Energy storage system based on a bidirectional one-leg converter for educational purpose

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Abstract—An educational scale model of the power electronics of an energy-regenerating system (e.g. EV, e-bike, electric kick scooter) is proposed. Four LFP batteries connected in series make up the accumulator or battery pack. LFP technology has been chosen because it does not tend to deflagrate when abused by a user (short-circuited, overheated), and hence it is safer than other chemistries (such as LiCoO₂ or LiMnO₂). In addition, this battery pack could replace lead-acid batteries used all over the world in cars and motorbikes, since it has a similar voltage (12.8 V) but a lower weight and size.

The power electronics module is connected to a DC low-voltage 24 V bus. It allows not only to power up the motor using the batteries, but also to regenerate energy if used in conjunction with a KERS. The DC-DC conversion is carried out by a Buck-Boost converter, which permits to adjust to any voltage both in the side of the battery and in the side of the motor, ensuring system stability. The employed control system is “droop” type, meaning that the bus current is proportional to the variation of its voltage around a nominal value. The sense of the flow (discharge or charge) is determined by the sign of this variation, which should not exceed 5 V.

As for the control, a dsPIC will be used. No power higher than 50 W will be allowed in any sense. A commercial Battery Protection Circuit Module and driver will be included.

Index Terms—Engineering Education, Energy Storage, One Leg Converter, Power Electronics, Droop Control.

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I. INTRODUCTION

An educational workbench on renewable energy-related power electronics has been proposed in order to increase interest in this field [1]. This paper has been written as a part of this workbench, where students develop projects closely related with renewable energies. The reason for this is simple: not only are they the most desirable ones nowadays, but they also are on the brink of becoming the standard sources of the energy we consume.

Since most of them are variable and hard to anticipate, one can either rely on alternative, non-renewable sources of energy or store some “clean energy” for a period of time. Since the latter is more sustainable, it is clear that the development of renewable energies will go hand by hand with new ways of storing energy. One of the most broadly developed of these technologies are batteries.

Batteries are an intrinsic part of our lives, being one of the technical fields whose future is most promising. Using almost any means of transport implies that energy has to be stored in the form of chemical energy and converted into mechanical energy. Today, this is carried out by burning fossil fuels, which increases the emissions to the environment and has unwanted effects on it. However, it is clear that concern about the health of the future generations and about the sustainability of the planet leads to other technologies. Lithium-ion batteries are a quick method of storing energy that is cleaner and will most likely be used in the future as a substitute for the less environmentally-friendly. Lighter than traditional NiMH and lead-acid batteries, they are widely used in smartphones and, more recently, electric vehicles. They provide a higher power density and can give more power, being the most technological ones.

Whilst all Li-ion technologies have been developed widely, each of them serves for different purposes. Lithium iron phosphate batteries (hereafter LFP batteries) are safer than other Li-ion batteries due to their stability when abused. If compared to other technologies (e.g. LiCoO$_2$, LiMnO$_2$), full oxidation of the cathode material yields ferric phosphate, a safer compound [2]. Therefore, they are used in electrical cars, bikes and other means of transport, where the security is imperative.

In this paper, the Battery Management System of a 4S battery pack will be developed. The module will be connected to a 24V DC bus, since it is conceived for educational purposes. Energy can be both drawn from the bus to the battery pack and vice versa. It has been designed so that the whole structure is modular: several of these circuits can be attached to the bus and will work together without having to communicate. Adding or
subtracting a module would not cause any trouble to any of the modules and they will keep working normally. This is accomplished via Droop Control, by which the voltage of the bus varies slightly. This variation serves as information and dictates how each module has to behave. If power is injected to the bus, e.g. by a solar panel or a wind turbine, all the battery/supercapacitor modules will share the work of absorbing it, according to previously fixed specifications.

The possible applications of this module are unlimited. It can be fit into cars and replace the lead-acid batteries used nowadays; or used in e-bikes and electric kick scooters or any other mobile devices that need a lot of power.

The power module consists of a one-leg converter, due to the fact that it is able to allow current flow in both senses. As illustrated in Figure 1, the power electronics module works as a boost converter when drawing power from the battery, and as a buck converter otherwise.

**Figure 1:** Bidirectional Buck-Boost converter or One Leg Inverter, via SchemeIt [3].

II. PROBLEM DESCRIPTION

It is not easy to find a way to control several modules in parallel that does not involve tedious and expensive communications. If all the modules were to work without communicating, some could start taking the energy others give, increasing energy losses dramatically. The Droop Control is a solution to this problem, albeit at the expense of a constant bus voltage.

The Droop Control is an effective way to manage the current the module is absorbing or giving. This value is calculated by a voltage dependent function, which may (but does not have to) be linear. The exact function
depends on the type of accumulator used. In this case, since LFP batteries have been chosen, a linear function seems the best option.

Once the current reference has been calculated, the converter has to adapt the duty cycle of both transistors to follow it. This process might not be as straightforward as the voltage regulation usually carried out by this devices and many parameters, such the battery voltage, bus voltage, coil resistance, etc. are involved and the value may vary in a non-linear way.

It is important to note that the simplest regulation, consisting in an open-loop duty cycle adaptation, might reach the calculated value if the circuit remains constant. This, however, is a sine qua non: once the temperature increases, the coil resistance might differ from the sting one, leading to inconsistency between the reference value and the steady-state value. It is therefore essential to design a closed-loop control that prevents this discrepancy from happening.

III. THEORETICAL DESIGN AND CALCULATIONS

The aforementioned topology has been chosen due to its multiple advantages. The one-leg converter offers a two-way conversion, being able to work both as a boost, allowing to inject energy to the bus, and as a buck, storing energy in the battery.

Both converter transistors showed in Figure 1 are run by a microcontroller. In every cycle of the MCU, energy is stored in the inductor in the form of magnetic field, charging it. This energy is then released to the bus. The time this processes occur relative to each other define the way energy is transferred by the converter. This topology is therefore widely used for voltage conversions.

This whole cycle can be seen as the filling of a pail of water at a certain rate and then discharging it. The longer the pail has been filled up, the more water it will contain and the more forceful the discharge of water will be.

The output voltage of a buck-boost converter can be easily derived, but an expression relating the current the module gives to or draws from the bus to the duty cycle of both transistors is needed. They may not be on at the same time, since this would short out the bus. Conversely, if the battery voltage is lower than the bus voltage and both transistors are both off, the parasite diodes will both be polarized and will not conduct. Therefore, if operating normally, one of the transistors will be on while the other is off, and vice versa.

For the calculations, the MOSFETs will be replaced with normal switches (Figure 2).
Figure 2: Equivalent circuit for calculations, via SchemeIt [3].

If M2 is on the ON and M1 on the OFF position (this state will be hereafter referred to as S1), the equivalent circuit can be represented as (Figure 3):

![Equivalent circuit at state S1, via SchemeIt [3].](image)

In this case, the following equation can be derived using Kirchhoff’s junction rule:

\[ i_a = i_b + i_c = i_{bat} + C \cdot \frac{dv_{bus}}{dt} \]  \hspace{1cm} (1)

Since the bus voltage and the battery voltage are known, the current of the battery can be expressed as:

\[ v_{bus} - v_{bat} = \frac{L \cdot di_{bat}}{dt} + R \cdot i_{bat} \]  \hspace{1cm} (2)

If M1 is on the ON and M2 on the OFF position (this state will be hereafter referred to as S2), the equivalent circuit is (Figure 4):
Figure 4: Equivalent circuit at state S2, via SchemeIt [3].

Kirchhoff’s laws can be applied as well, and the equations for the current can be derived as follows:

\[ i_a = i_c = C \cdot \frac{dv_{bus}}{dt} \]  \hspace{1cm} (3)

\[ v_{bat} = -L \cdot \frac{di_{bat}}{dt} - i_{bat} \cdot R \]  \hspace{1cm} (4)

The average equations can now be derived. For a variable \( x \) taking two different values, \( x_{S1} \) at S1 and \( x_{S2} \) at S2, the average value is defined as:

\[ \bar{x} = d \cdot x_{S1} + (1 - d) \cdot x_{S2} \]  \hspace{1cm} (5)

The previous equations can be therefore converted into average equations by applying what has been illustrated in equation (5):

\[ d \cdot \bar{v}_{bus} - \bar{v}_{bat} = L \cdot \frac{d\bar{i}_{bat}}{dt} + R \cdot \bar{i}_{bat} \]  \hspace{1cm} (6)

\[ \bar{i}_a = d \cdot \bar{i}_{bat} + C \cdot \frac{d\bar{v}_{bus}}{dt} \]  \hspace{1cm} (7)

The differential terms of the equations (6) and (7) can be removed for the steady state equations, leading to the following expressions:

\[ D \cdot V_{bus} - V_{bat} = R \cdot I_{bat} \]  \hspace{1cm} (8)

\[ I_a = D \cdot I_{bat} \]  \hspace{1cm} (9)

And the current drawn from the bus (according to the sense of the current previously adopted) can be derived from equations (8) and (9) as:
\[ I_{bus} = I_a = \frac{D \cdot (D \cdot V_{bus} - V_{bat})}{R} \]

If both \( V_{bus} \) and \( V_{bat} \) are known and the coil resistance does not change, the regulation can be easily done in an open loop, since there is a value of the duty cycle that corresponds to each value of the current reference. Equation (10) has been represented in Figure 5, but only for values of duty between 0 and 0.8. This is due to the fact that the current grows asymptotically for values of \( D \) approaching 1:

![Figure 5: Current drawn from the bus vs duty cycle of the converter, via MATLAB [4].](image)

It can be seen that there is a minimum around \( D=0.27 \), and the converter can both inject and draw power from that value onwards. This can be also seen when equation (10) is solved:

\[
D = \frac{V_{bat} \pm \sqrt{V_{bat}^2 - 4 \cdot V_{bus} \cdot R \cdot I_{bus}}}{2 \cdot U_{bus}}
\]

In this paper, only the positive square root will be considered, since the negative one is not necessary. The converter will not be operating from the minimum to 0.8, as represented in Figure 5, but only in a certain region that is dependent on the battery and bus voltage, maximum current allowed, etc.

The first regulation control can be represented as illustrated in Figure 6:

![Figure 6: Open loop control for the converter.](image)
As explained before, the bus intensity reference depends on the voltage of the bus. Since it will be linear, it can be calculated as:

\[ I_{ref} = I_{min} + \frac{I_{max} - I_{min}}{V_{max} - V_{min}} \cdot (V_{bus} - V_{min}) \]  

(12)

The maximum value of the current drawn from or given to the bus will be bounded to 1.66 A in both directions, so that the power never exceeds 50 W. The maximum voltage accepted will be 30 V, and the minimum 18 V. The region of normal operation is from 19 V \((V_{min})\) to 29 V \((V_{max})\). With these values, the conversion from bus voltage to current allowed by the converter is as illustrated in Figure 7:

![Figure 7: Bus-voltage-dependent bus intensity reference calculation.](image)

The control can also be done in closed loop. If that is the case, the control loop is as described by Figure 8. The upper part of the diagram is the feed forward, the same as in Figure 6, and it gives a first approximation of the value of the duty cycle. Then, due to the fact that slight variations might occur in the components (more specifically in the coil resistance), a closed-loop regulator (lower chain) leads the value of \(I_{bus}\) to its reference.
IV. SIMULATION

A simulation of the circuit has been carried out on PSIM. The first circuit has been built up as follows (Figure 9):

The power circuit is colored red, while the control circuit is colored green. In order to carry out the calculations of the duty cycle, it is necessary to measure the bus and battery voltage, as well as the bus current. Since the bus current has higher variations than the current through the battery (whose variation is the ripple of the
inductor), it is easier to measure the latter. However, both need to be filtered before transmitting the value to the MCU.

The first open-loop simulation has been thought so that the converter is able to follow a bus intensity reference while the battery and the bus voltage are varying. This conveys the idea explained in Figure 6: a simple feed-forward regulation of the duty cycle with known and constant circuit parameters is able to achieve the reference value. This reference is given by a voltage source at the bottom of the design. Since it is the first and simplest simulation, no droop control has been performed in this case. The results of the simulation can be seen in Figure 10. Even if the battery and bus voltage behave in an uncontrolled manner, the MCU is able to adapt the duty cycle so that the final intensity matches the reference.

![Figure 10: Results of the open-loop simulation on PSIM [5].](image)

The results are very positive, since the reference value is reached within a reasonable period of time. However, a slight variation of the coil resistance (from 0.3 Ω to 0.4 Ω) would cause a significant deviation from the reference value, as demonstrated in Figure 11:
Since the inductor resistance may very well vary with temperature, it is necessary to introduce a close-loop regulation. Adding a PI regulator, the results are much better, as shown in Figure 12. In this case, and for the circuit parameters used hitherto, the $K_P$ selected was 0.007, and the $K_I$, $5 \cdot 10^{-7}$.
If the droop control is introduced with the restrictions introduced in Figure 7, the current reference will be proportional to the bus voltage. Since calculating a fully functional load is computationally difficult, there are two possibilities to simulate other devices connected to the bus. The easiest one is to connect a slightly variable voltage source to the bus. The more elaborated and maybe realistic one is to connect one or several current sources and a capacitor to it. Injecting current to the bus would cause the voltage of the capacitor to rise, prompting the activation of the module. Since the current depends on the bus voltage proportionally, the module gradually absorbs more current until the equilibrium is reached. For the first case, the results are the following (Figure 13):

![Figure 13: Complete droop control, results on PSIM [5].](image)

Note the saturation at the maximum value of the intensity, defined above. The closed-loop control introduces a faster system response and corrects any possible error between the reference and the steady-state value. The better results can be seen in Figure 14, where two current sources have been added with a capacitor, as explained before. This is conceived to simulate a solar panel (cosine wave) and a sudden start of a device (step wave).
Figure 14: Final circuit in PSIM [5].

Figure 15: Final results on PSIM [5].

V. COMPONENTS

The election of the components is very important for the design. In this converter, there are several to be chosen, such as the MCU, the transistors, the capacitors, the PCM, etc. (Figure 16).
Some of the components were already defined at the proposal of this paper. For example, the selected cells were 4 LFP batteries, each having a nominal voltage of 3.2 V. The batteries could have any capacity, but it is recommended that their continuous discharge rate exceeds 2 A.

The chosen PCM was the “Protection Circuit Module PCM-L04S04-92: 4S 12.8V LiFe LiFePO4 Battery PCM 4A Over-Charging Discharging Protection based on SM492”. This module is able to protect the batteries from both overcharge and undercharge and from overcurrent. The module will disconnect the batteries if the voltage is below 2.0 V (re-connecting them at 2.3 V) and if it is above 3.9 V (releasing at 3.8 V). Likewise, if the current exceeds 10 A, the module will protect the batteries as well. The module was suggested in the proposal [1].

The Microchip dsPIC30F3010 [6] was selected as MCU. The dsPIC family is faster than normal microcontrollers, and allows to perform a very high number of operations while holding a comparatively big amount of data. It is also optimized to perform multiplications inside the DSP motor. This module was already suggested in the proposal as well [1].

The power MOSFET IRF540 [7] has also been selected. The maximum drain current is less than 2 A and cannot be substantially higher even in case of failure, due to the presence of an inductor limiting current variations. This MOSFET withstands up to 23 A at 10 V and 100ºC, ensuring security. It also allows a drain-to-source voltage of 100 V, which is more than adequate for this application.

The driver selected was the IR2110 [8]. It is compatible with the voltage range of the MOSFET and it is very robust.
The inductor has been chosen seeking a compromise between the dynamics of the system and non-excessive harmonics. Simulations have shown that a good value is 1 mH.

VI. CONCLUSIONS

In this paper, a bidirectional buck-boost converter using droop control has been designed, both for an open loop regulation and for a closed loop one. The circuit can be used modularly in a bus, and might be useful for a variety of applications. The simulations carried out were satisfactory. An analysis of the components has also been performed.

References


