

# Liquid Mixing Enhancement by PLC-Based Chaotic Dynamics Implementation

Hamzah Abdulkareem

 Department of Electric  
 Engendering

 University of Basrah  
 Basrah, Iraq

hamzaabd413@gmail.com

Fadhil Rahma

 Department of Electric  
 Engendering

 University of Basrah  
 Basrah, Iraq

fadhilrahma.creative@gmail.com

Jawad Radhi

 Department of Electric  
 Engendering

 University of Basrah  
 Basrah, Iraq

alali.jhana@yahoo.com

**Abstract** In this paper, we present a new programmable chaotic circuit based on the dynamical chaotic system introduced by E. Lorenz. The design and realization of the model are accomplished by using a programmable logic controller (PLC). The system can be modeled and realized with a structured texted. The nonlinear differential equations of Lorenz model are solved numerically. The generated chaotic signal by using PLC is applied to a single-phase induction motor via a variable frequency drive to create a chaotic perturbation in the experiments of liquid mixing. Colorization liquid experiments shows that the generated chaotic motion effectively makes an enhancement of the mixing process in the stirred-tank mixer model in our laboratory.

**Index Terms**— Programmable logic controller (PLC), Structured Texted (ST), Chaos, Lorenz System, Chaotic Mixer.

## I. INTRODUCTION

Recently, the interesting of design and implementation of chaotic systems have been increased. It has been discovered that chaos is applicable in many application fields such as secure communications, engineering, medicine [1-3]. Many chaotic systems have been discovered. The first discovered system is, the Lorenz. In 1999, Chen and Ueta developed the Lorenz system by introducing state feedback on the second equation, this changing presented a new chaotic attractor called Chen attractor [4]. In 2002, Lü and Chen introduced a new chaotic system with name Lü system [5]. In 2002, Lü et al. collected the above chaotic systems into a new chaotic system-unified chaotic system [6].

Theoretical design and system realization of various chaotic systems have been a main subject of applications in the real-world of many chaos-based technologies and information systems [7-10]. Programmable logic controller (PLC) is a programmable device with special design for industrial applications and digital computing. In

general PLC is the most important and accepted computers in the industry. It gives a robust and reliable system and uses a type of memory which can be programmed it to store instructions and to form many functions such as sequencing, counting, conditional, and arithmetic timing for control many kinds of processes and machines by digital or analog input and output. In addition to the above properties, PLC has other advantages such as: good versatility, the installation is flexible, the ability of anti-interference is good, the ease in learning and using, have small volume, low energy consumption, high performance per cost ratio [11-14].

Mixing is usually represented an important part in many processes on the industry such as reactants in the chemical reactor, blending of ingredients, food processing. It can be considered that the good mixing is one of the most primary and critical process in the industry. The product quality depends strongly on the mixing. The annual cost of the inefficient mixing in the industries has been estimated to be as much as \$10-billion in the USA alone. Therefore, the researchers have been

investigated in some methods for mixing enhancement. In the last years, the progress in understanding the chaos theory and nonlinear technologies has led to the emergence of some ideas to take advantage of some properties of chaos in different industrial fields, particularly in the liquids mixing operations [15-17].

This paper, introduces a programmable implementation of the dynamical Lorenz system based on PLC. Also in this work, we introduce our design, implementation and experiments of the chaotic mixer based on a stirred tank model, and show that it is enabled to work under the different kinds of the control signals, especially chaotic signals. The laboratory experiments have been performed to evaluate the quality and the efficiency of mixing when a various motion perturbation schemes are applied

The reset of paper is arranged as follows: Section II discusses XEC-DN32H PLC device. Section III describes the Lorenz model. Circuit implementation will introduced in Section IV. The mixer design, the mixer implementation, the experiment and the comparison between two kinds of mixing are discussed in Section V. A brief conclusion is given in Section VI.

## II. PROGRAMMABLE LOGIC CONTROLLER

### A. PLC ARCHITECTURE

PLCs are defined as programmed devices that can be programmed by the user to do various control systems. The main parts of a PLC system are the central processing unit (CPU), the unit of power, memory, input and output connection section, communication interface section and the device of programming[16,17]. Fig. 1 shows the basic structure of PLC [14].

- The central processing unit (CPU) or simply the processor is the microprocessor chip. It reads the coming signals from input and according to these signals, it makes the control action depending on the user defined program stored in the memory.
- The memory unit is the unit where a program needed for microprocessor is stored. Also used to store the processing input data and buffering output data.

- The power supply unit is needed to convert the AC voltage to the suitable DC voltage for the processor and circuits in PLC.
- The input and output connection modules enable the processor to receive the information from the external input devices and send the output signals to the output external devices. The input almost connected to sensor or switches such as shaft encoder, flow sensor or temperature sensor. The output often connected to controllable device such as VFDs, solenoid valves, magnetic relay, magnetic contactor, solid state relay, etc. In general, the input/output models are divided into analog and digital type according to the kind of signal.
- The communication interface module enables PLC to transmit and receive information on communications networks.

In this paper a Ls XEC-DN32H compact PLC with digital to analog converter (DAC) module (XBF-DV04A) has been used.

### B. XEC-DN32H

The XEC-DN32H is one of XGB PLCs series include 200 KB of memory size with 0.083  $\mu$ s/step processing speed and facilities to be programmed by using one of three languages which are agreeing with the IEC standard by using XG5000 software package. Each of these enables any compact of programming languages to be used for any project. These languages are [20-23]

- A Ladder Diagram (LD) is a low-level graphical language that uses a software device (symbol) to represent relay logic. The basic symbols are contacts and coils that are connected by links.
- A Sequential Function Chart (SFC) this language similar to the computer flowchart, the basic concept of SFC is an action box, which have a code written with any programming language taken by the programmer.

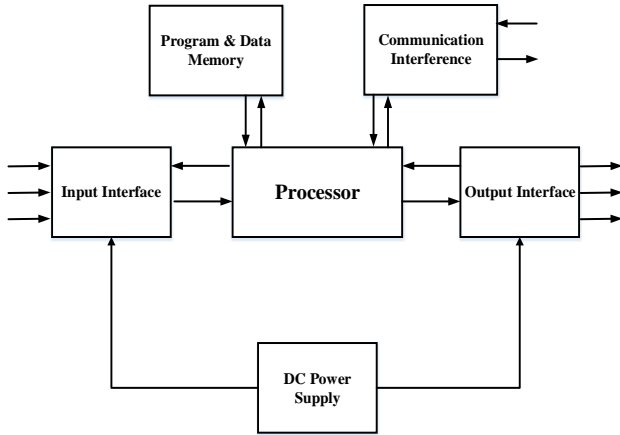


Fig. 1 A basic structure of Programmable Logic Controller.

- A Structured Texted (ST) is a high level programming language, resemble to C or PASCAL, ST is very useful for complex program which allow iteration and conditional statement in programs.

### III. CHAOTIC SIGNAL GENERATOR USING PLC

In recent years, various dynamical systems have been successfully implemented by using different methods such as discrete components, digital signal processor kit (DSP kit), field-programmable analog array (FPAA), field programmable gate array (FPGA) [24-26] . In this paper, for the first time a new method of realization and generation of chaotic dynamics on a PLC is introduced. XEC-DN32H/DC compact PLC with analog to digital converter model (XBF-DV04A) is used in this paper project and the structured texted mode (ST) for programming and realizing various systems.

After the system implementation is modelled in PLC software tool, then the programed system is downloaded to the PLC device via USB interface. Experimental measurements can be performed from I/O connections on the PLC. The dynamic range of signals inside the PLC is obtained through voltage signals in differential mode. This meaning that any chaotic system is designed by supposing that the states variable of the dynamical system are voltage signals.

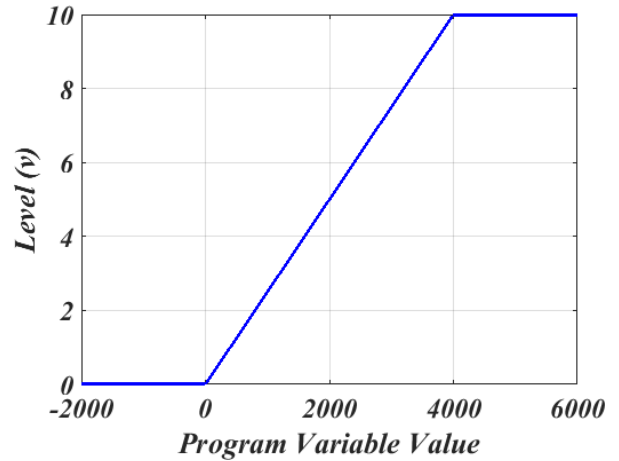


Fig. 2: The characteristics of the (XBF-DV04A) module.

To generate chaotic systems from PLC processor, it must be rescaled systems in a manner that make it compatible with characterizes of the DAC module which shown in Fig. 2. Then a transformation from continuous-time systems to discrete-time systems must be applied to the rescaled systems.

Suppose that the general form of a dimensionless continuous-time chaotic system is

$$\begin{aligned} \dot{x}_1(t) &= G_1(x_1, x_2, \dots, x_n) \\ \dot{x}_2(t) &= G_2(x_1, x_2, \dots, x_n) \\ &\vdots \\ \dot{x}_n(t) &= G_n(x_1, x_2, \dots, x_n) \end{aligned} \quad \dots (1)$$

Where  $G_j (j = 1, 2, 3 \dots, n)$  are the system functions which have a nonlinear term. For  $\mathbf{M}_{1j} \leq \mathbf{x}_j \leq \mathbf{M}_{2j}$ , if the range of  $\mathbf{x}_j$  is not compatible with (XBF-DV04A) module characteristics, a rescaling and shifting processing must be applied as following:

$$\mathbf{x}_j = \frac{\mathbf{x}_j}{\mathbf{a}_j} - \mathbf{s}_j \quad \dots (2)$$

Where  $(\mathbf{M}_{1j} + \mathbf{s}_j \geq 0, \mathbf{s}_j \geq 0)$  and  $\mathbf{a}_j = \frac{4000}{\mathbf{M}_{2j} + \mathbf{s}_j}$ .

The applying of these changing on the system (1) is yielding

$$\begin{aligned}
\dot{X}_1(t) &= G_1 \left( \frac{X_1}{a_1} - s_1, \frac{X_2}{a_2} - s_2, \dots, \frac{X_n}{a_n} - s_n \right) * a_1 \\
\dot{X}_2(t) &= G_1 \left( \frac{X_1}{a_1} - s_1, \frac{X_2}{a_2} - s_2, \dots, \frac{X_n}{a_n} - s_n \right) * a_2 \\
&\vdots \\
\dot{X}_n(t) &= G_1 \left( \frac{X_1}{a_1} - s_1, \frac{X_2}{a_2} - s_2, \dots, \frac{X_n}{a_n} - s_n \right) * a_n \quad \dots (3)
\end{aligned}$$

The discretization of Equation (3) performs by using Range-Kutta 4 with step size  $h$  as follows

$$\begin{aligned}
X_1(k+1) &= X_1(k) + [R_{11} + 2R_{12} + 2R_{13} + R_{14}]/6 \\
X_2(k+1) &= X_2(k) + [R_{21} + 2R_{22} + 2R_{23} + R_{24}]/6 \\
&\vdots \\
X_n(k+1) &= X_n(k) + [R_{n1} + 2R_{n2} + 2R_{n3} + R_{n4}]/6 \quad \dots (4)
\end{aligned}$$

Where

$$\begin{aligned}
R_{i1} &= G_i[X_1(k), X_2(k), \dots, X_n(k)]ha_i \\
R_{i2} &= G_i[X_1(k) + 0.5R_{11}, X_2(k) + 0.5R_{21}, \dots, X_n(k) + 0.5R_{n1}]ha_i \\
R_{i3} &= G_i[X_1(k) + 0.5R_{12}, X_2(k) + 0.5R_{22}, \dots, X_n(k) + 0.5R_{n2}]ha_i \\
R_{i4} &= G_i[X_1(k) + R_{13}, X_2(k) + R_{23}, \dots, X_n(k) + R_{n3}]ha_i \quad \dots (5)
\end{aligned}$$

For  $i = 1, 2, 3, \dots, n$ .

Equations (4) and (5) are programmed by using ST language to realize the desired chaotic system with PLC. Therefore, to design and implementation the dynamical system in the PLC, the flowchart of programming should be followed as shown in Fig. (3).

#### IV. PLC BASED LORENZ SYSTEM IMPLEMENTATION

Over fifty years later (1963) Edward Lorenz created the following system [27]:

$$\begin{aligned}
\dot{x} &= \sigma(y - x) \\
\dot{y} &= rx - y - xz \\
\dot{z} &= xy - bz \quad \dots (6)
\end{aligned}$$

Where  $(x, y, z) \in \mathbb{R}^3$  and  $\sigma > 0, r > 0, b > 0$ . This system is called Lorenz system. In fact, this system describes hydrodynamic flow. The variable  $x$  is proportional to the intensity of convection motion,  $y$  refers to the temperature difference between ascending and descending currents, and  $z$  is the distortion of the vertical temperature profile. According to Lorenz, the fixed parameter values are chosen  $\sigma = 10$  and  $b = 8/3$ . To obtain the chaotic behavior from Lorenz system  $r$  should be satisfy  $r > r_H \approx 24.74$ . Where  $r_H$  is bifurcation value, and at  $r = r_H$  the Hopf bifurcations occur.

To implement the Lorenz system by using PLC, a rescaling process has been performed in system (6) in order to accommodate with the permitted swing voltage of the analog to digital model of PLC.

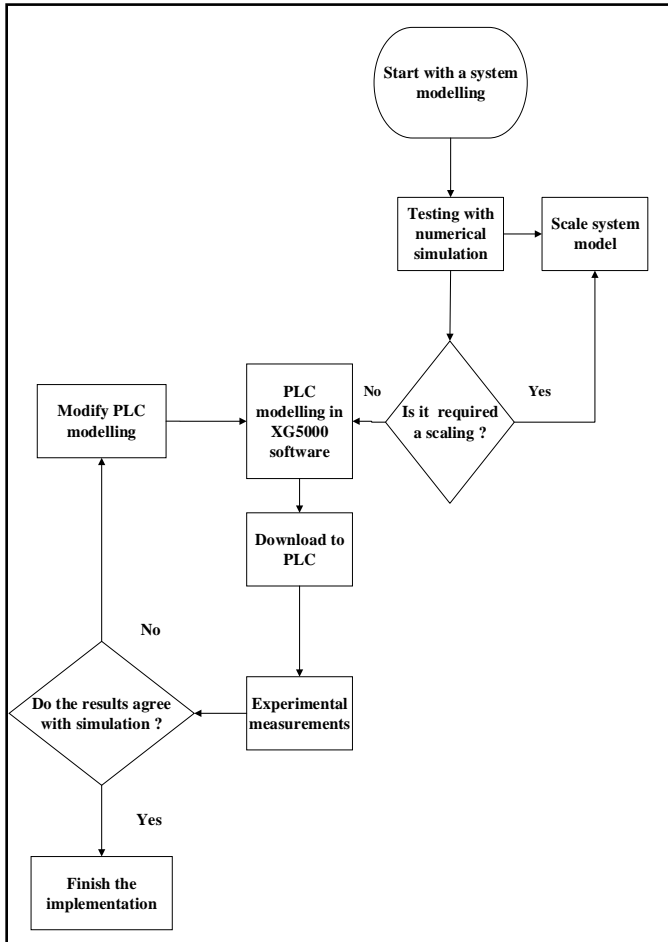


Fig. 3 Flowchart for general programming of chaotic systems implementation in PLC.

```

1 IF _10N THEN
2   %UX0.1.32:=1;
3   %UX0.1.33:=1;
4   %UX0.1.34:=1;
5 END_IF;
6 K_11:=dx(x,y);
7 K_12:=dy(x,y,z);
8 K_13:=dz(x,y,z);
9 a:=x+(h*0.5*K_11);
10 b:=y+(h*0.5*K_12);
11 c:=z+(h*0.5*K_13);
12 K_21:=dx(a,b);
13 K_22:=dy(a,b,c);
14 K_23:=dz(a,b,c);
15 a1:=x+(h*0.5*K_21); b1:=y+(h*0.5*K_22);
16 K_31:=dx(a1,b1);
17 K_32:=dy(a1,b1,c1);
18 K_33:=dz(a1,b1,c1);
19 a2:=x+(h*K_31);
20 b2:=y+(h*K_32);
21 c2:=z+(h*K_33);
22 K_41:=dx(a2,b2);
23 K_42:=dy(a2,b2,c2);
24 K_43:=dz(a2,b2,c2);
25 m:=(K_11+(2*K_21)+(2*K_31)+K_41)/6;
26 n:=(K_12+(2*K_22)+(2*K_32)+K_42)/6;
27 o:=(K_13+(2*K_23)+(2*K_33)+K_43)/6;
28 d:=x+(m*h);
29 i:=y+(n*h);
30 g:=z+(o*h);
31 x:=d;
32 y:=i;
33 z:=g;
34 p1:=REAL_TO_INT(x*rr);
35 p2:=REAL_TO_INT(y*nn);
36 p3:=REAL_TO_INT(z*mmm);
37 %UW0.1.3:=p1;
38 %UW0.1.4:=p2;
39 %UW0.1.5:=p3;
  
```

Fig. 4 Program code in ST used to implement the Lorenz attractor.

The rescaled Lorenz model is

$$\dot{X} = \sigma(Y - X)$$

$$\dot{Y} = 100[r(0.01X - 20) - (0.01Y - 20) - (0.01X - 20)(0.0125Z)]$$

$$\dot{Z} = 80[(0.01X - 20)(0.01Y - 20) - \beta(0.0125Z)] \quad \dots (7)$$

The substituting of equation (7) into (5) gives

$$R_{11} = \sigma[Y(k) - X(k)]h$$

$$R_{21} = 100[r(0.01X(k) - 20) - (0.01Y(k) - 20) - 0.0125Z(k)(0.01X(k) - 20)]h$$

$$R_{31} = 80[(0.01X(k) - 20)(0.01Y(k) - 20) - \beta(0.0125Z)]h \quad \dots (8)$$

$$R_{1i} = \sigma[(Y(k) + 0.5R_{2(i-1)}) - (X(k) + 0.5R_{1(i-1)})]h$$

$$R_{2i} = 100[r(0.01(X(k) + 0.5R_{1(i-1)}) - 20) - (0.01(Y(k) + 0.5R_{2(i-1)}) - 20) - 0.0125(Z(k) + 0.5R_{3(i-1)})(0.01(X(k) + 0.5R_{1(i-1)}) - 20)]h$$

$$R_{3i} = 80[(0.01(X(k) + 0.5R_{1(i-1)}) - 20)(0.01(Y(k) + 0.5R_{2(i-1)}) - 20) - 0.0125(Z(k) + 0.5R_{3(i-1)})\beta]h \quad \dots (9)$$

For  $i = 2,3$ , and

$$R_{14} = \sigma[(Y(k) + R_{23}) - (X(k) + R_{13})]h$$

$$R_{24} = 100[r(0.01(X(k) + R_{13}) - 20) - (0.01(Y(k) + R_{23}) - 20) - 0.0125(Z(k) + R_{33})(0.01(X(k) + R_{13}) - 20)]h$$

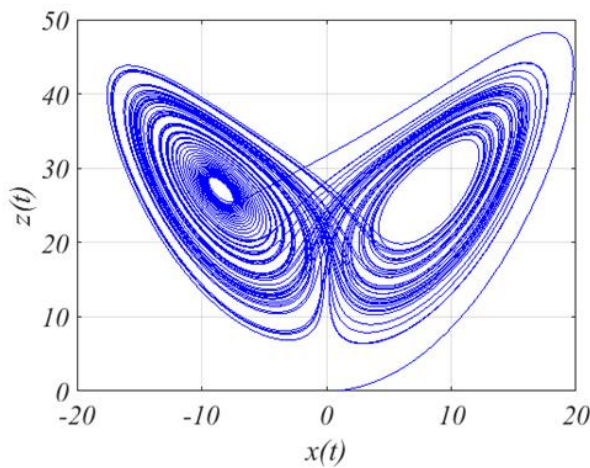
$$R_{34} = 80[(0.01(X(k) + R_{13}) - 20)(0.01(Y(k) + R_{23}) - 20) - 0.0125(Z(k) + R_{33})\beta]h \quad \dots (10)$$

Therefore, it is obtained

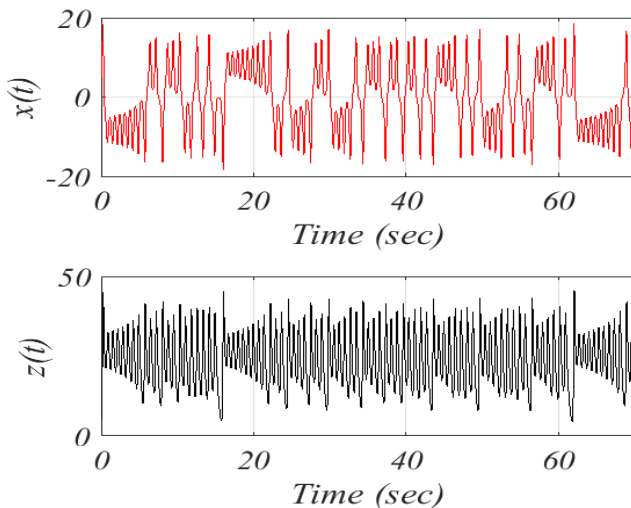
$$X(k + 1) = X(k) + [R_{11} + 2R_{12} + 2R_{13} + R_{14}]/6$$

$$Y(k + 1) = Y(k) + [R_{21} + 2R_{22} + 2R_{23} + R_{24}]/6$$

$$Z(k + 1) = Z(k) + [R_{31} + 2R_{32} + 2R_{33} + R_{34}]/6 \quad \dots (11)$$

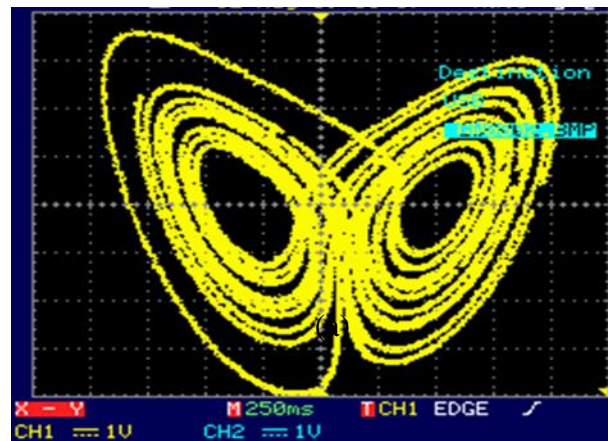


(a)

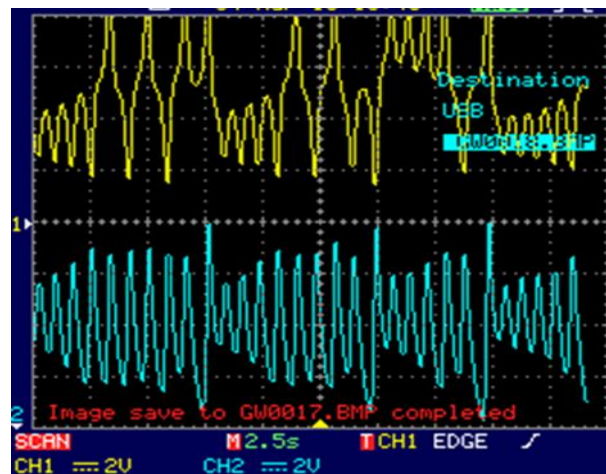


(b)

Fig. 5 Simulation results of transient chaos of Lorenz system with parameters  $\sigma = 10$ ,  $b = \frac{8}{3}$ , and  $r = 28$ .(a) Phase portrait ( $x(t)$  versus  $z(t)$ ). (b) Time series of  $x(t)$  and  $z(t)$ .



(a)



(b)

Fig. 6 Experimental observations showing the chaotic behavior of the system with parameters  $\sigma = 10$ ,  $b = 8/3$  and  $r = 28$ . (a) Lorenz butterfly attractor ( $x(t)$  versus  $z(t)$ ). (b) Time domain waveforms ( $x(t)$  is channel 1,  $z(t)$  is channel 2).



Lorenz system is programmed by modelling equations (8, 9, 10 and 11) in the PLC. This modeling occurs by two steps. The first step being the creation of the subprogram of three differential equations and the second step is computing the numerical solution of the Lorenz system. Fig. 4 shows the main program of Lorenz system.

The PLC iteration process can be described as follows: start with any initial conditions but not the equilibrium points. Then, use PLC to investigate the above equations, subsequently a sequence of  $x(k), y(k), z(k)$  generate for  $k = 1, 2, 3, 4, 5, 6, \dots$ . According to equation (2), a rescaling of the generation sequences has been applied to make these sequences fit with DAC module. Then, the rescaled sequences convert to analog signals by using DAC module. Figures 5 and 6 show the simulation and the experimental observation of the chaotic Lorenz system by using computer and the XEC-DN32H PLC.

## V. Experimental design and implementation

### A. Mechanical Design

The chaotic mixer has been designed and built based on one of the famous industrial models (stirred tank model). This device is used to generate a complex perturbation, especially the chaos perturbations, into the steady liquids mixed. Fig. 7 shows a schematic diagram of the mechanical design of this device. Some of the possible variables that effect on the mixing quality include the impeller position, impeller type, impeller velocity, impeller discretion, tank volume, tank shape, tank velocity, tank dictation and so on. Only the impeller velocity will be considered in the mixer design, while it has been fix all other variables in the mixing process.

A firm platform used to fix the whole setup. The stirred tank is the container, which have the liquids for mixing. The tank used here is a laboratory beaker with dimensions (280 mm high and 180 mm diameter). Impellers are fixed at the same level through the tank for all processing of mixing. The impeller used in the proposed mixer is symmetrical four- impellers, these impellers has been implemented by using 3D printer. Design and the building of these impellers is shown in Fig. 8.

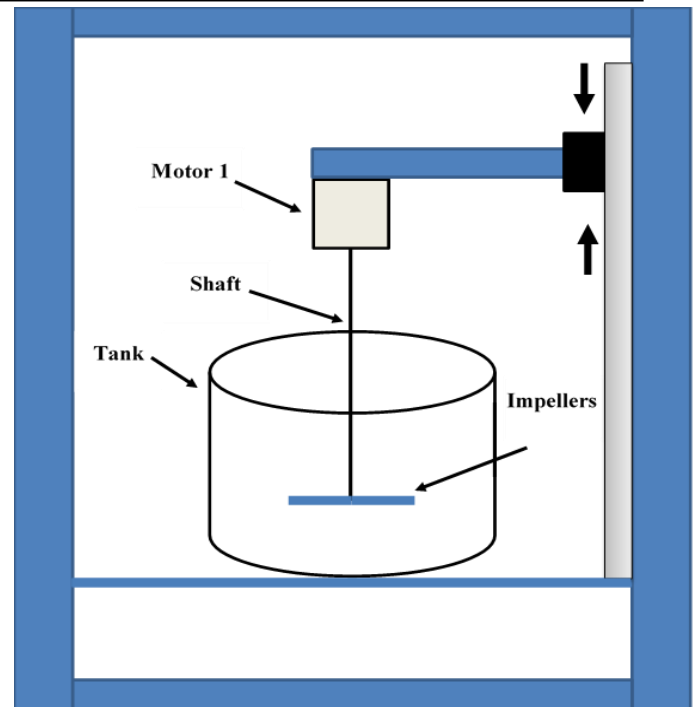


Fig. 7 The mechanical design of proposed mixer

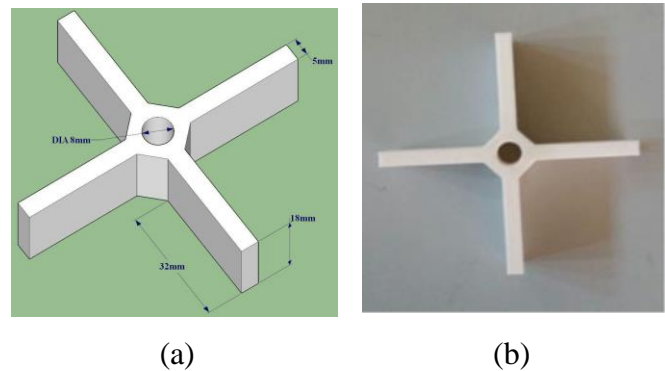


Fig. 8 Impellers of the propose mixer. (a) Design. (b) Implementation by using 3D printer

### B. Electrical Design

The main driving forces of the experimental are the Motor 1 in Fig. 7 So that the investigation of the mixer performance due to driving signals of different patterns is require an appropriate control circuit to rotate the motor. This circuit must be capable of working under various types of a non-feedback control signals. This section will discuss the interference between the control signal generation and the motors. Fig. 9 illustrates a schematic diagram of the overall control circuit design. A program of the desired control signal has been written in the computer by using XG5000

package software. This program is downloaded to PLC to configure these signals at the PLC output. It must take into consideration the frequency of the PLC output signals. The high frequencies of the driving motor signals will cause large changes in the drawn power of motors and this cause only very low response of the motors due to the mechanical inertia. Therefore, the control signal frequencies are set in the several Hertz range, so the motor can rotate in synchronization model with the control signals. As Motor 1 is a single-phase induction motor, a variable frequency drive (VFD) used to make cabling between the motor and the control signal. Depending on the voltage value of the control signal, the VFD will drive the motor at the corresponding by using the V/F ratio control method.

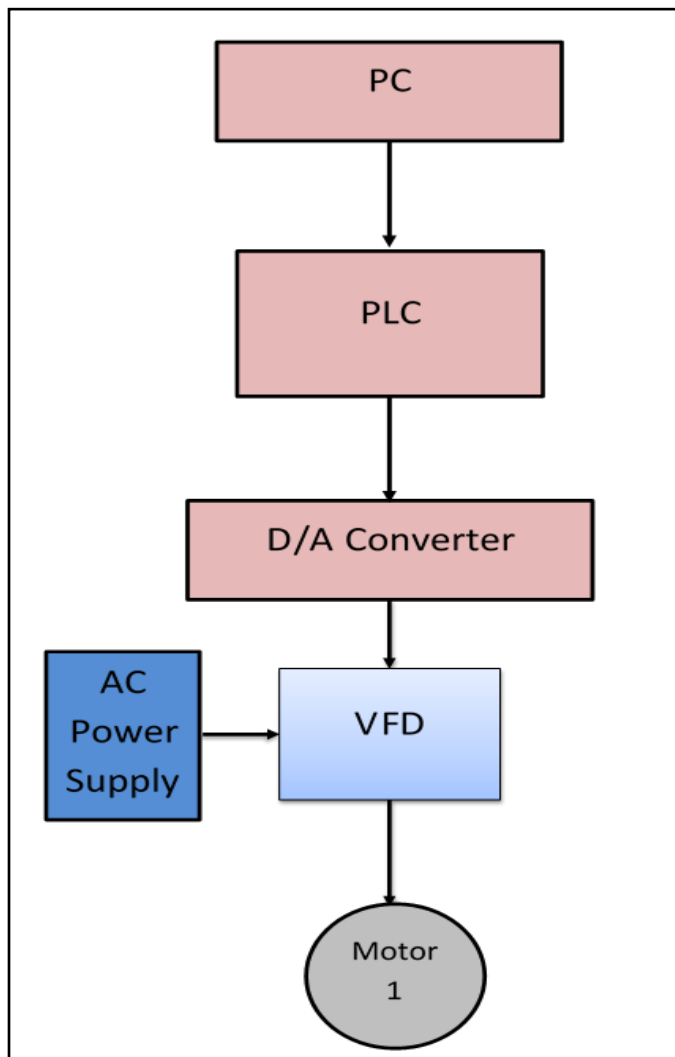


Fig. 9 Scheme diagram of the control circuit

### C. Experimental Results

This section introduces the experimental results on liquid mixing due to the chaotic velocity of impellers by chaotified Motor 1 based on Lorenz system and the results of the natural mixing. The main objective of the experiment is to make a comparison and showing the effect of the chaotic mixing over constant speed mixing. The experiment is depending on the principle of colorization of some chemical liquids based on its acid value when an amount of material knowing as indicators is added to these liquids. The chemical materials used in this experiment are a corn syrup, 1N HCl acid and 0.5N methyl orange indicator. To make a comparison between the mixing results a periodically photo will be recorded of the mixing material. These photos have been taken by using a Nikon 3300 camera (with resolution 24.4 MP). The overall experiment of liquids mixing can be described in the following steps:

- Add a 2000 ml of the corn syrup to the beaker.
- Add a 10 ml of the HCl to the corn in the beaker.
- Add a 1.5 ml from the methyl orange indicator to the beaker.
- Drive the mixer by the desired mixing system.
- Record the results by using camera.

The existence of HCl will make the solution have acid properties, so a red color will appear during the mixing process due to the indicator. The mixing lead to the quickly read colorization of solution refer to the best type of the liquid mixing. Fig. 10 illustrates the overall experiment.

After the implementation of Lorenz system in the PLC. One of its state such ( $x$ - state) will take as a control signal. ( $x$ - state) has connected to (VI pin) in VFD. Due to this connection, the VFD will convert the voltage value of the control signal ( $x$ -state) at any moment to the corresponding frequency. This means the motor will change its speed according to the control signal ( $x$ -state). Fig. 11 shows the synchronous speed of Motor1 under two types mixing and the mixing results can explain in table 1.



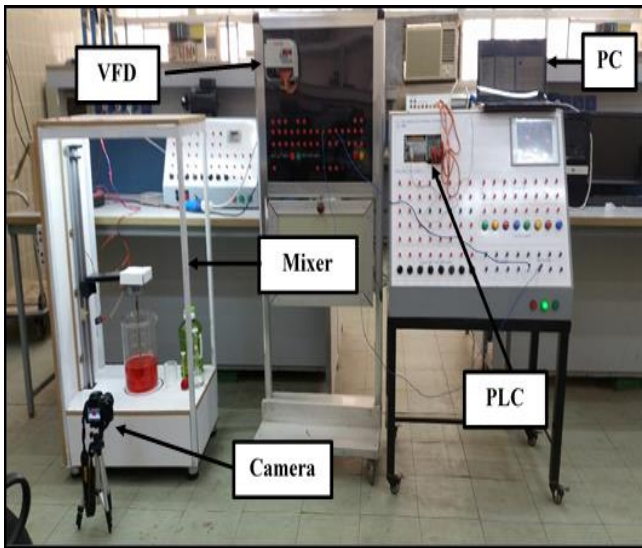


Fig. 10 The overall experiment of the liquids mixing

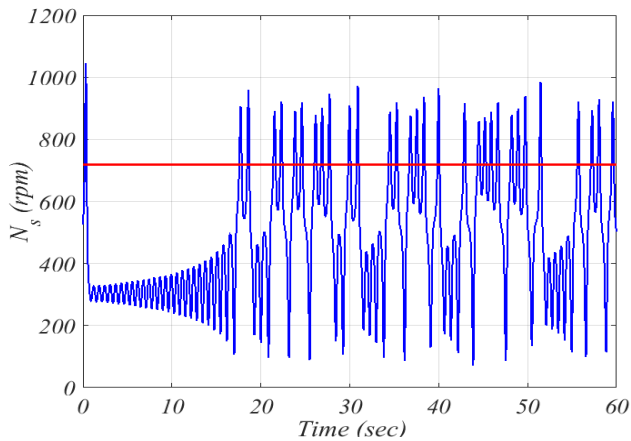


Fig. 11 The synchronous speed of Motor1 under two types mixing. Blue refer to the Lorenz mixing and red refer to the natural mixing.

### V. CONCLUSION

In this paper, we have introduced a new method for the design and implementation of a chaotic behavior generator by using PLC and its application in the liquid mixing. Both simulations and experimental verifications have been discussed. PLC-based the chaotic Lorenz system used as a chaotic signal to generate the chaotic perturbations to mix flows in the stirred-tank mixer model for the liquid colorization experiments in the laboratory. The experimental results clearly show that chaotic mixing required a shorter time than the time of constant speed mixing, so it has proved the activity of the chaotic mixing.

Table 1. Snapshots analog the evolutions of the natural and the chaotic mixing.

Natural Mixing	Chaotic Mixing	Time (sec)
		6
		10
		14
		18
		22
		26
		30
		110

## REFERENCES

- [1] G. A. Al-Suhail, F. R. Tahir, M. H. Abd, V.-T. Pham, and L. Fortuna, "Modelling of long-wave chaotic radar system for anti-stealth applications," *Communications in Nonlinear Science and Numerical Simulation*, vol. 57, pp. 80-96, 2018.
- [2] M. H. Abd, F. R. Tahir, G. A. Al-Suhail, and V.-T. Pham, "An adaptive observer synchronization using chaotic time-delay system for secure communication," *Nonlinear Dynamics*, vol. 90, no. 4, pp. 2583-2598, 2017.
- [3] F. R. Tahir, K. M. Abdul-Hassan, M. A. Abdullah, V.-T. Pham, T. M. Hoang, and X. Wang, "Analysis and Stabilization of Chaos in Permanent Magnet DC Motor Driver," *Int. J. Bifurc. Chaos*, vol. 27, no. 11, p. 1750173, 2017..
- [4] G. Chen, and T. Ueta, "Yet another chaotic attractor," *International Journal of Bifurcation and chaos*, vol. 9, no. 07, pp. 1465-1466, 1999.
- [5] S. Yu, J. Lu, G. Chen, and X. Yu, "Generating grid multiwing chaotic attractors by constructing heteroclinic loops into switching systems," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 58, no. 5, pp. 314-318, 2011.
- [6] J. Lü, G. Chen, D. Cheng, and S. Celikovskiy, "Bridge the gap between the Lorenz system and the Chen system," *International Journal of Bifurcation and Chaos*, vol. 12, no. 12, pp. 2917-2926, 2002
- [7] J. Lü, and G. Chen, "A new chaotic attractor coined," *International Journal of Bifurcation and chaos*, vol. 12, no. 03, pp. 659-661, 2002.
- [8] A. Buscarino, L. Fortuna, and M. Frasca, "Experimental robust synchronization of hyperchaotic circuits," *Phys. D Nonlinear Phenom.*, vol. 238, no. 18, pp. 1917-1922, 2009.
- [9] J. Lü, and G. Chen, "Generating multiscroll chaotic attractors: theories, methods and applications," *International Journal of Bifurcation and Chaos*, vol. 16, no. 04, pp. 775-858, 2006.
- [10] R. Caponetto, G. Dongola, L. Fortuna, and A. Gallo, "New results on the synthesis of FO-PID controllers," *Commun. Nonlinear Sci. Numer. Simul.*, vol. 15, no. 4, pp. 997-1007, 2010.
- [11] S. Abdallah, and S. Nijmeh, "Two axes sun tracking system with PLC control," *Energy Conversion and Management*, vol. 45, no. 11-12, pp. 1931-1939, 2004.
- [12] K. Yau and K.-P. Chow, "PLC forensics based on control program logic change detection," *J. Digit. Forensics, Secur. Law*, vol. 10, no. 4, p. 5, 2015.
- [13] S. Abdallah, and R. Abu-Mallouh, "Heating systems with PLC and frequency control," *Energy Conversion and Management*, vol. 49, no. 11, pp. 3356-3361, 2008.
- [14] R. Bayindir, and Y. Cetinceviz, "A water pumping control system with a programmable logic controller (PLC) and industrial wireless modules for industrial plants--an experimental setup," *ISA Trans*, vol. 50, no. 2, pp. 321-8, Apr, 2011.
- [15] Z. Zhang, G. Chen and S. Yu, "Hyperchaotic signal generation via DSP for efficient perturbations to liquid mixing", *International Journal of Circuit Theory and Applications*, vol. 37, no. 1, pp. 31-41, 2009. Available: 10.1002/cta.470 [Accessed 11 June 2019].
- [16] S. Ye, K. T. Chau, and S. Member, "Chaoization of DC Motors for Industrial Mixing," vol. 54, no. 4, pp. 2024-2032, 2007.
- [17] Z. Zhang and G. Chen, "Liquid mixing enhancement by chaotic perturbations in stirred tanks", *Chaos, Solitons & Fractals*, vol. 36, no. 1, pp. 144-149, 2008. Available: 10.1016/j.chaos.2006.06.024.
- [18] G. Valencia-Palomo, and J. A. Rossiter, "Novel programmable logic controller implementation of a predictive controller based on Laguerre functions and multiparametric solutions," *IET Control Theory & Applications*, vol. 6, no. 8, pp. 1003-1014, 2012.
- [19] X. Yang, Q. Zhu, and H. Xu, "Design and practice of an elevator control system based on PLC," *Proc. - 2008 Work. Power Electron. Intell. Transp. Syst. PEITS 2008*, pp. 94-99, 2008.
- [20] N. He, V. Oke, and G. Allen, "Model-based verification of PLC programs using Simulink design." pp. 0211-0216.
- [21] M. Jamro, "POU-oriented unit testing of iec 61131-3 control software," *IEEE Transactions on Industrial Informatics*, vol. 11, no. 5, pp. 1119-1129, 2015
- [22] S. S. Peng, and M. C. Zhou, "Ladder diagram and Petri-net-based discrete-event control design methods," *IEEE Transactions on Systems, Man,*

and Cybernetics, Part C (Applications and Reviews), vol. 34, no. 4, pp. 523-531, 2004.

[23]T. Ovatman, A. Aral, D. Polat, and A. O. Ünver, "An overview of model checking practices on verification of PLC software," *Software & Systems Modeling*, vol. 15, no. 4, pp. 937-960, 2014.

[14]M. A. Aseeri, M. I. Sobhy, and P. Lee, "Lorenz chaotic model using filed programmable gate array (fpga)," in *The 2002 45th Midwest Symposium on Circuits and Systems*, 2002. MWSCAS-2002., 2002, vol. 1, p. I-527.

[25]R. Caponetto, A. Di Mauro, L. Fortuna, and M. Frasca, "Field programmable analog array to implement a programmable Chua's circuit," *Int. J. Bifurc. Chaos*, vol. 15, no. 5, pp. 1829–1836, 2005.

[26]S. Yu, J. Lü, W. K. S. Tang, and G. Chen, "A general multiscroll Lorenz system family and its realization via digital signal processors," *Chaos An Interdiscip. J. Nonlinear Sci.*, vol. 16, no. 3, p. 33126, 2006.

[27]E. Lorenz, "Deterministic nonperiodic flow", *Journal of the atmospheric sciences*, Vol. 20, pp. 130-141(1963).