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Adaptive Fractional Order PID Controller Design of a Pacemaker based on Heart Rate Control Strategy

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Abstract- *At present, most of the patients with irregular heartbeats especially the men complain that they undergo shallow breathing. Shallow breathing takes place when the heart does not properly pump blood to the lungs. There is a rapid growth of shallow breathing cases and its impact is significant on the health of patients. When a heart beats too slowly or unevenly, it does not deliver blood and oxygen to the body properly and effectively. These problems can be overcome, by designing a proper controller or control system that will regulate the heartbeats properly and effectively. This paper mainly emphasizes the design of the Proportional-Integral-Derivative controller (PID), Tilt-Integral-Derivative controller (TID), Fractional Order PI controller (FOPI), and Fractional Order PID controller (FOPID) based on heart rate control strategy of a pacemaker.*

Keywords**: Artificial Intelligence (AI), FOPID Controller, IAE, ITAE, Genetic Algorithm (GA), TID Controller**

1. INTRODUCTION

The human being's heart is a muscular internal organ about the size of a human fist [1]. It lies just behind and slightly to the left of the breastbone [3]. It pumps blood through the mesh of veins and arteries. The blood supplies the essential nutrients and oxygen (O_2) to the human body and aids in removing metabolic wastes [2]. The bloodA. through the mesh of veins and arteries must flow in a normal pattern. When the blood flows too slowly or unevenly through the veins and arteries, it causes shallow breathing. The diagnosing process of irregularities of a human being's heart is very essential otherwise; the sufficient amount of blood and oxygen will not flow to the body [4], [5]. The irregularities in a patient's heart can be monitored and detected using electrocardiography (ECG) [10]. It is possible to save human beings from heart problems by properly and continuously measuring and observing the variations in the pattern of electrical signals [4], [5]. Heart diseases are rapidly growing and their impact on the health of human beings is significant. Heart diseases arise due to stress, anxiety, thinking, and so on. To get over the heart diseases, pacemakers are used to regulate and maintain the heart rate by sending electrical signals to the heart thus save human beings from minor and major heart attacks [6].

In literature, various methodologies are available that regulate and maintain the heart rate of a human. In this work, PID, TID, Fractional Order PI, and Fractional Order PID controllers are designed to maintain and regulate the heart rate based on heart rate pacemaker control strategy. To achieve better results, these controllers are tuned/ optimized using an artificial intelligence technique; Genetic Algorithm (GA). PID is feasible, robust and its concept is simple. TID resembles with PID but the tilted gain replaces the proportional gain It is easy to tune than PID [8]. FOPID being an advanced PID controller is more robust and flexible than PID and TID because it has five gain parameters [9]. Moreover, it yields better output responses. GA is easy to understand, it can be easily incorporated and it has robust parameters, it has a simple concept, and better efficiency [7]. The three controllers are compared based on peak value (PV), settling time (ST), steady-state error (E_{SS}), Integral of Time Multiplied by Absolute Error (ITAE), and Integral of Absolute Error (IAE). The entire work is carried out in MATLAB/SIMULINK.

This work is organized as: section 2 explains the system description, section 3 explains the simulation work, and section 4 discusses the conclusion.

2. SYSTEM DESCRIPTION

2.1 Pacemaker

A pacemaker (PM) is a device that stimulates the muscles of the patient's heart when it beats too slowly or unevenly or when the patient undergoes shallow breathing. It comprises of a sensing part and an output part [4].

a. Sensing Part: This part of the pacemaker helps in sensing the heart rate of a patient.
b. Output Part: This part of the pacemaker helps in sending electrical signals to the muscles of the patient's heart, thus regulate the heart rate of a patient.

2.2 Mathematical Modeling

Fig. 1 shows the conduction model of the heart [11-12].

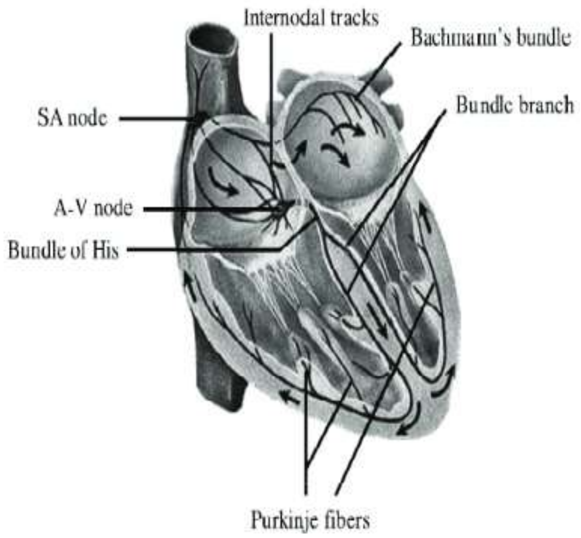

Fig -1: Conduction Model of Heart

The various components of this model are tabulated in Table I.

Table I. COMPONENTS OF CONDUCTION MODEL

S.NO	Components	Values
01	Capacitor	1 μF
02	Resistor	1 Ω

The sum of currents flowing through the capacitor and the resistor is the stimulus current [11]

$$\mathrm{Is} = \mathrm{C\,Ic} + \mathrm{R\,Ir} \quad (1)$$

Where Is is the stimulus current, I_C and Ir are the currents flowing through the capacitor and resistor respectively.

$$\mathrm{Is} = \mathrm{C}\frac{dv}{dt} + \frac{V}{R} \quad (2)$$

The drop in voltage across the membrane due to the current flowing is [11]

$$\mathrm{V} = \mathrm{R}\,(1 - e^{-t\,R/C})\mathrm{Is} \quad (3)$$

Now, if a load of pacemaker is assumed to be fixed, then [11] gives the equation of energy

$$\mathrm{W} = \mathrm{Z}\,I_S^2\,t \quad (4)$$

Where W is the energy usage, Z is the load impedance, and t is the stimulus time.

2.3 Types of Controllers

The controllers used in this paper to regulate the heart rate based on the pacemaker are

1. Proportional-Integral-Derivative Controller (PID)
2. Tilt-Integral-Derivative Controller (TID)
3. Fractional Order Proportional-Integral Controller (FOPI)
4. Fractional Order Proportional-Integral-Derivative Controller (FOPID)

The controller gains of these controllers based on Genetic Algorithm (GA) are tabulated in Table II.

Table II. CONTROLLER PARAMETERS

S.NO	Controller Gains	GA-PID	GA-TID	GA-FOPI	GA-FOPID
01	K_P	6.1900		0.3707	0.3553
02	K_I	4.1528	15.8070	0.0290	0.0089
03	K_D	9.9031	6.5702		0.0043
04	K_T		13.8795		
05	λ			0.2310	0.0321
06	μ			0.3104	0.2134

3. SIMULATION RESULTS

The SIMULINK model of the pacemaker is shown in Fig. 1 [4], [5], [10].

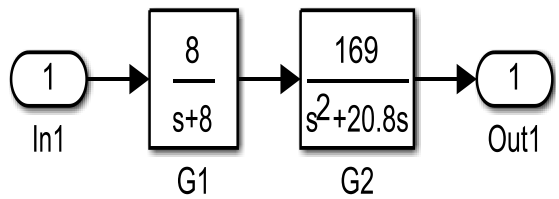

Fig -2: SIMULINK Model of Pacemaker

The SIMULINK models, output responses, and error responses of a pacemaker with PID, TID, FOPI, and FOPID controllers are shown in Fig. 3-Fig. 15 and the results are tabulated in Table. III

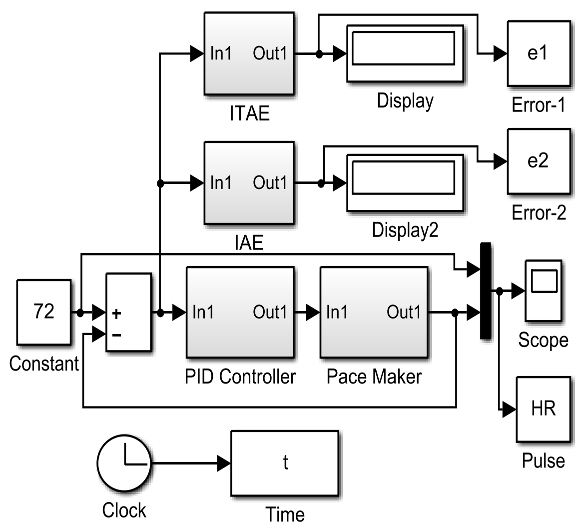

Fig -3: SIMULINK Model of Pacemaker with PID controller

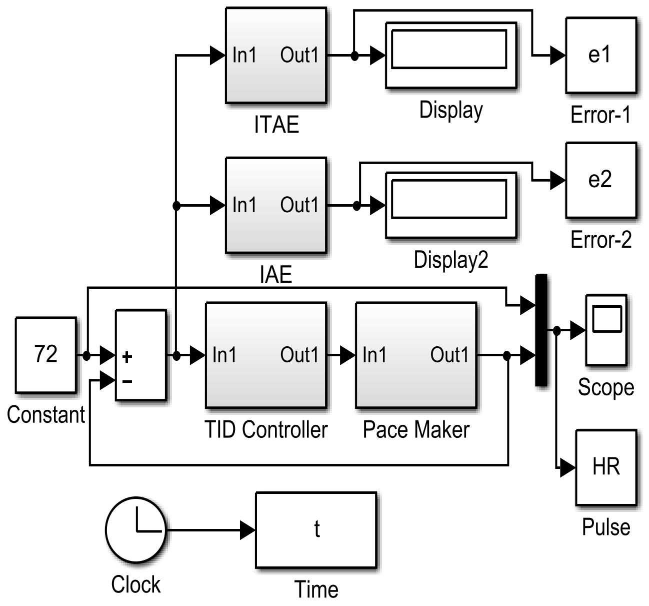

Fig -4: SIMULINK Model of Pacemaker with TID controller

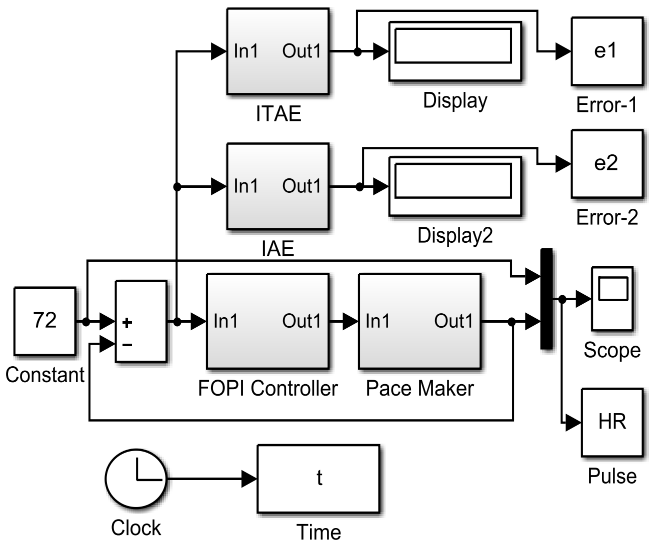

Fig -5: SIMULINK Model of Pacemaker with FOPI controller

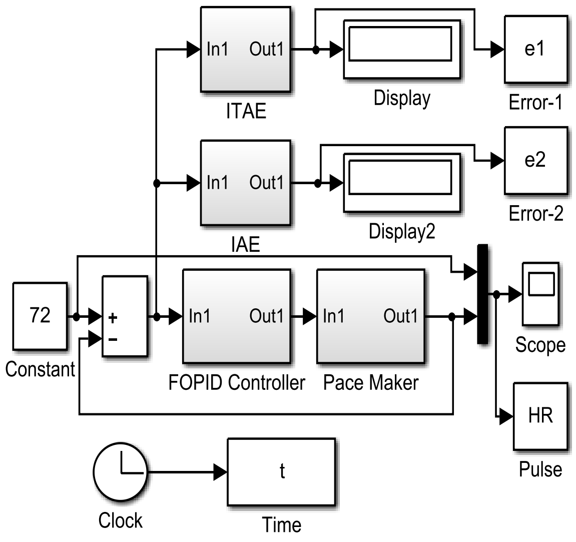

Fig -6: SIMULINK Model of Pacemaker with FOPID controller

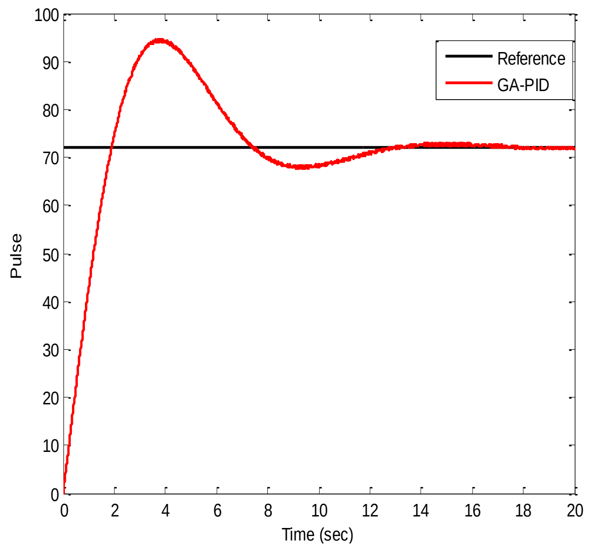

Fig -7: Output Response of Pacemaker with PID controller

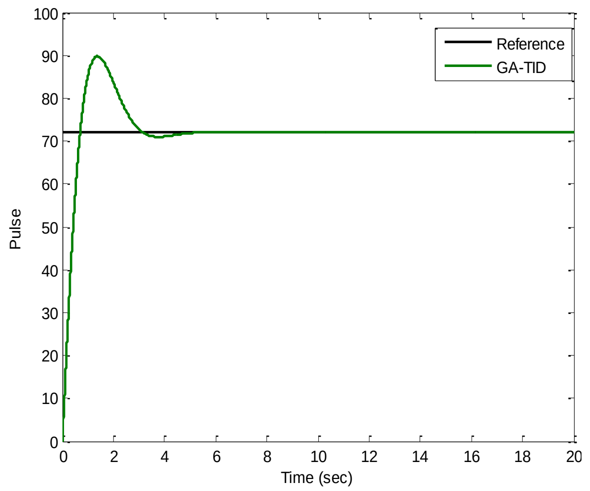

Fig -8: Output Response of Pacemaker with TID controller

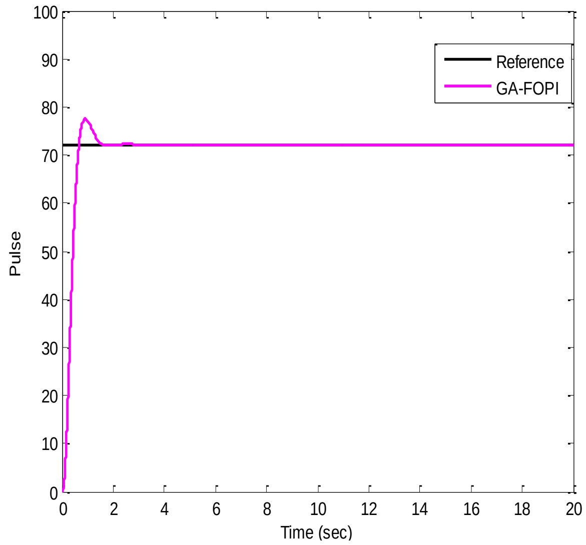

Fig -9: Output Response of Pacemaker with FOPI controller

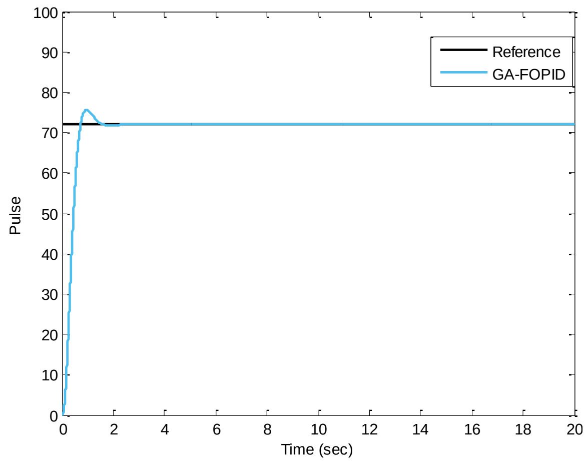

Fig -10: Output Response of Pacemaker with FOPID controller

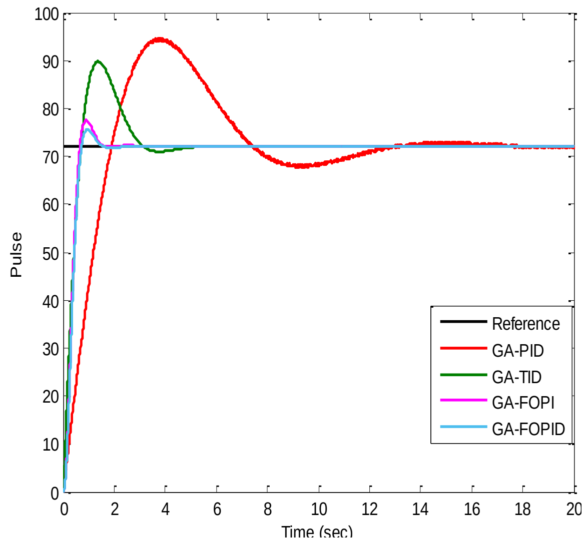

Fig -11: Overall Output Response of Pacemaker

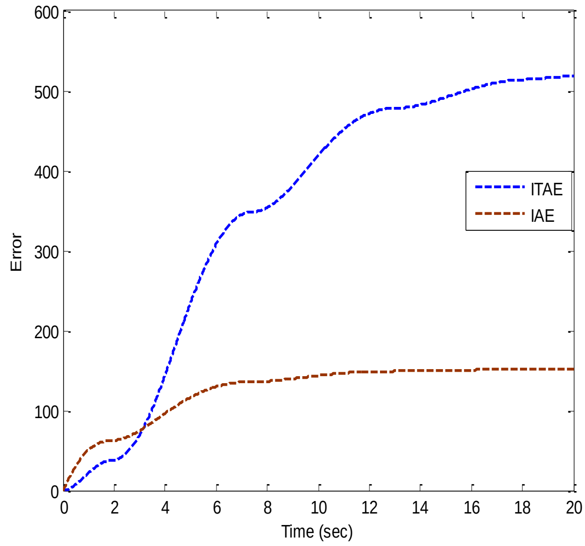

Fig -12: Error Response with PID controller

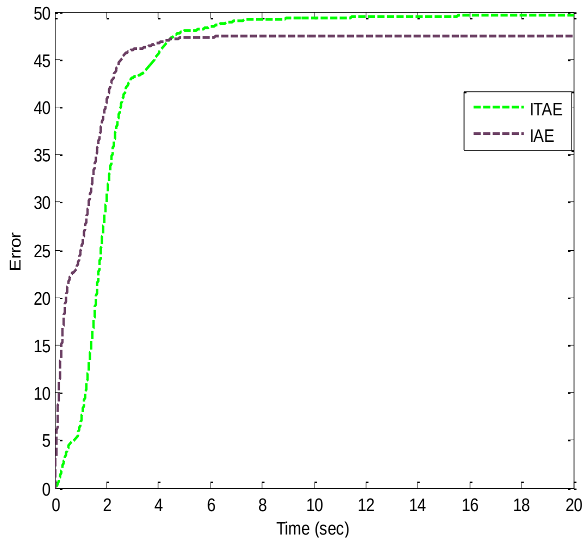

Fig -13: Error Response with TID controller

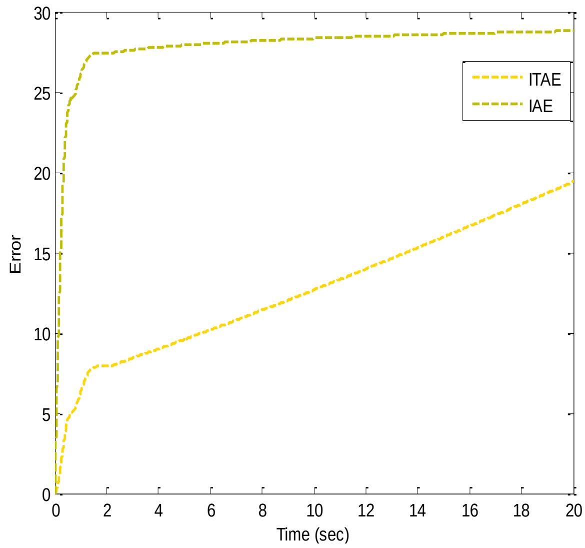

Fig -14: Error Response with FOPI controller

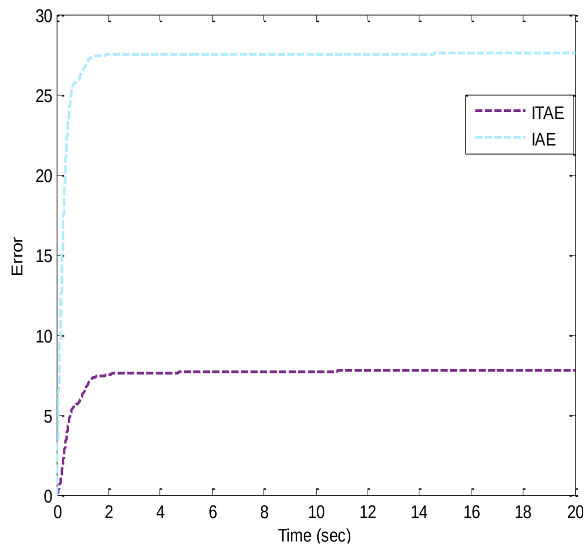

Fig -15: Error Response of Pacemaker with FOPID controller

Table III. COMPARISON BETWEEN PID, TID, FOPI AND FOPID CONTROLLERS

S.NO	Specifications	GA-PID	GA-TID	GA-FOPI	GA-FOPID
01	PV (pu)	94.526	89.812	77.564	75.601
02	ST (sec)	15.213	6 .316	3.431	3 .238
03	E_{SS}	0.32	0.15	0	0
04	ITAE	519.1	49.6	19.3	7.79
05	IAE	151.7	47.5	28.8	27.5

4. CONCLUSION

Heart rates indicate different types of heart diseases. The basis of the pacemaker is heart rate. The patients with irregularities such as shallow breathing must use pacemakers. In this paper, to achieve better output responses, PID, TID, FOPI, and FOPID controllers with the GA technique are designed to maintain and regulate the heart rate of a patient. Based on the output responses, the performance shown by the FOPID controller is far better than PID, TID, and FOPI controllers. The quantitative comparison of time-domain specifications viz.- peak value, settling time, steady-state error, ITAE value, IAE value with GA-FOPID indicate much superior performance.

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