Development of Virtual pH Analyzer with PID Gain Scheduling Control Method

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***Abstract*—This paper presents the development of virtual pH analyzer that equipped with PID Gain Scheduling control method. This project is implemented using LabVIEW and the functionality of the instrument is tested. The outcome of the project is the flexible instrument that replaces the traditional instrument for pH measurement and control.**

Keywords:
pH Analyzer; LabVIEW; PID Gain Scheduling

I. INTRODUCTION

The rapidly developed in the instrumentation field such as sensing, hardware and software technologies known as virtual instrument [1] give a new scenario to create flexible and sophisticated instruments for various applications. From literature [3], the virtual instruments are defined as the software-oriented instrument that utilize the computing power, display and connectivity capabilities of modern computers applications for measurement and control [2].

In the past, the measurement of pH involves the use of multiple instruments such as pH electrode, pH meter connected to a strip chart recorder and some other data acquisition devices. Figure 1 shows the conventional pH meter setup. The conventional pH meters were solely indicator instrument, no pH control system element and unable to modify with new processing method. In some cases, most of the time a sensor failure would result in a false indication of neutral pH value of 7. Also, there were no error indicators, no alarms triggered; even the actual process was too acidic or alkaline.

Figure 1: Conventional pH Meter

Today, some pH analyzers have already advanced diagnostics, but it is costly. For new trends in pH technology, there are many problems occurred in majority of well-known industrial when utilized the pH sensor in the traditional pH analyzer such as aging of the pH glass, need to plug the reference junction and can effect poisoning of the reference electrode [8].

The research work carried out by [5] where the objective for this paper is to find the best combination between a various pH sensitive materials and detection methods depend on the type of physical and chemical behavior applications. This paper discusses various pH sensitive materials and detection methods, their physical and/or chemical behavior applications. The results were showed that the pH measurement was applied to find the chemical characteristics of a substance. Finally, certain materials can not only be detected by standard detection method but also with other detection techniques.

This project is aim to develop the virtual pH analyzer that replace the conventional technique of pH measurement. Basically, this project is a continuation work done by [27] in which the improvement of the previous work includes the additional features which is pH control system using PID Gain Scheduling.

The experiment of [6] also implemented gain scheduling control method. When applied the optimal gain switching operate in a different load points, the digital governor to have a substantial reduce the noise on the command signal and up to 42% faster responses to desired performance. In the non-linear control strategies, digital governor to have a 2.5% to 2% reduction in speed overshoot on startups, and an 8% to 1% reduction in undershoot on load rejections.

Ker-Wei, Yu and Jia-Hao Hsu [7] also implemented PID Gain Scheduling. In this experiment, the instrument is modified by using fuzzy system control to keep the heading angle of vessel on the fixed direction for the nonlinear ship dynamic performance. The simulation result for the performance of the proposed controller is quite good.

II. OBJECTIVE

The objective of this project is to improve the previous virtual pH analyzer in term of pH of control system. Other than that is to evaluate the functionality of virtual pH analyzer with PID Gain Scheduling control is discussed whether it's functioning well or not.

III. pH ANALYZER

The pH meter is designed to measure voltages of an electrode that sensitive to the hydrogen ion concentration, relative to another electrode which exhibits a constant voltage. The measurement can determine whether the substance is an acid or a base, and it will give the exact alkalinity or acidity of the substance. The sensing electrode provides a potential proportional to the logarithm of the hydrogen ion activity in the sample [9].

Figure 2 shows the virtual pH analyzer developed by [27]. The developed pH analyzer consists of two main parts namely pH meter and pH analyzer.

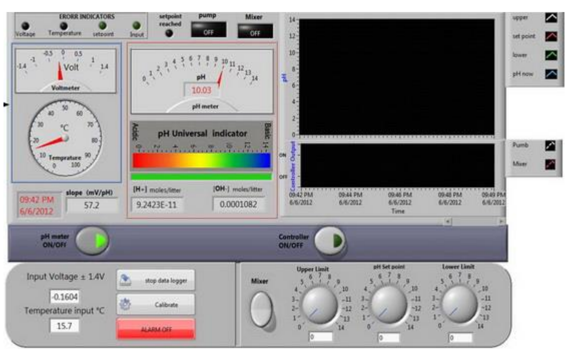

Figure 2: Front panel of virtual pH analyzer

According to this project, pH meter was used to indicate the pH value whereas the pH analyzer was used as the controller. The pH of the solution is measured using pH sensor. Then, this measured signal will be compared to the desired value via pH analyzer.

However, the control method implemented in the previous virtual pH analyzer only comprise of ON-OFF pH control. The pH analyzer provides ON/OFF control system so that the signal to the actuator controlling the reagent addition is always set in one of two positions, either fully open (ON) or fully closed (OFF). However, this result to rapid cycling and it could damage the final control element [15].

Hence, the efficient and flexible instrument with an easy way to test and simulate the pH measurement needs to be created to replaces the traditional instrument for pH measurement and control such as PID Gain Scheduling control method. The simulation using LabVIEW can save the time, reduce calibration errors, and limit the amount of calibration solution used.

IV. THEORY OF pH MEASUREMENT

The pH is a measure of the acidity or alkalinity of a water solution. The measurement of hydrogen depends on an ion concentration in a liquid solution. A solution with a low pH value is called an "acid," while one with a high pH is called a "alkaline." The common pH scale extends from 0 which is a strong acid to 14 is strong alkaline, with 7 in the middle representing pure water is neutral.

The acidity or alkalinity of a water solution is determined by the relative number of hydrogen ions (H+) or hydroxyl ions (OH-) present. Acidic solutions have a higher relative number of hydrogen ions, while alkaline also called basic solutions have a higher relative number of hydroxyl ions. Acids are substances which either dissociates to release hydrogen ions or react with water to form hydrogen ions. Bases are substances that dissociate to release hydroxyl ions or react with water to form hydroxyl ions [11].

The pH value of a solution is measured by using pH electrode. The pH electrode uses a specially formulated, pH sensitive glass in contact with the solution, which develops a potential (voltage) proportional to pH of the solution [12]. The electrode can measure pH value using Nernst equation. It develops a potential that gives the output voltage, Vo proportional to pH value [4]. The output voltage of the pH electrode is temperature dependent as described by Eq. (1).

$$E = Eo + (0.000198\,)\,TpH \qquad ..(1)$$

Where; E = total measured voltage (mV)
Eo = intersect point value
T= measured temperature (K)

Temperature has a significant effect on pH measurement. Means, the temperature will effects on electrode slope [6]. Table I shows the Nernst slope variation with temperature effects on pH electrode.

TABLE I: NERNST SLOPE VARIATION TO TEMPERATURE

Temperature ºC	Nernst slope (mV/pH)	Temperature ºC	Nernst slope (mV/pH)
0	54.20	40	62.14
10	56.18	50	64.12
20	58.17	60	66.10

25	59.16	70	68.09
30	60.15	80	70.07

The isothermal point for ideal pH electrode is 0mV at 7pH with a Nernst slope of -59.16mV/pH at 25^{0}C. Nernst slope in the range of -55mV/pH to -60mV/pH and an asymmetry potential of ±15mV. The error will increase the temperature change. For this case, the correction factor based on 0.003pH/^{o}C/pH unit away from pH 7 is applied to the get the final reading of the pH analyzer.

V. pH Control System

The control system used to test a sample against a legal requirement by monitoring and controlling different chemical plants such as waste water treatment, electrochemistry and precipitation plants, production of pharmaceuticals, fermentation, and food production. Good pH control can be important for product quality as well as environmental compliance and at the same time the robustness of these processes [13], [15].

The pH control system can be defined as a system that measures the pH of an input solution and controls the addition of a neutralizing agent to maintain the output solution at the pH of 7, or within certain acceptable limits. A PID Gain Scheduling is a best suited for test the functionality of virtual pH analyzer.

A. *PID Controller and Tuning*

Most of the PID tuning methods available concentrate on improving tracking performance of the closed loop [14]. The PID controller performance is depends on the adjustment of the controller gains known as tuning. PID controller provides robust and reliable performance for most of the systems if the PID parameters are tuned properly [29], [30]. There are various tuning methods available in the literature. One of the most tuning methods is Integral of the time weighted absolute error (ITAE) [16], [17]. Minimizing ITAE is commonly referred to literature as a good tuning criterion to obtain PID parameters [18].

Using ITAE tuning rule, the controller gains can be calculated using Eqn. (2), Eqn. (3) and Eqn. (4).

$$K_p = \frac{0.965}{k}\left(\frac{L}{T}\right)^{-0.855} \quad \text{... (2)}$$

$$T_i = \frac{T}{0.796 + (-0.147)\left(\frac{L}{T}\right)} \quad \text{... (3)}$$

$$T_d = 0.308T\left(\frac{L}{T}\right)^{0.9292} \quad \text{... (4)}$$

Where;
K_p = Gain
T_i = Integral time
T_d = Derivative time

The term L and T in the equation represent the time delay and process time constant. Normally, the industrial process is represented using first order plus dead time (FOPDT) model as shown in Eqn. (5).

$$Gp(s) = \frac{ke^{-Ls}}{Ts + 1} \quad \text{... (5)}$$

B. *PID Gain Scheduling*

Gain scheduling is a PID Advance improvement control of a process with gains and time constants that vary according to the value of the control variable.

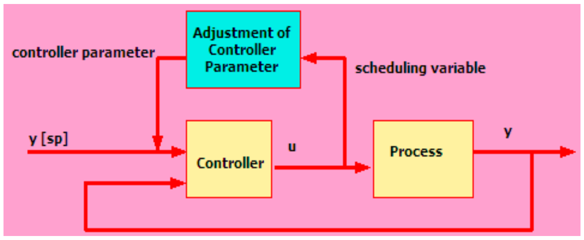

Figure 3: Gain Scheduling Block Diagram

The process model in Figure 3 applied equation as shown in Eqn. (6).

$$Gp(s) = \frac{4.8e^{-420s}}{3397s + 1} \quad \text{... (6)}$$

Features of Gain Scheduling

There are many features when applying gain scheduling control system in applications [10, 28]:

- Gain scheduling generates powerful linear design tools on difficult nonlinear problems of the system.
- Gain scheduling does not require severe structural assumptions on the plant model, and the approach can be used in the absence of complete, analytical plant models.
- Design by gain scheduling conserve well-understood linear observation and is carried out using the physical variables in the plant model.
- Gain scheduling is linear design are applied to the linear system at each operating conditions, and the wealth of linear control method.

- Gain scheduling enables a controller with constant parameters to respond rapidly to changing operating conditions.
- Gain scheduling is a very effective technique to cope with processes that change their characteristics with operating conditions.
- The computational burden of linearization scheduling approaches is often much less than for other nonlinear design approaches.

Assume that proper values of the PID parameters K_p, T_i and T_d are found when using the gain scheduling method for a set of values of the Gain Schedule (GS) variable. These PID parameter values can be stored in a parameter table of the gain schedule Table II. From this table proper PID parameters are given as functions of the GS.

TABLE II: GAIN SCHEDULE/ PARAMETER TABLE OF PID CONTROLLER PARAMETERS

GS	K_p	T_i	T_d
GS_1	K_{p_1}	T_{i_1}	T_{d_1}
GS_2	K_{p2}	T_{i_2}	T_{d_2}
GS_3	K_{p_3}	T_{i_3}	T_{d_3}

The controller parameters were determined at a number of operating conditions based on the scheduling variables [19].

VI. METHODOLOGY

The development of the virtual pH analyzer can be divided into two phases: pH meter and pH analyzer.

A. Flow Chart of pH Meter:

The pH meter VI code was developed as described by the Figure 4.

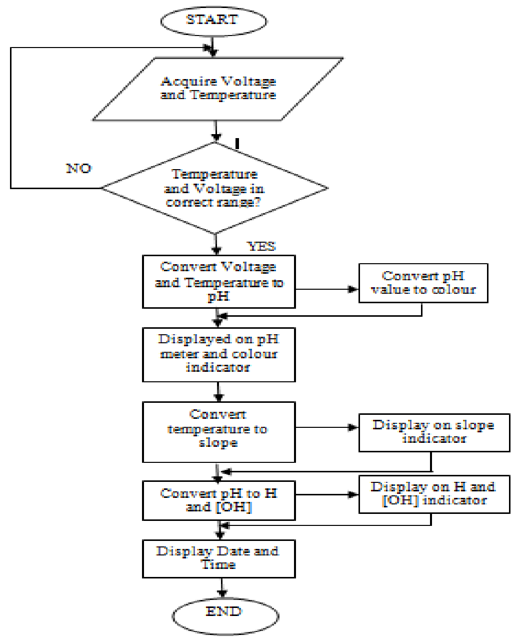

Figure 4: Flow Chart of pH Meter

Interpretation of Flow Chart:

- The VI acquires input voltage and temperature in correct range.
- The inputs will convert using Nernst formula such in Eqn. 1.
- The pH value was converted into color based on the type of substances and display on pH meter and color indicator.
- Next, it will convert temperature to slope, and pH to H and OH. The indicators will indicate for this measurement.
- The data also displayed the date and time measurement.

B. Flow Chart of pH Analyzer:

In this project, several sets of data containing a feature that have been extracted using PID Gain Scheduling method are being used. These data contain the input and control variable to test the functionality of virtual pH analyzer. All the components of virtual pH analyzer are performed in a loop structure that runs until the user decides to stop the operation of the instrument. Figure 5 shows the flow of the pH measurement for with and without gain scheduling.

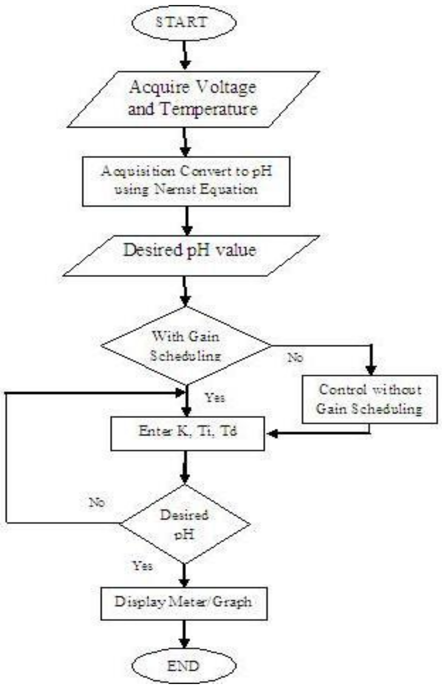

Figure 5: Flow Chart of pH Analyzer

Interpretation of Flow Chart:

- Start to test the functionality of virtual pH analyzer.
- VI acquires input voltage and temperature in the specific range of pH meter.
- Data Acquisition converted into pH using Nernst formula in Eqn. 1.
- The user can choose to select whether want to utilize with gain scheduling or without gain scheduling.
- If ≥ 1; please enter the value of process gain, K; gain, K_c; Integral time, T_i; and Derivative time, T_d. If ≤ 0; the simulation implemented control without gain scheduling. Please enter the value of K, K_p, T_i, and T_d.
- If ≥ 1; the output pH will display on the graph. If ≤ 0; turn to correct the pH value.
- End the simulation of pH measurement.

C. Design Process Flow Chart:

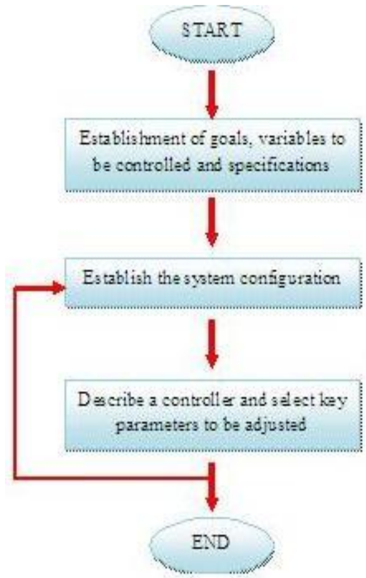

Figure 6: Design Process Flow Chart

Figure 6 shows the design process flow chart of gain scheduling. Gain scheduling enables linear design methods to be applied to nonlinear problems.

The stability and performance properties of the obtained gain scheduling controller can then be evaluated through both testing the functionality by LabVIEW [20], [21]. It refers to a system where the changing controller parameters based on measured operating conditions such as the scheduling variable can be the set point, the process variable, a controller output, or an external signal. It is effectively controls a system whose dynamics change with the operating conditions.

Many different design concepts can be configure as gain scheduling. The concepts using gain scheduling have made additional method such as the system is modified to be Fuzzy Gain Scheduling [7].Therefore, more advanced scheduling techniques have received considerable attention in recent years by various other ideas such as [6], [22], [23], [24], [25], [26], [28].

PID Gain Schedule VI can be used to apply different sets of PID parameters for different regions of operation of the controller. It selects range parameters to be adjusted and outputs one set of PID gains from a gain schedule based on the current value of its gain scheduling value input. For example, to implement a gain schedule based on the value of the control variable, wire the control variable value to the gain scheduling value input and wire the PID gains out output to the PID gains input of the PID VI such in Figure 3.

Table III shows the range of PID parameters to test the functionality of virtual pH analyzer.

TABLE III: PID PARAMETERS RANGES

Range of Process Gain, K	K_p	T_i	T_d
$0 \le K \le 2.8$	2.04	4367	150
$2.9 \le K \le 3.2$	1.8	4367	150
$3.3 \le K \le 3.7$	1.56	4367	150
$3.8 \le K \le 4.8$	1.2	4367	150
$4.9 \le K \le 5.7$	1.02	4367	150
$5.8 \le K \le 6.9$	0.84	4367	150
$7 \le K \le 8$	0.72	4367	150

Figure 7 shows gain scheduling input process gain, K that contains in the PID Gain Scheduling VI.

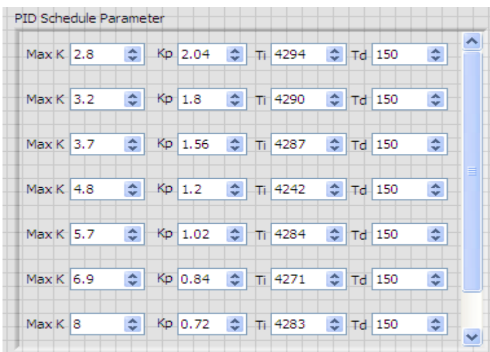

Figure 7: Gain Scheduling Input Process Gain, K

Finally, if the performance does not meet the specs, then the design process iterates the configuration. The designation establishes the system configuration again.

VII. RESULTS AND DISCUSSIONS

Figure 8 shows the front panel of the developed pH analyzer as a virtual instrument. Figure 9 shows the block diagram where programming modules for the pH meter while Figure 10 shows the pH analyzer were developed. The controls and data displays for the system are designed so that the observation and control of the system can be done via software environment. This measurement has 2 functions which can test the functionality with and without gain scheduling.

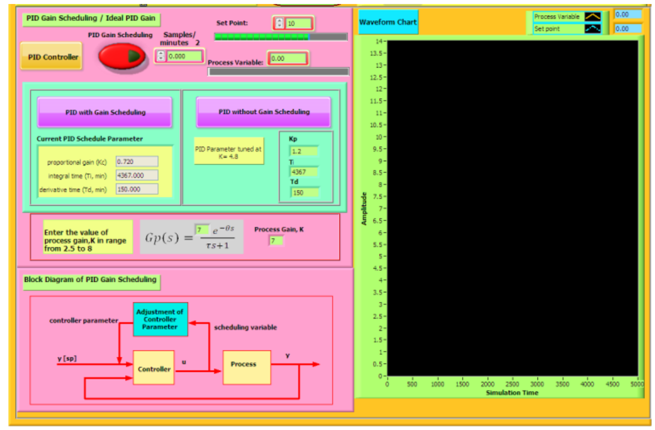

Figure 8: Front Panel of Virtual pH Analyzer

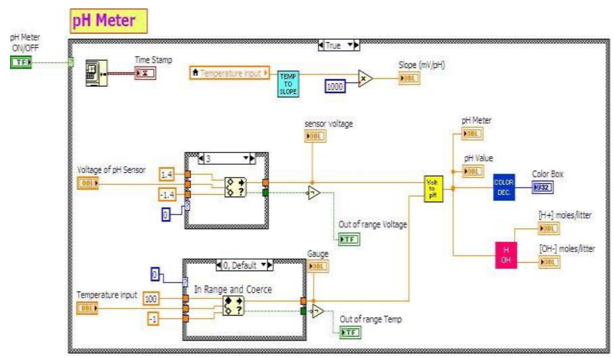

Figure 9: Block Diagram of pH Meter

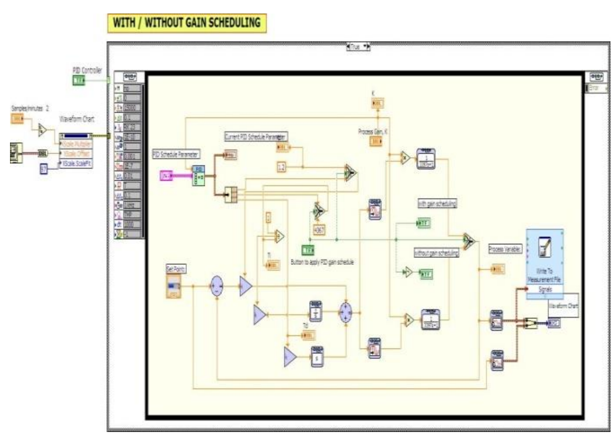

Figure 10: Block Diagram of Virtual pH Analyzer

A. *Control without Gain Scheduling*

The PID parameters, K_p= 1.2, T_i = 4367 sec and T_d =150 sec. Figure 11 shows the process response with *K* =*7* is observed.

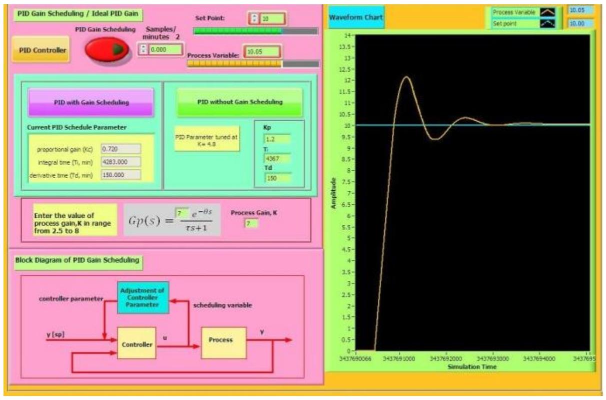

Figure 11: Process Response without Gain Scheduling at *K= 7*

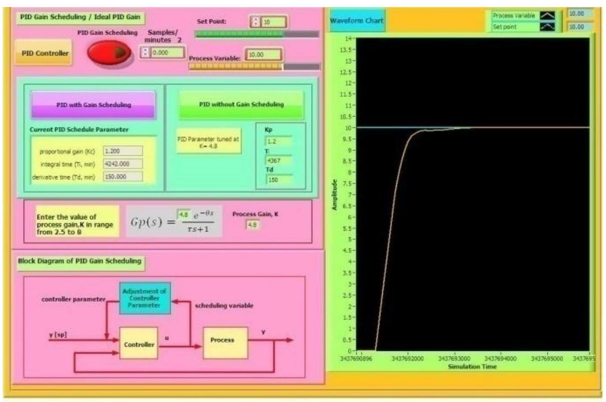

Figure 12: Process Response without Gain Scheduling at *K= 4.8*

From the result, the response for K = 4.8 is more stable such in Figure 12 than K = 7 in Figure 11. However, when the process gain increase at K = 7, the response for the percent overshoot (%OS) is higher than K=4.8.

Table IV shows the percent overshoot for a process without gain scheduling method. In term of overshoot for process gain, K = 7, the high percent overshoot with 20% compared to process gain, K = 4.8 is 0%.

TABLE IV: DYNAMIC PERFORMANCE WITHOUT GAIN SCHEDULING

Process Gain, K	**Percent Overshoot (%OS)**
4.8	0
7.0	20

B. Control with Gain Scheduling

The proportional control gain, K_p is correspond to the different value process gain are as shown in Table V with constant T_i = 4367 sec and T_d = 150 sec.

. TABLE V: PARAMETER LOOKUP TABLE FOR DIFFERENT GAIN

Process Gain, K	**Kp**
2.8	2.04
3.2	1.8
3.7	1.56
4.8	1.2
5.7	1.02
6.9	0.84
8	0.72

The response when implement the gain scheduling method to the process is as shown in Figure 13.

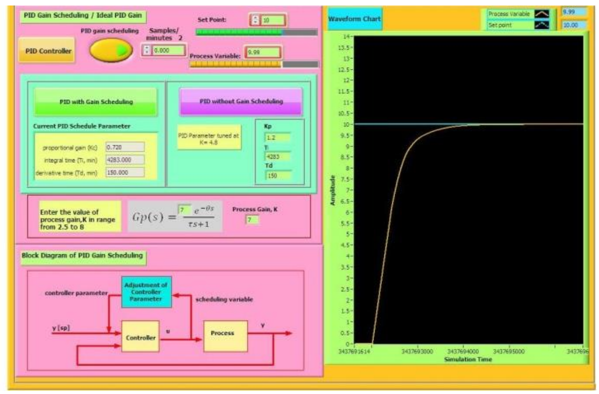

Figure 13: Process Response with Gain Scheduling at K=7

It is observed that the functionality evaluation improved when implement the gain scheduling control method in the process that follow the condition in Table V. In term of percent overshoot with using gain scheduling give zero overshoot.

TABLE VI: COMPARISON IN DYNAMIC PERFORMANCE

Process Gain, K=7	**Percent Overshoot (%OS)**
Without gain scheduling	20
With gain scheduling	0

C. Gain, K>8; Out of Range

The same PID parameters, K_p= 1.2, T_i = 4367 sec and T_d =150 sec is tested with and without gain scheduling by observed K=10.

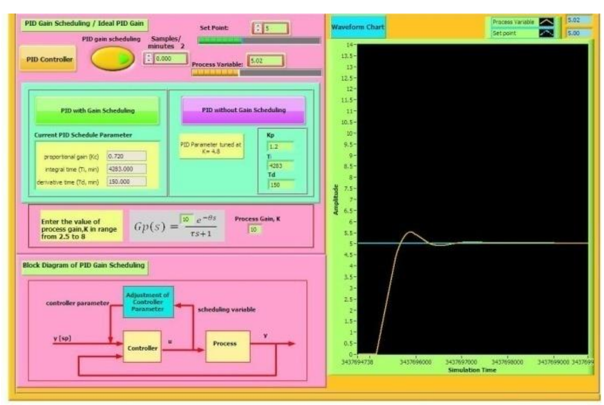

Figure 14: Process response with gain scheduling at K=10

From Figure 14, the evaluation graph is functioning well because the percentage of overshoot is only 10%, but it still can't to be reference of the range of gain, K in tested the functionality of evaluation.

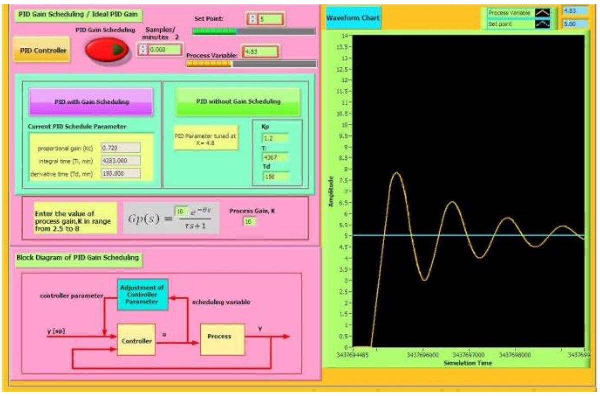

Figure 14: Process Response without Gain Scheduling at K=10

From Figure 14, the result from graph is high percentage of overshoot 60%. Table VII shows the data of percentage overshoot when K=10 where it is out of range of gain, K.

TABLE VII: COMPARISON IN DYNAMIC PERFORMANCE

Process Gain, K=10	**Percent Overshoot (%OS)**
Without gain scheduling	60
With gain scheduling	10

Finally, from the result in Table VI, the comparison in functionality evaluation with gain scheduling control method is better than when implement without gain scheduling. This is because the performance with gain scheduling is stabilized with 0% of overshoot characteristic. The graph shows smooth rapidly simulate in the system. For this case, prove that gain scheduling is perhaps one of the most popular approaches to non-linear control design and has been widely and successfully applied in field's applications process control.

CONCLUSION

Previous virtual pH analyzer [27] is improved with additional features which is implemented PID Gain Scheduling control. Virtual pH analyzer with PID Gain Scheduling control is successfully design and functioning well. For future development, it is recommended to improve the additional method by applying fuzzy logic controller which combines with PID gain scheduling to develop a virtual pH analyzer for pH measurement. The improvement by using fuzzy logic concepts is to compute the control action that incorporates a conventional design such as PID to certain plant nonlinearities due to universal approximation capabilities [31]. Other than that, design the hardware such as USB to connect the LabVIEW software and the pH measurement directly.

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