CONTROL OF A BRUSHLESS DC MOTOR WITHOUT SENSORS OF POSITION TO BE APPLIED IN ARTIFICIAL CIRCULATION

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Abstract. The motor performance is a very important characteristic to artificial blood circulation devices that use an electrical motor such a responsible component by blood pumping, is the motor performance. The absence of brushes in a Brushless direct current (DC) motor, provides special characteristics in comparison to common motor. Therefore, it is highly recommended for that blood pumping application. However, to operate, that kind of motor it is necessary an electronic controller that needs to know the instantaneous rotor's position. Generally, this information is obtained with a set of "Hall" devices installed on the stator structure. Nevertheless, in some applications, because of the physical space available on assembly, the use of "Hall" sensors is not allowed. Further, the position of sensors makes necessary additional wires between the motor and the controller and, in case of sensor fault, whole system is committed. This work presents a method of BLDC motor drive with no sensor, called " Sensorless ", based on the detection of back electromagnetic force(BEMF). The system was tested, in a first moment, on the electric simulator PSPICE®, and then, through an implemented system in our laboratory. The obtained results were appraised and discussed according to the characteristic of some blood pumps.

Keywords: Brushless, Sensorless, Controller, Back-EMF, Artificial Circulation.

1. Introduction

The main objective of this work is to show a technique for "Brushless DC" motor drive without positioning sensors, called "Sensorless technique". The meaning of this work, is to be applied in pumping blood devices, where the position sensors can not be used. Besides, the sensorless technique can be applied as a redundant system of a dependent positioning sensor system.

For properly operation of the motor, the electronic controller, responsible for the commutation process of the motor coils, needs the information of instantaneous rotor's position. That information is generally supplied by a set of magnetic sensors ("Hall" sensors) assembled on the motor structure. However, the use of sensors imposes some factors as: additional wires between motor and controller; in case of sensor's fault, the whole operation of the motor is committed; the motor's performance depends on a correct positioning of sensors, which it is not an easy task. Usually in blood pumps, specially in implantable ones, the cable connecting the motor to the controller has sensors and supply coil wires. It induces degeneration on sensors signals because of spikes during the coil commutation process.

This work presents a technique that are capable to send the instantaneous position information to the electronic driver without sensors, so the controller makes the coil commutation properly.

The instantaneous rotor position is obtained by the back electromagnetic force (BEMF) detection, which is induced in the stator's windings due the rotor's spindle.

This work is organized in that way: in this introduction, some artificial circulation devices are presented, which are the motivation of the this work; the follow item, shows the BLDC motor characteristics of operation; after this study, some driver techniques without sensors are investigated and one technique are deeper analyzed.

This technique was analyzed, initially, by the electronic simulator PSPICE®, where the system behavior was observed – item 3, so a prototype was constructed and some working conditions were imposed to analyze the system output. Finally, from the results, the possible applications of this method of control were discussed.

1.1 Devices for Artificial Circulation

This chapter presents some devices used for blood artificial circulation, and the motor driver is presented.

Basically, the drive method for two types of blood pump are presented: the continuous blood flow pump and the pulsatile blood flow pump. Both have a BLDC motor as pumping element.

1.1.1 Continuous flow Blood Pump

A pump for cardiopulmonary bypass that applied the axial and centrifugal pumping principles, (ANDRADE, 1996), uses a BLDC motor, Fig. (1). The motor control system for this device uses a set of Hall sensors. The system has an analogic input that controls the speed of the motor (1000~3000rpm).

Figure 1. Blood pump for cardiopulmonary bypass "Spiral Pump" (ANDRADE, 1996).

In these devices, a failure in any position sensor can make the whole system inoperative, what is unacceptable during surgical procedures. So, the use of a sensorless circuitry as a redundant system is an alternative in case of fault of any Hall sensor. Another application can be the driver totally through the sensorless method.

In ventricular assist devices with axial flow (DAMM, 1993, p. 44-48), the central element is BLDC rotor, Fig. (2), with permanent magnets inside.
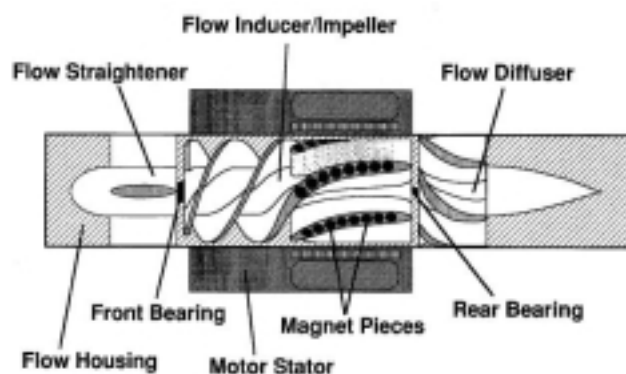

Figure 2. The Axial Baylor/NASA Blood Pump. (MIZUGUCHI, 1995).

The use of Hall sensor is not possible because of it's device geometry. So, to drive this device is indispensable the use of a method without sensors. As the flow of blood is always present through rotor, the system is always in movement and, although the stator coils are not being excited, there will be production of BEMF due the rotation of the rotor.

The sensorless system detects the BEMF and informs the commutation instant to the controller. Then, the controller makes the coil commutation properly in the closed loop operation, allowing the control rotation speed (6000~13000rpm).

1.1.2 Pulsatile Blood Flow Pump

Pulsatile pumps with alternated ejection of the pumping chambers, is a BLDC motor is turning in the two rotation directions. This device was presented by Andrade (1998) and it is a biventricular support device with a BLDC motor as responsible element for pumping, Fig. (03). Hall sensors are installed in the stator structure close to the rotor to get the commutation instant of the motor. The adoption of a system without sensors to drive this device in open loop is not possible because of its operation mode. Sensorless system starts only in open loop mode. After detection of the BEMF, the controller switch to closed loop mode (IIZUKA, 1985). However, for pulsatile pumps, the sensorless system does not works because of three reasons:
1. The controller must reverse the motor direction before switching to closed loop mode;
2. Working in open loop mode, the motor torque is insufficient to eject the blood from the chamber;
3. In the very first stage of operation in open loop mode, the motor may turn in opposite direction.
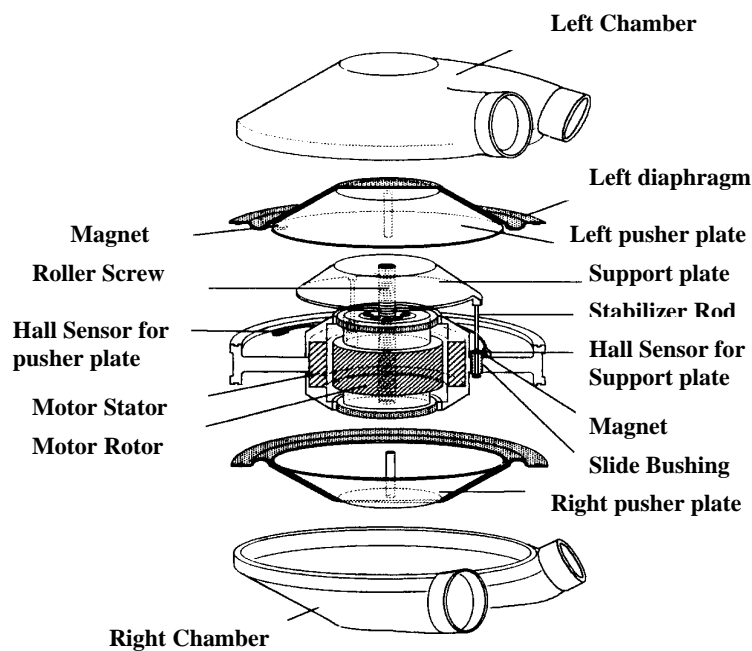

Figure 3. Auxiliary Total Artificial Heart (ANDRADE, 1999).

2. The Brushless DC motor

The brushless DC motor (BLDC) is a synchronous motor which has a set of permanent magnets as part of the rotor, while the coils, are assembled on the stator and produces the magnetic field, responsible for the movement of the rotor.
The BLDC motors can be divided in two categories: those that the magnetic flow happens in the radial direction, and those that the magnetic flow happens in the axial direction, also called "pancake".
The operation of a BLDC motor is very similar to the step motor, where through the strategic commutation of the stator coils is possible to change the produced electromagnetic field orientation and than to control the movement of the rotor.

The choice of the motor type is a commitment solution between the desired torque and the allowed cost. A motor with a larger number of poles provides a stabilized torque output in low rotations (HENDERSHOT JR., 1994). The optimum number of magnetic poles is a complex relation between the geometry and material's properties. In many

projects, the need of cost reduction induces a preference for rotor with a smaller number of magnetic poles (HANSELMAN, 1994).

Another issue that influences on the torque is the motor size, once the torque is lineally proportional to the rotor's length and to the square diameter of the rotor (HANSELMAN, 1994).

Because of the spin, through the interaction between the permanent magnets of the rotor and the stator's coils, a BEMF appears, whose waveform depends on the windings placement on the stator compartment (HANSELMAN, 1994). The BEMF amplitude is directly proportional to the rotor speed and the sinusoidal or trapezoidal waveform, depends on the geometry of the stator.

The choice of the motor type depends on the desirable characteristic: 1) motors with sinusoidal BEMF waveform provide more torque stability in low rotation speeds, even so, the electronic controller is more complex; 2) motors with trapezoidal BEMF waveform offers a simpler electronic controller, although in low rotations the torque ripple is perceptible. The controller needs to know six switches commutation instants, so it can control the windings current in wye or delta connection.

Wye connected motors, supplies a larger torque stability (HANSELMAN, 1994); delta motors, presents a larger ohmic loss, torque ripple, even so, for the same torque amount supply, the delta connection needs just 2/3 of the magnetic material of a wye motor.

In blood pumps, due to size limitation, the choused motor have a trapezoidal waveform and delta connected windings.

The BLDC motor with trapezoidal BEMF waveform, can control through H-bridge driver, as shown in Fig. (4). The switches are controlled in pairs on the following order: S1 and S2, S1 and S6, S5 and S6, S5 and S4, S3 and S4, and S3 and S2 (HANSELMAN, 1994). The reason of that sequence is to minimize the transient effects caused by the coils switching.
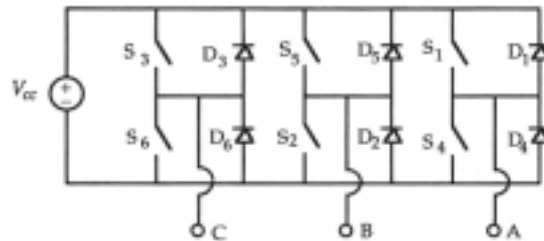

Figure 4.   H-bridge driver. The switches (S1 to S6) are transistors that control the current flow in the coils, connected in A,B and C. The diodes (D1 to D6) represent the transistors junctions (HANSELMAN, 1994).

The Fig. (5) shows a schematic diagram of a BLDC motor whose windings are connected in delta, where: E_N is a BEMF of the N phase; R and L are the coil resistance and the inductance, respectively; I_n is the line current; I_N is the phase current, S_N are the driver switches (transistors) and D_N are diodes that represent the transistors junctions.

The commutation sequence is made in six steps, so it provides a 360 electrical degrees. The relationship among electrical and mechanical degrees depends on the number of poles of the rotor (HANSELMAN, 1994).
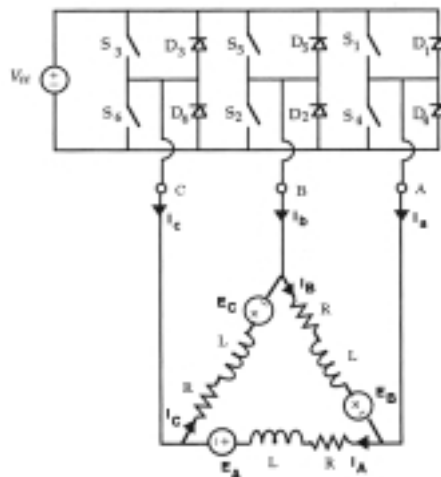

Figure 5. Delta Connection (HANSELMAN, 1994).

3. Sensorless Driver

In order to operate properly, the switches that control the current flow on to the BLDC stator windings should be rightly controlled in the correct instant.

By the way, the commutation among each one of these six steps should be made in the correct instant, depending on the rotor instantaneous position. Generally, the rotor instantaneous position information is obtained through a set of Hall effect sensors assembled on the motor structure. Thus, that position information is sent to the control system that makes the interpretation and provides the right commutation sequence of the bridge driver switches (transistors).

The proposed technique by Lin (1989) for a wye connected BLDC motor is based on the principle that as the magnetic flow and the current are in phase, the signals with rotor exact positions is achieved by the current detection and processing. The Fig. (6) shows this circuit. The inputs of the instrumentation amplifier (V1 and V2) are tied up on a resistor that is connected in series with the corresponding winding. Then, three of these are necessary to detect all commutation instants. The output signal of the instrumentation amplifier is compared to a voltage, which is very close to zero. Finally, the comparator output are a clock source to a JK flip-flop configured as a "toggle". The flip-flop output signal means the windings commutation instants (S_n).
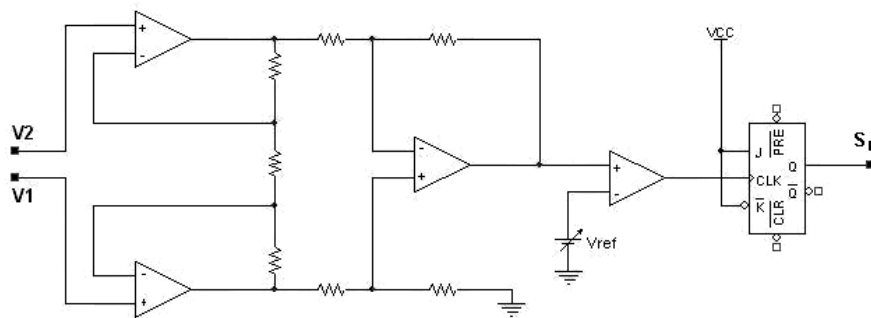

Figure 6.   Phase current detection circuitry (LIN, 1989).

Once the motor type used in blood pump is delta connected, a dual process of the technique proposed by Lin (1989) was accomplished. He shows a circuitry that samples the current. We developed a circuitry that samples differential voltage among of delta vertices instead of current on the wye connection.

The reason of that choice, was based on the fact that BEMF signal changes on the winding commutation instant, and therefore, through the sampling of the differential voltage and comparison with a reference level, the commutation instants is possible to know.

According to the Fig. (5), the sampled voltages are V_{AC}, V_{BA} and V_{CB}. This circuit was implemented on the electric simulator PSPICE® (Microsim Corporation, USA). The study was made on the general case, where the used model was a sinusoidal type (MICROSIM, 1996). In this moment of study, the BEMF zero crossing was important. The duty cycle of pulse wide modulator (PWM) was fixed in 50%. Figure (7) presents the simulation results.

A circuitry with comparators and differential amplifiers was assembled. Figure (8) shows this assembly, where a static and dynamic studies was accomplished for behavior system analysis.

4. Results

The Fig. (9) shows the results of an experiment where the rotation speed was analyzed. The goal of this experiment was the comparison between the Hall signal (top of figure) and the detected signal by the sensorless (bottom of the figure). So, it was reported that close to 2000 rpm the system presents instabilities that commit the operation. The cause of that instabilities is the BEMF amplitude reduction as the speed decrease (prompted on the figure).

For verification of system dynamic answer, a step of speed was imposed both in the system with Hall sensors, and in sensorless system. Figure (10a) shows the behavior of the system with sensor when, initially, a 4500 to 3000 rpm step was applied, and then a 3000 to 4500 rpm. The accommodation time for 2% of the final value was 2,13 seconds. The Fig. (10b) shows the behavior of the sensorless system for the same step of speed, where the accommodation time for 2% of final value was of 2 seconds.

In agreement with the obtained results, the detection technique of the motor winding commutation signals through differential voltage measurements were effective during the tests with delta connected BLDC motor for the 2000 rpm up to 5000 rpm speed range. A speed step was applied to test dynamic behavior showing the same behavior for the systems with and without sensors. The time of accommodation, in both cases, stayed around 2 seconds. However, this is not critical because, for the application object of this work, does not happen any abrupt variation.
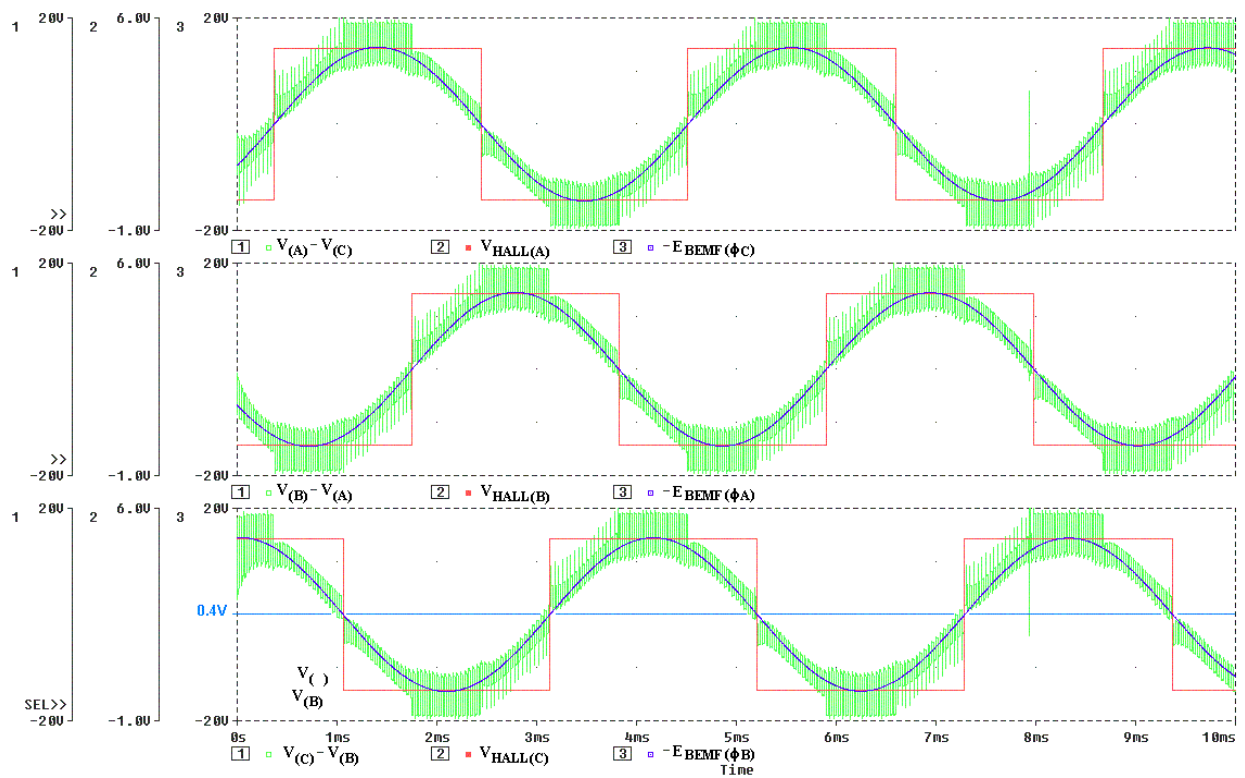
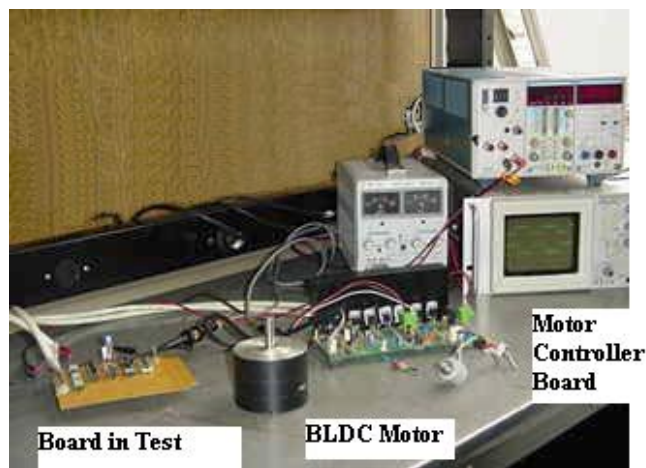Figure 7. Simulation Results of a delta BLDC.

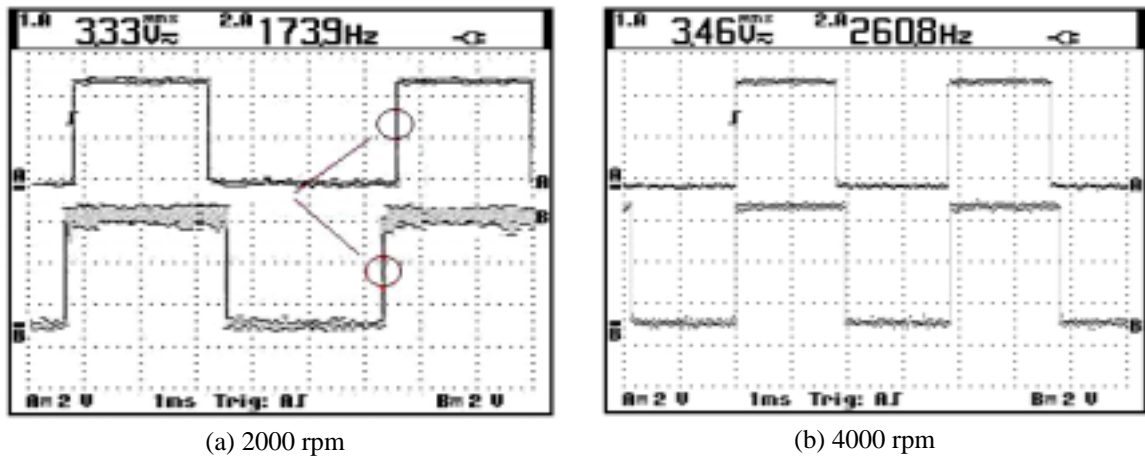Figure 8. Assembly for test and verification of presented "sensorless" technique.

(a) 2000 rpm   (b) 4000 rpm

Figure 9. Comparison between the Hall signals and the detected signals in different speeds.
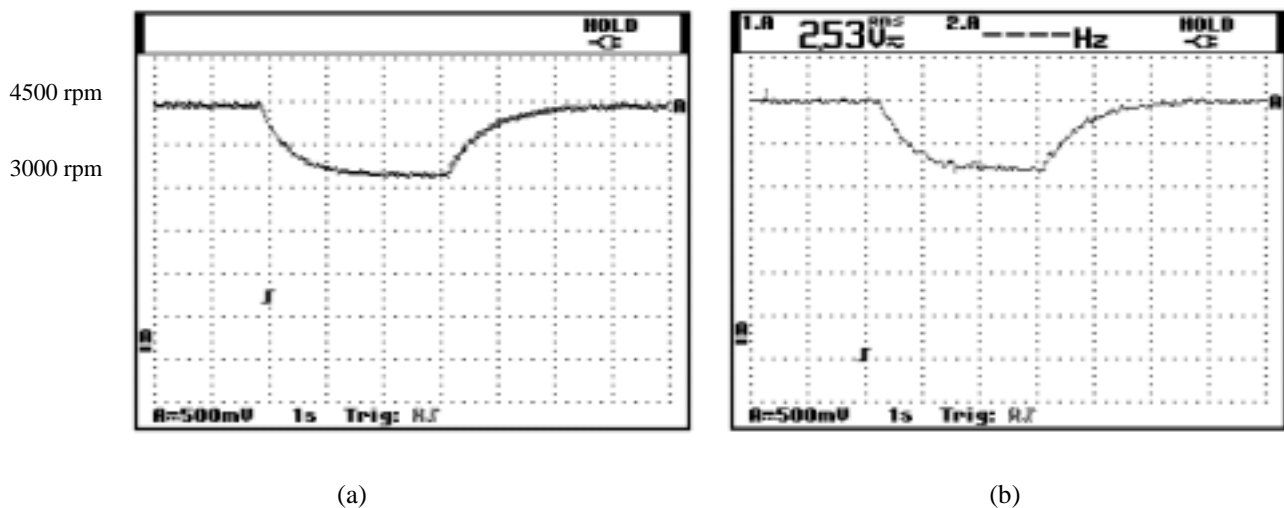

(a)   (b)

Figure 10. Results of speed step application. (a) System with sensors; (b) Sensorless system.

5 Conclusion

In this work was showed a sensorless technique for Brushless DC motors drive (BLDC).

In a first moment, some techniques with wye connected BLDC motor to detection of commutation instants was analyzed. Another detection technique was discussed through the differential voltages on the BLDC delta vertices. A behavior analysis of a delta connected motor was made through a computer simulation tool.

This technique was assembled and validated through the obtained experimental results. A direct comparison was accomplished among the signals of the assembled circuitry and the signals of the Hall sensor.

With the results on Figs. (9 and 10) we can conclude that the technique here discussed can be used as a redundant element of Hall sensor, increasing the equipment security. According to the experimentally obtained speed range, it is inside of the speed range of continuous flow blood pumps.

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