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## Responsive Cardiac Pacemaker Using VHDL

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**Abstract:** This paper is aimed to design a single chamber rate responsive cardiac pacemaker, implement it in VLSI. A state machine approach has been followed to achieve the desired purpose. The heart of the pacemaker system rests in the pulse generator which forms the major portion of the paper. It has been developed using VHDL and implemented in hardware using FPGA. In the FSM, first an input event is detected. Once this input is detected a timer is set for approximately 0.8 sec, which will be the time between heartbeats, thus giving us 72 heartbeats per minute. Once the timer expires we check to see if a new event is detected. If one is detected we repeat the process of detection and waiting. If one has not been received we need to stimulate the heart and then repeat the process of detection and waiting. The code has been optimized and modified for different pacemaker modes. Adequate effort has been put in for designing a sensing circuit from ECG and maintains the data like events occurred using data compression techniques. It closes with pacemaker testing for real life applications and scope for further work in the field.

**Index Terms:** Pulse Generator, Timer, Timing Engine, VHDL.

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### I. Introduction

The pacemaker is a device implanted inside human body to correct improper functioning of the heart. It consists of three components: the pulse generator, the pacing leads, and the sensing circuit. The pulse generator contains the pacemaker's power source and digital circuitry. A lithium/silver vanadium oxide battery having a 10yr shelf life is the main power source. The digital circuitry is bifurcated into a microcontroller that handles high-level control and manipulation, and a sequencer for handling routine pacing function. In this components are encompassed in the VHDL code written and dumped into the FPGA board which controls the execution of pacing considering the inputs from the other components of the device. The pulse generator receives its inputs as an electrical pulse through a sensing circuit from the heart, via electrodes or electrodes. The pulse generator senses the heart's own electrical activity and responds according to the way it has been pre-programmed. Electrical stimulus from the pulse generator move through the pacing leads into the electrode tip. The leads for a pacemaker are used to stimulate the atrium or the ventricle on the right side of the heart. As such the leads perform the dual function of transmitting signals to and fro the pulse generator.

The sensing circuit performs the needed signal conditioning on the signals from the heart and processes them to convert into a form more acceptable to the pulse generator. It acts as an interface between the leads and the generator.

### II. Background

The following diagram shows a model of a basic single chamber pacemaker. This paper focuses on the timing engine of the pacemaker which controls when it paces and when it does not according to the patients need. In this case, the pacemaker timing engine is programmed by the physician through the physicians interface block, it receives notification of intrinsic events from the sense detection block, and it tells the pace pulse generation block when to pace.

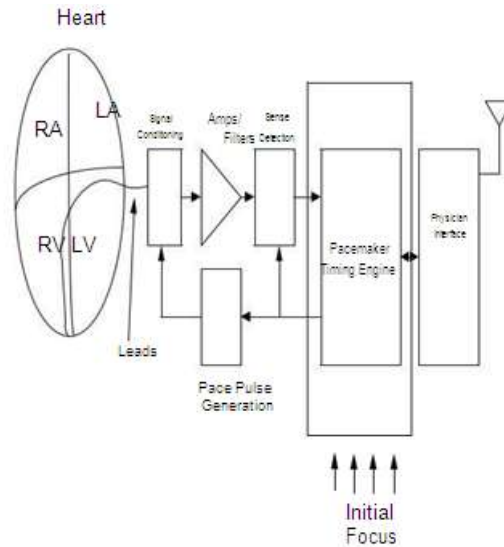


Fig 1. Basic single chamber pacemaker

The Pacemaker Timing Engine operates as follows:

- If intrinsic contractions are not detected after a programmed interval (e.g. 1000 ms corresponding to 60 beats per minute), the pacemaker stimulates the heart with a pacing pulse.
- If intrinsic events are detected, the pacemaker inhibits (does nothing) for that cardiac cycle and restarts its timer for another programmed interval looking for intrinsic contractions.
- As a natural human heart has a refractory period where once an intrinsic event occurs, the heart will Most likely not contract again for a certain period (can be around 200 ms), thus this pacemaker will also ignore events that occur within a programmed interval of either a pace or sense.

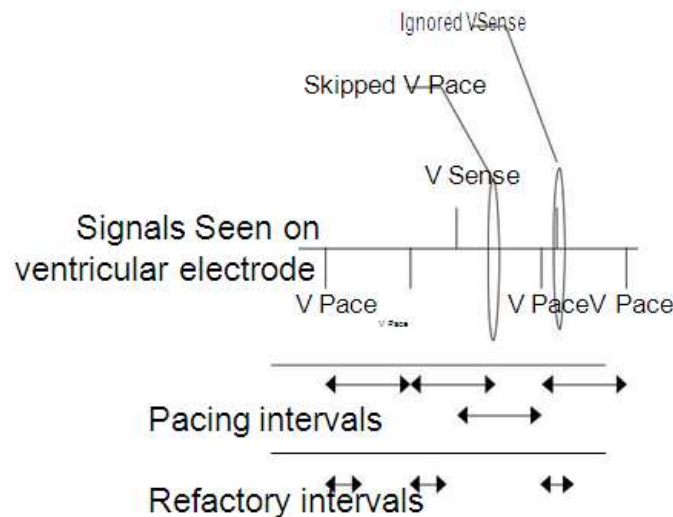
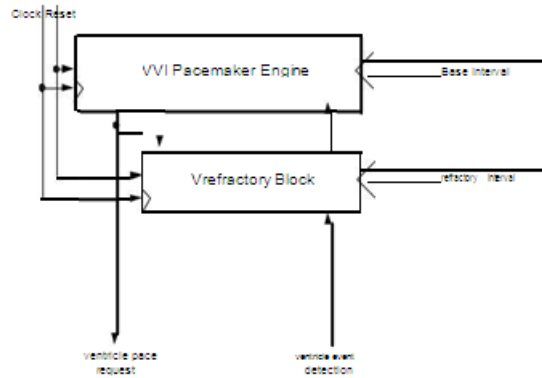


Fig 2. Interval of Either A Pace or Sense

### III. Design Of A Pacemaker Engine

While our initial design will be for a simple single channel pacemaker (termed VVI for Ventricular Pacing, Ventricular Sensing and Inhibiting), my intent is to incrementally expand it to a channel pacemaker. This means that the design needs to follow a layered approach in order to manage complexity and to allow for future growth. The following diagram shows the internal architecture of the block at a very high level.





**Fig 3.** The Internal Architecture of Pacemaker

The following sections break apart the design of the two blocks shown above and a general purpose timer that was used in both blocks.

#### IV. Cardiac Cycle

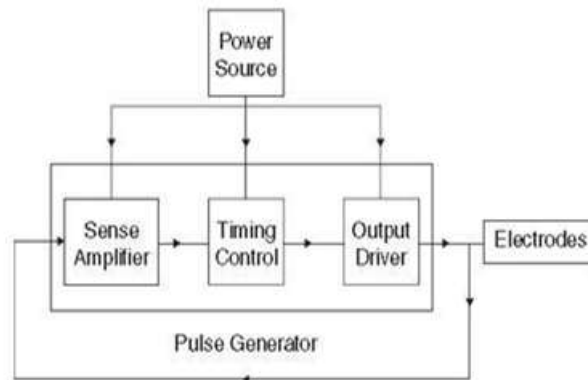
The pressure changes in the major blood vessels and the four chambers cause the valves to open and close and directly affect the flow of blood through the heart. The following phases of Atrial, ventricular, and aortic pressure take place over one cycle.

They are:

- Atrial Systole
- Ventricular Systole
- Late Diastole
- Early Diastole

The different phases of the cardiac cycle culminate in finally enabling the blood to be pumped throughout the body. Each part of the cycle has its special significance: some like the late diastole occurs non visible by most electrocardiograms. Yet it is registered under certain special conditions giving a hint about the improper working of the heart. The discussion of implication of each of the phases is beyond the scope of our discussion. A brief idea about the cycles would suffice our purpose.

#### V. Pulse Generator: The Heart Of Pacemaker



**Fig 4.** Block Diagram of a Pulse Generator

The most important part of the pacemaker is the pulse generator (denoted as timing control in the diagram), and hence, the major portion of the project concentrates on this topic. The different kinds of pulse generators available and that has been designed in the due course of this project. Various constraints have been considered and a cumulative approach has been followed in designing the end result. A finite state machine is used to implement a simple demand pacemaker. A demand pacemaker is one in which there is no competition between the intrinsic pacing of the heart and the artificial pacing of the device. In other words, the pacer paces only in the absence of an R wave and so there is no competition between the two pacemakers. Depending on the number of chambers involved the number of states of the machine changes. A Mealy model of the machine has been used for the purpose. Depending on the present state and the current input (sensed intrinsic pace) the output

and next state changes at every state. The basic process of pacing is described below. First an event is detected, in this case an R- wave. Once the R-wave is detected a timer is set for approximately 0.83 seconds, which will be the time between heartbeats, thus giving us 72 beats per minute. Once the timer expires it is checked to see if a new R-wave is detected. If yes, the process of detection and waiting is repeated. If no, the heart is stimulated then the process of detection and waiting is repeated. It was first done for a single chamber model (assuming pacing is needed just by the ventricles, atria functioning properly) and extend it to dual chamber (where both atria and ventricles are paced) Later the Rate Responsive pacemaker is designed considering a more practical design for the device. Finally the pacemaker is extended to different modes of working and results are observed.

### VI. Single Chamber Pacemaker

A Single Chamber Pacemaker is one in which only one of the two chambers of the heart-atrium and ventricle is paced. Since there are, in total four chambers, we consider each side of the heart separately. As such, there are two chambers to be considered. Now, if in a pacemaker, one of the two is paced, it is called as a single chamber pacemaker. Usually it is the ventricles that are paced because they have stronger muscles and hence, a more powerful contraction owing to the fact that they have to pump the blood to a longer distance as compared to the atria.



Fig 5. RTL Schematic of Single Chamber Pacemaker

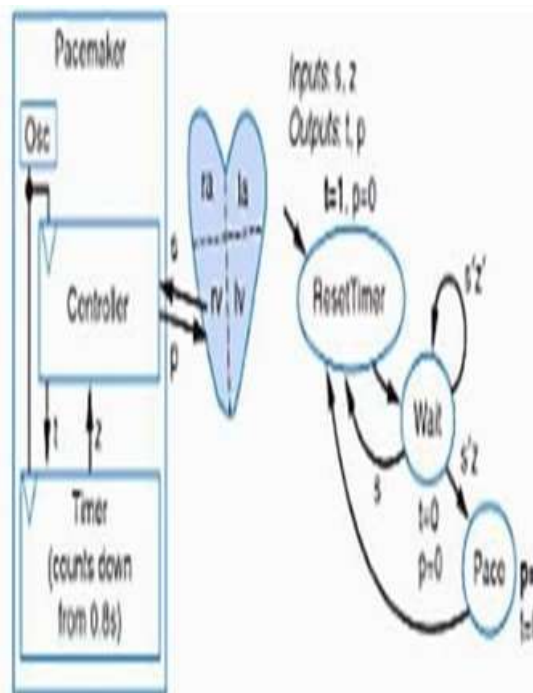


Fig 6. State Diagram of Single chamber pacemaker

**State Diagram of Single chamber pacemaker**

State Table Inputs are:

s: *sensing parameter*: 1 if contraction is sensed. z: *timer output*: 1 if timer reaches 0.

**Outputs:**

t: *output to timer*: 1 if timer is to be reset.

p: *output to heart* : 1 if pacing needs to be done.

**Table 1:** State Table of Single Chamber Pacemaker

State	Functionality	Inputs	Inputs	Outputs	Outputs
		s	z	p	t
A	Wait	0	0	0	0
B	Pace	0	1	1	0
C	Reset	1	0	0	1
	Timer	1	1	0	1

**V. Pacemaker Modes**

Pacemakers pulse generators can be of various types depending on the modes of pacing. The human body has different requirements and those vary from one person to another. Accordingly the pacemaker used for one person cannot be generalized for all. Depending on the needs of the patient and the programmability options, the pacing pulse can be sensed as inhibited or triggered by the R wave of the ECG. Also there are competitive or non-competitive modes of pacing depending on if the intrinsic pacing of the heart is sensed by the pacemaker or not. Pacemakers can be:

- **Demand:** if the pacemaker senses the presence of an R wave and paces only if the R wave is not present.
- **Non Demand:** if the pacemaker paces the heart irrespective of the presence of an intrinsic R wave.
- **Triggered:** if the pacemaker paces the heart every time a R wave is detected i.e the pacing function is triggered by the R wave.
- **Inhibited:** if the pacemaker paces the heart every time a R wave is skipped i.e the pacing function inhibited by the R wave.

As examples, the DDDR, VVI and DDI modes have been specifically programmed and results were observed. The following table shows the different working modes.

**Table 2:** Pacemaker Modes

I	II	III	IV	V
Chamber(s) paced	Chamber(s) sensed	Response to sensing	Rate modulation	Multisite pacing
O = None	O = None	O = None	O = None	O = None
A = Atrium	A = Atrium	T = Triggered	R = Rate modulation	A = Atrium
V = Ventricle	V = Ventricle	I = Inhibited		V = Ventricle
D = Dual (A+V)	D = Dual (A+V)	D = Dual (T+I)		D = Dual (A+V)

### VI. Vrefractory Block

This block was separated into two elements:

- A controller ->VRefController
- A data path -> a timer.

The following diagram shows the basic structure and the state-machine of the controller.

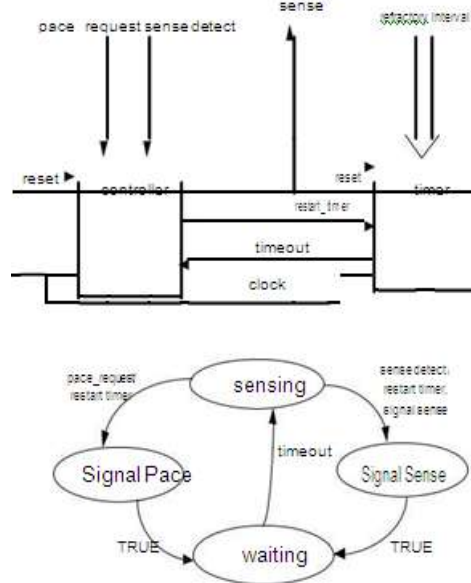


Fig 7. State-Machine of the Controller

The controller was implemented using a combination of structural and behavioral VHDL with the idea of using Mux's to implement the control logic for the state machine.

### VII. VVI Pacemaker Engine

The VVI Pacemaker Engine was broken into a similar structure to the V Refractory block discussed above. The only difference is the functionality and that the controller was implemented using the dataflow style with just combinational logic controlling the progression of the state machine. The timer is held in recirculation mode and merely reset on every paced and sensed event by the controller. As shown, this result in a three state state-machine with all unused states automatically transitioning to the reset state.

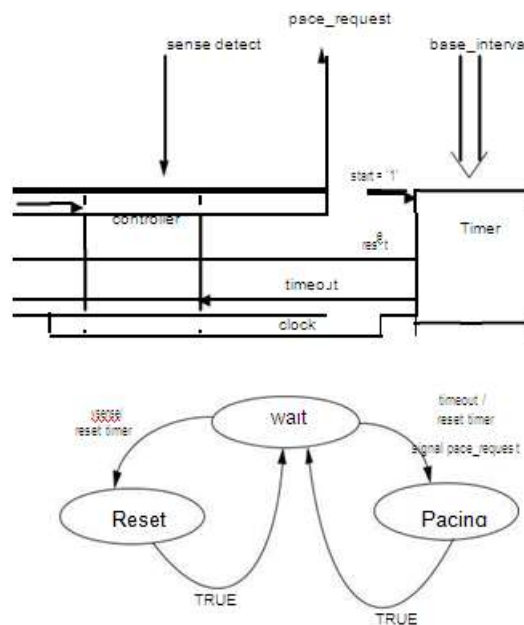
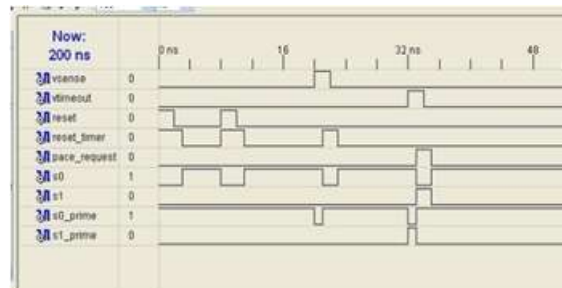


Fig 8. VVI Pacemaker Engine State-machine of the controller



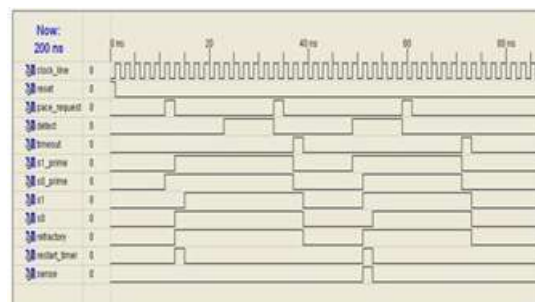
- If start is not held high, it resets and stops at zero.
- If the timeout value is changed from 255 to the value less than the current count, the timer times out immediately. This is a safety feature.

The following simulation result shows the tests conducted for the VVI controller. In the case of systems driven by timers, testing the controller separately is a great way to speed up the system. The test shows the system responding to the vsense, vtimeout and reset inputs, while delivering the appropriate reset\_timer and pace\_request outputs.



**Fig 11.** Tests Conducted for the VVI Controller

For the final example, the following diagram shows the test results for the VRefController block.



**Fig 12.** Tests Conducted For the VRefController block

## IX. Conclusion

The testing methodologies for the device were discussed and the more suitable method was verified. Finally, the device was implemented in hardware and conclusions drawn from giving approximate inputs and observation of outputs. Minor errors were observed which were worked upon for reduction.

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