Journal of Engineering and Applied Sciences 13 (Special Issue 6): 5266-5275, 2018
ISSN: 1816-949X

PLC Based Fuzzy Controlled Ethanol-Water Separation System

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Abstract: The project work focuses on employing the controlling and on-line monitoring of ethanol-water solution separation using fuzzy logic approach through Programmable Logic Controller (PLC) implementation. The mixture is commonly found during the conversion of sugars into alcohol, hence, separation is needed for utilization of separated solvents for further use. The technique adopted for the purpose is through the distillation which is relying upon the controlling of the boiling points of the solvents under relevant pressure. Thus, control can be efficiently accomplished through intelligent controllers like Fuzzy Logic Controllers (FLC). It smartly controls the boiling temperature of the solution and provides the desired response per rules. Sugeno Model has been used for the purpose. The FLC has been implemented on the PLC DVP-10SX11R through fuzzy Temperature Control command (FTC). The performance of the system can be evaluated and monitored on the HMI.

Key words: PLC DVP, FLC, FTC, PAC, ethanol-water mixture, distillation

INTRODUCTION

The research carried out in this study follows the future research by Ansari *et al.* (2016) which also presented the approach to separate and collect the ethanol-water solution through conventional method based on PLC Siemens S7-300 in which heater was controlled through relay-based approach, a simple on-off method. But due to inertia stored in the heater can increase the temperature unnecessarily and ultimately the wastage of power. Such inertia can be utilized instead through variable control method by employing different controllers. The power consumption can be reduced greatly according to the FLC rules based on Sugeno Fuzzy Model as FLC are the universal approximators, proving remarkable performance for wide variety of practical problems (Lee, 1990). FLC provides a means of converting a linguistic control strategy in which parameters are fuzzified and a decision is made based on the control rules (Castro, 1995). Due to its enormous performance, FLC has been adopted in various applications (Pappis and Mamdani, 1977; Graham and Etezadi-Amoli, 2000; Ioannides, 2004; Soomro *et al.*, 2016).

The arrangement of the project is in such a way that the system controlling brain is DVP-10SX11R PLC whose FTC command fuzzifies the input value and compares with set-point then an error signal is processed according to the equations based on Sugeno Model and provides the defuzzified value which works as the control input to the Phase Angle Control (PAC) IC TCA-785 of SCR based AC Voltage controller. Hence, fine control of temperature in the distillation column can be achieved intelligently. The RTD PT100 can be used for measuring the temperature of the homogenous solution and at required set-point the lighter solvent will be evaporated leaving behind heavier one. The whole system can also be monitored even recorded using HMI. The block diagram of the system is shown in Fig. 1.

Ethanol possesses several applications by Garcia *et al.* (2007) a fuzzy logic-based system for diagnosis and control of an anaerobic wastewater treatment plant was developed containing ethanol and carbohydrates. Ethanol purified from such system can be used in thermal plasma reformer as well (Tsai *et al.*, 2007).

A programmable logic controller is a compact decision-making system that endlessly screens the position of devices coupled as inputs. It is a decision-making system with jobs to manipulate logic, sequencing, judgement, mathematics data interpretation and counting abilities. It may be perceived as an engineering computer that has a central processor unit, memory, input output interface and a software development device. The central processing unit offers the cleverness of the controller (Haque *et al.*, 2014;

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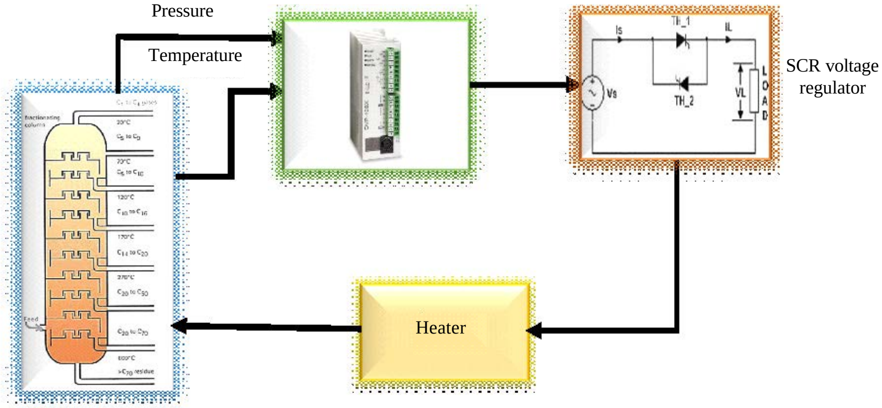

Fig. 1: Block diagram

Guo *et al*., 2009). The implementation of FLC on PLC has been done frequently, like in one of the study (Aydogmus, 2009) the results from the MATLAB Sugeno Fuzzy Model has been put in to practice through the PLC arithmetic logic operations. FLC membership functions can also be implemented in PLCs through their corresponding software. In Graham and Etezadi-Amoli (2000), speed control of DC motor is performed by PLC using the elegant and effective fuzzy. With not only limiting to DC, PLCs can also work with greater flexibility on controlling the speed of induction motor as compared to conventional V/F control system (Ioannides, 2004) but with the involvement of FLC (Arrofiq and Saad, 2007) and PID type FLC (Saad and Arrofiq, 2012), the stability in respond to disturbance and sudden changes in reference speed can be achieved more progressively.

The study provides the solution to save power by utilizing the stored inertia and further improvement in the service and production of industry by managing the whole system smart and intelligent by providing the design of continuous monitoring and controlling of the distillation of homogeneous mixture of ethanol-water.

MATERIALS AND METHODS

Distillation system design: The feed stream taken having temperature is 30°C with 50% fraction of ethanol and 50% of water in a mixture and standard density of mixture is = 887.4 kg/m^2. Required pressure of the distillation column is 1.17 bar to avoid back pressure.

Simulation of ethanol-water distillation using aspen HYSYS V3.2: Before going for the implementation, some calculations should be made to achieve the conditions of the process variable for finer controlling. Aspen HYSYS is the simulation software used for the process

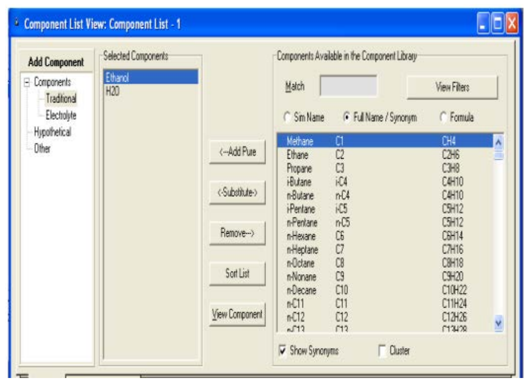

Fig. 2: Components list

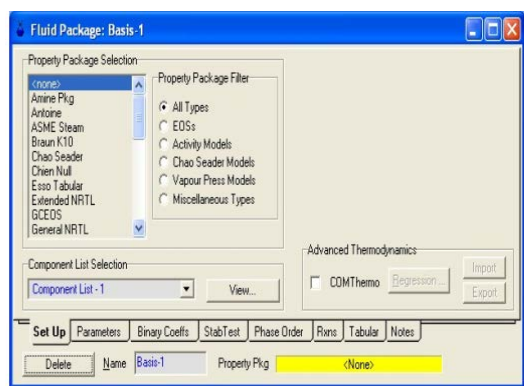

Fig. 3: Fluid package

optimization in design and operations (Hanyak, 2012). Figure 2 shows the components selected for the simulation and Fig. 3 shows the fluid package selection which contains the components and property method to be used by HYSYS V3.2 in its calculations for flow sheet. It may also contain other information such as reactions

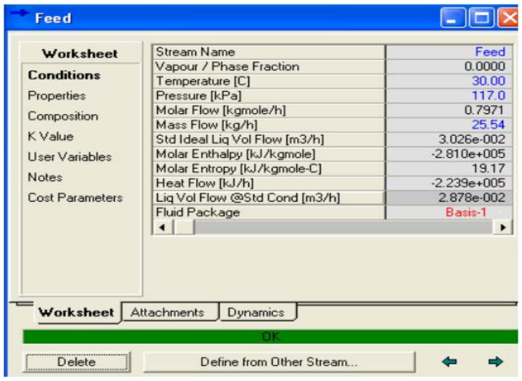

Fig. 4: Feed stream specification

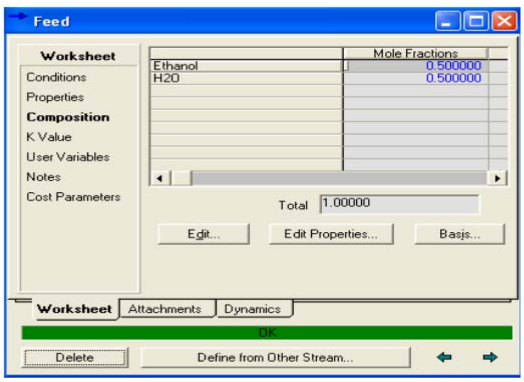

Fig. 5: Mole fraction

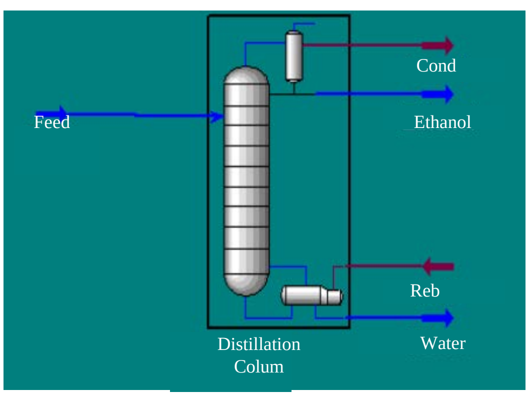

Fig. 6: Distillation design model

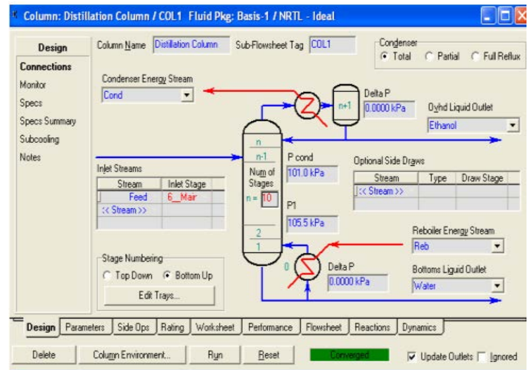

Fig. 7: Converged distillation column

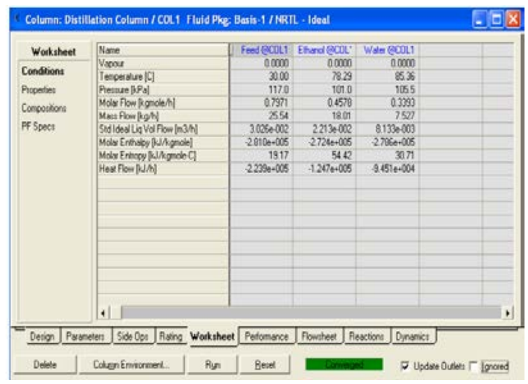

Fig. 8: Converged results

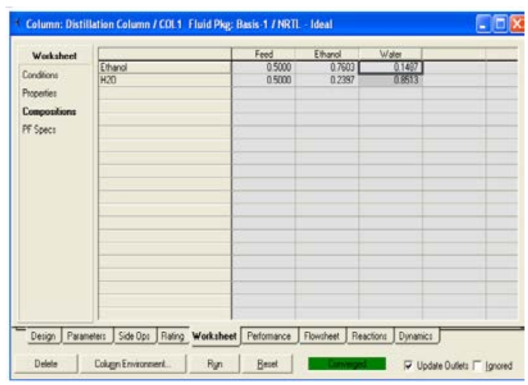

Fig. 9: Converged compositions

and interaction parameters. In this case NRTL (Non-Random Two Liquid) model has been selected. The properties of input feed stream are shown in Fig. 4 and the composition specifications are shown in Fig. 5.

Now, install the distillation column by picking the block as shown in Fig. 6. Connect the all required output streams as well. Double-click on the column and you will see that HYSYS automatically calculate all the required parameters and appropriate results. Figure 7 shows the converged model.

Figure 8 tells the worksheet of the upper stream ethanol and lower stream water calculated results and specifications. Figure 9 shows the calculated

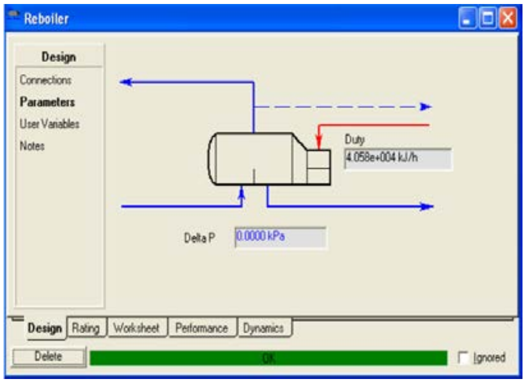

Fig. 10: Duty of reboiler

compositions which prove that the ethanol evaporates at 78.29°C and at 101 kPa with purity level of 76%. Whereas water is obtained at the bottom with purity level of 85% and overall energy is consumed by reboiler is shown in Fig. 10, the consumption for the process is 4.058×10^4kJ/h which is equal to 11.27 kW.

Fuzzy logic controller design: The temperature input is fed to the Sugeno model of fuzzy logic approach and according to the rules and equations output is sent to the control circuitry of the SCR voltage controller to control the RMS voltages of the heater. The strategy of a fuzzy logic controller needs the selection of membership functions. The membership functions should be selected in such way; they shelter the entire universe of discourse. Provided, taken care that the membership functions overlay each other. This is finished to evade any kind of cutoff with esteem to the slight fluctuations in the inputs. After the suitable membership functions are selected, a rule base should be formed. It consists of several fuzzy if-then rules that completely describe the performance of the system. These instructions very much bear a resemblance to the human thinking process, thereby delivering artificial intelligence to the system.

The fuzzy model is SISO, thus, requiring single input Temperature and single output. The input to the fuzzy logic controller is temperature ranging from 0-100°C. Whereas PLC decimal value has been ranging from 0-1000 decimal with the rate of 10/°C. So, normalization is done in the range in of 0-100. Table 1 shows the fuzzy set membership function of temperature (°C).

The output is based on the Sugeno Model equation which is as follows. Y represents the output and X represents the input variable. Equation 1 shows the relationship.

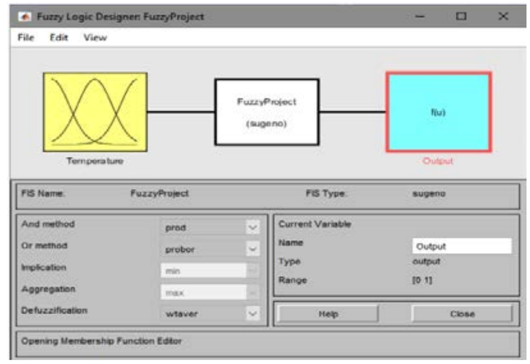

Fig. 11: FIS editor window in MATLAB

Table 1: Fuzzy sets and membership functions for Temperature (°C)

Fuzzy set or label/ Set description	Range	Membership function
Low		
Temperature is in the range of 0-38°C	0-0 0-450 450-500	Trapezoidal
Middle		
Temperature is in the range of 30-80°C	450-500 500-800 800-840	Trapezoidal
High		
Temperature is in the range of 75-100°C	800-840 840-1000 1000-1000	Trapezoidal

$$Y = \begin{cases} 2000 & <X<500 \\ -5.88x+4940 & 500<X<840 \\ 0 & X>840 \end{cases} \quad (1)$$

The rule base for deciding the output of the inference system consists of 03 if-then rules. The relationship of the rule base is as follows:

- If the temperature is low then output is constant high
- If the temperature is in middle then output is linearly decreasing
- If the temperature is high then output is zero

Design of fuzzy logic controller using MATLAB: The fuzzy logic controller must be planned conferring to the rules and data base. The stages for the succeeding are publicized under along with the membership functions. Figure 11 shows the Sugeno Model FIS Window.

The membership functions for input temperature and for output are shown in Fig. 12 and 13, respectively and Fig. 14 shows the rules implemented in the FIS Model. The surface view model is shown in Fig. 15. The input can be changed in the window and output in Fig. 16 and 17.

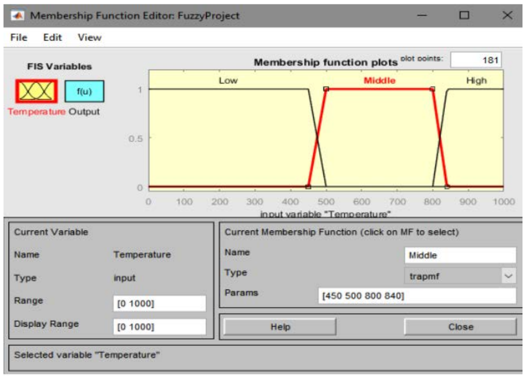

Fig. 12: Membership function for variable temperature

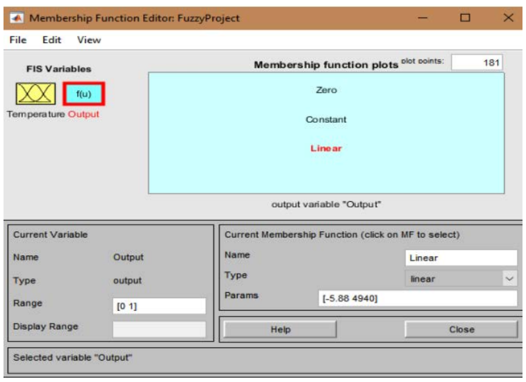

Fig. 13: Membership function for variable output

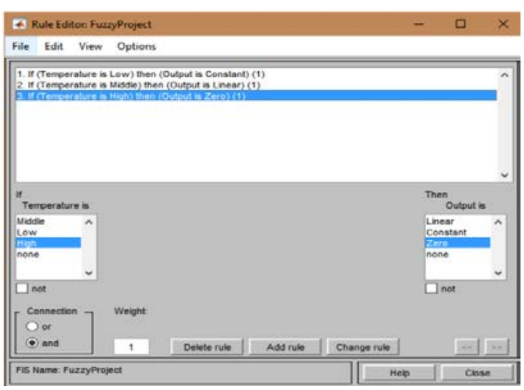

Fig. 14: Fuzzy rules implementation

The fuzzy logic controller is therefore depicted and using the rule viewer and the outputs are confirmed. Hence, designing of the fuzzy logic controller is now finished. Such FIS can now be implemented in DVP-PLC 10SX11R using FTC (Fuzzy Temperature Control) command. The controller can be developed accordingly to get the desired outcomes during the simulation. Hence,we discover that scheming a fuzzy logic controller using the Sugeno Fuzzy Model is very appropriate and does not entail any inelegant strategies.

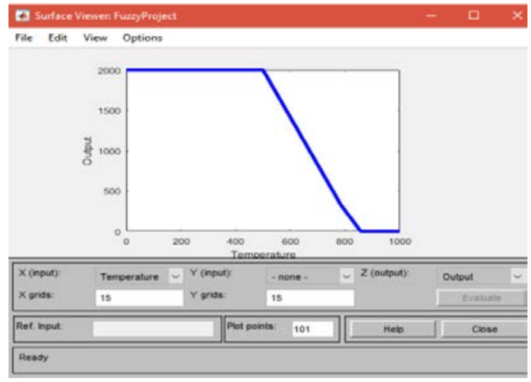

Fig. 15: Surface view of the FIS Model

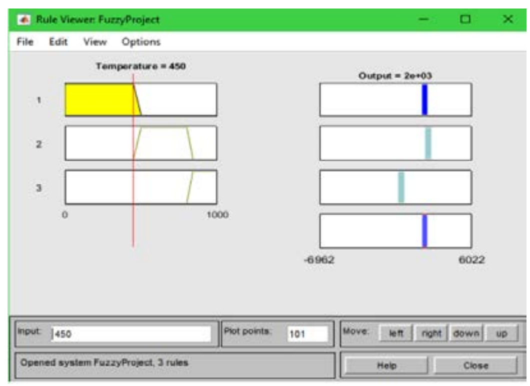

Fig. 16: Defuzzified output at input = 450

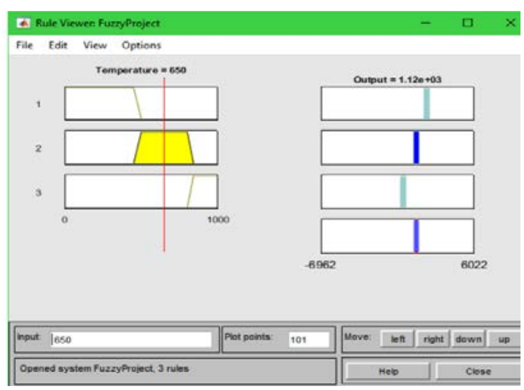

Fig. 17: Defuzzified output at input = 650

RESULTS AND DISCUSSION

The overall system design consists the DVP-PLC which is working as a brain, making the required decision based on the fuzzy logic approach, a temperature sensor RTD (Resistance Temperature Detector) with its conditioning circuit giving the required values of 4-20 mA as output in the range between 0-100°C. A passive pressure transducer giving the output of 4-20 mA in the range of 0-58 psi (a) of the distillation column. An immersion heater which is connected through SCR voltage regulator which maintains the temperature of the column by providing transitively heating. The control signal required for control circuitry IC TCA785 is 4-20 mA or 0-10 V which provides the required firing angle for the thyristor. The overall system can be monitored through HMI.

The feed stream is fetched continuously in the distillation column, so, the system is termed here as the continuous. PLC takes the values of RTD in terms of decimal values shown in the Table 2 and provides the fuzzified value to the FLC through FTC command which compares the current temperature with the set-point and according to the equations based on the Sugeno Fuzzy Model output is sent to the control circuit of the AC voltage controller which variably controls the RMS voltages of the heater, Table 3 shows the relationship between defuzzified decimal values and control signal (DC current) of regulator. The heater is being running variably until the temperature of the column is reached at 80 °C at standard pressure of 14.5 psi. At this temperature and pressure the alcohol is vaporized completely from the solution and collected in the container via. condenser and leaving behind only one solvent that is water. The water is then drained out through the solenoid valve SOV and collected in the container. The operation can be monitored and controlled manually as well through HMI touchscreen.

Table 2: RTD output vs. temperature vs. decimal values

RTD output (mA)	Temperature (°C)	Decimal value	RTD output (mA)	Temperature (°C)	Decimal value
4.00	0	200	13.6	60	680
5.60	10	280	15.2	70	760
7.00	20	350	16.8	80	840
8.80	30	440	18.4	90	920
10.4	40	520	20.0	100	1000

Programming approach: The software used for programming purpose is WPL-SOFT, it is compatible programming software for DVP-PLC. Ladder language programming has been used for the purpose. The programming flowchart is shown in Fig. 18.

Table 3: Decimal values vs. Current Values vs. RMS voltages

Decimal value (K)	Current value (mA)	RMS voltages (V)	Decimal value (K)	Current value (mA)	RMS Voltages (V)
400	4	0.00	1410	14.1	103.7
600	6	0.84	1600	16.0	143.0
800	8	3.73	1800	18.0	190.0
1000	10	22.80	2000	20.0	220.0

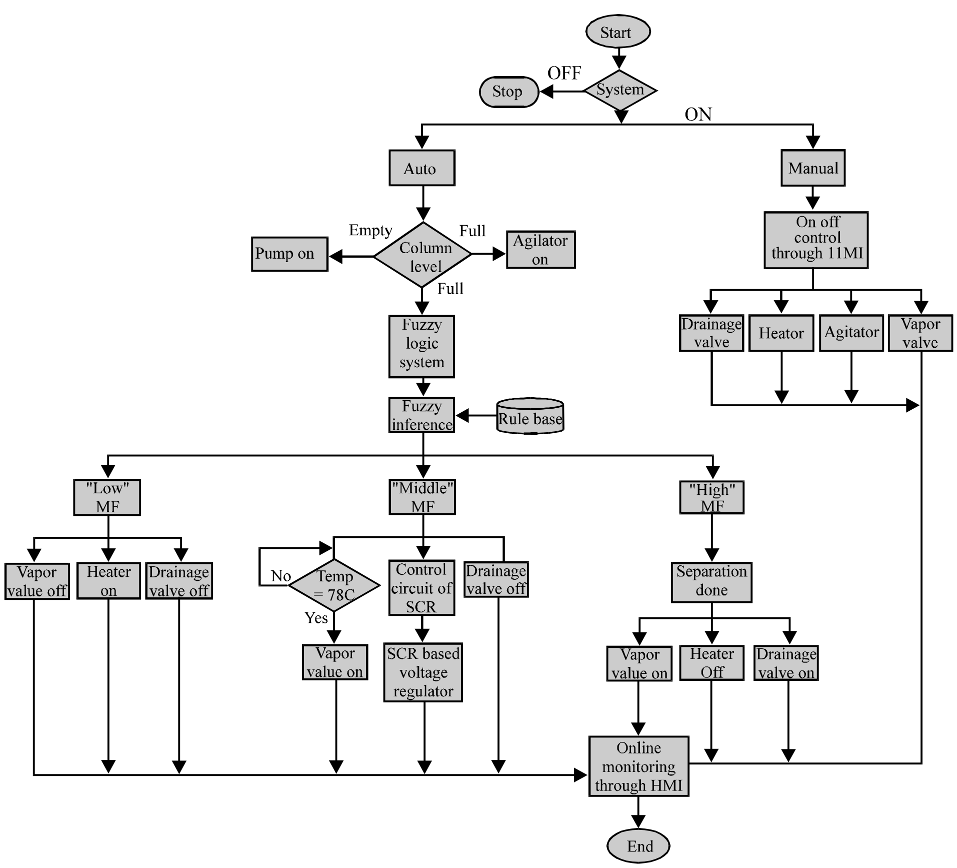

Fig. 18: Programmming flowchart

Figures 19-22 preview the results of the implemented defuzzified value. The defuzzified output is fed to the control circuit of the AC voltage controller whose firing angle 'α' is controlled through PAC IC TCA-785 which vary accordingly to the inverse relationship that when 4-20 mA (0-10 V) varies, phase angle also varies in 0-180°C range. AC voltage controllers are the thyristor devices that convert a fixed alternating voltage directly into variable alternating voltage without change in frequency (Mahar *et al*., 2012; Larik *et al*., 2011). The Simulink Model of ac voltage controller feeding resistive load R = 50 Ω of heater is shown in Fig. 23.

Input is sinusoidal voltage whereas for firing angle (α = 45, 90, 135°), supply input and load currents and load voltage waveforms feeding (Fig. 24-35) to resistive load of 50 Ω of heater along with the FFT analysis to show the Total Harmonic Distortion (THD) produced in the load are shown in Fig. 24-35 and Table 4 represents the calculation at different firing angles.

The above results show that at resistive load the current and voltages are in phase. At α = 45°, the THD is 26.44% by increasing the firing angle THD increases as well. The RMS voltages and currents are decreasing desirably. The harmonics in the signal show the involvement of dc components which effects the power factor of the system. As the firing angle increases, the power factor reduces as well which in return increases the heating effect, hence at lower current values greater heating is achieved at lower time rate.

Table 4: Characteristics of AC VC feeding Resistive load at α = 45, 90, 135°

Firing angle (α)	Supply current (Is) (A)	RMS Load Voltage (VL) (V)	RMS Load Current (IL) (A)	Power factor
45°	4.1830	209.20	4.1830	0.909
90°	2.5470	127.40	2.5470	0.554
135°	0.8035	40.18	0.8035	0.174

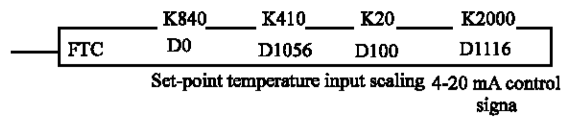

Fig. 19: FTC output at input 410

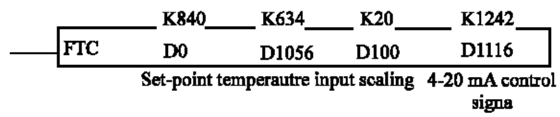

Fig. 20: FTC output at input 634

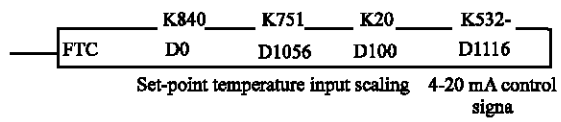

Fig. 21: FTC output at input 751

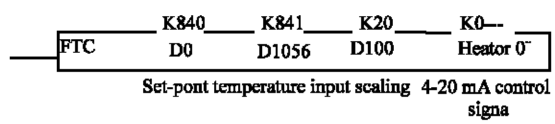

Fig. 22: FTC output at input 840

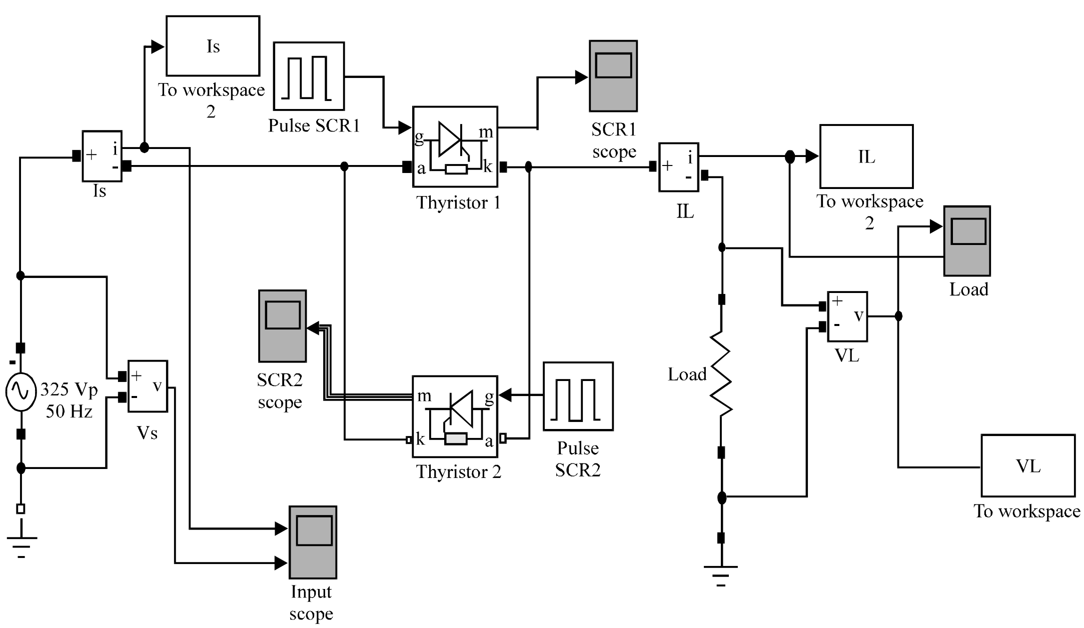

Fig. 23: AC Voltage controller Simulink Model

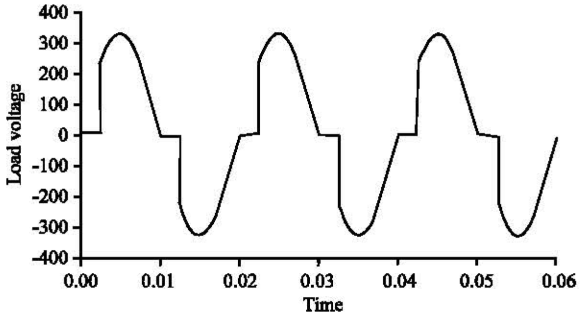

Fig. 24: Load Voltage (VL) at α = 45°

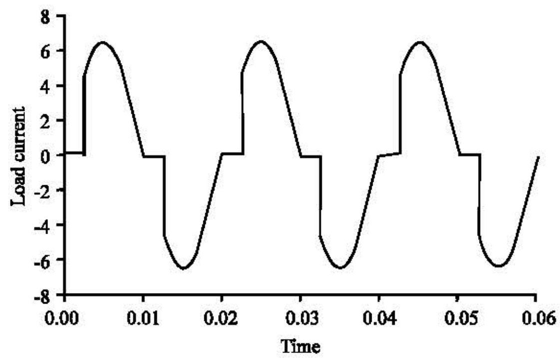

Fig. 25: Input and Load current (Is, IL) α = 45°

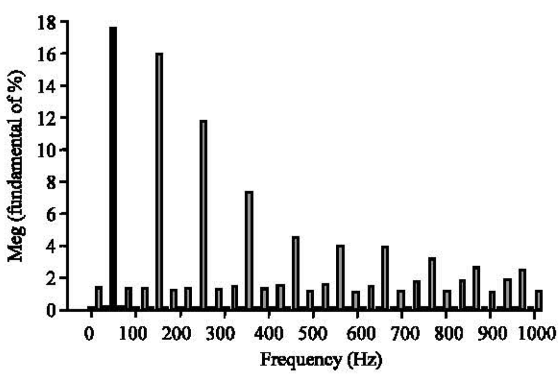

Fig. 26: Load voltage THD α = 45°

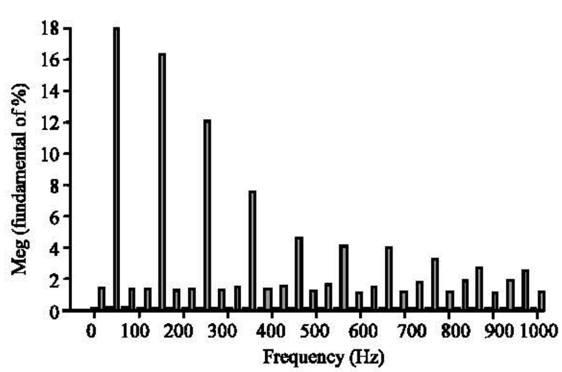

Fig. 27: Load current THD (Is, IL) α = 45°

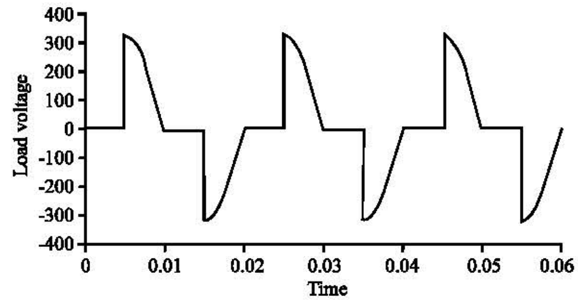

Fig. 28: Load Voltage (VL) at α = 90°

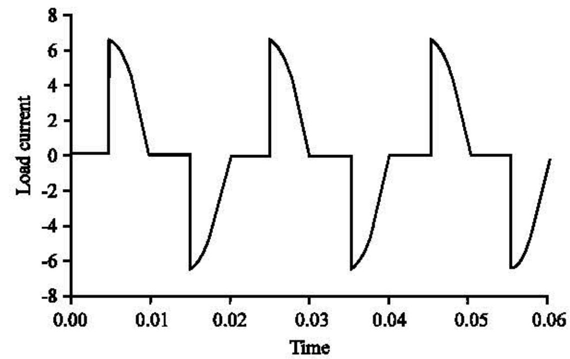

Fig. 29: Input and load current (Is, IL) α = 90°

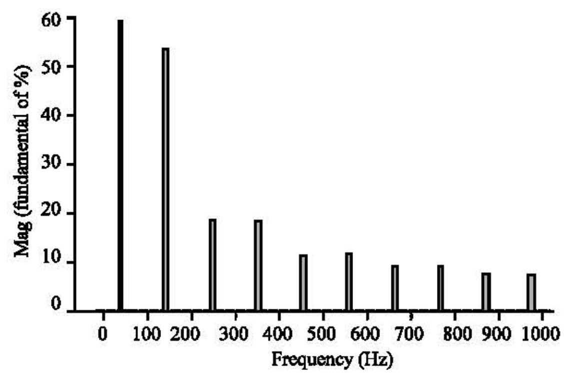

Fig. 30: Load voltage THD α = 90°

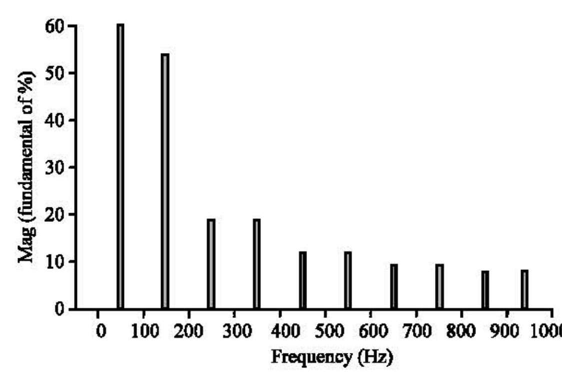

Fig. 31: Load current THD α = 90°

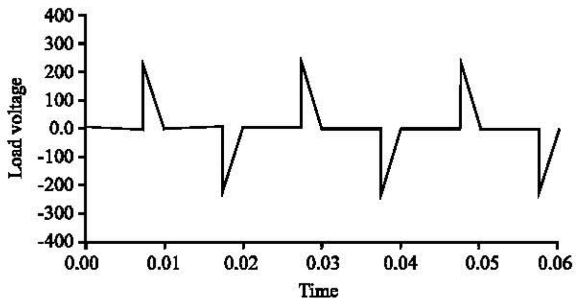

Fig. 32: Load Voltage (VL) at α = 135°

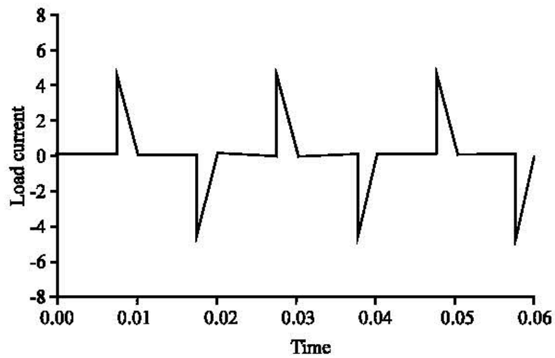

Fig. 33: Input and load current (Is, IL) α = 135°

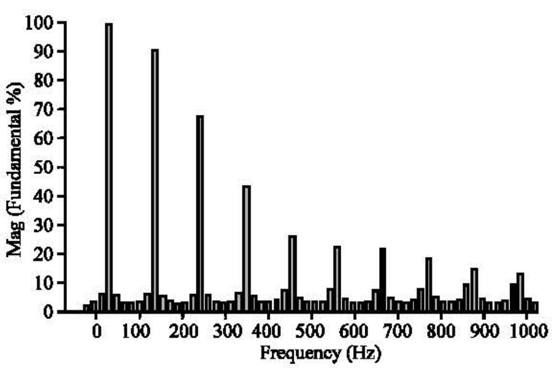

Fig. 34: Load voltage THD α = 135°

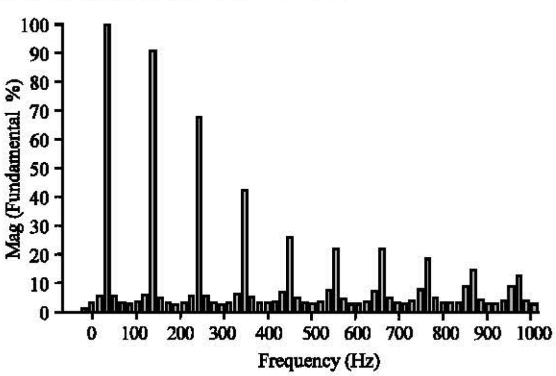

Fig. 35: Load current THD α = 135°

CONCLUSION

The study has presented the smart and intelligent system for the distillation of the ethanol-water mixture based on FLC controller which is implemented through DVP-PLC. The overall analysis and design from the simulation to the implementation have also been presented. The study presents the smart solution to the complete distillation by utilizing the inertia produced in the heater and taking the advantage of the lower power factor of AC voltage regulator in terms of heat energy. The HMI interface has also been implemented for the monitoring of the parameters. The presented analysis also successfully demonstrates the potential of the idea.

RECOMMENDATIONS

This project can also be controlled by Logix 5000 of Allen-Bradley, Siemens fuzzy PLC as well. The separated water pH level can also be controlled by adding required amount of minerals, acids and basics.

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