Comprehensive Design Process of a Power Source for a Mechanical Respirator

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ABSTRACT This paper addresses different aspects of design process of a power source for a mechanical respirator. It displays a detailed design procedure for an boost power factor correction converter as a power supply for a DC/DC converter that powers the mechanical respirator. It also has an internal energy source, and an algorithm that detects the absence of a main power supply and low battery voltage. Besides, strategies and control schemes for the converter are proposed. This work also suggests a digital control and equations in difference to be implemented in a microprocessor. The system simulations are consistent with the real implementation observing proper operation.

INDEX TERMS Control, converter, mechanical respirator, power supply.

I. INTRODUCTION

Medical device power supplies must meet energy quality and power quality standards [1]. According to [2], energy quality consists of maintaining the operation of the medical device facing energy supply and power quality interruptions. According to [2], it is responsible for the quality of the voltage and current waveforms; power factor illustrates the efficiency of power consumption when converted to useful power [2].

In medical centers, some devices are sensitive to energy quality and power quality. In [3], data centers, communication systems, hospitals among others are considered as critical loads.

The interruption of energy supply can occur for noticeably short periods of time, from few seconds up to several hours. According to [2], energy quality is classified in different time scales called short, medium, and long term power variations, given the medium term power variation, which considers a time scale of minutes up to hours. For a mechanical ventilator, it is essential to guarantee suitable quality of energy in the medium term, because the interruption of its operation can lead the patient to death; therefore, it is vital that the energy supply of the mechanical ventilator has a backup energy source in the event of an interruption of the electrical energy service to which it is connected. The backup power source must ensure the operation of the mechanical ventilator in the medium term, i.e. for several hours.

On the other hand, power quality is defined in [2], mainly dealing with the quality of the voltage and current waveforms, especially that the waveform of the current follows at every moment the waveform of the voltage (at the input of the power supply of the device), this is known as power factor (PF). In [4], the power factor is considered as an performance index that measures the relative efficiency of energy consumption, that is, how much energy the power supply takes from the network is transformed into useful work. In this context, for mechanical respirator the power quality must also be guaranteed. In this work, the power factor is considered as an indicator of power quality for the power supply of the mechanical respirator.

Considering that power supply for a mechanical respirator must have energy quality and power quality, in [5] it is stated that converters are promising candidates for energy quality control, and in [6] a stage consisting of the buck-boost power factor correction converter used to achieve high power factor; therefore, in this work is considered a boost power factor correction converter (BPFCC), which by means of control loops achieves that the waveform of the input current \( i_{ac} \) follows at every moment the waveform of the input voltage \( v_{ac} \), achieving a high power factor, thus giving power quality to the device.

In addition, an array of batteries \( B \) is established, placed at the output of the converter to obtain an internal energy
source, which supplies energy when there is no supply of the energy grid, giving energy quality to the power supply of the mechanical respirator.

Since this power supply requires signaling when the energy supply network and the battery voltage fall outside the values necessary to maintain its operation, the algorithm capable of detecting the previous situations and generating the corresponding signals is established, which determines the absence of electrical energy from the network and battery low voltage.

Since the power supply for a mechanical respirator involves requirements such as energy and power quality seen above, then a design procedure is established taking into account key parameters as those observed in Figure 1.

This article establishes the detailed design procedure for a BPFCC as a power supply for a DC/DC converter that powers a mechanical respirator; it also has an internal energy source, and an algorithm that detects the absence of main power supply and low battery voltage.

A. PAPER APPROACH AND DOCUMENT ORGANIZATION

This paper addresses different aspects of design disregarded in previous works; therefore, to observe the contribution made in this article, a comparison of the proposed design methodology of the BPFCC with works carried out by other authors is shown in Table 1. Regarding the BPFCC, the respective model was developed in [7]. In addition, in this work the driving losses in the model were taken into account. Regarding the values of \( L \) and \( C \), in [8] and this work, the equations were delivered and explained. Besides, this work includes restrictions to find these values. In reference to the selection of semiconductors, in [8] and this work, considerations were given to select semiconductors; about the controllers, in [8] the design equations for the BPFCC control circuit were presented and explained. References [9], [10] and this work proposed strategies and control schemes for the BPFCC, likewise, in this work a digital control was suggested and the equations in difference were obtained to be implemented in the microprocessor.

This work analyzes and explains the operation of the BPFCC as a battery charger and its visual alarms and operation; likewise, an algorithm was proposed to generate such visual alarms that indicate the condition of energy sources.

The design process of the BPFCC begins in section II, which models the circuit finding the transfer functions that relate key variables in the circuit such as the current in the inductor \( i \) with the duty cycle \( d \), and the voltage in the capacitor \( v \) with the output of the voltage controller \( u_2 \). Subsequently, from the electrical specifications of the turbine, the user interface, the DC/DC converter that powers the turbine, and the line voltage, the design procedure is started in section III selecting the values of the inductance \( L \), the capacitor \( C \), the reference of the power semiconductors \( S_1, S_2 \) and the diode bridge following the proposed procedure, which is explained in detail in section III-A. Then, using the control scheme of Figure 2, and the parameters selected in Table 2, the PID controller of the current loop and the PI controller of the voltage loop are tuned in section III-B.

The mechanical respirator includes backup batteries to ensure continuous operation in the absence of power supply. Using the battery model proposed in [11], in section IV, the normalized state of charge is defined \( S_n C_n \), which indicates the stored electrical charge of the battery and calculates the estimated battery charging time charged by the BPFCC as constant power source.

According to [1], the respirator must have an alarm system that detects the change to the internal power source when the supply network falls outside the values necessary to maintain operation. Therefore, in section V an algorithm is established to detect the absence of power supply and the low load of the battery.

For the implementation of the circuit prototype, in section VI, the description of the electrical components of the BPFCC is made as the type of capacitor, inductance cores, types of power semiconductors \( S_1, S_2 \), as well as the diode bridge, and the gate handling circuit, among others.

Finally in section VII, the results of the design procedure are shown, simulating the process of loading the battery using the BPFCC as a charger, demonstrating that BPFCC operates as a source of constant power. In addition, the total charge time of the battery from a state of null charge is evidenced, on the other hand, the waveforms of the input voltage and current for different output power values are shown; likewise, the waveform of the output voltage is illustrated and the operation of the algorithm of section V, which indicates the detection of the lack of electrical network and battery low charge state.

![FIGURE 1. Topics involved in the process of designing the power source for a mechanical respirator.](image-url)
II. CIRCUIT ANALYSIS

A BPFCC is an AC/DC converter as shown in Figure 2, which consists of a capacitor \( C \), an inductance \( L \), a switch \( S_1 \), and a load \( C_a \), which is a DC/DC converter to power the turbine of the mechanical respirator and its operating interface. In order to obtain a unit PF in the BPFCC, the input current must follow the waveform of the input voltage and, likewise, the output voltage must be kept constant.

**FIGURE 2.** BPFCC circuit.

Figure 3 shows the equivalent circuits for the two modes of operation considering the losses in conduction, as well as the waveforms of the inductance voltage and the capacitor current originated by these operation modes.

The first mode arises during the interval \( d T_s \), where \( d \) and \( T_s \) are the duty cycle and the switching period, respectively. In this mode, the transistor turns on and the diode turns off, hence, the transistor \( S_1 \) is replaced by a resistance \( r_D \), which is the transistor’s on resistance. The second mode appears during the interval \((1 - d) T_s \), in this mode, the transistor is turned off and the diode is turned on, then the diode \( S_2 \) is replaced by a constant voltage source \( V_D \), which is the direct anode-cathode voltage drop. In both operation modes a resistance \( r_L \) in series representing the losses in inductance is added to the inductance model.

The average circuit model is obtained by performing the methodology suggested in [12] consisting of averaging the waveforms \( i_C' \) and \( v_L' \) over a switching period, having

\[
\frac{L}{dt} = v_g - (r_L + r_D) i - (1 - d) (v + V_D) \tag{1}
\]

\[
C \frac{dv}{dt} = (1 - d) i - I_o \tag{2}
\]

To find the design equations able to properly select the components of the BPFCC. The steady state of the BPFCC must be obtained between 0 and \( \pi \), for this, the following assumptions are made: first, the input voltage is defined by the expression \( V_p \sin(\theta) \), where, \( V_p \) is the peak input voltage, \( \theta = \omega t \), with \( \omega \) being the line angular frequency; second, the output capacitor is large enough so that the voltage

**FIGURE 3.** Equivalent circuits and waveforms.
ripple produced by the switching and line frequencies can be approximated to zero, except when the voltage ripple is to be determined; third, to achieve a unit PF and bringing the switching component closer to zero, the input current is defined by the expression \( I_p \sin (\theta) \), where \( I_p \) is the peak input current; finally, BPFCC losses are approaching zero; as a result, the steady-state duty cycle is given by

\[
D = \frac{V_p}{V} \sin (\theta) + \frac{\omega L I_p}{V} \cos (\theta) + 1, \tag{3}
\]

where, \( V \) is the voltage of the capacitor in steady state. On the other hand, as \( V_p \gg \omega L I_p \), then, (3) can be approximated to

\[
D = -\frac{V_p}{V} \sin (\theta) + 1, \tag{4}
\]

the waveform of the current \( i \), in steady state over a switching period is illustrated in Figure 4, where \( I \) is the steady-state current of the inductance defined by the expression \( I_p \sin (\theta) \); likewise, \( \frac{V}{L} \) is the slope of \( i \) for the interval \( DT_s \), therefore, the current ripple can be expressed as

\[
\Delta I = \frac{DT_s V_g}{L}, \tag{5}
\]

where, \( V_g \) is the steady-state voltage \( V_g \), defined by the expression \( V_p \sin (\theta) \); thus, substituting (4) in (5), it is obtained:

\[
\Delta I = \frac{1}{f_s} \left[ -V_p^2 \sin^2 (\theta) + VV_p \sin (\theta) \right], \tag{6}
\]

where \( f_s \) is the switching frequency; likewise, using (6) the maximum value of the current ripple can be deducted obtaining equation (7).

\[
\Delta I_{\text{max}} = \frac{V}{4f_s} \tag{7}
\]

**FIGURE 4. Inductance current waveform \( i \) over a switching period.**

On the other hand, taking into account the assumptions made above, replacing (4) in (2) and simplifying, then

\[
i_c = \frac{-V_p I_p}{2V} \cos (2\theta) - I_o, \tag{8}
\]

if losses in the BPFCC are not considered the power of the input port is equal to that of the output port, having:

\[
\frac{V_p I_p}{2} = V I_o, \tag{9}
\]

then

\[
i_c = \frac{-V_p I_p}{2V} \cos (2\theta) \tag{10}
\]

the low frequency voltage ripple of the capacitor is given by:

\[
\Delta V = \frac{1}{\omega C} \int \Delta i d\theta = -\frac{V_p I_p}{4\omega C V} \sin (2\theta), \tag{11}
\]

calculating the maximum and minimum value of (11), and taking their difference, the peak-peak voltage ripple is obtained:

\[
\Delta V_{p-p} = \frac{V_p I_p}{2\omega C V}, \tag{12}
\]

as the average circuit model of the BPFCC is a nonlinear system, the model must be linearized to design the current control loop, so that it is multiplied by \( \frac{1}{L} \) and \( \frac{1}{C} \) to (1) and (2) respectively:

\[
\frac{di}{dt} = f_1 = \frac{1}{L} V_g - \left( \frac{R_L + R_D}{L} \right) i - \left( \frac{1 - d}{L} \right) (v + V_D) \tag{13}
\]

\[
\frac{dv}{dt} = f_2 = \left( \frac{1 - d}{C} \right) i - \frac{1}{C} I_o, \tag{14}
\]

approximating (13) and (14) using the Taylor series without the higher-order terms around the operating point:

\[
\frac{d\hat{x}}{dt} = A\hat{x} + B\hat{u} = \frac{\partial f}{\partial x} \bigg|_{p_s} \hat{x} + \frac{\partial f}{\partial u} \bigg|_{p_s} \hat{u} \tag{15}
\]

\[
\frac{d\hat{y}}{dt} = C\hat{x} + D\hat{u} = \frac{\partial h}{\partial x} \bigg|_{p_s} \hat{x} + \frac{\partial h}{\partial u} \bigg|_{p_s} \hat{u}, \tag{16}
\]

where, \( x, u, p_s, h, \) and \( f \) are the vectors of states, inputs, states and steady-state inputs, outputs and functions respectively, these vectors are given by:

\[
f = \begin{bmatrix} f_1 \\ f_2 \end{bmatrix} \quad x = \begin{bmatrix} i \\ v \end{bmatrix} \quad p_s = \begin{bmatrix} I \\ V \end{bmatrix} \quad u = [d] \quad h = [i] \tag{17}
\]

The transformation of the representation of the linear model of the BPFCC into space of states to transfer function is given by equation:

\[
\frac{i(s)}{d(s)} = G_{id} (s) = C \left[ sI - A \right]^{-1} B \tag{18}
\]

\[
G_{id} (s) = \frac{V + V_D - R_D I}{L C s^2 + (R_L + R_D) C s + (1 - D)^2} \tag{19}
\]

Due to the speed of the internal current loop, any dynamics associated with it can be disregarded, while obtaining the transfer function of the voltage loop, to study its performance [13]. Likewise, the bandwidth must be limited, so that there is no distortion in the inductance current, as a result, from Figure 2 it is deduced:

\[
i_r = Hv_g u_2, \tag{20}
\]

for obtaining a null steady-state error, \( i_r \) must be equal to \( i \), which is why (20) becomes

\[
i = Hv_g u_2, \tag{21}
\]
replacing $i$ and $v_g$ with their steady-state values in (21) and averaging over a line period:

$$\langle I_p \rangle = HV_p(u_2)$$

(22)

also, it averages to (8) over a line period, having:

$$C\frac{d\langle v \rangle}{dt} = \frac{V_p}{V}(I_p) - I_o,$$

(23)

then (22) is replaced in (23) obtaining:

$$C\frac{d\langle v \rangle}{dt} = \frac{V_p^2}{V}H(u_2) - I_o,$$

(24)

linearizing (24) around the operating point:

$$C\frac{d\hat{v}}{dt} = \frac{V_p^2}{V}H\hat{u}_2,$$

(25)

applying Laplace transform to equation (25) is obtained:

$$sCV(s) = \frac{V_p^2H}{V}U_2(s),$$

(26)

in this way the transfer function $G_{VU_2}(s)$ is given by:

$$G_{VU_2}(s) = \frac{V(s)}{U_2(s)} = \frac{V_p^2H}{CVs},$$

(27)

hence, (27) is the transfer function where the output is the voltage of the capacitor and the input is the output of the voltage controller $C_2(z)$, which will be used for the design of the same controller.

III. DETAILED DESIGN-PROCEDURE

The design procedure of the BPFCC begins, from the electrical specifications of the turbine, the user interface, the DC/DC converter that feeds, and the line voltage. Also, it is explained in detail how the value of the inductance $L$ and the capacitor $C$ are selected, as well as the design of the current controllers $C_1(z)$ and voltage $C_2(z)$.

A. POWER STAGE

Figure 5 is employed for selecting the inductance $L$, capacitor $C$, mosfet $S_1$, diode $S_2$, and the diode bridge, described below.

The value of the maximum average power absorbed by the respirator and interface $P_i$ is 60 W; the input voltage range of the DC/DC converter is from 200 V to 240 V; the value of the efficiency of the DC/DC converter $\eta_1$ is 0.91; therefore the value of the average power $P_o$ maximum supplied by the BPFCC is given by:

$$P_o = \frac{P_i}{\eta_1} = 66 \text{ W}$$

(28)

The value of $V$ is determined by calculating the average of the input voltage range of the DC/DC converter, which is 220 V. On the other hand, if an efficiency of the BPFCC $\eta_2$ of 0.91 is assumed, the value of the average power $P_i$ maximum that absorbs the BPFCC of the line voltage $v_{ac}$, is given by equation:

$$P_i = \frac{P_o}{\eta_2} = 73 \text{ W}$$

(29)

If the value of $V_p$ is equal to 170 V, then the value of $I_p$, corresponds to:

$$I_p = \frac{2P_i}{V_p} = 0.86 \text{ A}$$

(30)

To find the value of $\Delta I_{max}$ in the BPFCC operating in continuous conduction mode (CCM), the following criterion is used,

$$0.2I_p < \Delta I_{max} < 0.5I_p,$$

(31)

a value of $\Delta I_{max}$ of 0.25$I_p$ is selected, which is within the range of this criterion, suitable, a $f_s$ of 50 kHz is assumed, as a result, the value of the inductance is solving $L$ of (7).

$$L = \frac{V}{4f_s\Delta I_{max}} = 5 \text{ mH}$$

(32)

The value of the voltage ripple of a suitable regulator is below 1% of its average output voltage. Nevertheless, the BPFCC is only a pre-voltage regulator, which is why the value

FIGURE 5. Summary of the BPFCC power stage design procedure.
of its voltage ripple may be below 5% of its average output voltage, according to equation (33).

\[ \Delta V_{p-p} < 0.05V, \]  

substituting (12) in (33) is obtained

\[ \frac{V_{p}I_{p}}{2\omega CV} < 0.05V, \]  

thus, the constraint to choose the value of the capacitor is solving C of (34), corresponding to:

\[ C > \frac{V_{p}I_{p}}{0.1\omega V^2}, \]  

where \( \omega \) is equal to \( 2\pi 60 \) \( \text{rad/s} \), hence the value of \( C \) of 220 \( \mu \)F, which complies with this restriction.

In order to select \( S_1 \), the maximum direct current of drain \( I_D \) and the drain to source breakdown voltage is considered \( V_{DS} \). No matter how high the gate voltage is, the drain to source on voltage cannot be significantly decreased, unless the operating current of drain is in the triode region and away from the point where the channel is strangled; in conclusion, to obtain a low drain to source on voltage, specifically around 1 V, with a current value of drain equal to \( I_p \), \( S_1 \) must be selected with a maximum value of \( I_D \) that meets the condition:

\[ 3I_p < I_D < 5I_p, \]  

since the on resistance from drain to source is inversely proportional to the maximum value of \( I_D \) [14]. The value of \( V_{DS} \) is chosen high enough, so that the peak voltage of the dispersion inductance plus the output voltage of the BPFCC allow a suitable margin of safety; therefore, the drain to source breakdown voltage is selected 30% more above the output voltage of the BPFCC. Accordingly, it must comply with:

\[ V_{DS} > 1.3V, \]  

thus, it is chosen a transistor \( S_1 \), the IRF740 MOSFET device, which meets these conditions. Device \( S_2 \) is selected considering the reverse voltage \( V_R \), the average forward current \( I_F \) and the switching frequency. As the BPFCC operates in CCM, it is important to select \( S_2 \) with a fast recovery feature [8], hence, it can use the conditions (36) and (37) to choose \( V_R \) and \( I_F \) respectively. Then, it is selected for the diode \( S_2 \) the MUR460 device, which meets these conditions.

On the other hand, the diode bridge is chosen based on voltage in reverse \( V_{R1} \) and the average forward current \( I_{F1} \), this diode bridge is for general purpose. The value of \( I_{F1} \) is chosen above half the average value of the current of inductance due to the same justifications that were already exposed in the selection of \( S_2 \); likewise, half of the average value of the inductance current over a line period is equal to \( I_p \), then, the condition for selecting the value of \( I_{F1} \) is given by:

\[ I_{F2} > \frac{3I_p}{\pi}, \]  

The value of \( V_{R1} \) is selected less than the value of \( V_p \), to avoid exceeding the value of \( V_{R1} \), when the line voltage increases; therefore, the condition to select the value of \( V_{R1} \), is given by:

\[ V_{R1} > 1.3V_p, \]  

accordingly, the KBP204 device is chosen as the diode bridge, which meets these conditions.

### B. BPFCC CONTROL LOOPS

The control scheme of the BPFCC is illustrated in Figure 2, this control scheme consists of the loops of current and voltage. The purpose of the current controller is for \( i \) to follow the form of \( v_{r} \) to increase the PF, simultaneously, the goal of the voltage controller is to regulate \( v \) to a constant value defined by \( V_r \). In order to design the current and voltage controllers, a summary is made with the values of the components obtained in section III-A as the value of the inductance and capacitor; some circuit parameters that were also defined in section III-A are maximum line voltage and current values, and switching frequency; as also, other important circuit parameters such as the losses in conduction of the transistor, the diode and the inductance; the steady state of the input and state variables, and finally the value of the charge current. This summary is presented in Table 2.

#### TABLE 2. Values of the circuit parameters.

| Circuit parameters | Symbol | Value      |
|--------------------|--------|------------|
| MOSFET             | \( S_1 \) | IRF740     |
| Diode              | \( S_2 \) | MUR460     |
| Diode bridge       |        | KBP204     |
| Inductance resistance | \( r_L \) | 0.4Ω       |
| On resistance \( S_1 \) | \( r_D \) | 0.34Ω      |
| Direct voltage \( S_2 \) | \( V_D \) | 1.05 V    |
| Inductance         | \( L \) | 5 mH      |
| Capacitor          | \( C \) | 220 \( \mu \)F |
| Line voltage \( V_e \) |     | \( V_p \sin(\theta)V \) |
| Inductance current | \( I \) | \( I_p \sin(\theta)A \) |
| Switching frequency | \( f_s \) | 50 kHz   |
| Peak line voltage  | \( V_p \) | 120 V/2V |
| Peak line current  | \( I_p \) | 0.86 A   |
| Capacitor voltage  | \( V \) | 220 V     |
| Output current \( I_o \) |        | 0.3 A    |

#### 1) CURRENT LOOP CONTROLLER

It can be seen in Figure 6 the power circuit of the BPFCC inside the current control loop is in blue, which is why the transfer function \( G_{id}(s) \) of the linear model of the BPFCC is needed to design the current controller. The most critical \( G_{id}(s) \) replaces the values of Table 2 in (19) and evaluates \( \theta \) in \( \pi \) obtaining:

\[ G_{id}(s) = \frac{44210s}{s^2 + 162.4s + 66.7} \]  

A sampling time equal to \( T_s \) is selected, where \( T_s = \frac{1}{f_s} \) and the value of \( f_s \) is given in Table 2, then, it is discretized to (40) using the zero-order retention method, having:

\[ G_{id}(z) = \frac{0.8828z - 0.8828}{z^2 - 1.997z + 0.9968} \]
where, $I$ are the proportional, integral and derivative gains respectively, in the discretization of a PID with filter in the differentiator (Figure 8) and is given in Figure 7, the delay $z^{-1}$ must be included within (41) producing the equation (42).

$$G_{ud}(z) = \frac{0.8828z - 0.8828}{z^3 - 1.997z^2 + 0.9968z} \quad (42)$$

The transfer function (42) is used to tune the current controller $C_1(z)$, this controller is PIDF type in parallel which is a PID with filter in the differentiator (Figure 8) and is given by equation (43).

$$C_1(z) = \frac{u_1(z)}{e_1(z)} = P_1(z) + I_1(z) + D_1(z), \quad (43)$$

where, $P_1(z)$, $I_1(z)$ and $D_1(z)$ are the proportional, integral and derivative gains respectively, in the discretization of $I_1(z)$ it is employed the trapezoidal method, meanwhile, for $D_1(z)$ it is used the backward method, since using the same method in both controllers causes instability in the differentiator [15], then:

$$P_1(z) = \frac{w_1(z)}{e_1(z)} = K_{p1} \quad (44)$$

$$I_1(z) = \frac{x_1(z)}{e_1(z)} = K_{i1} \left( \frac{T_s}{2} \right) \left( \frac{z+1}{z-1} \right) \quad (45)$$

$$D_1(z) = \frac{y_1(z)}{e_1(z)} = K_{d1} \left( \frac{1}{T_f + T_s \left( \frac{z}{z-1} \right)} \right) \quad (46)$$

The denominator and numerator are divided from (45) and (46) by $z$, then, $w_1(z)$, $x_1(z)$ and $y_1(z)$ are solved; finally, the inverse $z$ transform is applied, to obtain the equations in differences given by the following equations:

$$w_1[n] = K_{p1} e_1[n] \quad (47)$$

$$x_1[n] = x_1[n-1] + K_{i1} \left( \frac{T_s}{2} \right) (e_1[n] + e_1[n-1]) \quad (48)$$

$$y_1[n] = \left( \frac{T_f}{T_f + T_s} \right) y_1[n-1] + \left( \frac{K_{d1}}{T_f + T_s} \right) (e_1[n] - e_1[n-1]) \quad (49)$$

The proportional constant $K_{p1}$ delivers the gain of the controller that stabilizes the system; the integral constant $K_{i1}$ decreases steady-state error and improves relative stability; the derivative constant $K_{d1}$ increases plant stability and reduces overdrive; on the other hand, the filter time $T_f$ prevents the derivative action from amplifying the noise [15]–[17]. In order to find the values of the driver constants $C_1(z)$ is tuned using the PID Tuner application of MATLAB®, choosing the PIDF, with the parameters response time and transient behavior of 131.5 $\mu$s, and 0.58 $s$ respectively, thus, the constants of $C_1(z)$ are $K_{p1} = 0.504$, $K_{i1} = 3 \times 10^3$, $K_{d1} = 4.1 \times 10^{-6}$, and $T_f = 0.21 \times 10^{-6}$.

2) VOLTAGE LOOP CONTROLLER

Figure 9 displays, in red, the voltage control loop, within this loop is the controller $C_2(z)$ responsible for keeping $v$ in a constant value fixed by $V_r$. From equation (9), it is observed that the BPFCC circuit is a power source, hence, the output of

![FIGURE 6. BPFCC control diagram, current loop.](image)

![FIGURE 7. Delay time between calculation and load the duty cycle.](image)

![FIGURE 8. PIDF control diagram of the BPFCC current loop.](image)
the controller is connected $C_2(z)$, to the multiplier block as illustrated in Figure 9, so that $C_2(z)$ governs the peak value of $i_r$ and thus get $v$ to be constant.

To obtain the $G_{VU}(s)$ for the design specifications defined in section III-A, the values of Table 2 and $H$ are replaced, which is equal to 0.005 in (27) producing:

$$G_{VU}(s) = \frac{2975.21}{s},$$  \hspace{1cm} (50)

using the ZOH discretization method, the transfer function that defines the voltage loop in the domain $z$ is given by:

$$G_{VU}(z) = \frac{0.059504}{z - 1}.$$  \hspace{1cm} (51)

From $G_{VU}(z)$, $C_2(z)$ is tuned as a PI-type controller in parallel, as shown in Figure 10.

Thus, $C_2(z)$ is expressed as the sum of the proportional action $P_2(z)$ and the integral $I_2(z)$ having:

$$C_2(z) = \frac{u_2(z)}{e_2(z)} = P_2(z) + I_2(z),$$  \hspace{1cm} (52)

where, $P_2(z)$ and $I_2(z)$ are the proportional and integral gains respectively, for $I_2(z)$ the trapezoidal discretization method is used obtaining the following equations:

$$P_2(z) = \frac{w_2(z)}{e_2(z)} = K_{p_2},$$  \hspace{1cm} (53)

$$I_2(z) = \frac{x_2(z)}{e_2(z)} = K_{i_2} \left( \frac{T_i}{2} \right) \frac{z + 1}{z - 1},$$  \hspace{1cm} (54)

when applying the inverse $z$ transform to (53) and (54), the difference equations for the proportional and integral voltage loop controllers are obtained:

$$w_2[n] = K_{p_2}x_2[n]$$  \hspace{1cm} (55)

$$x_2[n] = x_2[n - 1] + K_{i_2} \left( \frac{T_i}{2} \right) (x_2[n] + x_2[n - 1])$$  \hspace{1cm} (56)

To find the controller values, $C_2(z)$ is tuned using the PID Tuner application of MATLAB®, choosing the PI with the parameters response time and transient behavior of 0.11 s and 0.37 s respectively, so that the constants of $C_2(z)$ are $K_{p_2} = 0.0048$, $K_{i_2} = 0.12$.

**IV. BPFCC OPERATING AS A BATTERY CHARGER**

To ensure continuous operation in the absence of main supply, mechanical respirators must have backup batteries. In the case of the mechanical respirator powered by the proposed BPFCC it is used an arrangement of 16 batteries connected in series ($B$), each of these batteries are 12 V-2 A h. $B$ is connected to the BPFCC circuit as illustrated in Figure 11, in the analysis carried out in section II it is not considered $B$ since when the batteries of $B$ are fully charged, the current flowing towards $B$ is much less than the current flowing to the DC/DC converter that feeds the turbine of the mechanical respirator and its operating interface. Then, the current flowing into $B$ can be disregarded.

The load of $B$ occurs when the turbine of the respirator is turned off, hence most of the power that the BPFCC can supply is absorbed by $B$. In [11], it is proposed a simple model of the battery in state of charge, which consists of a continuous voltage source in series with the resistance in charging mode, therefore, the model of $B$ is shown in Figure 12.

The continuous voltage source $V_b$ and the resistance in load mode $R_b$ are defined by:

$$V_b = 192 + 14.2SoC_n$$  \hspace{1cm} (57)

$$R_b = \frac{72.7 + \frac{12.56}{106 - 3SoC_n}}{SoC_n},$$  \hspace{1cm} (58)

where $SoC_n$ is the normalized state of charge of $B$, which is an important parameter that indicates it stored electrical charge. The range of values of this parameter is $0 \leq SoC_n \leq 1$, when the value of $SoC_n$ is the unit, it indicates that $B$ is fully

---

**FIGURE 9. BPFCC control diagram, voltage loop.**

**FIGURE 10. PI control diagram of BPFCC voltage loop.**
charged; besides, if the value is zero, notice that $B$ has no stored charge, also, $\text{SoC}_n$ is expressed as:

$$
\text{SoC}_n = \text{SoC}_0 + \frac{1}{C_n} \int_0^t I_b dt,
$$

(59)

where $\text{SoC}_0$ is the normalized initial state of charge, $C_n$ is the rated capacity in ampere-hours, and $I_b$ is the load current of $B$ [18]. Another important parameter is $\text{SoC}_m$ which indicates the total power in watt-hours that can be supplied by $B$, from full charge to cut-off voltage.

When $B$ tries to absorb a power value greater than or equal to $P_o$ the output of the voltage controller $u_2$ delivers its maximum value which is the unit; thus, the value of the amplitude of the reference current is equal to $I_p$, as a result, the BPFCC operates as a power source and its value is given by equation:

$$
P_o = VI_b = \frac{\eta_2 V_b I_p}{2}
$$

(60)

Replacing the BPFCC with a power source and $B$ for its model in a state of charge, the circuit of Figure 13 is obtained, the sum of voltages around the loop of this circuit is given by:

$$
-V + R_b I_b + V_b = 0,
$$

(61)

taking (60) is cleared $V$ and replaced in (61) producing:

$$
-\frac{P_o}{I_b} + R_b I_b + V_b = 0,
$$

(62)

multiplying by $I_b$ on both sides it is obtained:

$$
R_b I_b^2 + V_b I_b - P_o = 0,
$$

(63)

solving $I_b$ of (63), the charging current of $B$ is obtained in terms of the resistance in load mode, the continuous voltage source and the power supplied by the BPFCC, corresponds to:

$$
I_b = \frac{-V_b + \sqrt{V_b^2 + 4R_b P_o}}{2R_b}
$$

(64)

where the values of $P_o$, $V_b$ and $R_b$ can be determined by (28), (57) and (58) respectively. Figure 14 shows the load current of $B$ versus its normalized state of charge.

Since $I_b$ is approximately constant in the range of values of $\text{SoC}_n$, the value of $I_b$ is the average between the maximum and minimum values, which is equal to 0.325 A. Assuming $\text{SoC}_0$ equals to zero, and considering that $C_n$ in $B$ is equal to 2 A·h, the time in hours $B$ takes to reach a unit $\text{SoC}_n$ value is equal to 6.15 h (using equation (59)).

**V. ALGORITHM TO DETERMINE THE ABSENCE OF LINE AND LOW BATTERY**

According to [1], the respirator must be equipped with an internal energy source capable of feeding the respirator for at least 30 minutes, when the supply network falls outside the values necessary to maintain normal operation. In addition, it must have an alarm system to detect the change to the internal power source; then, the BPFCC has visual alarms that indicate the lack of electrical network and low load level of $B$. To cause these alarms, the average value of $v_g$ and $v$ is determined using the expression:

$$
A = \frac{a}{T},
$$

(65)

where $a$ is given by:

$$
a = \int_0^T x dt
$$

(66)
x is the signal that is averaged, and $T$ is its period as seen in Figure 15, it can be approximated (66) by the Backward-Euler summation:

$$a(kT_s) = T_s[x(0) + x(T_s) + \cdots + x((k-1)T_s) + x(kT_s)]$$  \hspace{1cm} (67)

**FIGURE 15.** Approximation of $a$ through the Backward-Euler summation.

In (67) $T_s$ is the switching period of the BPFCC, it is transformed (67) into the following equation in differences:

$$a[n] = a[n-1] + T_s x[n],$$  \hspace{1cm} (68)

that can be rewritten (68) as:

$$a[n] = a[n-1] + T_s x[n],$$  \hspace{1cm} (69)

so that, it can be approximated (66) through

$$A(kT_s) = \frac{a(kT_s)}{T_s},$$  \hspace{1cm} (70)

transforming (70) into an equation in differences is obtained:

$$A[n] = \frac{a[n]}{T},$$  \hspace{1cm} (71)

where $n$ is the number of iterations made by (69), which are determined by the constant $k$, having:

$$k = \frac{T}{T_s} = 416.6 \approx 416,$$  \hspace{1cm} (72)

it is used (71) to average $v_g$ and $v$, therefore it is obtained:

$$M[n] = \frac{m[n]}{T},$$  \hspace{1cm} (73)

$$B[n] = \frac{b[n]}{T},$$  \hspace{1cm} (74)

where $M[n]$ and $B[n]$ are the mean values of $v_g$ and $v$, respectively; likewise, $T$ is equal to 8.33 ms, $m[n]$ and $b[n]$ are given by:

$$m[n] = m[n-1] + T_s v_g[n],$$  \hspace{1cm} (75)

$$b[n] = b[n-1] + T_s v[n],$$  \hspace{1cm} (76)

In this way, it is implemented (73), (74), (75) and (76) in the algorithm displayed in Figure 16, which generates two logical signals that indicate the presence of electrical network (PN) and loaded battery (LB).

The presence of an electrical network is evidenced with a high level in the PN signal and a low level that indicates the absence of power supply, in the same way, LB in high indicates the full charge of the battery and a low level of LB indicates the lack of battery charge.

**VI. IMPLEMENTATION OF THE BPFCC PROTOTYPE CIRCUIT**

The implemented BPFCC prototype circuit is shown in Figure 17. In section III-A it was calculated the values of the capacitor and the inductance of the BPFCC. For the capacitor, an aluminum electrolytic capacitor from 220 $\mu$F to 350 V was used, the inductance was constructed from two Philips 3C85 ferrite nucleus type E, and the iron width in between was experimentally adjusted to obtain an inductance value of 5 mH.

Also, in section III-A it was selected the power semiconductors $S_1$ and $S_2$, as well as the diode bridge, which were the IRF740 MOSFET, MUR460 diode and KBP204, respectively. Texas Instruments UCC27524 integrated circuit powered by 15 V was used as a gate handler. Through the integrated circuit of Texas Instruments TLV2374, powered with 3.3 V including three out of the four amplifiers used in differential topology, the reference current of $v_g$ and the feedback output voltage were obtained; in addition, the inductance current was sensed using a resistance of 0.1 $\Omega$ of 2 W.
FIGURE 17. Implemented BPFCC prototype circuit and components.

Figures 17(b), 17(c), and 17(d) illustrate the battery array, the DC/DC converter with its load which is the turbine and the mechanical respirator, respectively.

VII. SIMULATION AND EXPERIMENT RESULTS

The results of the design procedure and the BPFCC connected to $C_a$ and operating as a battery charger were verified using simulation software, then a prototype of the BPFCC was built in the laboratory.

The waveforms of the inductance current and voltage in the capacitor were obtained by simulating the BPFCC with a current source as a charge that emulates $C_a$. In this simulation, the circuit parameters and values of the components shown in Table 2 were used; nevertheless, the conduction losses of $L$ were not considered, $C$, $S_1$, $S_2$ or the diode bridge. The high frequency current ripple in the inductance $L$ is shown in Figure 18, comparing the value of $\Delta_{I_{\text{max}}}$ with the value chosen in section III-A to find the value of the inductance, it is observed that these values substantially coincide.

FIGURE 18. Inductance current ripple.

Figure 19 illustrates the low frequency ripple in the capacitor $C$, the value of $\Delta V_{p-p}$ is below 5% of the average output voltage, which is equal to 220 V, then the restriction set in (33) to find the capacitor value is met.

Table 3 and Figure 20 correspond to the simulation of the BPFCC with a battery as a charge, to verify the analysis that was made in section IV of the BPFCC operating as a charger. In this simulation, the values of the components and the circuit parameters are in Table 2. The parameters $I$ and $I_o$ were not used, nor were the driving losses of $L$, $C$, $S_1$, $S_2$ or the diode bridge considered. On the other hand, the battery parameters are nominal voltage 192 V, $C_n = 2$ Ah and $SoC_0 = 0$. In the results recorded in Table 3, it can be seen that the maximum value of PF is 0.9908, which occurs when $SoC_n = 1$, while the minimum value of PF is 0.9902, which originates when $SoC_n = 0$, then the PF is quite high when the BPFCC operates as a battery charger. In addition, it is seen that for different values of $SoC_n$, the value of $P_o$ remains almost constant, these results of $P_o$ ratify that the BPFCC operates as a power source when charging batteries as previously said in section IV. Besides, the results of $I_b$ are observed for the different values of $SoC_n$, comparing these results in simulation with those generated by Figure 14. Thus, it can be stated that these results are consistent.

TABLE 3. Values of $I_b$, $V$, PF and $P_o$ for different values of $SoC_n$.

| $SoC_n$ | $I_b$ [A] | $V$ [V] | PF | $P_o$ [W] |
|---------|-----------|---------|----|-----------|
| 0       | 0.3381    | 194.6   | 0.9903 | 66.43     |
| 0.1     | 0.3381    | 194.6   | 0.9903 | 66.43     |
| 0.2     | 0.3360    | 196.1   | 0.9904 | 66.02     |
| 0.3     | 0.3345    | 197.5   | 0.9904 | 66.16     |
| 0.4     | 0.3325    | 199.0   | 0.9904 | 66.30     |
| 0.5     | 0.3308    | 200.4   | 0.9905 | 66.43     |
| 0.6     | 0.3288    | 201.9   | 0.9906 | 66.52     |
| 0.7     | 0.3270    | 203.4   | 0.9906 | 66.65     |
| 0.8     | 0.3250    | 205.0   | 0.9906 | 66.77     |
| 0.9     | 0.3228    | 206.8   | 0.9906 | 66.91     |
| 1       | 0.3191    | 209.9   | 0.9908 | 67.13     |

Figure 20 shows the variation of $SoC_n$, $I_b$, and $V$ with the time achieved in the simulation, when the BPFCC charges a battery with a zero $SoC_n$, it is observed that the time the battery takes to reach a $SoC_n$ unit is around 6.25 h; on the other hand, the time that was calculated in section IV was 6.15 h, which is below the simulation result. However, it is
a suitable approximation since, $I_b$ was taken constant when used (59) to calculate it.

Figures 21-24 are related to the experimental prototype of the BPFCC that has as load $C_a$, using the values of the components and the circuit parameters shown in Table 2, except the parameters $I$ and $I_o$. Figures 21-23 show the waveforms of the current and input voltage ($i_{ac}$ and $v_{ac}$) of the BPFCC for output power values $P_o$ of 73 W, 53 W and 37 W, respectively. Acceptable, power factors for these values of $P_o$ are 0.99, 0.99 and 0.98, respectively, as the power factor is reasonably high for different output power ranges. In addition, these results show that the proposed model of the BPFCC considering the losses in conduction in section II, as well as the design of the current controller using a PID compensator in section III-B were conclusive to achieve a power factor close to the unit.

Figure 24 illustrates the waveform of the output voltage of the BPFCC, for an output power of 73 W, it is observed that the voltage remains constant at a value around 220 V, thus, the proper functioning of the voltage controller is ratified using a PI compensator designed in section III-B.

Figure 25 corresponds to the experimental prototype of the BPFCC with an array of 16 batteries connected in series as a charge and connected to a variable alternating voltage of 60 Hz.

The algorithm presented in section V indicates the lack of electrical network and low load level in the array considering PN and LB signals. The experimental prototype used the
values of the components and the circuit parameters shown in Table 2, except the parameters \( I_i \), \( I_o \), and \( V_t \), the batteries in this array are 12 V-2 A h. In Figure 25(a), the transition from high to low of the PN signal is shown, when the peak line voltage \( V_p \) is below 110 V; likewise, in Figure 25(b) the transition from low to high of the PN signal is illustrated, when the peak line voltage \( V_p \) is above 140 V. On the other hand, in Figure 25(c), the transition from high to low of the LB signal is shown, when the voltage of the array \( V \) is below 170 V. Besides, in Figure 25(d), the transition from low to high of the LB signal is shown, when the voltage of the array \( V \) is above 210 V. These results confirm how the algorithm originates visual alarms that indicate the lack of electrical network, as well as the low charge level of the battery array, aiming at complying with what is specified by [1].

FIGURE 25. Waveforms of the transition of PN and LB signals.

VIII. DISCUSSION
In this work, a design methodology of the BPFCC was proposed as a power source for a mechanical respirator in which, first, a model was obtained to establish the requests in the driving of semiconductors; second, the equations and constraints were presented and explained to find the values of the inductance and the capacitor; third, the criteria for the selection of power semiconductors were given; fourth, strategies and control schemes were given for the BPFCC. Additionally, a digital control was suggested and the equations in difference were obtained for implementation in the microprocessor; fifth, the operation of the BPFCC as a battery charger was analyzed and explained. Finally, an algorithm was proposed for the generation of visual alarms to indicate the condition of energy sources. However, a model that considers the losses in induction and switching can be obtained. Also, other strategies can be proposed for the control loops of the BPFCC such as robust, sliding, neural networks, bioinspired algorithms, among others. In section VII, the values of the ripple of the inductance current and the voltage of the capacitor obtained through simulation software were shown and compared with the theoretical analysis carried out in section III-A; however, the values of this ripple could not be measured on the prototype circuit of the BPFCC implemented in the laboratory given that the laboratories do not have a current clamp or a differential tip with wide bandwidth. In section VII, the variations of the current and voltage of the battery over time were illustrated, in addition, the time the battery takes when it goes from a \( \text{SoC}_n \) null to unit was given, these variations were achieved using simulation software and were also verified with the results obtained in section IV; however, it was not possible to take measurements of current and voltage over time for the battery array when connected to the BPFCC prototype circuit; besides, the laboratories do not have an oscilloscope capable of performing and recording this measurement for long periods of time when the array goes from a null to a unit \( \text{SoC}_n \).

IX. CONCLUSION
In this document is proposed a detailed design methodology for the BPFCC considering key aspects illustrated in Table 1, such as model, losses, control system and the alarms generated.

The model considers the driving losses in the circuit; the model equations are analyzed to find the values of \( L \) and \( C \) regarding the respective restrictions. In addition, multiple considerations to select the semiconductors and the proposal of strategies and control schemes for the BPFCC are established.

A PIDF digital control is available, which is obtained from the equations in difference, and then implemented in the microprocessor. In this way, the waveform of the input current \( i_{ac} \) follows at every moment the waveform of the input voltage \( v_{ac} \) as in Figures 21-23, verifying that the BPFCC manages to maintain a high PF close to 1, in the face of load variations.

On the other hand, the operation of the BPFCC as a battery charger is analyzed and explained and its visual alarms, thus avoiding the use of another additional power source to charge the batteries. In the same way, an algorithm for the generation of visual alarms is proposed, which indicates the condition of the energy sources.

The proposed system is able to detect and signal the absence and restoration of the power supply and the low level of charge in the battery; in addition, it detects when the battery is fully charged.

Further works can cover other types of control strategies, such as neural networks, bioinspired algorithms, among others to achieve both a high PF and to detect the absence of line and low battery.

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