E-ISSN 2581 – 7957
P-ISSN 2277 – 3916

CVR Journal of Science and Technology, Volume 21, December 2021
DOI: 10.32377/cvrjst2111

Considerations to Achieving Pulsatility for Left Ventricular Assist Devices through BLDC Motor by using Closed Loop Control system with PID Controller

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Abstract: **In the past few years, several people have been diagnosed with several heart failures. Implantation of the ventricular Assist life saving device, gives support for the heart to function normally. Mechanical circulatory support systems such as Ventricular Assist Devices (VADs) and Total Artificial Hearts (TAHs) are commonly used to replace a diseased heart and play an important role in saving people's lives. Mechanical circulatory devices known as left ventricular assist devices (LVADs), these devices are currently, the most commonly used to help patients with a variety of heart issues. In the beginning, pulsatile flow devices are used, and further advance switched to continuous-flow devices. Despite the fact that these devices have many benefits, they have reported several difficulties during work. Several trials were performed to prevent these problems. The aim of this study is to achieve pulsatility in Ventricular Assist Devices. This paper describes the design of a closed-loop control with a PID controller system that has been implemented to achieve pulsatile flow in a device by varying the speeds of the BLDC motor. Its performance is evaluated and should be compared with the standards.**

Index Terms: **Total Artificial Hearts, *Left Ventricular Assist Devices, Pulsatile flow, BLDC motor, PID controller***

I. INTRODUCTION

In the past few years, cardiac disease is the main cause of death for many people. Due to less availability of heart donors, many people who are having difficulty with heart disease are waiting for replacement of their hearts with normal hearts die. One of the best suitable solutions has come to this above problem; there is a need to develop a VAD device that will assist the circulatory system of the body [1]. This resulted in the development of Mechanical Circulatory Support Devices (MCSDs). The step towards the development of Mechanical Circulatory Support Devices (MCDs) [2] started in 1957 and the field of MCD was first introduced in 1964 [3-4]. Mechanical circulatory support devices are used to assist in pumping the blood circulation from the heart to other parts of the entire body in case of heart failure. In order to implant these devices in a patient's body, they have to undergo many clinical experiments, which involve various designs, an appropriate pump speed setting to achieve a desired blood flow rate based on the patient's body, detecting potential risk from inappropriate device operation, and different optimizations are required. In general, there are two types of devices. They are the Total Artificial Heart (TAH) and the Ventricular Assist Devices (VADs). The total artificial heart replaces the complete human heart and the ventricular assist devices assist the human heart in case of weakened heart or heart failure.

Since implantation of the initial ventricular assist devices, a constant development of the suitability of these devices has been made. The first-generation mechanical circulatory support devices were developed in 1964. They are very large-sized devices that are unreliable due to small fatigue cracks that require external power supply and control. Noise emission, infections of cannulas, and malfunctions induced by tears in the membrane or degradation of valves make everyday life difficult and sometimes cause fatal complications [5]. These mechanical circulatory pumps have a one- to two-year lifespan. The second-generation mechanical circulatory support devices were developed in the 1990's and improved patient outcomes by reducing size, susceptibility to infections, reducing noise, and providing continuous flow devices which are mechanically reliable and enhance the quality of life. The second generation of left ventricular assist devices is more frequently used. This paper presents various closed-loop control techniques to achieve pulsatile nature in continuous flow devices with the usage of Brush Less DC (BLDC) motor for both extracorporeal and implantable type TAHs & VADs. By regulating the speed of the motor & pump at the rate of required natural heartbeat pulsation flow is possible [6-7]. To get the required speed of the motor, we use different types of controllers. In this work, a closed-loop control system with a PID controller is used to control the speed of the BLDC motor to achieve the pulsatile flow of blood.

Received on 26-08-2021, Revised on 23-09-2021, Accepted on 13-11-2021.

II. LITERATURE REVIEW

Praveen Kumar C et al., [1] explained the efficiency of the heart pump is very low (12-20%). Hence, in this paper variation of efficiency is discussed and they are considered the average value of efficiency as 15%. The developed device has three-phase twin axial flow BLDC motors that are inserted symmetrically for balancing the axial pull forces. In order to get a large volume in the pump chamber and lower speed, the pump impellers may be placed in this hole. The motor has a passive magnetic bearing that doesn't involve contact and friction, thus reducing blood damage.

Gregory K. MacLean et al., [2] explained, a comparison between Nickel and Cadmium (Ni/Cd) and lithium battery cells are taken and assembled into a multicell battery pack. In this, they used 2 different rectangular prismatic Ni/Cd cells and 5 different rechargeable lithium battery cells and determined the temperature at 37 °c by charge/discharge cycles.

P J Ayre et al., [3] conducted an experiment and investigated, to consider the effects of non-pulsatile and pulsatile flows utilizing in vitro mock loops, and acute (N=3) and chronic (N=6) ovine experiments. An average flow estimation algorithm was derived from the RMS pump impeller speed and RMS input power by utilising the non-pulsatile and pulsatile mock loops. Using this algorithm, we can estimate the flow effectively in a rotatory blood pump without implanting additional invasive sensors.

Allen Cheng et al., [4] discussed the comparison between the continuous-flow and pulsatile-flow left ventricular assist devices, and explained the disadvantages and advantages of various devices.

R. Basanth, Anil K. Puppala [5] discussed simulation models to achieve pulsatile flow of blood by using different controllers. A combination or hybrid model of PID and fuzzy logic controllers has given a good response with fewer ripples and a lower percentage of peak overshoot in the motor speed.

III. DESIGN OF VENTRICULAR ASSIST DEVICES

Before knowing the workings of LVAD, the study has been done on the functioning of the heart. The human heart is one of the most important organs in the human body responsible for sustaining life. The human heart is divided into four chambers, namely two ventricles and two atria. The ventricles are the chambers that pump blood, and the atriums are the chambers that receive blood. The right atrium and ventricle make up the right portion of the heart, and the left atrium and ventricle make up the left portion of the heart. The right and the left regions of the heart are separated by a wall of muscle known as the septum. The chambers of the heart work together and relax to pump blood throughout the heart. The shown in figure 1 describes the structure and functioning of the human heart.

After studying the study on the functioning of the heart, the work of Ventricular Assist Devices, which are used to assist the pumping function of end-stage heart failure, is presented. These devices are implanted inside the body and are connected one end is attached to the apex of the left ventricle, this chamber is used to pumps blood out of the heart into the body and the other end is attached to the aorta which is connected as the main artery of the heart which is used to carry the oxygenated blood to the entire other organs body. The structure and functioning of the heart are shown in figure1.

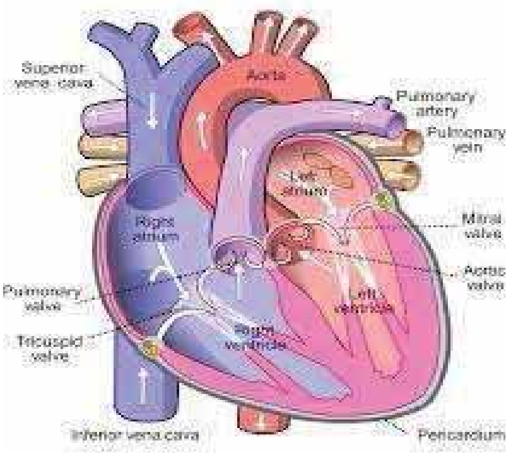

Figure 1. Structure and functioning of the heart.

Blood flows from the heart to the pump. It is continuously sent from the left Ventricle Assist chamber via the apical inflow canal and propelled through a pump housing where the magnetic field generated by a rotatory pump transfers blood through the outflow valve to the ascending aorta. A percutaneously tunnelled driveline connects the pump to the external system controller and power source. The figure shown in 2 shows how left Ventricular Assist Devices are implanted into the human body.

Figure 2. Left ventricular Assist Device connected to the heart with controller and battery assembly

The system's electronic controller is the main component that is placed outside the body. It has both manual and fixed settings that modulate pump speed, and provides signals and alarms that help to operate the system in case there is any malfunction in the device for future analysis. These Ventricular Assist Devices carry 4 to 10L per minute of blood at different speeds. VAD has a centrifugal, pulsatile flow, implantable rotatory pump presently in clinical practice. This Ventricular Assist Device operates via a hydro-magnetically levitated rotor without mechanical bearings and can deliver blood up to 4.5 to 5.5L/min through the heart. Firstly, by affording further decrease, this 140g pump can be implanted in the pericardial space, thus eliminating the need for the design of a pump pocket. This small pump size also makes the device more effective for minimally invasive implantation techniques. The absence of mechanical contact within the pump eliminates friction and heat generation which also improves device durability and reliability of the device. Generally, the pump is set at a speed in the range of 2400 to 3200 rpm to allow the blood to pass at a rate of between 3 and 8L/min. The battery packs which power the devices can deliver 4 to 6h of support when fully charged. This battery life span is 6 to 7 years. This cable connects the pump to the batteries through a small hole in the abdomen.

IV. DESIGN OF LEFT VENTRICULAR ASSIST DEVICES

A. Internal Structure of LVAD

The structure of LVAD is shown in figure 3. The design of the LVAD must be done in such a way that it must be mini-sized and be able to fit inside the body. The design of LVAD requires different components.

They are;

- Motor
- Pump
- Rotor
- Inlet valves
- Outlet valves
- Impeller units.

The above all are assembling which is used as a covering for these parts of the pump. Before designing the LVAD there is a right to know about how the LVAD internal structure looks like.

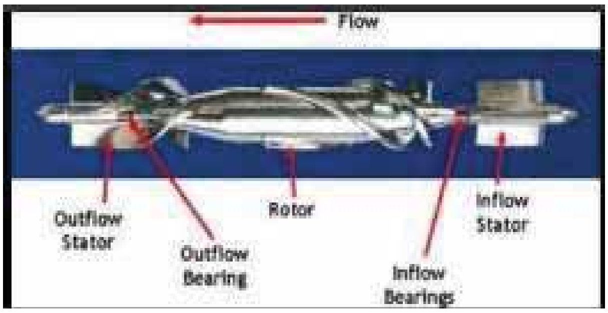

Figure 3. The internal structure of the LVAD pump

Figure 3 represents how the pump of the LVAD looks internally. It consists of an inflow stator from where the blood enters into the input to the pump from the inlet valve. It is attached to the one-end rotor of the motor with a shaft and bearings for smooth rotation of the inflow stator. This inflow stator will rotate when the rotor starts rotating and it is used to manage the flow of the blood inside the pump. After this inlet stator, there is a rotor that is a rotor known as the impeller part of the pump. This impeller unit consists of a blade around it. This impeller unit is used in this system because the impeller is a rotating part of the pump which is able to convert the mechanical energy given by the motor into pump output, which is fluid output by rotation. After the rotor, it consists an outflow stator which is also connected other end to the rotor with the help of outflow bearings. This will allow the blood to flow drive from the pump to the outlet valve.

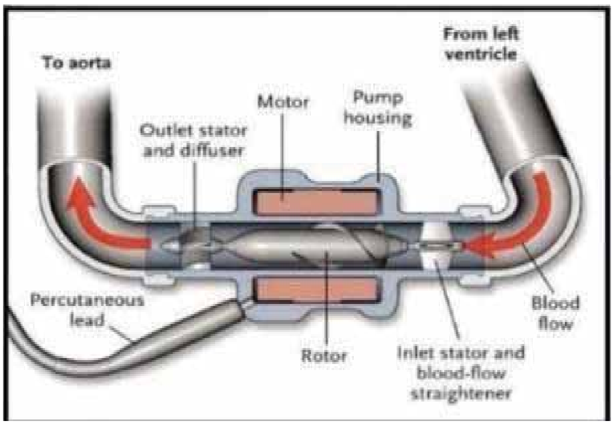

Figure 4. The internal structure of the LVAD with inlet and outlet valves

Figure 4 represents the entire internal structure of the LVAD which has an inlet and outlet stator valve. The inlet valve is connected at the left ventricle from where the rich blood will enter from the right ventricle. From this inlet valve, the blood pumps into the pump of the device. The outlet valve is connected to the Aorta, which is considered as the main artery of the heart, which will deliver rich blood to the entire body. From the output side of the pump, the blood will enter into the outlet stator valve and from there the blood will be pumped into the aorta. This outlet valve is attached to the pump with the help of strain relief. This strain relief is also known as bend relief, is required because it gives mechanical support to the valve when the load is applied to the valve.

B. The Brushless DC Motor

The internal structure of LVAD is discussed in above section A. From the above discussion, it is clear that the pump which is present in LVAD is the main key component in which the motor is present and due to which blood is allowed to flow from the LVAD to the entire body. The motor is an important part of the pump which should be very compact and can be fitted inside the pump. During this left ventricular assist device project, a Brush less DC (BLDC) motor was used. These Brushless DC motors are widely used nowadays in various applications, right from motor vehicles and industrial applications to aircraft for control applications. The main reasons for the increasing usage of brushless DC are less weight, miniature size to power ratio, better acceleration performance, less maintenance and electrical noise compared to a brushed DC motor.

A Brush less DC motor is a type of synchronous motor which is powered by direct current and provides the output in the form of alternating current by different switching signals. The construction of the Brushless DC motor is the same as the permanent magnet synchronous motor. There are many types of DC motors; however, two are common types of DC motors they are brushless DC motor and Brushed DC motor. The Brushed DC motor was invented in the 18th century. These DC motors consist of commutators and brushes assembly on the rotor. Due to these brushes, the rotor spin occurs, making contact with the stator, along with the rotating commutator segments, which ultimately causes power losses. They have a low-speed range due to limitations imposed by the brushes, and electromagnetic interference (EMI) generated by brush arcing, which can be significant in a low-power motor. Another disadvantage of a brushed DC motor is the resistance between the surface of the brush and the commutator of the sliding brush contact, which causes a voltage drop in the motor circuit, which is known as brush drop that consumes energy. So, considering the above disadvantages of the brushed DC motor, the common other type of motor is known as the Brushless DC motor (BLDC). These BLDC motors came into existence around the 1960's. The development of semiconductors in the solid-state electronics field allowed us to eliminate the commutator assembly in DC motors.

Figure 5. BLDC motor with Electronic Speed Controller

The figure 5 represents the BLDC motor which is being considered for testing purposes in this study. BLDC motors and synchronous motors are similar in construction and operation. They are powered by DC electricity with the help of an inverter circuit which produces AC electricity as an output which is used to drive each phase of the motor as a closed-loop controller. This controller will provide the current pulses to the motor windings, which will control the speed and torque of the motor. To rotate the BLDC motor, the stator windings must be energized in a sequence. The communication circuit the motor must know the position of the rotor in order to energize it following the correct winding. In order to this BLDC motor, have a hall effect sensor present inside the motor stator part during manufacturing. In a three-phase BLDC motor, typically there are three hall sensors mounted on the stator of the motor. Whenever the rotor magnetic pole moves near the hall sensor, it will produce a signal indicating the passage of a rotor pole near the sensor. Based on these switching of this three-hall effect sensor (from low to high or from high to low) combinations we can determine the position of the rotor information and according to the position, the stator windings are energized.

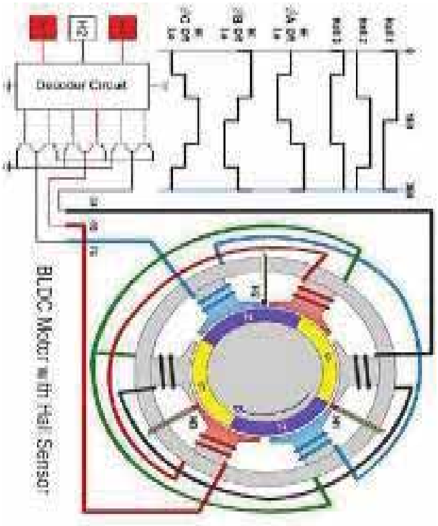

Figure 6. BLDC motor with hall sensors

The figure 6 represents the BLDC motor which is considered for testing purposes in this study. In VADs most commonly used motor is the Brush Less DC motor. This is because BLDC motor has many advantages over compared to other motors and the requirements for VAD's are meet by BLDC motor they are required speed and blood flow rate. This is because the BLDC motor has more advantages over many other motors and the requirements for VAD's are in the range of 15w to 20w. In this study, for testing of the motor, an A2212/1000kV BLDC Brush less DC motor was used, which has a 7V to 12V input voltage and 0.5A of no-load current. From the study of the functioning of the heart, it is clear that the heart must pump blood at 5 to 10liters per minute. The pulsatile flow of blood can be achieved by maintaining constant torque at variable speeds with a motor-pump-waterflow sensor set which is used in TAH and VADs. This is the reason for using BLDC motors in these VAD devices. The BLDC motor has many advantages, like high torque to weight ratio, less noise compared to a brushed DC motor, better acceleration performance, losses are less, increase in reliability, higher efficiency, and a longer lifetime. So, the BLDC motor is the perfect choice for TAHs and VADs.

C. Block Diagram of BLDC Motor with Other Devices

After studying the internal structure of the LVAD, it is clear that it uses the motor inside the pump which is used for the flow of blood through the left ventricle of the heart to the aorta in figure 7 .Before implanting the BLDC motor inside the pump to design the LVAD, the speed of the motor must be controlled by using a microcontroller and verified that when the power supply is given to the motor, it must rotate at the desired speed. This motor speed can be tested by using different components they are Arduino nano, BLDC motor, Potentiometer, Water flow sensor, Batteries, Pump.

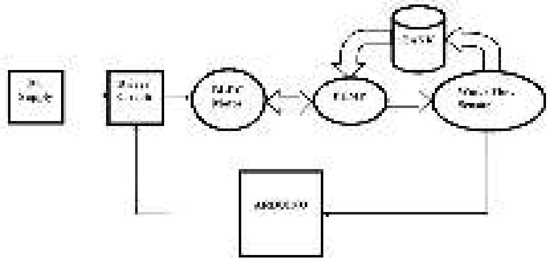

Figure 7. Block diagram of BLDC motor with water flow sensor

D. VAD prototype BLDC motor assembly of the centrifugal pump

In this, a self-designed proto type left ventricular assist device (LVAD) system was used as shown in figure 8. This system consists of a centrifugal blood pump, a BLDC motor, a control device, and a power supply system shown in the below figure.

Figure 9. VAD with centrifugal pump

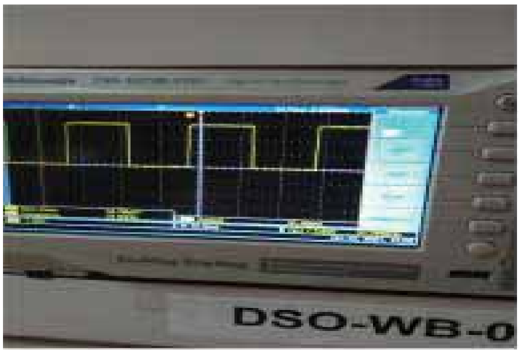

Figure 9. Output wave form view in CRO with pulse width modulation (Time period) of 31.4ms

TABLE I.
SPEED VARIATION WITH FREQUENCY FOR DIFFERENT PULSE WIDTH INPUT VALUES.

Speed (RPM)	Total Time (msec)	On-Time (msec)	Frequency (Hz)	Duty Cycle (t-ON/T)
1100	31.44	13	31.8	0.413
1200	32.76	17	30.5	0.518
1300	33.84	17	29.5	0.502
1400	34.4	17	29.1	0.494
1500	37.64	13	26.6	0.340
1900	49.76	25	20.1	0.502

Figure 9 represents the output wave form view in CRO with a pulse width (Time period) of 31.4ms and table 1 represents the speed variation with frequency for different pulse width input values.

E. Block Diagram of Closed-Loop Control System

From the figure shown below 10, it is seen that how the speed of the BLDC motor can be manually controlled by using a potentiometer and the speed of the motor can be determined by using the water flow sensor. In the below system, there is manual speed control of the motor is considered. But when the motor is used in the design of an LVAD, which is placed inside a person's chest, the speed of the motor must be automatically controlled by using a PID controller to achieve a pulsatile flow of blood.

So, this is the reason the closed-loop control system is considered in this study.

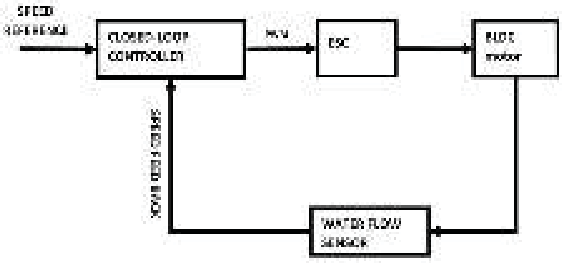

Figure 10. Block diagram for LVAD through BLDC Motor by using a closed-loop control system with a PID controller.

The above figure 10 represents the block diagram for the automatic speed control of the motor by using a closed-loop control system with PID controller. In this block diagram, the components used are the Arduino nano, BLDC motor, Controller (ESC), water flow sensor, and a battery that powers the BLDC motor.

F. Algorithm for Closed-Loop Control System

STEP 1: Set and initialize all the required variables, Input & Output, ARDUINO digital pins to use BLDC motor, Water flow sensor.

STEP 2: Integrate the BLDC motor, Water Flow sensor with ARDUINO and run the motor with initial speed.

STEP 3: Send the reference set speed values as input to the BLDC motor.

STEP 4: Calculate the error, change in error, e-speed previous, e-speed sum, using the flow rate obtained from the water flow sensor.

STEP 5: Pass the error and change error, e-speed previous, e-speed sum values as the inputs to the PID controller.

STEP 6: In PID controller parameters, proportional gain Kp, integral gain Ki, and derivative gain Kd affect the system's overall performance.

STEP 7: Repeat the steps from step three to STEP six until the error is zero or within the specified range.

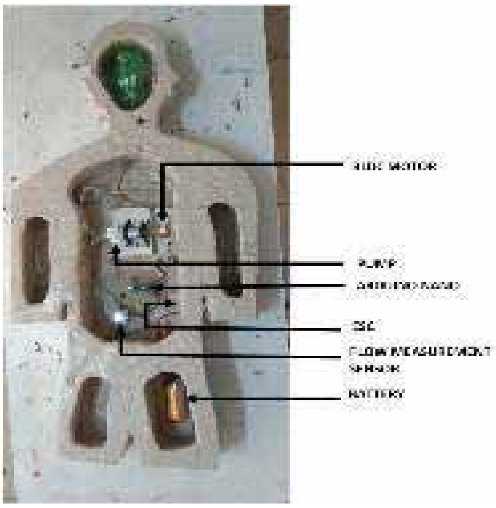

Figure 11. Experimental setup for closed-loop control system

Figure 11 represents the experimental setup of a closed-loop control system. By this setup, the code is written by using Arduino software and dumped in the Arduino nano board and the speed of the motor is varied at different speeds flow rate is recorded and are verified with the previous results.

V. BATTERIES USED AND ENERGY TRANSFER IN LVAD

The use of lithium-ion batteries has grown significantly in recent years. Lithium is the lightweight metal that has the greatest electrochemical potential and also has the high energy density per weight of all metals that are found in nature. Recently, in a wide range of applications, lithium-ion batteries have been used because their rate of self-discharge is much lower than half of the discharge rate of lead-acid batteries.

Despite the advantages of Lithium-ion, they have certain limitations. These lithium ions are brittle in nature. The batteries to maintain the safe operation, they require a protective device to build into individual battery pack. This protective device is also called a Battery Management System (BMS). This system limits the peak voltage of each cell during charging and prevents the cell voltage from dropping below a threshold during discharging. The BMS is a protective device which also overcharges and discharging currents, over voltage during charging, and monitors the cell temperature. The rechargeable battery pack used for Ventricular Assist Devices should be as small and light weight as possible for easy and effective operation. The use of rechargeable lithium cells in implantable medical devices may yield batteries that are smaller in size, lighter weight, provide more energy, require low maintenance and are environmentally safer than those of NiCad batteries. However, NiCad cells are less preferred than lithium batteries because of their high discharge cycle and longer life cycle. So, in recent studies for giving power supply to LVAD Lithium-ion batteries are more used. Two lithium-ion 14V battery packs were used to give power supply.

These battery packs are connected to the controller external to the body and the controller will supply the power to the motor which is implanted inside the body. In this study, we gave power supply to the motor by using a Lithium-polymer battery rated at 11.1V, 2200mAh, which is a very small size and weight. Various batteries were considered for supplying power to Ventricular assist Devices starting from Battery and external controller transfer energy via a percutaneous lead cable to an implanted VADs.

A. Percutaneous Cable Type Transmission

Percutaneous cables shown in figure 11 are used to transmit power from a source that is located external to the human body and control data between a controller and implantable pumps. These types of cables traverse through the patient's skin and supply power to the implanted motor. But these types of drive lines have many disadvantages, like they have a constant risk of bacterial colonization and infection. There is a high possibility that wired type transmission systems are easy to damage and high infection is the major cause.

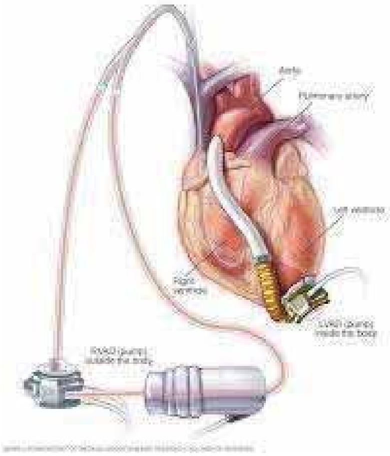

Figure 12. Percutaneous cable type transmission

VI. EXPERIMENTAL RESULTS

This study implemented a closed-loop control system with a PID controller to achieve the pulsatile speed of the BLDC motor and the flow rate of the water flow sensor which is placed inside the pump which is used to design the LVAD.

A. Results obtained from serial monitor of a closed loop system with a PID controller

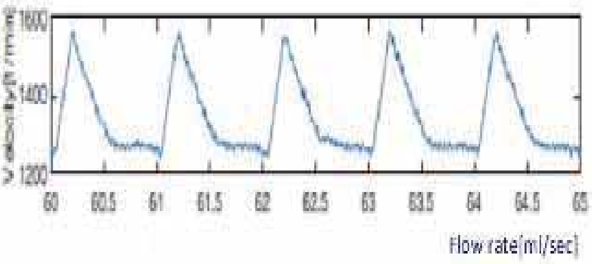

Figure 13. Expected Graph

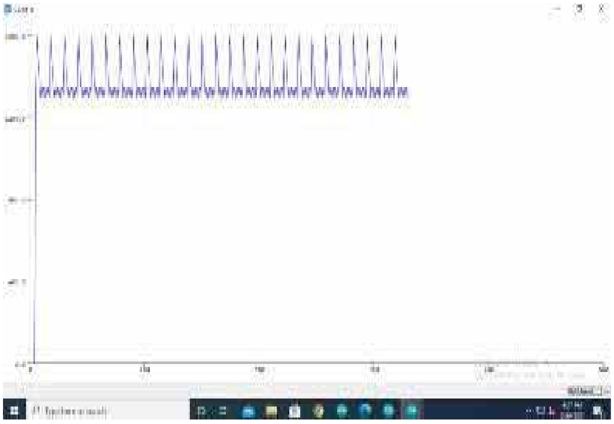

Figure 14. PID Controller Output graph (From Serial Monitor)

Figure 15. Flow rate output (From Serial Monitor)

From the above figures 13,14 and 15, it is observed in the serial monitor outputs that the motor speed and flow rate values vary at certain intervals of time.

So, this is how the speed of the motor can be varied and flow rate obtained by using PID controller from the water flow sensor which is used to design the Ventricular Assist Devices that are used to pump the blood in a pulsatile manner that is shown in figure 14 which represents the normal functioning of the heart. The speed of the motor is varied in a closed-loop control system with PID controller to achieve the blood flow in pulsatile nature. Due to these variations in the speed of the motor the blood which is pumped from the LVAD will resemble the normal heart pumping.

The experimental results for the closed-loop control system with PID controller are obtained for different speeds at different intervals and flow rates and are tabulated as below.

To get the pulsatile flow of blood, these are the speeds considered from the previous results and are used in this work. This work is done by using an Arduino nano through which the closed-loop control system with PID controller operation is done and made to rotate the motor at different required speeds and flow rates of the pump.

TABLE II.
DIFFERENT SPEEDS AT DIFFERENT INTERVALS OF TIME

S. No	Speed (rpm)	Time(sec)
1	1350	0+
2	1650	2
3	1600	4
4	1550	6
5	1500	8
6	1450	10
7	1400	12

TABLE III.
DIFFERENT SPEEDS AT DIFFERENT FLOW RATES

S. No	Speed (rpm)	Flow rate (ml/sec)
1	1350	0+
2	1650	373.33
3	1600	460
4	1550	457.78
5	1500	455.6
6	1450	420
7	1400	64.44

TABLE IV.
DIFFERENT SPEEDS AND FLOW RATES WITH ERRORS

S. No	Speed (rpm)	Flow rate (ml/sec) (S1)	Flow rate (ml/sec) (S1)	Error (S2-S1)
1	1350	0+	0	0
2	1650	373.33	368.02	-5.31
3	1600	460	461.3	1.3
4	1550	457.78	458.86	1.08
5	1500	455.6	456.2	0.6
6	1450	420	423	3
7	1400	64.44	67.06	2.62

These motor speeds, which are varied during specific intervals of time, are plotted in the graph and the graph shown below in figure 16 depicts the obtained output between speed and time.

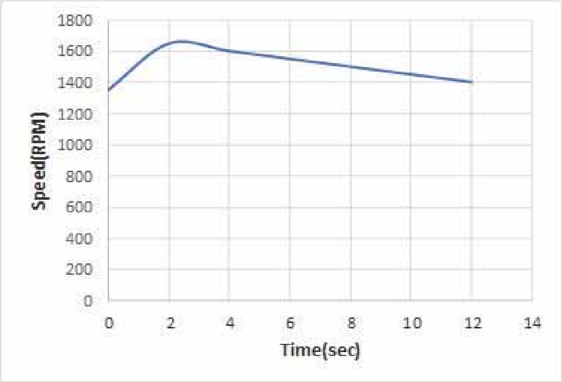

Figure 16. Pulsatile speed is obtained with the BLDC motor by using a closed-loop control system.

The little overshoot in the graph is observed, because initially, the heart is in a contraction state in which the blood is pumped with some pressure of the left ventricle to the aorta. Hence the closed-loop system is set up for starting speed to be high. After that, the heart will move into a relaxation state in which the heart is slowly relaxed. Due to this speed is gradually reduced and made constant.

VII. CONCLUSIONS

The pulsatile flow of blood in Ventricular Assist Devices can be achieved by varying the speeds of the motor. The BLDC motor offers a practical solution for VADs because of its weight, dimensions, and simplicity in control of the speed of the motor. Control of the BLDC motor speed can be achieved by using different methods. In this study, the design of a closed-loop control system with a PID controller was used to achieve the various speeds of the motor at different intervals of time. By using this closed-loop with PID controller system pulsatile flow of blood is obtained which resembles the normal functioning of the heart. Although this closed-loop system is easy to implement, it has some disadvantages. If there are no disturbances in the system, this closed-loop system works normally. But if there are any disturbances in the system like communication failure, it will affect the speed of the motor. Because of the disturbances present in the system ripples will form. These ripples may lead to instability flow of blood inside the body. To overcome this type of problem in this project, a PID control program was developed using error and change in error in flow rate to reduce the disturbance. With this control, the normal functioning of the heart is restored. In this way, the closed-loop with PID control system was developed. The closed-loop system with PID control reduces the ripples and smaller peak overshoots in motor speed compared to PI control. So, for the future, we can use a closed-loop control system with hybrid fuzzy with PI, PID control can also use to reduce smaller ripples furthermore effectively.

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