

Real Time Monitoring and Control of Scale Formation in the Geothermal Energy Generation Systems: A case study of Olkaria II, Kenya.

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Abstract

Exploration of Geothermal power has gained momentum in the recent past as it has proved to be dependable, has reduced green gas emissions, meet diversification needs, provides least cost base load mode of generation and is inexhaustible for billions of years to come. However, the development and exploitation of geothermal resource face a notable challenge of scale formation on the steam lines and most surface equipment, leading to reduced and expensive production. Scaling occur mainly due to deposition of solids carried by steam. One of the important scale solubility factor is the pH of the brine. Low pH levels are for example associated with Non Condensable Gases (NCGs) carryover which enhances scaling. Currently, use of Organic Rankine Cycle (ORC) and a secondary working fluid to drive turbines for initially differently designed geothermal systems, use of combined cycle plants or use of pH mod has led to reduced scaling and additional production. Use of ORC and combined cycle plant is not cost effective especially for modular wellhead plant while pH mod considers only scaling in reinjection pipelines. Scaling challenge therefore is still at large especially for initially installed single flush geothermal stations like Olkaria II leading to losses of large amount of energy.

This study explored the design and implementation of a virtual, real time scale level monitoring and control for geothermal energy generation system based on a physical T5554 analytic process control system. A virtual system was designed using Siemens NX and programmed using Totally Integrated Automation (TIA) software, PORTAL V14 via Programmable Logic Controller -1200 PLC, CPU 1214C DC/DC/DC 6ES7 214-1AG40-OXBO hardware. A set point pH of 6.5, an appropriate point to prevent silica scaling, as guided by the practice in Olkaria II was used with the PID of the PLC to control the pH of the analytic process control system. The virtual and the physical model were then linked to achieve communication through a channel called Open Platform Communication (OPC) via KEP server, which is an interoperability standard for secure and reliable exchange of data in industrial automation. Siemens NX design was configured to communicate with KEP server via External Signal Configuration feature. This facilitated the merger of control signals between Siemens NX design and TIA design. The TIA portal used links that specified the sensor and actuator control signals. The system was verified by taking pH readings of the two systems concurrently. When the pH Data of of the two systems were compared, they indicated a standard deviation of 8.25578E-4 in an acidic condition and a standard deviation of 0.01325 upon acidic condition correction by a metering pump of the physical T5554 analytic process control system, to a value around the set point. The deviation was so small that it did not affect the working of the system. This confirmed that the digital model could be used to accurately represent the physical system to achieve scale monitoring and real time control through managing the always changing brine pH in geothermal fields.

Key words: Geothermal systems, Scaling, Real time scale monitoring, Real time scale control.

I. INTRODUCTION

Access to clean, reliable and adequate energy is a key necessity towards economic and social development. For a long time, half of the electricity supply in Kenya is met by hydropower but recurring drought and changing climatic conditions rendered the hydro resource unreliable^[1] leaving customers susceptible to outages and black out during dry seasons .Electrical energy obtainable from geothermal sources is preferred as it lead to reduced green gas emissions , meet diversification needs ,is continually available and is associated with falling tarriffs in electricity bills due to their nature of least cost base load^[1]. It has a high capacity factor at over 95% as compared to hydro power which runs at 42% below capacity^[1]. Currently, Kenya; is the eighth largest geothermal producer in the World^[2] and has highest geothermal potential in Africa with 10000MW at 55%, followed by Ethiopia with 5000MW at 38.45%, and Djibouti with 1200MW at 6.6%^[1]. Geothermal is expected to be an essential resource in the future of Kenyan power system^[3]. In fact, the

frequency of geothermal installation and capacity loads generated on numerous sites in Kenya have greatly outpaced the hydro power^[1]. Geothermal accounts for 50% of Kenya's Clean Energy Investment at US\$ 3.4 Billion between 2010-2018^[4].

However, to benefit effectively from geothermal resources, careful management of steam field is crucial to ensure that resources are not depleted and that hazardous chemicals are properly managed^[5]. All the relevant parameters in an operating geothermal system need to be monitored to allow action and to preserve production integrity^[6]. The steam which is the carrier of energy from the subsurface, comes in impure form and causes a lot of corrosion and scaling to most of auxiliary and surface equipment along the way^[7]. Scaling is the deposition of solids in the streamlines and it forms the major cause of difficulty in geothermal systems^[7]. Scale prevention and control is an important consideration for geothermal system, as it affects production during operations and the amount of load produced^[11]. Current research indicates that strategies such as use of Organic Rankine Cycle (ORC) bottoming plant, combined cycle plants, silica gel to bind the dissolved silica or pH mod can be used to mitigate silica scaling^[9]. However, addition of an ORC and use of combined cycle plants is not typically cost effective especially for modular wellhead plants^[14]. The pH mod strategy on the other side, only takes care of re-injection pipelines^[15] and not the other important parts of the geothermal system. At the same time, use of pH modification and NCGs injection need routine monitoring of the systems^[15]. Use of silica gel is not appropriate because formation of silica monomers and the required turbulence activity may lead to brine heat loss leading to reduced production. These challenges means that scaling challenge is still at large, especially for initially designed single flush geothermal stations like Olkaria II which lead to great losses.

Olkaria II is a high temperature liquid dominated type, with a down average temperature of between 230° -260° C, with heat source magmatic intrusions located at the depths of about 5-8 km and high chloride bicarbonate waters with low pH and high gas content ~ 0.75 % in steam by weight^[12]. Olkaria II started production in 2003 when KenGen commissioned two 35MW units and a third one of 35MW in 2010^[7]. Olkaria II which works on a single flush plant cycle started with unit 1 turbine taking a steam at a flow rate of 69.4kg/s^[7]. Two years down the line, the steam chest pressure increased from 3.5 bar-4.1 bar and a steam consumption increased to 72.2Kg/s with turbine power generation capacity of 34.3MWe out of rated 35MWe^[6] due to Sulphur deposition reducing the efficiency and power output^[12]. Geothermal power production running parameters which include pH, pressure and temperature^[10] are kept in logs and computer backups, and its' analysis determine the effectiveness of the power plant performance. Individual equipment and process logs are used to evaluate equipment and plant status. Production parameters for Olkaria II are recorded manually and others are backed up in computers for easy recall, and they give a good indication on the status of the equipment and plant, but they fail to quantify the maintenance problem^[7] unless the system is opened to access the internal parts. This leads to production stoppage in Olkaria II for scaling removal leading to great losses. Elimination of 'manual' monitoring of scales build up is of utmost importance in order to realize efficient use of geothermal energy and to ensure continual production.^[7] Scaling of geothermal equipment need to be automatically monitored and mitigated as early as possible because controlling is easier than removing scales^[11]. There is need to develop an automated method for scale monitoring and prevention to reduce downtime and costly manual maintenance. Since one of the factor that determines the solubility of silica is the pH^[9] and considering that it also affects the stability of minerals in geothermal brine^[10], pH then forms an important consideration if scaling challenge has to be dealt with. This study presents the design and implementation of a Real Time Monitoring and Control of Scale Formation by use of pH variation, in the Geothermal Energy Generation Systems, represented as analytic process control system model T5554, as access to an actual geothermal system was a challenge. The research made use of using digital twin technology, which forms a key component in the fourth industrial revolution^[3] as it harnesses automation for industrial processes through connectivity of devices which encompasses; digitalization, internet of things, networking technologies, cloud computing and cyber physical systems^[16].

II. MATERIALS AND METHODS

The research involved coming up with a digital model /virtual representation in cyberspace for an existing physical geothermal system represented as an analytic process control system model T5554 as shown in Figure 1, for real time scale monitoring and control, by use of variable pH. This involved a closed loop system for control as it was designed to receive operating information from the analytic control system and make appropriate adjustment based on this information. A change in pH into acidic status in the analytic process control system as in Olkaria II, would therefore trigger the necessary action in order to maintain the required set point value through the digital model leading to reduced or avoidance of scale silica build up. The pH set point used was 6.5, a level in which optimum load power production tends to happen in Olkaria II. This research was therefore used to show how scaling challenge can be dealt with in geothermal systems, through managing inappropriate pH levels that tends to enhance scaling^[9]. The digital model used was designed using Siemens NX 12.0.2 and programmed via Totally Integrated Automation (TIA) platform to synchronize in functionality and

geometry with the physical analytic process control system and then, the two systems were linked together for information flow, as shown in the adopted model, in Figure 2.



Figure 1: The Physical, T5554 Analytical Process Control System^[17]

The Siemens NX which is a powerful design software was used to design discrete Computer Aided Design (CAD) components of the analytical process system after determining their actual dimensions and then, using an integrated application called Mechatronics Concept Designer (MCD), assembling the various components in to one system. MCD application was also used to assign physical properties, motions and relevant joints to CAD models similar to actual systems to enable it simulate to ensure that the virtual system represented the working conditions of the actual analytic process control system^[3]. TIA on the other side was considered because it is effective in programming Programmable Logic Controllers (PLCs) hardware as it enables online communication, real time monitoring and integration with other features^[3]. The T5554 Analytical Process System used a Proportional Integral Derivative (PID) controller to correct variance or error whenever the process variable pH was below the Set Point pH. Process reactor tank which included an agitator to mix, held the process fluid and allowed the reagent to mix. Control inlet valve and eductor pump were used as manipulation instruments in this research, to change the pH of the reactor tank solution, to acidic status creating a resemblance status like that of Olkaria II, which caused disturbance in the reactor tank of the system. A sensor with a pH electrode determined the pH of the solution in the reactor tank, and this was fed as analogue processing input into the 1200 PLC, CPU 1214C DC/DC/DC 6ES7 214-1AG40-OXBO which then controlled the output of the Electronic metering pump by addition of basic solution to the reactor tank to ensure that the pH was corrected back to the Set Point value. The pH level measured by the electrode was transmitted as a 4-20mA signal and it provided a feedback to control the electronic metering pump device for basic solution dosing. Since the pH sensor was giving out an analogue output, it was scaled, normalized and then fed into the PLC.

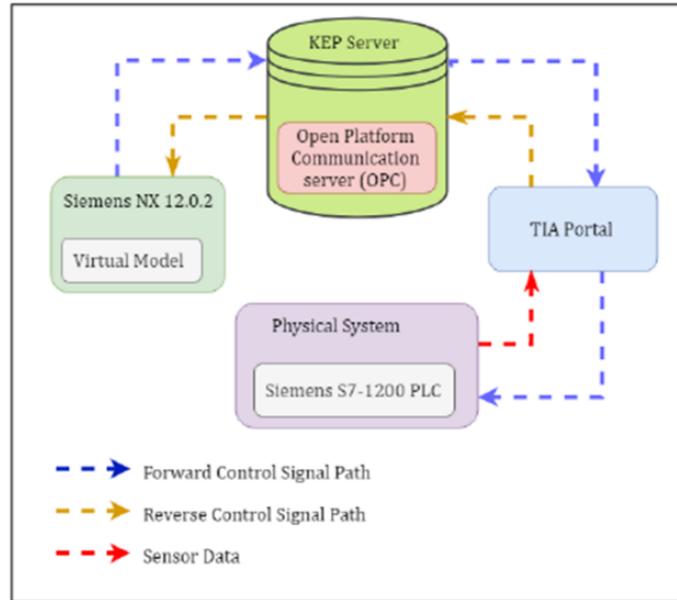


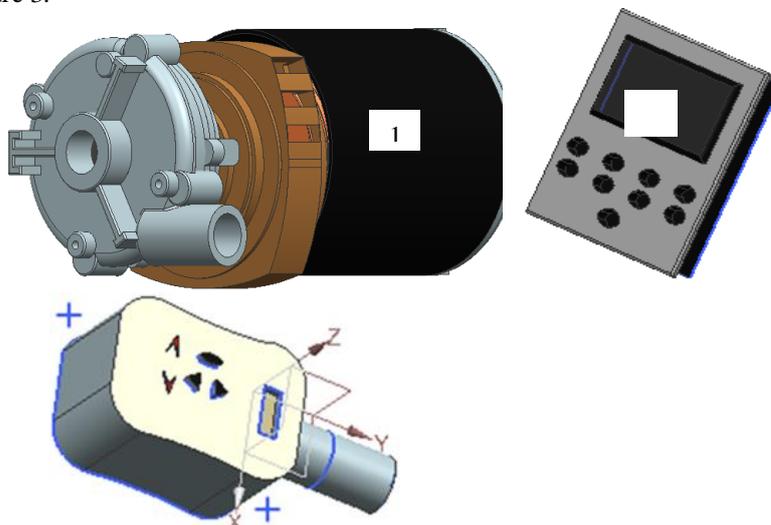
Figure 2: Block diagram of digital twin implementation ^[3]

The sensors input of the system were assigned to the PLC input module addresses whereas the respective actuators were assigned the PLC output module addresses. The physical processes were defined and sequenced in code through the use of ladder network diagrams and then downloaded to PLC. The 6.5 pH set point of the fluid was to be maintained as programmed in the cyclic interrupt block of the PLC to achieve the control. To achieve communication between the virtual and the physical model, a communication channel called Open Platform Communication (OPC) via KEP server which is an interoperability standard for secure and reliable exchange of data in industrial automation was used. Siemens NX was configured to communicate with KEP server via External Signal Configuration feature and this facilitated the merger of control signals between the Siemens NX and TIA. The TIA portal used links that specified the sensor and actuator control signals. Through the KEP server, information was exchanged between the physical and the digital system and vice versa and these enabled simulations. Upon completion of the model assembly and the communication set up between the virtual and actual systems, the entire system was subjected to a series of repeated experiment runs for comparison in terms of pH readings both for acidic and upon correction by metering pump status

III. RESULT

Designing of the virtual model Scale Detection system

Designing of the virtual model Scale Detection system represented as T5554 Analytical Process Control System was successfully done using Siemens NX, starting with the discrete components, some of which are shown in Figure 3.



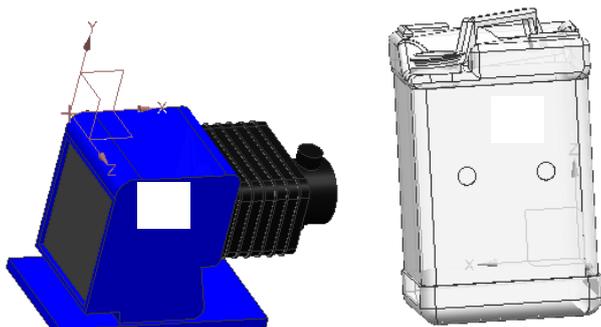


Figure 3: Some of the discrete components of the virtual system designed using Siemens NX namely; Rotor, PID Controller, pH transmitter, metering pump and acid tank ,1-5 respectively.

The discrete parts were assembled together to one system as per Figure 4. The physical properties, motions and relevant joints to CAD models similar to actual system were assigned using MCD, to enable it simulate motion of the actual system as shown in Figure 5.

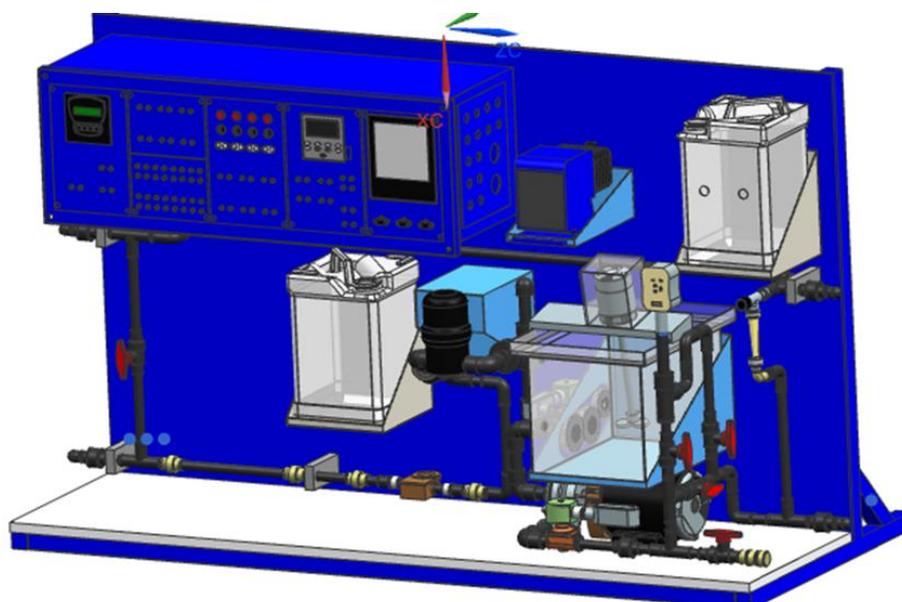
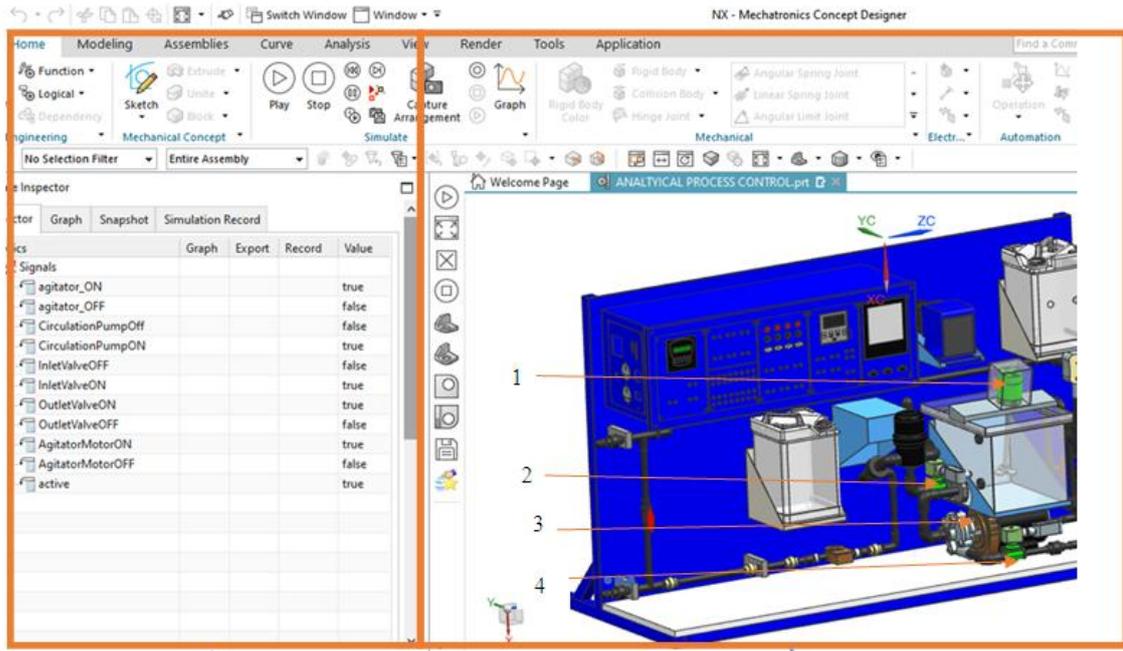


Figure 4: Designed virtual model of scale detection system using Siemens NX



Itemized Energized physical properties of the virtual system using MCD

Energized virtual system

Figure 5: Designed virtual model of scale detection system showing some energized physical properties as shown by display change of agitator motor, inlet valve, circulation pump, and outlet valve (labelled 1-4) respectively.

Designing the scale control system

To achieve scale detection control system using variable pH, program blocks of 1200PLC-CPU 1214C DC/DC/DC which included; main Organisation block (OB), cyclic interrupt and function blocks, and PLC tags were created as shown in Figure 5 and 6.

	Name	Data type	Address	Retain	Acces...	Writa...	Visibl...	Comment
1	NX_AgitatorMotor	Bool	%M1.0		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
2	NX_CirculationPump	Bool	%M1.1		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
3	NX_InletValve	Bool	%M1.2		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
4	NX_OutletValve	Bool	%M1.3		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
5	<Add new>				<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	

Figure 5: The PLC inputs and output tags of the created virtual analytic control system

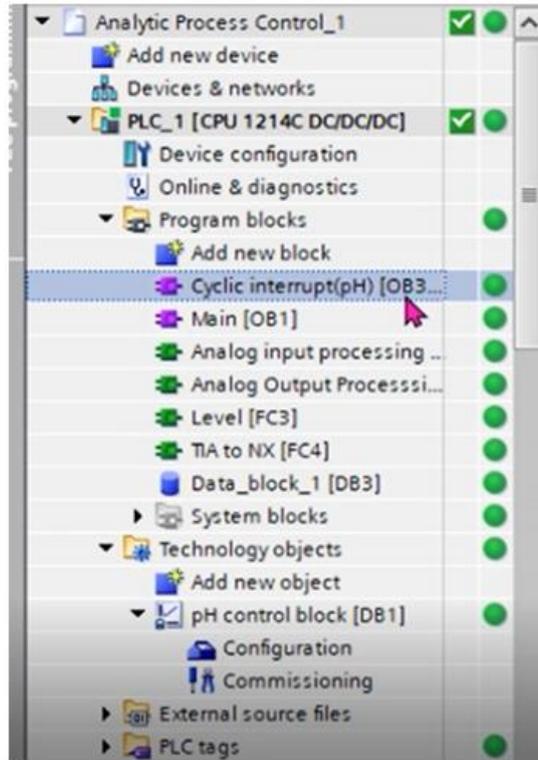
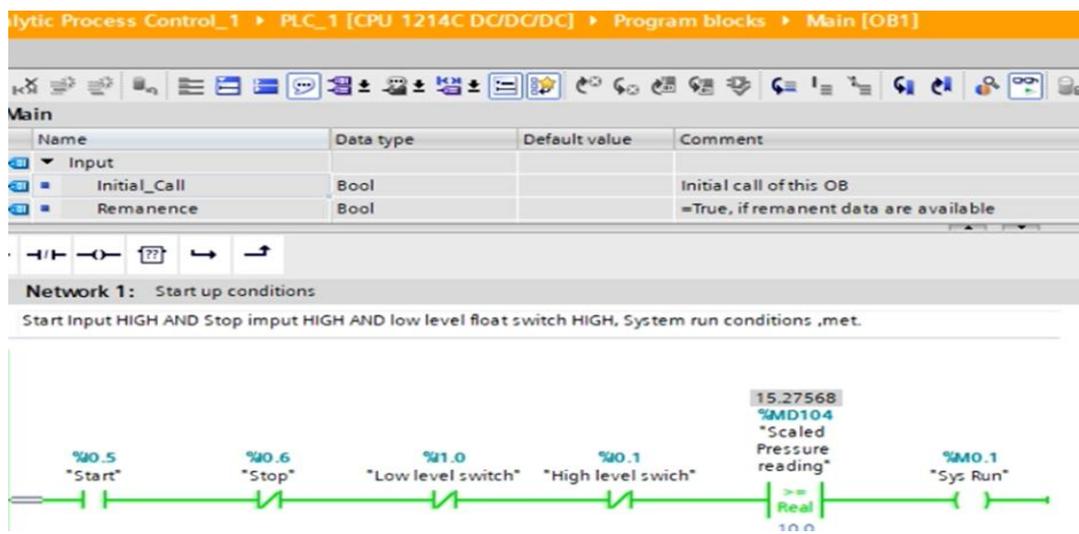


Figure 6: Online status of the function blocks and the PLC tags of the virtual analytic control system

The physical process of the virtual analytic process system was defined, sequenced, programmed and configured successfully using Siemens TIA portal V14 through the use of ladder network as shown in Figure 7, in the main Function Blocks of the 1200PLC-CPU 1214C DC/DC/DC, where (a) represent the satisfied startup conditions for the analytic process control system, (b) represent the satisfied conditions for running the valves and circulation pump whereas (c) represent the satisfied condition for running the agitator and (d) represent the satisfied condition for running analogue input and output signal respectively.

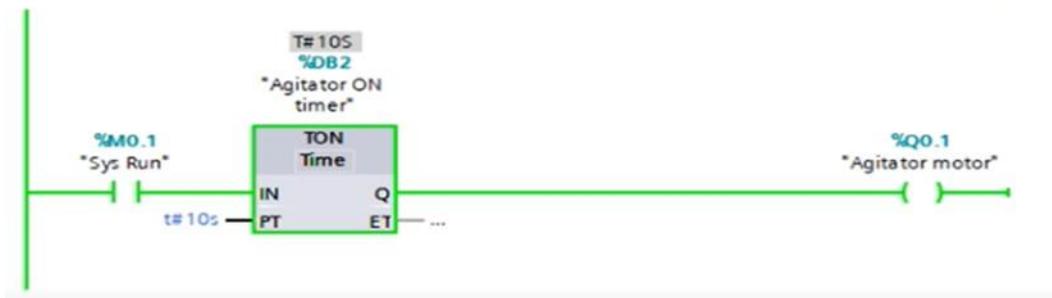


(a)

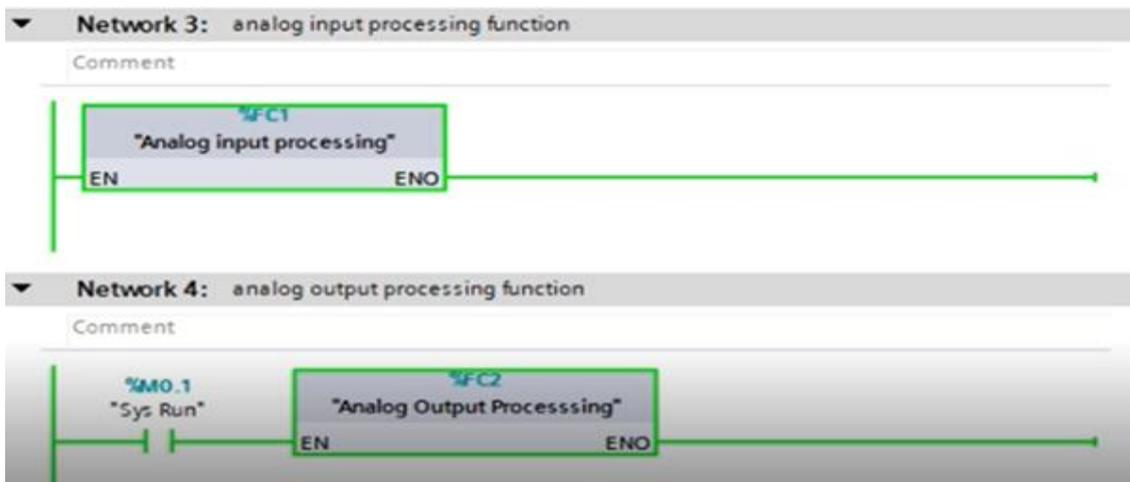


b

▼ pH reading less than the setpoint AND System Run conditions Met, tank inlet valve, tank outlet valve and circulation Pump ON.
5 Second ON timer for the agitator motor.



c



d

Figure 7: Simulations of physical processes of the analytic process system in the function blocks of the PLC using TIA

Online access to the CPU of the PLC was permitted when TIA portal is open. The Cyclic Interrupt Program Block of the CPU was used as shown in Figure 8, with the Proportionate Integral Derivative (PID) controller to execute, as shown in Figure 9, whenever the pH was below the 6.5 set point.

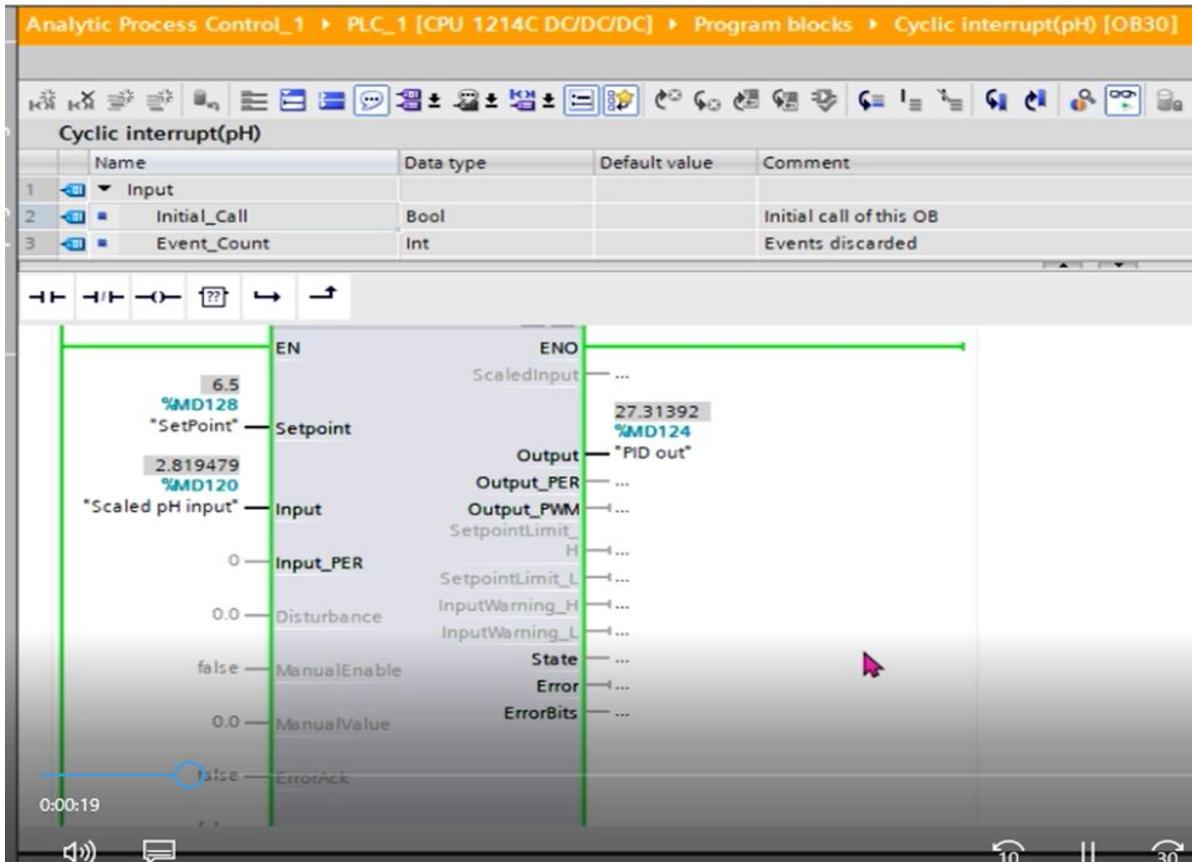


Figure 8: Used Cyclic interrupt with the PID controller to execute for pH levels below set point

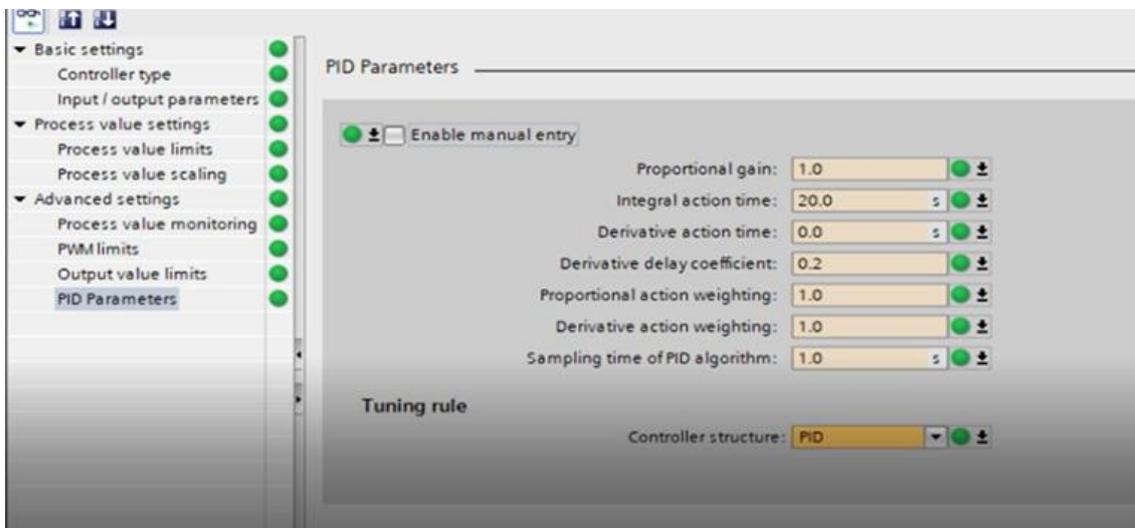


Figure 9: PID Parameters for the analytic control system

The measured variable pH, was analogue input, and so it was scaled and normalized using SCALE_X and NORM_X converters as shown in Figure 10, to machine value. The output was then fed to flow control valve (output) of the metering pump to add more base to the system in order to adjust to the set point value.

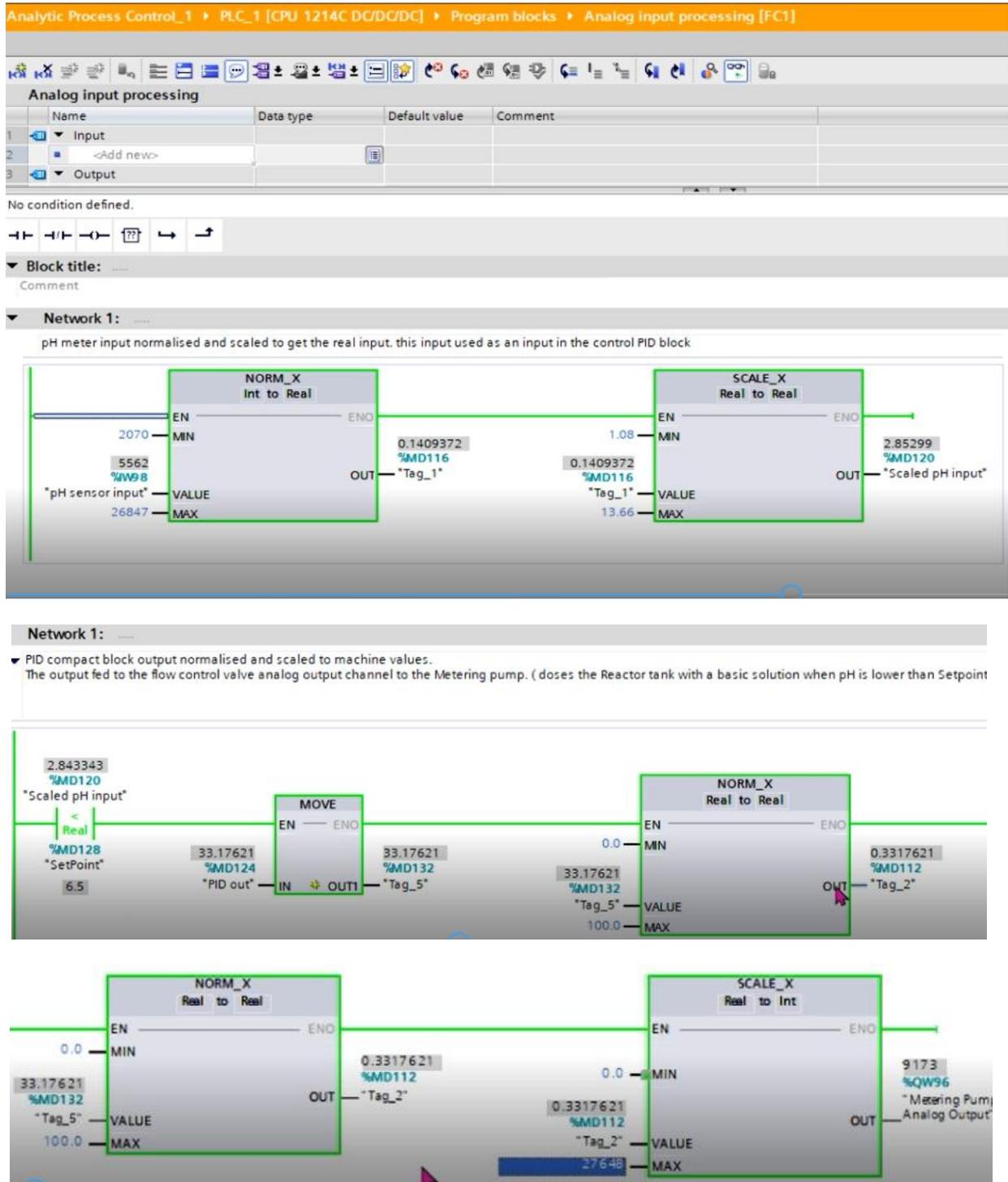


Figure 10: Normalized and scaled analogue input from pH sensor and the respective normalized and scaled analogue output from a metering pump

The PID controller took appropriate action to ensure that the process variable and the set point were nearly equal. The control signals between the Siemens NX and TIA were merged as shown in Figure 11 and the two systems were integrated for communication via KEP server as shown in Figure 12 and the two systems were run side by side is as shown in Figure 13.

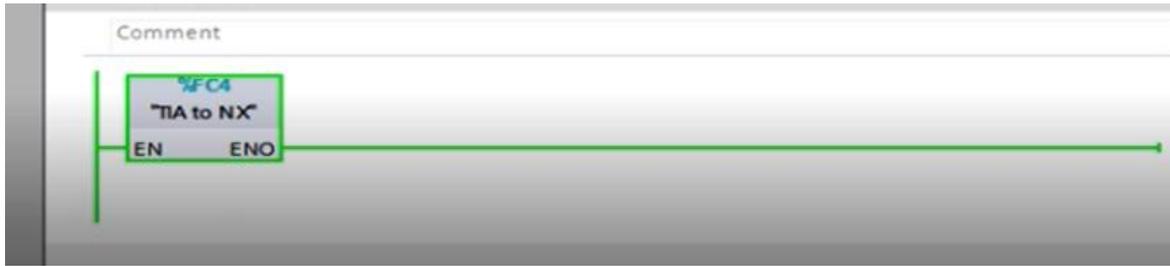


Figure 11: Merger of control signals between the Siemens NX and TIA

Item ID	Data Type	Value
Analytic_Process_Control.S7 1200._CurrentPDUSize	Word	240
Analytic_Process_Control.S7 1200._Slot	Byte	1
Analytic_Process_Control.S7 1200._Rack	Byte	0
Analytic_Process_Control.S7 1200.OutletValveOff	Boolean	1
Analytic_Process_Control.S7 1200.NX_OutletValve	Boolean	1
Analytic_Process_Control.S7 1200.NX_InletValveOFF	Boolean	0
Analytic_Process_Control.S7 1200.NX_InletValve	Boolean	1
Analytic_Process_Control.S7 1200.NX_CirculationPumpOff	Boolean	1
Analytic_Process_Control.S7 1200.NX_CirculationPump	Boolean	0
Analytic_Process_Control.S7 1200.NX_AgitatorMotorOff	Boolean	1
Analytic_Process_Control.S7 1200.NX_AgitatorMotor	Boolean	0

Figure 12: Integration of Siemens NX with KEP server

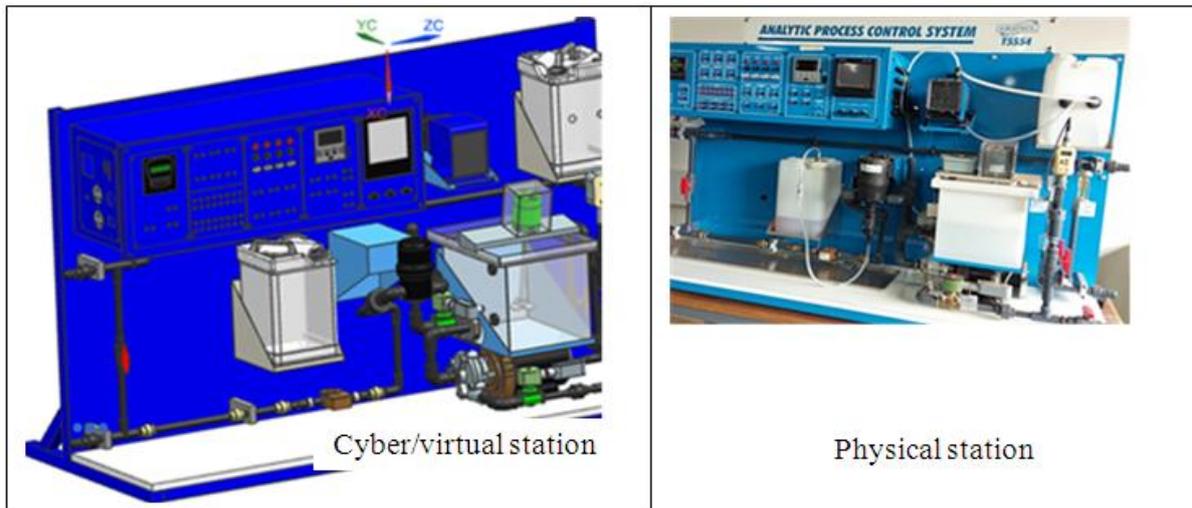


Figure 13: Virtual and Physical system run side by side

IV. DISCUSSION

The eductor pump of the analytic process control system introduced the acid water (Diluted H_2SO_4) in to the reactor tank and the pH readings for the virtual and physical systems was recorded via video camera as agitation happened in the reactor tank, as shown in the Table 1. The data in graph form is as per Figure 14.

Table 1 Acidic pH experiment data for Physical and Virtual system

Time in Seconds	Physical station pH reading (in the pH meter)	Virtual station pH reading (PID)	pH lag
1	2.812	2.814	0.001
2	2.813	2.814	0.001
3	2.806	2.806	0.000
4	2.814	2.814	0.000

5	2.810	2.812	0.002
6	2.806	2.808	0.002
7	2.822	2.824	0.002
8	2.817	2.817	0.000
9	2.824	2.826	0.002
10	2.816	2.816	0.000
11	2.823	2.824	0.001
12	2.820	2.822	0.002
13	2.817	2.818	0.001
14	2.814	2.814	0.000
15	2.815	2.817	0.002
16	2.827	2.829	0.002
17	2.823	2.824	0.001
18	2.831	2.832	0.001
19	2.837	2.837	0.000
20	2.824	2.825	0.001
Mean	2.81855	2.81965	0.00105
STD	0.00797	0.00798	8.25578E-4

The metering pump was set on automatic mode, and repeated runs made with respective acid water in the reactor tank. The pump introduced basic water (Diluted NaOH) in to the reactor tank. The pH readings for the two systems was recorded via video camera as follows in Table 2 and data represented in graph as per Figure 15.

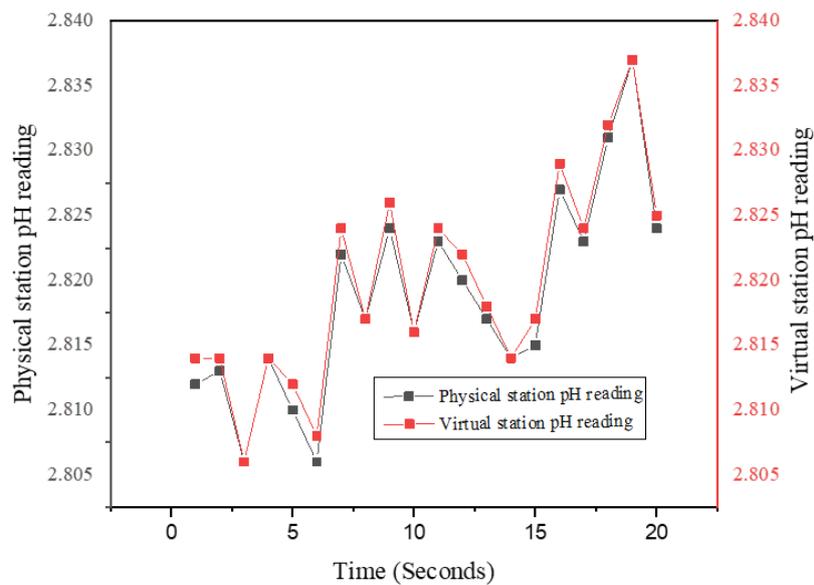


Figure 14: Graph illustrating respective acidic pH readings for the physical and virtual system

Table 2: Corrected pH Basic values for Physical and Virtual system

Time in Seconds	Physical station pH reading (in the pH meter)	Virtual station pH reading (PID reading)	pH lag
1	2.840	2.842	0.002
2	3.241	3.242	0.001
3	4.082	4.084	0.002
4	4.271	4.272	0.002
5	4.632	4.633	0.001
6	5.243	5.244	0.001
7	5.342	5.344	0.002
8	5.651	5.710	0.059
9	5.842	5.860	0.018
10	6.018	6.019	0.001

11	6.410	6.413	0.003
12	6.832	6.840	0.008
13	7.012	7.013	0.001
14	7.012	7.013	0.001
15	7.201	7.203	0.002
16	7.324	7.325	0.001
17	7.650	7.652	0.002
18	8.170	8.170	0.000
19	8.240	8.240	0.000
20	8.342	8.342	0.000
Mean	6.06775	6.07305	0.00535
STD	1.64215	1.64119	0.01325

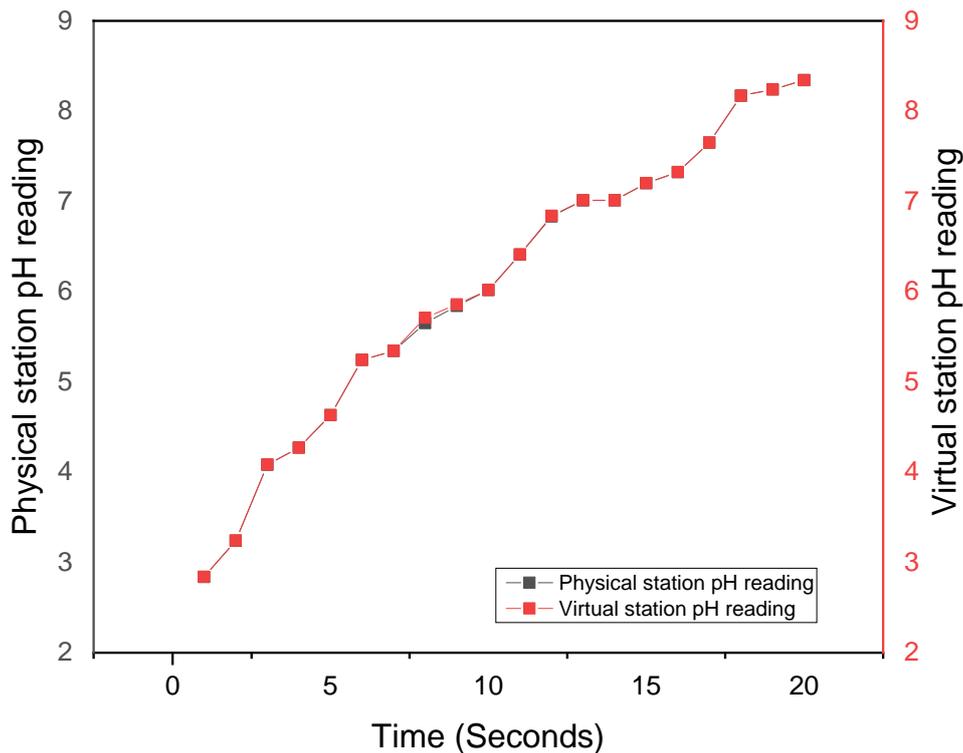


Figure 15: Graph illustrating respective pH readings for the physical and virtual system after correction by the metering pump

In both cases that is, before acidic condition correction and after, there is was an observable pH lag in the readings of the two systems. For example, a Standard Deviation of $8.25578E-4$ was obtained with the recorded acidic pH data between the two systems. On the other side a Standard Deviation of 0.01325 was obtained between the recorded basic pH values for the two systems. The time lag could be as a result of hardware used or communication speed between the two systems. The time lag was however so small that it did not affect the working of the system.

The metering pump of the analytic control system however only worked well for some time. For example, in a few experiment runs, the acidic conditions of the system were properly corrected by adding basic solution proportionately up to the set point pH of 6.5. In subsequent runs as indicated in Figure 15, the correction exceeded the expected set point of 6.5 to around a pH of 8.342. Linear regression analysis of the varying virtual system pH input and the PID output % response was done. Of course, the two variables have a significant relationship as shown in Figure 16 below, where a higher % response value meant that the PID had responded more in changing the varying input towards the set point. The correction of the acidic pH condition especially in the final experiment runs, took place to around 39% due to the faulty metering pump. Upon troubleshooting, it was established that the metering pump's IC had partially blown previously and it is the one which was leading to the indicated inconsistency in the correction of the acidic condition. The metering pump finally failed completely and replacing it was beyond the scope of this research. Otherwise with a properly working metering pump, then, then the digital model could be used to accurately represent the physical system

and achieve scale monitoring and real time control through managing the always changing brine pH in geothermal fields.

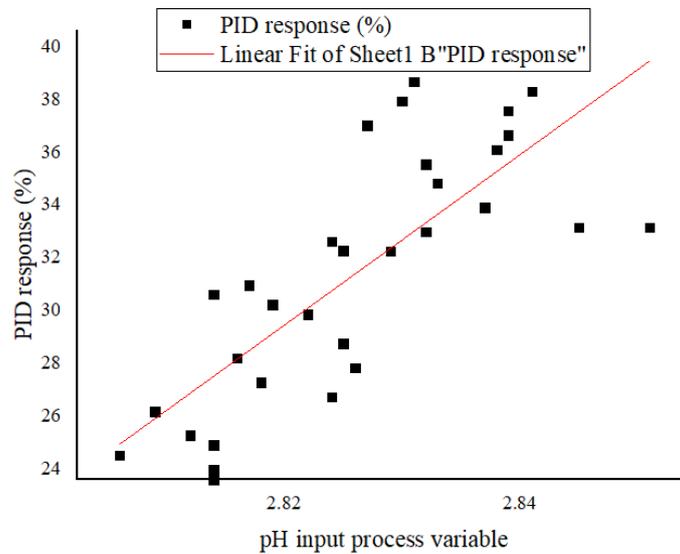


Figure 16: Linear regression analysis of the pH input of the analytic process control machine and the PID output % response.

V. CONCLUSIONS

Use of Siemens NX and TIA software to design and program the analytic process control system model T5554 respectively and the subsequent linking of the physical and virtual system using KEP server was successfully done. The virtual system designed was able to mimic the actual system. Of course, there was a challenge of the faulty metering pump but to a great extent, the research was successful. Use of digital twin technology in geothermal system in managing and controlling scales will therefore help achieve fourth industrial revolution. This system would also help inexperienced personnel to real time switch control the scaling challenge due to pH variance from a computer.

Through the research it was noted that there is no standard model on Digital Twin Architecture and so no consensus on how to build one. More research can be done to generate one.

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