A Novel Design of an Adaptive PID Controller for Cardiac Pacemaker

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Abstract: ***Biomedical engineering deals with the application of various concepts of engineering in the field of medicine and biology mainly for health care purposes thereby improving patients quality of life. Out of the various techniques, the primary focus is to develop a reliable and optimized technique for electro simulation of heart. The present work deals with an improvement in the design of control system for regulating the heart rate of a pacemaker in an efficient way. An Adaptive PID controller based on the Delta rule and Adaptive Correction Factor is proposed in this paper. The Adaptive PID controller is implemented using an Adaptive Loop incorporating MIT rule with the Delta rule. The PID parameters are modified by an Adaptive Correction Factor. Simulation results were performed on the developed cardiovascular system of humans and results show that the proposed adaptive PID controller produces superior control performance than conventional PID controller. Simulations were done in Matlab/Simulink.***

Keywords: Adaptive PID Controller, Adaptive Correction Factor, MIT Rule, Delta Rule, Pacemaker, Heart Rate.

1. Introduction

In carrying out the various functions, certain body parts generate their own signals, which can be used for monitoring or conveying useful information about their corresponding functions and they are bioelectric signals associated with heart rate, brain activity, nerve conduction etc. Bioelectric potentials are actually ionic voltages produced as a result of electrochemical activity of certain special types of cell. By using suitable transducers capable of converting ionic potential to electrical voltage, these natural monitoring signals can be measured and results can be displayed to aid the physician in diagnosis. The most commonly implanted biomedical device [1] is the cardiac Pacemaker which is designed to detect and monitor whether the patients heart beat is within the specified range. The basic block diagram of an implantable pacemaker is as shown in fig 1. The Electrocardiogram (ECG) detector checks the normal rhythm of heart and heart beating rate. Electrical simulations will be applied to the heart if abnormal heart beating is detected. One of the major design criterions of implantable device is the low power consumption.

The rhythmic action of heart is mainly due to the regularly occurring action potentials originating from the natural pacemaker located in the sino atrial node. Each impulse will be propagated to the atrio ventricular node through the myocardium. ECG signal are characterized as a recurrent sequence of three waves namely: the P wave, QRS complex(combination of Q, R and S waves) and T wave as shown in fig.2. Of the three waves, the QRS complex has more energy with higher amplitude than P and T waves over the RR interval (interval between two adjacent R waves). To precisely monitor the heart-beat rate of the patients, QRS complex (or R wave) must be detected with high accuracy.

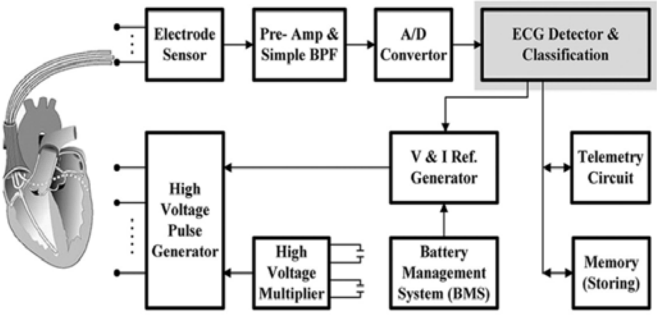

Figure 1: Implantable Pacemaker

The normal heart rate depends on the continuous and periodic performance of the natural pacemaker and integrity of neurons in conducting pathways.

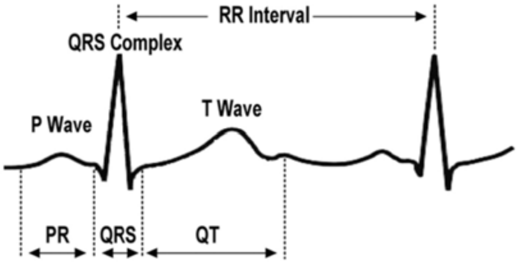

Figure 2: QRS Complex

But in some certain conditions, the heart will be paced at a much slower rate than required resulting in a situation where heart cannot supply required blood supply to meet the physical demands. In these cases, an artificial method of pacing is required to ensure that heart beat is sufficient for meeting physical demands of the body. A device capable of generating and delivering artificial pacing impulses to heart is called as a Pacemaker and usually consists of a pulse generator and appropriate electrodes.

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An optimal single-pulse stimulus to minimize the pulse amplitude in pacemakers to treat sudden cardiac arrest based on Yanagihara, Noma, and Irisawa (YNI) model is proposed in [2]. YNI model describes the potential behavior of sinoatrial node in heart. The VFF-RLS algorithm in [3] does not require a pre-specified forgetting factor. Forgetting factor is obtained by minimizing mean square of noise free error signal obtained by optimization technique. The use of fuzzy logic enables to achieve set point with shortest settling time and rise time than conventional PID Controller. Reference [4] deals with the various sensors used with the pacemakers and the recent developments in the various pacing systems. Design used in [5] for the automatic tuning of PID controller gains is by the use of intelligent predictors like Artificial Neural Networks (ANN) which provides an online automatic tuning for PID controller gains. Steepest-descent search directions are computationally simple, numerically robust and offers a convergence speed that is highly dependent on the eigen value speed ratio of Hessian matrix [6]. An adaptive loop by combining PID and Delta rule is implemented in [7]. Delta Rule is implemented using Adaptive Linear Neural neuron. The output of PID Controller will be used for updation of ADALINE's weight. The genetic neurofuzzy controller proposed in [8] works according to real time optimization and combines fuzzy logic; genetic algorithm and neural network to model a dc motor. Studies show that fuzzy method can be effectively implemented to control the heart rate using artificial pacemaker. Design method in [9] proposed a heart rate controller for artificial pacemaker using fuzzy and PID. The mathematical model of the cardiovascular system using transfer function method is proposed in [10].

The relay feedback tuning strategy is not suitable for time varying property. To overcome this [11] uses a relay feedback auto tuning strategy based on Ziegler Nichols method which can adjust control parameters online according to Fuzzy Logic Control Principle. A Gradient descent method is used to train PID Controller in [12] for online updation of the parameters where a Wavelet Neural Network [WNN] is used to identify the control system dynamics. Adaptive learning rate using Lyapnovs method is used to guarantee the convergence. A grey predictor using fuzzy self tuning is proposed in [13] for a nonlinear control system in which the Grey Predictor is adjusted using Fuzzy Control. A Single-neural identification-free adaptive intelligent controller based on grey prediction [14] is developed for multi input and multi-output(MIMO) system with time-delay in which the MIMO system is decomposed into a set of multi-input-single-output subsystems.

In this paper, an Adaptive PID controller is designed with an Adaptive Loop using an Adaptive Correction Factor; Delta rule and MIT rule. The adaptive PID controller is implemented using an adaptive loop by incorporating MIT rule with the Delta rule. The remaining of the paper is organized as follows. The second section deals with Pacemaker and is followed by PID controller. Fourth section deals with Adaptive correction Factor; MIT Rule and Delta Rule. Fifth section deals with the adaptive PID controller and is followed by simulation of Pacemaker. Seventh section deals with Results and Discussions. Conclusion and Future work is drawn in last section.

2. Pacemaker

A medical device that regulates the rhythmic action of heart using electrical impulses is called as a Pacemaker. The impulses will be delivered by electrodes which will be in contact with the heart muscles. A pacemaker basically consists of an electronic unit for generating impulses and a lead to carry the generated impulses to the heart. The electrode arrangement for use in cardiac pacemaker can be in the form of bipolar or unipolar system. In bipolar system, two electrodes are placed on the heart itself while in unipolar system, one electrode is placed on the heart while the other electrode will be placed anywhere in the body. Pacemaker can be broadly classified into two main types:

- External Pacemaker: used when heart block occurs as an emergency and will exist only for a short period of time
- Internal Pacemaker: used as a long term pacing because of permanent damage this prevents heart from normal triggering.

The primary objective of a pacemaker [4] is to treat abnormalities in heart rhythm and to maintain an adequate heart rate. Pacemaker helps a person with abnormal heart rhythm to resume normal lifestyle. Modern pacemakers allow cardiologists to select the required pacing mode for individuals since they are externally programmed. Reliability of modern pacemakers allows them to be used not only for pacing but also for other diagnostic purposes. Pacemakers can be used for continuous cardiac monitoring and for treating problems related with rhythm of heartbeat, as they provides electrical stimuli to chambers of heart to maintain proper rate. During irregular rhythm of heart (arrhythmia); the heart will not be able to pump enough blood for satisfying the oxygen needs of the body. Pacemakers can determine the time external stimuli must be given to the heart by calculating the time of incoming contraction of heart muscles. Pacing systems usually have three main parts:

- Pacemaker with body sensors
- Pacing Leads carrying pacing impulses
- Programmer

Pacemaker uses low energy electrical pulses to overcome the faulty functioning of heart. Pacemakers can:

- Speed up slow heart rhythm.
- Help control variations in heart rhythm.
- Make sure the ventricles contract normally.
- Coordinate electrical signaling between the upper and lower chambers of the heart.
- Coordinate electrical signaling between the ventricles.

3. PID Controller

The Proportional Integral Derivative Controller is the widely used feedback controller. The input of the PID controller is an error value which is the difference between measured

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process variable and desired setpoint. The PID controller algorithm has three constant parameters:

- Proportional term [P] : depends on the present error
- Integral term [I] : depends on accumulation of past errors
- Derivative term [D] : prediction of future errors

The output u(t) of the PID controller is given by:

$$u(t) \propto \left[e(t) + \int e(t) + \frac{d}{dt} e(t) \right] \qquad (1)$$

that is:

$$u(t) = Kp\, e(t) + Ki \int e(t) + Kd \frac{d}{dt} e(t)] \qquad (2)$$

where K_p, K_i, and K_d are the three constant PID parameters.

The basic PID controller is as shown in fig 3.

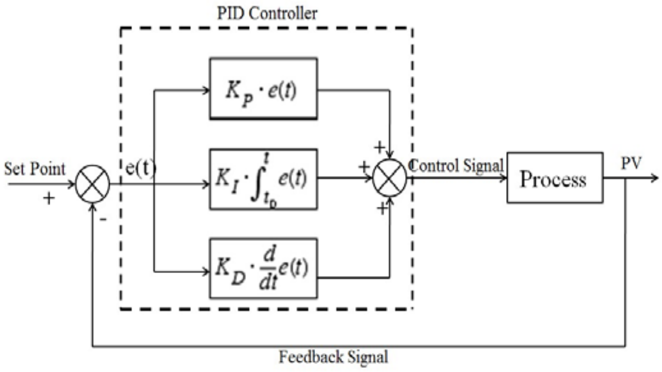

Figure 2: PID Controller

4. Adaptive Correction Factor, MIT Rule & Delta Rule

4.1 Adaptive Correction Factor

The paper proposes a modification for the conventional PID controller by an Adaptive Correction Factor c(t) which modifies the output of the PID controller. The Adaptive Correction Factor can be estimated through delta rule as:

$$c(t+1) = c(t) + \eta e(t) u(t) \qquad (3)$$

4.2 MIT Rule & Delta Rule

The main objective of the Model Reference Adaptive

Controller is to create a closed loop controller with parameters that can be updated to change response of the system. The three main factors to be considered for designing model reference adaptive controller using MIT rule are:

- Structure of the Model
- Structure of Controller
- Tuning gain

Defining tracking error as the difference between plant output y_p and model output y_m

$$e = yp - ym \qquad (4)$$

Considering a cost function J(θ) to minimize the error, where

$$J(\theta) = \frac{1}{2} e^2(\theta) \qquad (5)$$

To determine the updation parameter θ, an equation is formed for the change in θ. Since the primary objective is to minimize the cost function, the parameters are varied in the negative gradient of J. Minimizing the cost function

$$\frac{d\theta}{dt} = -\Upsilon e \frac{\partial e(\theta)}{\partial \theta} \qquad (6)$$

The relationship between change in θ and the cost function is called as MIT Rule. The expression $\frac{\partial e}{\partial \theta}$ is called as Sensitivity Derivative which determines how the parameter θ will be updated. Another efficient way to minimize the cost function is by applying the sign-sign algorithm. The above equation changes to

$$\frac{d\theta}{dt} = -\Upsilon sign(e) sign\left(\frac{\partial e(\theta)}{\partial \theta}\right) \qquad (7)$$

Delta rule is a gradient descent algorithm based learning rule for updation of weights of inputs to artificial neurons in single-layer neural network. Delta rule is an error correcting rule and model reference adaptive controller allows parameters that can be updated to change the system response; combining delta rule and the MIT Rule helps the PID controller to dynamically improve the system response thereby making it adaptive. Delta rule states that

$$w(k+1) = w(k) + \eta e X \qquad (8)$$

where η is the learning rate; e is the error and X is the input vector.

5. Adaptive PID Controller

The main objective is to make an adaptive PID controller by combining the Delta rule and the MIT rule along with the Adaptive Correction Factor. The PID weights are updated through an adaptive algorithm based on Widrow-Hoff Rule based on the Least Mean Square algorithm [2]. LMS algorithm states that sum of squares of differences between actually observed value and the computed value must be minimum.

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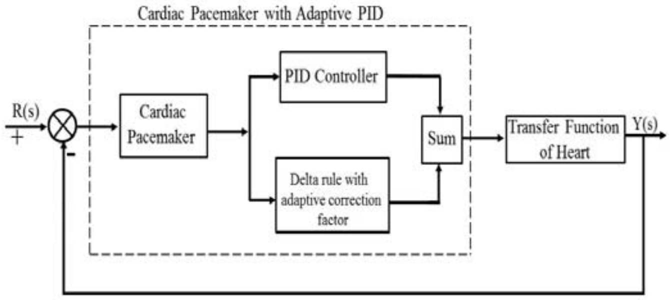

Figure 4: Proposed Adaptive PID Controller

In the proposed adaptive loop as in fig 4, R(s) is the actual heart rate; Y(s) is the desired heart rate. The PID parameters are multiplied by an Adaptive Correction Factor which modifies the parameters and also improves its dynamic response and behavior. After applying Adaptive Correction Factor, output u(t) of PID Controller is:

$$u_{pid}(t) = u(t)c(t) \qquad (9)$$

Modifying equation the above equation as:

$$u_{pid}(t) = c(t)[K_p e(t) + K_i \int e(t)\, dt + K_d \frac{d}{dt} e(t)] \qquad (10)$$

Here, the aim is to update the PID parameters against the changes in system which may be due to uncertainty of the plant or external disturbances. Updation of PID parameters is done by using the well defined error correcting Delta rule as in equation 8. The learning rate in Delta rule can be updated by using the Sign-Sign algorithm. Sign-Sign algorithm is implemented here taking into account of error and change in error with respect to time. The tracking error is defined in terms of the difference between output of ideal PID and original PID. Since the output of ideal PID is assumed as zero, the error can be approximately inferred as U_{pid}. Using the above design parameters, the learning rate η can be modified as

$$\eta = sign(U_{pid}) sign(U'_{pid}) \qquad (11)$$

where U'_{pid} is the change in PID output with respect to time. Applying delta rule to the PID; the basic design equation is:

$$w(k+1) = w(k) + \eta Upid \qquad (12)$$

Using equation 11, the above equation changes to

$$w(k+1) = w(k) + sign(U_{pid}) sign(U'_{pid}) U_{pid} \qquad (13)$$

The proposed system is applied to the mathematical model of the human heart to show its stability.

6. Mathematical Modeling

The mathematical model of the human heart can be represented by the proven Sino atrial (SA) model-Yanagihara, Noma, and Irisawa (YNI) model in [2]. The accurate action potentials in heart can be simulated using the YNI model. Numerical simulations performed using the YNI models are more reliable than other models. YNI model is kind of Hodgkin Huxley type which is based on voltage clamp data in which current voltage relationship is depicted and the spontaneous action potential is simulated.

The YNI model includes time dependent and independent currents. The four time-dependent currents namely: sodium current I_{Na}; potassium current I_K; slow inward current I_S ,and delayed inward current activated by hyperpolarization I_h. The time-independent current is leakage current I_l. The equivalent electrical circuit model of a cell membrane can be represented as in fig 6. The transmembrane currents in iA/cm^2 can be expressed as:

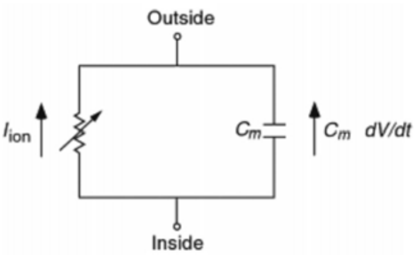

Figure 5: Electrical Circuit Model of Cell Membrane

$$C_m \frac{dV}{dt} + I_{Na} + I_K + I_l + I_s + I_h = I_{app} \qquad (14)$$

where C_m denotes capacitance of cell membrane; I_{app} is the external applied current. The slow inward current I_S is the most significant current in YNI model. The above equation can be simplified as

$$C_m \frac{dV}{dt} + I_{ion} = C_m \frac{dV}{dt} + \frac{V}{R_m} = I_{app} \qquad (15)$$

where C_m and R_m represents capacitance and resistance of cell membrane respectively.

The simplified block model for regulating the heart rate of a patient using the pacemaker can be represented as in fig 7.

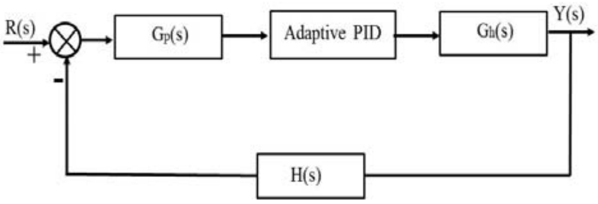

Figure 6: Block Diagram for Artificial Control of Heart Rate using Pacemaker

In the block diagram, R(s) is the actual heart rate; $G_p(s) = 8/(s+8)$ is the transfer function of pacemaker; $G_h(s)$ is the transfer function of heart; H(s) = 1 and Y(s) is the desired heart rate. The cardiovascular system including the heart can be modelled as an under damped second order system and hence the mathematical model of the heart simulated [10] is as described in equation 16.

$$G(s) = \frac{169}{s^2 + 20.8s} \qquad (16)$$

Usually heart rate of humans varies between 60-100. The normal heart rate of humans is around 72 beats/min. Heart rate decreases to around 60 in old age. The heart rate can increase/decrease in order to supply oxygen according to physical demands. The adaptive PID Controller is used for regulating the heart rate.

7. Simulation Results

The proposed controller is designed in Matlab/Simulink and can work in real time optimization. Computational cost plays a major role in implementing previous methods using fuzzy logic; genetic algorithm and neural network. The cost can be considerably reduced using the proposed method as it does not include any sort of fuzzy rules or membership functions.

Figures 7 shows the response of PID controller tuned with fuzzy [9] for heart rate 65 and fig 8 shows the response of proposed adaptive PID.

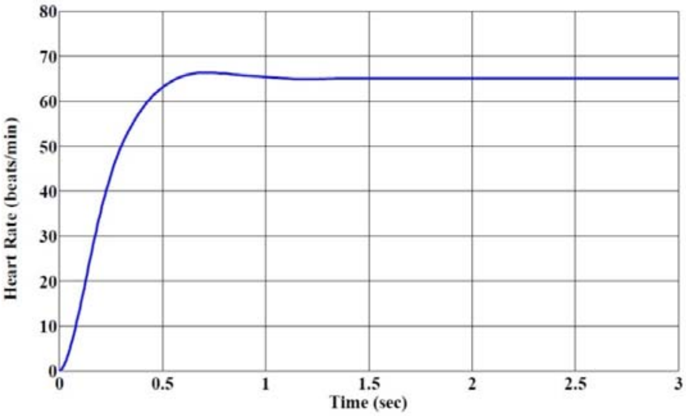

Figure 7: Response of PID Controller tuned with fuzzy for HR=65

Figures 9 shows the response of PID controller tuned with fuzzy [9] for heart rate 75 and fig 10 shows the response of proposed adaptive PID.

Figures 11 shows the response of PID controller tuned with fuzzy [9] for heart rate 85 and fig 12 shows the response of proposed adaptive PID.

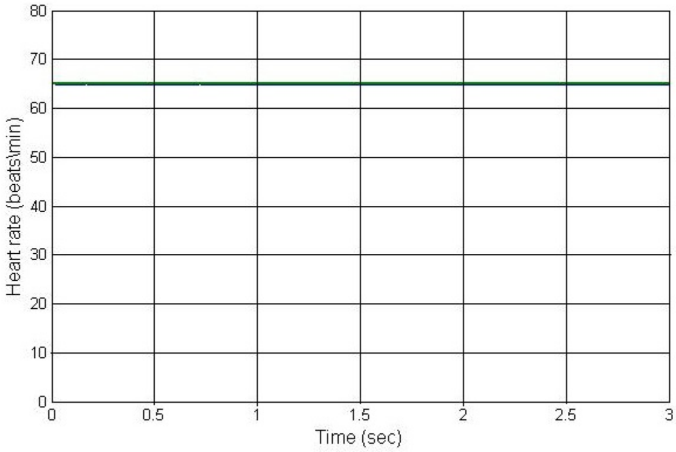

Figure 8: Response of Adaptive PID Controller for HR=65

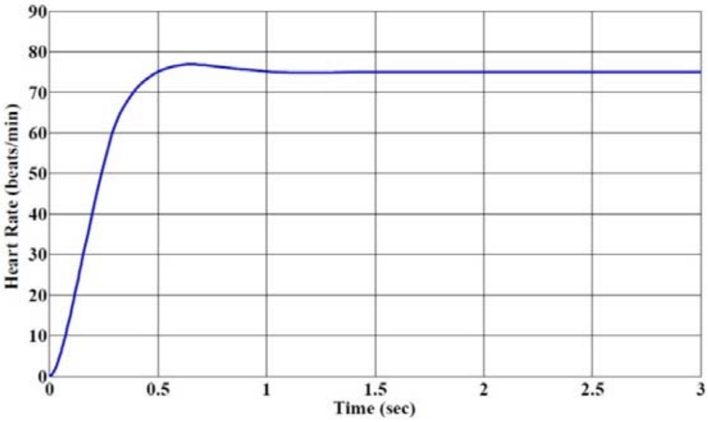

Figure 9: Response of PID Controller tuned with fuzzy for HR=75

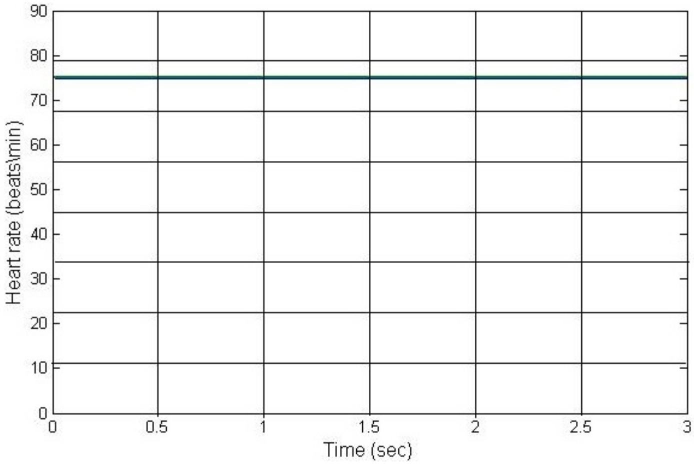

Figure 10: Response of Adaptive PID Controller for HR=75

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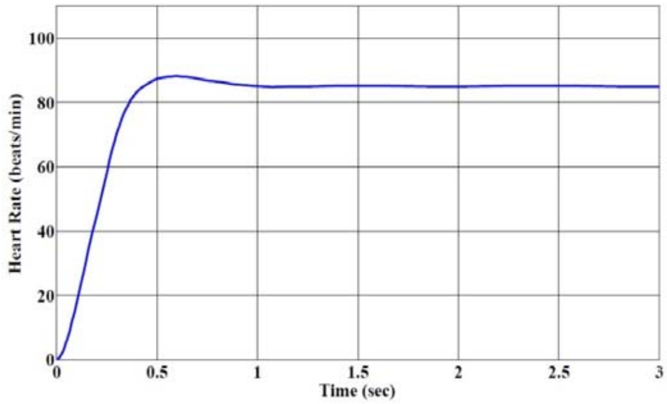


Figure 11: Response of PID Controller tuned with fuzzy for HR=85

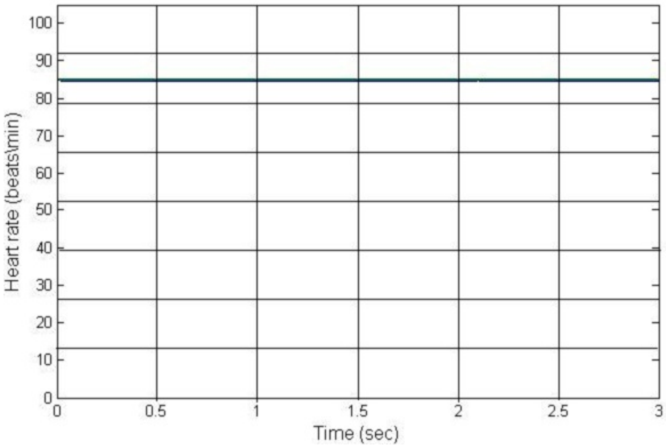
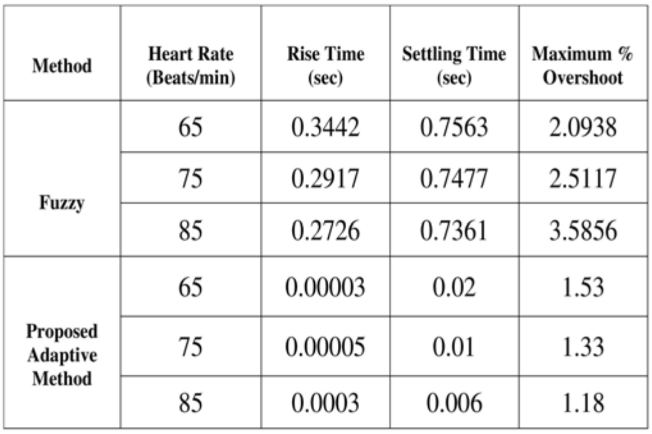


Figure 12: Response of Adaptive PID Controller for HR=85

From the figures, it is evident that, the transient response as well as the steady state response has increased. The controller shows dynamic character. The system adaptive and robust uses the proposed adaptive loop. The proposed method reduces settling time and overshoot. The comparison of transient & steady state response for both the methods is given in figure 13.



Method	Heart Rate (Beats/min)	Rise Time (sec)	Settling Time (sec)	Maximum % Overshoot
Fuzzy	65	0.3442	0.7563	2.0938
	75	0.2917	0.7477	2.5117
	85	0.2726	0.7361	3.5856
Proposed Adaptive Method	65	0.00003	0.02	1.53
	75	0.00005	0.01	1.33
	85	0.0003	0.006	1.18

Figure 13: Comparison of both methods

8. Conclusion & Future Work

Heart diseases can be estimated from Heart Rate signals which form the basis of functioning of pacemaker. The performance of pacemaker is not only governed by the sensors and other associated circuitry, but also by the performance of controller. In this paper, an adaptive PID controller is designed to control the heart rate of pacemaker. It is implemented through an adaptive loop consisting of MIT rule; Delta rule and an Adaptive Correction Factor. The method makes the controller robust and adaptive. By the proposed method, the transient response and steady state response can be improved. Also, the controller needs to be tuned only once after that it will adapt itself automatically to the changes in the system. In this paper, the learning rate of Adaptive Correction Factor is adjusted manually. As a future work, the parameter η can be adjusted automatically. The above stated is proved with the help of simulation results.

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