**SE 3K04 Assignment 2**

**Part 1: Pacemaker Design**

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## Description

The stateflow, built using Simulink (A matlab-based graphical programming environment), creates a model of a reactive system in the form of a pacemaker. Several states were created in a finite state machine variant, using the control logic functionalities that are available in Simulink.

## Parameters

Section notes:

1. Monitored variables are the parameters indicated the activities from the natural heart and the pacemaker.
2. Programmable Parameters implemented to stateflow from data stored in DCM
3. Programmable Input and Output Quantities to FRDM-L64F: describes the data used and generated from stateflow diagrams.
4. Output to FRDM-L64F from SimulinK describes : the data that feeds into FRDM-L64F outside the stateflow diagram.
5. Initialization values describes the initial value set into the specific parameters
6. Limitations of parameter explains the important min max value for programmable parameters

#### **Monitored variables (monitored by Heartview)**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Variable Name** | **Input to Device** | **Output from Device** | **Min** | **Max** | **Unit** | **Description** |
| Atrial pace signal voltage | True |  | 0 | 3.3 | Volt | Measured natural heart atrial amplitude |
| Ventricle pace signal voltage | True |  | 0 | 3.3 | Volt | Measured natural heart Ventricle amplitude |
| Atrial pacing amplitude |  | True | 0 | 5 | Volt | Measured paced heart atrial amplitude |
| Ventricle pace  amplitude |  | True | 0 | 5 | Volt | Measured paced heart Ventricle amplitude |
| Natural heart beat per minute | True |  | 0 | 180 | Bpm | Measured beat per minute from the natural heart |
| Pacing beat per minute |  | True | 0 | 180 | Bpm | Measured beat per minute from pacemaker |
| Atrial natural pulseWidth | True |  | 0 | 20 | ms | Measured pulse width from the natural heart |

#### **Programmable Parameters for Pacemaker**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Variable** | **Min** | **Max** | **Unit** | **Description** |
| Lower Rate Limit | 40 | 150 | bpm | Lower rate limit, minimum beats per minute |
| Upper Rate Limit | 60 | 150 | bpm | Upper rate limit bpm |
| ARP | 0 | 600 | msec | Atrial Refractory Period, time in msec after an atrial pace where atrium sensing is disabled |
| VRP | 0 | 600 | msec | Ventricular Refractory Period, time in msec after a ventricular pace where ventricular sensing is disabled |
| Atrial Amplitude | 0 | 5 | volt | The desired amplitude of atrial pacing. Converted to a duty cycle percentage for Pins D3,D5,D6 inputs. |
| Atrial Pulse Width | 0 | 100 | msec51 | Pulse width of atrial pacing |
| Ventricular Amplitude | 0 | 5 | volt | The desired amplitude of ventricular pacing. Converted to a duty cycle percentage for Pins D3,D5,D6 inputs. |
| Ventricular Pulse Width | 0 | 100 | msec | Pulse width of ventricular pacing |

#### **Programmable Quantities regrading Stateflow**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Variable Name** | **Input to Stateflow** | **Output from Stateflow** | **Min** | **Max** | **Current Value** | **DataType** | **Description** |
| btn2 | True |  | 0 | 1 | Control by FRDM-L64F SW2 | boolean | controls switching between atrial pacing and ventricular pacing |
| btn3 | True |  | 0 | 1 | Control by FRDM-L64F SW3 | boolean | Control decision whether inhibits a pulse |
| Pulse  width | True |  | 0 | 20 | 10 | double  (ms) | controls  the time between the charge  and discharge of during one pace |
| sensing | True |  | 0 | 1 | 1 | boolean | control the value of sensingCTRL |
| PACE\_CHARGE\_CTRL |  | True | 0 | 1 | Control by states | boolean | Output to pin D2 in FRDM-L64F to start and stop charging of C22 capacitor |
| PACE\_GND\_CTRL |  | True | 0 | 1 | Control by states | boolean | Output to pin D10 in FRDM-L64F for current flow in atrium and ventricle |
| ATR\_PACE\_CTRL |  | True | 0 | 1 | Control by states | boolean | Output to pin D8 in FRDM-L64F for current flow to atrium when pacing |
| ATR\_GND\_CTRL |  | True | 0 | 1 | Control by states | boolean | Output to pin D11 in FRDM-L64F for discharging capacitor c21 when pacing atrium |
| VENT\_GND\_CTRL |  | True | 0 | 1 | Control by states | boolean | Output to pin D12 in FRDM-L64F for discharging capacitor c21 when pacing ventricle |
| Z\_ATR\_CTRL |  | True | 0 | 1 | Control by states | boolean | Output to pin D4 in FRDM-L64F for analyzing atrial electrode impedance |
| Z\_VENT\_CTRL |  | True | 0 | 1 | Control by states | boolean | Output to pin D7 in FRDM-L64F for analyzing ventricular electrode impedance |
| sensing\_CTRL |  | True | 0 | 1 | Control by states | boolean | Output to pin D13 in FRDM-L64F for Frontend\_CTRL specified for activate sensing circuitry |
| msecPerBeat | True |  | 0 | 1500 | 60000/LRL | double | Convert msecPerBeat to a sec unit |
| atr\_detect | True |  | 0 | 1 | Control by states | boolean | Connected to pin D0 in FRDM-L64F for ATR\_CMP\_DETECT |
| vent\_detect | True |  | 0 | 1 | Control by states | boolean | Connected to pin D1 in FRDM-L64F for VENT\_CMP\_DETECT |
| paceLocation |  |  | 0 | 1 | Control by states | boolean | Indicate mode for atrium or ventricle. 0 atrium, 1 ventricle |
| LRL |  |  | 40 | 150 | 60 | double | Lower rate limit, minimum beats per minute |
| URL |  |  | 60 | 150 | Not set | Double | Upper rate limit |
| ARP |  |  | 0 | 600 | 250 | int | Atrial Refractory Period, time in msec after an atrial pace where atrium sensing is disabled |
| VRP |  |  | 0 | 600 | 250 | int | Ventricular Refractory Period, time in msec after a ventricular pace where ventricular sensing is disabled |

#### 

#### 

#### **Output to FRDM-L64F from Simulink (not from Stateflow)**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Variable Name | Min | Max | Current Value | DataType | Description |
| dutyCycle | 0 | 100 | 66 | double | Set the duty cycle of PACING\_REF\_PWM |
| dutyCycle1 | 0 | 100 | 66 | double | Set the duty cycle of VENT\_CMP\_REF\_PWM |
| dutyCycle2 | 0 | 100 | 66 | double | Set the duty cycle of ATR\_CMP\_REF\_PWM |

#### **Initialization values**

|  |  |
| --- | --- |
| Variable Name | Initialized Value |
| pulseWidth | 10 ms |
| LRL | 75 beats/min |
| msecPerPace | 60,000/LRL ms |
| ARP | 250 ms |
| VRP | 250 ms |
| sensing | 0 (boolean) |
| paceLocation | 0 (boolean) |
| PACING\_REF\_PWM  (Frequency / Initial duty cycle) | 2000 Hz /50 |
| VENT\_CMP\_REF\_PWM  (Frequency / Initial duty cycle) | 2000 Hz / 50 |
| ATR\_CMP\_REF\_PWM  (Frequency / Initial duty cycle) | 2000 Hz/ 50 |

#### 

#### **Limitations to parameter**

|  |  |  |
| --- | --- | --- |
| Variable Name | Min/Max Value | Reason |
| pulseWidth | 0msec / 20 msec | Pulse with should not be too long so that the time between pacing and discharge will be too long which create a temporary non zero net current that is harmful to the patient |
| dutyCycle/dutyCycle1  /dutyCycle2 | 0% / 100 % | All duty cycle of PWM is specified from 0% to 100% |
| LRL | 40 bpm / 150 bpm | Minimum heartbeat should be low enough to not overwork the heart, but should be enough to keep a high enough blood pressure. |
| URL | 60 bpm / 150 bpm | Heart should be allowed to beat faster than average during exercise for example. |
| VRP/ARP | 0 msec / 500 msec | 0 if not enabled, 500 seems to be the maximum that would be required. Since the LRL will typically be around 60 bpm , meaning the longest typical time between paces would be around 1000-1500 msec, a 500 msec refractory period seems the longest that could be desirable. |

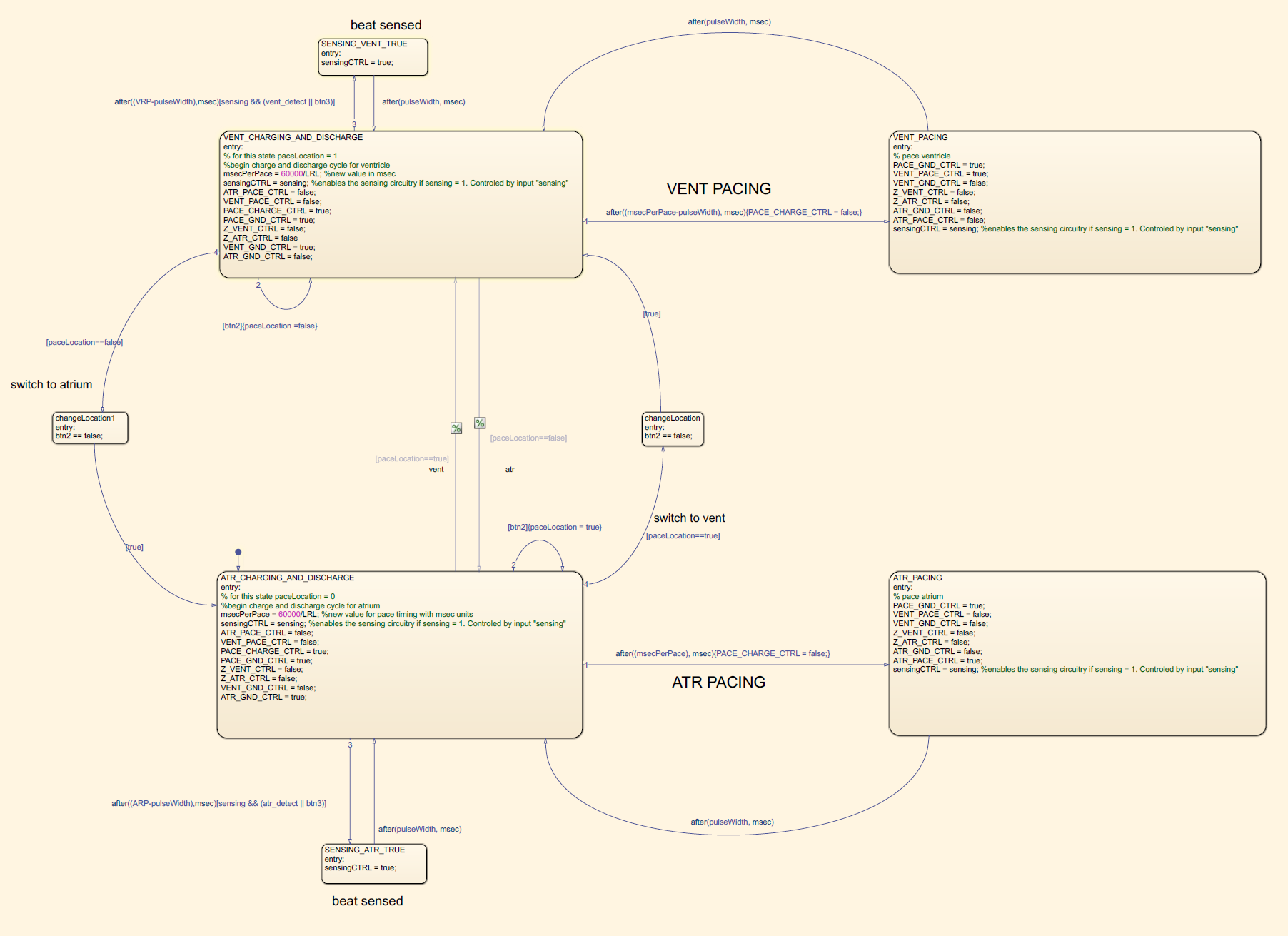
## 

## Simulink Model

### States

|  |  |
| --- | --- |
| State name | State description |
| VENT\_CHARGING\_AND\_DISCHARGE | This state is responsible for prepare ventricular pacing by charging capacitor C22 and then discharging capacitor C21 after the ventricle been paced(charge flow back through heart in order to result a net zero current ) |
| VENT\_PACING | This state is responsible for discharging capacitor C22 and letting the current flow through the ventricle to pace the heart. |
| ATR\_CHARGING\_AND\_DISCHARGE | This state is responsible for prepare ventricular pacing by charging capacitor C22 and then discharging capacitor C21 after the atrium been paced(charge flow back through heart in order to result a net zero current ) |
| ATR\_PACING | This state is responsible for discharging capacitor C22 and letting the current flow through the atrium to pace the heart. |
| SENSING\_VENT\_TRUE | This state is responsible for activate the sensing circuit for VVI pacing mode |
| SENSING\_ATR\_TRUE | This state is responsible for activate the sensing circuit for AAI pacing mode |
| changeLocation1 | This state is on the path switching from ventricular mode to atrium mode, this state reset the value of btn2 to 0. |
| changeLocation | This state is on the path switching from atrium mode to ventricular mode, this state reset the value of btn2 to 0. |

### State Diagram



#### **Description of Diagram**

There are a total 8 states in the diagram. The upper part of the diagram shows ventricular pacing and sensing logic. The lower part of the diagram is for atrial pacing and sensing.

For AOO and VOO pacing mode, the parameter called *sensing* will be set to false. Thus, the state only goes through VENT\_CHARGING\_AND\_DISCHARGE, VENT\_PACING for VOO and ATR\_CHARGING\_AND\_DISCHARGE, ATR\_PACING for AOO .

**AOO Pacing Sequence:**

For AOO, starting with the charging capacitor C22, PACE\_CHARGE\_CTRL is true for charging, PACE\_GND\_CTRL is also true but does not take effect until it goes to the next stage for pacing. ATR\_GND\_CTRL is also true for preparing discharging capacitor C21 after the pacing stage. After a period of time from parameter *msecPerPace* (60000/LRL) the stage goes to ATR\_PACING. ATR\_GND\_CTRL is false and ATR\_PACING\_CTRL is set to true to let the C22 discharge the current to the heart . While the PACE\_CHARGE\_CTRL is set to false to prevent connecting voltage directly to the patient's heart. After a period of time in msec specified by *pulseWidth* parameter, the stage will go back to the ATR\_CHARGING\_AND\_DISCHARGE stage. ATR\_PACE\_CTRL will be set to false and ATR\_GND\_CTRL is true for discharging the capacitor C21 to create a net zero current in the heart.

For both states, Z\_VENT\_GND\_CTRL, Z\_ATR\_GND\_CTRL, VENT\_PACE\_CTRL, and VENT\_GND\_CTRL are set to false.

**VOO Pacing Sequence:**

For VOO, starting with the charging capacitor C22, PACE\_CHARGE\_CTRL is true for charging, PACE\_GND\_CTRL is also true but does not take effect until it goes to the next stage for pacing. VENT\_GND\_CTRL is also true for preparing discharging capacitor C21 after the pacing stage. After a period of time from parameter *msecPerPace* (60000/LRL), the stage goes to VENT\_PAING. VENT\_GND\_CTRL is false and VENT\_Paing\_CTRL is set to true to let the C22 discharge the current to the heart . While the PACE\_CHARGE\_CTRL is set to false to prevent connecting voltage directly to the patient's heart. After a period of time in msec specified by *pulseWidth* parameter. The stage will go back to VENT\_CHARGING\_AND\_DISCHARGE stage.VENT\_PACE\_CTRL will be set to false and VENT\_GND\_CTRL is true for discharging the capacitor C21 to create a net zero current in the heart.

For both states, Z\_VENT\_GND\_CTRL, Z\_ATR\_GND\_CTRL, ATR\_PACE\_CTRL, and ATR\_GND\_CTRL are set to false.

**AAI and VVI Pacing and Sensing Sequences:**

For AAI and VVI pacing mode, input parameter *sensing* will be set to true by the DCM and thus *sensingCTRL* will also be true (the output to pin D13 FRONTEND\_CTRL). As such the program is switched from either AOO or VOO to instead AAI or VVI pacing mode. Then the program will perform sensing logic while in the CHARGING\_AND\_DISCHARGE state. After ARP or VRP minus *pulseWidth* amount of time (this accounts for the *pulseWidth* amount of time that already elapsed since the last pace while moving from the PACING state to the CHARGING\_AND\_DISCHARGE state), the diagram checks whether there is an inhibition for pacing done by btn3. If btn3 is pressed the stage will go to SENSING\_ATR\_TRUE to inhibit a pulse. If btn3 is not pressed, the program will check on atr\_detect or vent\_detect which is connected from ATR\_CMP\_DETECT or VENT\_CMP\_DETECT. It will then go to SENSING\_ATR\_TRUE if either is true. Otherwise it will continue with the next pace as usual once msecPerPace has elapsed.

For AAI, if atr\_detect is high, this means ATR\_CMP\_DETECT from FRDM-L64F is high, which means a natural atrial heartbeat has been detected. In this case, (if ARP has elapsed) control will move from ATR\_CHARGING\_AND\_DISCHARGING state to SENSING\_ATR\_TRUE. It will wait in this state for the duration of pulseWidth before returning to ATR\_CHARGING\_AND\_DISCHARGING to implement the same process for pacing described in AOO pacemode.

For VVI, If vent\_detect is high means VENT\_CMP\_DETECT from FRDM-L64F is high, which means a natural ventricular heartbeat has been detected. In this case, (if VRP has elapsed) control will move from VENT\_CHARGING\_AND\_DISCHARGING state to SENSING\_VENT\_TRUE. It will wait in this state for the duration of *pulseWidth* before returning to VENT\_CHARGING\_AND\_DISCHARGING to implement the same process for pacing described in VOO pacemode.

**Location Control:**

When btn2 is pressed, the state will change from VENT\_CHARGING\_AND\_DISCHARGING to ATR\_CHARGING\_AND\_DISCHARGING or vice versa. During the state changeLocation and changeLocation1, *btn2* will be reset to false for next input detection and paceLocation will be changed to true and false according to the state. When state is VENT CHARGING AND DISCHARGING, paceLocation is true. When state is for ATR CHARGING AND DISCHARGING, paceLocation is false.

### Transition Table

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Source State** | **Event** | **Condition** | **Entry Actions** | **Condition Actions** | **Exit Actions** | **Transition**  **Actions** | **Destination State** | **During**  **Actions** |
| VENT\_CHARGING\_AND\_DISCHARGE | True | [paceLocation==false] | msecPerPace = 60000/LRL  sensingCTRL = sensing;  ATR\_PACE\_CTRL = false;  VENT\_PACE\_CTRL = false;  PACE\_CHARGE\_CTRL = true;  PACE\_GND\_CTRL = true;  Z\_VENT\_CTRL = false;  Z\_ATR\_CTRL = false  VENT\_GND\_CTRL = true;  ATR\_GND\_CTRL = false; | NC | NC | NC | changeLocation1 | NC |
| True | after((msecPerPace-pulseWidth), msec) | Same as above | PACE\_CHARGE\_CTRL = false | NC | NC | VENT\_PACING | NC |
| True | after((VRP-pulseWidth),msec) | Same as above | NC | NC | NC | SENSING\_VENT\_TRUE | NC |
| True | [btn2]{paceLocation = false} | Same as above | NC | NC | NC | State =VENT\_CHARGING\_AND\_DISCHARGE | NC |
| VENT\_PACING | True | after(pulseWidth, msec) | PACE\_GND\_CTRL = true;  VENT\_PACE\_CTRL = true;  VENT\_GND\_CTRL = false;  Z\_VENT\_CTRL = false;  Z\_ATR\_CTRL = false;  ATR\_GND\_CTRL = false;  ATR\_PACE\_CTRL = false;  sensingCTRL = sensing; | NC | NC | NC | VENT\_CHARGING\_AND\_DISCHARGE | NC |
| ATR\_CHARGING\_AND\_DISCHARGE | True | after((msecPerPace), msec) | msecPerPace = 60000/LRL;  sensingCTRL = sensing;  ATR\_PACE\_CTRL = false;  VENT\_PACE\_CTRL = false;  PACE\_CHARGE\_CTRL = true;  PACE\_GND\_CTRL = true;  Z\_VENT\_CTRL = false;  Z\_ATR\_CTRL = false;  VENT\_GND\_CTRL = false;  ATR\_GND\_CTRL = true; | PACE\_CHARGE\_CTRL = false; | NC | NC | ATR\_PACING | NC |
| True | after((ARP-pulseWidth),msec)  [sensingCTRL && (atr\_detect || btn3)] | Same as above | NC | NC | NC | SENSING\_ATR\_TRUE | NC |
| True | [paceLocation==true] | Same as above | NC | NC | NC | changeLocation | NC |
| True | [btn2]{paceLocation = true} | Same as above | NC | NC | NC | ATR\_CHARGING\_AND\_DISCHARGE | NC |
| ATR\_PACING | True | after(pulseWidth, msec) | PACE\_GND\_CTRL = true;  VENT\_PACE\_CTRL = false;  VENT\_GND\_CTRL = false;  Z\_VENT\_CTRL = false;  Z\_ATR\_CTRL = false;  ATR\_GND\_CTRL = false;  ATR\_PACE\_CTRL = true;  sensingCTRL = sensing; | NC | NC | NC | ATR\_CHARGING\_AND\_DISCHARGE | NC |
| SENSING\_VENT\_TRUE | True | after(pulseWidth, msec) | sensingCTRL = true; | NC | NC | NC |  | NC |
| SENSING\_ATR\_TRUE | True | after(pulseWidth, msec) | sensingCTRL = true; | NC | NC | NC |  | NC |

## 

## Design Decisions

The stateflow of all the pacing modes were created in one chart. For this assignment in particular, the Duty Cycle was given a manual value. Six different states were created called

ATR\_CHARGING\_AND\_DISCHARGE, ATR\_PACING, SENSING\_ATR\_TRUE, VENT\_CHARGING\_AND\_DISCHARGE, VENT\_PACING and SENSING\_VENT\_TRUE. Moving through these states allows us to change to and access the AOO, VOO, AAI and VVI modes. This was decided because it made cycling through the different states easy to manage.

Mode AOO uses the ATR\_CHARGING\_AND\_DISCHARGE and ATR\_PACING states to charge the capacitor, pace the Atrium accordingly and then discharge the capacitor. The circuit can be broken down to charging capacitor C22, disconnect power and pace the heart, and discharge capacitor C21 to GND for zero net current to the heart. ATR\_CHARGING\_AND\_DISCHARGE state is both responsible for charging the capacitor C22 before pacing and discharging capacitor C21 after pace. Then the state ATR\_Pacing is only designed for allowing current flow through the atrium to generate a successful pace.

Mode VOO uses the VENT\_CHARGING\_AND\_DISCHARGE and VENT\_PACING states to charge the capacitor, pace the Ventricle accordingly and then discharge the capacitor.The circuit can be broken down to charging capacitor C22, disconnect power and pace the heart, and discharge capacitor C21 to GND for zero net current to the heart. VENT\_CHARGING\_AND\_DISCHARGE state is both responsible for charging the capacitor C22 before pacing and discharging capacitor C21 after pace. Then the state VENT\_Pacing is only designed for allowing current flow through the atrium to generate a successful pace.

The Mode VVI uses the state SENSING\_VENT\_TRUE to finish the sensing of the ventricle

heartbeat and the mode AAI uses the state SENSING\_ATR\_TRUE to finish the sensing of the atrium heartbeat. The time duration of each sensing action is designed according to the Ventricular Refractory Period or Atrial Refractory Period. These describe the period of time following a pace or natural heartbeat where the sensing circuitry will not be active. This prevents any false senses due to the heart depolarization.

## 

## Testing

|  |  |  |  |
| --- | --- | --- | --- |
| **Test Case** | **Mode Selected** | **Result (pass/fail)** | **Additional Description** |
| Have continuous pace to the atrium | AOO,AAI | pass | Paces are consistent timings |
| Have continuous pace to the ventricle | VOO,VVI | pass | Paces are consistent timings |
| Atrium pace follows all programmable parameters | AOO,AAI | Pass (except variation of pacing amplitude) | The pacing follows the all parameter inputted but the amplitude is varying a little. |
| Ventricle pace follows all programmable parameters  listed in the document. | VOO,VVI | Pass (except variation of pacing amplitude) | The pacing follows the all parameter inputted but the amplitude is varying a little. |
| Pacemaker does not pace during the normal heartbeat | AAI,VVI | Pass |  |
| Pacemaker does not pace when inhibition (button3) is press | AAI,VVI | Pass |  |
| Pacemaker can be switched back and forth for mode regarding atrium and mode regarding ventricle | AOO,VOO,AAI,VVI | Pass |  |
| After each pace follows a recharge pulse | AOO,VOO,AAI,VVI | Pass | The recharge pulse is almost at same amplitude with pace pulse, it is not ideal but due to hardware limitation |
| Amplitude of pacing are in a designed range (not larger than 5V) | AOO,VOO,AAI,VVI | Pass |  |
| Pacemaker are able to change according to user input | AOO,VOO,AAI,VVI | Pass |  |
| Pacemaker are able to sense the heartbeat | AOO,VOO,AAI,VVI | Pass |  |
| Pacemaker is able to vary the threshold amplitude with which a heartbeat is sensed | AOO,VOO,AAI,VVI | Pass |  |

## Requirement Changes That Are Likely

* Now all the programmable parameters such as LRL, URL, ARP, VRP and duty cycles are controlled by constant input in the simulink. This will be changed when the project gets into the next phase where all the parameters are controlled by the user though DCM.
* Button2 for switching modes of AOO,VOO,AAI,VVI also needs to be changed to let users put requests through DCM.
* Button3 for pacing inhibition also needs to be changed to let users put requests through DCM.
* The pacemaker should have the ability to be expanded for future accommodation of more pacing mode and parameters.

## Design Decision Changes That Are Likely

* By connecting the board to the DCM with real time communication, users will be able to adjust the parameters and send to the stateflow the form input of parameters will be changed .
* Button 2 and Button 3 will be removed then use input that can be adjusted through DCM this will be done by connecting the board to the DCM with real time communication.
* The simulink model will be focused on designing a clearer and modularized shape in order to add more elements easier.
* Inputs to Pins D3, D5 and D6 will be made variable for separate amplitude for atrium and ventricle pacing.