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Development of Low-Cost Ventilator for Emergency Use

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ABSTRACT: Ventilators provide temporary ventilatory support and respiratory assistance to patients who cannot breathe for themselves or require assistance to maintain adequate ventilation due to illness. Modern-day ventilators use multiple sensors and controls, making them sophisticated machines to manufacture. The collapse of the supply chain during the COVID-19 pandemic increased the production time of ventilators. The alternate ventilator designs developed to quell these issues provide the basic functionalities to ensure that the patient is alive. This paper explains the low-cost ventilator we designed for emergency use.

Keywords: Ventilator, Low-Cost Ventilator, Proportional Solenoid Valve, Buck Converter and Arduino.

I. INTRODUCTION

Ventilators provide temporary ventilatory support and respiratory assistance to patients who cannot breathe for themselves or require assistance to maintain adequate ventilation due to illness or anesthetics. Ventilators consist of a breathing circuit (A flexible tubing), monitors, a control system, a pneumatic system, an electric system, and alarms. In hospitals, ventilators receive medical air and oxygen supply via the centralized gas supply, and the power supply is either by an electrical wall outlet or a battery. The commercially available ventilators are microprocessor controlled, which regulate the pressure, volume, and FiO2(Fractional Inspired oxygen). The low-cost ventilator is the need of the hour. The production of conventional ventilators takes a longer time due to sophisticated control systems and high-grade parts. The ongoing pandemic has exposed the supply chain, making it vulnerable to massive demand. A shift from the typical ventilator design, using readily available components like proportional solenoid valves, and pressure valves, makes it easy to design and produce on the go. These industrial-grade components are accurate, and they cost less, reducing the unit cost of production. The low-cost ventilator can assist patients in remote areas, where the conventional ventilator is a farfetched thought. This paper provides an overview of the low-cost ventilator we designed and its potential uses for patients in need.

II. LITERATURE SURVEY

Traditional ventilator systems can be simulated using simplified ventilator model using effective simulation tools for parameter study [1]. The research paper [1] simulations are based on MATLAB package which explain the settings of Positive End Expiratory Pressure [PEEP], Volume Controlled Ventilation [VCV] with pause timings along with gas inflow and outflow waveforms. The research paper [3] discusses the ventilation for patients suffering from Acute Respiratory Disease Syndrome [ARDS]. The tidal volumes of oxygen necessary for predicted body weight is stored as a lookup table and fuzzy logic is used to optimize the oxygen ratio. Research paper [4] discusses the concept of mechanical ventilation with pulse oximeter in synchronization. The paper describes the design and construction of Microcontroller-based ventilator using PIC18F4550 along with sensors and peripherals to achieve optimal ventilation. Fuzzy logic-based algorithm for optimization is also discussed. The research paper [5] enlists preliminary designs for simple, easy-to-build portable ventilators. Bag Valve mask-based design, coupled with robotic arm is discussed in detail.

III. PROPOSED DESIGN OF VENTILATOR

Ventilators consists of two main sub-systems, the Pneumatic System and the Control system. These systems in tandem work to support the patient and ease their breathing by forcing the compressed air into their lungs, and remove the exhaled gases.

3.1 Pneumatic System

The pneumatic system in the ventilator controls the intake of compressed air and output of exhaled gases, i.e., the inhalation and the exhalation cycle. In the inhalation cycle, based on the set parameters, the compressed air is regulated into the system at 17PSI – 20PSI (References [6]).

The Control System activates the proportional solenoid valve based on the user input and the pressure in the pathway is recorded. The valve manages the required flow rate to maintain a positive pressure in the system. The air passes through an Air filter which filters out the bacterial and particulate matter from the airway system and feeds it to the dual limb breathing circuit. The indicated makes the inhalation cycle. The exhalation cycle is the breathing out, i.e., out of the patient and out of the system. The exhaled air is again filtered out to prevent the outflow of fluids (mucus, and saliva). A Proportional Solenoid Valve maintains the exhalation ratio, maintaining a positive end pressure by not letting the air to exit the system all at once. The Exhaust end pressure is an important parameter to be maintained to make sure the lungs (alveolar sacks) do not collapse and potentially kill the patient. The aforementioned, cycles complete the pneumatic system, and it's basic likewise working.

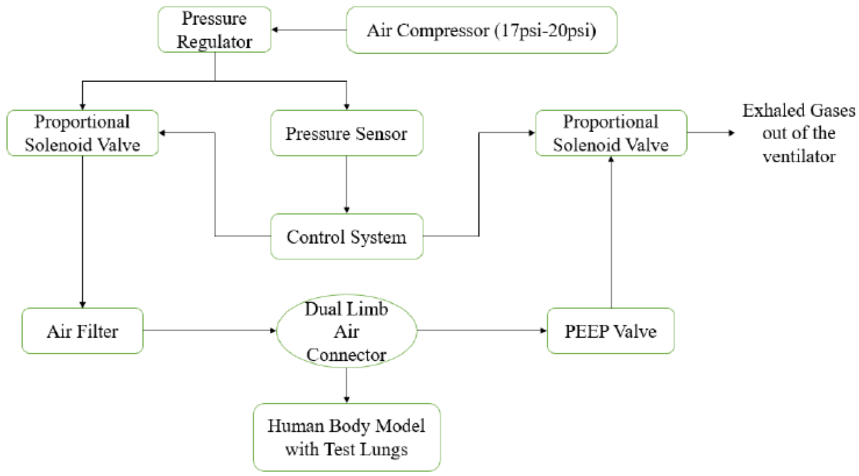

Figure. 1. Pneumatic System of Low-Cost Ventilator

3.2 Control System

The control of the ventilator is accomplished by using a microcontroller that looks after the functioning of the system to support the needs of the patient. The doctor who is monitoring the patient feeds the User input data (the Inspiratory to expiratory ratio (I:E ratio) and the Time Setting). Based on these set parameters the microcontroller sends a PWM signal with a set duty ratio to the solenoid valve. As per the I:E ratio set, the breathing cycle is operated in two halves.

In the inspiration cycle, based on the input valve timing as mentioned in the code, the microcontroller feeds the PWM pulses through the driver circuit to open the proportional solenoid valve-1 (PSV-1) to appropriate level. During this cycle the PSV-2 remains closed.

The air enters the lung through PSV-1. In the expiration cycle, for the remaining time the proportional solenoid valve-2 (PSV-2) is open facilitating the gases to move from the lung to the atmosphere. The PWM pulses control PSV-2. As the I:E ratio are updated, the microcontroller changes the inhalation and exhalation time accordingly based on the set time and operates the PSV valves.

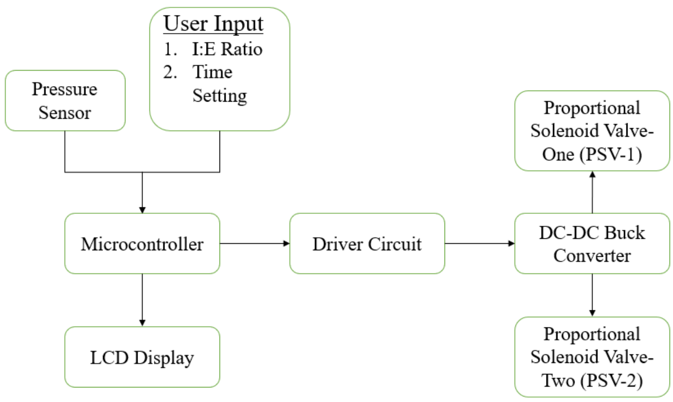

Figure. 2. Control system of Ventilator

IV. ELECTRONICS DESIGN

The control of PSVs (Proportional Solenoid Valve) play a crucial part and having an interface for showing relevant data is beneficial. The electronics design incorporates a power converter, two input knobs and an LCD display. Arduino Uno microcontroller was used as the brain of the circuit. Arduino platform is easy to use platform with readily available libraries and a versatile programming IDE.

4.1 Power Circuit Design

PSV (Proportional Solenoid Valve) requires a minimum 8.5V to operate. As the microcontroller (Arduino Uno) has a maximum voltage of 5V dc, we require an additional dc-dc converter to drive the proportional solenoid valve. The dc-dc converter has a fixed 24V dc input and the output varies as per the gating of the MOSFET. The PWM pulses arising from the microcontroller is given as the gating pulse to the MOSFET through a MOSFET driver. The I:E (Inspiration to Expiration) ratio and the Time settings are displayed on an LCD display.

4.1.1 Buck Converter (DC – DC Converter)

A buck converter (step-down converter) is a DC-to-DC power converter which steps down voltage (while drawing less average current) from its input (supply) to its output (load). It is a class of switched-mode power supply (SMPS) that generally contains at least two semiconductors (a diode and a transistor, although modern buck converters often replace the diode with a second transistor for synchronous rectification) and at least one element of energy storage, A capacitor, inductor, or a combination of both. To reduce voltage fluctuation, filters made of capacitors (sometimes combined with inductors) are usually added to the output (load-side filter) and the input (power-side filter) of such converters.

4.2 Need for Driver Circuit

The microcontroller cannot be connected to the power stage as there is a risk of high current entering the lower power circuits during mishaps, causing the damage of microcontroller, hence, an additional stage is added which acts as a buffer. The circuit uses Opto-Coupler based isolation between Signal stage and Power stage circuits.

V. INTEGRATION OF COMPONENTS AND SOFTWARE CONTROL

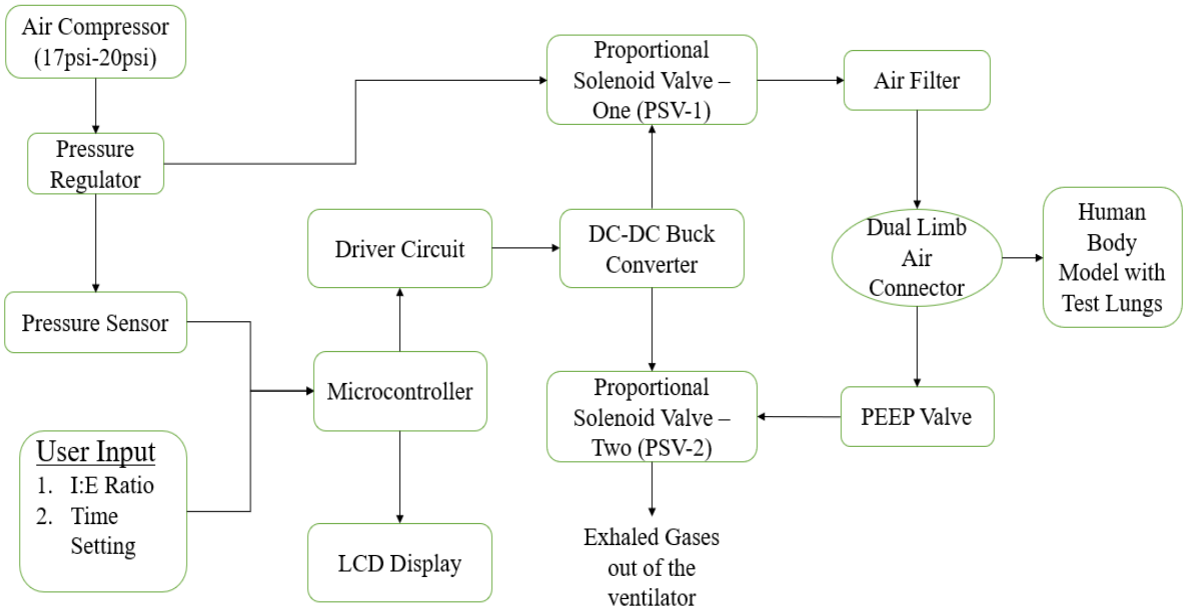

Figure. 3. Consolidated block diagram

5.1 Valve Control

Arduino-Uno board is programmed to generate the PWM (Pulse Width Modulation) pulses having switching frequency of 10kHz. The PWM pulses are fed to the MOSFET of the step-down chopper in order to vary the output DC (Direct Current) voltage. The variable voltage obtained from the step-down chopper is fed to the PSV in order to open or close the valve to set I:E ratio. PSV1 and PSV2 are used for inhalation and exhalation settings independently by varying the voltage fed to these valves. The microcontroller is used to generate two independent PWM pulses that are required to be given to two individual step-down choppers. Step-down chopper-1 produces variable voltage, which is fed to the PSV1 for inhalation setting and similarly Step-down chopper-2 produces variable voltage, which is fed to the PSV2 for exhalation setting. Hence, I:E (Inspiration to expiration) ratio can be controlled in the software control as per the needs, depending on the patient's condition.

5.2 Software Control

The software plays a vital role, controlling the entire ventilator system. The software detects the user input data such as the pathway pressure, I:E ratio, and time setting. Based on the set parameters, the PWM signals drive the proportional solenoid valve. An LCD unit displays the user input parameters. The software controls all the operations without snags, and at a set time, this makes the system automatic and only changes operation when the user gives a new setting. The microcontroller is the brain of the ventilator, executing all the operations effectively. The embedded-C code is uploaded to fulfill the software control of the ventilator.

5.2.1 Algorithm for the ventilator operation

1. Start.
2. Set the input I:E ratio (Inspiration to Expiration ratio).
3. Read the analog values of the set I:E ratio from the ADC (Analog to Digital Converter) to set the corresponding valve operation time.
4. Operate the PSV1 (Proportional Solenoid Valve–1) with respect to the inspiration cycle time. Let the PSV2 (Proportional Solenoid Valve–2) be closed.
5. Operate the PSV2 (Proportional Solenoid Valve–2) with respect to the expiration cycle time. Let the PSV1 (Proportional Solenoid Valve–1) be closed.
6. Check for change in I:E ratio.
7. If there is change in I:E ratio, go to step 3, else go to step 4 and continue the cycle.
8. Stop.

VI. SIMULATION AND RESULTS

Individual components in the ventilator were simulated, tested and calibrated to obtain the desired results, to operate the ventilator.

6.1 Simulation of DC-DC Buck converter

Based on the DC-DC converter design, the components were modelled and simulated for their performance using LTSpice software.

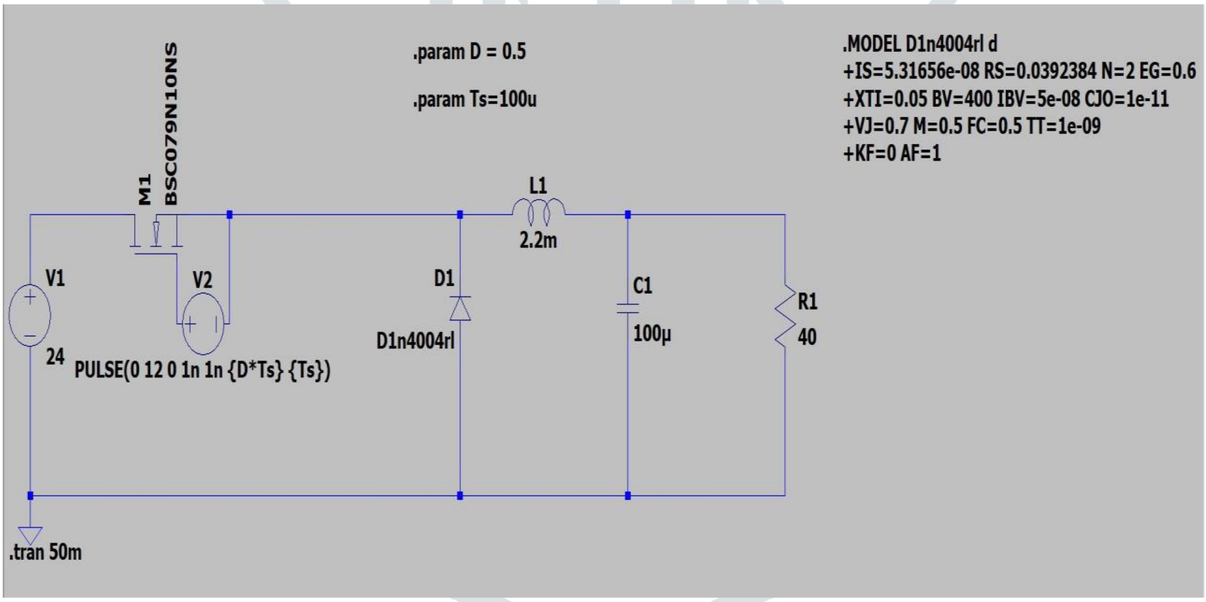

Figure. 4. Circuit simulation of DC – DC converter

The diode model was obtained from open-source platform and the equivalent model of MOSFET has been used in the simulation. The duty cycle is set at 50% and frequency of operation is set at 10kHz. The load is the solenoid valve. The resistance of the solenoid valve is 40Ω, hence is used in the circuit as the load equivalent.

The results of simulation are as follows:

Figure. 5. Current Waveform of Buck Converter

Figure. 6. Voltage Waveform of Buck Converter

Sl. Number	Digital Data	Duty Ratio (in percentage) [%]	Output Voltage (in volts) [V]	Ideal Voltage (in volts) [V]
1	225	25	5.6	6
2	512	50	11.8	12
3	615	60	14	14.4
4	820	80	18.8	19.2

Table. 1. Output of DC – DC converter using software control

6.2 Building Physical circuit

The current and voltage levels are in accordance to the designed values. Hence, the physical circuit was built.

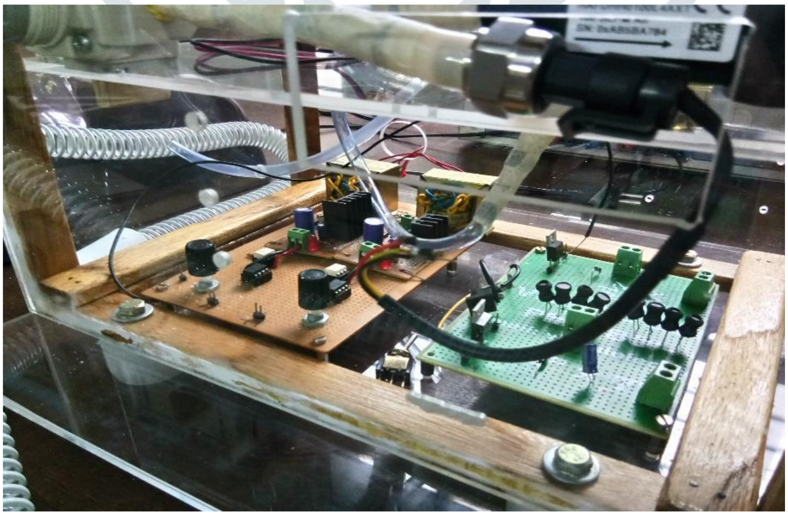

Figure. 7. PCB of DC-DC converter[right], with signal circuit[left]

6.3 PWM Generation using Arduino

The opening and closing of valves control the breathing pattern of the patient. The PWM pulses are required to operate the solenoid valves for this purpose. The output of PWM is a result of the software control (which is mentioned in the section 5.2).

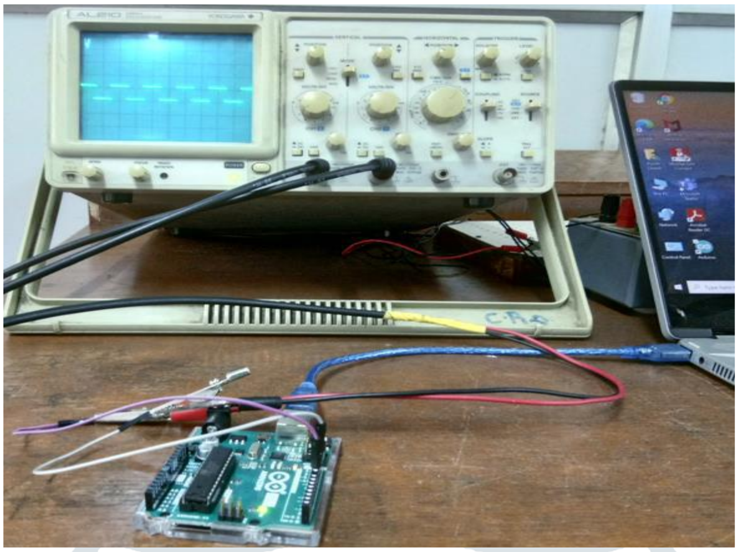

Figure. 8. PWM generation using Arduino Uno Microcontroller

6.4 Driver Circuit

The current and voltage pulses from the Arduino Controller is not sufficient to turn in the MOSFETs and hence cannot operate the Power circuit for the valve control. This challenge is tackled by using an additional MOSFET driver circuit (as explained in section 4.2).

Figure. 9.a. Inhalation cycle output waveform with a set duty cycle

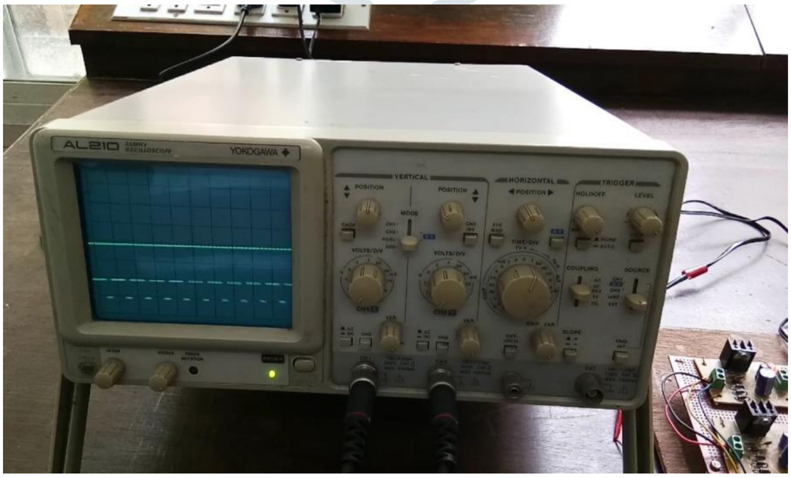

Figure. 9.b. Exhalation cycle output waveform with a set duty cycle

6.5 Combined Working Model

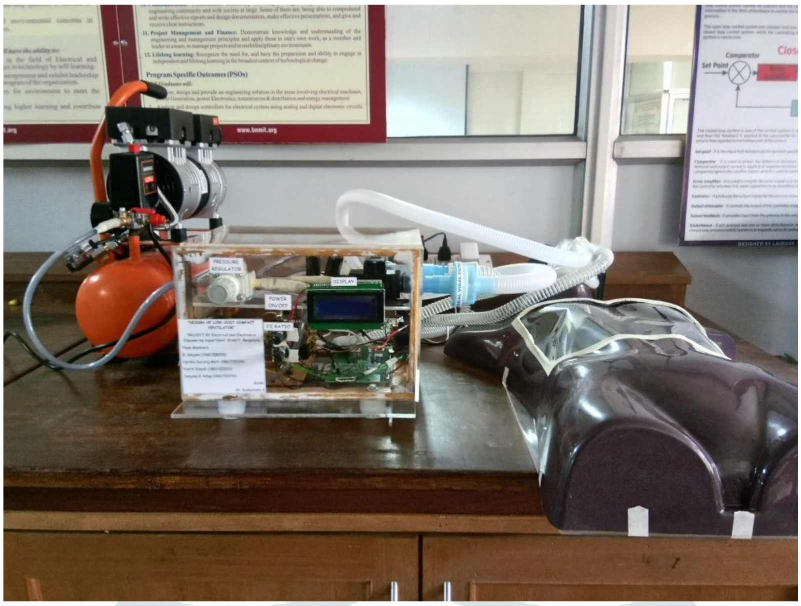

Figure. 10. Working Ventilator of Low-Cost Ventilator with Human lung model

As per the software control, the test lung expands and contracts based on the set I:E ratio and the Time setting.

VII. SUMMARY

The goal of designing the low-cost ventilator is to make the unit ready and available to support the needs of patients at a lower cost. To meet this goal, we designed a CPAP, non-invasive type ventilator system. It provides ventilation, with options to set the time and the inspiration to expiration ratio. This paper describes the design and testing of the ventilator system. This paper further describes the currently available system and the benefit of implementing our approach to reduce the unit cost.

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