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Pressure - Volume Controlled Mechanical Ventilator: Modeling and Simulation

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Abstract

In this publication, the pressure and volume controlled type ventilator, providing breathing artificially, has been modeled. Based on the types of ventilators used in clinical medicine, airflow (q) and volume (v) signals vary. This publication has produced the transfer function of the ventilator by taking the ratio of the Laplace transform of paw(t) and q(t) signals, creating [Q (s) / Paw (s)] as a result. Then having obtained the mathematical models of known and used airflow and volume signals in clinical medicine, LabVIEW and MATLAB / Simulink environment based simulations were carried out using the signals present. Pressure-controlled ventilator has been fully modeled with satisfactory simulations results obtained. Volume controlled ventilator has also been modeled, using approximate theoretical mathematical model, and the model has produced satisfactory results as well except a limited and acceptable approximations error. Then the two types of ventilators have been defined in the form of block diagrams using both Simulink and LabVIEW with all the parameters therein. In both simulations environments airway pressure is taken as input, and airflow as output. Volume signal had been obtained by integrating airflow signal properly. Literature surviliance and search have revealed that although input and output behavior of the system were present, transfer function of both types the ventilators has not been studied and simulated in different mediums, comparatively. This study differs from previous studies as it uses transfer functions representing both pressure and volume controlled types of ventilators. The simulations of the output signals, (q,v) signals, have also been done using the LabVIEW and Matlab / Simulink environment with the input signals as paw and system transfer function. Consequently, the modeling of the system generating signals used in clinical medicine and their verification and monitoring in simulation environments have been obtained.

Keywords: Mechanical Ventilator, Pressure Controlled Ventilator, Volume Controlled Ventilator, Air Pressure, Air Flow, Volume, LabVIEW, Matlab / Simulink

1. Introduction

As it is known and observed, breathing in healthy subjects is autonomous whereas in subjects with lung disease and/or respiratory failure it can not be performed automatically. Then artificial breathing needs to be performed. The device performing artificial breathing is called ventilator and the process is named as ventilation. [1-4]

Ventilation history as a process requiring scientific attention goes to Hippocrates time 460 BC, because during this period, as an crucial matter, air was under scientific concern. Hippocrates scientifically realizes that in cases of drowning in the water, a cannula needs to be placed in the airway tract of the patient in order to send air through. [5]

Aristotle observed in 380 BC that the animals die in stuffy room and fresh air is the basic need for life. [6] To test that idea, the first experiments were performed using fire bellows, the primitive form of fire extinguishers, in 1493 by Paracelsus. [7] The first example of the application of mechanical ventilation is the cannula placed in the trachea of a dog by Vesalius in 1541 aiming to improve the dog's heart beat. [8] In 1635 Robert Hooke observed that, in case of stand-still (not functioning) patient's thorax, with the supply of air application properly, patient life can be saved. [9] In 1786 the first time in history, Kite has revealed the importance of the volume limitation during ventilation. [10] Courtois has chosen to use piston cylinder instead of bellows in 1790 for the first time and had achieved artificial ventilation. [11]

In 1864, Alfred Jones has introduced a negative pressure ventilator, also called "spirophore" type ventilator. [12] In 1876, Woillez has developed steel made spirophore which is accepted as the first model of the lungs. [13] Crafoord, Frenckner and Anderson have designed a ventilator type in 1940, called "spiropulsator" which is able to implement termed intermittent positive pressure. [14] Mörch has produced the first piston able to accomplish intermittent positive pressure in 1941. [15] Engström had applied successfully the first positive pressure based mechanical ventilation to some diseases in Denmark in 1952 and Sweden in 1953 in modern sense. [16] Since 1980 microprocessor based ventilators, pressure control and volume control, have spread rapidly with new modes of ventilation. In this study, firstly the mathematical model of the pressure-controlled ventilator and then the mathematical model of the volume controlled ventilator have been derived and simulated with proper simulation environments. Then the two types of

ventilators had been expressed in the form of block diagrams using Matlab-Simulink and LabVIEW with all parameters. In both models, airway pressure is the input, and the airflow is taken as output. And volume signal is obtained by the integration of the air stream signal. The transfer function of both type of ventilators has not been obtained in previous studies in the past, although both input and output behavior of the system were known. Two difference of this paper from previous studies published in the literature is the use of the transfer functions representing both pressure and volume controlled ventilators, separately. The system has been simulated using LabVIEW and Matlab / Simulink environment taking (paw) as input and its derived transfer function with the output signals named (q, v). As a result, clinically relevant signals of respiratory system has successfully been obtained and observed in the simulation environments used as well, based on the mathematical models developed and tested.

2.Method

Mechanical ventilation is the process done through a machine in case of inadequate or non-existing breathing in patients. Respirator is the name given to this device. Rapid advances in intensive care medicine, particularly in recent years, have made ventilation an integral part of the therapy. Figure 1 gives the block diagram of the basic mechanisms of ventilation process on the basis of three main components. The following components are needed in a ventilation application: **Ventilator** assures the patient breathing. **External oxygen supply** applies the oxygen from the outside world to the system. **Mixer is** the part / section of the ventilator mixing oxygen and air at a certain rate. **User interface** has two functions: it displays the data received from the patient and the device as well as it sets the modes of ventilation type required. Operations can be performed using the facilities of the monitor. **Moisturizer and breathing system** is the system connecting ventilator and the patient properly. The instrument is used to recognize technical and operational errors.

Mechanical ventilation is done by applying positive or negative pressure ventilators. Both types of ventilation create a pressure gradient between the mouth and the alveoli of the lungs allowing it to flow the air into. Signals observed during the exchange of breathing is given below, Figure 2. Paw (cm H_2O) values between -20 and +60, t (sec) value range is given as the chart 0-6. The main objectives of mechanical ventilation are as follows: To improve and regulate the gas exchange mechanisms, to provide adequate oxygenation and / or to ensure carbon dioxide elimination, to reduce the work of breathing until no-pathology case obtained leading to respiratory failure, maintain normal acid-base balance and hold the airway canal stay open.

According to the pressure within the chest, there are two types of ventilation: Positive pressure ventilation and negative pressure ventilation. Positive pressure ventilation is implemented in two ways: invasive and non-invasive. Whether non-invasive or invasive methods are used, the basic operational principles of mechanical ventilation depend on the changing modes of opening and closing of the valves. In the practice of mechanical ventilation the start of inspiration is generally called the mode type. The modes used in mechanical

ventilation shall be regulated by setting buttons on the device, then it is applied to the patient.
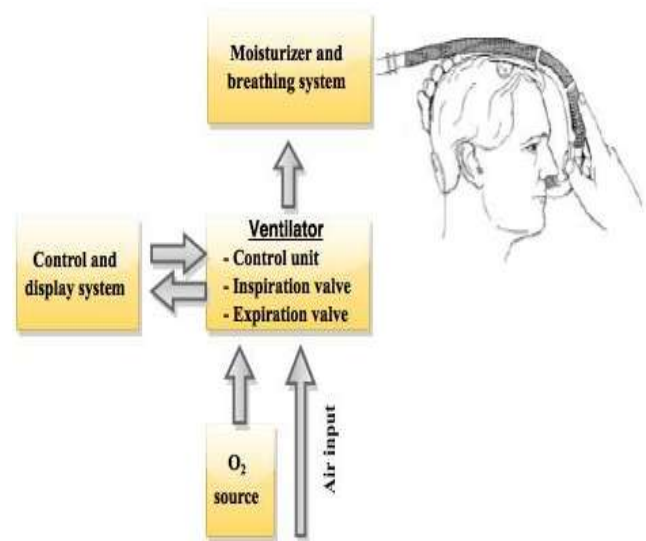
Figure 1. The basic components of a ventilation device
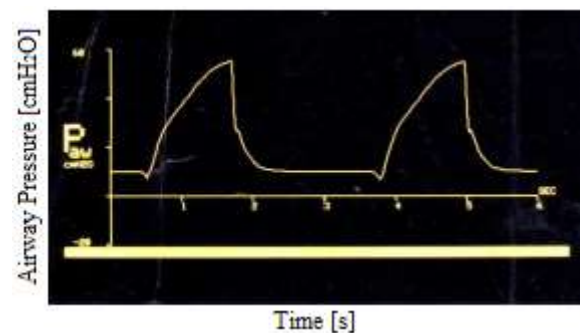
Figure 2. The shape of the observed signal in breathing

Mechanical ventilation modes are divided into controlled and assisted modes. The assisted mode is also called assisted ventilation mode. The common feature of these modes is the inspiration valve, it stay open at regular intervals, depending on the number of respiratory-minute set. Each breath comprises a fixed time and regardless of the patient's respiratory condition that does not change.

Control modes can be divided into two as volume and pressure controlled, according to the inspiratory flow target. Briefly the mode known as VCV (Volume Controlled Ventilation) uses the square mode current wave shape. the the most important advantage of minute based ventilation is to keep it constant / stable. It has the potential to create significant complications / trauma depending on the air pressure (barotrauma). For this reason, the airway pressure should be monitored closely.

In case of volume controlled modes, there is a phase called plateau or pause and this phase is included in the inspiratory phase as well. While keeping both inspiratory and expiratory valves closed, the tidal volume (breath volume) is kept in the lung. Thus what is called as the gas exchange needs to be increased accordingly, inputing of O_2-outputing of CO_2. Basically the parameters need to be set on the device based on volume-controlled modes are as follows: tidal volume, minute

respiratory rate (frequency), I/E ratio or inspiratory duration, pause duration, positive end-expiratory pressure (PEEP) and the value of FiO_2 (Fraction of inspired oxygen), the oxygen ratio of the gas supplied to the patient fresh.

The current waveform of PCV (Pressure Controlled Ventilation) is in slow down form. In this mode, there is no need to worry about the complications such as barotrauma and too high the airway pressure. However, tidal volume and minute ventilation should be monitored closely. As the changes in these parameters directly affect the excretion of carbon dioxide.

Basically the parameters need to be set on the device based on pressure-controlled modes are as follows: inspiratory pressure, minute respiratory rate (frequency), I/E ratio or inspiratory time, PEEP value and FiO_2 value. Volume-controlled and pressure-controlled ventilators have been compared, and a comparison is given in **Table 1**.
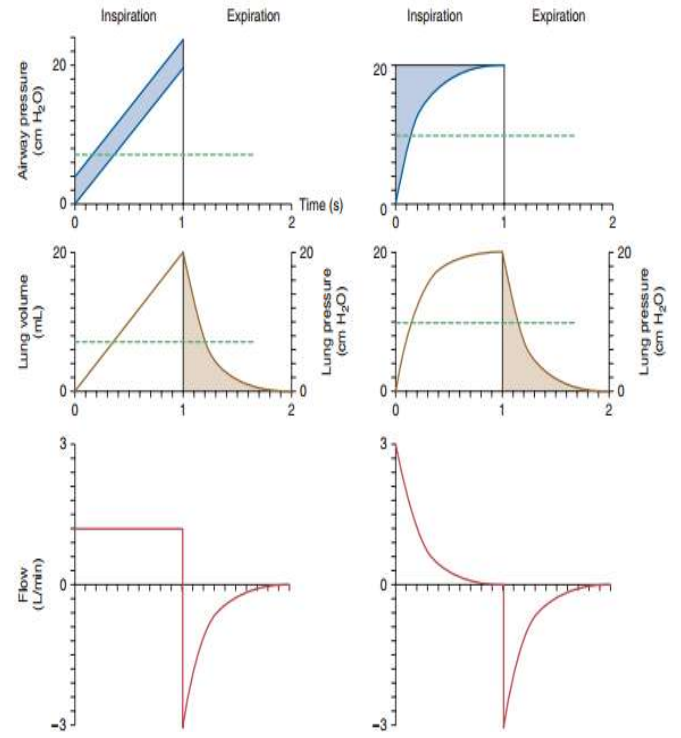
Table 1. Volume controlled and pressure-controlled comparison of the ventilators

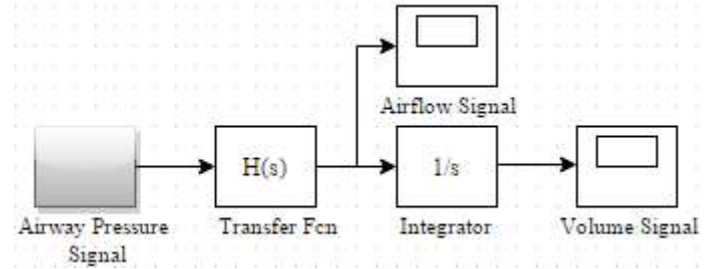| Volume Controlled Ventilator (VCV)	Pressure Controlled Ventilator (PCV)
In VCV type instruments, all modes are independent of peak airway pressure (PAP) and plateau pressure (PP), system designed to provide constant V_T distribution.	In PCV type instruments, regardless of distributed V_T, fixed airway peak pressure (PAP) and plateau pressure (PP) are provided.
The inspiratory flow rate is constant.	The inspiratory flow rate is variable.
Inspiration current shape is square.	Inspiratory flow pattern is exponentially slowing down.
Tidal volume is constant.	Tidal volume is variable.
The pressure is variable.	Airway pressure is constant.

Airway pressure, volume and airflow graphics of both of the ventilation modes are shown below respectively. [17]

2.1. Controlled Ventilator Model

Figure 3 is a graph of airway pressure as input of the system and airflow and volume are taken as outputs of the system. Using known relationship between airflow and volume, the system is expressed by the following block diagram, Figure 4. In this block diagram, H(s) and volume are both unknown parameters. The transfer function of total system is obtained by the rate of the Laplace transform of the airflow signal to the Laplace transform of airway pressure signal. The airflow signal is obtained simply by multiplying the transfer function with the airway pressure signal. This signal is passed from the integrator, and the volume signal has been obtained. Using this basic approach, pressure-controlled and volume-controlled ventilator models have been developed accordingly.

Figure 3. Volume-controlled and pressure-controlled ventilation modes graphs

Figure 4. The general block diagram of a mechanical ventilator model

2.1.1. Pressure Controlled Ventilator Model

In Figure 3, pressure-controlled ventilation mode observed for airway pressure and airflow were obtained on the time axis of the signal using theoretical mathematical formulation as follows:

$$p_{aw}(t) = 20u(t) - 20u(t-1)$$

$$q(t) = 3e^{-0.2t} - 3e^{-0.2(t-30)}u(t-30) \quad t \geq 0$$

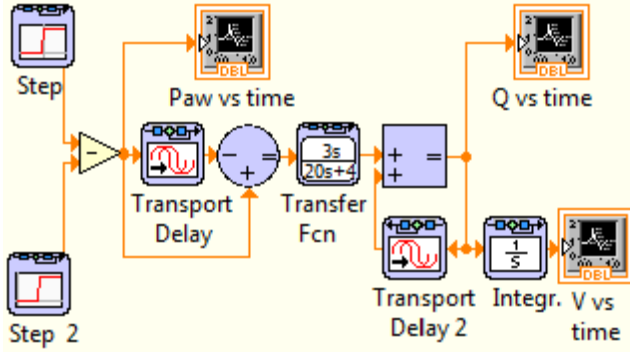Laplace transforms of these signals are given as follows:

$$P_{aw}(s) = \frac{20}{s} - \frac{20e^{-s}}{s} = \frac{20(1-e^{-s})}{s}$$

$$Q(s) = \frac{3}{s+0.2} - \frac{3e^{-30s}}{s+0.2} = \frac{3(1-e^{-30s})}{s+0.2}$$

The transfer function of H(s), as a LTI (Linear Time Invariant) system, is as given below:

$$H(s) = \frac{Q(s)}{P_{aw}(s)} = \frac{3s}{20s+4} \frac{(1-e^{-30s})}{(1-e^{-s})} \quad \ldots\ldots\ldots(1)$$

Block diagram of this system are given with the representation of LabVIEW in Figure 5.

Figure 5. LabVIEW Based block diagram of Pressure-controlled ventilator model

2.1.2. Volume Controlled Ventilator Model

This model was created, shown in Figure 3, utilizing the graphics of volume controlled ventilation mode. The equations governing the airway pressure and airflow signals on the time axis of are written as follows:

$$p_{aw}(t) = \begin{cases} 20t & ; \ 0 \le t \le 1 \\ 0 & ; \ \text{otherwise} \end{cases}$$

$$q(t) = 1.2u(t) - 1.2u(t-30) - 3e^{-0.2(t-30)}u(t-30)$$

$$t \ge 0$$

The Laplace transform of the these two signals is found as follows:

$$P_{aw}(s) = \frac{-20se^{-s} - 20e^{-s} + 20}{s^2}$$

$$Q(s) = \frac{1.2s + 0.24 - e^{-30s}(4.2s + 0.24)}{s^2 + 0.2s}$$

The transfer function of the system is defined as the ratio of the airway signal to the airflow pressure signal:

$$H(s) = \frac{Q(s)}{P_{aw}(s)} =$$

$$\frac{1.2s^2 + 0.24s - e^{-30s}(4.2s^2 + 0.24s)}{20s + 4 - e^{-s}(20s^2 + 24s + 4)} \quad \ldots\ldots\ldots(2)$$

The block diagram of equation (2), the transfer function equation of H(s), is given in Figure 6 using Matlab/Simulink environment. The block diagram of equation (2) is given

below in Figure 7, using 1/1 and 2/2 degree Padé approximations of the transfer function equation of H(s).
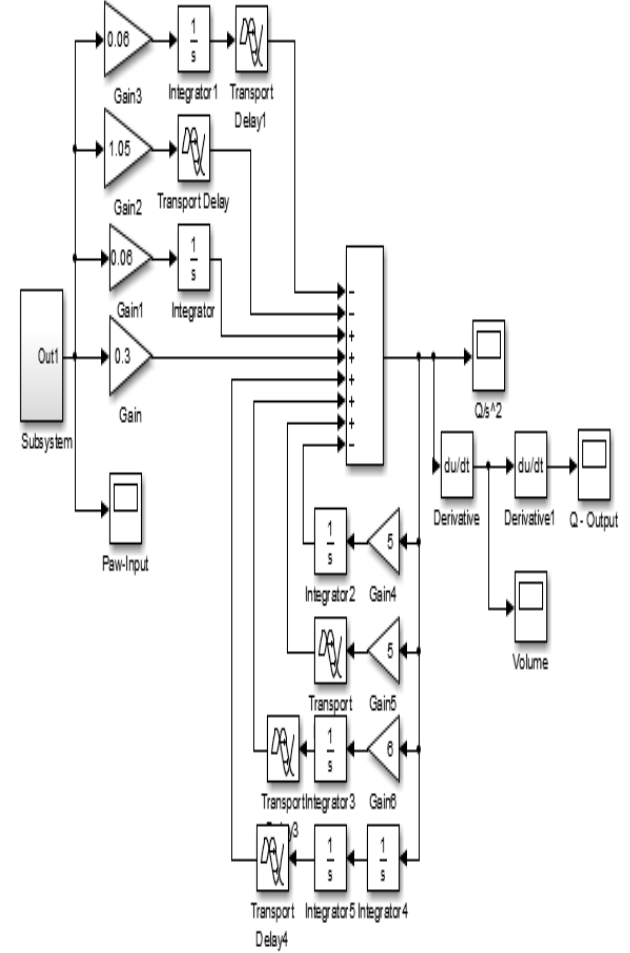
**Figure 6.** Fully equivalent modeling of Volume-controlled ventilator in Simulink environment
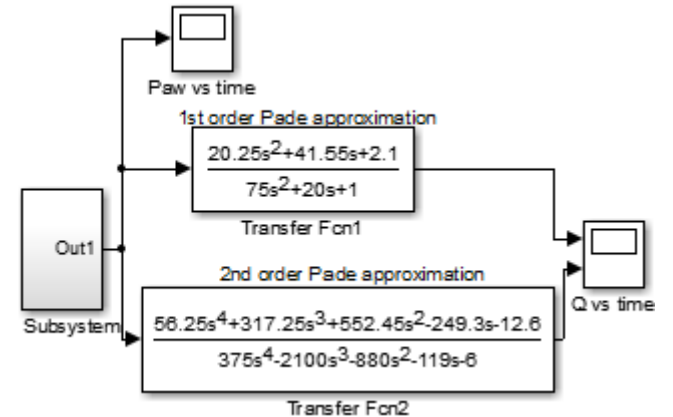
Figure 7. The block diagram of H(s) transfer equation using 1/1 and 2/2 degree Padé approximations generated

An alternative solution used in modelling H(s) transfer function is the backward approach method (backward approximation), and by using this method the second-order discrete-time system has been modeled and simulated

accordingly, the simulation and model obtained using Simulink block diagram is given below in Figure 8.
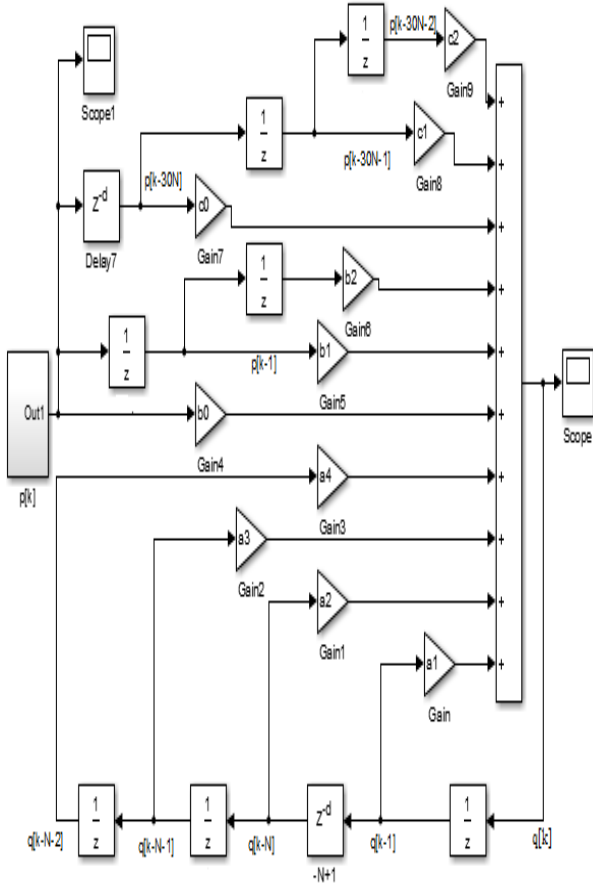
Figure 8. The simulation model of the second order discrete time system using backwards approach method

The second alternative solution method used in H(s) transfer function modeling is the volume-controlled ventilator model using approximation based airway pressure signal.

2.1.3. An Approximate Model of Volume-Controlled Ventilator

When the expression of the airflow signal q(t) is used as it is, and the airway pressure signal is changed as follows, having an exponential function in the form given below:

$$p_{aw}(t) = \begin{cases} 21^t - 1 \ ; \ 0 \le t \le 1 \\ 0 \qquad \ ; \ \text{otherwise} \end{cases}$$
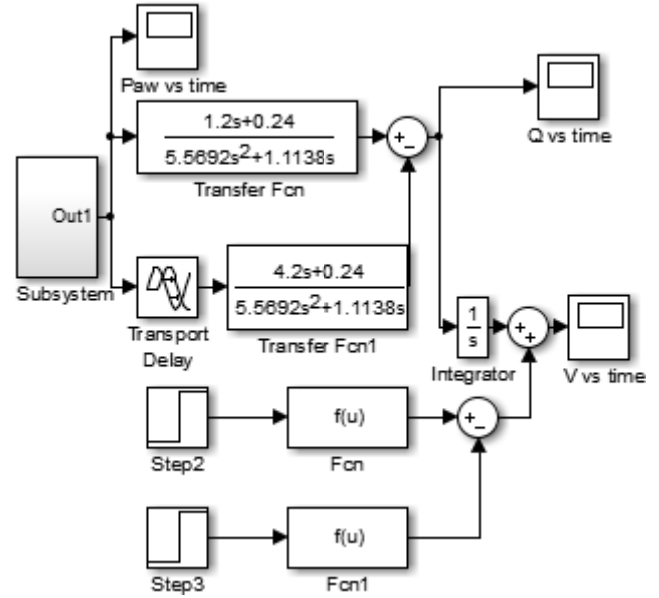
$$q(t) = 1.2u(t) - 1.2u(t-30) - 3e^{-0.2(t-30)}u(t-30)$$

$$t \ge 0$$

Here the new transfer function is defined as the ratio of Q(s) to the integral of airway pressure, $p_{aw}(t)$, which is a constant.

$$T(s) = \frac{Q(s)}{\int p_{aw}(t).dt} =$$

$$\frac{1.2s + 0.24 - e^{-30s}(4.2s + 0.24)}{5.5692s^2 + 1.1138s} \quad ....(3)$$

Simulink based block diagram and simulation of the equation (3) or the transfer equation T(s) based on the approximate model used is as follows in Figure 9.


Figure 9. Simulink based block diagram of volume-controlled ventilator using approximate model

3. Results

The simulation results of pressure-controlled and volume-controlled ventilation models using LabVIEW and Matlab / Simulink environments respectively were conducted. In the light of the information given in the previous section, volume-controlled ventilator simulation models are two types: exact and approximate. Obtained simulations results for airway pressure versus time, airflow versus time and volume versus time graphs for both ventilator models are given in Figures 10-15), the results are in conform with the Figure 3, as the standard.

3.1 Simulation Results
3.1.1. Pressure Controlled Ventilator (PCV)
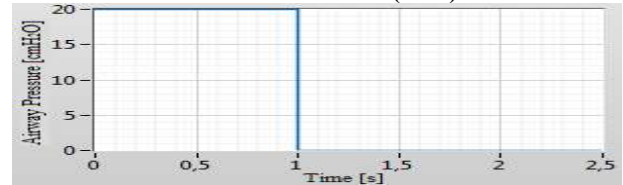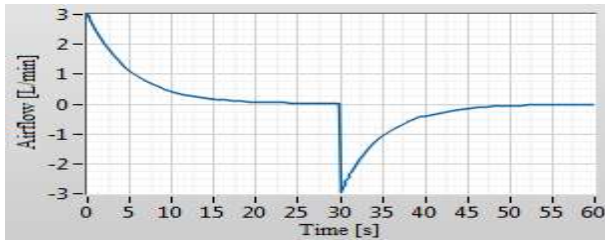

Figure 10. Airway pressure versus time graph
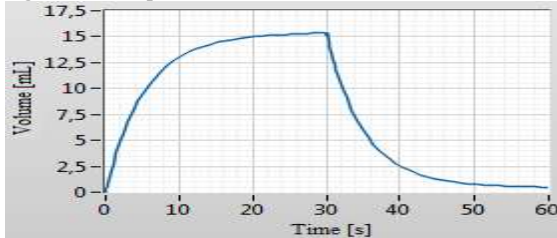
Figure 11. Graph of airflow versus time

Figure 12. Graph of volume versus time
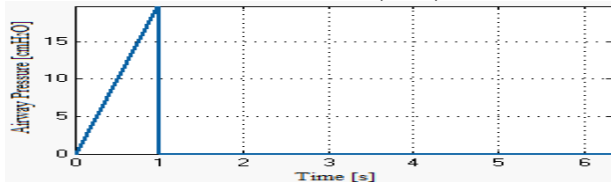
3.1.2. Volume Controlled Ventilator (VCV)

Figure 13. Graph of airway pressure versus time
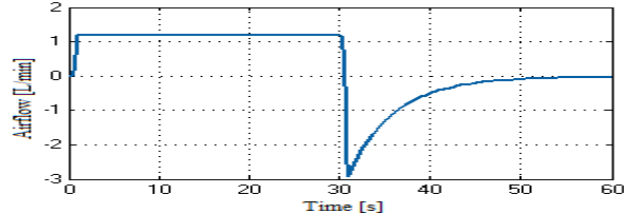

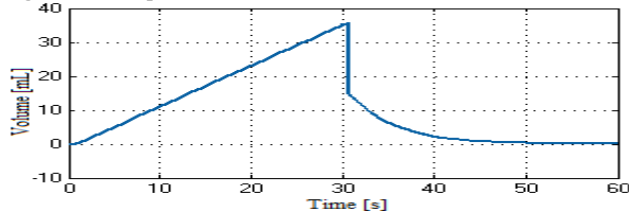**Figure 14.** Graph of airflow versus time

Figure 15. Graph of volume versus time

As seen from the above input and output waveforms of the PCV and VCV graphics, it is observed that the clinical set values, observed clinically with patients in hospitals, have been obtained using models suggested with the simulation environments used. Therefore it is confirmed by the simulation models as well that developed and proposed models perform to the target values expected clinically.

4. Conclusions and Recommendations

Pressure-controlled and volume-controlled ventilators are mathematically modeled. Waveforms of both models of ventilators have proved positive in the sense of clinical expectation and values, based on LabVIEW and MATLAB/

Simulink simulation environments, within the accuracy limits of the simulation. Pressure-controlled ventilator model produced very good results. The transfer function of the pressure-controlled ventilator model is obtained by the multiplication of sub-system's transfer function of $(3s/(20s+4))$ with the ratio of the delay function $(1-\exp(-30s))/(1-\exp(-s))$, respectively. However, for volume-controlled ventilator model, system has no subsystems as well as have no ratio between delays of the whole system. This last model has been used as reference to build block diagrams in simulation environments. System has specifically designed 7-gains, 6 integrators, 5-time delay units (two for 30 sec, three for 1 sec) and 2 blocks of derivatives. When this model executed in Matlab/Simulink environment, it produced an output with amplitude of 20×10^{29} (airflow) and amplitude of -8×10^{14} (volume). With this data, it could easily be concluded that the system is not stable. To obtain stable system and to verify output characteristics of the volume-controlled type ventilators, different methods have been tried and tested. Padé approach has been used in order to obtain the fractional equivalence of $\exp(-30s)$ and $\exp(-s)$ terms standing for time delays in Equation (2). Using 1/1 degree Padé approach for Equation (2) results in the form of the transfer function:

$$H(s) \approx \frac{20.25s^2 + 41.55s + 2.1}{75s^2 + 20s + 1}$$

When this transfer function simulated it has been observed that obtained airflow and volume waveforms were not in conformance with clinical airflow and volume signals. Therefore, in order to produce waveforms signals appropriate to clinical limits / range, 2/2 Pade degrees approximation was used. The following transfer function was obtained when 2/2 degree Padé approximation is used in the equalion (2) with the resulting transfer function, H(s).

$$H(s) \approx$$

$$\frac{56.25s^4 + 317.25s^3 + 552.45s^2 - 249.3s - 12.6}{375s^4 - 2100s^3 - 880s^2 - 119s - 6}$$

The transfer function defining the whole system, H(s), is loaded into the simulation system using block diagrams. It has been observed that the expected airflow signal / graph could not been produced / obtained. Therefore, it has been shown that by increasing the degree of Padé approximation, the similarity of the clinical and simulated signals could not have been achieved satisfactorily. Therefor, the signal affinity will not be realized at the desired level. By using backward approach (backward approximation) method in equation (2), discrete-time simulation model of the second-order systems is prepared and tested. Even this method could not produce the expected result. Therefore different models have been looked after for a few other opportunities for system modeling. Namely; if airway pressure defined using approximate function and airflow function kept as it is suggested, the system expressed and tested with those simulations has given satisfactory results. To develope this research further some suggestions are presented below:

-Solution method is one important simulation parameter for pressure-controlled type ventilator, therefore solution method for the model parameters must be defined as "ODE solver - Gear's Method (variable)".

-The input signal to volume-controlled type ventilator model is defined as 20t, by selecting the closest signal possible

within the time interval specified will produce closer simulation results.

- Padé approximations work quite well at low frequencies, in other words it gives precise results for systems with slowly varying components. Therefore, the equation (2) is a system containing both slow and fast varying components leading to nonappropriate systems with Padé approximation.

-The next study will focus on assisted-mechanical ventilation mode modeling and analysis and its integration with modes modelled. The results obtained clearly confirm that the objectives of the study have satisfactorily been reached.

5. Acknowledgement

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