Bi-Directional Flyback DC-DC Converter for Supercapacitor Stack for Hybrid Renewable Energy System

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ABSTRACT

Energy Storage Systems (ESS) is quite necessary for renewable energy; they give them more autonomy and better power quality solving intermittency issues by supplying power when sources are unavailable. This work proposes an integrated bi-directional flyback converter (IBFBC) topology to interconnect a supercapacitor (SC) module to a hybrid renewable energy system. The proposed topology uses the symmetric nature of flyback converter topology to simplifying the bi-directional needs with minor components than half and full bridge topologies. Also, this topology features a magnetic isolating transformer which serves as an additional protection to the SC module and DC bus. The IBFBC, has been designed to store energy by charging up a Maxwell Technologies™ +48Vdc 165F SC module from a +24Vdc source, and once it was fully charged, supply power to the +24Vdc source via a single device. The IBFBC is controlled by means of increments of fixed duty-cycle steps in order to charge-up the SC module, and using the state-space average control technique to discharging stored energy.

Keywords: Flyback, bi-directional converter, supercapacitor.

1. Introduction

Renewable energy technologies have taken great importance in the present and future of energy supply for humanity development. However, many renewable energy technologies are already mature enough to be exploited such as wind, photovoltaic, and hydraulics, etc. It is well known that these technologies central issues are intermittency and energy storage [1], for that purpose traditional is used Pb and Ion-Li batteries. Nevertheless, their high energy density but low power density may cause stress at high power demands and may cause further damage [2]. On the other side, supercapacitors have a high power density and low energy density, causing no damage at high power, but reducing the autonomy of the device [3–5].

Hybrid Energy Storage Systems (HESS) attempt to enhance the energy storage using two or more storage technologies, in this case, supercapacitors and batteries are considered. The combination of SC and batteries offer high power density (from SC) and high energy density (from Batteries), reducing the stress in the system caused by high power demand and, at the same time, giving more autonomy to the HESS. Many forms of interconnect SC and batteries are reported in the literature [6–11], but in this case, it is proposed a bi-directional converter (IBFBC) because offers the possibility to charge and discharge the storage device, saving components and space, which is sometimes a relevant design factor. Also, due to its high power density, the SC can damage the converter, or failure on the energy bus can damage the converter and the SC as well. The flyback topology was chosen due to its simplicity, isolating transformer, and symmetric nature; also requires minor replacements of the components and adjustments such transformer secondary windings number, transformer turns ratio and components or circuit add-ons [12, 13].

In this work, the interconnection of a SC module to a mobile Hybrid Renewable Energy System (HRES) via an integrated bi-directional flyback converter (IBFBC) is shown in figure 1. Two renewable energy sources (wind turbine and photovoltaic panels) to supply +24Vdc bus, and then an IBFBC is used to interconnect with a SC module.

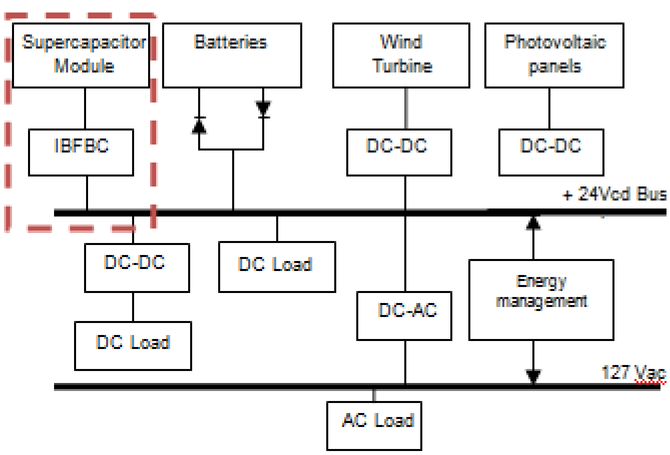

Fig. 1. Hybrid Renewable Energy System scheme and SC module interconnection via the IBFBC (red rectangle).

2. Proposed IBFBC Approach

In figure 2 the topology of an IBFBC proposed in J.L. Durán work [14] work is shown, which contains: a high-frequency single-phase transformer, a main switch (S_1) a filter capacitor C_i in the primary side, and the addition of the IGBT switch (S_2) to the D_2 diode, and then, grounded to the SC module cathode. As well, it uses the SC module itself as a secondary side filter capacitor, and the leakage inductance L_{l1} and L_{l2} for both sides of the transformer, respectively; and finally, the magnetization inductance L_m. This topology charges up the SC module and can discharge its full energy to the +24Vdc bus as well.

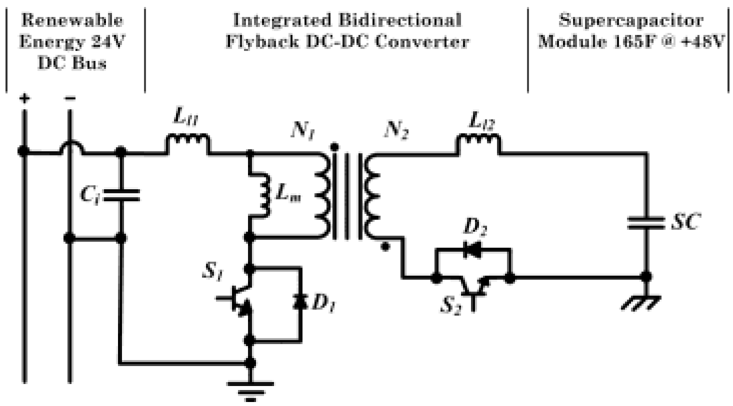

Fig. 2. Proposed topology of an Integrated Bidirectional Fly-Back Converter (IBFBC).

2.1 Bi-directional DC-DC Converter Design

2.1.1. Power Stage Design

The design parameters chosen for this topology that are obtained from, DC bus nominal voltage, the SC module datasheet and form the high frequency transformer previously designed, are described as follows:

V_{SC} = +48.6Vdc [=] Supercapacitor rated voltage.
C_{SC} = 80 F [=] Capacitance.
E_{max} = 2.48 Wh/kg. [=] Maximum supercapacitor energy.
$V_{o,dc}$ = +24Vdc [=] DC-bus output voltage.
fs = 20 kHz [=] Switching frequency.
$N_2/N_1 = n$=1 [=] IBFB transformer turns ratio.
d_1 and d_2 [=] Duty cycles for S_1 and S_2 power switches respectively.

This proposed topology has two main functions, to charge and discharge an SC module. So the design could be separated in two conditions; however, the methodology of the analysis of the conditions is practically the same. For the first condition of charge, is used the +24Vdc bus to charge the SC module, and during this process the regulation does not have to be rigorous due to the use of the supercapacitor module as a filter capacitor. However, the control must be set to not have an over-voltage condition above the nominal +48Vdc and protect internally the SC cells. The second condition corresponds to the discharge, and this will be triggered by the overall energy management. When this condition operates, the main IGBT switch (S_1), will be in off the state, but an internal fast & soft inverse diode (D_1) will be conducting under discharge condition, and supply power from de SC module to the DC bus. In this case, the regulation of the output power becomes important, so an adequate control must be properly designed. Some important parameters are the duty cycle and the voltage in the diodes and switches. The following expression defines the duty cycle for the main IGBT (S_1):

$$d_1 = \frac{1}{\left[\left(\frac{V_d}{V_0}\right)\cdot\left(\frac{N_2}{N_1}\right)+1\right]} \tag{1}$$

where, d_1 is the charge operation duty-cycle in S_1; V_d the input voltage; V_o the output voltage; and N_1 and N_2, the inductor primary and secondary turn number, respectively. Considering the topology symmetry, the duty cycle for the discharge operation, is done by:

$$d_2 = \frac{1}{\left[\left(\frac{V_o}{V_d}\right)\cdot\left(\frac{N_1}{N_2}\right)+1\right]} \tag{2}$$

Now, the voltage in the switch and the diode can be useful to select the parts avoid damage and validate the simulation and design with the experimental results. The IGBT switches *S1* and *S2* voltages are obtained by next expressions.

$$V_{sw} = \left[\frac{1}{(1-d)}\right]\cdot V_d \tag{3}$$

$$V_{sw2} = \left[\frac{1}{(1-d)}\right]\cdot V_o \tag{4}$$

Where: d is the duty cycle for the corresponding operation (charge or discharge). Moreover, the voltage of the diode is given by:

$$V_{diodo} = \left(\frac{N_2}{N_1}\right)\cdot V_d + V_0 \tag{5}$$

2.1.2. Control Stage Design

The control of the IBFBC was separated in two stages, one for charge and another for discharge. Both control strategies were written in separated PIC18F2680 microcontrollers in micro C programming language. The control strategy for the charge is the next:

For the supercapacitor charging operation, a simple step control was designed. The program code was set for to start with a low duty cycle (50%) until a 25V potential is reached. Then, is increased in steps of 5% duty cycle, every 5V until the 70% is reached, and finally, is shutdown the pulse when the charge process is complete. This control strategy was selected for its simplicity and knowing that the +24Vdc source is constant, so it is just matter to set manually the duty cycle and shut it down in the end**.** On the other hand, for the discharge operation an average state space control was designed. For this topology, the matrices corresponding *to* ON state, A_1 and B_1 based on input and SC X_1 and X_2 currents are:

$$\begin{bmatrix} X_1 \\ X_2 \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}}_{A_1} + \underbrace{\begin{bmatrix} \frac{1}{L_m} & 0 \\ 0 & -\frac{1}{C} \end{bmatrix}}_{B_1} \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} \tag{6}$$

where, L_m is the magnetizing inductance, and U_1 and U_2 are input and output voltage, respectively; and the matrices C_1 and E_1 based on the output voltage are done by the follow expression,

$$V_o = \underbrace{\begin{bmatrix} 0 & 1 \end{bmatrix}}_{C_1} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + \underbrace{\begin{bmatrix} 0 & 1 \end{bmatrix}}_{E_1} \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} \tag{7}$$

Now, once are have the matrices during “ON” state, the matrices on the “OFF” operation based on L_m and SC currents A_2 and B_2 are,

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \end{bmatrix} = \underbrace{\begin{bmatrix} \frac{re}{L_m}\left(\frac{N_1}{N_2}\right)^2 & \frac{1}{L_m}\cdot\frac{N_1}{N_2} \\ \frac{N_1}{C\cdot N_2} & 0 \end{bmatrix}}_{A_2} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + \underbrace{\begin{bmatrix} 0 & -\frac{re}{L_m}\cdot\frac{N_1}{N_2} \\ 0 & -\frac{1}{C} \end{bmatrix}}_{B_2} \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} \tag{8}$$

Finally, the matrix C_2 and E_2 are obtained based on the output voltage in the OFF state,

$$V_o = \underbrace{\begin{bmatrix} re\frac{N_1}{N_2} & 1 \end{bmatrix}}_{C_2} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + \underbrace{\begin{bmatrix} 0 & -re \end{bmatrix}}_{E_2} \tag{9}$$

Once the matrices of the topology are obtained, the transfer function can be determined by the following expression:

$$TF(s) = C \cdot [sI - A]^{-1} \left[(A_1 - A_2) \cdot \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} \right] \tag{10}$$

This transfer function is computed with the Matlab™ software to obtain the bode plot, and from that plot adjust the desired cross frequency, which has to be at least the 20% of the switching frequency.

2.2.3. Charge and Discharge Logistic

Due to the topology employed, the charge and discharge operation of the converter will be done by an external energy management system. To protect the converter, and avoid enabling the charge and discharge operation at the same time, the control board has been limited by relays as shown in figure 3.

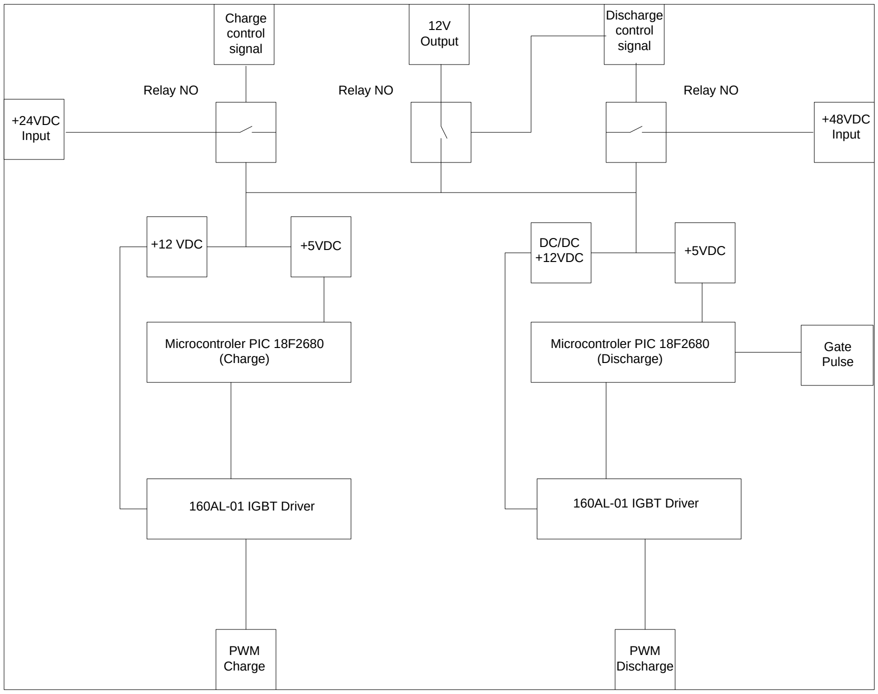

Fig. 3. Integrated Bi-directional FlyBack Converter Control Board distribution

The inputs of the board, both +24Vdc and +48Vdc (for the DC bus and the SC module), are limited by relays in both sides. An external energy management sends a control signal that activates the normally open relays to charge or discharge the SC module when needed. Once activated, the power will flow to a +12Vdc voltage regulator (for a charge) and a +12Vdc DC-DC converter for discharge. Those regulators will supply power to an insulated gate bipolar transistor (IGBT) driver and a +5Vdc voltage regulator to energize the corresponding microcontroller. The microcontrollers will generate the chosen pulse, either charge or discharge, and will be sent to the IGBT driver to get the output pulse with modulation (PWM). In addition to the PWM pulse output for charge and discharge, an additional gate was implemented, this for put in or out the load during the discharge operation.

3. Simulation and Experimental Results

The simulation and experimental results of the IBFBC design are discussed in this section. So, the duty cycles are 67% for the charging operation and 33% for the discharge operation. Based on these parameters, and the ones exposed in section 2, simulation results of charge and discharge have been done using PSIM™ Software. In figure 4, the voltages and currents in diode, D_2, as well as in power switch S_1 are shown for the charge operation.

3.1. Simulation Results

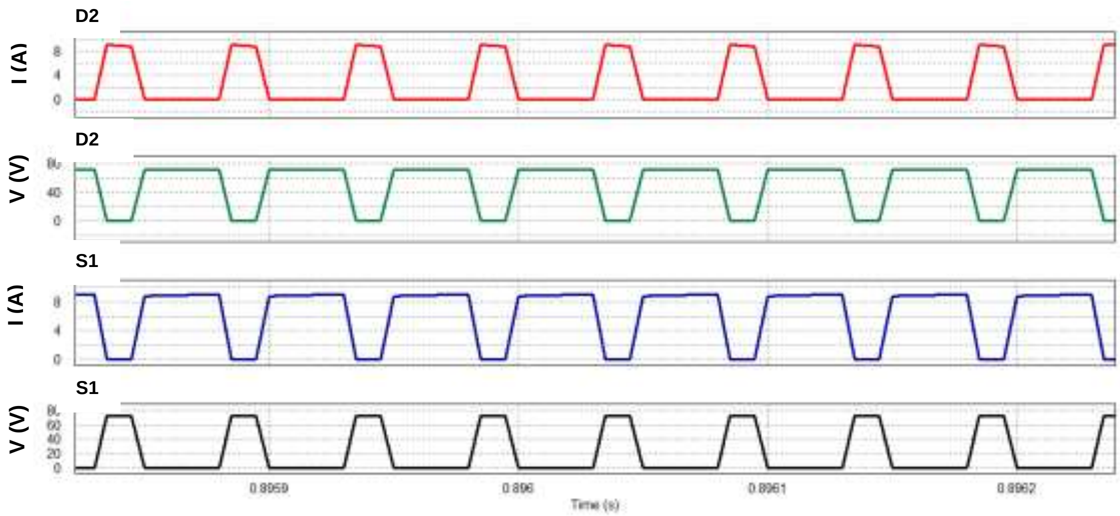

Fig. 4. Integrated Bi-directional Flyback Converter charge operation (24V-48V) D_2 and S_1 waveforms simulation used PSIM™.

The simulation results show that the values obtained from ec. 1 to 5 during the design of the converter are accurate by giving the same values. The waveforms show that voltages and currents between diode D_2 and switch S_1 are complementary forming the voltage and current in the transformer, suggesting a correct and stable operation [12, 13]. The discharge simulation results (figure 5), shows the voltage and current waveforms generated by the diode D_1 and switch S_2.

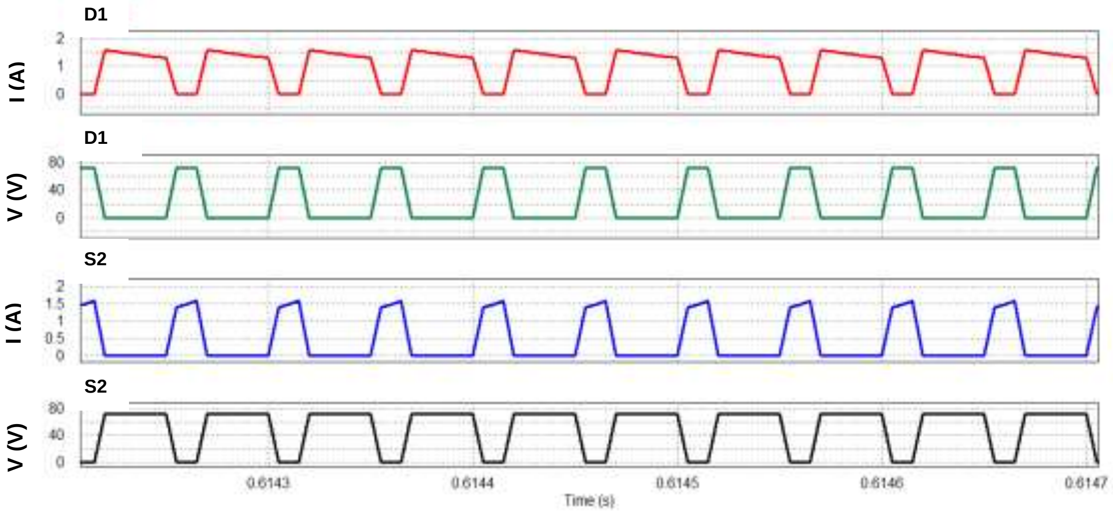

Fig. 5. Integrated Bi-directional Flyback Converter discharge operation (48V-24V) D_1 and S_2 waveforms simulation in PSIM™.

3.2. Experimental Results

Like in the charge operation waveforms, it can be appreciated that values are close to the ones obtained during the converter design. Also, voltage and current waveforms through diode D_1 are complementary to the switch power device, S_2, waveforms forming the voltage and current on the inductor suggesting stability and correct operation as well. On following paragraphs, the waveforms during experimental operation will be presented. Figure 6 shows the 33% PWM signal, D_1 current, and the S_2 voltage and current waveforms. It can be seen that wave-forms values obtained in experimental tests are similar to the ones obtained during design and simulation, confirming the design. The switch voltage, V_{SW}, presents a peak due to leakage inductance losses due to the manual high-frequency transformer construction therefore; a snubber RCD circuit was added to reduce the voltage peaks on the IGBT S_2. The S_2 voltage V_{sw} can be seen to be anti-proportional to the S_2 current and proportional to D_1 current which suggest the correct operation of the proposed topology. Moreover, it can be seen that current wave-forms shows a capacitive effect, probably due to the high transformer inductance L_m and the leakage inductance L_l in the circuit and transformer conductors.

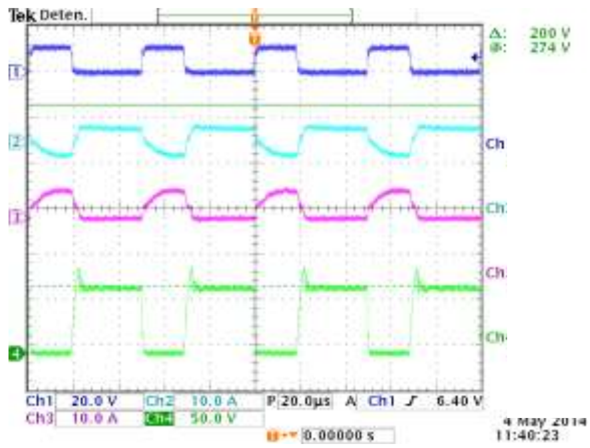

Fig. 6. Experimental results of the converter waveforms at 33% PWM signal (dark blue), D_1 current in A (cyan), S_2 current in A (pink) and S_2 voltage in V (green) during discharge operation.

For the charge operation (figure 7), the waveforms, it can be seen that are complementary to the discharge waveforms, suggesting the change of the output power and, therefore, the correct operation of the converter. Because of the voltage peak present in S_1 voltage, a RCD snubber was also added to the IGBT switch S_1. And, as seen in figure 6, leakage inductance in the circuit makes a deformation in S_1 and D_2 current wave-forms.

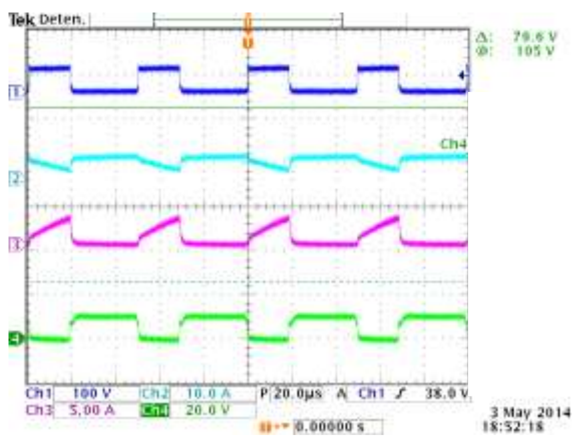

Fig. 7. Experimental results of the converter waveforms S_1 voltage in V (dark blue), S_1 current in A (cyan), D_2 current in A (pink) and 63% PWM signal (green) during charge operation.

Now that the correct converter bidirectional operation has been set, the SC module charge performance is shown in figure 8. It can be seen that the converter can charge the SC module from a +24Vdc source in an approximate time of one and a half hours. The charge curve shows a fast initial increase to +25Vdc in the SC voltage and then the charging rate starts to drop with the increasing voltage in the SC terminals regardless of the increasing duty cycle.

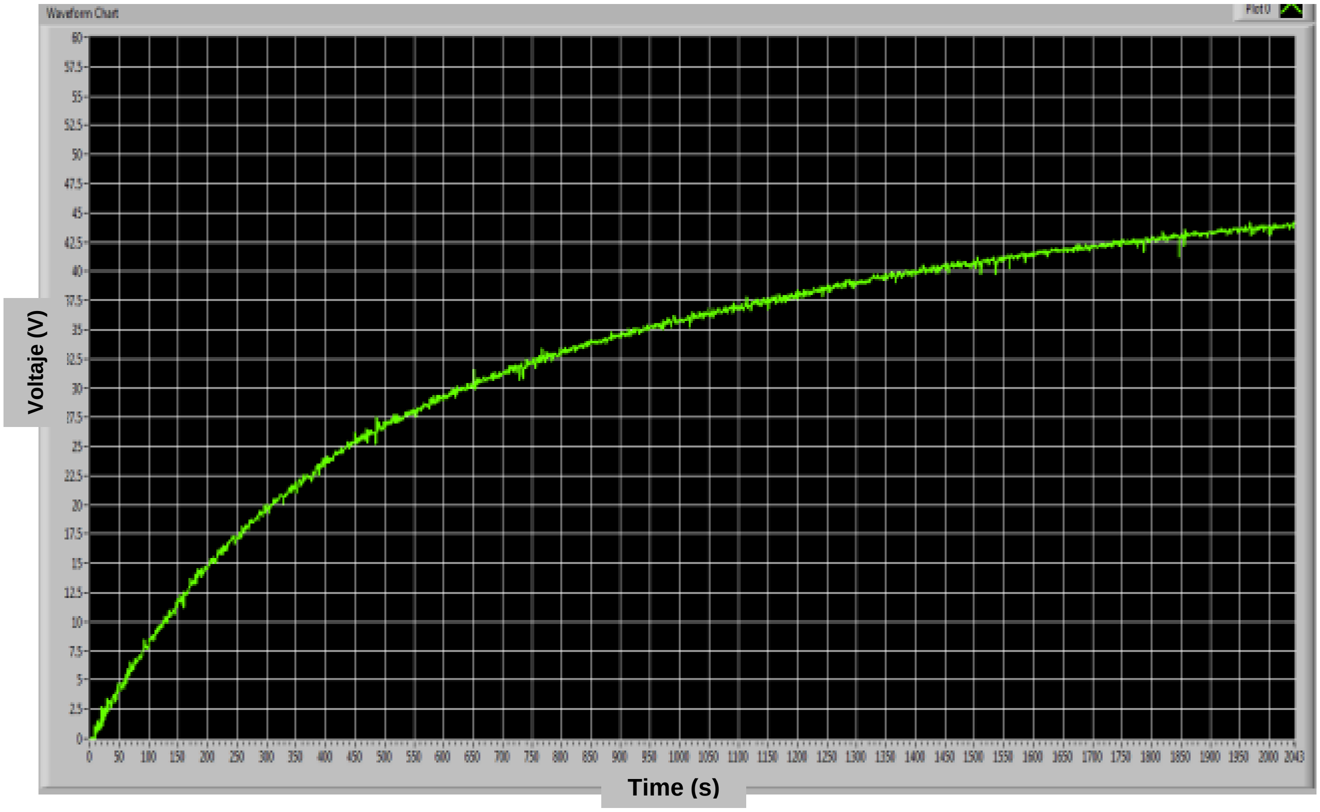

Fig. 8. Supercapacitor module from 0 to +48Vdc charge via IBFBC

4. Summary and perspectives

In this paper, a topology of an integrated bi-directional flyback converter (IBFBC) has been proposed to operate as an interconnection power device for supercapacitors in hybrid renewable energy systems. Simulation and experimental results were presented, giving a fully operating converter; the topology has been presented with a simple design that can save space, and economic resources, due to the utilization of a high-frequency single-phase transformer and the use of an IGBT switches with antiparallel diodes employed for the bi-directional operation. The IBFBC is able to charge a +48Vdc, 165F SC module in an average charging time of an hour and a half, and allows a 20% discharge used a +24Vdc Bus.

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