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Production and Control of Biodiesel from Jatropha-Curcas Oil

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Abstract*— Continuously increasing energy demands made biodiesel an attractive alternative fuel. Implementation of biodiesel from Jatropha-Curcas oil in Sudan will give many advantages like supporting the agricultural and rural economy, reduction in air pollution, and reduction in dependency on imported crude oil. In this paper biodiesel produced in order to design an appropriate control strategy. The reaction of biodiesel production which is the alkaline tranestrification was done in a small scale Batch Reactor, and then a Continuous Stirred Tank Reactor was designed for the control requirements. Two control systems were studied: conventional and digital cascade systems. The transfer functions of the loops were determined firstly, and then the methods of tuning were applied to get the ultimate gain and period. Also Ziegler-Nichols technique was used to determine the optimum parameters for the response simulation of the system. Digital systems need no Z-N optimization in fact that they are self –tuned; and this is very clear of the very low gains obtained from Root-Locus and Bode plots.

Index Terms— **Biodiesel, Cascade Control, Digital Control, Jatropha-Curcas.**

I. INTRODUCTION

Biodiesel refers to any equivalent ester based oxygenated biofuel produced by transesterification process from renewable biological material [1]. Biodiesel is a renewable fuel source that can replace petroleum diesel in compression ignition engines and has significant effects in reduction of virtually all regulated emissions [2]. Jatropha-Curcas (J. Curcas) is a plant that is inedible and it is a viable choice as feedstock for biodiesel due to the ease of growing in low nutrient soils [2], [3]. Experimental data concerning reaction conditions, process parameters, as well as the amounts and concentrations of the chemicals were used to find the most efficient method of producing biodiesel from J. Curcas oil. The transestrification reaction is reversible endothermic reaction, and the yield of production depends mainly on the reaction temperature, the reaction time, and the reactants ratio.

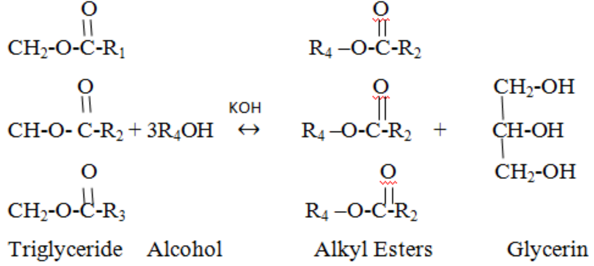
The effectiveness of a chemical plant is determined by the interplay between the process, the modes of operation and the control system [9]. The topic of this paper is to assess the feasibility of the results compared to fossil fuel diesel and integration of process design and control system design to control the reaction temperature.

II. MATERIALS AND METHODS

Materials used for biodiesel production were: Jatropha-Curcas oil, methanol, and potassium hydroxide. The reaction mechanism was investigated in a Batch Reactor, and then a Continuous Stirred Tank Reactor (CSTR) had been designed and controlled for the large scale production of biodiesel. The research has two main parts: production and control. For the production process the following steps had been done:1) Oil free fatty acid determination, 2) Alkaline Catalyzed Transesterification 3) Separation of Biodiesel, 4) Purification and Dehydration of Biodiesel, and 5)Biodiesel Analysis. And for control strategy two control systems were analyzed and compared: conventional cascade and digital cascade control systems; and this is done by: 1) Mathematical modeling including design of the Continuous Stirred Tank Reactor, 2) Transfer functions identification, and 3) Systems tuning.

Alkaline Catalyzed Transesterification:

Through research, it was decided that an alkaline catalyzed transesterification reaction is the most commonly used method for producing biodiesel, as well as the most economically beneficial method [4].



$CH_2\text{-O-}C(=O)\text{-}R_1$ / $CH\text{-O-}C(=O)\text{-}R_2$ / $CH_2\text{-O-}C(=O)\text{-}R_3$ + $3R_4OH \xleftrightarrow{KOH}$ $R_4\text{-O-}C(=O)\text{-}R_2$ (×3) + $CH_2\text{-OH}$ / $CH\text{-OH}$ / $CH_2\text{-OH}$

Fig 1: Transestrification reaction of triglycerides via alkaline catalyst

Full production procedures can be found elsewhere in the literature.

Conventional Cascade Control

Cascade control consists of two loops: the primary loop and the secondary loop. The controlled variable is the reactor temperature. This strategy is work as follows: the primary controller measures the reactor temperature (T_r) and decide how to manipulate the jacket temperature (T_j) to satisfy its set point. This decision is transmitted to the secondary controller in the form of a set point. The secondary controller is then manipulates the signal to maintain the jacket temperature at the set point provided by the primary controller [8] as shown in figure 2.

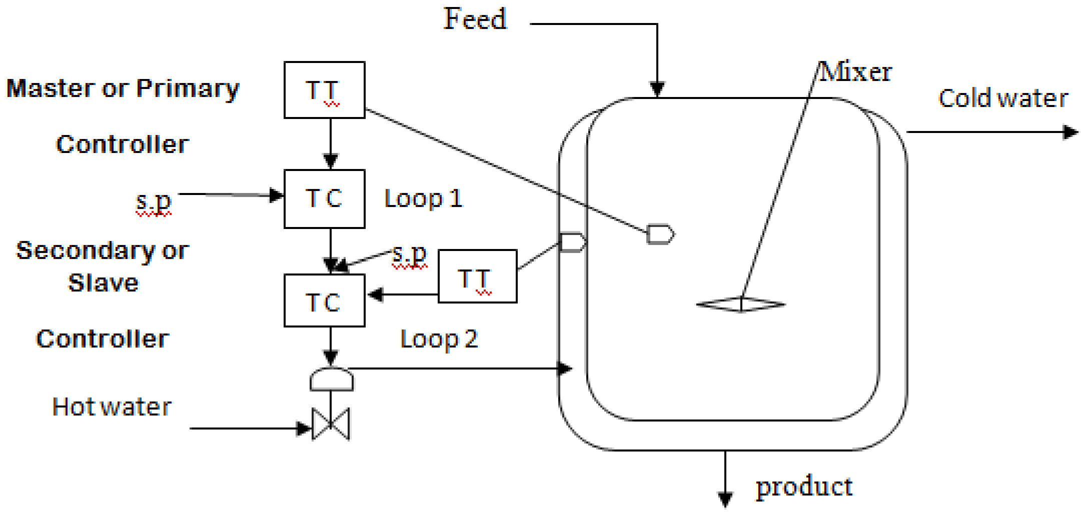


Fig 2: Temperature Conventional Cascade Control for a CSTR

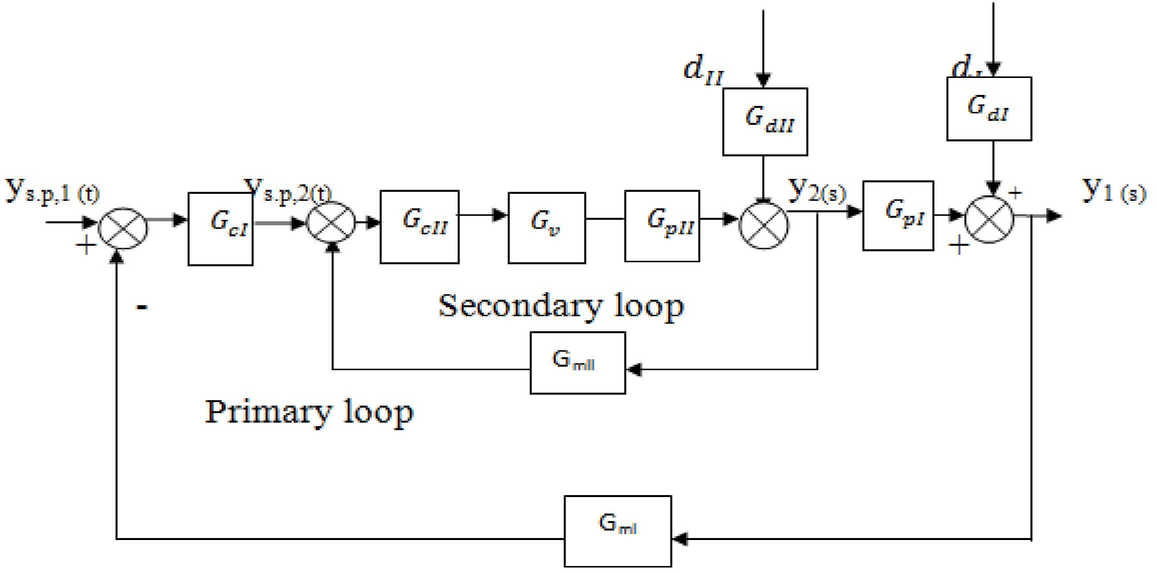


Fig 3: Block Diagram of Conventional Cascade Control

By applying energy balance around the reactor and around the reactor jacket the transfer functions of the processes ($G_{PI}$and G_{PII}) were identified as follows:

$$G_{PI} = \frac{T_{(S)}}{T_{0(S)}} = [\frac{1}{\tau_1 S+1-k_1}] -[\frac{k}{\tau_1 S+1-k_1}]*[\frac{T_{j(S)}}{T_{0(S)}}] \qquad \text{……….. (1)}$$

$$G_{PII} = \frac{T_{j(s)}}{T_{j0(s)}} = [\frac{1}{\tau_2 S+1-k_2}] -[\frac{k}{\tau_2 S+1-k_2}]*[\frac{T(s)}{T_{j0(s)}}] \qquad \text{………...(2)}$$

Also for $G_{V,}$ G_{mI} and G_{mII} the mathematical modeling was applied and the transfer functions were identified as:

$$G_m = \frac{1}{\tau_p s+1} \qquad \text{………....(3)}$$

$$G_V = \frac{K_V}{\tau s+1} \qquad \text{…………(4)}$$

The Proportional -controller transfer function is:

$$G_C(s) = k_c \qquad \text{…………(5)}$$

The secondary loop was tuned firstly to get K_{CII}, and then the primary loop was tuned to get K_{CII}. Different tuning methods were used: direct substitution method, Root Locus Analysis, and Bode plot. Closed loop Ziegler-Nichols method was applied to determine the optimum ultimate gains and to calculate the controller adjustable parameters (k_C,τ_I, and τ_D).

Table 1: Controller optimum parameters for closed loop Ziegler-Nichols Method [7]

Type of controller	**k_c**	**τ_I**	**τ_D**
P	0.5 k_c	-	-
PI	0.465k_c	P_u/1.2	-
PID	0.6k_c	P_u/2	P_u/8

Routh-Hurwitz and Roots Solving methods were used to test the system stability.

Digital Cascade Control:

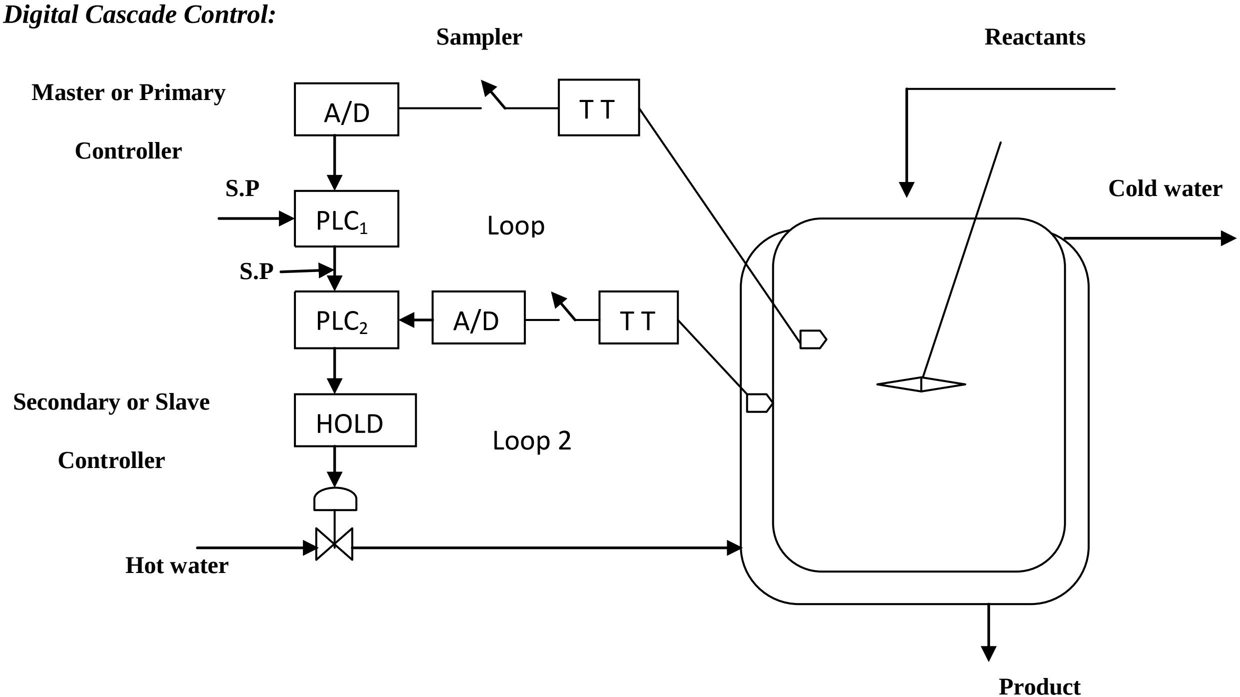


Fig 4: Digital Cascade Temperature Control System for a CSTR

To analyze the system digitally firstly the transfer functions of the conventional cascade control were converted from s-plane to z-plane. MATLAB formats were used in analyzing this system. There is a MATLAB function called c2d to convert the continuous system to discrete system. The basic command is:
sys_d = c2d(sys,Ts,’zoh’) [5].
The imaginary (Im(z)) versus the real(Re(z)) was drawn, and show the lines of constant damping ratio(zeta) and natural frequency (ω_n).The stability boundary is not the imaginary axis, but it is the unit circle z=1; the system is stable when all poles are located inside the unit circle and unstable when any pole is located outside [6].

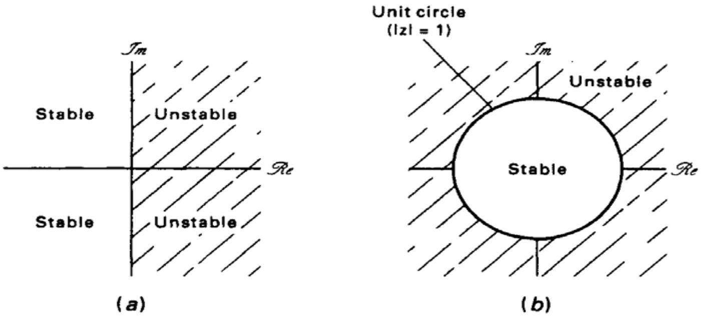


Fig 5: Regions of stability and instability: a) s-plane; b) z-plane [6]

The mechanics of drawing the Root-Locus and Bode methods are exactly the same in the z-plane as in the s-plane [5]. By using MATLAB format and from the plots the stability was tested, and the gain was determined.

III. RESULTS AND DISCUSSION

Biodiesel from Jatropha-Curcas oil was produced and analyzed in professional laboratories, and the results were shown in table 2. The highest conversion of 82% was obtained when operating for 2 hours at 65°C with a ratio of 0.4:1 v/v of methanol to oil. The results show that the biodiesel from Jatropha oil has relatively closer fuel property values to that of diesel.

Table 2: physical properties of Jatropha biodiesel, fossil diesel and biodiesel standard properties

Properties	**Unit**	**Petroleum Diesel**	**Sudanese biodiesel Standard Specifications**	**Jatropha-oil**	**Produced biodiesel (Jatropha Methyl-ester)**
Density(at15°C)	kg/m^3	880	860-900	930	887
Flash point	°C	47-50	57 mini	174-240	162
Kinematic viscosity(40 °C)	mm^2/s	2.27	2.2- 8.8	49	6.957
Cetane number	----------	45-55	47 mini	40-45	40
Net calorific value	MJ/kg	42.5	40	38.5	44
Sodium/potassium	ppm	---------	5 max-combined	---------	1-combined
Distillation temperature,90% recovered	°C	347.8 max	375 max	----------	350.6 max
Acid number	mgKOH/g	------------	0.5 max	2.17	0.17

Control strategy

The transfer functions for the conventional cascade loops had been determined, and the block diagram is as follows:

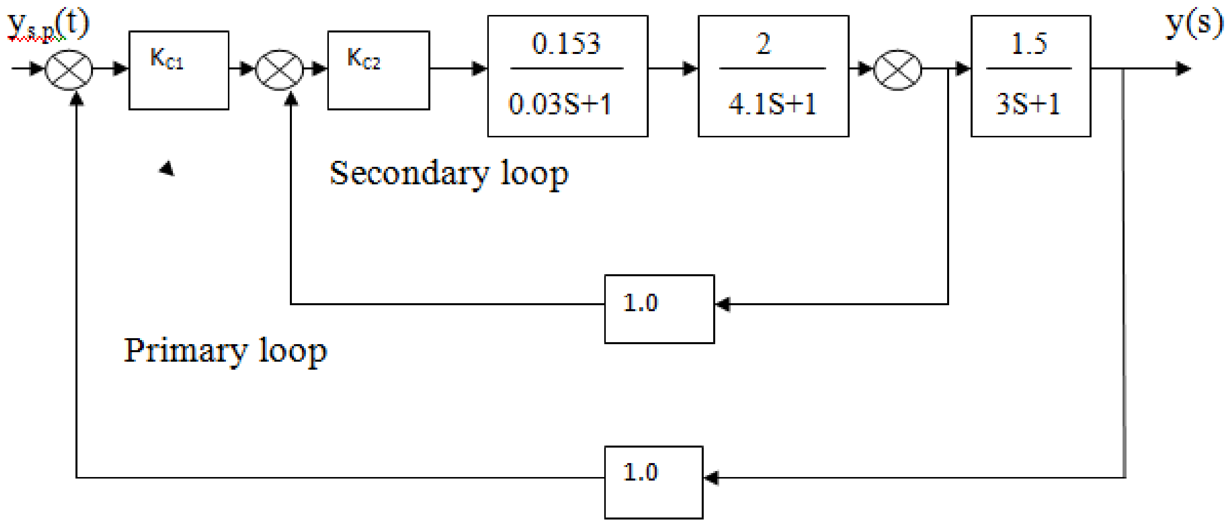


Fig 6: Cascade control block diagram

The value of k_{C2} was determined by tuning the secondary loop firstly. Rout-locus and Bode plots were applied and the system was found to be unconditionally stable, therefore any values of k_C can be used. By comparing the response for different values of k_C the value of k_C =700 which has the minimum settling time was chosen to calculate k_{C2}. Then the loop was reduced to:

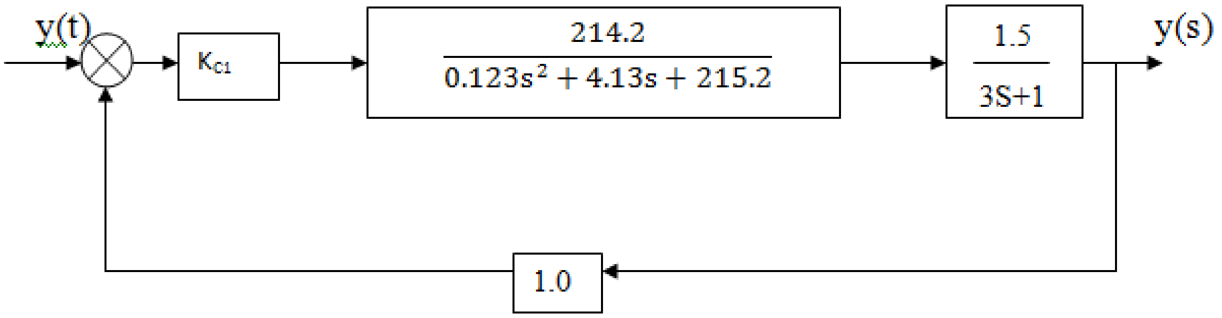


Fig 7: The block diagram of the reduced cascade loop

For this loop:

The open-loop transfer function (OLTF) = $\frac{321.3k_{cI}}{0.369s^3+12.51s^2+649.73s+215.2}$ ……….... (6)

The overall transfer function G(s) = $\frac{321.3k_{cI}}{0.369s^3+12.51s^2+649.73s+215.2+321.3k_{cI}}$ ……..….(7)

The characteristic equation is:

$0.369S^3+12.51S^2+649.73S+215.2+321.3K_{CI}=0.0$ …..……..(8)

Methods of tuning

1. ***Root -Loucs Method***

OLTF = $\frac{312.3k_{cI}}{0.369s^3+12.51s^2+649.73s+215.2}$ ……………(9)

The values of the ultimate gain k_u and the cross-over frequency ω_{co} were determined by using MATLAB:

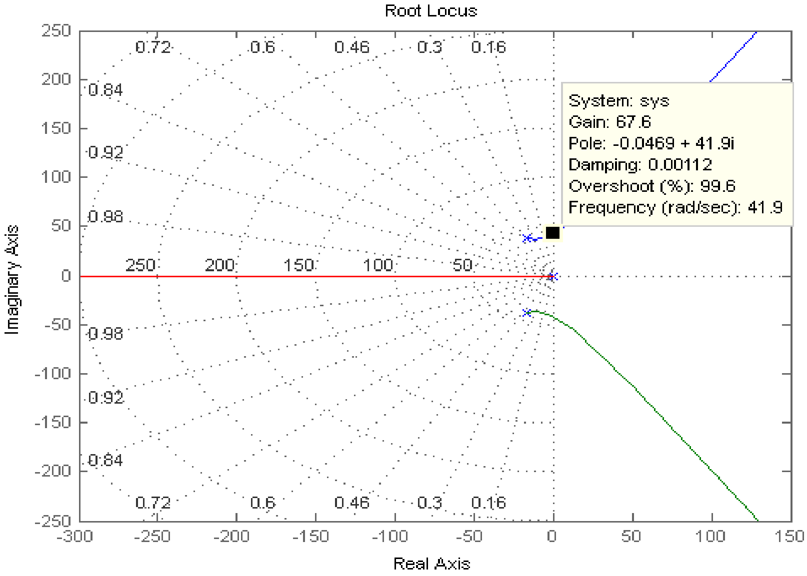


Fig 8: Root Locus for the primary loop

2. *Bode Plot Method*

Referring to the above OLTF in MATLAB:

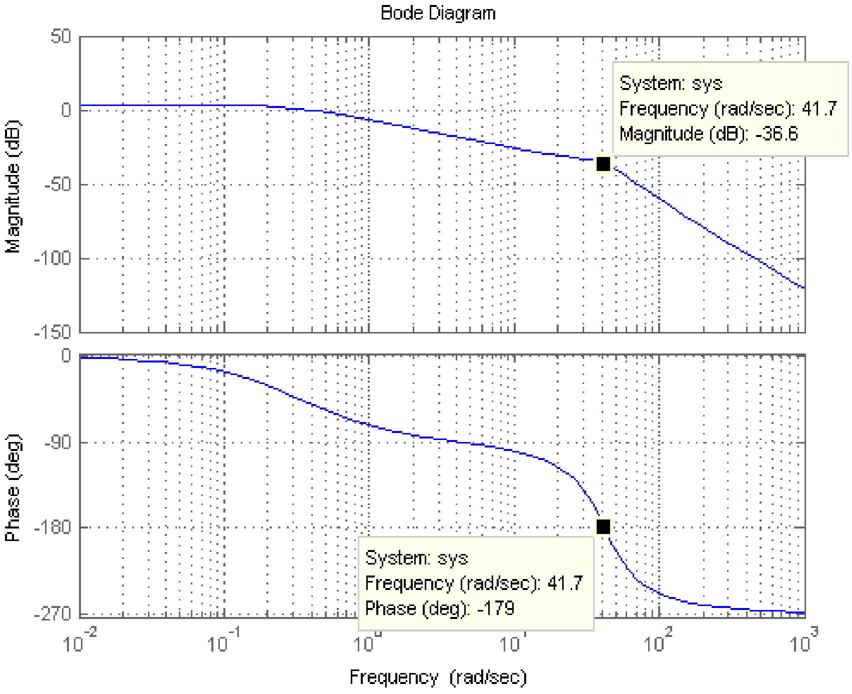


Fig 9: Bode plot for the primary loop

Table 3: Comparison between the methods of tuning used

Method	**K_u**	**ω_{co} (rad/s)**	**$P_u = 2\pi/\omega_{co}$ (s)**
Direct substitution	69.244	41.962	0.1497
Root-locus	67.6	41.9	0.1499
Bode plot	67.61	41.7	0.1507
Routh- Hurwitz	67.9	41.96	0.1497
The average	68.089	41.881	0.150

Table 4: Ziegler-Nichols tuning parameters

Type of controller	**K_C**	**$\tau_{I,}$ (s)**	**τ_D (s)**
P	34.622	--------	---------
PI	31.5198	0.125	---------
PID	41.546	0.075	0.019

The response due to a step change in the set point was plotted by using MATLAB, and it is as follows:

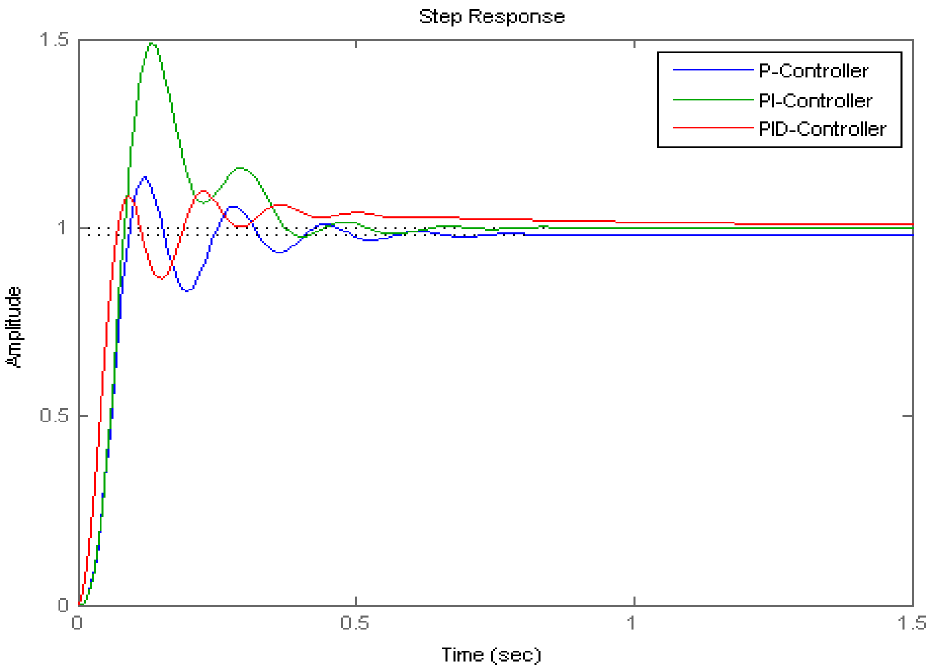


Fig 10: Response due to a step change in the set point

PI-controller has the minimum settling time (0.416 sec), while the PID-controller has the least overshoot (9.5%).

PID-controller is recommended because the overshoot of temperature may affect the reaction rate and the product quality (temperature sensitive reaction).

Digital Cascade control:

For P-controller, the closed loop transfer function is:

$$G(s) = \frac{11124.05}{0.369S3+12.513S2+649.73S+11339.25} \qquad \text{………….(10)}$$

The converted G (z) is:

$$G\ (z) = \frac{0.004585z2+0.01674z+0.00387}{z3-2.552z2+2.29z-0.7124} \qquad \text{…………. (11)}$$

Discrete Root Locus:

$$OLTF\ (z) = \frac{0.0045z^2+0.0163z+0.00376}{z^3-2.57z^2+2.28z-0.71} \qquad \text{……….(12)}$$

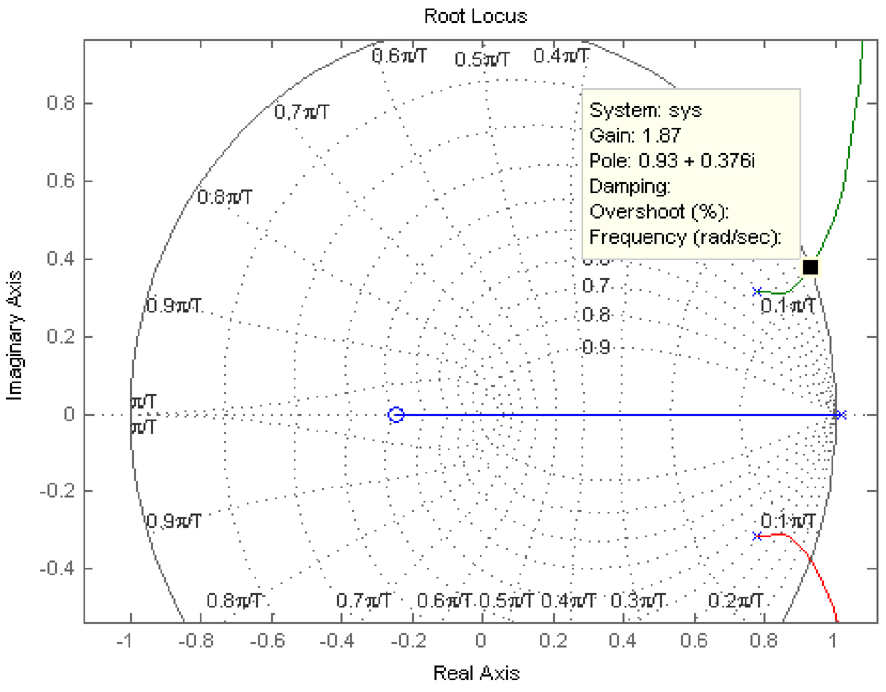


Fig 11: Discrete Root-Locus

Discrete Bode plot:

AR=0.542, K_u= 1/AR= 1/0.542 = 1.845

Table 5: Comparison between the methods of tuning used for the discrete system

The method	**K_u**
Root-locus	1.87
Bode	1.845

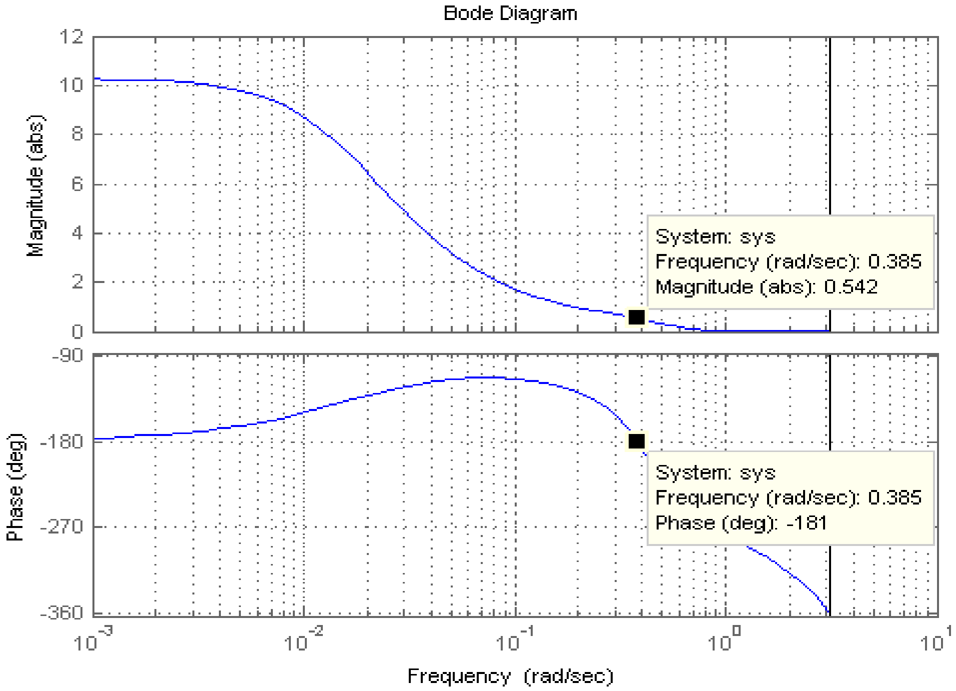


Fig 12: Discrete Bode Plot

Table 6: Comparison between control systems used

Parameter	**Cascade control system**	**Digital control system**
Ultimate gain, $K_{u,\ average}$	34.622	1.86
Ultimate period, $P_{u,average}$ (s)	0.150	0.155
Cross-over Frequency, $\omega_{co,\ average}$ (rad /s)	41.881	40.5
Settling time, T_s (s)	0.416 min	0.465
Overshoot, os(%)	9.5 min	15.8
Notes	T_s min for PI and os min for PID	This results at T=1/100 sec

IV. CONCLUSION

By comparing the physiochemical properties of produced biodiesel from Jatropha-Curcas oil with the standard Sudanese biodiesel specifications it was found that the properties of produced biodiesel are within the range of the standards. In order to eliminate any production disturbances, and for safety and economic issues; it is important to develop a control strategy. The reaction is temperature sensitive; hence a temperature control systems was designed and analyzed. Conventional cascade control system and digital control system were considered. The stability was tested in all systems using Routh-Hurwitz, Direct Substitution, Root locus, and Bode methods, also the systems were tuned using Zigler –Nichols method. It was found that the systems are all stable, and PID controller was suitable in cascade control system for its less overshoot (9.5%). Digital control system had small gain (K_u = 1.86) compared with the conventional cascade control system (K_u = 34.622); this is due to its discontinuous and fast response.

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