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High efficiency multi power source control constant current/constant voltage charger lithium-ion battery based on the buck converter

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ABSTRACT

This paper proposes the design and simulation of a constant current/constant voltage (CC/CV) multi-power source lithium-ion (Li-ion) battery charging system based on the Buck typology. The aim of this new design that uses the Buck converter with multiple numbers of sources, is to provide sufficient energy for battery charging, with an analog switch to select the active source that has priority to guarantee the continuity of the charging without interruption. As well as the transition between the charging modes is smooth that is provided by a multiplexed switcher. At the same time is increases the efficiency of the system by using fewer power dissipation components and low output ripple. The obtained results show that the Li-ion battery can be successfully charged without reducing its life cycle. In the global, those technics allow reducing financial costs. This allows such a solution to be well-positioned in the industrial market (electric vehicles (EV) and medical).

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1. INTRODUCTION

The so-called "lithium-ion" batteries have become ubiquitous in our daily lives. They can be small in a mobile phone or assembled by the dozens in an electric car or medical equipment. They are the subject of intense research in the industrial sphere, given the challenge that represents electricity storage. The proposed solution will cover the problem of the switching between the sources and its transition flexibility to avoid any undesired interruption during charging or equipment operation which will also increase the efficiency and overall performance of the system and use fewer components to achieve those functionalities. Therefore, the design of a multi-power source is recommended to guarantee and offer the continuity of the operation of the equipment.

The challenge of our design lies in switching between sources of different types with priority conditions according to active or the available source, and at the same time keeping the efficiency of charging without creating noisy response at the transition between the constant current/constant voltage (CC/CV) charging method, Figure 1 showing the voltage and current of charging for a lithium-ion (Li-ion) battery by using this method [1], [2]. it will charge a battery with a constant current firstly until the battery voltage increases to the constant voltage limit. After the CC charging regime, the charging process goes into the CV regime to prevent the overcharging [3]–[5].

Our method builds on: i) checking the existence sources by using Hysteresis comparators which compare the input voltage with a reference voltage Vref, ii) ensuring the switch between sources using a logical circuit that drives the source to the power stage by priority and iii) modified direct current (DC-DC) Buck converter allows ensuring the CC/CV charging modes with a proposed mode selector system, while always avoiding voltage drops due to switching between sources and ensuring high efficiency [6], [7]. This paper is organized: the second part will cover the descriptions and simulations of the proposed battery charger that includes the switching solution, so it will present in detail the architecture and functionality of each block composing the proposed Buck-type converter to charge the Li-ion battery. The results of the simulations of the circuit will be illustrated in the 4th section and a conclusion will be presented afterwards.

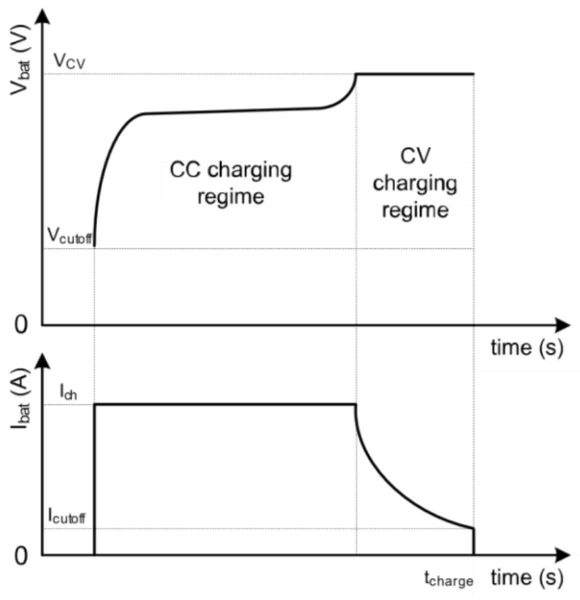

Figure 1. CC/CV modes charging

2. THE PROPOSED BATTERY CHARGER

The industrial market always tends to look for solutions for continuous power supply during operation of Li-ion batteries used in electric vehicles and medical equipment. Our solution comes to answer these needs with a circuit comprising a combination of two architectures, each with its own functionalities aimed at providing uninterrupted power supply even when changing power sources based on renewable energies. Adding the challenge of keeping the battery charging efficiency.

2.1. Multi power source control

Our proposed multi-source solution offers an uninterrupted power supply to the battery by switching between three sources by priority according to the availability, while avoiding voltage drops and keeping a high efficiency and less losses of the system by reducing the number of metal-oxide-semiconductor field-effect transistors (MOSFETs) transistors. Figure 2 illustrates the blocks that build our method used:

a) Sources: We have three sources classified according to priority. For instance, in electric vehicles (EV) application we could have these following sources: source 1: sector, source 2: photovoltaic (PV) solar panel on top side, source 3: wireless charger in bottom side.
b) Comparators: They are Schmitt trigger type that makes the comparison between the input voltage and a reference voltage Vref in order to verify the existence of the input source. at the output of each comparator, we have logical signals that specify the active sources (c1, c2, c3) [8].
c) Source selector logical circuit: responsible for meeting the priority conditions of the sources using AND/NOT logic gates that check those following equations:

$$\mathrm{En}_1 = \mathrm{C}_1 \quad (1)$$

$$\mathrm{En}_2 = \mathrm{C}_2 \times \overline{\mathrm{En}_1} \quad (2)$$

$$En_3 = C_3 \times \overline{En_2} \times \overline{En_1} \quad (3)$$

When the source 1 is present (C1=High), En1 will be active so the load will be powered by the voltage Vsource1. For the load to be taken by second source Vsource2, it is necessary the non-existence of the 1st source $(\overline{En_1})$ and the presence of the second source (C2=High). In order the system to be powered by the third source, of course it is necessary the presence of source 3 (C3=High) and the non-existence of the primary and second source $(\overline{En_1}, \overline{En_2})$.

d) Gate driver: This block has as inputs the logical signals En which designate the active sources and a pulse width modulation (PWM) input with the purpose of driving it to the gates of the P-channel metal-oxide-semiconductor (PMOS) that related with an active source.
e) Multiple HS half-bridge: The switching part of the power stage, consisting of two elements a three back-to-back PMOS, each one of them related to a specific input voltage, represents a power source, and a low side N-type metal-oxide-semiconductor (NMOS) for the synchronous type. The dual structure of the PMOS protects the circuit against reverse currents and keeps a good efficiency using fewer number of transistors [9]–[11].

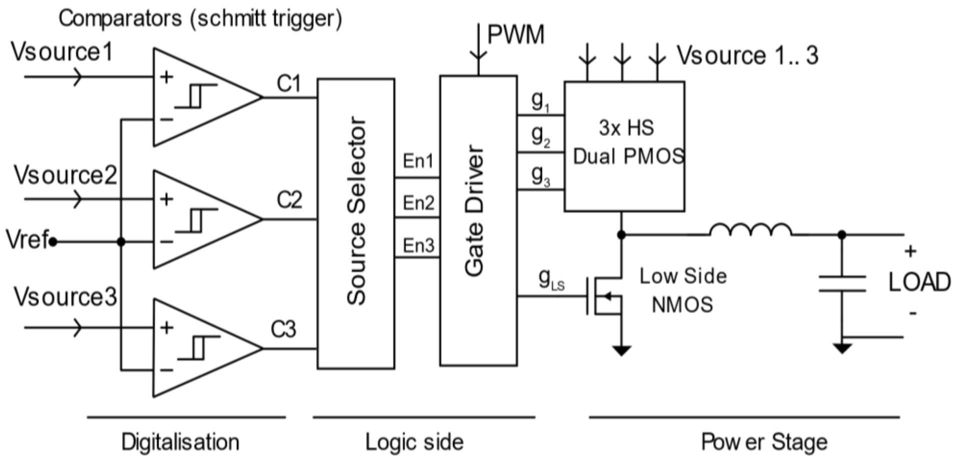

Figure 2. Diagram of multi power source control

2.1.1. Schematic

The design of the proposed model predictive speed control (MPSC) solution is made using a combination of digital and analog components well-chosen according to their performance. As already mentioned, the operation of our MPSC is to check the existence of sources by comparison with reference voltage and choose the right source by priority. The challenge is always to cancel the load current and voltage errors when changing the voltage sources.

2.1.2. Enables signals vs output voltage waveform

In this simulation shown in Figure 3, we used three sources of the same type with an input voltage Vin=12 V and a delay in time in order to observe the output voltage Vout being switched between the sources. Taking for instance when t=2 ms, we notice the non-existence of Vin1, the deactivation of Vin2 and the activation of Vin3, so Vout will switch between second and third source. This is illustrated in the Figure 4, the system made a switch between the sources without undergoing any undershoot on Vout and even disturbances. After visualizing the Vout signal by applying all the possible switching cases, we can conclude that our system is well efficient and has met all the specification requirements. The following equations describes the conditions of simulation show in (4), (5). Open loop control by pulse-width modulation (PWM) signal which has the following specification (Fsw=200 KHz, D=50%).

$$D = \frac{ton}{ton+toff} = \frac{ton}{T} = 1/2 \quad (4)$$

$$\frac{Vout}{Vin} = D(duty\ cycle) \quad \Leftrightarrow \quad Vout = \frac{Vin}{2} = \frac{12}{2} = 6V \quad (5)$$

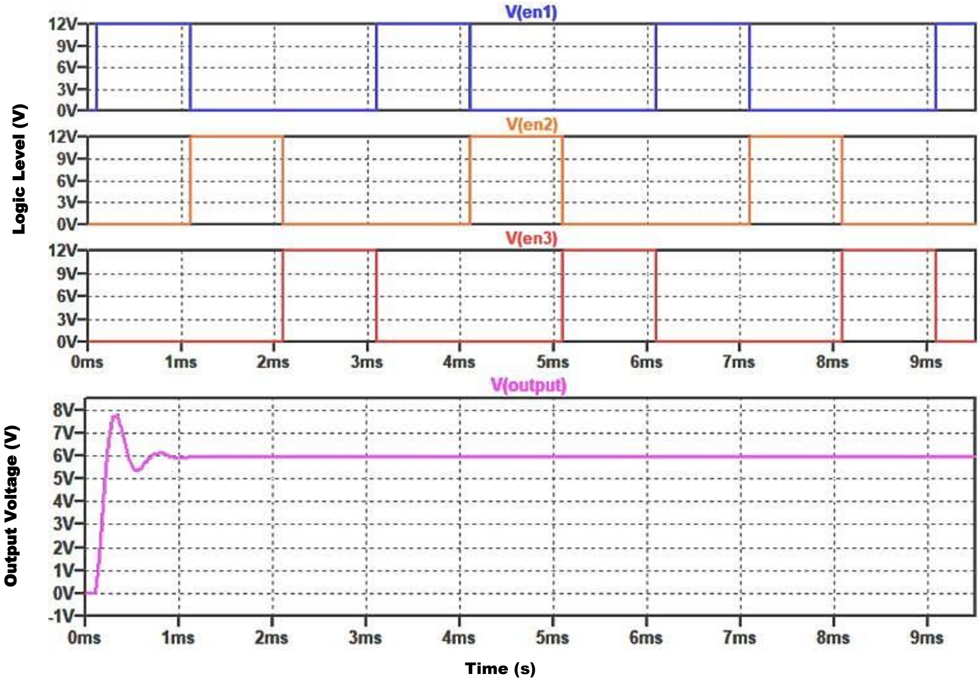

Figure 3. Simulation

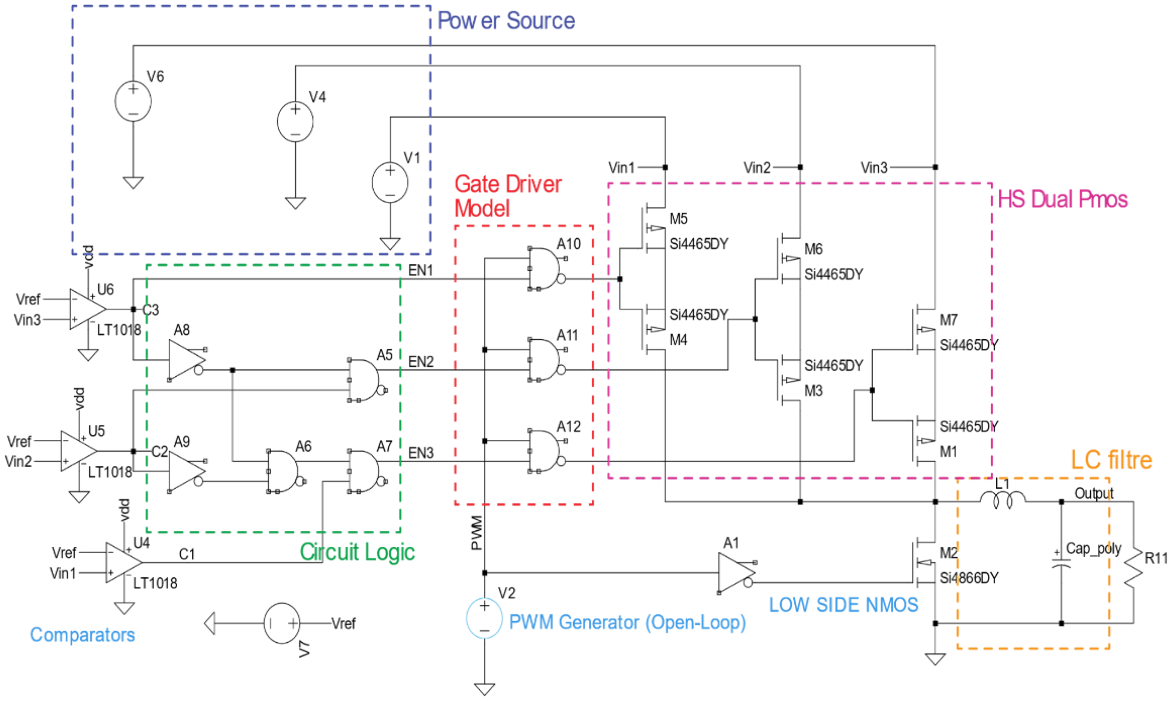

Figure 4. Block diagram of the proposed MPSC Li-ion battery

2.2. Proposed CC/CV Buck converter typology battery charging with modes

The technique of using the pulse source and no dissipative output filter allows the transfer of energy with high efficiency. That is, less power is lost in the converter itself. In order to regulate the output voltage, a voltage reference and an error amplifier are added to the circuit. The four basic blocks (the pulse generator, the modulator, the output filter, and the compensator) are combined to form a complete feedback control DC/DC converter as shown in Figure 5. The design of the circuit begins by selecting various operating parameters and component values, largely determined by the basic operating requirements, namely: input voltage range, output voltage, output current range, operating frequency [12]–[14]. The proposed charging CC/CV modes using buck converter with blocks: power stage, compensator, PWM comparator, CC/CV mode switcher and finally voltage and current Schmitt trigger comparator is represented in Figure 6. The system was designed block by block to ensure that each one worked properly, and then the system blocks were assembled so that the impedance between the output and the input was matched.

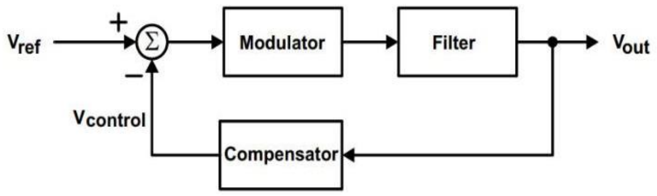

Figure 5. Buck converter typology

2.2.1. Schematic

The design of this circuit was made according to the desired load specifications aiming at a load in CC/CV mode with a high efficiency by using components known in the market. The difficult constraints that make this circuit complex with its parameters is the grouping of output and input impedances between two linked blocks. Figure 6 illustrates the composition of the proposed Li-ion battery CC/CV charging with a Buck converter by block each with its functionality:

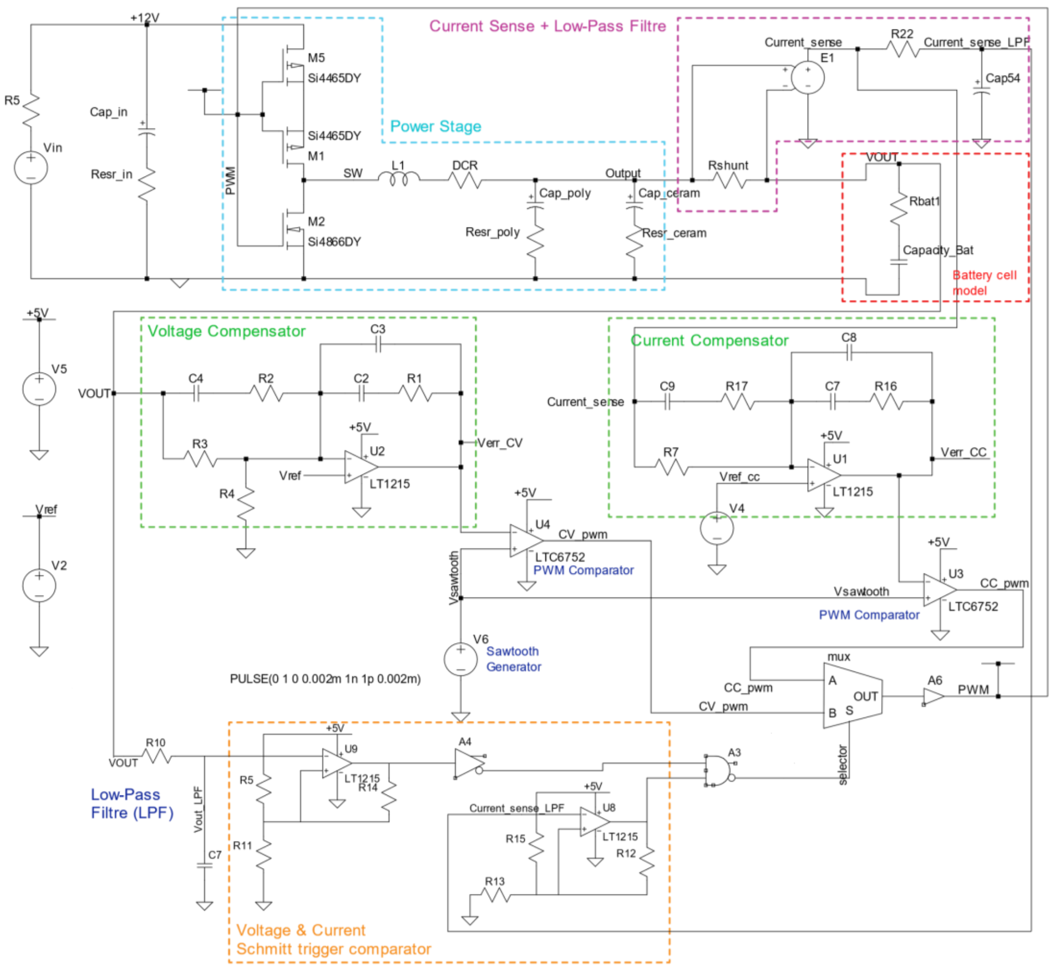

Figure 6. Block diagram of the proposed CC/CV charger for Li-ion battery

a. Power stage

Consisting of a low-pass LC filter that converts the square signal (situated at the common point of switching) to a continuous signal, the values of the inductor L and its resistance series DC resistance (DCR), are well chosen so that the response of the loop is fast and, in a way, to allow the use of fewer capacities on the account of the less of the root mean square (RMS) current. Also, they are chosen to allow fewer energy losses in the core. The following (6) represents the transfer function of the lossy LC filter with an output capacitor, and the bode diagram is shown in Figure 7 [15], [16].

$$H_{Filter}(s) = \frac{(1+CR_S)s}{1+\frac{R_L}{R}+\left(\frac{L}{R}+R_C C+R_L C+\frac{R_L R_C C}{R}\right)s+\left(\frac{R+R_C}{R}\right)LCs^2} \tag{6}$$

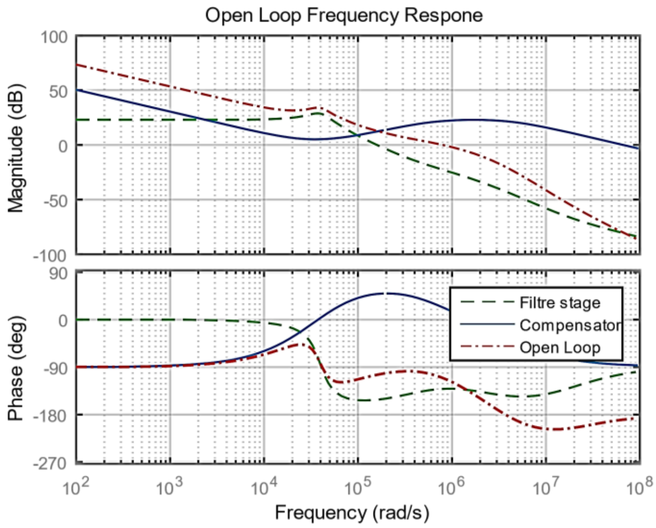

Figure 7. Voltage control open loop frequency response

b. Compensator (voltage and current)

We used a Type III compensator can have a phase plot going above zero degree at some frequencies, and therefore it can provide the required phase boost to maintain a reasonable phase margin. The Type III compensator has three poles (one at the origin) and two zeros. which arranged to have two zeros and two poles, and the loop crossover frequency is placed somewhere between the zeros and poles. For this kind of design, the transfer function can be rewritten as [17]–[19]:

$$C(s) = \frac{Vo}{Vi} = -\frac{(sC_2R_2+1)[sC_3(R_1+R_3)+1]}{R_1(C_1+C_2)s(sC_{12}R_2+1)(sC_3R_3+1)} \tag{7}$$

Using the frequency analysis by matrix laboratory (MATLAB) software, we find the values of the capacitive and resistive components included in the compensator by the choice of a crossover frequency f_{xover} based on the switching frequency and with placing the poles and zeros in the reason to boost the phase margin up to 180° and have a critically damped transient response. The founded values are: For the voltage compensator components:

C1=8.548 pF, C2=2.3411 nF, C3=1.1307 nF
R1=31.59 KΩ, R2=15.26 KΩ, R3=1.15 KΩ
For the voltage divider: R_{div}=5.11 KΩ
And for the current compensator: C1=11.57 pF, C2=1.75 nF, C3=4.81 nF
R1=5 KΩ, R2=13.75 KΩ, R3=330.3 Ω

The results obtained are the following: The estimated phase margin is 102.2° at the frequency of 86.5 Khz for the voltage control, which is sufficiently high compared to the rule of thumb value 45°, and for the current control loop which has an additional block upstream of the filter stage block, such as a feedback control current measurement gain, the obtained value is 78.62° at 56.48 Khz which is also a satisfactory value.

c. PWM comparator

It makes the comparison between the output of the compensator (CC_error/CV_error) and a sawtooth signal to generate the signal (CC_PWM/CV_PWM) of control. The latter is responsible for having the desired current or voltage according to the active mode of charge CC/CV using a fast comparator (high bandwidth) capable of catching up the switching frequency [20]. In our circuit, we have chosen LTC6752 which belongs to the family of high-speed comparators.

d. CC/CV mode switcher

It is represented by a multiplexer (MUX) with inputs CC_PWM and CV_PWM operating under the conditions seen in Table 1. The operation of this MUX is controlled by the selector described in (8) which ensures the change of mode between CC and CV. From the Table 1, we can see that the load voltage and current are the main conditioning elements for the mode change.

Selector:

$$S = \overline{Vcomp * Icomp} \quad (8)$$

Table1. Modes of operation in accordance with the combinations of the comparators

Output Conditions		Output Comparator		Mode
Voltage	Current	Vcomp	Icomp	Out (MUX)
Vout>Vcharge	Iout>Icharge	'0'	'1'	CV
Vout>Vcharge	Iout<Icharge	'0'	'0'	CV
Vout<Vcharge	Iout>Icharge	'1'	'1'	CC
Vout<Vcharge	Iout<Icharge	'1'	'0'	CV

e. V/C hysteresis comparator and lowpass filters (LPFs)

In noisy environments specifically with switching power supplies that generate electromagnetic interferences disturbing the acquisition and the measures taken by the circuit. We manage to use low-pass filters and hysteresis type comparators to eliminate the noise. In our circuit and optimization purposes, we used this technique of voltage comparison and filtering shown in Figure 8 to avoid disturbances due to changes in CC/CV charging modes and allowing to have a good functionality during the charging of the Li-Ion battery [21], [22].

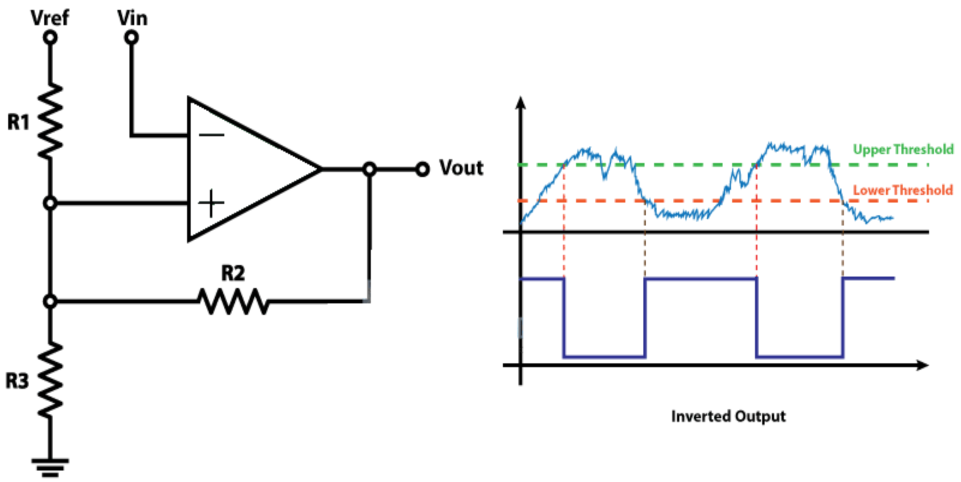

Figure 8. Hysteresis comparator

3. RESULTS OF COMBINATION OF THE TWO SOLUTIONS

The block diagram of the proposed Li-ion battery CC/CV charging with the proposed multi power source control is shows in Figure 9. The combination of the two solutions was a bit complex to keep the high charging efficiency in CC/CV modes and to avoid errors when switching between the voltage sources. The simulation of the circuit illustrated below clearly shows the stability and efficiency of our design and the good choice of the components used.

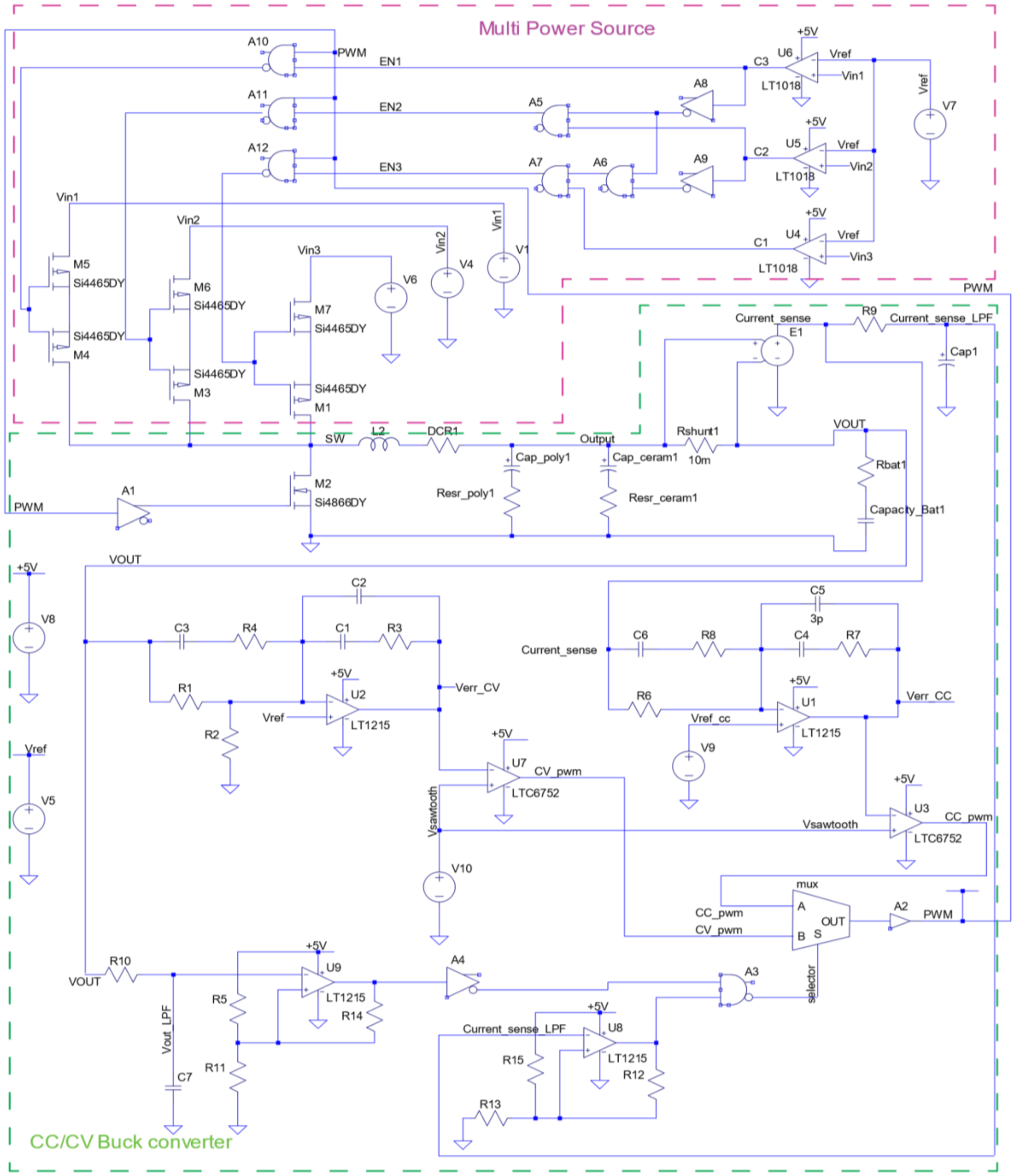

Figure 9. Circuit diagram of the proposed charger with MPSC

The simulation of the proposed charger is shows in Figure 10. The brown curve: charging voltage of the battery; The green curve: charging current of the battery; The blue curve: voltage signal of the mode of charging selector, 5 V represents the CC and 0 V represents the CV mode. By noticing Figure 10, we can see that there are CC/CV charging modes controlled by the selection voltage. The latter allows to change the charging mode from constant current to constant voltage by performing a state change from ‘1’ to ‘0’ with a creation of a little spike in current and voltage due to the compensation delay.

The power conversion efficiency of the proposed battery charger is presented in Figure 11. The maximum efficiency of our charger is higher than the stated architectures that can reach its maximum 97% between 3 A to 7 A [23]–[26]. As expected, the obtained results are much better compared to other work. Table 2 summarizes the performance characteristics of the proposed Li-ion battery CC/CV charging with the proposed multi power source control.

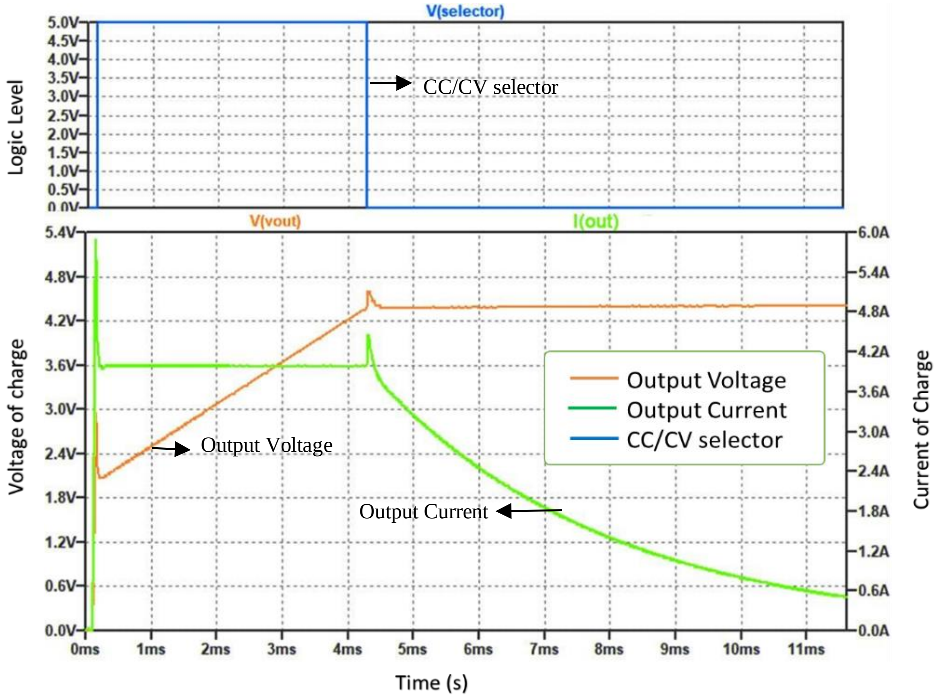

Figure 10. Charging battery

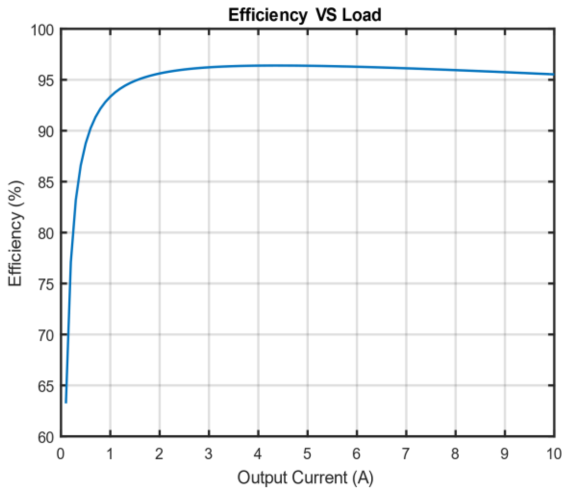

Figure 11. Power efficiency of the proposed Li-ion battery charger

Table 2. Performance summary and comparison

Method	[23] 2015 LDO-Based	[24] 2017 Current-Mode Smooth Transition	[25] 2019 Dual Switching Control (buck-booster converter)	[26] 2021 charge mode selection based 0.18 um CMOS	This work Multi source control (Buck converter)
Supply Voltage (V)	4.8-5	4.5-5.5	13.5	2.7-4.5	12
Output voltage (V)	2.5-4.2	4.194	4.5	4.2	4.4
Current charge(A)	448 m	600 m	4	1	4
Efficiency (%)	87	92.49	-	90.9	95

4. CONCLUSION

To conclude, the proposed architecture presents a good choice for Li-ion batteries in different domains as efficient charger for limited energy sources like renewable energies. Therefore, this solution will minimize the power dissipation during charging to maximize the charged capacity of the battery in different conditions. Using CC and CV modes can also increase the state of healthy for its sustainability's. The result of the simulation presents a power efficiency up to 95% and better performance in terms of current charge than can reach 4,000 mA in short time and low output ripples. Based on this performance, we see that our solution can be well imposed on medical applications or electrical vehicles.

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