Energy management in an airflow regulator

T. Bieler F. Bonvin Y. Perriard
Swiss Federal Institute of Technology
DE – LEME, ELG 034
EFPL, 1015 Lausanne
Email: thierry.bieler@epfl.ch Tel: +41 21 693 48 02 Fax: +41 21 693 26 87

Abstract

Artificial respirators are using an electric source of energy to supply the various active components, which control the airflow. A portable or autonomous respirator (urgency, war, ambulance, etc), needs a battery or an energy container to be supplied with great reliability. This paper describes an industrial project that uses only the pneumatic energy to supply all the electronic components. Furthermore, the generator used for the electric supply regulates the airflow by controlling its phase currents.

1. Introduction

The goal of this paper is to show the development of an autonomous volumetric pump for an artificial respirator, whose size is adapted to a restricted volume (Fig. 1). The energy aspect is fundamental and the study of the various components of this regulator is the subject of this paper. The project combines innovating technologies applied to a medical environment.

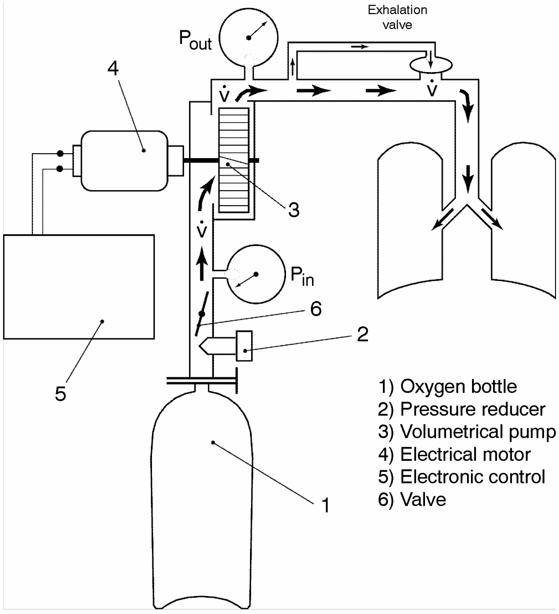

Fig. 1: Diagram of the volumetric pump regulator.

The studied volumetric pump must pulse the air at a fixed ratio and flow to satisfy a patient breathing cycle, as shown in Fig. 2.

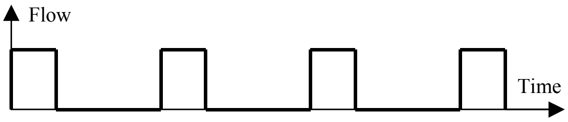

Fig. 2: Pulsed air by the volumetric pump.

The air bottle gives out air under pressure. The motor, which regulates the flow, generates electrical energy only when the flow is sufficiently positive. But as all the electronics needs quite constant energy, it must be supplied by stored energy, when the air is stopped.

2. State of art

The first generation of artificial or assistance breathing systems were mechanically fully controlled.

The current generation uses micro-controllers to master the airflow. It enables adding more functions like alarms, over/under-pressure detection or better adaptation to the normal breathing of the patient. The airflow regulation is often made with a precise restriction of the air.

The use of electronics requires an electrical power supply. This is currently obtained with a standard battery or rechargeable one. The life of the batteries is directly dependent of the number of functions provided by the system : regulation, alarms, display with backlight, etc. It is lasting from 10 hours for rechargeable batteries with the maximum of functions, to 2 years for lithium batteries with limited functions.

3. Volumetric motor

In order to produce a mechanical torque from air under pressure and to deliver to the patient a regulated airflow, a gear-motor (Fig. 3) has been chosen. This motor will be called “air-motor”.

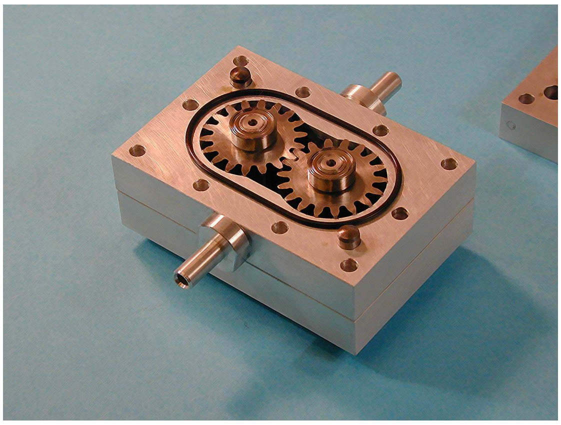

Fig. 3: Inside the air-motor.

The air-motor, coupled to a brushless DC motor, produces electrical energy with a good power conversion. As the airflow is proportional to the speed of the air-motor, it can be controlled by regulating the speed of the electrical motor.

With this design, the two main functions (producing electricity and regulating the airflow) are satisfied.

The air-motor has to be very precisely manufactured to avoid space between sprockets and housing that would result in air lost.

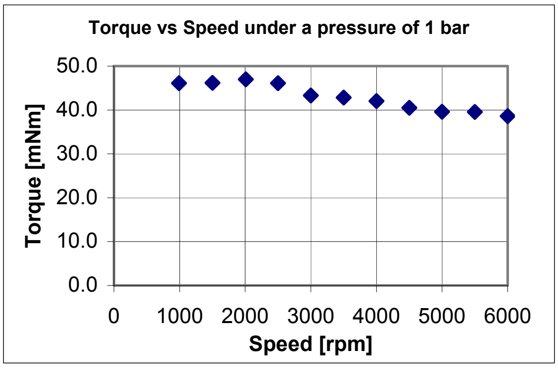

Fig. 4: Measurement of the air-motor torque vs speed.

Figure 4 shows the torque-speed characteristics of the air-motor. As this motor has a low torque friction, the produced torque is only slightly reduced and allows working easily at high speed. Figure 5 shows the friction torque of the air-motor.

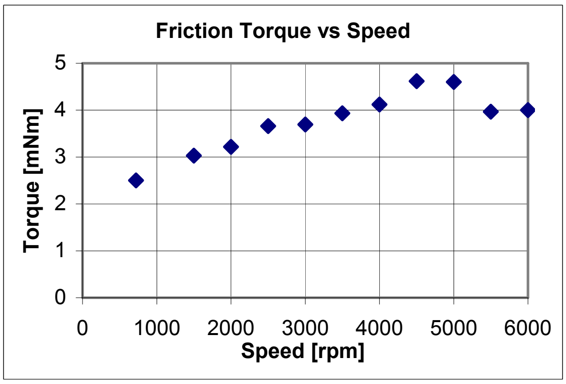

Fig. 5: Measurement of the air-motor torque friction.

This diagram is not very regular due to mechanical resonances appearing on the sprockets at high speed.

4. Power management

For this kind of applications, power management is essential because the electrical energy is not produced continuously. Energy has to be stored during the breathing in phase to supply the electronics during the breathing out phase.

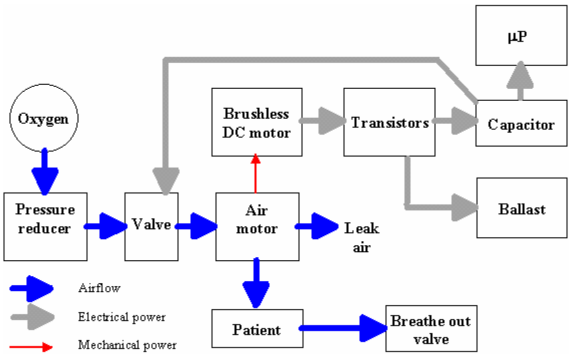

Fig. 6: Interaction between components

Many solutions have been studied to store energy:

a) The use of rechargeable batteries has been rejected because it takes too much time to reach a sufficient voltage to supply the system.

b) The solution using a flywheel has also been rejected because of its size, the maintenance and the mechanical complexity to reduce friction to the maximum.

c) Ultra-capacitors would be a nice solution, energy is stored in a small volume and components are cheap. But because of their high internal resistor, cycles of 1.5 to 6 seconds are impossible to reach. Maybe their use will be possible in a few years. Nevertheless, ultra-capacitors are used to supply the alarm system of the respirator to provide energy for a long time when standards capacitors are empty.

d) The only possible solution is to use a standard capacitor. The speed to store and release is good. The only disadvantages are the price and the size though still reasonable.

The energy is stored in the capacitor, which can be put in different places:

1) In parallel with the power bridge.
2) In an intermediate stage.
3) In parallel with the electronics.

Such three schemes are presented in Fig. 7 with a simple DC motor.

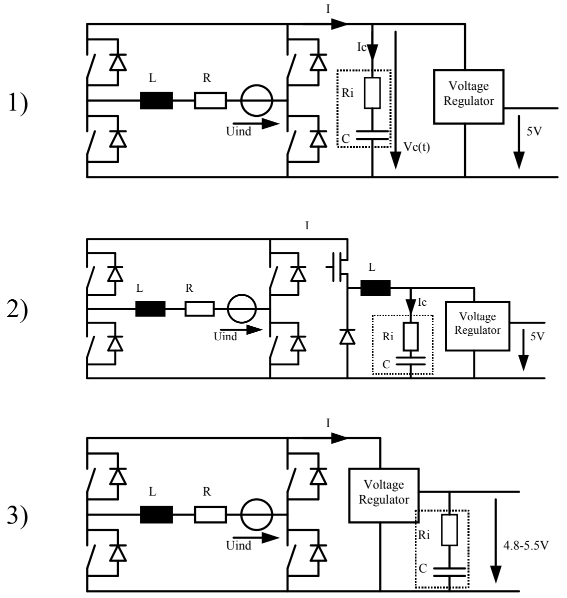

Fig. 7: Power electronics for a capacitor energy container. (Here represented with a DC motor).

The first solution is easy to build and does not need extra components. The DC conversion to supply the DSP is not bad. But, because of the not constant bridge voltage, the regulation of the brushless DC motor is more difficult. The capacitor behaves like an additional inertia on the system when it is empty and increases the time to reach the nominal speed. In this case, it is not possible to switch off the voltage regulator during breathing out phase to minimize quiescent current.

The second solution makes it possible to separate the storage capacitor and the transistor bridge (no increasing of time to reach nominal speed when capacitor is empty) but requires further components and generates more losses due to the additional DC/DC conversion. It is also not possible to switch off the voltage regulator.

The third solution makes it possible to switch off the regulator and to avoid quiescent current during the breathing out phase. But only a small ratio of the energy contained in the capacitor (between 4.8V and 5.5V) is used. This is the only possible solution that uses ultra-capacitors currently on the market but needs a long initialization time to load the capacitor at the first cycle.

Eventually, the first solution has been chosen because of the better efficiency of the DC/DC conversion, which is more important, compared to the saving of time to reach nominal speed.

5. Producing electrical energy

The brushless DC motor, used as a generator, has to produce electrical energy. A 6 transistors bridge using PWM controls the motor. This makes it possible to elevate the voltage: the voltage of the bridge is always comprised within 40 to 60V even if the back EMF voltage of the motor is down to 5V.

A producing energy limit appears at low speed. For this motor, the torque equation is:

$$T=\frac{3}{2}k_a\frac{1}{Z_s}\left[\hat{U}_s\cos(\varphi_s-\delta)-k_a\Omega\cos\varphi_s\right] \qquad (1)$$

With: Z_s = phase impedance
k_a = back EMF voltage factor
$\hat{U}_s$ = peak voltage of the power supply
φ_s = angle between voltage and current
δ = angle between phase voltage and back EMF voltage

For a three-phase short-circuit motor, the lower reachable speed without supplying the motor with external energy is:

$$T_{sc}=\frac{3}{2}k_a\frac{-k_a\Omega\cos\varphi_s}{Z_s} \qquad (2)$$

For low speed, Z_s can be approximated with R (phase resistor) and $\cos\varphi_s$ with 1:

$$T_{sc}=-\frac{3}{2}k_a^2\frac{\Omega}{R} \qquad (3)$$

So the speed of the short-circuit motor, driven by a constant torque, is:

$$\Omega=-T_{sc}\frac{2}{3}\frac{R}{k_a^2} \qquad (4)$$

Any higher speeds can produce usable energy to supply the electronics, On the other hand any lower speeds are impossible because the mechanical power produced by the air-motor is lower than the necessary power to generate the negative torque.

In our application, the theoretical minimal speed is 800 rpm and the minimal speed required to supply the electronics is about 1200 rpm.

The maximal speed is limited by the air-motor but is much higher than the maximal speed needed in this application.

The way to drive the motor is not the best to reach the minimal speed: because of the PWM, if the ratio is not 100% (which may not produce available electricity), the current is not constant and the TRMS (true root mean square) current is higher than the mathematical mean. It results that to maintain a constant mean current with a pulsed current, copper losses, which are proportional to the TRMS current, are higher. But, to produce available electricity, using PWM (or any other pulse modulation) is the only possibility.

Figure 8 shows a measure of the available current under 50V compared to the speed for two different pressures.

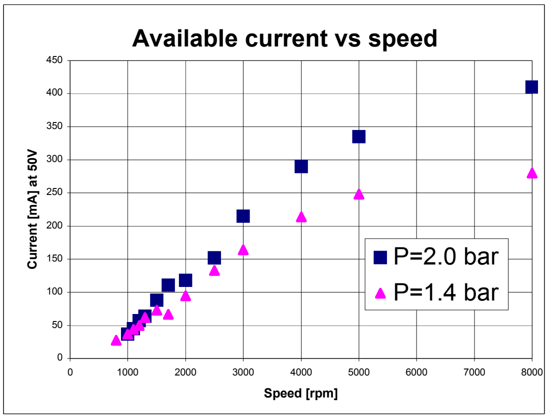

Fig. 8: Available current vs speed.

6. Components limitation

In chapter 5, the lower speed limitation has been determined. But this speed depends on the motor. Using a bigger motor makes it possible to reduce this minimal speed because, for a same back EMF voltage, the resistor of the motor's coil is smaller. But another constraint is important too: the acceleration of the system. Using a bigger motor will increase the inertia. With the scaling laws, it is possible to evaluate the effect of increasing the size of the motor on the inertia and the torque in shortcut.

The asterisk (*) will be used to represent the quotient between two homothetic values. For example, S' represent the homothetic section of the original section S:

$$S^* = \frac{S'}{S} \tag{5}$$

And a section is a multiplication of two lengths:

$$S = l \cdot l \quad \text{and} \quad S' = l' \cdot l' \tag{6}$$

Then: $$S^* = \frac{S'}{S} = \frac{l'^2}{l^2} = l^{*2} \tag{7}$$

Back EMF scale value, coil number of turns, speed and magnetic field are constant:

$$U^*_{EMF} = \frac{d}{dt} \oiint \vec{B} \cdot d\vec{S} = l^{*2} \tag{8}$$

Phase resistor scale value (section and length are modified):

$$R^* = \frac{\rho^* \cdot l^*}{S^*} = \frac{l^*}{l^{*2}} = \frac{1}{l^*} \tag{9}$$

Phase current in shortcut scale value:

$$I_{sc}^* = \frac{U^*_{EMF}}{R^*} = l^{*3} \tag{10}$$

Torque in shortcut scale value for a constant speed:

$$T_{sc}^* = U^*_{EMK} \cdot I_{sc}^* = l^{*5} \tag{11}$$

Inertia scale value:

$$J^* = \iiint r^2 dm = \iiint r^2 \rho dV = l^{*5} \tag{12}$$

Where dm is a weight element, dV a volume element, r the distance from the rotational axis and ρ the specific gravity.

So the inertia is proportional to the torque in shortcut: $J^* = T_{sc}^*$. The system has to satisfy a limited time to reach the maximal speed and has to be able to run at a defined minimal speed. These requirements are difficult to satisfy together and the equations above show that for two identically designed motors but with different sizes, any improvement on one parameter directly worsen the other.

7. Prototype and measures

Figure 9 shows a picture of the prototype and Figure 10 a picture of the electronics. The inside of the air-motor is shown in Figure 3.

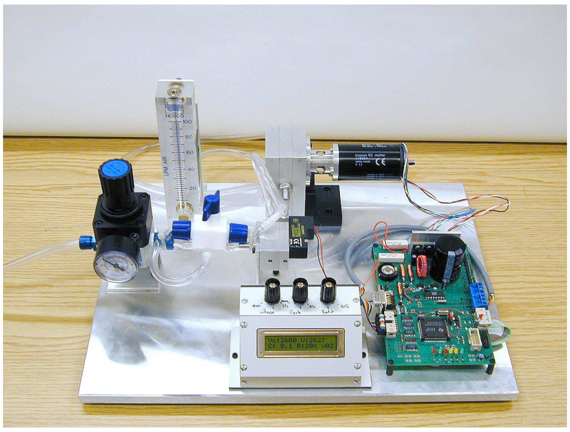

Fig. 9: picture of the prototype.

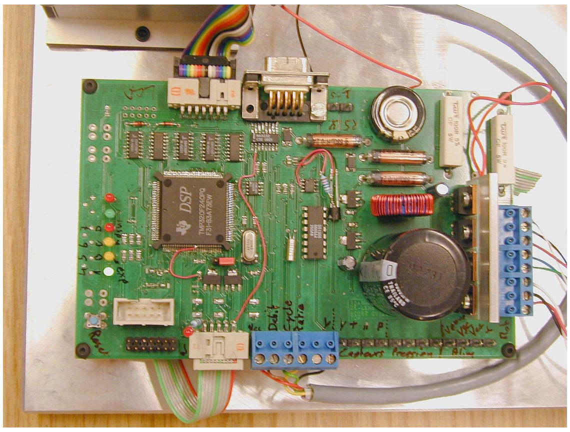

Fig. 10: picture of the electronics.

The prototype works correctly and has proven the availability of an autonomous emergency breathing system.

Figure 11 shows the voltage of the storage capacitor on a cycle.

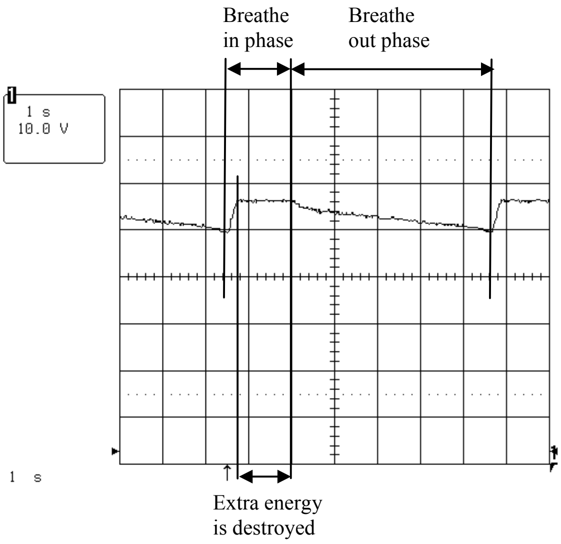

Fig. 11: voltage of the storage capacitor (1s/div).

Figure 12 shows the acceleration of the system. Measurement is realized with a DC motor coupled on the system.

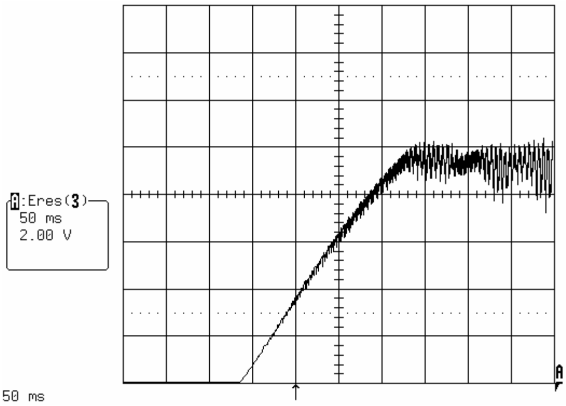

Fig. 12: acceleration of the system from 0 to 6000 rpm (50ms/div).

8. Conclusion

This project has proven that a smart electronics can be supplied, without necessarily using batteries. An electrically self-contained apparatus allows improving reliability and reduces maintenance. Other applications are possible using the concept of producing energy from an air or liquid flow like a volume counter or a flow meter for water with radio data transmission and absolutely no maintenance.

Avoiding batteries is also beneficent to the environment.

Symbols

*	Scaling value
δ	Angle between phase voltage and back EMF
ρ	Copper conductivity, specific gravity
φ_s	Angle between voltage and current
Ω	Rotational speed
dm	Weight element
dV	Volume element
k_a	Coefficient of the back EMF of the motor
l	Length for scale laws
r	Distance from rotational axis
$\hat{I}_{ph}$	Peak phase current in the electrical motor
I_{sc}	Current in shortcut
J	Inertia
N	Number of coil turns in the electrical motor
R	Phase resistor of the electrical motor
S	Wire section of the electrical motor
T	Torque
T_{sc}	Torque in shortcut
U_{EMF}	Back EMF of the electrical motor
$\hat{U}_s$	Peak voltage of the motor's sinus supply
Z_s	Impedance of motor's coils

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