Electrical modeling and characterization of the faulty state of the artificial ventilators

Karim Zouaq[1] *and Youssef* Mejdoub[1]

[1]RITM Laboratory, Higher School of Technology, CED Science de l'ingénieur, ENSEM, Hassan II University, Casablanca, Morocco.

Abstract. This paper presents an electrical model for detection and diagnosis of different types of faults that mostly occur in the intensive care devices as well as anesthesia devices. This simplified model, that includes the one-compartment CR model for the respiratory system, is well-described in such manner the maintenance agent should gain an understanding of the artificial ventilator basics without any deep medical knowledge or advanced medical staff contribution. Also, presenting the electrical-pneumatic system analogy can significantly help electronics and electrical engineers to well-understand how the ventilator is working and what are the crucial parameters that should be monitored. In the context of the maintenance field action, the model is able to predict the ventilator waveforms abnormality and then help to predict failure in the ventilator itself that lead to helping the IA researcher to think for suitable algorithms for predictive maintenance of medical devices. The model is mathematically described and the circuit is then simulated in Cadence Virtuoso Platform using 130 nm technology. The validity of the proposed model has been assessed using a real ICU ventilator connected to an artificial lung test and running VCV mode.
Keywords— Artificial ventilator, RC model, IA, Predictive maintenance, VCV.

1 Introduction

The Corona Virus Dieses 2019 (COVID-19) pandemic [1] has dramatically affected the world in an unprecedented manner and has fundamentally changed the nature of science and engineering work as such, many electrical and electronics engineers, in several countries, have thought to better use their technical and service knowledge to contribute and prioritize proposals that have a strong potential for immediate impact in the fight against COVID-19 in theirs countries. In addition, some governments have started to engage a significant number of engineers with different skills to develop some alternative solutions and share some ideas that could be helpful and lead to some real actions at a different public hospitals and private clinics to overcome the difficulties possibly faced when defeating COVID-19 [2]. Critical care devices as well as anesthesia machines are considered critical technology and engineering area because malfunctions can cause a patient's death. Therefore, qualified medical service organization must perform preventive maintenance and repair due to the fact that the biomedical staff don't have sufficient level of education, training, spare part, or service experience to repair and maintain complex critical care devices and anesthesia machines, [2].

In this context, it will be tricky to reach the expected objective of the preventive maintenance that led to dramatically increasing the amount of failure of medical devices [3]. To well-understand the mechanical ventilation concept and the interaction between the ICU ventilator and the patient, the electrical engineer must require some advanced medical skills and clinical experience. In addition, life support technologies (resuscitation, intubation and mechanical ventilation) are critical skills needed by most patients who must endure stay in ICU. Two complementary parts are therefore required to repair and efficiently maintain the artificial ventilator, medical knowledge and engineering artistry. In the context of the maintenance, predicting failure [4] should be the light of the end of the channel to overcome any incident caused by the ventilator as a critical medical device directly connected to the patient. In this era, many works have been performed to predict failures in the different medical devices using intelligent artificial tools [5 - 10].

In the critical healthcare situation, the artificial ventilator is the key, and for immediate or quick repair and maintenance, the electronics and electrical engineers and biomedical staff should acquire some medical skills through electrical models. Thus, the ventilator consists of three main parts: pneumatic part, electronic part and the device software that means the software controls the pneumatic through the electronic circuits. Technically, the device is considered as a mechatronic system, and therefore performing analogies between electronic and pneumatic parameters, [11], should help to understand how the ventilators interact with the patient, without a deep medical knowledge or clinical experience. Waveform of the ventilator is the key indicator for predicting critical failure. In fact, any faulty part of mechanical blocs, electrical blocs or software will directly affect the waveform response of the ventilator. In the Volume-Controlled Ventilation (VCV) mode, the pressure sensor is responsible of the pressure data of the airways that build the displayed waveform, and any faulty pressure value led to affecting maintenance part of the ventilator.

This paper is organized as follows. Section I introduces the main concept and purpose of modeling the failure. Section II explores the monitoring concept of mechanical ventilation using VCV ventilator waveform. Section III presents VCV circuit design and its mathematical description. Section IV shows the simulation of the circuit model and its results in 130-nm CMOS technology. Section V introduces the diagnostic approach using the proposed model. Finally, section VI provides a summary of the paper.

2 Monitoring ventilation using waveforms

Ventilators waveforms are widely used to monitor mechanical ventilation and provide doctors with relevant information at the ICU and they mainly produced from calculation of airway pressure P_{aw} and flow dV. Volume- Controlled Ventilation (VCV) is the most important mode commonly used for adult patients [12] in which the ICU ventilator delivers a set flow shape to achieve a set tidal volume (V_T). Alternatively, Pressure-Controlled Ventilation (PCV) should be applied to patients requiring one lung anesthesia and may be superior to VCV in patients with respiratory disease [13]. In fact, VCV offers the safety of a pre-set tidal volume and minute ventilation but requires the clinician to appropriately set the inspiratory flow, flow waveform, and inspiratory time. In this context, modeling VCV mode should be adequate scenario for detecting and predicting critical failure possibly caused by the ventilator. The figure 1 presents how like look the airway pressure evolution in the respiratory system when the patient is ventilated with VCV mode. Three main parameters, which determine the respiratory system performance includes the peak pressure (P_{peak}), the plateau pressure ($P_{plateau}$) and the end expiratory pressure that called the Positive end-expiratory pressure (PEEP).

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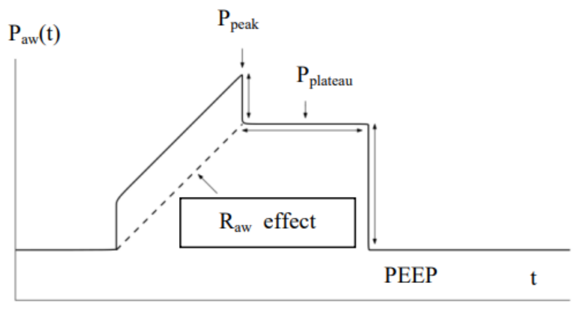

Fig. 1. Typical waveform of VCV mode in healthy state

2.1 Electrical modelling and characterization of the VCV mode

Using the electrical/pneumatic analogy as showed in the table 1, the proposed electrical model of the VCV mode is based then on RC network, R_{aw} and C_p, and a current generator, I_v which generates sinusoidal waveform. The voltage source, V_p, is used to generate an off-set voltage to be added to the output main voltage.

Table 1. Mechanical–electrical analogies

Mechanic	Electric
Volume	Quantity of charge
Pressure	Voltage
Flow	Current
Compliance	Capacitance

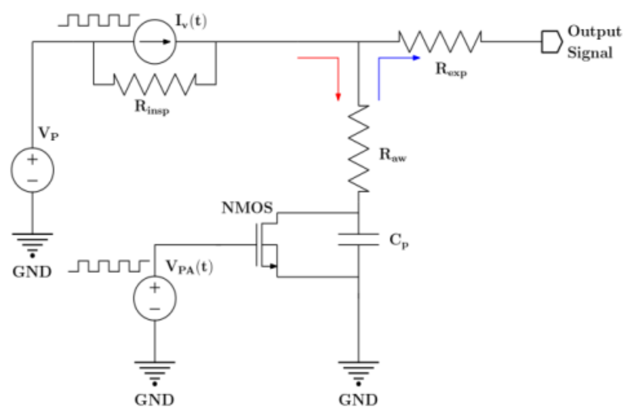

Fig. 2. Proposed VCV model for modeling and predicting failure of the artificial ventilator

The NMOS transistor that is controlled by pulse voltage source that delivers periodic square pulse as a function of time and is independent of the current through the source, is used for pause operation, resulting in a simple barrier to avoid the capacitor C_p, to discharge its current through the series resistor Raw. To model the global behaviour of the VCV mode, the components of the circuit can be divided into two main categories:

1. RC network that presents the respiratory system of the patient.

2. The active components (voltage source, current source and the NMOS switch) that models the ventilator.

2.2 Mathematical analysis

Assuming that the function *sgn* $(\acute{\omega}_0 t)$ is periodic in t with the period $T = 2\pi / 2\acute{\omega}_0$ and with only one positive zero crossing per period, used to describe a rectangular clock signal $I(t) = I_0\, sgn\, [\sin(\acute{\omega}_0 t + \varphi(t))]$. $I(t)$ is the current signal, produced by switching the transistor NMOS that is applied to the RC circuit. Note that T_i is the width of the rectangular current signal inside the interval $[0, T]$, as:

$$I(t) = \begin{cases} I_0, & 0 \le t < T_i \\ 0, & T_i \le t \le T \end{cases} \quad (1)$$

For the first case, $0<t<T_i$, the current $I(t)$ flows through the RC network, then the voltage across the circuit is given by:

$$v(t) = RI(t) + \frac{Q(t)}{C} \quad (2)$$

Based on the charging process of the capacitor, the voltage $v(t)$ can be calculated as:

$$v(t) = RI_0 + \frac{Q_0(1 - e^{-(\frac{t}{\tau})})}{C} \quad (3)$$

Where Q_0 is the maximum value of the charge on the capacitor and $\tau = RC$ is termed the time constant.

For the case, $T_i<t<T_p$, the transistor M_1 is open to avoid the discharging process of the capacitor C thought the resistance R. Therefore, the charge quantity Q_0 remains constant over the period $[T_i, T_p]$ and the voltage across the capacitor can be expressed as:

$$v(t) = \frac{Q_0}{C} \quad (4)$$

For the case, $T_p<t<T_p$, when the transistor N_1 is closed, the circuit is broken without introducing any additional resistance. The capacitor C will discharge itself through R. The current $I_{dis}(t)$ at any time during the discharge is:

$$I_{dis} = -\tau Q_0 e^{-(\frac{t}{\tau})} = -I_0 e^{-(\frac{t}{\tau})} \quad (5)$$

The charge can be easily expressed as:

$$Q = Q_0 e^{-(\frac{t}{\tau})} \quad (6)$$

The voltage can be also written as:

$$v = \frac{Q_0}{C} e^{-(\frac{t}{\tau})} \quad (7)$$

The above functions can be plotted on a graph, as depicted in the figure 4, in which the value on the x-axis is the voltage response, current and charge, respectively, and the y-axis is the time value at which charging/discharging process occurs.

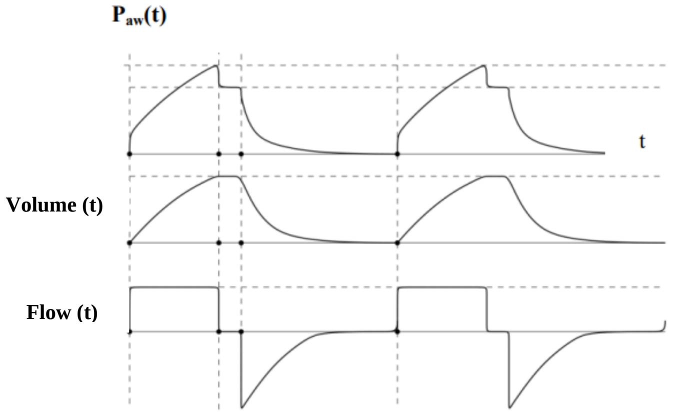

Fig. 3. Plotted waveform of VCV mathematical model

2.3 VCV simulation

The Figure 4 illustrates the behavior of the VCV mode when Iv signal and V_p signals are applied according to the breath cycle, then the NMOS switches as per as the desired plateau duration. Thus, it's seen that the capacitor C_p behaves according to the applied current (flow); the capacitor is charged during the inspiration and discharges through the resistor Raw during the expiration.

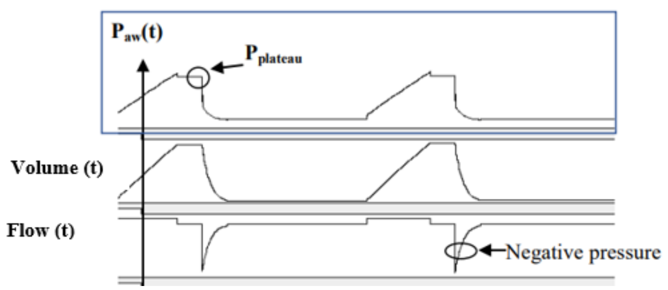

Fig. 4. Simulated VCV waveform using cadence virtuoso

3 Discussion

3.1 Waveform comparison

In the artificial ventilation, curves (also known as scalars) are real-time graphical representations of a variable (pressure, flow, or volume) according to time. They considered as the key indicators of the health of the ventilator. The figure 5 presents how the real ventilator monitors the flow, the pressure and the tidal volume inside the respiratory system of the patient.

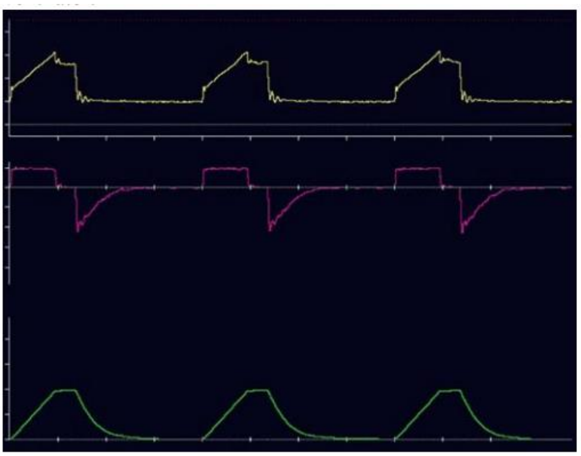

Fig. 5. Clinical VCV waveform (patient waveform)

It's seen that the simulated waveform and the calculated waveform are identical to the clinical waveform directly connected to the real patient which will prove the validity of our model. Thus, the model will be able to predict faulty state of the ventilator. In fact, any critical failure should led to having a bad curve.

3.2 Diagnostic Algorithm

3.2.1 Peak and Plateau pressure

Plateau pressure as well as peak pressure, during VCV mode, are considered as the most important measurements during VCV mode, because they provide information about a patient's respiratory system.

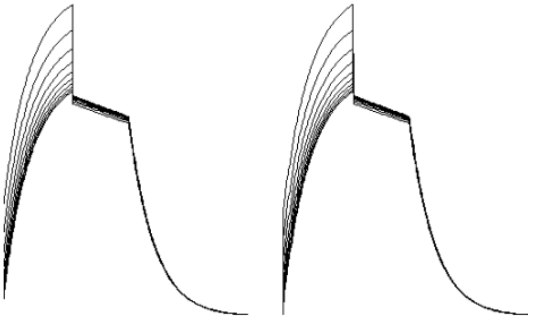

Fig. 6. Pressure waveforms with inspiratory pause function of resistive component of respiratory system

From the figure 6 and figure 7, the simulation result of the electrical model output function of the airway resistance. Thus, it has seen that increasing R_{aw} led to increasing the peak (P_{peak}) while the plateau voltage remains normal. This means the source of peak is mainly the increased resistance value of the circuit. In the context of maintenance, this failure is caused by internal failure in the breathing system of the ventilator.

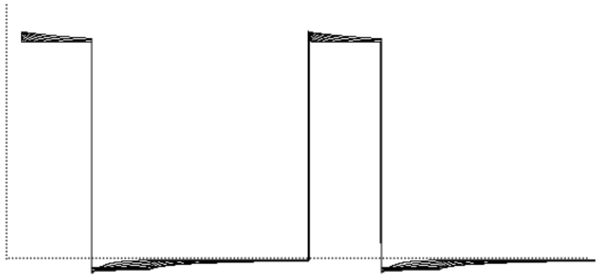

Fig. 7. Flow waveforms pause function of resistive component of respiratory system

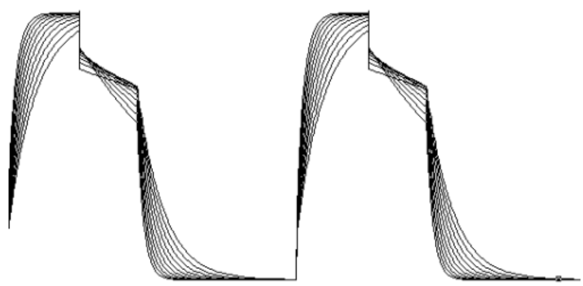

Fig. 8. Pressure waveforms with inspiratory pause function of elastic component of respiratory system

The figure 8 shows the simulation result of the electrical model output function of the compliance. We can see that the charging and discharging of the capacitor is function of the value of C_p. In the ventilator, this situation means the presence of leakage in the pneumatic circuit either internal or external leakage, or a deep verification should be performed.

3.2.2 PEEP pressure

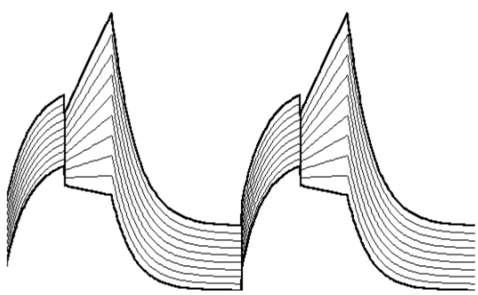

Fig. 9. Airway pressure function of PEEP

The figure 9 shows the variation of airway pressure when adjusting PEEP values. This situation happens mainly when one of the pneumatic valves is defective or the main board is in faulty state.

4 Conclusion

In the context of maintenance of medical devices, artificial ventilators are considered as critical components and predicting the failure should be an expected objective. Modeling the VCV mode using simple and effective circuit is presented. Calculated as well as simulated results using Cadence Virtuoso demonstrated a good approach for predicting failure and diagnostic. This circuit will be able to detect and predict critical failure based on the monitoring curve of the ventilator. Both pneumatic and electronic failures will be detected using the waveform of the ventilator. Since the respiratory response of the ventilator is pressure-based, a simple pressure sensor is able to detect all data and then possibly predict theses failures using IA tools.

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