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# 'MASTER'

## In Power Engineering

Title:

# Control of a BLDC Motor in a Mechanical Ventilator

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# *Dedication*

*At the end of this long path, I, ESSELAMI Amina, would like first to dedicate this work to my dear grandmother who left us a few days before sharing the pride of this achievement, then to my family especially my beloved parents for their unwavering support and encouragement throughout my whole academic journey. Their belief has been and will be a constant source of motivation that we are grateful for .*

*I also dedicate this project to my friends for all of the precious moments we had together and our teachers whose contributions have helped for achieving our academic goals.*

*Thank you for your prayers, inspiration, and support.*

*Amina.*

# *Dedication*

*I, Zahia Touati , have a great pleasure to dedicate this work to my beloved mom, who always supported me with her prayers, and my awesome dad, who made sacrifices for my success.*

*To my dear brothers and sisters Mohammed , Solaimane , Namira , Saloua , Zahra , & AbdErrahmane.*

*To my little angels Rassil , Razen , Djouri & Sidra .*

*To my brothers-in-law Khaled & Abdou .*

*to all my friends specially Amina , Selma , Kamar , Kahina ,Chahinez , Silia , Anis , Hocine , Joseph , Souhaib , Hamza & Oussama . Thank you all for sharing with me this amazing period of my life.*

*Zahia.*

# *Acknowledgment*

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*Their support and encouragement have been invaluable.*

# Abstract


The evolution of electronics and electric machines has played a pivotal role in advancing healthcare and facilitating the development of cutting-edge medical devices. This project explores the integration of Brushless DC (BLDC) motors into mechanical ventilation equipment, along with one of its control methods, to achieve the required performance.

This report provides an overview of essential aspects of mechanical ventilation systems, including their operational principles and the mathematical modeling of Brushless DC motors. It specifically emphasizes the utilization of a variable-speed BLDC motor to drive a blower, allowing for the generation of adjustable air pressure levels through the use of a Pulse Width Modulation (PWM) signal to control the supplied voltage. Consequently, this directly influences the motor's speed, which is proportionate to the output pressure. Additionally, a PID controller is employed to attain the optimum required pressure level while minimizing deviations.

In this research work, various tools and software are employed, including a designated motor driver and air pressure or flow sensors. These components are utilized to establish a mathematical relationship between input power and output pressure, enabling the implementation of an effective control process for this application

# List of abbreviations

**A/C :** Assisted Controlled.

**AC :** Alternating Current.

**BLDCM :** Brushless Direct Current Motor.

**DC :** Direct Current.

**ECMs** : Electronically Commutated Motors.

**FOC :** Field Oriented Control.

**I2C :** Inter Integrated Circuits.

**IC :** Integrated Circuits.

**ICU :** Intensive Care Unit.

**LabVIEW :** Laboratory Virtual Instrument Engineering Workbench

**MVS :** Mechanical Ventilation System.

**PCV :** Pressure Controlled Ventilation.

**PEEP :** Positive End Expiratory Pressure.

**PID :** Proportional Integrator Derivative.

**PIP :** Peak Inspiratory Pressure.

**VCV :** Volume Controlled Ventilation.

**PSV :** Pressure Support Ventilation.

**PWM :** Pulse Width Modulation.

**SCL :** Serial Clock.

**SDA :** Serial Data.

**SIMV :** Synchronized Intermittent Mandatory Ventilation.

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# General introduction

The integration of BLDC blowers into medical machines, particularly medical air compressors, represents a significant advancement in respiratory care. These blowers offer precise and efficient airflow regulation, contribute to the development of smaller and lighter equipment, and enhance patient well-being and safety. Furthermore, their durability and reduced maintenance requirements bolster the reliability and availability of mechanical ventilation systems, ultimately yielding positive outcomes for both patients and healthcare providers.

This project aims to implement a foundational system to provide a comprehensive understanding of mechanical ventilation support and the methodologies employed in this process. Specifically, it sheds light on the utilization of BLDC blowers in mechanical ventilators as an alternative to traditional actuators, focusing on the control of these blower-based ventilators operating in one of their numerous modes, the PCV mode.

The first chapter of this work comprises four main sections that introduce essential aspects of mechanical ventilation, beginning with its objectives. To facilitate a better understanding of this topic, the principles of breathing are explained, highlighting the distinction between normal and mechanically assisted breathing achieved through various types of artificial respirators, i.e., mechanical ventilators. Managing these devices is a critical process, as it necessitates precise parameter settings and qualified practitioners to achieve optimal ventilation support, given the different modes available, depending on the patient's condition.

The second chapter of this report provides an overview of BLDC motors, covering their construction and working principles, which are based on sensored commutation. Subsequent sections delve into torque and speed characteristics, exploring their variability based on the load/application in which the BLDC motor is utilized, as well as the control techniques employed to attain desired performance levels. Additionally, the mathematical model of this motor is considered, as it plays a crucial role in analyzing, optimizing, and evaluating its performance.

The third chapter demonstrates the essential components of the sub-systems of the BLDC blower-based ventilator (electric and pneumatic) and their function in providing ventilation support during breathing cycles. It also briefly describes the PCV ventilation mode to distinguish the different parameter settings required for optimal operation.

The final chapter provides a detailed description of the implemented ventilation system, listing all the hardware and software materials used, and explaining the system's operation. In this section, the results obtained for output pressure regulation using a PWM signal are also presented. The document concludes with a comprehensive summary of the project and outlines potential avenues for future research.

# Chapter I

## *Mechanical Ventilation System*

## (MVS)

# Introduction

To elucidate the principles of mechanical ventilation, it is essential to introduce the physiology of normal (spontaneous) breathing. Spontaneous breathing is defined as the movement of air into the lungs resulting from the work performed by an individual's respiratory muscles during inhalation and the passive exhalation facilitated by lung elasticity. In contrast, positive pressure ventilation involves the introduction of air into the lungs by applying positive pressure along the airways, reaching the alveoli through respiratory tubes in the case of invasive ventilation, or using a non-invasive mask [1].

Given the diverse health conditions of patients, various ventilation modes exist, each with its own set of regulatory procedures and numerous parameters to oversee. Consequently, one of the most critical aspects of the ventilation process is monitoring the interaction between the patient and the ventilator. This ensures that patients receive the appropriate amount of breathable air with an optimal support method [2].

Therefore, this artificial breathing process is achieved through the use of an artificial respiration machine, commonly known as a mechanical ventilator. This multifunctional device assists in a patient's breathing cycles by providing the necessary oxygenated air and monitoring vital signs.

**Fig 1.1** A Modern Mechanical Ventilator ( artificial respirator).

# 1. 1 Aim of mechanical ventilation

Mechanical ventilation is of great importance especially for patients of intensive care unit (ICU) for various reasons:

- To deliver an adequate concentration of oxygen into the lungs.
- To assist carbon dioxide ($CO_2$) optimum elimination.
- To decrease the amount of energy required for breathing so that the patient's body concentrates on fighting infection or recovering.
- To ensure full breathing for patients who can not breathe for several factors including : Nervous system issues ( brain or spinal cord problems), pulmonary insufficiency due to respiratory muscles atrophy or weakness, or undergoing general anesthesia ( or unconsciousness) [3].

# 1. 2 Spontaneous Breathing VS Ventilation Support

Spontaneous breathing refers to the normal, involuntary breathing performed by individuals without any external support. It is a rhythmic process characterized by repeated cycles of inhalation and exhalation, serving to meet the body's oxygenation requirements. Each breath comprises one cycle of inspiration followed by expiration [1].

This process is the result of contractions in respiratory muscles, namely the diaphragm and intercostal muscles, which expand the chest wall. This expansion increases lung volume, allowing air to flow through the trachea and reach the alveoli.

The entire process is under the control of the brain, which sends signals through the ascending respiratory pathway (the neural pathway responsible for breathing). These signals regulate vital signs in response to the body's activities.

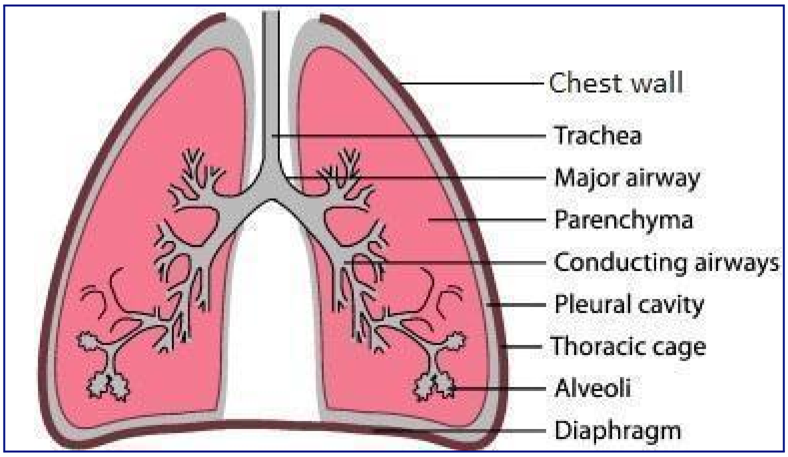



**Fig 1.2** Basic anatomical elements of the lung.

Mechanical ventilation, on the other hand, is a medical procedure designed to ensure optimal breathing support in cases of unconsciousness (resulting from anesthesia or health issues) or when any component of the respiratory system malfunctions (such as breathing muscles, lung injury, or neural pathway deterioration, among others).

Ventilation-assisted breaths are delivered through an artificial respirator machine that generates relatively high pressure directed to the lungs. During this process, the machine manipulates and adjusts various breathing parameters according to the patient's specific needs.

Table 1.1 illustrates the primary differences between these two methods of respiration.

| **Spontaneous breathing** | **Positive pressure mechanical ventilation** |
| --- | --- |
| Inspiratory muscles contract<br>⇓<br>Intrathoracic volume ↗<br>⇓<br>Intrathoracic pressure ↘<br>⇓<br>Pleural pressure ↘<br>⇓<br>Transpulmonary pressure ↗<br>⇓<br>Lung volume ↗<br>⇓<br>Alveolar pressure ↘<br>⇓<br>**Air flows into lungs until alveolar pressure equals atmospheric pressure** | Ventilator increases proximal airway pressure<br>⇓<br>Air flows into lungs<br>⇓<br>Alveolar pressure ↗<br>⇓<br>Transpulmonary pressure ↗<br>⇓[2]<br>Lung volume ↗ |

**Table 1.1** Events sequence during inspiration for spontaneous breathing and positive pressure ventilation.

## 1.3 Basic parameters and operating modes of mechanical ventilation

### 1.3.1 Lungs characteristics:

Mechanical ventilation operation is strictly related to the patient state. Lungs injury disturbs their characteristics; hence it noticeably affects ventilation parameters adjustment. There exist several lung properties of great importance when ventilation is processing including:

- **Airway Resistance** is defined as the change in transpulmonary pressure needed to produce a unit flow of gas through the airways of the lung [4].

- **Lung Compliance (C)** is a measure of the lung expandability or its ability to stretch and distend. It can be defined mathematically as the change in volume per change in the pressure :

$$C = \Delta V/\Delta P \tag{1.1}$$

### 1.3.2 Ventilation parameters:

For optimal ventilation support, it is decisive to select the right mode of mechanical ventilation according to the patient's needs. Before going through the details of this concept, a set of ventilation parameters that each practitioner must be familiar with, are identified in the following section [5].

- **Tidal volume (Vt in mL)** is a clinical parameter that allows for proper ventilation**,** it is defined as the amount of air inspired and expired during one cycle of breathing. This vital input helps keep oxygen and carbon dioxide levels stable in the blood.[5]
- **Minute volume (MV in mL)** is the quantity of gas exhaled from the lungs per minute; tidal volume multiplied by respiration rate.

$$MV = RR \times V_t \tag{1.2}$$

- **Flow Rate** can be defined as the maximum speed at which the tidal volume is delivered to the patient and it ranges between 60 L/min and 120 L/min.

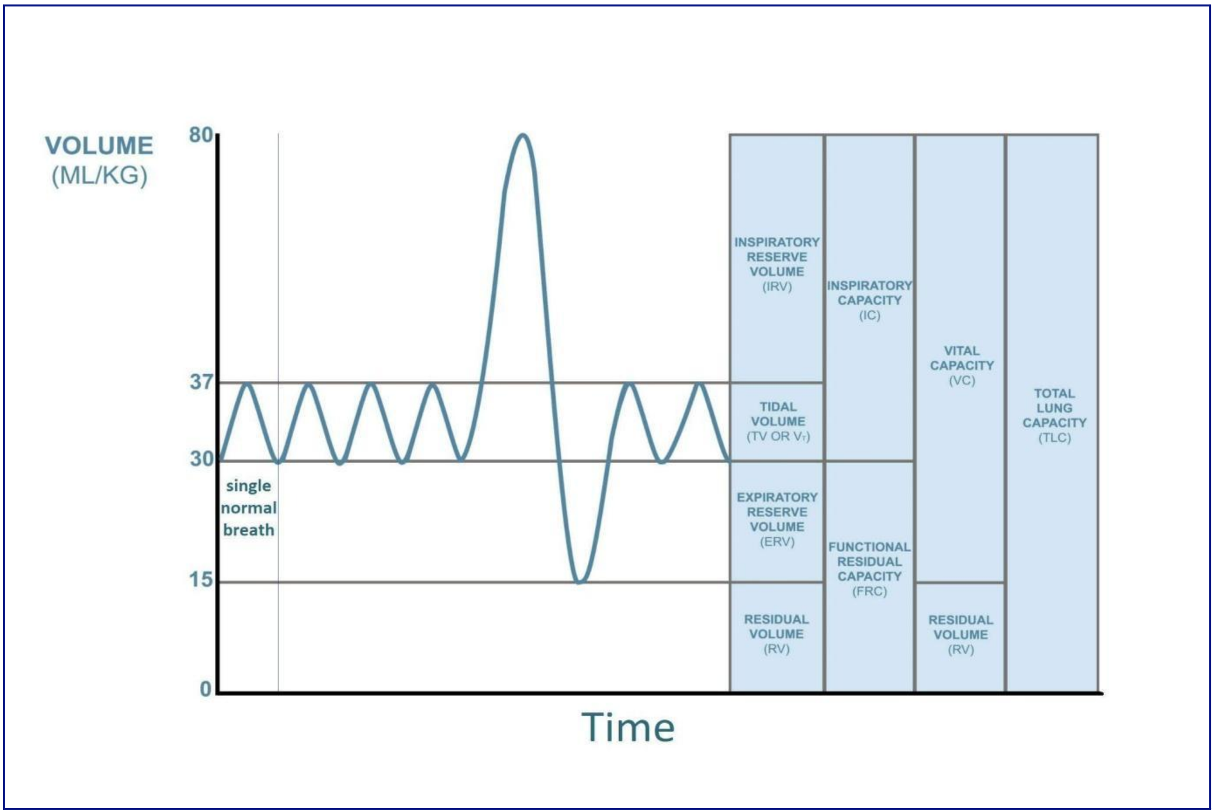



**Fig 1.3** Different lung volumes graph

- **Positive End Expiratory Pressure (PEEP in cm$H_2O$)** is an important parameter in mechanical ventilation therapy. It is a small positive pressure (slightly greater than the atmospheric pressure) applied to the lungs (alveolar pressure) at the end of each breath (expiration). For mechanically ventilated patients, PEEP acts against passive evacuation of the lung and prevents air sacs collapse (alveoli).

- **Peak Inspiratory Pressure (PIP in cm$H_2O$)** is the pressure delivered by the ventilator to overcome both airway resistance and alveolar resistance in order to obtain the tidal volume set earlier. It can be given by the following formula [6]:

$$\text{PIP} = (\text{airway resistance} \times \text{Flow}) + (\text{lung elastance} \times \text{Tidal volume}) + \text{PEEP} \quad (1.3)$$

- **Plateau pressure ($P_{plat}$ in cm$H_2O$)** is the amount of pressure required to keep the lungs inflated in the absence of airflow (basically measured at the end of inspiration), in other words it is the pressure that is essentially left over in the lung after the tidal volume has been delivered [7].

$$\text{Plateau pressure} = \text{Tidal Volume/Compliance} \quad (1.4)$$

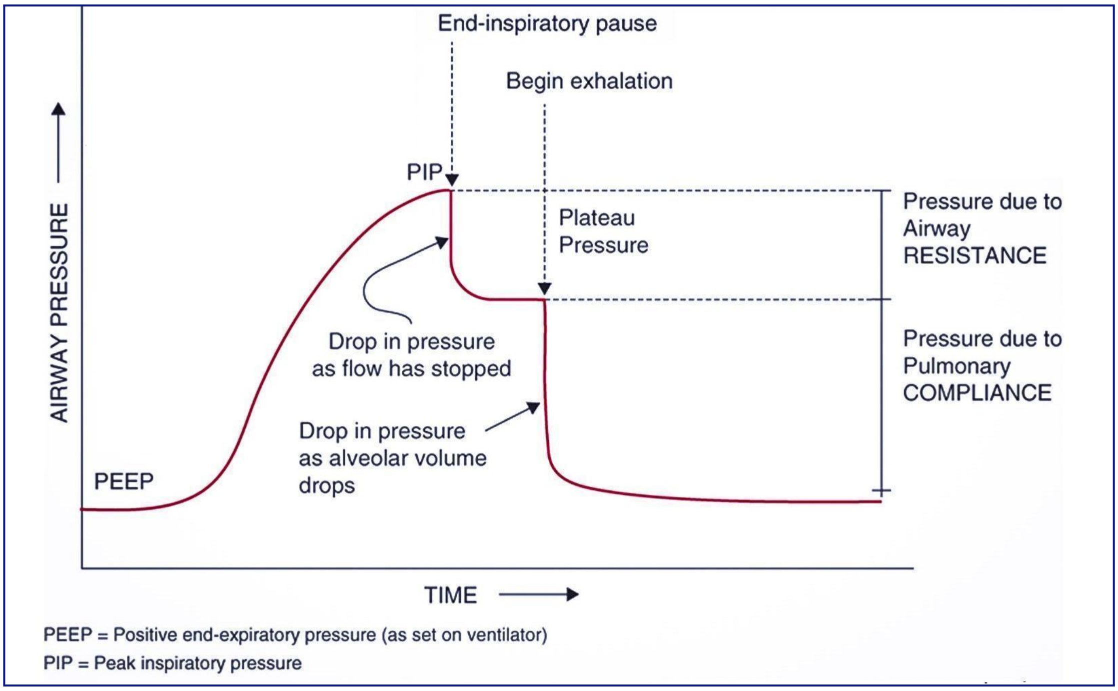



**Fig 1.4** Different pressure levels during a single breath.

- **Respiratory rate / frequency :** Determines how many breaths are taken within one minute, they can be mandatory, assisted/supported, or spontaneous. If the RR=12 breaths/min for example, then the ventilator delivers a breath each 5 seconds. At rest, the respiratory rate for an adult is about 15 breaths/min.

- **I : E ratio** is the time set for one cycle of inhalation compared to exhalation time and commonly ranges from ⅕ to ⅓ ( exhalation time might be 5 times longer than inhalation time).

- **$FiO_2$** is the fractional concentration of oxygen in the delivered gas mixture, and it ranges between 21% and 100% according to the body needs.

### 1.3.3 Operating modes of ventilation:

As mentioned previously, there are numerous modes of ventilation to help patient breathing. The most common modes of MV include:

- **Assisted/Controlled, Volume Cycled Ventilation (A/C, VCV)**: The inspiratory phase continues until a preset tidal volume has been delivered to the patient, then passive expiration is permitted.

- **Assisted/Controlled, Pressure Controlled/time cycled Ventilation (A/C, PCV)**: The ventilator delivers oxygenated air at predetermined pressure for a preset period of time followed by passive exhalation.
- **Synchronized Intermittent Mandatory Ventilation (SIMV) :** Mechanical breaths are delivered at a predefined rate if patient effort is insufficient or absent, or at the start of a spontaneous patient breath (if the trigger threshold is reached). Only baseline pressure (PEEP) allows patients to take spontaneous breaths in between mechanically assisted breaths. [8]

- **Pressure Support Ventilation (PSV) :**Pressure Support Ventilation (PSV) is a mode of mechanical ventilation that provides inspiratory pressure assistance to partially or fully support spontaneous breaths and reduce the work of breathing12. PSV can be used alone or in conjunction with Synchronous Intermittent Mandatory Ventilation (SIMV).[8]

## 1.4 Mechanical Ventilator types

### 1.4.1 Types of Electronically-controlled Ventilators

For ICU patients, medical complications and therapy stages are of different degrees of urgency. So, in order to ensure optimum ventilation support for the requiring person, it is recommended to utilize high efficiency and precision instruments that can assist different vital signs of the patient. This can be achieved using electronically controlled ventilators that can be divided into two major systems:

- **Pneumatic,** which is responsible for the air-oxygen mixture and delivery.
- **Electronic,** which is responsible for the control and operation of the whole machine to meet the required specifications (more details are provided in the third chapter).

#### 1.4.1.1 Electro-pneumatic ventilator

The pneumatic system of this type of ventilators contains a self inflating (Ambu bag) to push air-oxygen mixture into the lung airways. This bag is squeezed using an actuator that is controlled by an electronic circuit to maintain the required breathing rhythm. This type of ventilator is generally used for patients undergoing general anesthesia, since it is commonly provided with additional gas tanks ($CO_2$, N2, anesthetic gas…etc) to keep the patient under a stable level of anesthesia.

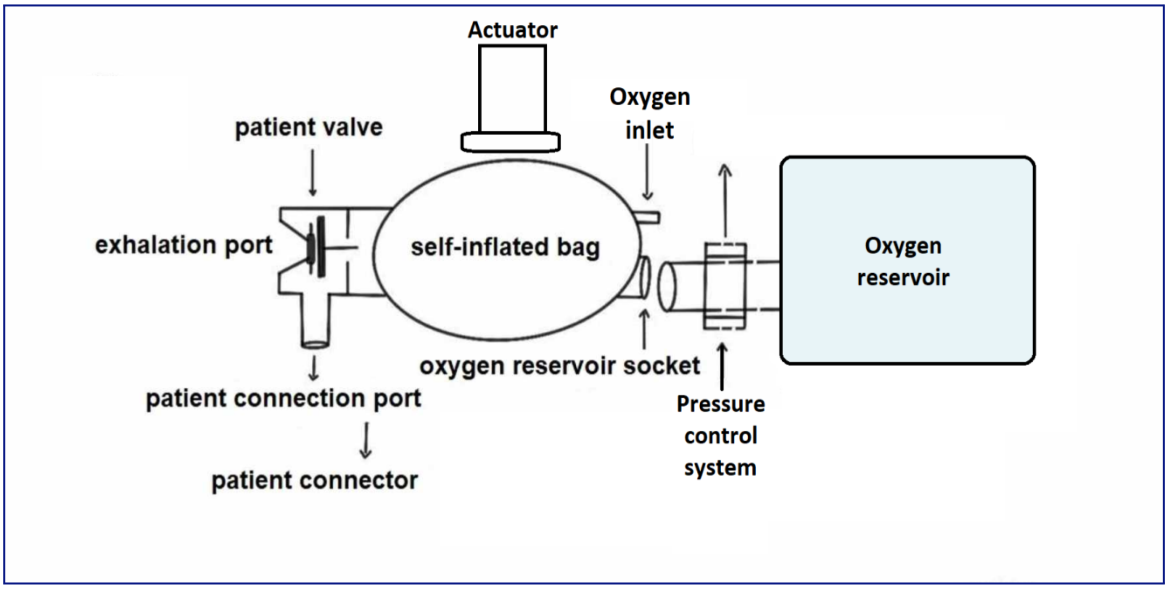



**Fig 1. 5** Electro-pneumatic ventilator basic diagram.

### 1.4.1.2 Blower-based ventilator

Instead of the self inflating bag, this type of ventilator contains a motor provided with a rotating impeller to generate the required positive air pressure/volume. The amount of pressure/flow rate delivered by the blower can be rapidly adjusted by adjusting the motor speed using one of its numerous control techniques. The blower based ventilator is mostly used for patients in coma situations or with breathing failure to compensate for their breathing incapability at the healthcare centers or even for domestic healthcare cases.

This project is considered with the operation of the blower-based ventilator, especially the BLDC blower closed loop control under the PCV mode to reach a predetermined pressure level.

## Conclusion

Each of the previously mentioned modes and ventilator type is proper for specific ICU patients at different stages of therapy (anesthesia, intubation, recovering, and weaning). This project focuses mainly on pressure cycled ventilation mode and on the operation and control of the blower-based ventilator in order to clarify the basic concept of this process.

# Chapter II

## *Overview on the BLDC Motor*

# Introduction :

A brushless DC motor (BLDC motor) is a type of motor that operates using direct current (DC) and incorporates permanent magnets. Unlike brushed DC motors, which rely on brushes and a commutator for current control, BLDC motors employ electronic commutation to regulate the current in the stator windings and produce motion. These motors are also known as synchronous DC motors or electronically commutated motors (ECMs).

The BLDC motor consists of two primary components: a stator, which usually consists of multiple coil sets, and a rotor, which is the rotating part of the motor and houses the permanent magnets.

There are two types of BLDC motors: outer rotor BLDC motors and inner rotor BLDC motors. As the names suggest, the outer rotor BLDC motor has the rotor positioned on the outside of the stator, while the inner rotor BLDC motor has the rotor situated inside the stator. Outer rotor BLDC motors are commonly used in applications requiring high torque, whereas inner rotor BLDC motors are preferred for high-speed applications [10].

BLDC motors are available in three configurations: single-phase, two-phase, and three-phase. Among these, the three-phase BLDC motor is the most prevalent variant in use [11].

# 2.1 BLDC Motor construction

The construction of a BLDC motor is very similar to that of an induction motor; it has a stator and rotor in addition to hall sensors to detect the position of the rotor.

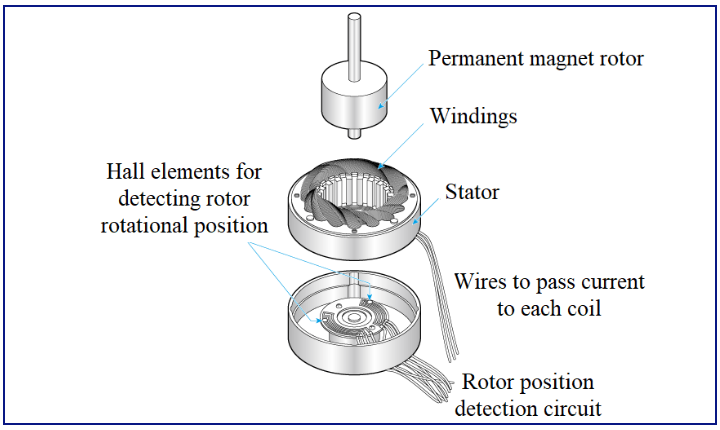



**Fig 2.1** BLDC motor construction .

### 2.1.1 Stator

The stator of a BLDC motor is designed in a similar manner to an induction motor. It is the stationary component of the motor and consists of multiple sets of coils. Each set contains several individual coils that are wound around a core. These coils generate magnetic fields that rotate in space, resulting in the generation of torque and movement. The windings can be arranged in either a star or a delta configuration. However, the majority of BLDC motors feature a three-phase stator that is connected in a star configuration [12].

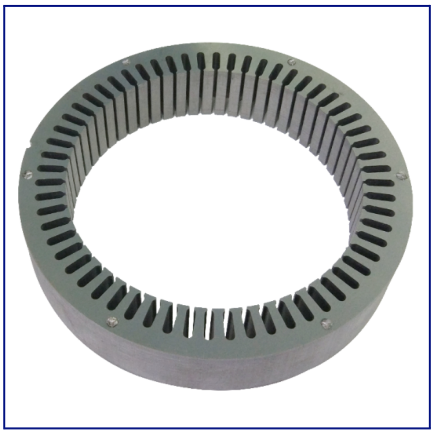


**Fig 2.2 BLDC** motor stator configuration

### 2.1.2 Rotor

The rotor of a BLDC motor is the component that rotates and is equipped with permanent magnets. Unlike a conventional DC motor that uses brushes and a commutator to switch the current in the windings, a BLDC motor utilizes electronic commutation to control the current flow in the stator windings [13].

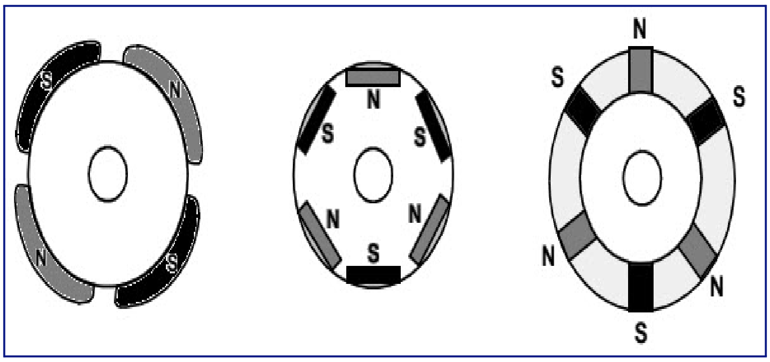



**Fig 2.3 BLDC** motor stator configuration

### 2.1.3 Hall sensors

Since there are no brushes in BLDC motor, hall sensors (position sensors) are used to detect the rotor position and send feedback to the electronic controller to decide which coil to energize; this method is called the direct position-detection method [14].

These sensors respond to the south (operate) and north (release) poles of an electromagnet's or permanent magnet's magnetic field. The Hall sensor will emit either a high-level signal or a low-level signal when the rotor magnetic pole passes close by, indicating whether the north magnetic pole or the south magnetic pole is passing by. The control system determines the position of the rotor and applies current to it.

Typically, there are two varieties of Hall sensors: the first type's waveforms have a 60-degree time lapse for each HALL phase, while the second type's waveform time lapse is 120 degrees [14].

Due to their low cost and simplicity of usage with the permanent magnets of the rotor, hall effect sensors are the most popular way to determine the position of the rotor in BLDC motors.

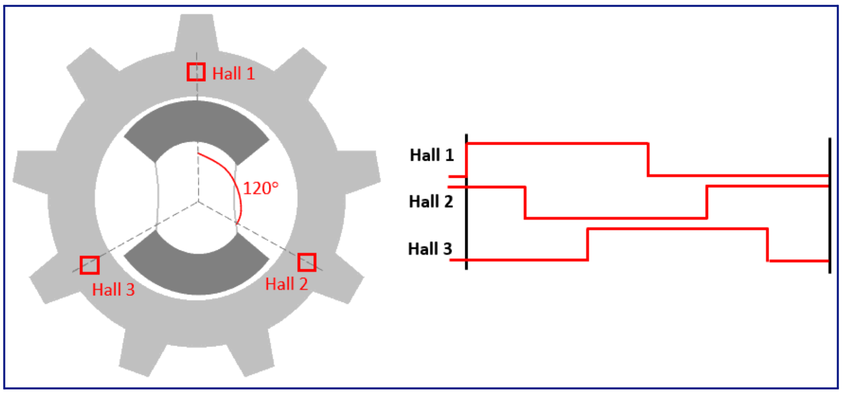



**Fig 2.4** Hall sensors signals for position detection

## 2.2 Working principle of BLDC Motor

As mentioned earlier, in a BLDC motor driven with direct current, the motor's operation is based on the interaction of an electric current and a magnetic field. The motor consists of a stator and a rotor. Permanent magnets in the rotor produce a magnetic field, whereas wire coils in the stator generate an electromagnetic field as current passes through them. The rotor rotates when electricity is applied to the stator windings because the magnetic field produced by the coils interacts with the rotor's magnetic field. An electronic commutation system controls the direction of the current flow in the stator windings. It switches the direction of the current flow when it is necessary to keep the rotor moving. To determine the position of the rotor and when to change the direction of the current flow, the electronic commutation system commonly uses a sensor or sensorless method. The sensorless system calculates the rotor's location using back-EMF (electromotive force) [15].

**Sensored commutation** involves the use of Hall Effect sensors or other position sensors mounted on the stator to detect the rotor position in a BLDC motor. The motor controller utilizes feedback from these sensors to determine the precise timing and sequence of current flow in the stator windings. This enables precise operation of the motor, particularly at low speeds and under various load conditions. Sensored commutation offers improved performance in these scenarios [16].

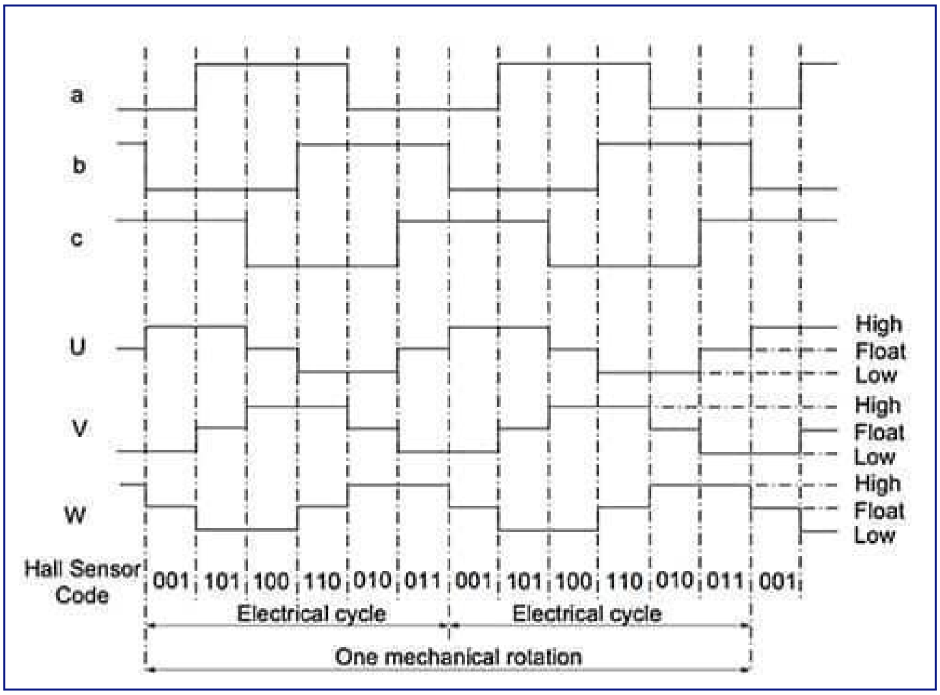



**Fig 2.5** Hall-effect sensor waveforms and winding status timing diagram for three-phase BLDC Motor.

On the other hand, **sensorless commutation** does not rely on external sensors to determine the rotor position. Instead, it estimates the rotor position based on the voltage generated by the motor's back-emf (electromotive force). When the rotor magnets pass by the stator windings, a voltage called back-emf is induced in them. By monitoring the waveform of the back-emf voltage, the motor controller can determine the rotor position and perform the necessary commutation. Sensorless commutation utilizes signal processing techniques and complex algorithms to implement this method. It simplifies the motor design by eliminating the need for position sensors, reducing costs, and improving reliability. However, sensorless control may be less precise at low speeds and in certain situations [16].

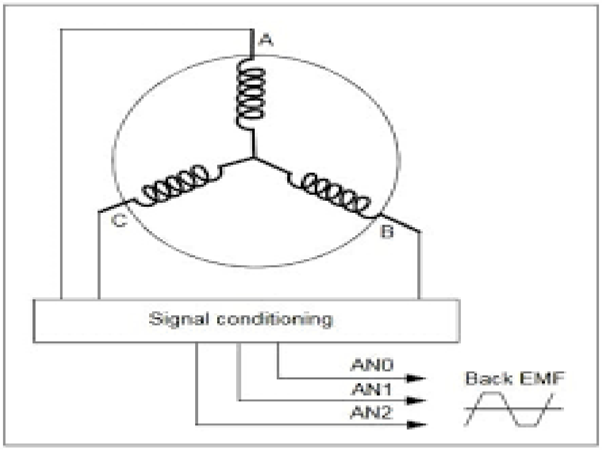



**Fig 2.6** Sensorless BLDC motor control using back EMF

## 2.3 Torque and Speed characteristics of BLDC Motor

A BLDC motor has two significant torque parameters: peak torque (TP) and rated torque (TR). The motor can handle continuous operation with a load up to its rated torque without exceeding its capabilities. Within the speed range up to the rated speed, the torque output of the BLDC motor remains constant. However, if the motor is operated beyond the rated speed, which can go up to 150% of the rated speed, the torque gradually decreases.

Certain applications require frequent starts, stops, and reversals of rotation with load demand torque levels higher than the rated torque. This increased torque demand occurs for a short duration, especially during motor startup and acceleration. It enables the motor to effectively overcome inertia and accelerate the load. It is crucial to consider these torque characteristics when selecting and designing BLDC motors for applications with varying load conditions, as well as to understand the limitations of torque output at different speeds. During the initial phase of motor operation, an additional amount of torque is necessary to overcome the inertia of both the load and the motor's rotor. This extra torque is required for effective acceleration, enabling the system to overcome resistance caused by the inertia of the load and the rotor. As long as the motor operates within the speed-torque curve, it can deliver higher torque, potentially reaching the peak torque value.

The speed-torque curve depicts the relationship between motor speed and the corresponding torque output. By operating within this curve, the motor can effectively provide higher torque levels, up to the maximum peak torque specified by its design [11].

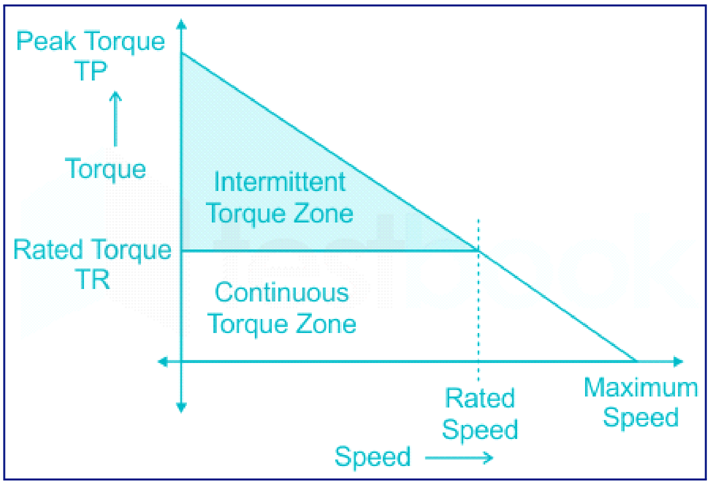



**Fig 2.7** Speed-Torque characteristics of BLDC Motor

# 2.4 BLDC Motor : mathematical modeling

Mathematical modeling of a Brushless DC (BLDC) motor entails creating a system of equations that depict the motor's electrical and mechanical characteristics. This model enables us to assess and anticipate the motor's performance across different operational scenarios.

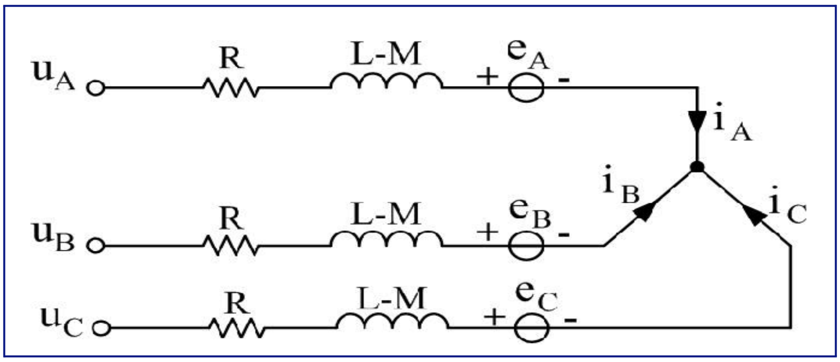



**Fig 2.8** Equivalent circuit of brushless dc motor.

The equations can be used to express the back electromotive force (EMF) produced during each phase of the motor:

$$\begin{aligned} Ua &= R\,ia + (L - M) + ea \\ Ub &= R\,ib + (L - M) + eb \\ Uc &= R\,ic + (L - M) + ec \end{aligned} \tag{2.1}$$

The matrix version of the BLDC motor's phase voltage equation can be written as:

$$\begin{bmatrix} UA \\ UB \\ UC \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} iA \\ iB \\ iC \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} iA \\ iB \\ Ic \end{bmatrix} + \begin{bmatrix} eA \\ eB \\ eC \end{bmatrix} \tag{2.2}$$

The phase voltage equation can be subtracted to produce the line voltage equation as:

$$\begin{aligned} Uab &= R(ia - ib) + (L - M) + (ea - eb) \\ Ubc &= R(ib - ic) + (L - M) + (eb - ec) \\ Uca &= R(ia - ic) + (L - M) + (ec - ea) \end{aligned} \tag{2.3}$$

The matrix version of the BLDC motor's line voltage equation can be written as:

$$\begin{bmatrix} uAB \\ uBC \\ uCA \end{bmatrix} = \begin{bmatrix} R & -R & 0 \\ 0 & R & -R \\ -R & 0 & R \end{bmatrix} \begin{bmatrix} iA \\ iB \\ iC \end{bmatrix} + \begin{bmatrix} L-M & M-L & 0 \\ 0 & L-M & M-L \\ M-L & 0 & L-M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} iA \\ iB \\ iC \end{bmatrix} + \begin{bmatrix} eA-eB \\ eB-eC \\ eC-eA \end{bmatrix}$$

During motor operation, the absorbed power from the source undergoes some losses, such as copper and iron losses. However, the majority of the power is effectively transferred to the rotor through the torque effect. This transferred power, referred to as electromagnetic power, can be determined by summing the product of the current and back-EMF of the three phases [11].

$$Pe = ea * ia + eb * ib + ec * ic \tag{2.5}$$

The electromagnetic power is totally turned into kinetic energy so:

$$Pe = Te * \omega \tag{2.6}$$

Where:

- **Te :** electromagnetic torque .
- ω **:** angular velocity of rotation .

## 2.5 Speed Control of the BLDC Motor

Controlling the speed of a brushless DC (BLDC) motor is crucial to achieve the desired operating rate. This can be accomplished by regulating the input DC voltage or current. It is worth noting that increasing the voltage results in a higher speed, and for this process there are several methods including:

### 2.5.1 PWM (Pulse-width modulation)

Pulse-width modulation (PWM) represents a simple approach to regulate the speed of a brushless DC (BLDC) motor. This technique serves as a control mechanism resembling a switch that rapidly cycles the DC voltage, generating a sequence of pulses. The duration of these pulses is what governs the power supplied to the motor, and hence the motor's speed.

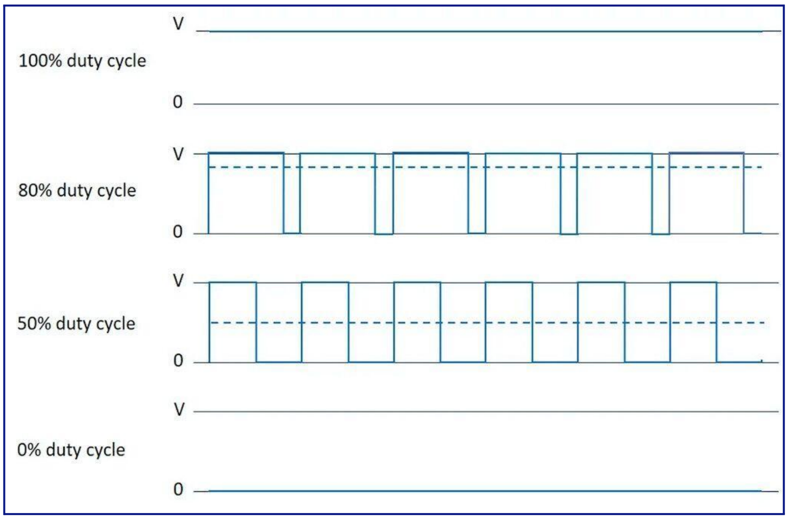



**Fig 2.9** Different Duty Cycles and Their Corresponding Output Voltages

### 2.5.2 Open-loop speed control

Open-loop speed control for a BLDC motor is a method of regulating the motor's speed without relying on sensor-based feedback. Instead, the control loop remains open, and the motor's speed is governed by modulating the duty cycle of the PWM signal. The open-loop control approach is straightforward, yet it might not deliver the same degree of precision and stability as closed-loop control methods.

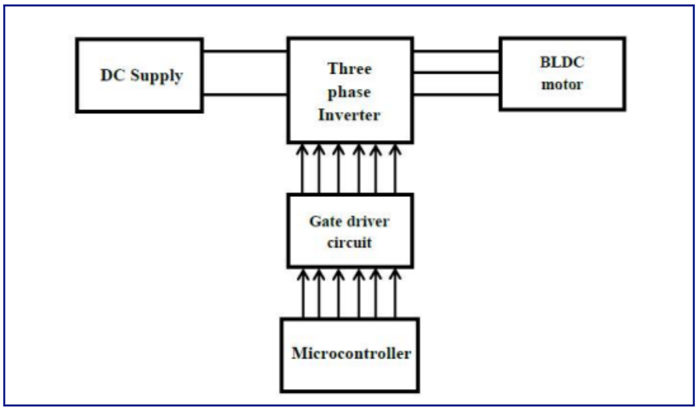



**Fig 2.10** Block diagram of open loop BLDC Motor

### 2.5.3 Closed-loop speed control

A closed-loop BLDC motor speed controller is a system that relies on sensor feedback to adjust the PWM signal and maintain the motor's desired speed. Sensor feedback, including measurements like current or speed, plays a crucial role in modifying the PWM signal via a control algorithm like a PID controller. The PID controller computes the error between the target speed and the motor's real speed, then adjust the PWM signal to minimize this difference.[17]

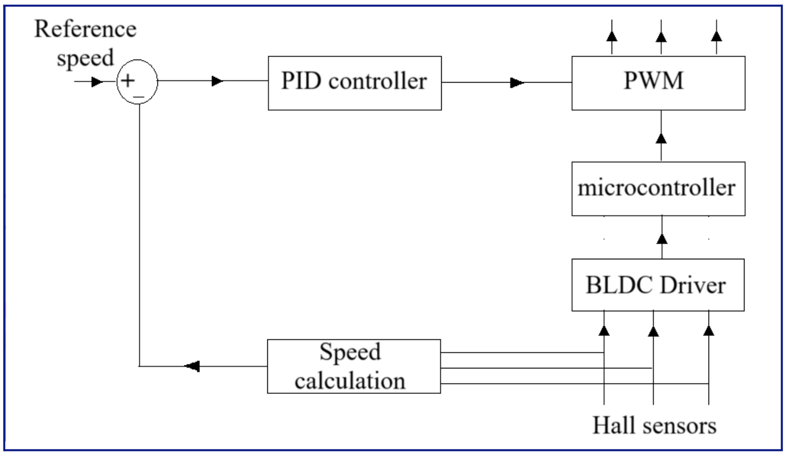



**Fig 2.11** Closed loop speed control.

# Conclusion

BLDC motors are widely used in various applications due to their numerous advantages over traditional brushed DC motors, including improved speed and torque characteristics, excellent dynamic response, high efficiency, long operational lifespan, noiseless operation, and the ability to operate at higher speed ranges. Due to these benefits, BLDC motors are extensively used in a wide range of industries such as automotive, appliances, aerospace, consumer electronics, medical equipment, instrumentation, and automation.

# Chapter III

## *BLDC Blower-based Ventilators*

# Introduction

After introducing the basics of mechanical ventilation and the BLDC motor, the structural and functional analyses of their combination will be discussed in this chapter.

As mentioned previously, the blower based ventilators are mostly used for patients in coma situations or with breathing failure to compensate for their breathing incapability. These ventilators are designed to be compact and efficient, and can be used in a variety of settings, including hospitals, clinics, and even at home.

# 3.1 Blower-based MV system construction

Similar to various electronic systems, blower-based mechanical ventilators (artificial respirators) consist of two major complementary systems : An electric system, and a pneumatic system [18].

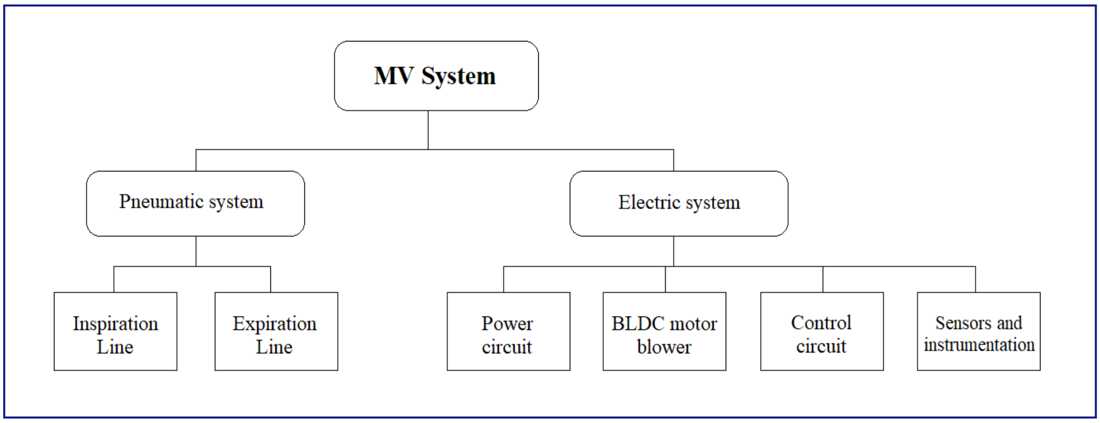



**Fig 3.1 :** Structural block diagram of the BLDC Blower-based MV system.

### 3.1.1 The electric system

The ventilator contains many interdependent elements and devices mainly include:

- **The power circuit:** It is responsible for processing high voltages and currents to deliver optimum supported power to the apparatus and prevents possible overcurrent/voltage that can damage other instruments.
- **Bldc motor based blower:** This type of machine aims to compress an inlet fluid to reach a certain level of pressure. This task is accomplished using an impeller that is rotated at adjustable high speed using a BLDC motor.

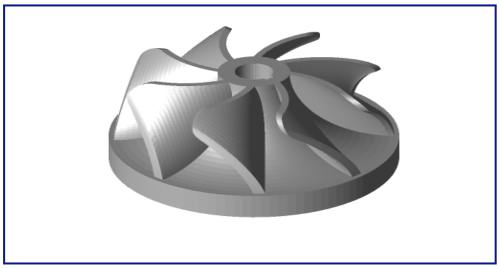


**Fig 3.2a:** 8 fins impeller.

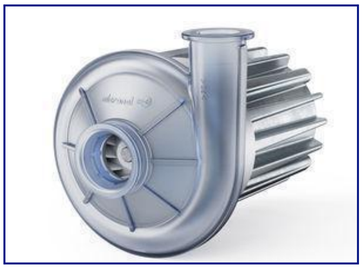


**Fig 3.2b: BLDC** motor based blower.

- **Control circuit:** It is the set of electronic instruments such as the microprocessor, the drivers, switches, pilot lights…etc. They serve to organize the operation of the whole system properly according to some given conditions.

- **Sensors:** The set of transducers used to detect, respond to, or collect data from the environment (data related to the patient's state in this case).

### 3.1.2 The pneumatic system

The pneumatic system of an artificial respirator acts like an intermediary between the air source, electric system, and the patient. The air-oxygen mixture is delivered from the apparatus to the patient at specific rates and then carbon dioxide is eliminated from the lungs through a set of tubes or pipes. It contains :

- **Oxygen supply:** In hospital institutions, $O_2$ gas may be accumulated issuing different sources including massive oxygen concentrators, liquid oxygen storage tanks, or oxygen plants made up of high-pressure oxygen cylinders.

- **Inspiration line:** When initiating a breath, oxygenated filtered air is delivered to the lungs through inspiration tubes that are provided with a unidirectional inhalation valve. This latter is opened or closed according to the preset time, or level of air pressure/volume inside the lungs.

- **Expiration line:** Similarly to the inspiration line, the expiration line is provided with a unidirectional exhalation valve that is inversely opened/closed compared to the inhalation valve [18].

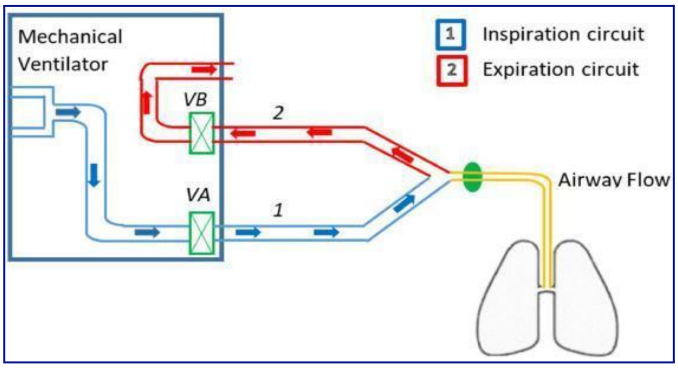



**Fig 3.3:** Inspiration and expiration lines of the pneumatic system of a mechanical ventilator

## 3.2 Functional analysis of the blower-based MV system

The blower based mechanical ventilators ensure oxygenated air compression using the centrifugal force of the impeller fixed to the rotor of the BLDC motor. As mentioned in the second chapter, the improved control characteristics of this latter, allows a better pressure/flow monitoring and fast response to sudden changes.

Similarly to all types of ventilation, the BLDC blower based MV process has four major phases: **the trigger phase, the inspiratory phase, the cycling phase, and the expiratory phase** [19].

- **The trigger phase** is the onset of an inhalation which is initiated when the ventilator detects a patient's effort to breathe or by mechanical ventilator settings; the trigger can be either time or air pressure/flow depending on the mode of operation. At this moment, the inspiratory valve is opened to permit the air-oxygen mixture to flow all along to the lungs through a nasal mask or an endotracheal tube. On the other hand, the expiratory valve is closed to prevent the leakage of the oxygenated air.
- **The inspiratory phase** is defined by the patient's breathing of air-oxygen mixture that is delivered by the blower to reach a specific level of pressure **(PIP)** or volume **(Vt)** through the inspiration line.
- **The cycling phase** is the brief period of time after inhaling has stopped but before exhalation begins where the **PIP** decreases to $\mathbf{P_{plat}}$ due to airway resistance. This can help optimize gas exchange within the lungs
- **The expiratory phase** is the patient's passive exhalation of breath to release the $CO_2$ gas through the expiration line when the expiratory valve is opened while closing the inspiratory valve (opposite process of inspiration).

This entire operation is cyclically repeated for about 12 to 15 times per minute for certain rates of pressure/volume depending on the variables set at the beginning of the process.

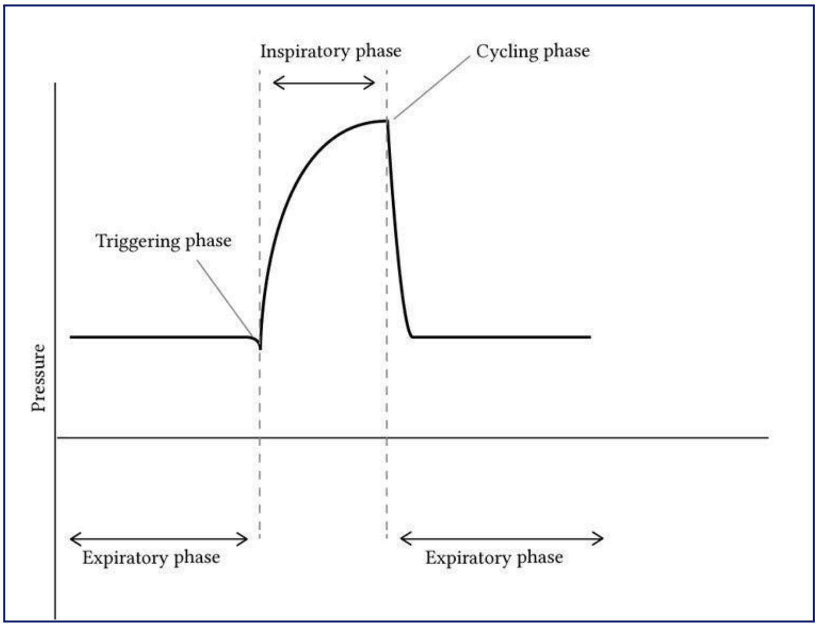



**Fig 3.4:** The major four phases of a mechanically ventilated breath.

**Note:** The difference between MV modes is mainly in the trigger and inspiration phases while the expiration is a passive process depending on the lungs elasticity for all breathing modes.

## 3.3 Pressure control ventilation PCV

Pressure controlled ventilation **(PCV)** is a mode of mechanical ventilation that is used for mandatory pressure control ventilation with predetermined maximum pressure **(PIP)** levels and the inspiratory time in order to achieve a desired tidal volume **(Vt)**. This mode is used on patients who may have a low respiratory rate of spontaneous respiration, in other words, they have some contribution in breathing (Critical coma situation or under general anesthesia).[20]

In order to perform the ventilation under the PCV mode, it is required to set the parameters of pressure controlled ventilation which involves adjusting the following parameters:

1. **Peak Inspiratory Pressure:** The practitioner sets the **PIP** (generally from **15 cmH$_2$O to 20 cmH$_2$O**) which is the maximum pressure delivered to the patient to ensure adequate oxygenation [21].
2. **Positive End Expiratory Pressure:** As mentioned in the first chapter, the PEEP is a residual pressure applied at the end of expiration to prevent the alveoli from collapsing. It is normally adjusted between **5 cmH$_2$O and 12 cmH$_2$O** depending on the severity of the patient's status [22].
3. **I:E ratio :** The **I:E** ratio is regulated (by the physician to monitor the patient's time of inspiration and expiration, which may affect the distribution of ventilation and perfusion in the lungs (set from ⅕ to ⅓) [21].

4. **The respiratory rate (RR or BPM) :** is the number of breaths per minutes and it can range between 10 to 15 bpm.[22]

The respiratory rate and the **I:E ratio** determine the trigger (breath initiation condition) for the PCV mode since they specify the time required for each breath as well as its initiation and end time.

## Conclusion

In practical medical application, mechanical ventilation in general, and the PCV modality specifically require more variables to be strictly set by the practitioner. For educational purposes, this project focuses on the mentioned PIP and PEEP parameters of the PCV to introduce the basic operation of this concept.

# Chapter IV

## *Implementation of BLDC*

## *Blower-based MV system*

# Introduction

The Objective of this chapter is to demonstrate the operation and control of the BLDC blower used in ventilators specifically to generate a desired level of pressure. For this sake, a basic system is implemented and controlled using some electronic components that are going to be described in the next sections in addition to the circuitry of the overall system.

# 4.1 System architecture

### 4.1.1 BLDC motor based blower

The brushless motor based blower used for this application is the wonsmart 24V blower. It can generate an air pressure up to **6.5 kPa**, an air flow that can reach **280 L/min,** and can be supplied with a maximum voltage of **24V**.

The blower has a total of 8 pins. Starting from the right, each of the 3 first pins is connected to one stator winding for excitation. The fourth pin is the ground connected to the neutral point of the star-connected stator windings. The 3 next pins are for the Hall sensors followed by the power pin Vcc.

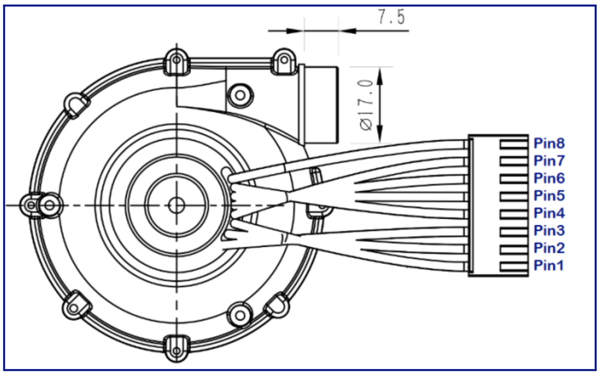



**Fig 4.1:** Wonsmart 24V blower (WS7040-24-V200).

### 4.1.2 BLDC motor driver

The driver supplies the necessary power to the motor to achieve the desired speed and torque. It typically consists of power transistors or MOSFETs, gate drivers, control logic, and protection circuits, all of which work together to ensure the motor operates smoothly.

The primary functions of a BLDC driver include:

1) **Commutation control:** This involves controlling the switching of the power transistors to energize the appropriate motor phases in the correct sequence.

2) **Speed control:** The driver regulates the motor's speed to meet specific requirements.

3) **Current sensing:** It monitors the current flowing through the motor, allowing for adjustments and protection.

4) **Fault detection and motor protection:** The driver is responsible for detecting any faults or issues in the motor's operation and taking protective measures when necessary.

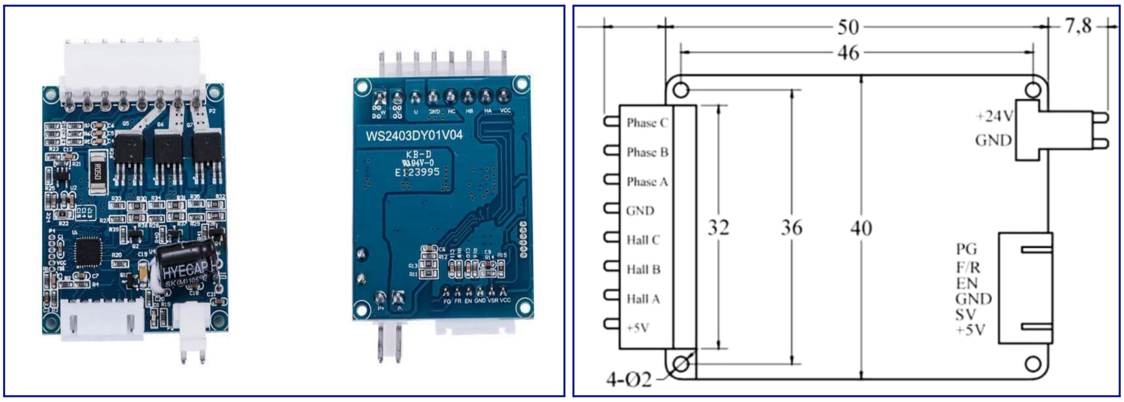



**Fig 4.2:** Wonsmart blower driver (WS2403DY01V04).

### 4.1.3 Microcontroller chip

The arduino mega microprocessor is used in this application to control each of the electronic components and the provided data.

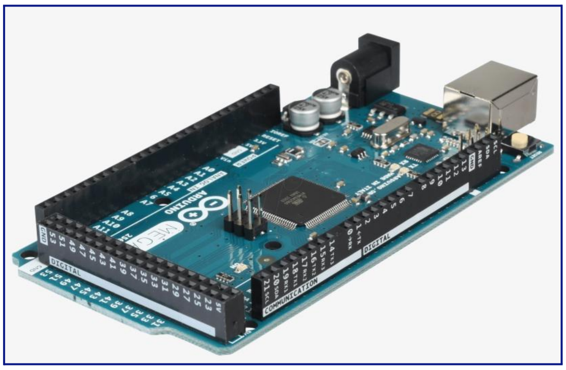


**Fig 4.3 :** Arduino mega 2560.

### 4.1.4 Pressure sensor

A pressure sensor is a device designed to measure and detect the pressure exerted on it by a fluid (gas or liquid). It converts the physical pressure applied to it into an electrical signal, which can be used for monitoring, control, or data acquisition purposes [23].

The bmp180 pressure\temperature sensor is used in this project for its large measurement range and its high precision (300 to 1100hPa) that matches the application. The device contains 4 pins : The **Vcc,** the serial data pin **(SDA)**, the serial clock signal pin **(SCK)**, and the ground **(GND).** It uses the I2C protocol to communicate with the microcontroller.

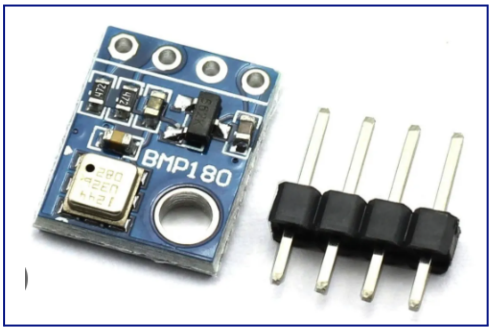



**Fig 4.4:** bmp180 pressure sensor.

The arduino microprocessor controls the input and output signals of both the driver that transfers them to the BLDC blower and the sensor that measures the output air pressure through an air pipe. The blower speed (hence its output pressure) is adjusted using the PWM signal depending on the preset level of pressure. The whole system is fed using a 20V power supply.

## 4.2 Software and technologies

### 4.2.1 LabVIEW software

LabVIEW, short for Laboratory Virtual Instrument Engineering Workbench, is a software development environment produced by National Instruments. It is a comprehensive Integrated Development Environment (IDE) designed for the creation of applications related to data acquisition, instrument control, and industrial automation. LabVIEW offers a graphical programming interface where users can develop applications by placing virtual instruments (function generators, oscilloscopes, data acquisition devices, and boolean and arithmetic operators…etc) onto a block diagram, then the built system variables/results can be monitored/displayed on the front panel which is a virtual control board designed by the programmer and accessible by the user. [24]

This IDE software includes several libraries to interface with the commonly used microprocessors and modules (arduino, raspberry, FPGA, sensors, measurement instruments…etc) and provides different examples to facilitate their usage.

- **LabVIEW Front panel**

The front panel of the Virtual Instrument (VI) is constructed using controls and indicators, which serve as the interactive input and output interfaces. Controls encompass components like knobs, push buttons, and dials, providing ways for users to input information. On the other hand, indicators involve elements like graphs and LEDs, presenting output data. Controls mimic the input mechanisms of instruments and contribute data to the VI's block diagram, while indicators replicate the output mechanisms of instruments, displaying the data acquired or generated by the block diagram.

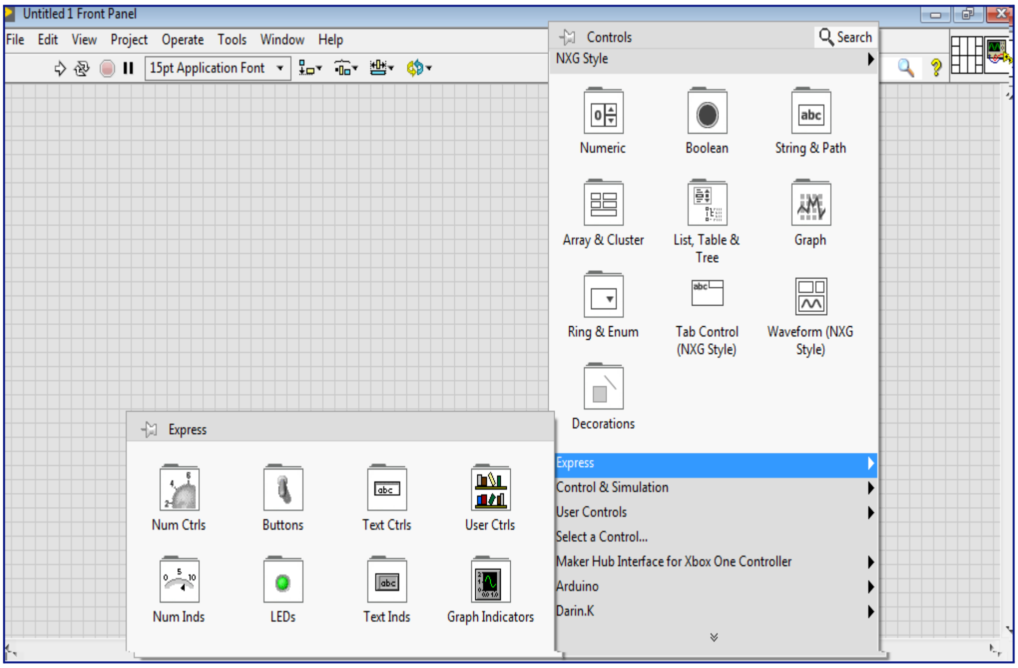



**Fig 4.5** LabVIEW front panel

- **LABVIEW Block Diagram**

The LabVIEW block diagram functions as a visual depiction of a LabVIEW program's source code. This diagram is an essential constituent of a LabVIEW VI (Virtual Instrument) and encompasses the program's logic and operational features.

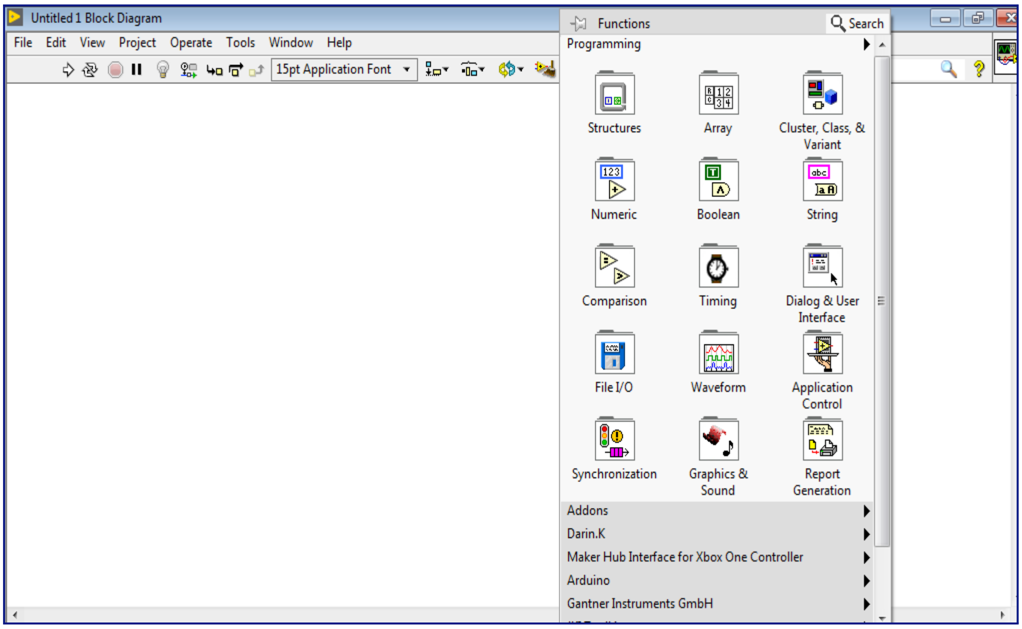



**Fig 4.6** LabVIEW block diagram

- **LabVIEW Linx library**

LINX is a library provided by the MakerHub community and is employed in LabVIEW to establish connections with embedded platforms. It offers a collection of virtual instruments (VIs) that enable users to communicate with hardware devices through LabVIEW including data reading/writing blocks, basic sensor settings, and signal controllers. By streamlining the interface process with embedded platforms, the library facilitates the development of applications that interact with these devices. Its application scope is broad, encompassing areas such as test and measurement, control systems, as well as research and development [25].

### 4.2.2 MatLab software

Matlab is a commercial numerical computing software developed by the company MathWorks. It was initially created in the late 1970s by Cleve Moler, a mathematics professor at the University of New Mexico and later at Stanford.

MATLAB (Matrix LABoratory) is a high-level programming language and interactive environment designed for numerical analysis, data visualization, and algorithm development. It is widely used in various fields, including engineering, science, mathematics, finance, and more. MATLAB provides a range of tools and functions that allow users to perform complex computations, manipulate data, and create visual representations of their work.

- **MatLab Simulink**

Mathworks' simulink is a graphical environment for designing, simulating, and analyzing multi-domain dynamic systems. Its main user interface consists of a graphical block diagramming tool and a set of block libraries that can be customized. It can either drive matlab or be scripted from it and enables close connection with the rest of the matlab environment. Simulink is frequently utilized in automatic control, digital signal processing, and model-based design.

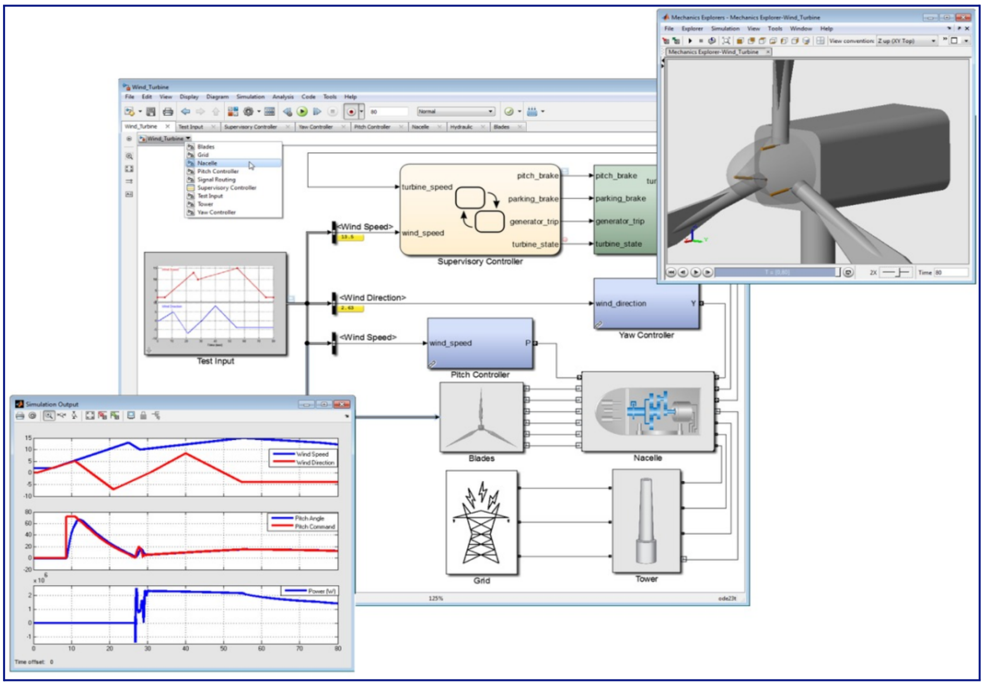



**Fig 4.7** An example of some Simulink blocks and functions.

### 4.2.3 I2C communication protocol

The I2C or Inter-Integrated Circuit is a synchronous serial communication protocol that enables data transmission between integrated circuits for short distance communication between a transmitting device (master) and receiving device(s) or slave(s) . It allows data transfer (one bit then another) using a shared set of two signal lines that are :

- **SDA (Serial data) :** The line used for sending and receiving data between the master and slave devices.
- **SCL (Serial clock) :** This line carries the clock signal that synchronizes the data transfer.

At the same time a data bit is transmitted on the SDA line, a clock pulse is generated to the SCL line so that the slave detects the start/end of each bit. [26]

I2C communication supports multi-slave systems since each slave device is identified with an address, this latter is first determined by the master device then the actual data is read from or written to the specified receiver (slave).

This protocol can be also used in multi-master systems provided that only one master device operates at a time. Unlike slaves that need address specification to receive commands, multi-master circuits require arbitration in order to synchronize the serial clock first then decide which master should operate first [27].

## 4.3 Overall System implementation and results

In this application, the blower is connected to its driver which is supplied by a variable DC source. The output air flow is delivered through an air pipe reaching the sensor that measures the generated pressure inside a small closed area (balloon for example) to model the lungs.

The programming of the arduino microcontroller is accomplished using the LabVIEW software to perform the necessary arithmetics, logic, and signal operations. In addition to the LINX library to interface with the arduino chip, control, and manage the different inputs and outputs.

The work done is divided into  tasks that are explained in the next section.

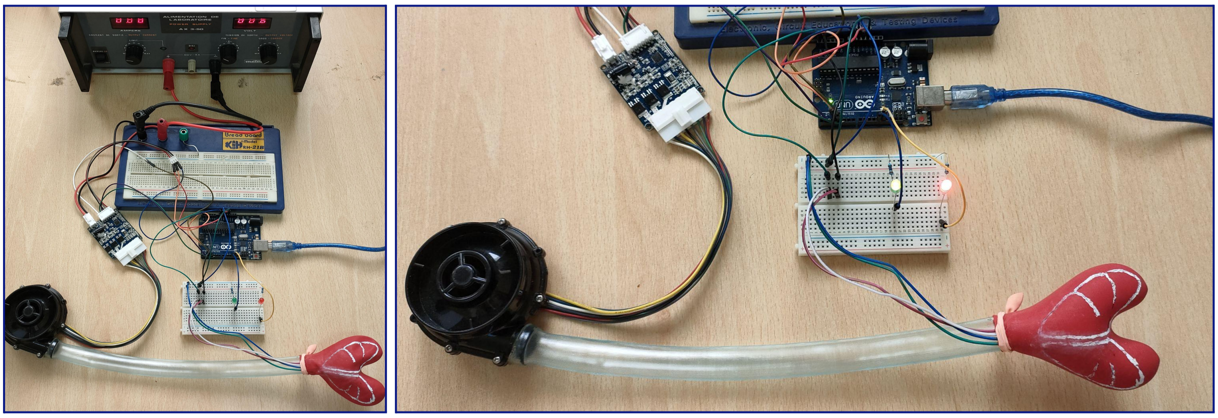


**Fig 4.8** The implemented circuit for the application.

### 4.3.1 Relation between the PWM signal and the output pressure

First, a LabVIEW code is created to read data from the BMP180 sensor using the LINX I2C protocol. Once the sensor is activated, a set of calibration data is retrieved from the sensor's EEPROM. Next, the register address for pressure measurement is specified, and the appropriate measurement command is issued. Finally, after obtaining the measurement data, the previously mentioned calibration parameters are employed to calculate the final value of the variable in physical units.

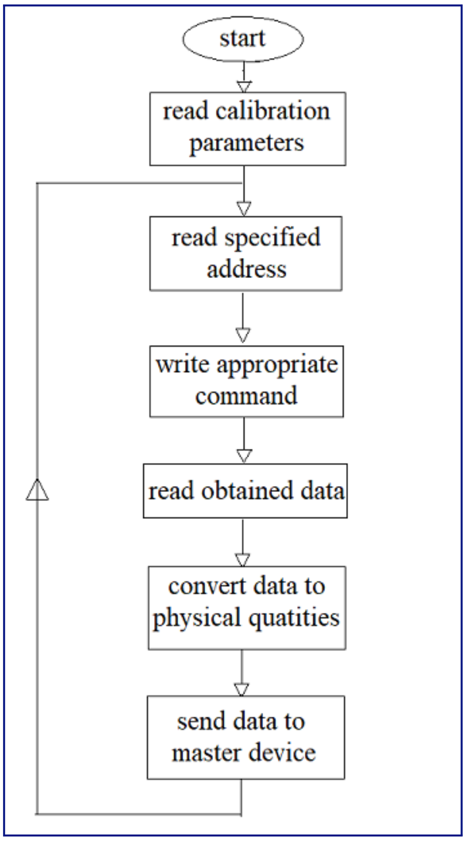



**Fig 4.9** Flowchart for the bmp180 sensor operation.

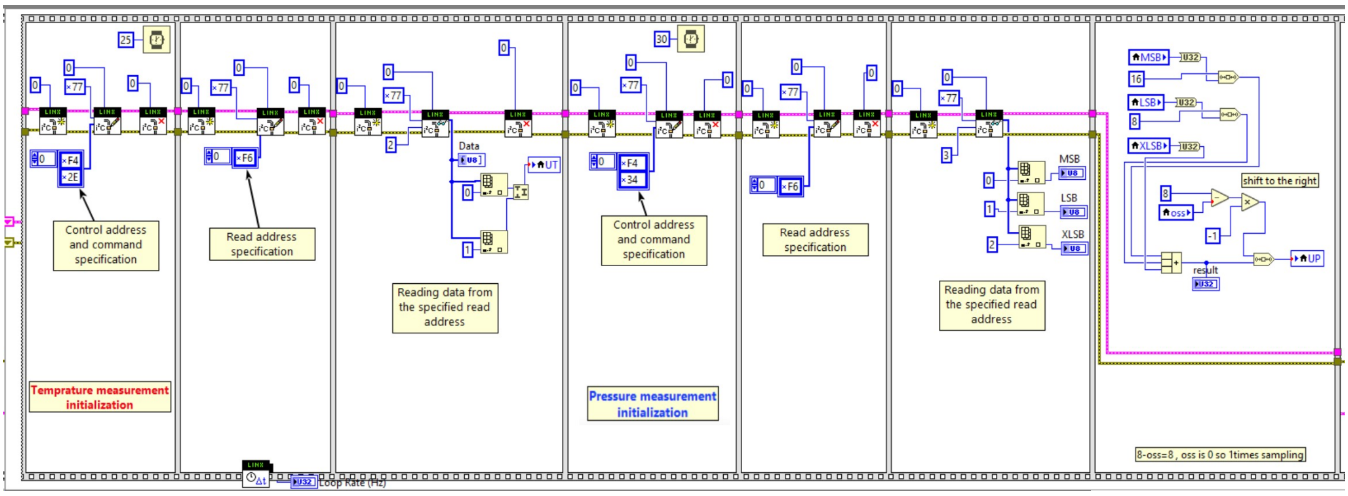



**Fig 4.10** Block diagram section for the bmp180 sensor readings (Temperature and pressure).

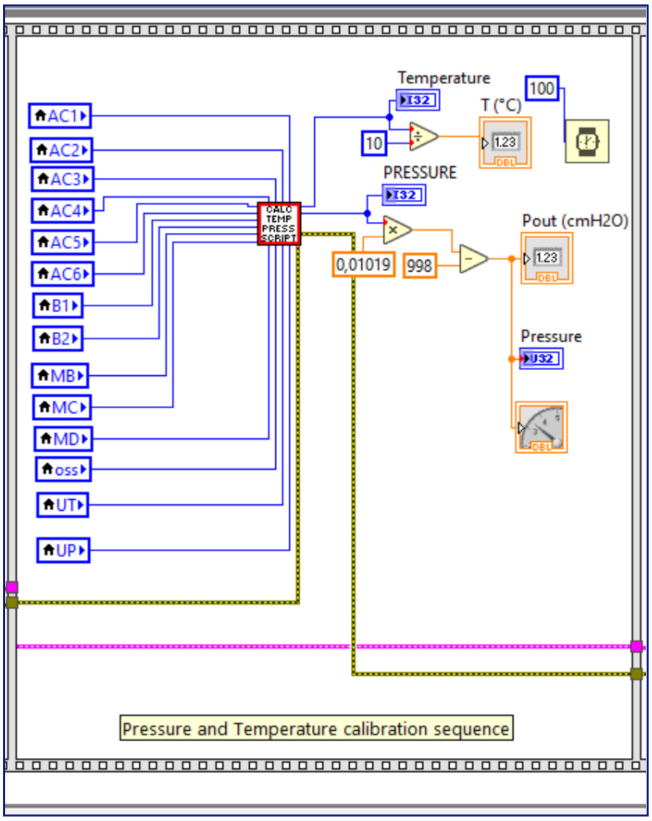



**Fig 4.11** Block diagram sequence for the calibration of bmp180 sensor readings.

The next step involves creating a simple code to generate a PWM signal with a manually adjustable duty cycle. The complete code is then uploaded to the microcontroller, which is connected to both the BLDC driver and the pressure sensor.

Upon powering the circuit, the motor's speed can be varied by adjusting the duty cycle of the PWM signal on the front panel, generated by the microcontroller. Additionally, the microcontroller enables the sensor to carry out the necessary measurements, and the obtained data are displayed on the LabVIEW front panel.

Initially, the speed of the BLDC blower is controlled using the PWM signal, which is manually adjusted to establish an approximate relationship between the duty cycle values (ranging from 10% to 100%) and the output pressure obtained at a voltage supply (VS) of 18V.

The BMP180 sensor records atmospheric pressure (P0) under normal conditions, while in positive pressure ventilators, it is assumed that P0 = 0. The pressure data obtained from the BMP180 is provided in hPa units, which need to be converted to cmH2O for this specific application. To determine the net air pressure generated by the motor, Equation 4.1 is employed:

$$1\ hPa = 0.01019\ cmH2O \text{ and}$$

$$P(t) = Ps - P0$$

**Hence :** $$Pout(t)\ cmH2O = 0.01019\ (Ps - P0) \qquad (4.1)$$

where: $P_{out}(t)$ is the net pressure delivered by the BLDC blower, $P_S$ is the Pressure measured by the sensor, and $P_0$ is the room's atmospheric pressure.

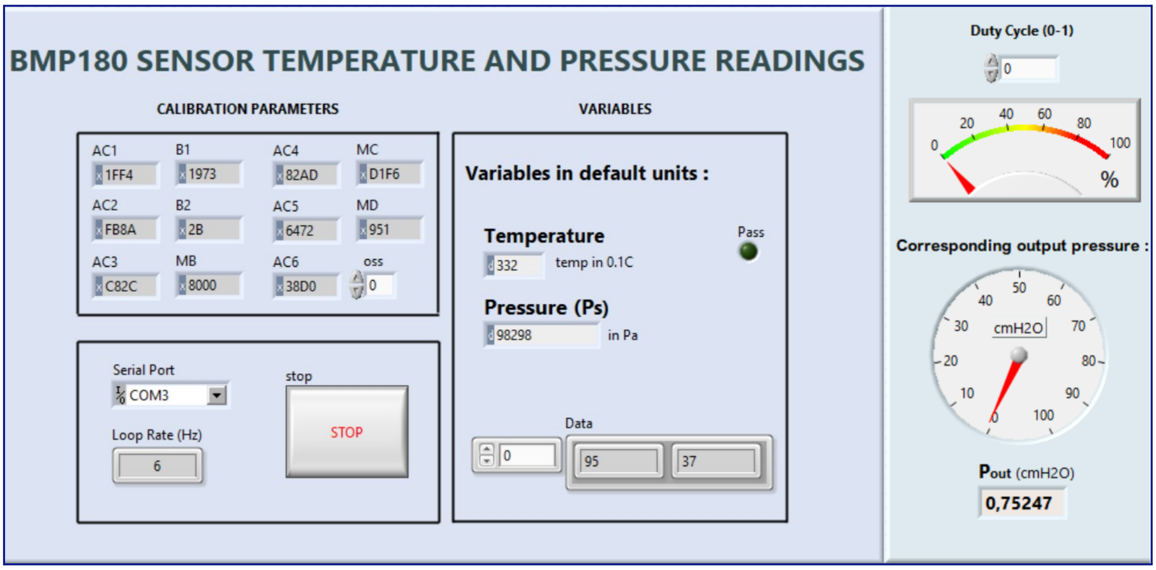
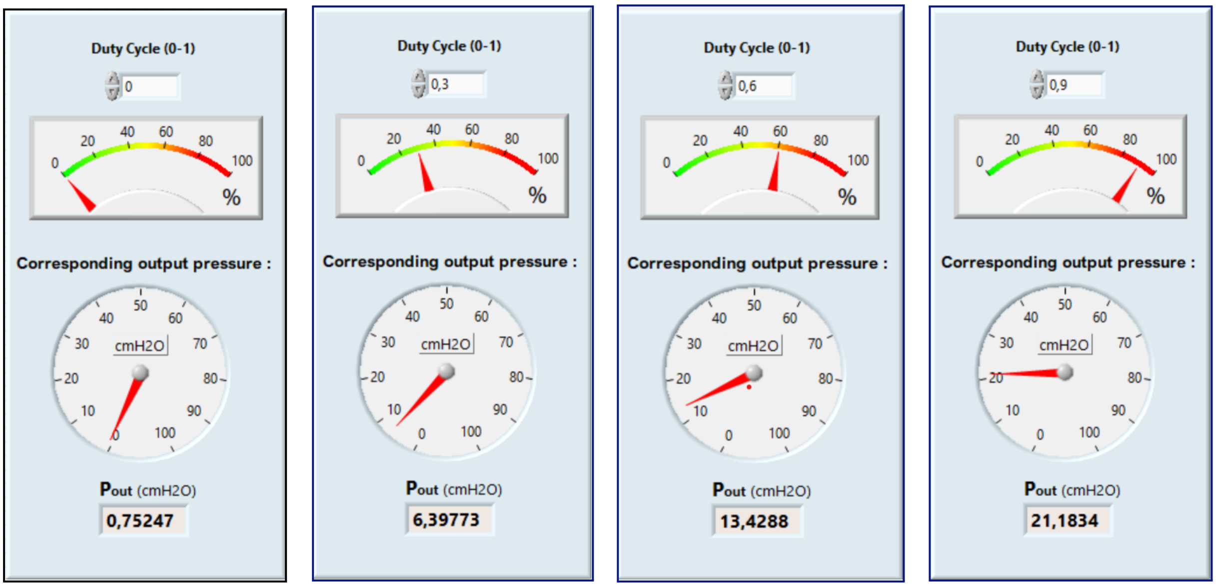



**Fig 4.12** LabVIEW front panel design for the PWM control and the bmp180 sensor readings.

After recording the duty cycle and the corresponding output pressure values P(t), Matlab software is employed to plot and deduce an approximated function of the duty cycle (DC) versus pressure levels, i.e., DC=f(P), using the curve-fitting application.

**Results and Discussion:**

The experimentally obtained results are presented in Table 4.1. The duty cycle values and their corresponding pressure levels for different voltage supply rates (VS) are recorded in table 4.1.




**(a)** **(b)** **(c)** **(d)**

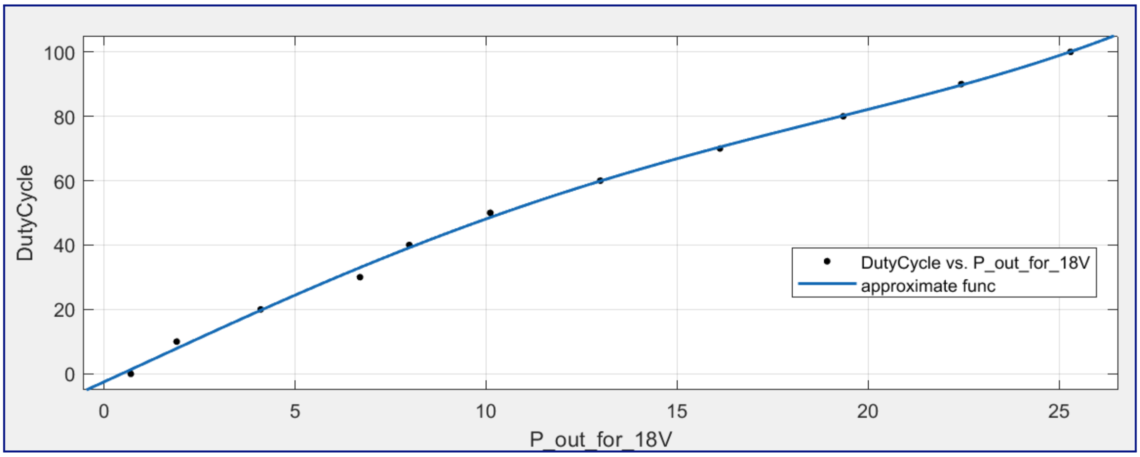
**Fig 4.13** Duty cycle rates with their corresponding output pressure levels.

Using the curve fitting tool of Matlab, an approximate function for the previous data (for $V_S$=18V) is obtained as shown in Fig. 4.13.

**Table 4.1**: The duty cycle values and the corresponding pressure levels

| **Duty cycle (%)** | | **0** | **10** | **20** | **30** | **40** | **50** | **60** | **70** | **80** | **90** | **100** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **$P_{out}$ ($cmH_2O$)** | **$V_S$= 18V** | 0.75 | 1.91 | 4.13 | 6.75 | 7.99 | 10.11 | 12.99 | 16.12 | 19.35 | 22.44 | 25.3 |

Using the curve fitting tool of matlab, an approximate function for the previous data (for $V_S$=18V) is given by :




Results

Linear model Poly4:
    f(x) = p1*x^4 + p2*x^3 + p3*x^2 + p4*x + p5
Coefficients (with 95% confidence bounds):
    p1 = 0.0002182 (-0.000391, 0.0008273)
    p2 = -0.008832 (-0.04061, 0.02294)
    p3 = 0.02928 (-0.5093, 0.5678)
    p4 = 5.434 (2.181, 8.688)
    p5 = -2.5 (-7.825, 2.825)

**Fig 4.14** Plot and function obtained for $\mathbf{D_C}$ **VS** $\mathbf{P_{out}}$ using MatLab.

$$\mathbf{D_C (P_{out}) = 0.00021} (P_{out})^3 \mathbf{- 0.00883} (P_{out})^3 \mathbf{+ 0.02928} (P_{out})^2 \mathbf{+ 5.434} (P_{out}) \mathbf{- 2.5} \quad \mathbf{(4.2)}$$

The equation is obtained for $V_S$= 18V .

It is clearly noticed that the output pressure increases as the duty cycle of the PWM signal increases since it increases the BLDC motor's rotational speed, hence, they are directly proportional.

### 4.3.2 BLDC blower control using PID

A proportional-integral-derivative (PID) controller is a type of control loop feedback controller that is commonly employed in industrial control systems. An error value is calculated by a PID controller as the difference between a measured process variable and a desired setpoint. The controller seeks to reduce errors by changing the process using a c-ontrolled variable; where: **Gc(S)** is the controller gain. There exist various techniques for tuning a PID loop, such as the Ziegler-Nichols method.

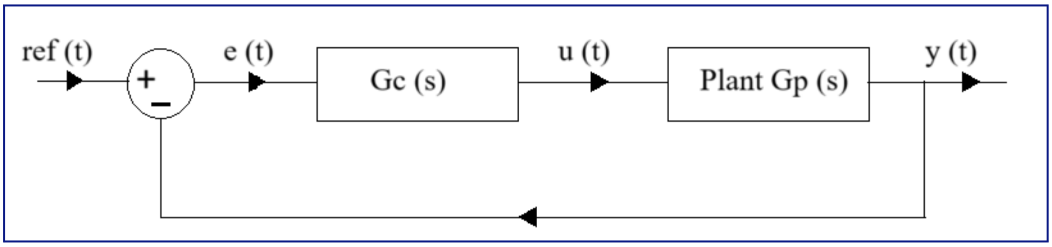



**Fig 4.15** Closed loop PID controller

**Ziegler-Nichols Closed-Loop Tuning technique**

The Ziegler-Nichols tuning method is a practical approach for adjusting a PID controller. It was created by John G. Ziegler and Nathaniel B. Nichols. The process starts by setting the I (integral) and D (derivative) gains to zero. Subsequently, the proportional (P) gain is incrementally raised, starting from zero, until sustained oscillations are observed. These oscillations amplitude and period are used to determine the appropriate values for the P, I, and D gains.

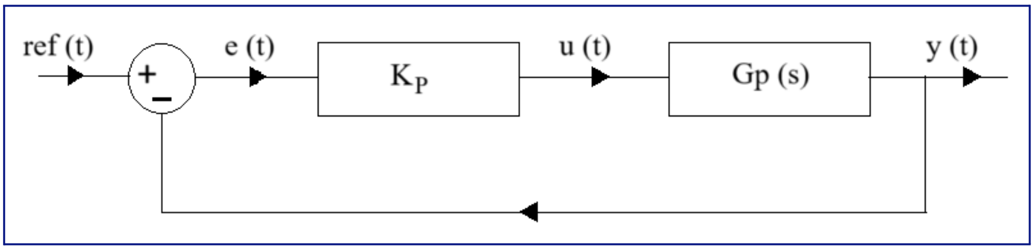



**Fig 4.16** Closed loop PID controller with gain $K_P$

**Table 4.2** : (Kp. Ti. Td) Closed-Loop Calculation using Ziegler-Nichols method.

| Type of controller | Kp | Ti | Td |
|---|---|---|---|
| **P** | 0.5Kcr | | |
| **PI** | 0.45Kcr | 0.83Pcr | |
| **PID** | 0.6Kcr | 0.5Pcr | 0.25Pcr |

This method of tuning a PID controller yields:

$$G_c(s) = K_p *(1+ \frac{1}{Ti*S} + T_d*S) \quad \textbf{(4.3)}$$

$$G_c(s) = 0.6\ K_{cr} * (1+ \frac{1}{0.5Pcr*S} + 0.125P_{cr}*S) \quad \textbf{(4.4)}$$

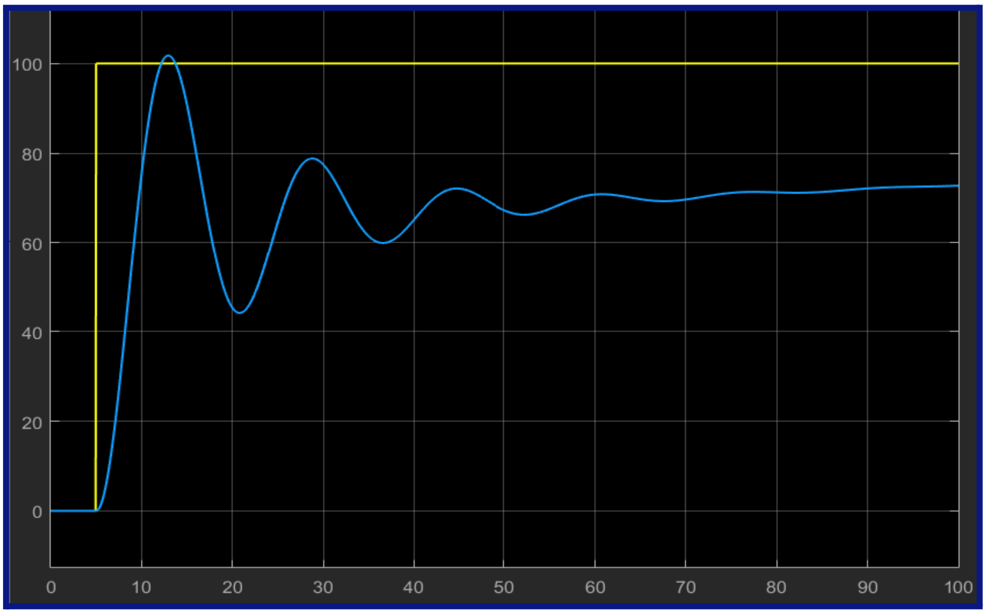
$$G_c(s) = 0.075\ Pcr\ *\ K_{cr}\ \frac{(S+\frac{4}{Pcr})^{\wedge}2}{S} \quad \textbf{(4.5)}$$

**Where : $K_{cr}$** is the critical gain

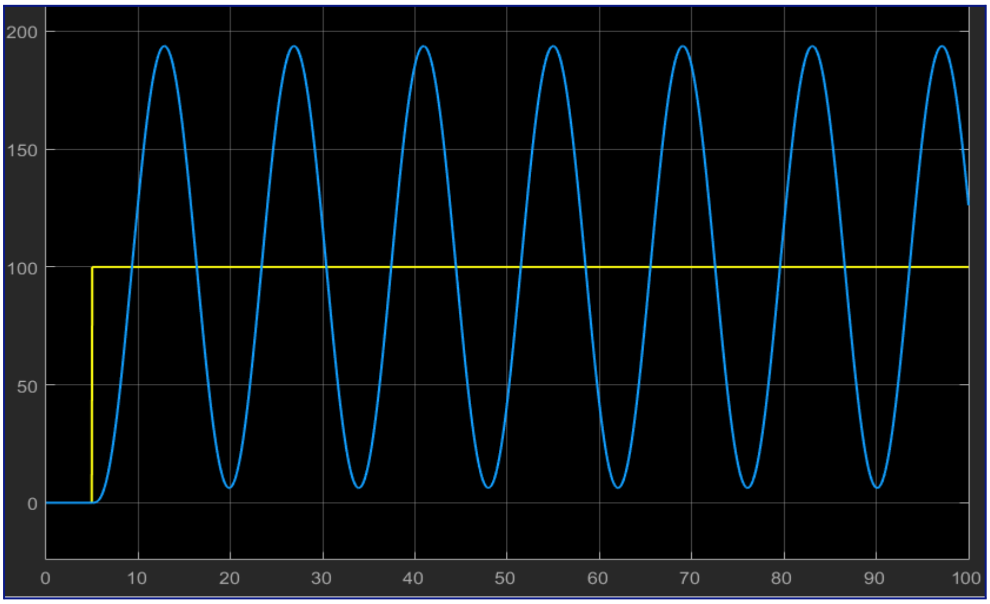
The transfer function of the system is given by:

$$Gp(S) = \frac{0.3412S^2 - 0.02326S + 0.02941}{S^3 + 1.009S^2 + 0.2498S + 0.03069} \quad \textbf{(4.6)}$$

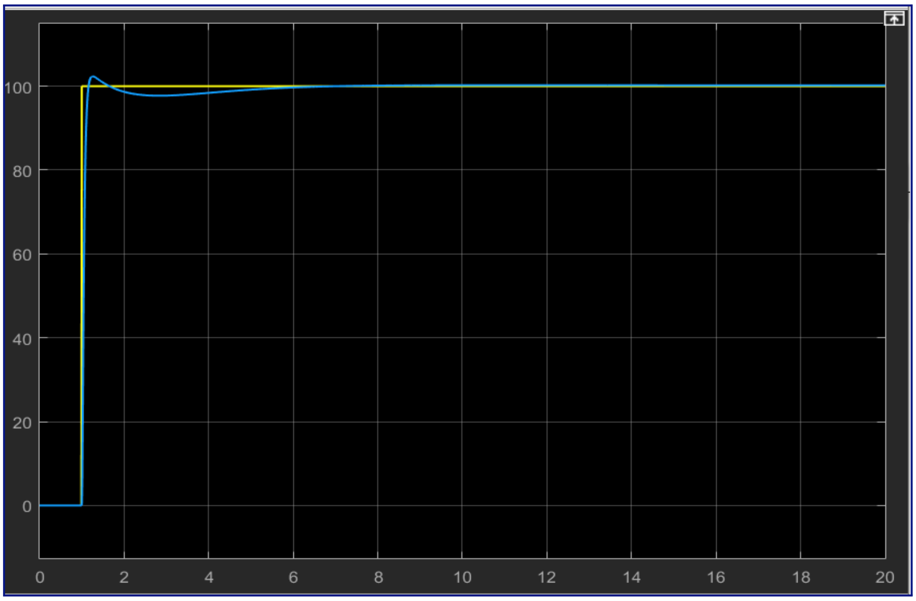
The Simulation results for tuning a closed loop pid controller using Ziegler-Nichols method are in Fig.4.17.




**(a)**




**(b)**




**(c)**

**Fig 4.17** Simulation results of closed loop using a PID controller tuned by Ziegler-Nichols method

Figure 4.17a shows the closed-loop system output at **Kp=1** with $\mathbf{K_I}$ and $\mathbf{K_D}$ shut off. Then, the proportional gain increases until $\mathbf{K_{cr}=16}$, where the system output exhibits oscillations with the same period. This is demonstrated in Figure 4.16b. Figure **4.16c** shows the system output after tuning by adjusting the integral and derivative gains to $\mathbf{K_I=1.65}$ and $\mathbf{K_D = 4.75}$.

### 4.3.3 BLDC blower control in MV system

➢ Pressure regulation with consideration of PIP and PEEP parameters:

To employ this blower as an air pressure source in a mechanical ventilator, it needs to be controlled automatically to maintain the output pressure within an appropriate range, spanning from PEEP (Positive End-Expiratory Pressure) to PIP (Peak Inspiratory Pressure). Achieving this goal necessitates a series of arithmetic and logical operations.

The next Algorithm describes the general structure and steps you might consider including in a flowchart for pressure regulation based on PEEP (Positive End-Expiratory Pressure) and PIP (Peak Inspiratory Pressure) parameters is as follows:

1. **Input Parameters :** which include PEEP and PIP (set by the practitioner).

   calculate f (PIP), then set $D_C$ to f (PIP).

2. **Measurement :** The output pressure ($P_{Out}$) of the Blower is measured by the sensor.

3. **Decisions and $D_C$ adjustment :** The control logic for pressure regulation is based on the PEEP (minimum pressure level) and PIP (maximum pressure level) parameters.

Is : $P_{out} \geq$ PIP ?

Yes : LED alarm on.

Set $D_C$ to f (PEEP).

No : Keep $D_C$ at f (PIP).

Is : $P_{out} \leq$ PEEP ?

Yes : Set $D_C$ to f (PIP).

No : Set $D_C$ to f (0).

Repeat step **2.**

This flowchart that provides an overview of how pressure regulation is managed based on PEEP and PIP parameters is illustrated in Figure 4.17. The actual details of the control logic and adjustments will depend on the specific requirements of the mechanical ventilator system.

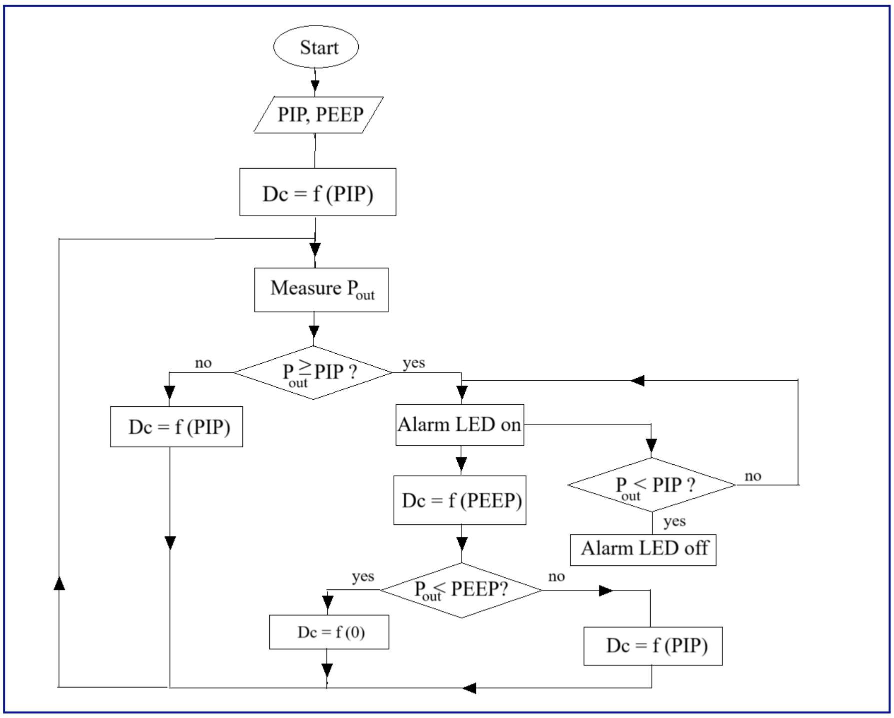



**Fig 4.18** Flowchart for pressure regulation depending on the PEEP and PIP parameters.

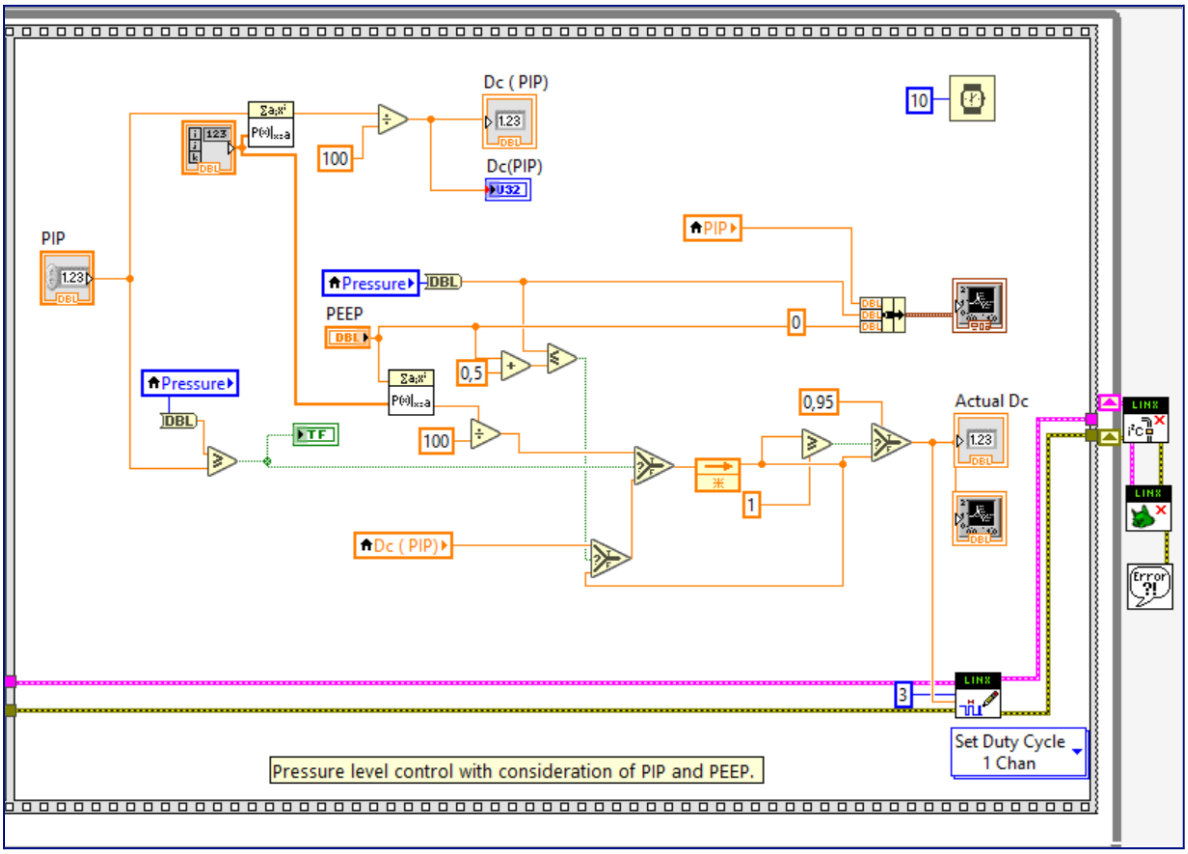



**Fig 4.19** Block diagram sequence for pressure regulation with consideration of PIP and PEEP.

## Results and discussion :

Figure 4.19 represents the result for the control of the output pressure within the boundaries : PEEP and PIP. These values are specified by the user depending on the requirements.

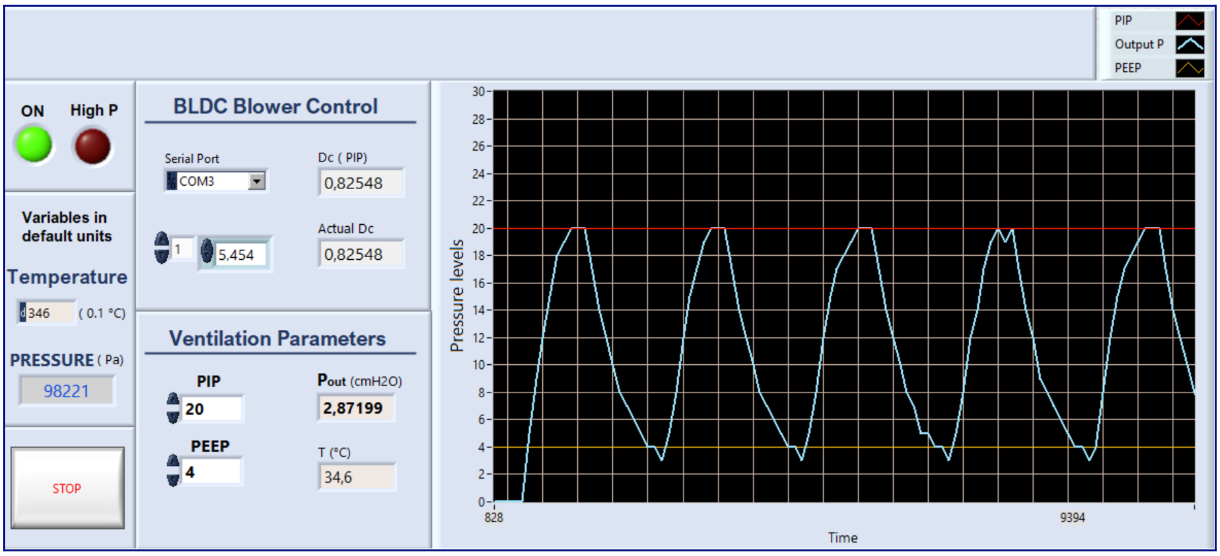



**Fig 4.20** Pressure control results within the preset levels PEEP and PIP.

The graph can be divided into repeated cycles that can be themselves divided into two phases :

- **Pressure increase :** This phase where the output pressure increases from PEEP to PIP level models the inhalation phase.
- **Pressure decrease :** This phase where the output pressure decreases from PIP to PEEP level models the exhalation phase.

It is remarkable that the control of the duration of both phases is not ensured in this case, however, the ventilation process strictly depends on these time periods that are adjusted using the variable I:E ratio.

➢ Pressure regulation with consideration of PIP, PEEP, and the exaltation duration :

The control of inhalation and exhalation periods is a crucial process during mechanical ventilation, so this algorithm should be provided with a function that allows the control of the duration of these phases and it can be achieved using the **elapsed time block** in the LabVIEW code depicted in Fig. 4.20.

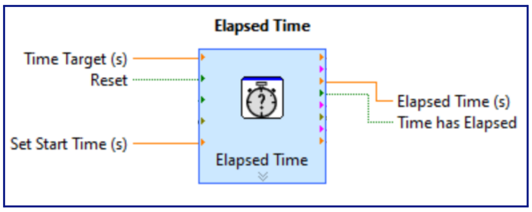



**Fig 4.21** elapsed time block with the necessary pins.

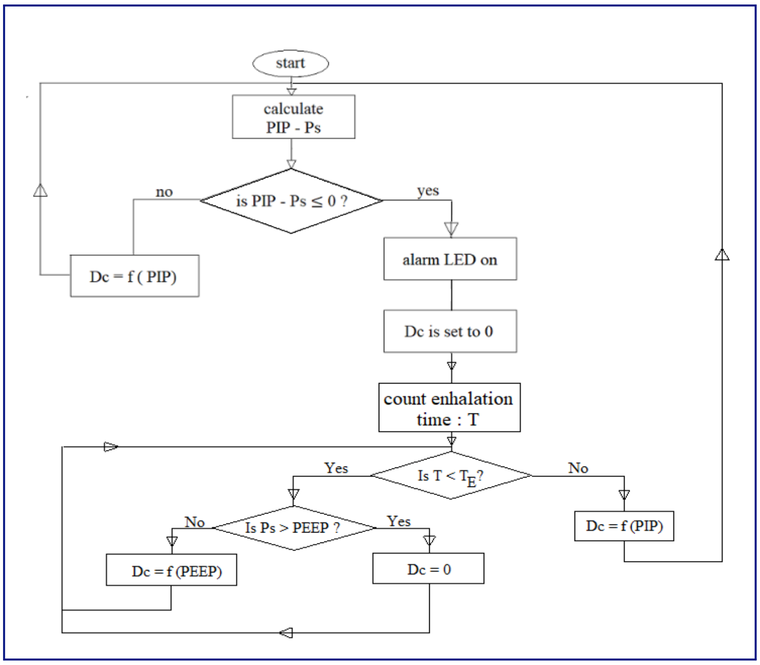
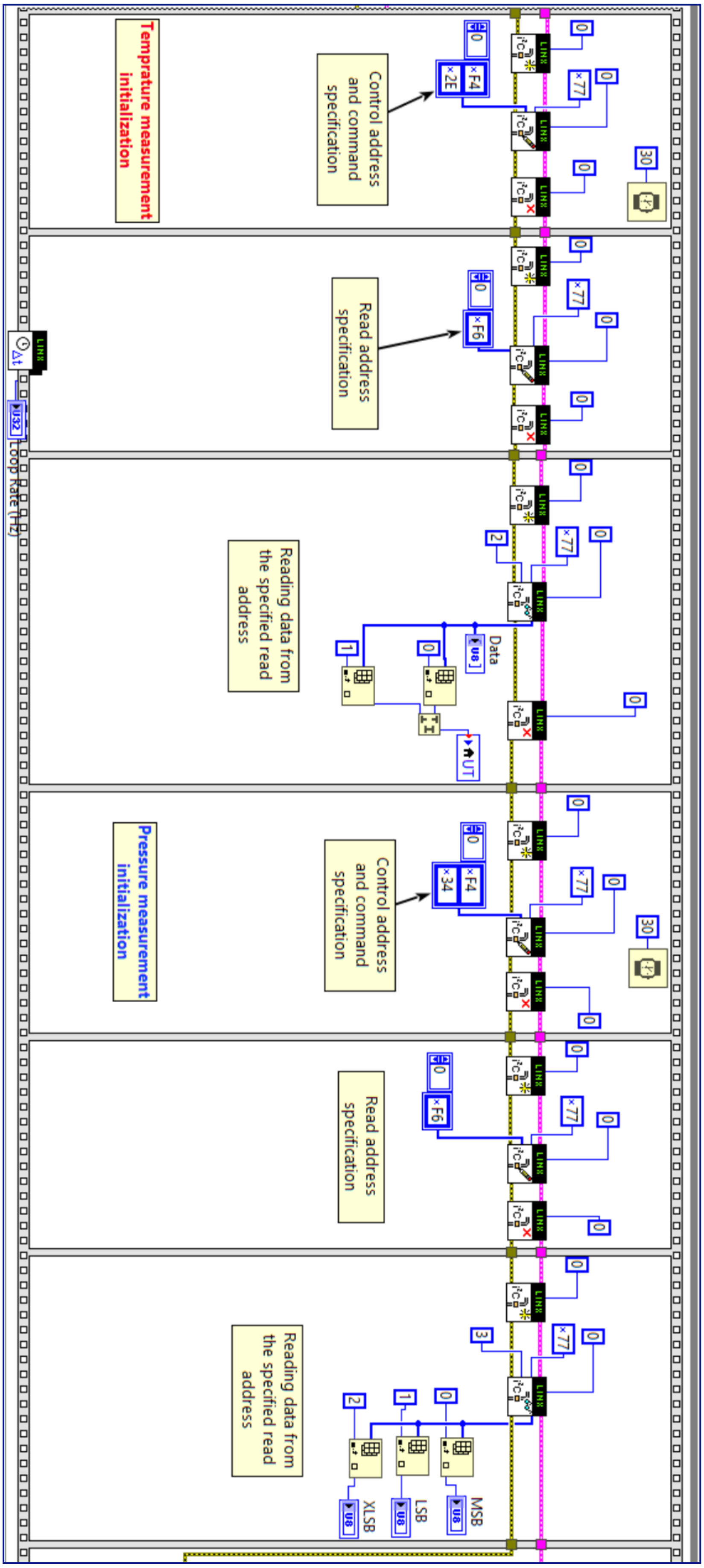



**Fig 4.22** Flowchart for pressure regulation with consideration of PIP, PEEP, and the exaltation duration $T_E$.


Temprature measurement initialization
Control address and command specification
Read address specification
Reading data from the specified read address
Data
Loop Rate (Hz)
Pressure measurement initialization
Control address and command specification
Read address specification
Reading data from the specified read address
XLSB
LSB
MSB

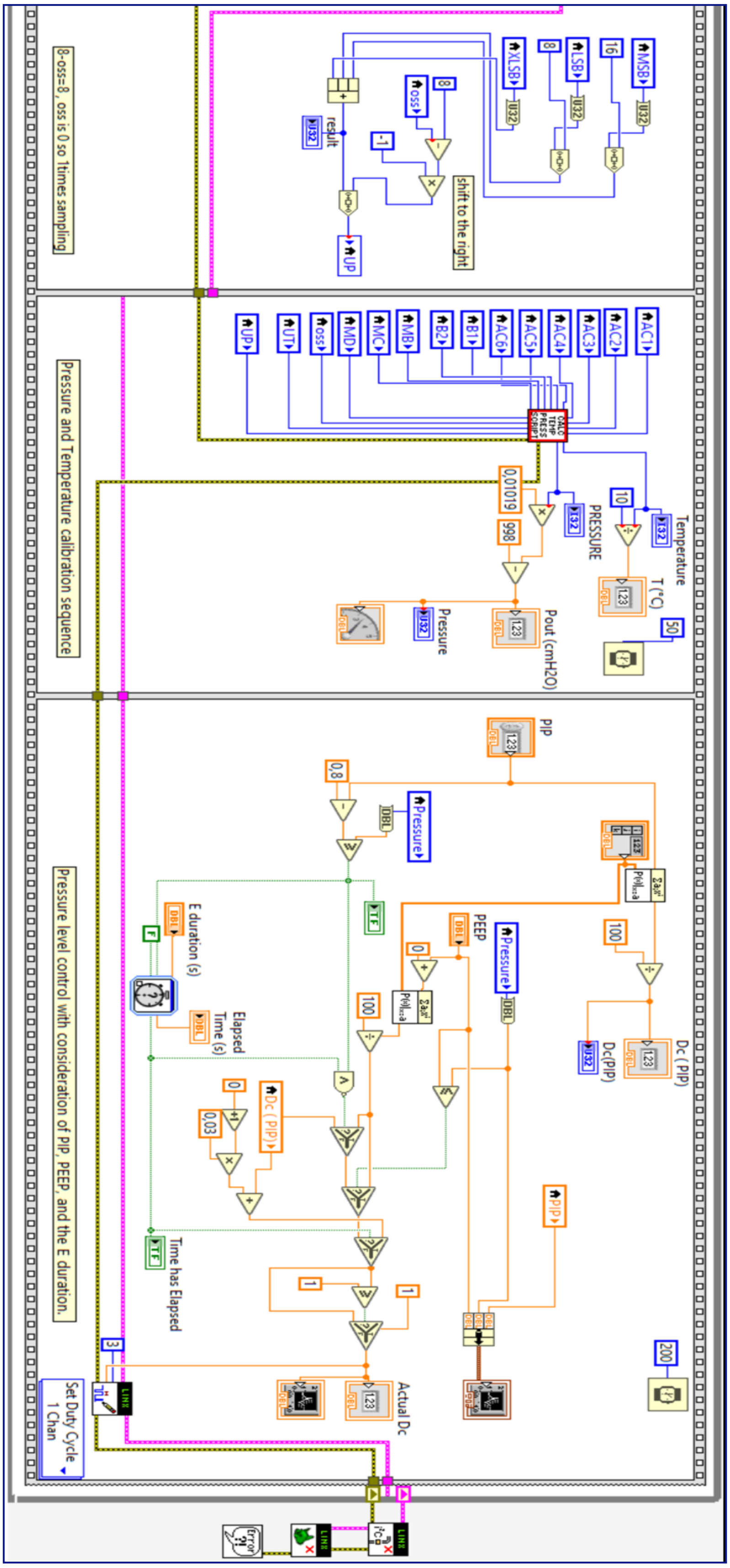



**Fig 4.23** Block diagram code for temperature and pressure measurements, and regulation with consideration of PIP and PEEP.

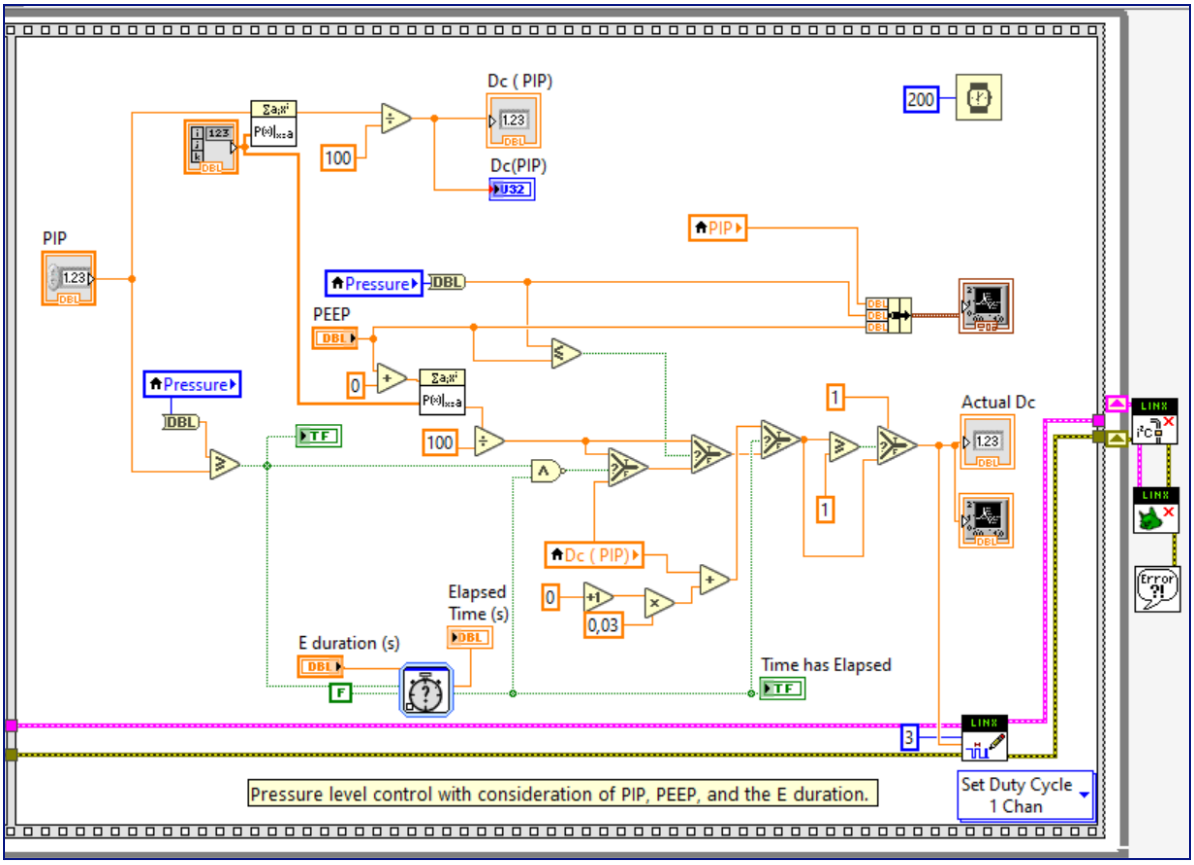



**Fig 4.24** Block diagram sequence for pressure regulation with consideration of PIP, PEEP, and the exaltation duration.

### Results and discussion :

The next three figures show the results for the pressure regulation with consideration of PIP, PEEP, and the exaltation (E) duration. The results are recorded and sketched for different ventilation parameters in order to demonstrate the operation of the system.

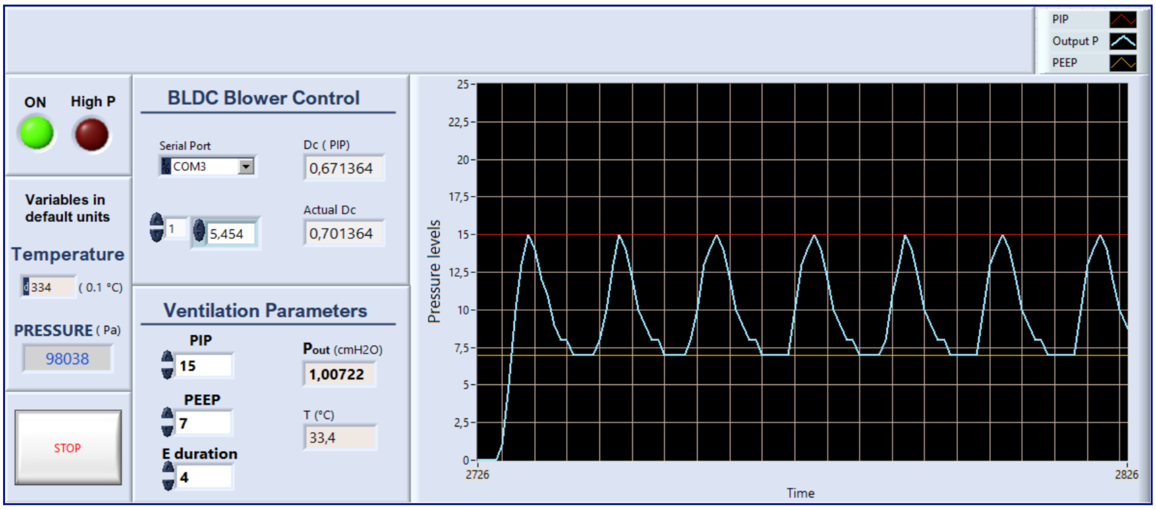



**Fig 4.25(a) :** PIP = **15 cm$H_2O$,** PEEP = **7 cm$H_2O$,** and E = **4s.**

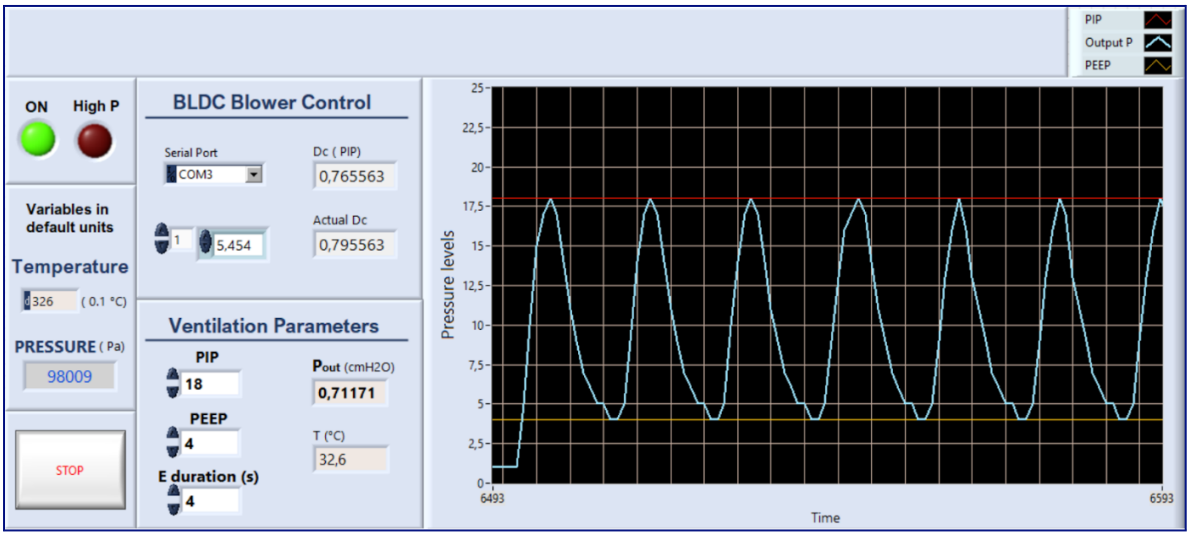



**Fig 4.25(b) :** PIP = **18** $cmH_2O$, PEEP = **4** $cmH_2O$, and E = **4s.**

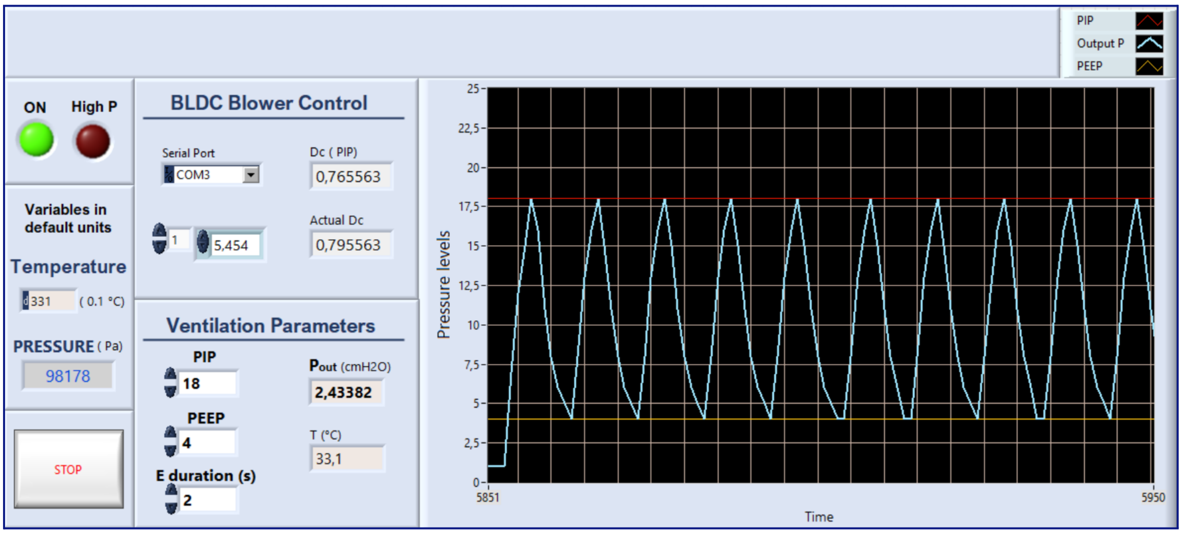



**Fig 4.25(c) :** PIP = **18** $cmH_2O$, PEEP = **4** $cmH_2O$, and E = **2s.**

**Fig 4.25** Results of the pressure regulation with consideration of PIP, PEEP, and the exaltation duration.

So far, the diagram built for this experiment permits the control of the BLDC blower to operate according to a set of important parameters (PIP, PEEP, and E timing) of the ventilation process with an indicator for pressure exceeding the maximum required level (high pressure alarm), in addition to the measurements of the temperature of the output pressured air.

# Conclusion

In the context of respiratory care, this work demonstrates the control of the BLDC blower using an adjustable PWM signal and its integration in mechanical ventilators. This type of motors is preferred to classic actuators for their numerous advantages including :

- High efficiency compared to classic actuators that can be strongly affected by frequent operation (the elasticity of the self-inflating gas tank is likely to deteriorate with time).
- BLDC motors require less maintenance than other types which increases the repair cost.
- They generate less unsatisfying noise mainly for patients.

In this project, The system implemented is a basic version of BLDC blower-based ventilators programmed using the LabVIEW software and MatLab for some identifications. It aims to introduce an effective technique for an open loop control for this motor to operate in suitable manner for ventilation support. The system successfully responded to the requirements and permitted the control of the output pressure of the BLDC blower using an adjustable PWM signal within the limit levels (PIP and PEEP) in addition to the duration of expiration phase.

Similar to different experiments, some implications and difficulties were faced during the implementation of this project and delayed its finalization. The unavailability of some components in addition to unfamiliar protocols and softwares (including the LabVIEW and the I2C communication) hampered the early completion of the work. Furthermore, the selection of the appropriate equipment for the application is a key task and required several tests and trials in order to achieve optimum results.

For further improvements and better outcomes, the system implemented may be provided with additional elements and components that can be interfaced with the previously used controller and programing software including :

- A flow sensor to detect the speed of the air delivered from the blower, hence both the inhalation and exhalation periods can be determined and controlled.
- Air valves with an inhalation and exhalation lines that operate alternatively to insure the flow of air in one direction.
- Oxygen or any additional essential gas reservoirs with their appropriate detectors for better support.

To sum up, for their multiple benefits, BLDC motors are reliable alternatives for other types of motors in different fields and applications noticeably for medical care that necessitate high precision and accuracy which can be even better improved during the upcoming decades.

# References


[1] Hooman POOR, Basics of mechanical ventilation - Icahn School of Medicine. New York, USA.

[2] Mechanical ventilation, ATS Patient Education Series © 2017 American Thoracic Society.

[3] John Landry, BS, RRT, Mechanical Ventilation Monitoring.

[4] John Landry, BS, RRT, Respiratory therapy zone, Ventilator Settings Explained: Mechanical Ventilation, 2023, May 23.

[5] Sasha Hallett; Fadi Toro; John V. Ashurst2, Physiology, Tidal Volume, National Library of Medicine, 2023, May 1.

[6] Komal Parikh, differentiating-peak-and-plateau-pressures, Critical care now, 2021, Jan 18.

[7] Mark A. Warner, Bela Patel,Mechanical ventilation, Emergency Medicine (2nd Edition), 2013.

[10] Austin Hughes, "Electric Motors and Drives " ,3rd edition, Senior Fellow, School of Electronic and Electrical Engineering, University of Leeds,2006.

[11] Introduction to Brushless DC Motors , September 27, 2019

[12] R. Krishnan ,"Permanent Magnet Synchronous and Brushless DC Motor Drives", Electrical and Computer Engineering Department Virginia Tech Blacksburg, Virginia, U.S.A.

[13] Pushek Madaan , Brushless DC Motors – Part I: Construction and Operating Principles, FEBRUARY 11, 2013.

[14] Padmaraja.Yedemale , "Brushless DC(BLDC) Motor Fundamentals " Microchip Technology Inc , AN885.

[15] Brushless DC Motor(BLDC), working principle & construction ,May 30, 2023

[16] Bijgedragen door De Noord-Amerikaanse redacteurs van DigiKey, How to Power and Control Brushless DC Motors, 2016-12-07.

[17] Speed control of BLDC motor, Electrical Concepts, May 18, 2016.

[18] Design and implementation of blower based mechanical ventilator - Pg.01, IEEE, Boumerdes.

[19] Allan F. Simpao, Jeffrey M. Feldman, David E. Cohen, Smith's Anesthesia for Infants and Children (9th Edition), January 2017.

[20] PRESSURE CONTROL VENTILATION, Basic Principles of Mechanical Ventilation, Open Library.

[21] Edgar Delgado, BS, RRT and Leslie A. Hoffman, Pressure Control Ventilation: Practical Steps for Patient Management, Relias Media, April 1, 2000.

[22] Danny Jost, What is a pressure sensor ? Fierce Electronics, Aug 27, 2019.

[23] The Basics of LabVIEW and Graphical Programming, S5 Solutions.com.

[24] LabVIEW MakerHub, LINX FAQ. www.labviewmakerhub.com.

[25] I2C Communication Protocol. https://www.geeksforgeeks.org.

[26] I2C Communication Protocol and how it works, https://www.seeedstudio.com.

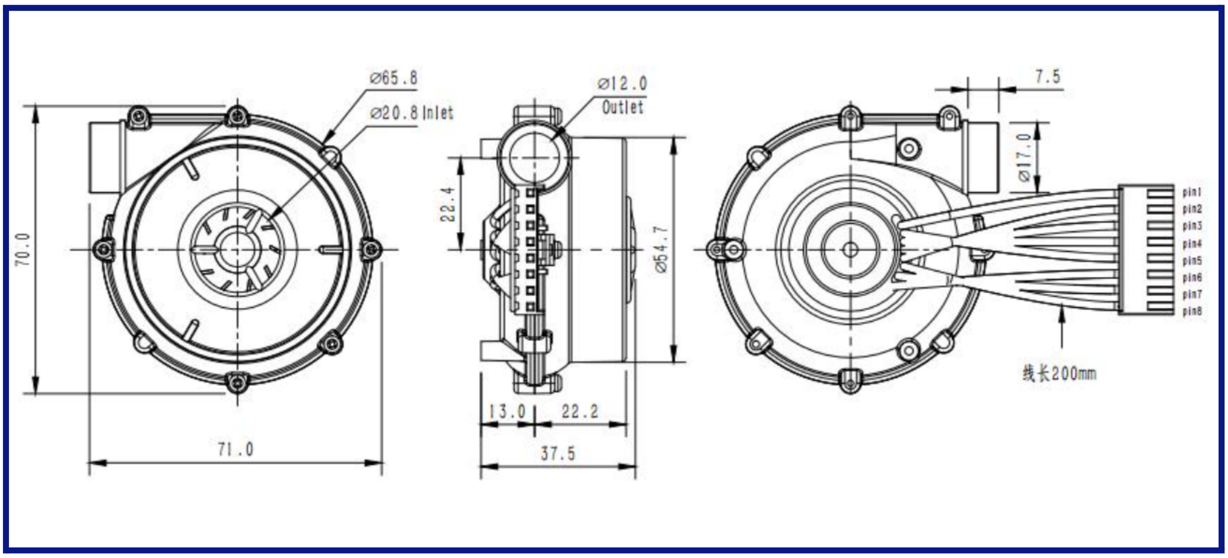
# Appendices

## A) WONSMART Blower WS7040-24-V200 characteristics:

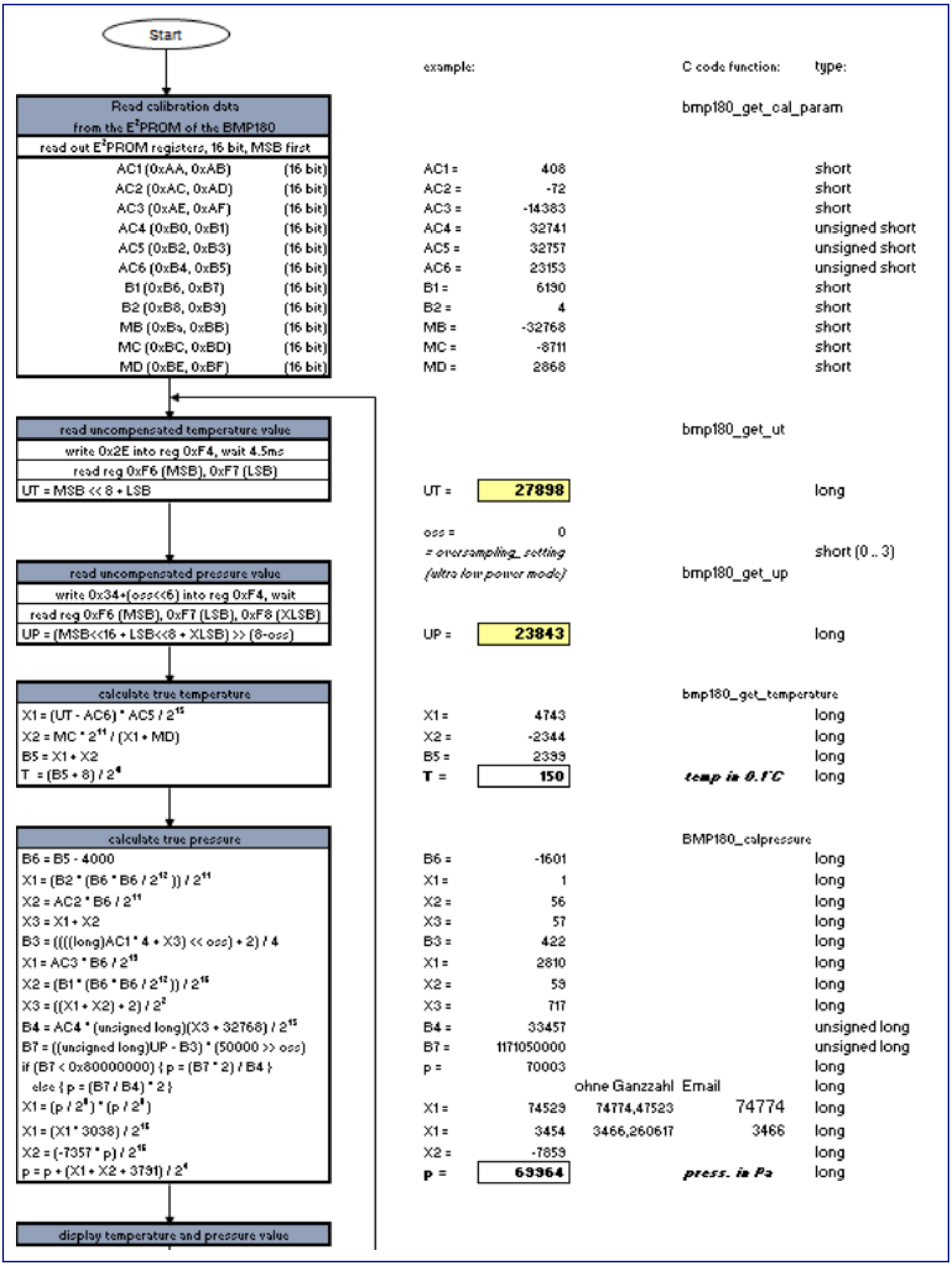
| | |
|---|---|
| Brand name:Wonsmart | High pressure with dc brushless motor |
| Blower type: Centrifugal blower | Applicable Industries: Manufacturing Plant |
| Electric Current Type: DC | Blade Material: plastic |
| Mounting: Ceiling blower | Voltage: 24vdc |
| Place of Origin:Zhejiang, China | Noise Level:70dba |
| Certification: CE, RoHS,REACH,ETL | Warranty: 1 Year |
| After-sales Service Provided: Online support | Static pressure: 8.5kPa |
| Controller: external | Speed Level:45000rpm |
| Housing material:PC | Weight: 85g |
| Motor type:Three Phase DC Brushless Motor | Unit size: D70mm*H40mm |

| | |
|---|---|
| Motor Type | Three Phase Brushless |
| Bearing Type | NMB Ball bearing |
| Dielectric Strength | 500VDC for 1min |
| Insulation Class | Classs F |
| Protect Class | IP20 |
| Operating Temperature range | -20 deg.C~+60.deg.C（No Condensation） |
| Life time(MTTF): | >20,000hours (under 25 degree C) |
| Hall Sensor | 60 |
| Speed @hall sensor frequency | 1HZ=60r/min |
| 24V version choose 24VDC-4A power supplier | |

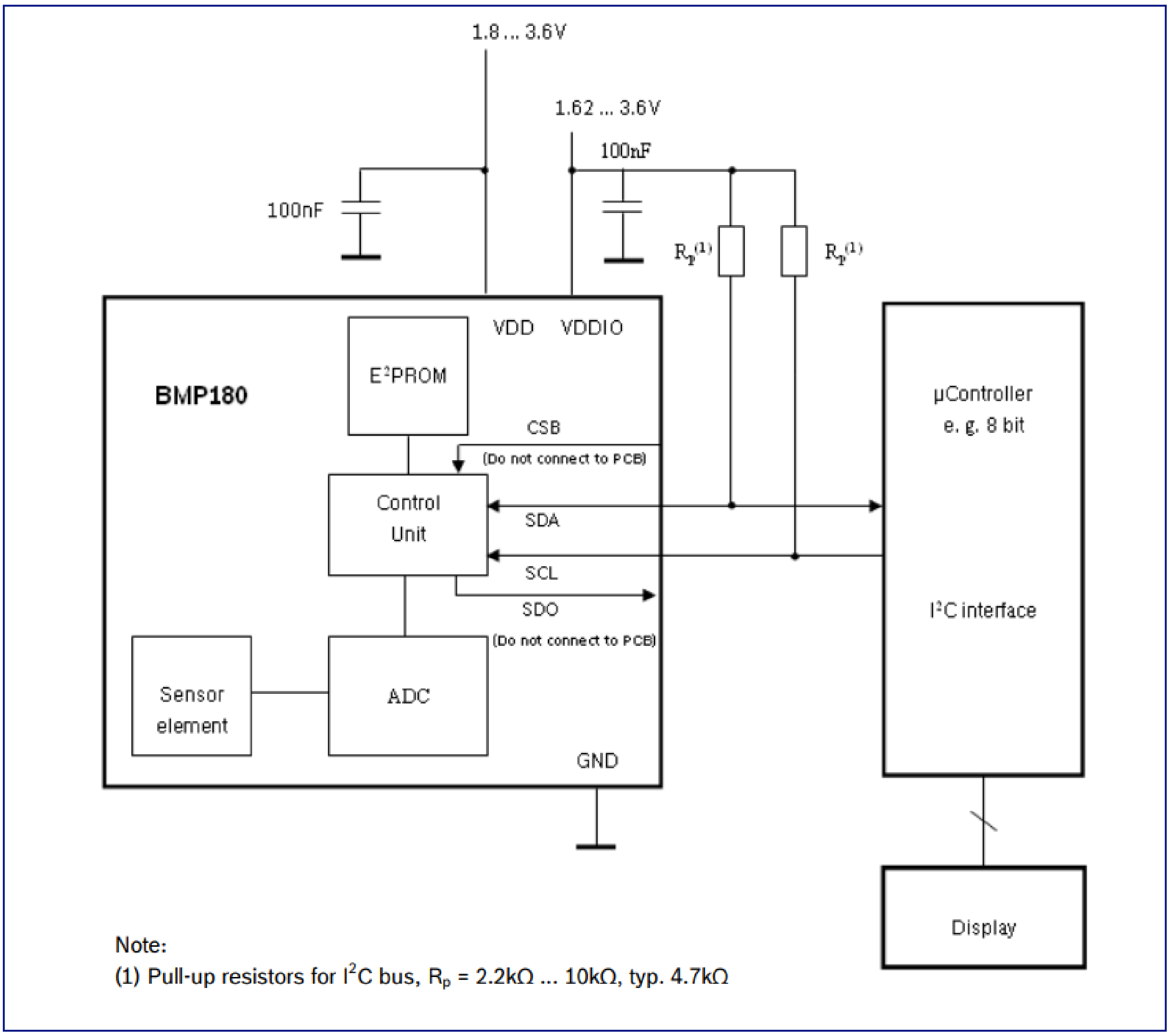
## WONSMART Blower appearance drawing:



## B) BMP180 sensor algorithm for pressure and temperature calculation :



**B) BMP180 typical application circuit:**




## Appendix C:

**Algorithm: Control of Inhalation and Exhalation Phases in Mechanical Ventilation**

**Input:**

- Desired Inhalation Duration (T_inhale)
- Desired Exhalation Duration (T_exhale)
- Initial State (Inhalation or Exhalation)
- Ventilation Start Time (start_time)

**Output:**

- **Control the duration of Inhalation and Exhalation phases**

**Initialization:**

- Set current_state = Initial State

- Set timer = 0

**Loop:**

**- If current_state is Inhalation:**

  - If timer < T_inhale:

    - Continue Inhalation

    - Increment timer by the elapsed time since the last loop iteration

  - Else:

    - Switch to Exhalation

    - Reset timer to 0

    - Record the end time of Inhalation (end_inhale_time)

    - Calculate the time to next Inhalation (T_next_inhale) as T_inhale - (end_inhale_time - start_time)

    - Sleep for T_next_inhale seconds

    - Set current_state = Exhalation

**- If current_state is Exhalation:**

  - If timer < T_exhale:

    - Continue Exhalation

    - Increment timer by the elapsed time since the last loop iteration

  **- Else:**

    - Switch to Inhalation

    - Reset timer to 0

    - Record the end time of Exhalation (end_exhale_time)

    - Calculate the time to next Exhalation (T_next_exhale) as T_exhale - (end_exhale_time - start_time)

    - Sleep for T_next_exhale seconds

    - Set current_state = Inhalation

**- Repeat the loop**

***Notes:***

- The algorithm initializes with the specified initial state (either Inhalation or Exhalation).

- It tracks the elapsed time using the timer variable.

- When the duration of the current phase is reached, it switches to the other phase.

- It calculates the time to the next phase based on the desired duration and the time elapsed since the last phase change.

- The algorithm repeats this cycle indefinitely to maintain controlled Inhalation and Exhalation phases.