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Temperature Control of Catalytic Cracking Process Using SCADA and PLC

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Abstract

Fluid catalytic cracking unit is an interactive process, where heavy distillates are converted to more valuable products. It is very difficult to model and control fluid catalytic cracking process because of complex kinetics of cracking and coke burning reactions. In this work, control strategy for fluid catalytic cracking unit has been developed based on mass balance equations in the reactor and regenerator systems. For control strategy, reactor temperature and regenerator temperature are taken as input variables whereas catalyst recirculation rate and regenerator air flow rate are taken as manipulated variables. PID control is implemented for fluid catalytic cracking process using PLC and SCADA.

Keywords

Fluid Catalytic Cracking process, PID control, PLC, SCADA.

I. Introduction

In Petroleum Refinery, crude cannot be used as fuel products because of the presence of both light and heavy hydrocarbons. To remove light fractions, distillation column is used. To remove heavy fractions, fluid catalytic cracking (FCC) unit is used. FCC meets the requirements of fuel engine. In order to meet environmental of fuels extra refining has to be done.

Catalytic cracking process is developed in 1920 by Eugene Houdry. It is the large scale application of fluidized beds that explains FCC unit, a major secondary conversion process in Petroleum refineries since 1942. Fluid Catalytic Cracking (FCC) is the main refinery process where higher molecular weight hydrocarbon is converted into lower molecular hydrocarbon by cracking. It provides 50% transportation fuels indirectly. It is a multi-component catalyst system with circulating bed reactor system with reactor-regenerator configuration (Ansari et al., 2000). There are three main basic functions in FCC process namely reaction, regeneration and fractionation (Jiang et al., 2003). In Fluid Catalytic Cracking Unit operation initially the gasoil is fed to unit along with recycle streams and preheated to temperature of 365oC-370oC and then enters the riser to be in contact with hot regenerated catalyst. The catalyst is maintained in fluidized state by the oil vapors. The catalyst recirculates between the reactor and regenerator section. Spent catalyst flows through the catalyst stripper to the regenerator, where most of the coke deposits burn off at the bottom of the unit. A fresh catalyst is added after removing the worn-out catalyst to optimize the catalytic cracking process.

Cracked hydrocarbon stream is separated into various products. Unconverted product like light cycle oil and heavy cycle oil are taken as side stream. Overhead product is given to stabilization section to recover LPG. (Elamurugan et al., 2011)

For control strategy in Fluid Catalytic Cracking process many types of controllers are implemented. Duraid (2011) have proposed decoupling control to prevent interaction between control loops. Hossein et al., (2013) have proposed fuzzy logic for FCC process to address its non-linearity. Boum et al., (2015) have proposed multivariable control and state estimation for FCC unit which is more reliable even when model mismatch obtained. Araromi et al., (2015) have proposed different designs of conventional controller to FCC unit in which IMC based PI control provide satisfactory result.

In this work, PID control for temperature control in FCC unit is done by combining PLC and SCADA.

II. Research Background

A. Mathematical Modeling

A mathematical model is used to represent a process in terms of equation form to perform control action for the process. It is obtained for fluid catalytic cracking process by utilizing riser-reactor model and regenerator model.

1. Riser-Reactor model

The model treats riser as an adiabatic plug flow reactor. The residence time of feed in the riser is just few seconds and hence the ideal reactor model is utilized (Elamurugan et al., 2010 and Karthika et al., 2012). Mass balance equation for reactor is shown in (1).

Input steam – [Output steam-Heat of reaction] = Rate of accumulation

Heat of Regenerator catalyst+ Heat of Feed +Heat of Steam–{Heat of Effluent– Heat of Spent catalyst+ Heat of Reaction} = Rate of Accumulation

$$\mathrm{F_s C_{ps} T_{reg}} + \mathrm{F_0 C_{p0} T_0} + \mathrm{F}_{st} \mathrm{H}_{st} - \mathrm{F_p C_{pp} T_{rea}} + \mathrm{F_d C_{pd} T_{rea}} + \Delta \mathrm{H_g} = (\mathrm{M_p C_{pp}} + \mathrm{M}_d \mathrm{C_{pd}}) \frac{dT_{rea}}{dt} \qquad (1)$$

Where, steady state value of

Mass of reactor product (M_p)	=314.76 kg.
Mass of spent catalyst (M_d)	=2316.86 kg.
Mass flow rate of reactor product (F_p)	=62.95 kg/sec.
Mass flow rate of spent catalyst (F_d)	=463.37kg/sec.

Input (Manipulated variable):
Regenerated catalyst feed rate (F_s) = 454.79 kg/sec.
Output (Controlled variable):
Reactor bed temperature (T_{rea}) = 503□ C (776 K).

2. Regenerator Model

The catalyst residence time in the regenerator is around 10 to 20 min. Temperature and amount of coke on catalyst are assumed to uniform throughout the regenerator (Brijet et al., 2015). Mass balance equation for regenerator is shown in (2).

Input steam – [Output steam-Heat of combustion] = Rate of accumulation

Heat of Spent catalyst+ Heat of Air – {Heat of Combustion– Heat of Regenerator catalyst – Heat of Flue gases} = Rate of Accumulation

$$F_d C_{pd} T_{rea} + F_a C_{pa} T_a - \Delta H_c - F_s C_{ps} T_{reg} - F_f C_{pf} T_{reg}$$

$$= (M_s C_{ps} + M_f C_{pf}) \frac{dT_{reg}}{dt} \qquad (2)$$

Where, steady state value of

Air temperature (T_a)	=500□C (773 K).
Mass flow rate of regenerated catalyst (F_s)	=454.79 kg/sec.
Mass of regenerated catalyst (M_s)	=4547.93 kg.
Mass flow rate of flue gases (F_f)	=75.00 kg/sec.
Mass of flue gases (M_f)	=75.00 kg.

Input (Manipulated variable):
Air rate (F_a) = 66.41 kg/sec.
Output (Controlled variable):
Regenerator cyclone temperature (T_{reg}) = 715.5□ C (988.5 K).

3. State space analysis

Two types of variables used in the modeling of dynamic system are input and output variables. The state space representation for a given system is not unique, except that the number of state variables is the same for different state space representation of the same system. State space realizations for control scheme is

$$A = A_p = A_d;\ B = \begin{vmatrix} B_1 \\ B_2 \end{vmatrix};\ C = C;\ D = \begin{vmatrix} D_1 \\ D_2 \end{vmatrix} \qquad (3)$$

Where p refers to the plant matrices and d refer to the disturbance matrices in (3). The linear time invariant model of the system is shown in (4).

$$X = A_x + B \begin{vmatrix} U_1 \\ U_2 \end{vmatrix};\quad Y = C_x + D \qquad (4)$$

Where,
U = Vector of manipulated variables.
Y = Vector of output variables.
D = Vector of disturbances.
X = Vector of system states.
A = Matrix represents the coefficients of state variables (T_{rea} and T_{reg}).
B = Matrix represents the coefficients of input variables (F_a and F_{rc}).
C = Identity matrix.
D = Matrix represents the coefficients of indirect variables.

The elements of state space A matrix is shown in (5).

$$A_{ij} = \frac{\partial F_f}{\partial X_i};\quad B_{ij} = \frac{\partial F_i}{\partial U_f} \qquad (5)$$

State space model is given in (6, 7).

$$\begin{vmatrix} T^0_{rea} \\ T^0_{reg} \end{vmatrix} = A(2x2) \begin{vmatrix} T_{rea} \\ T_{reg} \end{vmatrix} = B(2x2) \begin{vmatrix} F_{rc} \\ F_a \end{vmatrix} \qquad (6)$$

$$. \begin{vmatrix} T_{rea} \\ T_{reg} \end{vmatrix} = C(2x2) \begin{vmatrix} T_{rea} \\ T_{reg} \end{vmatrix} = B(2x2) \begin{vmatrix} F_{rc} \\ F_a \end{vmatrix} \qquad (7)$$

Matrix A is given in (8).

$$A = \begin{vmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{vmatrix}$$

$$\mathbf{A_{11}} = \frac{\partial f_1}{\partial T_1} = \frac{-F_p C_{pp} - F_d C_{pd}}{M_p C_{pp} + M_d C_{pd}}$$

$$\mathbf{A_{12}} = \frac{\partial f_1}{\partial T_2} = \frac{F_s C_{ps}}{M_p C_{pp} + M_d C_{pd}}$$

$$\mathbf{A_{21}} = \frac{\partial f_1}{\partial T_1} = \frac{F_d C_{pd}}{M_s C_{ps} + M_f C_{pf}}$$

$$\mathbf{A_{22}} = \frac{\partial f_2}{\partial f_a} = \frac{-F_s C_{ps} - F_f C_{pf}}{M_s C_{ps} + M_f C_{pf}}$$

$$A = \begin{vmatrix} -0.22 & 0.10 \\ 0.08 & -0.10 \end{vmatrix} \qquad (8)$$

Matrix B is given in (9).

$$B = \begin{vmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{vmatrix}$$

$$\mathbf{B_{11}} = \frac{\partial f_1}{\partial f_s} = \frac{C_{ps} T_2}{M_p C_{pp} + M_d C_{pd}}$$

$$\mathbf{B_{12}} = \frac{\partial f_1}{\partial f_a} = \frac{0}{M_p C_{pp} + M_d C_{pd}}$$

$$\mathbf{B_{21}} = \frac{\partial f_2}{\partial f_s} = \frac{-C_{ps} T_2}{M_s C_{ps} + M_f C_{pf}}$$

$$\mathbf{B_{22}} = \frac{\partial f_2}{\partial f_a} = \frac{-C_{pa} T_1}{M_s C_{ps} + M_f C_{pf}}$$

$$B = \begin{vmatrix} -0.21 & 0 \\ -0.10 & 0.16 \end{vmatrix} \qquad (9)$$

Matrix C and D are given in (10, 11).

$$C = \begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix} \qquad (10)$$

$$D = \begin{vmatrix} 0 & 0 \\ 0 & 0 \end{vmatrix} \qquad (11)$$

The FCCU is composed of two controlled outputs and two manipulated inputs. The input-output relation is shown in (12, 13, and 14).

$$T_{rea}(S) = H_{11}(S)\, F_s(S) + H_{12}(S)\, F_a(S) \qquad (12)$$

$$T_{reg}(S) = H_{21}(S)\,F_s(S) + H_{22}(S)\,F_a(S) \tag{13}$$

$$H_{11} = \frac{K}{\tau s + 1} e^{t_d s} \tag{14}$$

Table 1: System parameters for step change in catalyst flow rate

Controlled variable	$K \frac{°C}{Kg/sec}$	τ (sec)	t_d (sec)
T_{rea}	0.78	3.71	0.1
T_{reg}	-0.37	3.68	0.1

Table 2: System parameters for step change in air flow rate

Controlled variable	$K \frac{°C}{Kg/sec}$	τ (sec)	t_d (sec)
T_{rea}	1.14	19.03	4.11
T_{reg}	2.51	18.90	0.1

With the results obtained from Table 1 and Table 2 for step change in catalyst flow rate and air flow rate, the input-output relation is obtained shown in (15).

$$T_{reg}(s) = \frac{-0.37e^{-0.35}}{3.68\,s + 1} F_s(S) = \frac{2.51e^{-0.35s}}{18.9\,s + 1} F_a(S) \tag{15}$$

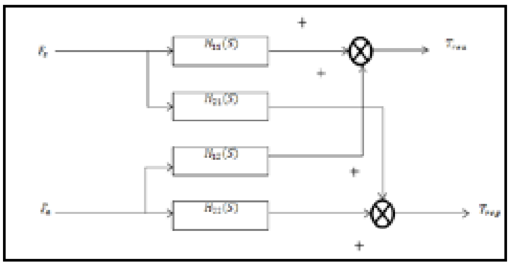


Fig.1 : Block Diagram of FCCU

Where, $H_{11}(s)$, $H_{12}(s)$, $H_{21}(s)$ and $H_{22}(s)$ are transfer functions relating the outputs (T_{rea} and T_{reg}) to the inputs (F_a and F_s) shown in Fig.1.

B. SCADA

SCADA (Supervisory Control and Data Acquisition) is very useful tool to gather data from remote locations to control equipment and conditions. SCADA system contains hardware and software components. The hardware in SCADA gathers and feeds data into a computer where SCADA software is installed. SCADA software receives information from RTU (Remote Terminal Unit) or PLC (Programmable Logic Controller).

SCADA performs functions like control, supervise, collect data etc. It is widely used in many large scale industries in the world. In this work, fluid catalytic cracking process is implemented in Wonderware InTouch 10.1 SCADA where PID control is used for control action.

C. PLC

PLC (Programmable Logic Controller) is a device where user can make program and download it into the memory card of PLC. Both discrete and logic sequence of instructions can be done.

PLC is more reliable in operation, flexible in control and programming languages, more speed in operation etc. In this work, S7-200 Micro PLC is used to adjust PID parameters in SCADA by interfacing with it. It can control a large number of devices to support the automation applications. For programming STEP7-Micro/WIN32 version4.0 is used.

In order to interface PLC to SCADA, software called KepserverEx V4.0 is used. It is a 32 bit windows application that provides a means of bringing data form wide range of industrial devices into client application on windows PC.

D. PID Controller

PID means Proportional-Integral-Derivative controller where, the proportional is used to handle the present and integral is used to handle the past by integrating the error over time, finally derivative is used to prevent future errors. The PID controller equation is shown in 16.

$$u(t) = k_p e(t) + k_i \int e(t)dt + k_d (de(t)/dt) \tag{16}$$

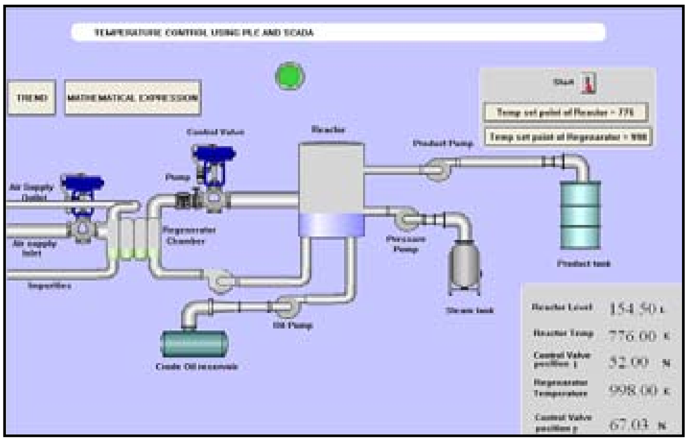
where,

u (t) = Controller output
e (t) = Error
k_p = Proportional gain
k_i = Integral gain
k_d = Derivative gain

III. Results and Discussions

1. SCADA implementation for FCC Unit

Fluid Catalytic Cracking unit is implemented in Wonderware InTouch 10.1 SCADA software shown in Fig.2.



Reactor Level 154.50 L
Reactor Temp 776.00 K
Control Valve position 1 52.00 %
Regenerator Temperature 998.00 K
Control Valve position 2 67.03 %

Fig.2. FCCU implemented in SCADA

The block diagram representation of the Fluid catalytic cracking process is shown in Fig.3.

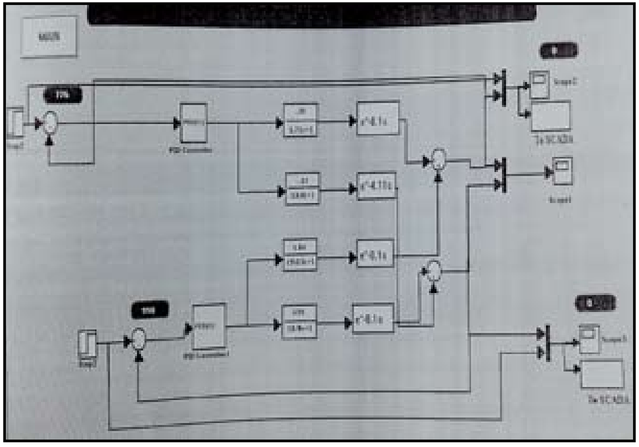


Fig.3 : Block Diagram of FCCU

2. PLC implementation for FCC Unit

PLC program is developed to control the fluid catalytic cracking process which is implemented in SCADA shown in Fig.4 (a), 4(b), 4(c), 4(d), 4(e) and 4(f).

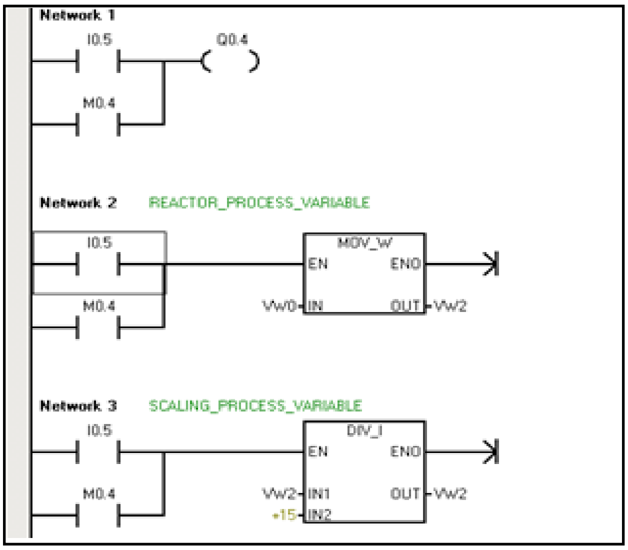


Fig.4(a) : PLC program

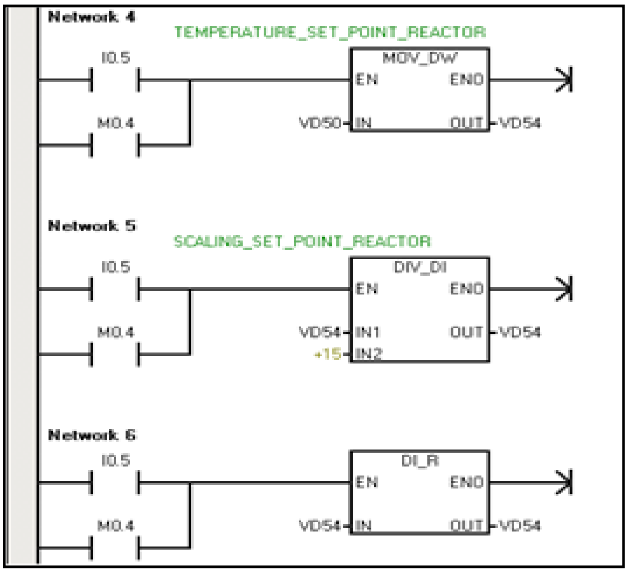


Fig.4(b) : PLC program

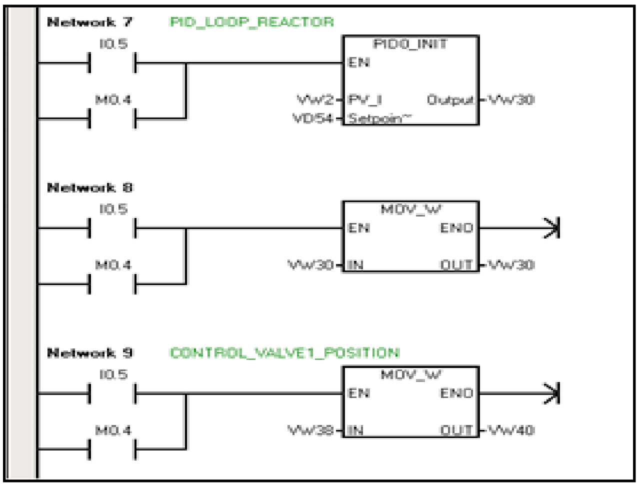


Fig.4(c) : PLC program

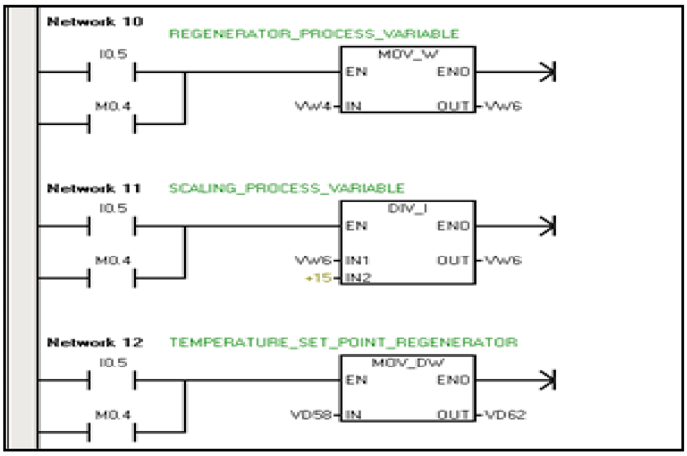


Fig.4(d). PLC program

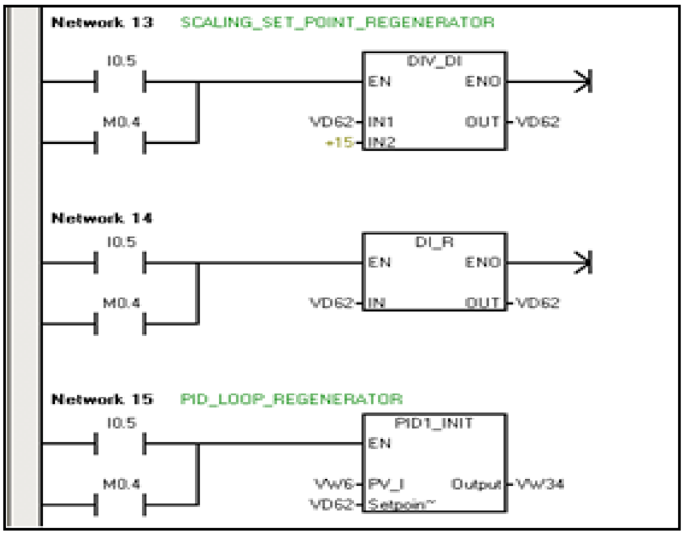


Fig.4(e). PLC program

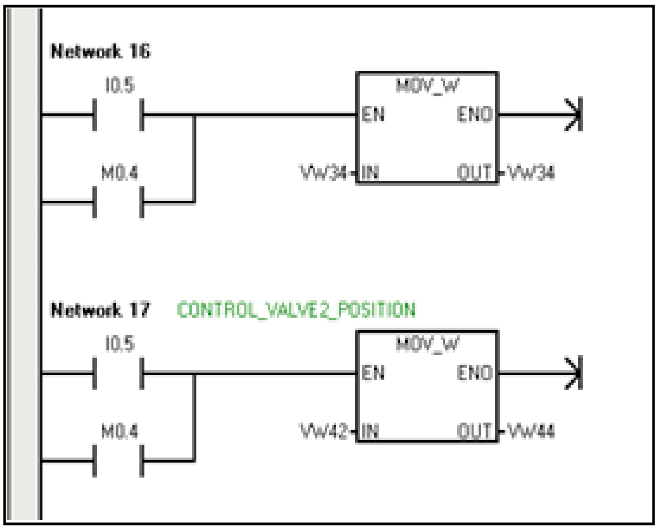
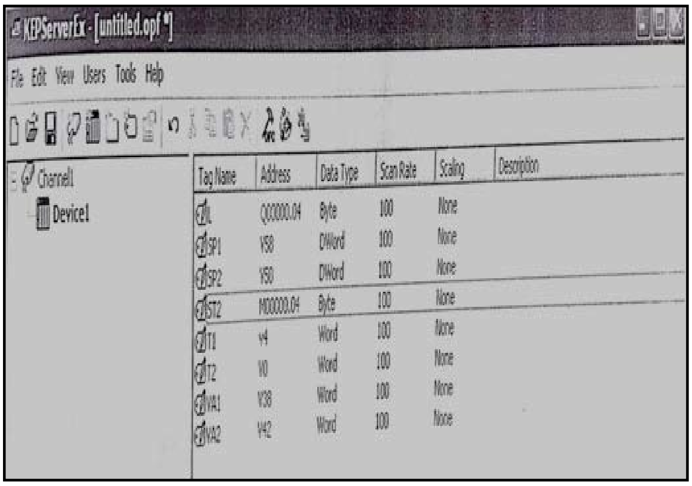


Fig.4(f) : PLC program

The PIC controller provides control for the FCC process to control the reactor temperature and regenerator temperature by controlling the catalyst flow rate and air flow rate.

3. PLC interfacing to SCADA for FCC Unit

PLC is interfaced to SCADA using kepserver. By interfacing PLC with SCADA, the values from SCADA can be given to PLC and the controlled value form PLC can be given to SCADA shown in Fig.5.



Tag Name	Address	Data Type	Scan Rate	Scaling	Description
L	Q00000.04	Byte	100	None	
SP1	V58	DWord	100	None	
SP2	V50	DWord	100	None	
ST2	M00000.04	Byte	100	None	
T1	V4	Word	100	None	
T2	V0	Word	100	None	
VA1	V38	Word	100	None	
VA2	V42	Word	100	None	

Fig.5 : Interfacing SCADA with PLC

While running the SCADA and PLC the current reading can be seen on the kepserver screen. The reading can be taken from OPC quick client window shown in Fig.6.

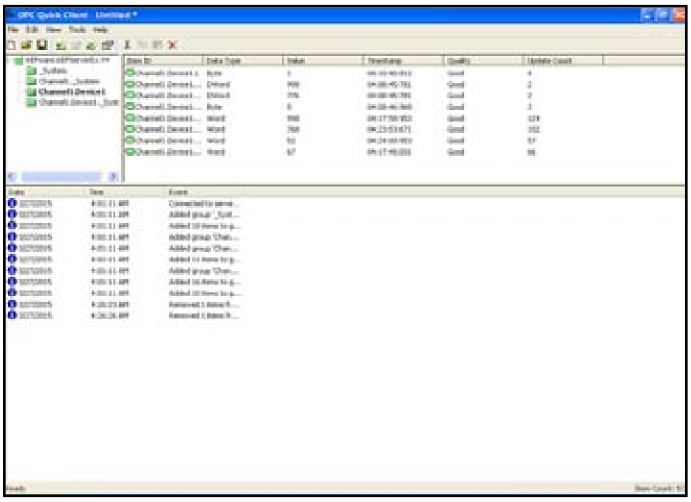


Fig.6 : OPC quick client windows

4. Response of the FCC process

The response of the reactor and regenerator temperatures of the FCC process which is controlled by the PID controller in STEP7 PLC is shown in Fig.7 and Fig.8.

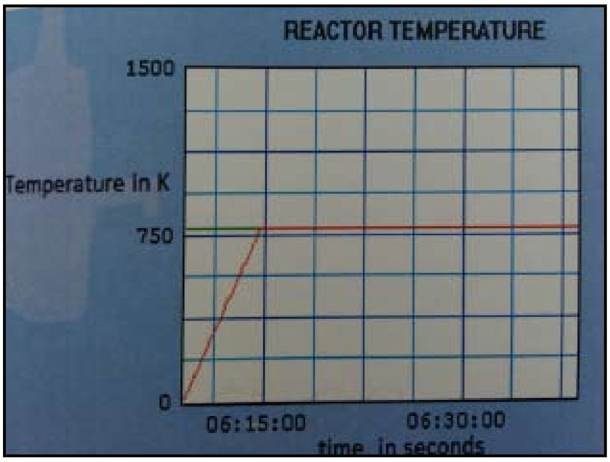


Fig.7 : Reactor Temperature

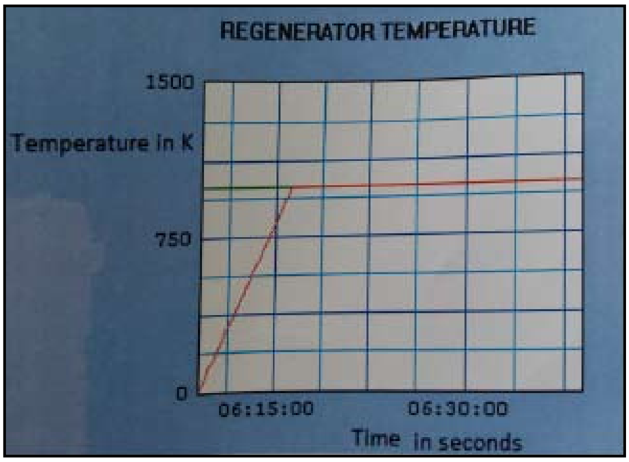


Fig.8. Regenerator Temperature

The above response graph shows the control of both reactor and regenerator temperature according to set point given.

IV. Conclusion

The Mathematical model of Fluid Catalytic Cracking Unit is derived using the mass balance equations of riser-reactor and regenerator. The PID control is implemented to control the reactor temperature and regenerator temperature using PLC and SCADA. The Fluid Catalytic Cracking process is implemented in SCADA using Wonder InTouch software and controlled by step-7 PLC which is interfaced to SCADA using kepserverEX.

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