Real Time Design and Implementation of Brushless DC Motor Drive based Continuous Positive Airway Pressure (CPAP) based Respirator System for Patients with Chronic Obstructive Pulmonary Diseases (COPD)

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ABSTRACT
This paper aims at designing a cost-effective, portable and easy-to-use brushless DC (BLDC) motor driven continuous positive airway pressure (CPAP) based respirator for patients with acute breathing trouble. The proposed system is intended to facilitate continuous monitoring of patient's condition with positive airway support provided by a brushless DC (BLDC) motor driven respirator blower fan by measuring Respiration Rate (RR). To measure the respiration rate, a pair of capacitive type respiration rate sensors are mounted below Right Nostril (RN) and Left Nostril (LN), in such a way that the nasal airflow during inspiration and expiration impinge on the sensor diaphragms directly. Due to irregularities in nasal airflow in some respiratory diseases, the respiration rate (RR) varies from the normal rate (12-20). Thus, a supporting airflow regulatory system has been designed to reduce abnormalities in respiration rate (RR). In this case a low cost sensorless commutated BLDC drive is implemented with a three phase inverter and microcontroller by using feedback of rotor rpm. A suitable cost effective algorithm has also been developed to generate an appropriate six transistor switching sequence to commute the BLDC motor according to the RR of the subject. The characteristics of the implemented drive give satisfactory outputs over a wide range of controlled speed variation from 200 to 2440 rpm which requires a match with the patient's breathing demand. The effectiveness of the designed system is populated by the real time experimental results.

Keywords
Positive Airway Respirator, Blower Fan, Brushless DC Motor, Respiration Rate, Chronic Obstructive Pulmonary Diseases.

1. INTRODUCTION
Chronic obstructive pulmonary disease (COPD) has become the fourth leading reason of death across the world which caused around 2.7 million deaths in 2000. By the end of 2020, COPD is expected to come up as a third most common cause of death [1]. There are two types of COPD diseases namely emphysema and chronic bronchitis. Emphysema (caused by continued smoking) and chronic bronchitis (caused by the exposure to indoor and outdoor air pollutants) both of them are major reasons of breathlessness. These diseases obstruct the windpipe to the lung and which may in turn choke the respiratory system if it is not taken care properly. In the earlier days, polysomnography was the method followed in order to diagnose the sleep related disorders but it involved time consuming procedure, caused some amount of discomfort as a number of electrodes are attached to the patient's body and was costly as well [2]. This led to the further developments of devices such as respiratory polygraphy which may be another option to detect sleep disorders. Both of these detection techniques are complex and required to be carried out in the presence of qualified healthcare staff. Because of these severe drawbacks, new trends in this field of healthcare came forward namely continuous positive airway pressure (CPAP) machine which was invented by Colin Sullivan in June 1980 and he applied this therapy initially for five patients with severe obstructive sleep apnea syndrome [3]. In this system, air is pumped under pressure into the airway of the lung so as to keep the windpipe to the lung open at the time of sleeping. This system comprises of a small machine with a hose that is placed at the side of the patient's bed.

This paper begins with introduction, given in Section I. In Section II, we have described the condenser type capacitive sensor. Section III puts forward the description of the drive system for three phase BLDC motor. After this, section IV throws light on the real time implemented hardware. Followed by, Section V which establishes the results describing the response of the sensor and aptness of the blower. Section VI concludes the work with the essence of outcome of this proposed scheme.

2. OVERVIEW OF THE PROPOSED SYSTEM
The CPAP machine proposed here provides a fixed airway pressure to the subject under study by eliminating the need of conventional cylinders of life-support gases. Moreover, the portability and robustness of the designed machine makes it a quick option to be considered into the field of healthcare [4]. While taking the subject under study to hospital, the proposed device can be considered as a very effective means of providing continuous air support.

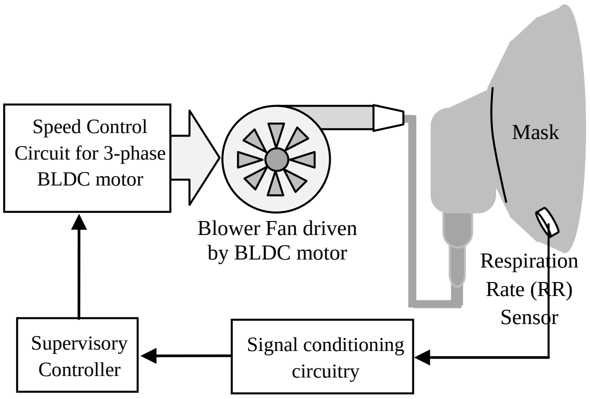

Fig 1: Schematic diagram of Positive Airway Respirator using BLDC driven blower fan

In order to provide a variable positive airway pressure and to overcome the drawbacks of the existing systems, this system is intended to serve for the patients with COPD. An idea of the proposed system is illustrated in Fig. 1.

3. DESCRIPTION OF THE PROPOSED SYSTEM

3.1 Sensor

A pair of electret (a dielectric material having a quasi-permanent electric charge or dipole polarization) condenser type capacitive sensors of exactly same make is mounted very close to the human nostrils on the inner side of a respiratory mask. The arrangement can be well understood from a side view of the same as depicted in Fig. 1. The necessity of two sensors comes into play because of the fact that human nostrils alternate the breathing once in a day and varies from person to person. The respiration is sensed by the diaphragm inside the sensor followed by a change in the capacitance and as a result, the voltage across it gives the intensity of the exhaled pressure. A cross-sectional view of a traditional electret condenser type sensor is shown in Fig. 2 which illustrates that the JFET fabricated inside the housing typically acts as a microphone preamplifier.

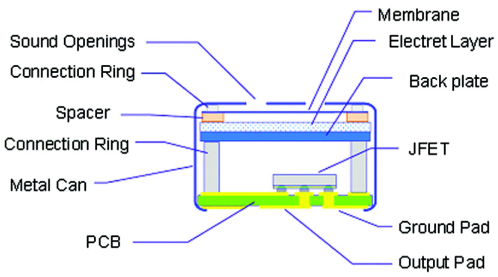

Fig 1: A cross-sectional view of the RR sensor [5]

3.2 Signal Conditioning Circuitry

The signal generated by the RR sensor is of the order of mV and contains noise generated due to the ambience [6]. The

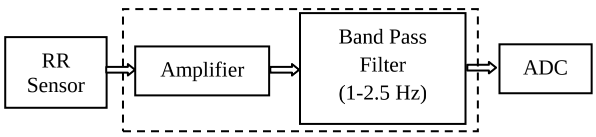

Fig 3: Block diagram of the signal conditioning circuitry

Analog-to-Digital Converter (ADC) requires the analog signal entering at its input to be of magnitude of the order of Volts (Range: 0-5 V). Thus the requirement of signal conditioning is well understood. The block diagrammatic representation of the signal conditioning circuitry is shown in Fig. 3. The Amplifier and the Filter, together condition the RR signal.

3.3 Supervisory Controller

The operational methodology of the entire system is governed by an algorithm followed by the Supervisory controller. As the name suggests, it is simply a microcontroller having a pre-written program (as per the algorithm) in it. A detailed discussion of the algorithm is presented in Section IV.

3.4 Speed Control Circuitry for three phase BLDC motor

This section puts forward the idea of controlled rotation in a three phase BLDC motor using an external commutation circuit. The drive power is given to motor windings via a three phase inverter consisting of six Bipolar Junction Transistor (BJT) switches [7]. The operation of the foresaid switches inside the driver follow a particular sequence which depends on the rotor position as well as the rotor speed, shown by Table I. The switching sequence is provided to the driver by a microcontroller, which takes a continuous feedback of the rotor position and the rotor speed [8]. The rotor position is estimated by zero crossing the back EMFs [9] generated in the three windings of the BLDC motor [10]. The rotor speed is measured and fed back to the microcontroller in order to verify the achievement of the desired rotational speed. The block diagram of the speed control circuit is shown in Fig.3.

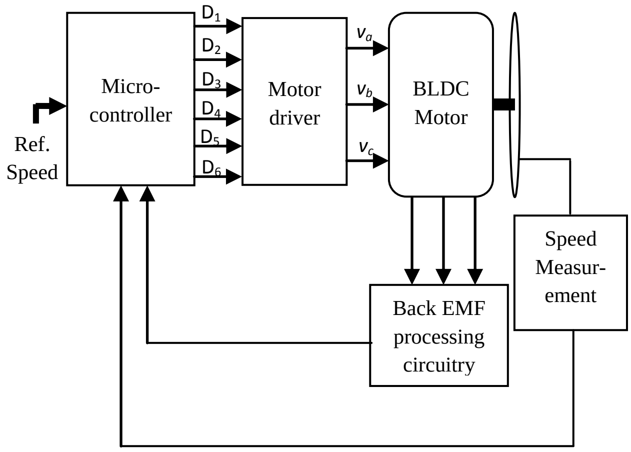

Fig 4: Block diagram of speed control circuit

The reference speed is generated as the motive to supply correctional volume of air to the subject under observation. This value is generated by the microcontroller and directly utilized for the speed control algorithm. On the other hand, back EMFs generated in the three windings are fed to the microcontroller, and the rotor position is roughly estimated which in turn determines the exact commutation sequence. The microcontroller generates six signals i.e., D_1, D_2, D_3, D_4, D_5 and D_6, which are supplied to the base terminals of the transistors used. The driver gives three phase supply to the motor i.e., v_a, v_b and v_c.

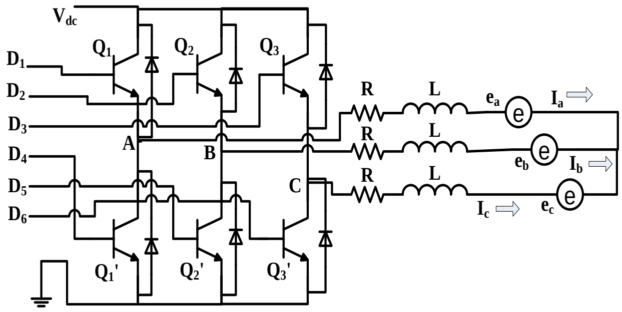

Fig 4: Six transistors based three phase inverter

The three phase six switch motor drive with the commutation lines by using transistor bases is shown in Fig.4. The voltage across the RR sensor is quantized by an ADC fabricated within the microcontroller.

3.5 Blower Fan driven by BLDC motor with Mask

The BLDC motor is coaxially coupled to a blower assembly of almost same size to that of motor [11]. The commonly available medical mask is used in the developed setup that houses the RR sensors optimally close to the nostrils of the subject under study [12]. The sensors are mounted in such a fashion that they can be removed while sterilizing the mask for re-using of the same mask. One end of a transparent flexible pipe supplying the correctional volume of air is attached to the mask and the other end is connected to the exhaust of the blower assembly.

4. ALGORITHM FOLLOWED BY THE SUPERVISORY CONTROLLER

In this section, the algorithm responsible for supplying correctional volume of air to the mask is described.

As soon as the device is powered ON, the blower starts to rotate at a predefined speed, which is in proportion to RR of a healthy subject. At first, the RR sensed is measured with the standard/normal RR (of a healthy subject) [13]. If the measured RR comes to be normal, then the previous supply volume of air is maintained. If the RR is found to be abnormal, then the necessary correctional volume of air is generated by optimally altering the BLDC motor speed. This whole idea is presented by a flowchart shown in Fig. 5. The Supervisory controller is programmed with the proposed algorithm as mentioned in subsection 3 of Section 3.

5. REAL TIME IMPLEMENTATION OF BLOWER DRIVEN BY BLDC MOTOR

The implemented hardware is built using six pairs of BC548 transistors with IN4148 diodes in anti-parallel connection operated by an 8-bit Atmel microcontroller ATmega328p-pu.

An appropriate algorithm considering a pre-defined transistor switching sequence is written to the microcontroller present in the said commutation system. The rotor speed is measured and fed back to the drive system by a photo diode pair.

The voltage across the RR [11] sensor is quantized by an ADC fabricated within the microcontroller [12]. This quantized value is made use of by the algorithm to determine the breathing pattern and accordingly a correction signal is generated. The designed real time hardware consisting of BLDC motor run blower fan operated by the 3 phase motor

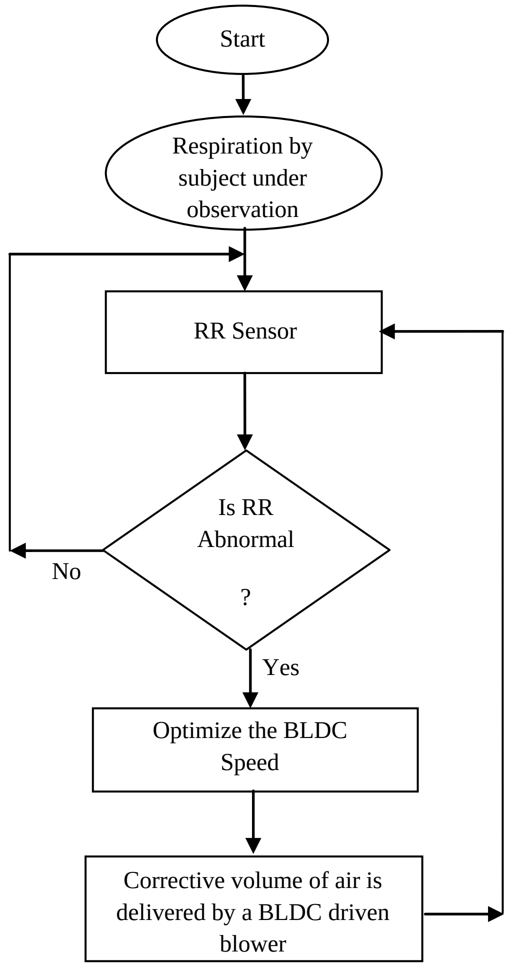

Fig 5: Flowchart of the proposed algorithm of operation for the supervisory controller

driver is shown in Fig.5. The blower is made operational at a desired speed till abnormality in breathing persists. The proposed algorithm of operation for the PAR [14] system is described by a flow chart as shown in Fig.6.

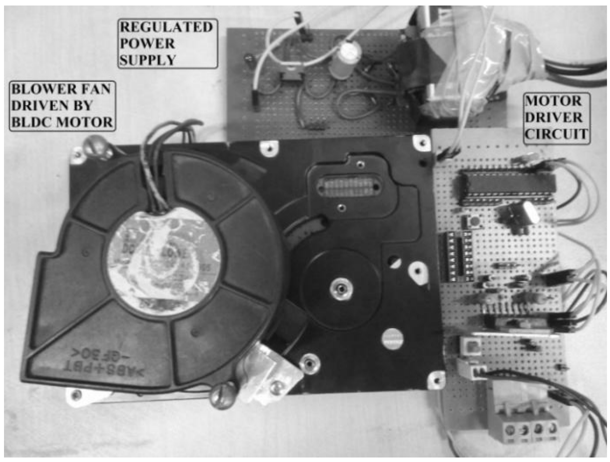

Fig 6: Real time implemented hardware

Moreover, the system is calibrated to cancel effects due to audio frequency noise and dc biasing. The signal conditioning circuit is chosen in such a fashion that low frequency signals will be eliminated.

Table 1. Specifications of the employed BLDC motor

Motor Parameters	Values
Rated DC voltage	12 V
Rated Current	110 mA
Stator Resistance	1.7 Ω
Torque Constant	14.5×10^{-3} Nm
Rated Speed	5400 rpm
Life of working	50,000 hours

The parameters of three phase BLDC motor used in our work are displayed in Table 1. It can be inferred by taking a look at the parameters that the proposed system can be a completely portable system. We have designed a regulated power supply of 12 volts as a power source from 230 V AC main. In order to make the system portable, a LiPo battery of same output can be made use of. The specifications of the used capacitive sensor are listed in Table 2. .

Table 2. Specifications of the RR sensor

Sensor Specifications	Values
Sensor type	Electret Condenser
Rated DC Voltage	10 V
Rated Current	0.5 mA
Frequency (F)	50 - 60,000 Hz
Sensitivity (F =1 kHz)	-42 ± 2 dB
Signal to Noise Ratio	60 dB

6. RESULTS

This section puts forward the real time experimental results

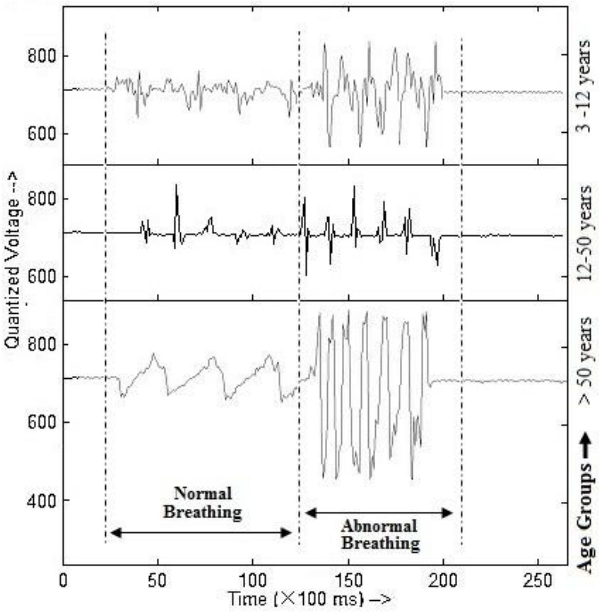

Fig 7: Response of the RR Sensor

obtained from the designed positive airway pressure respirator. The output of the RR sensor being analog in nature is taken via a 10 bit analog to digital converter (ADC) and is represented as quantized digital values ranging from 0 to 1023 (2^{10-1}) in Fig.7 along with normal and abnormal breathing regions for various groups. The system so developed was tested on three different age groups for better accuracy. The breathing pattern so obtained from the RR sensor is fed to the supervisory controller which obtains respiration rate to determine the correct rpm for the BLDC blower, shown in Fig.8. The exactness of the achieved rpm for the BLDC blower fan is cross checked via a rotor rpm feedback assembly. Three different kinds of response indicate the aptness in selecting the sensor. The various peaks indicate the minimum and maximum quantization levels for breathing. The peaks are a direct indication of the pressure of inhaled and exhaled air. Also, the air supplied by the blower is well within inhalable limits.

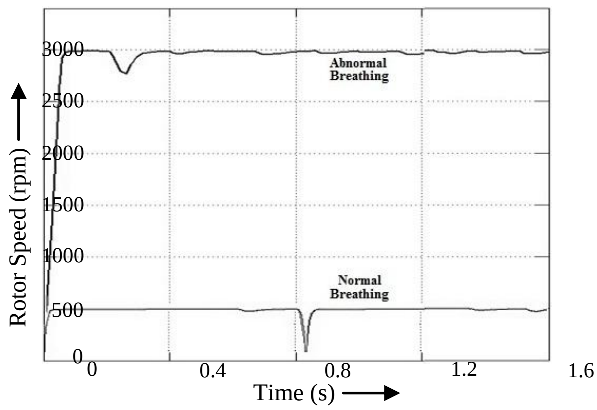

Fig 8: Variation of motor speed with breathing pattern

7. CONCLUSION

In this work, a pair of dispensable capacitive microphones has been considered as a sensor. The novelty of this system lies with the use of dispensable articles for implementation in real time. As we got the BLDC motor from scrap PC hard drive and sensors from thrown away ear phones. Thus, the overall system costs around INR 1000 including the microcontroller along with the associated circuitry. Moreover, the choice of sensorless drive of BLDC motor makes the system power efficient than conventional brushed DC motors. The main challenges are to modulate the speed of the BLDC motor more effectively and precisely position the sensors to obtain better result, though so far proportional modulation of motor speed has been achieved.

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