P_{cr}}{8}$

where K_{cr} = Ultimate gain; and
P_{cr} = Critical period

The open loop is used when the tuning process is done manually so that the feedback is not an input for the tuning process. Whereas a closed loop is controlled automatically or by online tuning, and the feedback from the tuning process become the input for the controller. Table 4 shows the formulas for calculating the controller parameters in closed-loop control.

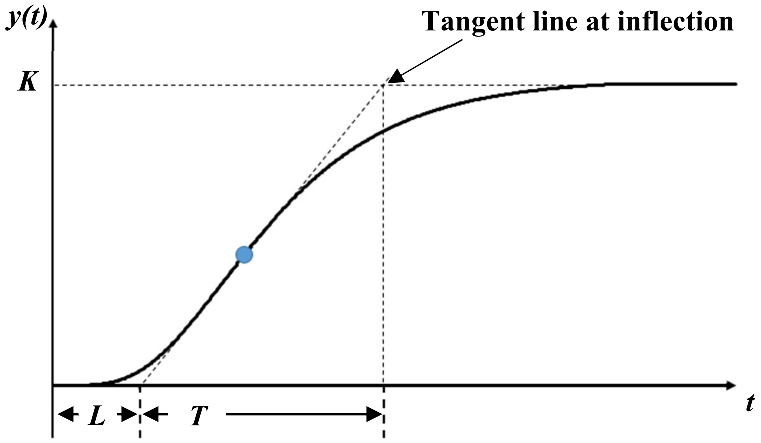

FIGURE 16: Response curve for Ziegler – Nichols first method (Korsane et al., 2014)

Ultimate gain is obtained from the results of online trial and error experiments where the response of the process is set to be steady-state or constant. If the amplitude cycle is too high, the controller gain must be reduced. If the amplitude is too low, then the controller gain must be increased and if the amplitude is constant then the controller gain is K_{cr}. The critical period P_{cr} is reached when the amplitude of the oscillation is constant (Figure 17). After obtaining K_{cr} and P_{cr} values, the controller gain, integral and derivative time constants can be determined using the formula from Table 4.

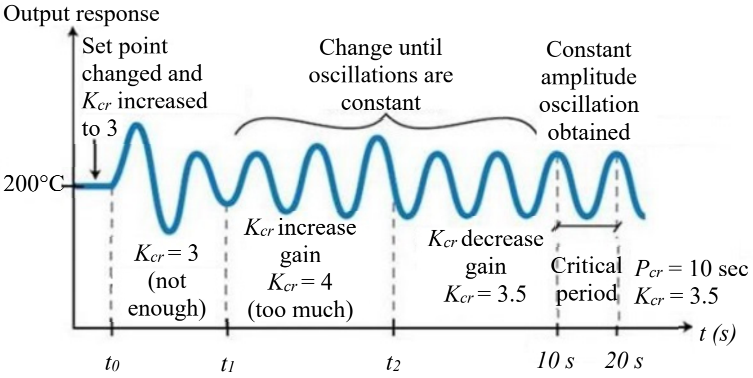

FIGURE 17: System tuned using the Ziegler-Nichols closed-loop tuning method (Control Laboratory, 2019)

3.5 Cohen-Coon method

Like the Ziegler-Nichols method, the Cohen-Coon method result in a quarter amplitude damping (Figure 15) and is designed for a non-interactive controller. So, if we have an interactive controller it should be converted to a non-interactive algorithm (Table 5).

TABLE 5: Cohen-Coon PID control formula (Cohen and Coon, 1953)

	Controller gain	**Integral gain**	**Derivative gain**
PI Controller	$Kc = \frac{0.9}{gp}(\frac{\tau}{t_d} + 0.092)$	$Ti = 3.33t_d \frac{\tau + 0.092t_d}{\tau + 2.22t_d}$	
PID Controller	$Kc = \frac{1.35}{gp}(\frac{\tau}{t_d} + 0.185)$	$Ti = 2.5t_d \frac{\tau + 0.185t_d}{\tau + 0.611t_d}$	$Td = 0.37t_d \frac{\tau}{\tau + 0.185t_d}$

3.6 Internal Model Control (IMC) method

The Internal Model Control (IMC) or sometimes called Lambda tuning is one of the well-known methods such as the Ziegler – Nichols method. It is a system model-based control developed by Garcia and Morari in 1982 (Muhammad et al., 2010). The Internal Model Method (IMC) has long been recognized, as well as Ziegler – Nichols, for its high tuning performance. The controller gain (Equation 11) is affected by the filter time constant. The greater the filter time constant, the smaller the controller gain. Meanwhile, integrals (Equation 12) and derivatives (Equation 13) are not affected by the time constant filter.

$$K_c = \frac{\tau}{g_p(\tau_{cl} + t_d)} \tag{11}$$

$$T_i = \tau \tag{12}$$

$$T_d = \frac{\tau_i}{4} \tag{13}$$

The value $\boldsymbol{\tau}_{cl}$ is a filter time constant that is determined by the user. Value of $\boldsymbol{\tau}_{cl}$ follows Equation 14 to obtain a very stable control loop. The higher the value of the filter time constant the slower the control loop and the smaller the filter time constant the faster control loop (Rivera et al., 1986, modified by Smuts, 2010c).

$$\tau_{cl} = 3\tau \tag{14}$$

3.7 Modelling data

The rock muffler system functions as protection when the power plant is supplied by excess steam which cannot be accepted by the turbines. It prevents the pressure in the pipeline from reaching higher values which could cause vibrations and damage to the pipe.

The turbine inlet pressure is maintained at 7.6 Bara and in the scrubber at 8.2 Bara. 0.6 Bara is estimated to be lost when steam passes through the scrubber vessel. To maintain this pressure a control system is needed on the rock muffler line where the pressure transmitter is installed for monitoring and become process variable when tuning PID. The control valve in this system is the final element that makes pressure adjustments in the pipeline so that the turbine inlet pressure is maintained (Figure 18).

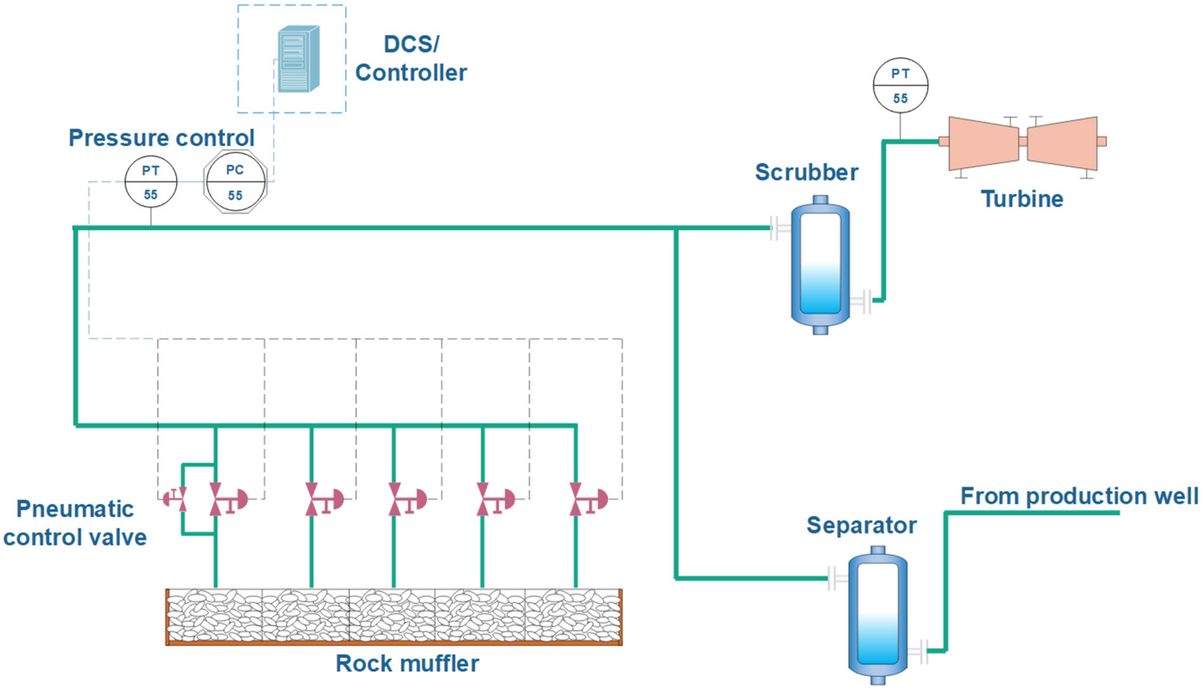

FIGURE 18: Vent station (rock muffler) pressure control

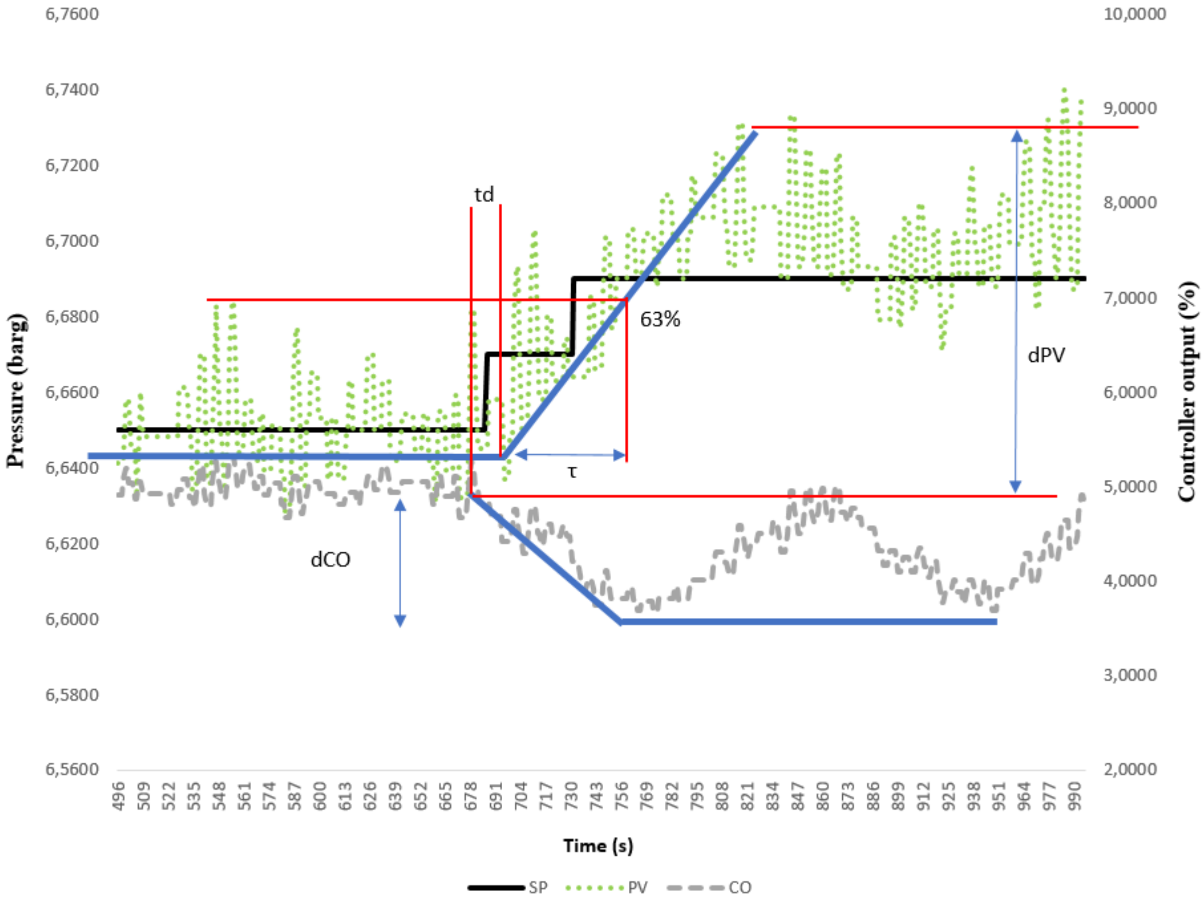

FIGURE 19: Vent station response data in units 3 and 4, Ulubelu

The following are real-time data taken from DCS on the vent station system (Figure 19). Data is in seconds and converted to minutes to determine controller parameters. The first step is to take the data where the steady state occurs when the setpoint is fixed. Secondly, the level between the controller response and the process variable is established and the dead time or delay time is determined. We also determine the difference in the value of the controller output (*ΔCO*) and the process variable at initial and steady-state conditions. Looking at the Ziegler - Nichols rule, the time constant is obtained from calculating 63% of the changes in process variables until steady state conditions occur. However, this applies to the self-regulating process.

$$\Delta PV = dPV = P_2 - P_1 \tag{15}$$

$$\Delta CO = dCO = CO_2 - CO_1 \tag{16}$$

4. MODELLING AND ANALYSIS CONTROL SYSTEM IN ULUBELU GEOTHERMAL FIELD

In making control system modelling, we need an appropriate method to analyse the system response. The Ziegler-Nichols method and the Internal Model Control (IMC) method are used for the modelling and analysis of pressure controls at the rock muffler station of the geothermal power plant in Ulubelu. The Ulubelu control system uses the closed-loop method where feedback is provided as controller input.

4.1 Modelling and analysis using the Ziegler-Nichols method

The Ziegler-Nichols method can be used for open-loop and closed-loop systems. Both of them use a different algorithm. The Ziegler-Nichols closed-loop tuning method is only applicable to closed-loop systems and cannot be applied in open-loop systems (Ikpe et al., 2016).

TABLE 6: Result of Ziegler – Nichols first method

Controller	K_c	T_i	T_d
PI	2.077	1.444	
PID	2.769	0.867	0.217

By entering the control parameter values from Table 3 we get a parameter controller as shown in Table 6 and by using a Python program we get a graphical controller and system response as shown in Figure 20. In the modelling results of the Ziegler-Nichols method can be seen that the process variable has an overshoot and oscillation occurs following the setpoint change. One of the characteristics of this method is the quarter amplitude response to setpoint changes.

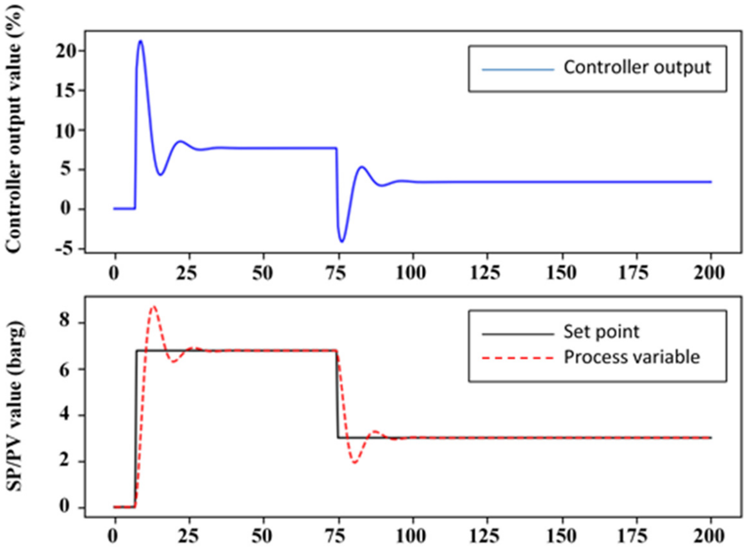

FIGURE 20: Ziegler-Nichols PI control modelling

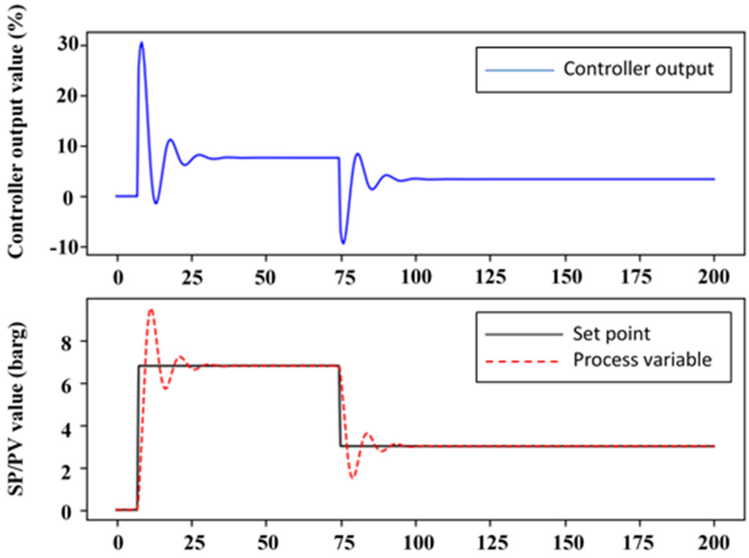

FIGURE 21: Ziegler-Nichols PID control modelling

Still using Table 6, but the parameters used are PID (K_c, T_i, and T_d) and still using the same equation modelling with graphs is obtained as in Figure 21. Rise time for PID control is better but the overshoot generated is higher.

In the graph in Figure 21, the response of the controller is better than using the PI control, but the overshoot becomes higher. So, an adjustment is needed to reduce the overshoot and make it more stable. Using the Python optimization program, we can produce better responses where the rise-time is slower, but overshoot and oscillation are more stable and can be tolerated (Figure 22).

By using the Python program modelling (Appendix I) the PID control using the Ziegler - Nichols method the result is optimized. The results of the optimization obtained by research (Ikpe et al., 2016) are not much different from Figure 22, but the resulting overshoot and oscillation is improved and can still be tolerated during operations. Optimization results are $K_c = 1.83$, $T_i = 3.75$ and $T_d = 0.0$.

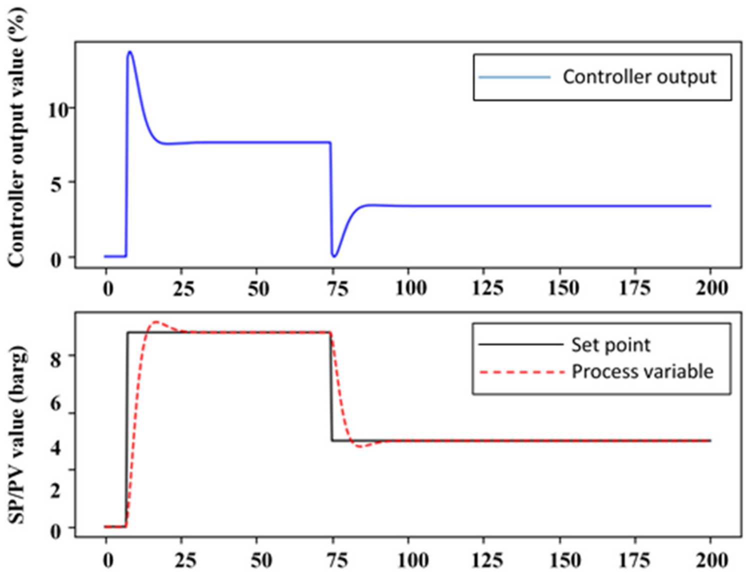

FIGURE 22: Ziegler-Nichols PID control modelling optimized

4.2 Modelling and analysis using the Cohen-Coon method

The second modelling approach is using the Cohen-Coon method (Cohen and Coon, 1953). The Cohen-Coon method is used for fast response control. The results for the controller parameters PI and PID are presented in Table 7. From these parameters we derive a model for the process variable and controller output as shown in Figures 23 and 24.

TABLE 7: Result of Cohen-Coon method

Controller	**K_c**	**T_i**	**T_d**
PI	2.424	0.765	
PID	3.777	0.925	0.148

Using the Cohen-Coon method produces a controller gain value that is smaller than from the Ziegler-Nichols method modelling and produces better (less) overshoot (Figures 23 and 24). But the overshoot that occurs is still above 5% and there is oscillation (Quarter Amplitude). Similarly, the controller output produces better peak values than the Ziegler-Nichols approach. The Cohen-Coon method is suitable for the control process in geothermal systems that require fast responses.

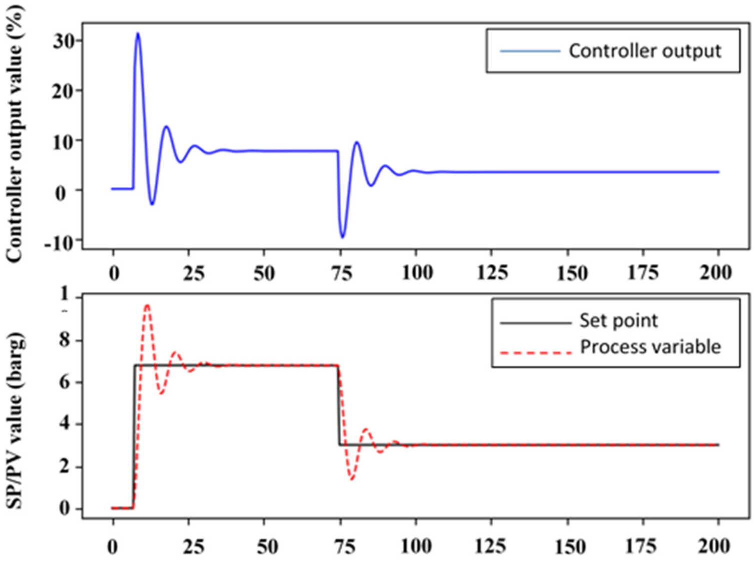

FIGURE 23: Coohen-Coon PI control modelling

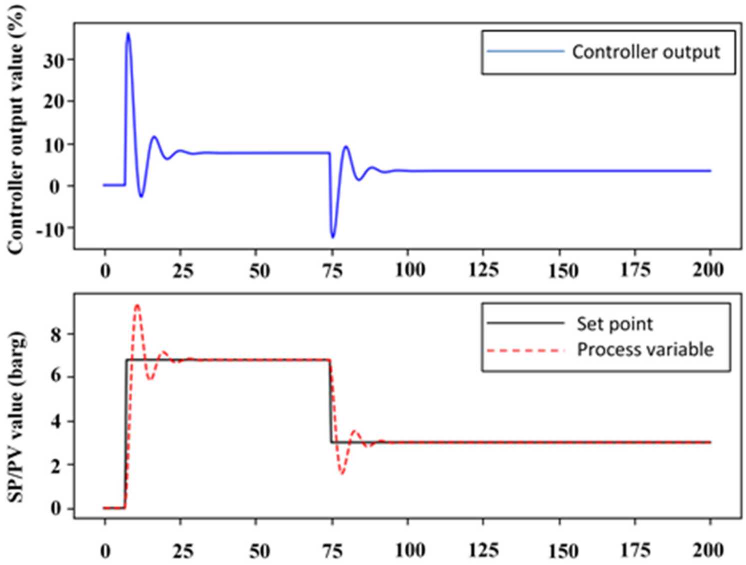

FIGURE 24: Cohen-Coon PID control modelling

4.3 Modelling and analysis using internal model control (IMC)

Internal Model Control is used if stable response results are expected but do not concern the resulting rise time. Usually, IMC has a relative slow rise time when compared to Ziegler-Nichols or Cohen-Coon. The following calculations are generated by entering data into Equations 8, 9, and 10. In the IMC method, the filter time constant used is $\tau_{cl} = \tau$, $\tau_{cl} = 3\tau$ and $\tau_{cl} = 6\tau$. Table 8 shows the results of *PI* and *PID* control calculations using the IMC algorithm where $\tau_{cl} = \tau$.

TABLE 8: Result of Internal Model Control (IMC), $\tau_{cl} = \tau$

Controller	**K_c**	**T_i**	**T_d**
PI	0.783	1.000	
PID	0.783	1.000	0.250

The Python program calculates and creates graphs as shown in Figures 25 and 26. The graph shows that the response of the process variable is fast. There is no overshoot but the controller output generated overshoot of more than 10%. For PID control, oscillation occurs before a steady state is reached. Likewise, for the output controller oscillation occurs when the setpoint changes.

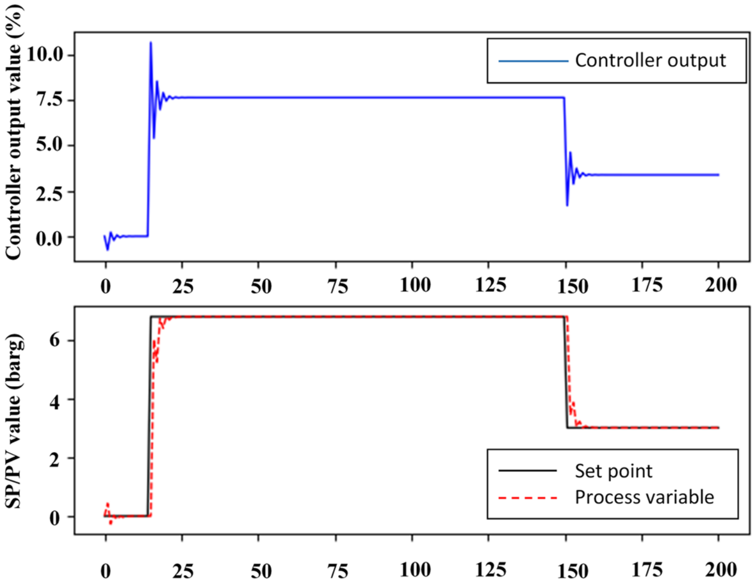

FIGURE 25: IMC PI control modelling, $\tau_{cl} = \tau$

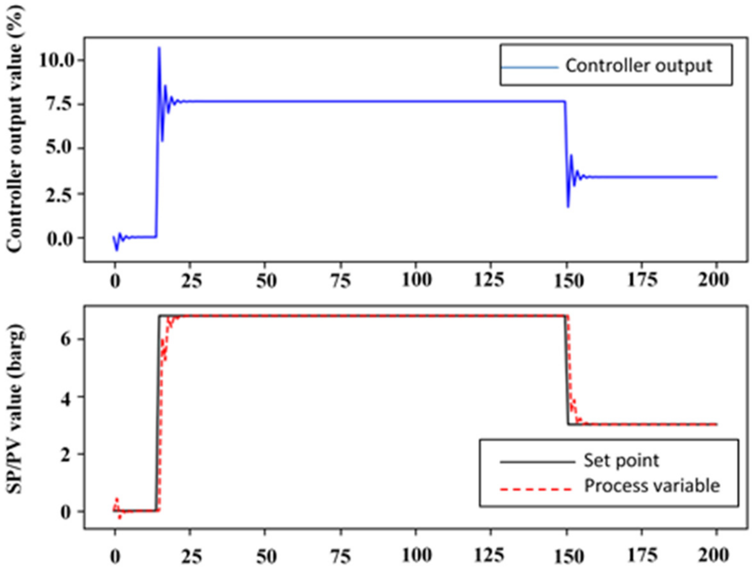

FIGURE 26: IMC PID control modelling, $\tau_{cl} = \tau$

TABLE 9: Result of Internal Model Control (IMC), $\tau_{cl} = 3\tau$

Controller	K_c	T_i	T_d
PI	0.327	1.000	
PID	0.327	1.000	0.250

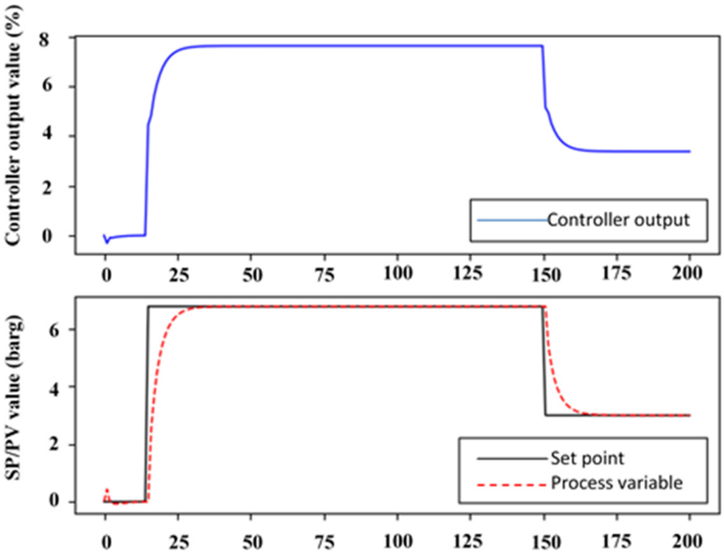

FIGURE 27: IMC PI control modelling, $\tau_{cl} = 3\tau$

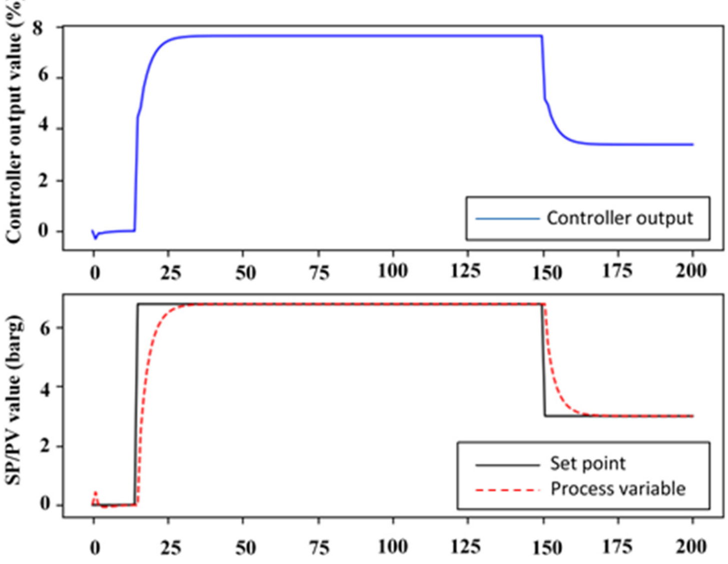

FIGURE 28: IMC PID control modelling, $\tau_{cl} = 3\tau$

The filter time constant $\tau_{cl} = 3\tau$ compared to $\tau_{cl} = \tau$ it looks more stable, but the rise time obtained is slower. Table 9 shows the calculation results for Internal Model Control (IMC) using $\tau_{cl} = 3\tau$. The difference to Table 8 is the gain controller K_c. The higher the filter time constant, the smaller the controller gain value, and the slower the response of the controller. The modelling results are shown in Figures 27 and 28. For PI and PID control using a time constant filter three times the time constant (3τ) the response is more stable, but the resulting rise time is slower.

If the time constant filter τ_{cl} is enlarged up to 6τ it will produce a smaller controller gain (Table 10). Figures 29 and 30 show the PI and PID control responses for the filter time constant 6τ and the resulting rise time is much slower.

According to Smuts (2010c), the response is optimized if a filter time constant of 3τ is used. One of the advantages of using the IMC method is that there is no overshoot. The IMC method is suitable for processes that require stable responses.

TABLE 10: Result of Internal Model Control (IMC), $\tau_{cl} = 6\tau$

Controller	K_c	T_i	T_d
PI	0.174	1.000	
PID	0.174	1.000	0.250

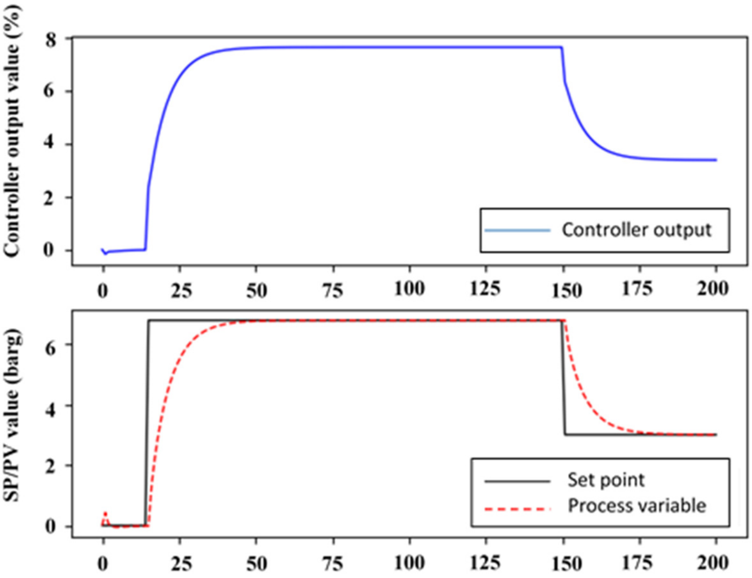

FIGURE 29: IMC PI control modelling, $\tau_{cl} = 6\tau$

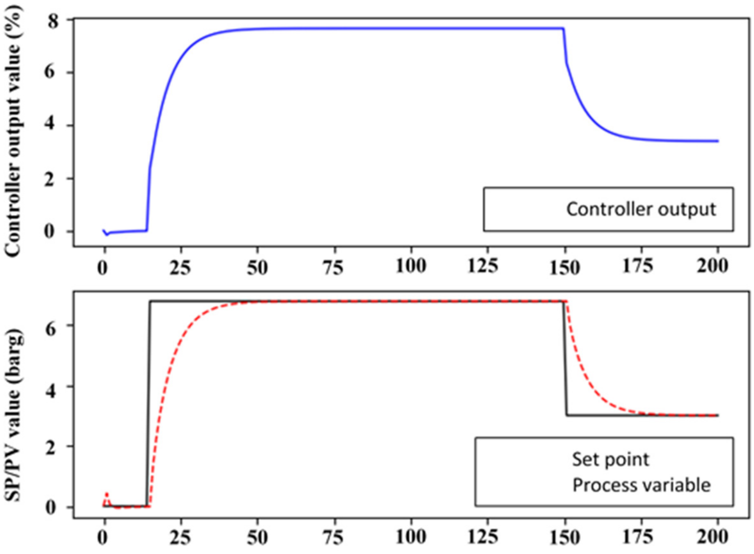

FIGURE 30: IMC PID control modelling, $\tau_{cl} = 6\tau$

5. CONCLUSION

Modelling results show that the methods used for tuning and optimizing produce different responses. The Ziegler-Nichols and Cohen-Coon methods produce a response that is fast but also produces a quarter amplitude response.:

- The Ziegler-Nichols method is easy and very simple to use, but requires fine-tuning, the controller setting is aggressive resulting in large overshoot and oscillatory response (quarter amplitude responses) and performance is poor for processes with a dominant delay.
- The Cohen-Coon method is suitable for a fast response control but still produces oscillations like Ziegler-Nichols. Overshoot and oscillation can be minimized by reducing the controller gain manually.
- The Python program is powerful for programming and can optimize the results of the Ziegler-Nichols and Cohen-Coon methods.

- Internal Model Control (IMC) is a stabilizing tuning method which is widely used for process control when stable response without overshoot and oscillation is needed. The disadvantage of the Internal Model Control (IMC) method is the very slow response.

In geothermal single-flash systems, there are a lot of control systems that have different responses and characteristics. Flow control in wells, pressure control in vent stations, pressure control MCV inlet turbine, and pH control in dosing systems are systems that can be categorized as self-regulating with different response control. For example, a vent station is a system that needs fast response for protection of pipelines if overpressure occurs, but MCV in turbines needs stable control because of its sensitivity to changes in the opening of the valve supplying steam into the turbine to generate electricity. Level control such as separator and condenser level control are categorized as non-self-regulating control or integrating control. Both have different response controls. Separator level control needs fast response and the condenser level needs stabilizing response control.

NOMENCLATURE

PV = Process variable
P = Proportional control
PI = Proportional and integral control
PID = Proportional, integral and derivative control
K_c = Proportional gain
T_i = Integral time constant
T_d = Derivative time constant
$e(t)$ = Error change of time
K_p = Proportional gain
K_i = Integral gain
K_d = Derivative gain
t_d = Dead time
S = Laplace frequency domain
$G(t)$ = Controller output in time domain
$G(S)$ = Controller output in frequency domain
Rise time = Time it takes for the response to rise from 10% to 90% of the steady-state response
Settling time = Time it takes for the error between the response $y(t)$ and the steady-state response y_{final} to fall to within 5% of y_{final}
Overshoot = Percentage overshoot, relative to y_{final}
Peak time = Time at which the peak value occurs

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APPENDIX I: Python program for PID modelling

Python programming

```
"""
Created on Mon Sep 2 11:16:26 2019
@author: Firdaus
"""
#PROGRAM PID CONTROL MODELING
from gekko import GEKKO
import numpy as np
import matplotlib.pyplot as plt

m = GEKKO()
tf = 200
m.time = np.linspace(0,tf,2*tf+1)
step = np.zeros(2*tf+1)
step[0:15]=0
step[15:150]=6.78
step[150:]= 3.0

#PID CONTROLLER MODEL
Kc = m.FV(value=9.19,lb=0.0,ub=10.0)
Kc.STATUS = 1
TauI =m.FV(value=0.45,lb=0.0,ub=10.0)
TauI.STATUS = 1
TauD = m.FV(value =0.03, lb=0.0, ub=10.0)
TauD.STATUS =1
OP_0 = 0.0
OP1_0=0.0
OP = m.Var(value=0.0, lb = 0.0, ub = 100.0)
PV = m.Var(value=0.0, lb =0.0, ub = 10.0)
SP = m.Param(value=step)
Int = m.Var(value=0)
err = m.Intermediate(SP-PV)
m.Equation(Int.dt()==err)
m.Equation(OP==OP_0+Kc*err+(Kc/TauI)*Int-Kc*TauD*PV.dt())
m.Obj(err**2)

#PROCESS MODEL
Kp = 0.83
TauP = 0.21
x = m.Var (value=0)
m.Equation(5.0*x.dt()+x==OP)
m.Equation(TauP*PV.dt()+PV==Kp*x)

m.options.IMODE=6
m.solve(disp=False)
LKc = str(round(Kc.Value[0],2))
LTi = str(round(TauI.Value[0],2))
LTd = str(round(TauD.Value[0],2))

plt.figure()
plt.subplot(2,1,1)
plt.plot(m.time, OP.VALUE, label='Controller Output')
```

```
plt.title('Optimilization PID Control')
plt.ylabel("Controller output Value")
plt.subplot(2,1,2)
plt.plot(m.time,SP.VALUE)
plt.plot(m.time,PV.VALUE)
plt.text(175.0,15.0, 'Kc = '+LKc)
plt.text(175.0,14.0, 'Ti = '+LTi)
plt.text(175.0,13.0, 'Td = '+LTd)
plt.ylabel ("SP/PV Value")
plt.xlabel("Time(m)")
plt.show()

print('Kc  : ' + str(Kc.VALUE[0]))
print('TauI  : ' + str(TauI.VALUE[0]))
print('TauD : '+ str(TauD.VALUE[0]))
```