3.7-V 100-mA Dual-Loop CC/CV Lithium-Ion Battery Charger With Programmable Current Regulation and Voltage Buffer

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***Abstract*—A hybrid based CC/CV dual loop system continues to remain the most effective approach for Li-Ion batteries charging for many applications. However, issues with adjustable regulators used in constant current circuits and error amplifiers for constant voltage pose risks to sufficient operation. This paper describes a novel design of a charging mechanism for Li-Ion batteries rated at 1C and 100 m - 500 mAh via a CC/CV dual loop feedback circuit, to manage a regulated current of 100 mA with a maximum 3.7 terminal voltage. The constant current circuit implements a programmable current source adjusted with external resistor ratios, RC network for noise reduction in the 10 Hz-100 kHz bandwidth range, and a supplementary series resistor to dampen resonant ringing against parasitic reactance. The method for constant voltage uses an error amplifier with negative feedback and reference from a 3 resistor divider for a reduced 8 mA current draw and designated voltage output for error detection. The output is then chained to a voltage buffer with high input and low output impedance for stability and high current isolation before leading to a MOSFET pass element handling battery charging, with regulation procedures when nearing the terminal voltage of 3.7 V. Moreover, onboard power input is 5 V regulated from the external powering device.**

***Index Terms*—Constant Current, Feedback, Reference Voltage, Programmable Current Source, Constant Voltage, Error Amplifier, CC/CV Charging.**

I. Introduction

EFFECTIVE reduction of power dissipation and adequate management against thermal stress continue to remain an integral task to accomplish in the existing CC/CV dual loop architecture [1] as unmitigated thermal buildup can accelerate cell degradation and thermal runway [7]. Many of them have continuous applications for charging stability in light weight electric vehicles [1]. Standard batteries run at an average nominal voltage of 3.6 - 3.7 with a maximum of 4.2 V, and many charging circuits take account of such circumstances through implementing a constant current period; topology where output current remains steady with a rising voltage independent from outside determinants until reaching the cutoff amount and transitioning to a regulation state through a pass element [4]. Conventional applications can separate into pre-made adjustable linear regulators with a set resistor to adjust steady output current, or a CMOS amplifier receiving negative feedback to drive an external BJT with an obligatory sense resistor to its emitter. Additionally, constant voltage (CV) mechanisms maintain fixed output when driving a load through a closed-loop LDO control architecture [3]. Its related infrastructures follow suit with constant current (CC) designs, as they include an error amplifier receiving negative feedback and reference voltage as a separate supply or through a divider network, before outputting to a pass element. Consequently, there exists a common execution of a hybrid CC/CV circuit with dual-mode operation [1][4] to select the first states depending on the threshold of current or voltage reached first.

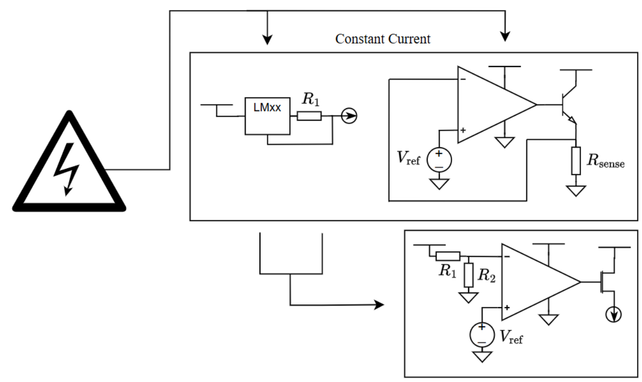

Fig. 1. Diagram for dual-loop Constant Current and Constant Voltage charging circuit framework.

Common usage of adjustable linear regulators to set the designated current output emerges with unwanted difficulties. Although LDOs require careful consideration to to for fast transient response [5], they struggle with having a lower response as a rapidly switching load can decreases or increases voltage output and cause a step-up in load current. This jeopardizes smooth output given a lack of instantaneous responses. Additionally, many regulators dissipate excess voltage as heat to regulate fixed current where unoptimal losses of power can cause conflicts with a disconnected or shorted battery, inducting high voltage for an unsuspecting load reconnected back to the circuit. This poses an issue with increasing the instance of a Li-Ion battery fire during brief moments of overcharging mechanisms to an LDO [7]. Consequently, constant voltage circuits with output from an error amplifier suffer from an inherent low slew rate during load transients [3] to a pass element for charging control. These are prevalent issues that come with the implementation of hybrid CC/CV systems in the design of Li-Ion battery charging circuits.

II. Constant Current Design

A. Programmable Current Source

When devoid of the use of an adjustable linear regulator from the LMxx series, we decide to opt for a programmable current source of the LT3092 with a set current draw created between the ratio of two resistors, R_{set} and R_{out}, with an accompanying RC network and set capacitor against unwanted resonance and reactance occurring between input and output lines [6]. A series resistor to input is set to damp the effects of the ringing for long trace lines that cause unwanted reactance, and a supplemental RC network to filter external noise [6]. Internally, the LT3092 includes an error amplifier for detection with a complementary Darlington pair as the primary pass element. V_{set} is determined to be 5 (Fig.2).

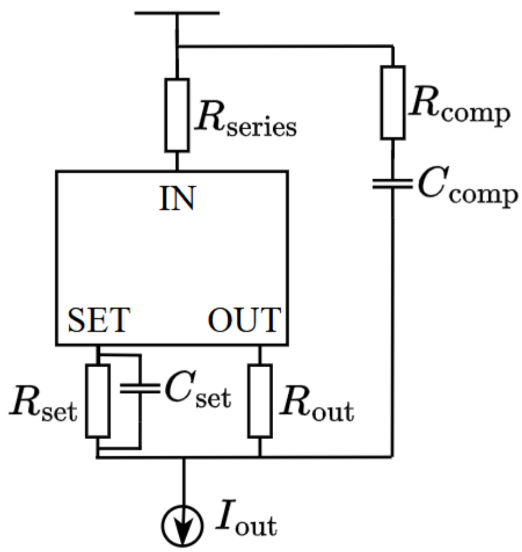

Fig. 2. Schematic for the LT3092 programmable current source featuring constant output and protection against resonance/reactance.

To formally calculate the output current, when assuming that the designated $I_{out} \geq 0.5$mA. The equation is given as follows:

$$I_{out} = \frac{10\,\mu\text{A} \cdot R_{SET}}{R_{OUT}} + 10\,\mu\text{A} \tag{1}$$

Where R_{out} is 10 and R_{set} is 100K such that:

$$I_{out} = \frac{10\,\mu\text{A} \cdot 100\text{K}}{10} + 10\,\mu\text{A} \tag{2}$$

The output of the programmable current source is now set to:

$$I_{out} \approx 100\text{mA} \tag{3}$$

Additionally, the series resistor is equal to 1 through injecting controlled resistance into a reactive network (reducing the Q value) caused by long trace length bring parasitic inductance [6]. In addition, added ceramic bypass capacitors to the input creates LC resonance to which the resistor absorbs energy to rapidly decay the resonance frequency. C_{set} reduces noise in a 10Hz - 100 KHz bandwidth region created from the internal reference current of $10\,\mu$A [6]. The supplemental RC network acts as a frequency compensation loop for stabilization. C_{comp} introduces a zero into the loop from stray capacitance from a phase shift back to reduce high frequency ringing. R_{comp} controls high frequency gain through damping the capacitor's impedance. The resistor of R_{comp} ranges from values of 100 - 5K, with its accompanying capacitor of 1000pF - $1\,\mu$F and the set capacitor between 0.01 - $22\,\mu$F as per suggested by the LT3092 datasheet. To determine the maximum output voltage as it continuously ramps up in value, we can use the following equation:

$$V_{out} = V_{in} - V_{dropout} \tag{4}$$

Assuming that the typical dropout voltage is 1.35 with an input of 5 from an external powering component:

$$V_{out} = 5 - 1.35 \tag{5}$$

$$V_{out} = 3.65\text{V} \tag{6}$$

The maximum output voltage of a given 100 mA source is 3.65V, with the least ideal case scenario of a greater breakdown value (1.50) resulting in a final output of 3.50V. During this moment, the output voltage would linearly rise up until it reaches a load resistance nearing 40 where it stagnates to a consistent value. Similarly, the constant current period of the charging loop experiences a chance in steady output current as the load resistance nears the 40 range, a period of output decreasing substantially from its original 100 mA peak as it transitions to the CV phase of the hybrid system (Fig. 3).

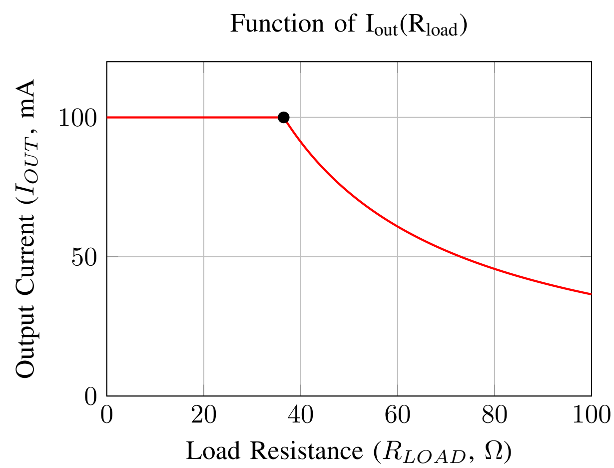

Fig. 3. The function of output current against load resistance from the programmable current source as apart of the CC architecture.

III. Constant Voltage Design

A. Error Amplifier Framework

The framework is based on the existing design located from Fig. 1, with a subsidiary error amplifier for negative feedback and reference voltage, both created from the supply configured through a 3 resistor divider network, for maintaining designated output under a specific current draw dictated by the component's characteristics from its datasheet. Both voltage dividers for each feedback mechanism of the op-amp are adjusted to reach the minimum and maximum voltage threshold (V_{th}) of the accompanying MOSFET acting as a pass element to dictate charging to the battery load.

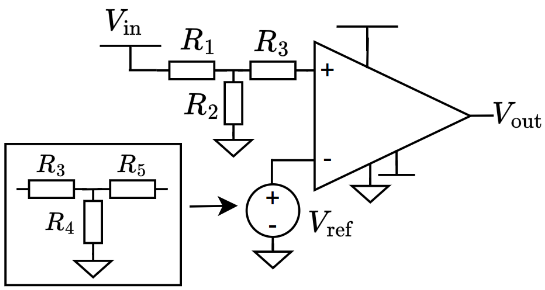

Fig. 4. Schematic for the constant voltage circuit as it features an error amp with 3 resistor divider networks for each feedback.

The maximum current limit of both inverting and non-inverting inputs are 10 mA, and receiving a specific target of 8 mA falls under a safe margin to guarantee safe operation. Reference voltage is configured through a 3 resistor divider of R_3 and R_4 to 2.87K, with R_5 to 500, the final output voltage across R_5 assuming a 5V supply, is 0.4. The minimum voltage threshold of the MOSFET is 0.8, so there comes a need to create a matching voltage that is supplemented from negative and positive inputs. Using the following equation:

$$V_{\text{out}} = A_{\text{OL}}(V_{+} - V_{-}) \tag{7}$$

Assuming that A_{OL} is 110 d_{b} with non-inverting input of 0.4V and a desired output voltage of 0.8V, rearranging yields the following:

$$V_{+} - V_{-} = \frac{V_{\text{out}}}{A_{\text{OL}}} \tag{8}$$

Isolating for V_{-} eventually gives:

$$V_{-} = -(\frac{V_{\text{out}}}{A_{\text{OL}}} - V_{+}) \tag{9}$$

substituting our given values creates the following:

$$V_{-} = -(\frac{0.8}{316,228} - 0.4) \tag{10}$$

$$V_{-} = 0.39999747 \tag{11}$$

We can approximate V_{-} to 0.4V to leave the conclusion that being able to achieve the minimum voltage threshold of the pass MOSFET requires that both inverting and non-inverting inputs be equal to each other, one a fixed reference while the other continually rises up until the output adjusts to be greater than the maximum threshold and turns the pass element off. Similarly, negative feedback is fed from a 3 divider network with the aim of R_3 achieving the required value and drawing 8 mA of current to the inverting terminal. R_1 and 2 yielding 125 with R_3 equal to 50, we can calculate the minimum input voltage using the following:

$$V_3 = V_{\text{in}}(\frac{R_3}{R_{\text{total}}}) \tag{12}$$

Solving for V_{in} then gives the following:

$$V_{\text{in}} = V_3(\frac{R_{\text{total}}}{R_3}) \tag{13}$$

As R_{total} is 300 with a desired output of 0.4, pulling in our values yields:

$$V_{\text{in}} = 0.4(\frac{300}{50}) \tag{14}$$

$$V_{\text{in}} = 2.4\text{V} \tag{15}$$

Therefore, a minimum voltage of 2.4 is needed to initialize initial current flow to a battery through the MOSFET, ending as the charging value approaches 3.7 from crossing its maximum V_{th} and creating a resulting deactivation. As apart of the constant current phase, voltage ramps up with a fixed current supply from the programmable current source [6]. When nearing a load resistance of 35 with slight delay from change in output current, it no longer increases at a linear rate and leads to a constant value as it transitions between a constant current stage to constant voltage that regulates charging to a load battery [2].

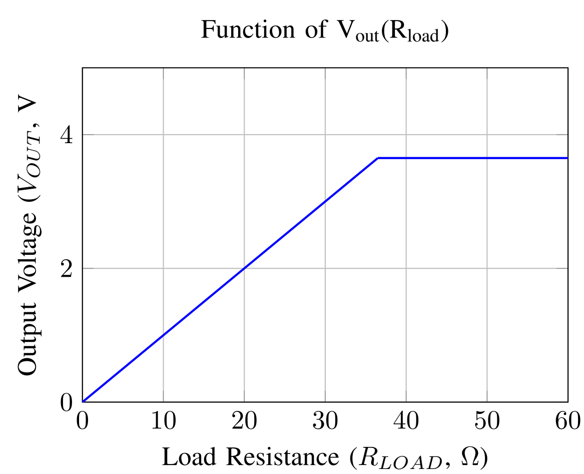

Fig. 5. The function of output voltage against load resistance from the programmable current source as it transitions to CV.

B. Voltage Buffer and MOSFET

An issue arises with the error amplifier as it struggles with apparent poor transient response time [5], where the CV infrastructure cannot react to a sudden change to its onboard load resistance. The resulting effect skews voltage output from a pass element which may hinder effective charging of a connected battery [3], and contributes to voltage ringing towards the feedback loop from parasitic properties of the powering MOSFET [4], due to capacitance and stray inductance. When implementing a high current voltage buffer between the output node of the error amplifier and pass element, it provides isolation between the amp and capacitive gate to better response time [3]. Additionally, the amplifier has a set speed limit for a changing output against feedback input and load resistance, such that adding a buffer would ensure fast response [3] from any corrections to the outputting MOSFET. Finally, high input and low output impedance is able to effectively dissipate displacement current to clamp the gate under the intended voltage. A series resistor is added.

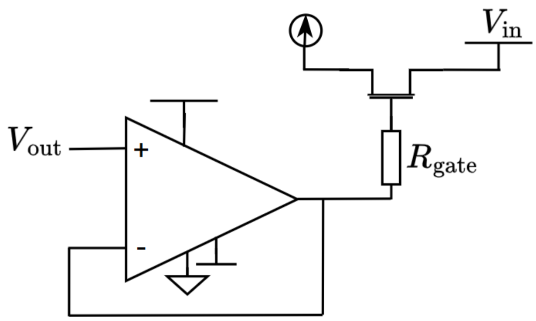

Fig. 6. Schematic for the buffer; receiving previous input from the error-amp and outputting to a pass element MOSFET.

IV. Conclusion

To conclude, traditional hybrid-based CC/CV systems are consistently used as the primary methods to effectively charge Li-Io batteries. Yet, there exists prevalent issues associated with these existing frameworks that affect adequate performance and present immediate problems in circuit design. In constant circuit frameworks, the use of adjustable regulators with a sense resistor to set desired current draw suffer from slow response rate against a changing load resistance. In addition, many dispel additional power into extra heat and creating instances of thermal runaway that pose safety concerns during the charging period of batteries. Constant voltage circuits are particularly hindered by transient timing between the output of an error amplifier feeding to a MOSFET with unwanted characteristics. Thus, we provide supporting modifications to the dual-loop system by implementing a programmable current source with resistor ratios to set a fixed output current with ramping voltage alongside series resistor and an RC network against long line reactance and resonance ringing. Given the issue of skewed response in constant voltage architecture, we introduce an elementary solution of a voltage buffer to supplement the output to the MOSFET's gate through a high input and low output impedance methodology for ensuring faster response to corrections from the error amplifier. There also exists transitions between CC/CV when nearing a load resistance between 30-40, as current decreases and voltage remains Invariable when approaching its maximum rate. Through practical usage of the provided solutions, battery charging technology for Li-Ion can hopefully improve for many applications light weight electric vehicles and their effective charging.

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