On/Off-Board 42V Switch Mode-Based Charger for Advanced Vehicles

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Abstract: **— With the ever increasing demand of electrical loads in vehicles, shifting towards a new voltage system is inevitable as current 14V system is not meeting the needs. An efficient and cost-effective switch mode-based 42V on/off -board battery charger system using push-pull topology is designed. Pulse width modulation (PWM) based feedback circuitry is employed to regulate the output voltage. Circuit is simulated first, before implementing practically. Circuit is tested successfully by charging three 12V batteries connected in series. Final converter was able to produce and regulate the voltage to 41.6V which is enough for charging.**

Keywords—on/off-board battery charger, economical, advanced vehicles, new standard in automotive voltage, push-pull, SMPS, PWM.

I. INTRODUCTION

New challenges and opportunities are created in engineering due to a great increase in electronic systems of vehicles together with the related demands of power. New features are being introduced every year like cruise control, distance measuring sensors, satellite navigation systems etc. Moreover, vehicular security system and control interfaces like light and window switches consume power even when the engine is switched off.

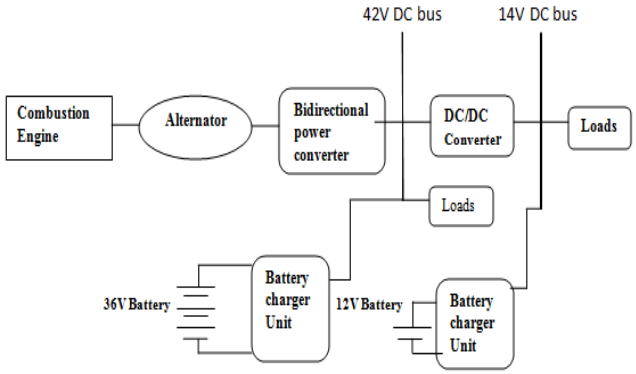

Figure1: Hybrid on-board 14/42V charging system

Figure 1 shows the block diagram for 14/42V hybrid on-board charging system [1]. Voltage buses at 14V and 42V would fulfill the power demands of the latest and upcoming electronic loads respectively.

Nowadays, automakers are installing high amperes batteries to meet the demand which requires the wire to be thick in size in order to overcome the I^2R losses. This affects the weight and overall cost of the vehicle. Also more space is required to compensate the wire. With more current, troubleshooting becomes difficult and heat loss increases.

In order to have a cost effective and power efficient system, automakers have to move from today's 14V system to around 42V system. With this system, we will be able to introduce steer-by-wire and brake-by-wire systems which will eliminate most hydraulic and mechanical systems of vehicles. So switching with electronic components will not pull energy from the engine [2]. Presently, 14V and 28V battery chargers are available in the market.

Implementation of a 42V system is due to the fact that it is safe and cost effective as DC voltages within the range of 60V are safe and do not require special materials. Exceeding the limit would require advanced materials and safety measures to be considered, thus, causing an increase in the cost of the system [3].

The idea of belt-driven starter-generators for 42V based future systems is given in [4]. These generators offer many plus points like smooth starting, suitable packaging and high efficiency.

A new methodology of using zero-voltage and zero-current switching (ZVZCS) DC/DC bidirectional converter is given in [5]. It is tested for 14/42V hybrid vehicles and has high efficiency. It contains two symmetric half bridges, both, at the input and output stages. At the input stage, in ZVS condition, MOSFETs turn-on and turn-off in ZCS condition at the output stage. So the converter has high power density and efficiency.

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"ON Semiconductor" published a handbook focusing on the use of switching regulators while designing the power supplies by showing possible techniques i.e. Linear & Switching regulators for designing the supplies. Until late 1970s, linear regulators were extensively used in designing the supplies where excess power is dropped across resistors or transistors, working in the linear region, making efficiencies of such regulators around 50%. While in switching regulators, transistors are used as switches making efficiencies as high as 90% [6].

II. SYSTEM SPECIFICATIONS

A. Electrical Stipulation

The charger works on 12V DC. The circuit compensates the changes either in the input voltage or in the load. Output is around 42V DC which is enough for charging the 3 batteries of 12V each. The circuit is also capable of supporting up to 4A current at 42V.

B. Notable Features

Salient features of the design include light weight, compact size, economical, high efficiency, overcharging and undercharging protection.

III. DESIGN OF CHARGER

Figure 2 shows the block diagram of the designed on/off-board SMPS charger. DC signal, either from the car's generator or from the rectifier of AC supply, is fed to the push-pull stage where it is chopped by MOSFETs in the inverter section and then boosted by a high frequency transformer. Output of the stage is then rectified and smoothened to charge the battery. Regulation of the output is done by a feedback path containing opto-isolator and PWM controller.

Each block of Figure 2 is discussed in detail.

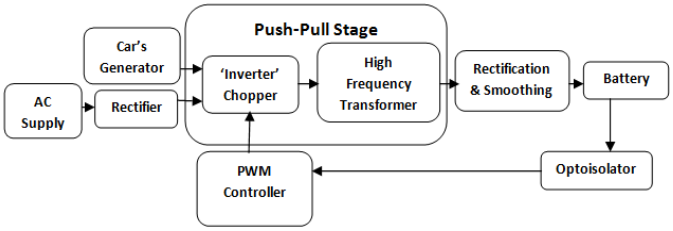

Figure 2: Block Diagram of on/off- board SMPS charger

A. Push-pull Stage

A push-pull converter is the one in which switching is done by the pairs of transistors. This makes sure the utilization of transformer's core more effectively than fly-back converter which uses single transistor only. Push-pull converter can easily be used for high power applications and is more efficient and creates less noise. The selection of MOSFET's and the design of high frequency transformer are discussed in this section.

1) *Selection of MOSFETs*

For switching at high frequency, MOSFETs are used. They are used in parallel to increase the power handling capability and to avoid excessive heating due to flow of maximum current from single MOSFET. Selected MOSFETs, IRAZ544n, are good to use at high frequency having specifications V_{ds}= 55V, $R_{ds\ (on)}$ =0.032Ω, I_d= 49A.

As we know that the gate of the MOSFET acts as a capacitor, therefore, its time constant should neither be too small to damage it by abrupt charging and nor too large to dissipate energy in the linear region. Therefore, all gate resistors are selected as 22Ω.

2) *Design of high frequency transformer*

Input voltages are boosted up to the required level at high frequency. Power is transferred to the secondary side during the conduction period of each MOSFET. Isolation between input and output is also achieved.

Ferrite core has been used for designing the high frequency transformer. It is available in many shapes but most widely used is EE type as shown in Figure 3 [7]. Core is designed to give more power than required.

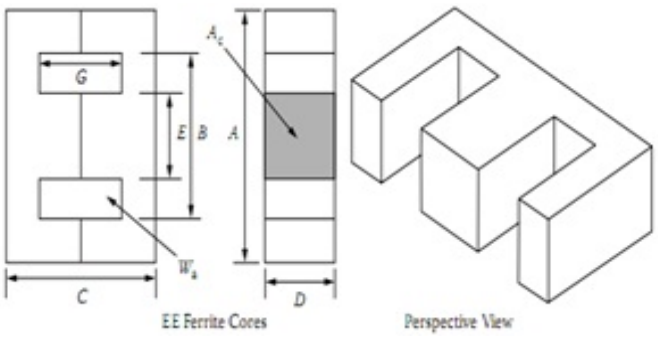

Figure 3: Dimensional outline of EE core

Output wattage = 44* 4 = 176W

Dissipation in diodes = 3W

Losses in filter = 4W

Total secondary power = 183W

Let's assume 95% efficiency then

Input power = 183/0.95 = 192W

Input current at 12V = 192W/ 12V = 16A

Selected core E-21 is capable of handling that much power.

Cross sectional area = $A_c = 1.490\ cm^2$

Window area = $G = W_a = 1.643\ cm^2$

Area product = $A_p = 2.448 cm^4$

Input impedance at primary = 12V/16A = 0.9Ω

Input inductance = $2\pi fL = 0.9$

Input inductance = L = 1.8uH

Selecting SWG=17 for handling 4A current at secondary winding and SWG=12 for handling 16A current at primary. 4 turns at each primary winding of center tap transformer, then turns at secondary can be calculated as:

$$Vs / Vp = Ns / Np \quad (1)$$

$44/12=N_s/4$

$N_s=15$

B. PWM Controller

The selection of IC and the settlement of its parameters is discussed in this section. There are various PWM ICs available but SG3525 has been selected for the following reasons:

- Built in soft start feature.
- Voltage regulation feature.
- Dead time control.
- Automatic shut down pin.
- Capable of sinking high current.
- Gate of the MOSFET can be controlled directly.

1) Desired frequency setting

Frequency of the pulses from SG3525 can be set using the combination of capacitor and resistor by formula:

$$f = 1/0.7 * C_t(R_t + R_d) \quad (2)$$

Operating frequency of 33 KHz is selected. As oscillator frequency must be two times the desired output frequency, therefore it is set to 66 KHz. By neglecting R_d,

$$C_t = 4.7nF \ \& \ R_t = 4.6K\Omega .$$

2) Soft start setting

Soft start is needed to avoid abrupt and sudden start and also it minimizes the inrush currents. A delay of 1ms is selected to provide the necessary soft start.

3) *Voltage regulation*

Output voltage is regulated against the variations in the input voltage. This is done by adjusting the duty cycle of MOSFETs. Since the actual output voltage is very high, therefore, it is scaled to a safe value, via opto-isolator, and then compared with the reference voltage; which is 2.5V. The error signal modulates the width of the pulses. Figure 4 and figure 5 are showing the control signals of comparator and the modulated pulse signal respectively.

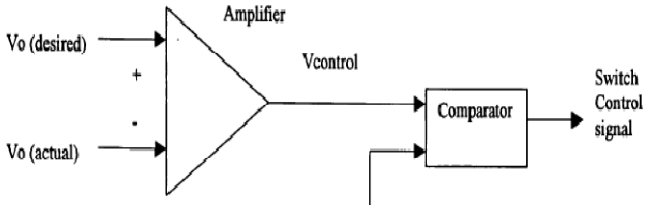

Figure 4: Control Signals of Comparator

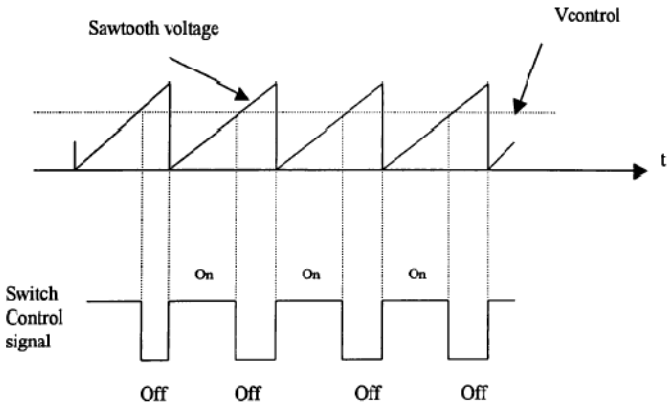

Figure 5: Modulated pulse signal

C. High frequency rectification

Since output of the ferrite transformer is of high frequency, therefore, ordinary diodes cannot be used for rectification as their reverse recovery time is large. Schottky diodes become an ideal choice for it because of their very small recovery time.

D. Smoothing capacitor

A capacitor is connected in parallel to the output of the rectifier to get the DC signal with minimum ripples. The value of smoothing capacitor can be calculated as:

$$Q = C * V \quad (3)$$

$$I = Q / t \quad (4)$$

$$C = (I * t) / V \quad (5)$$

$t = 1/66*10^3$ s, for full wave converter.

To keep ripples at approximately 50-100mV level,

C = 1000uF approximately.

E. Charging of batteries

A 12V battery is usually charged by 13.8-14.2V. As a single 36V battery is not available commercially, so three

12V, 7AHr batteries are used in series. Therefore, about 42V are needed for charging. Voltage drop across the diodes of the rectifier and also across the protection diode must also be considered.

By taking 35% of the rated current, i.e. 2.5A, the current limiting resistor can be calculated as:

$$R = V / I \quad (6)$$

$$R = 40.6\text{-}36 / 2.5 = 1.8\Omega$$

Figure 6 shows the circuit of 42V charger. Simulation is done in LTSPICE software. Input is taken as 12V DC.

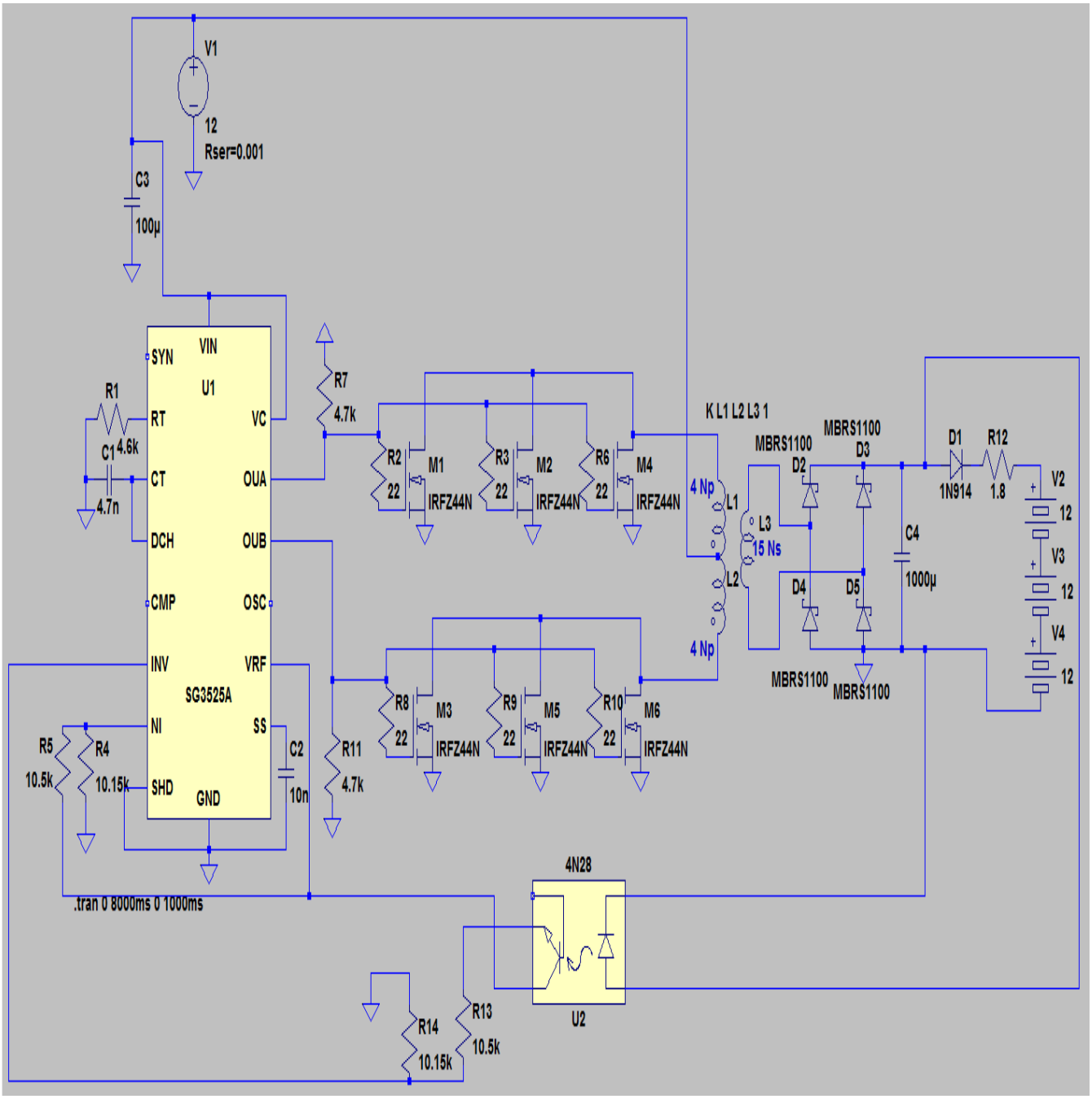

Figure 6: Circuit diagram of 42V charger

IV. SIMULATION AND EXPERIMENTAL RESULTS

Figure 7 shows the output of the ferrite transformer which is 44V. Modified pulse train from the chopper section is boosted from 12V to 44V. It will, then, be rectified and smoothened before applying to the battery.

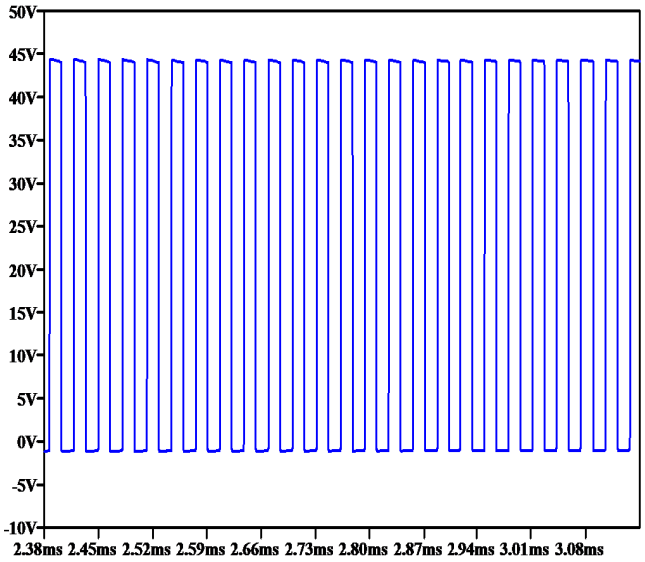

Figure 7: Output of the ferrite transformer

Figure 8 shows the regulated output of the charger circuit which is 40.2V. It also includes the drop across the rectification bridge and the protection diode. It can be seen that output voltage is almost smooth with ripples having the negligible magnitude of 62.1mV.

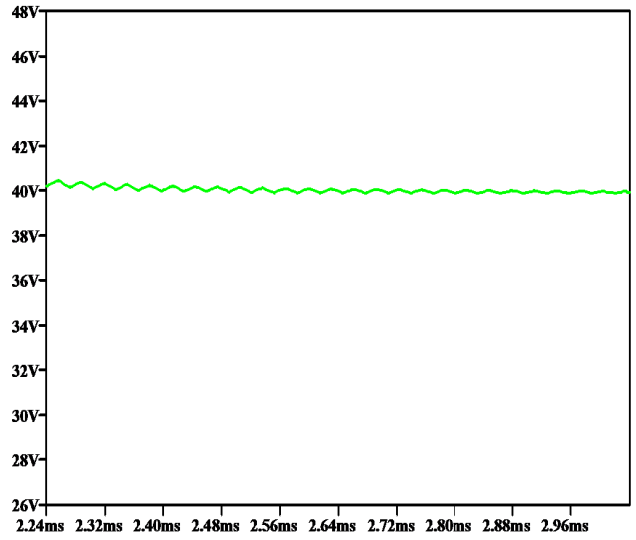

Figure 8: Final output of charger

Figure 9 shows the charging current of the batteries. It can be seen that the inrush current is limited to 3.3A due to the soft start feature of the converter. The charging current is, then, stabilized at 2.5A

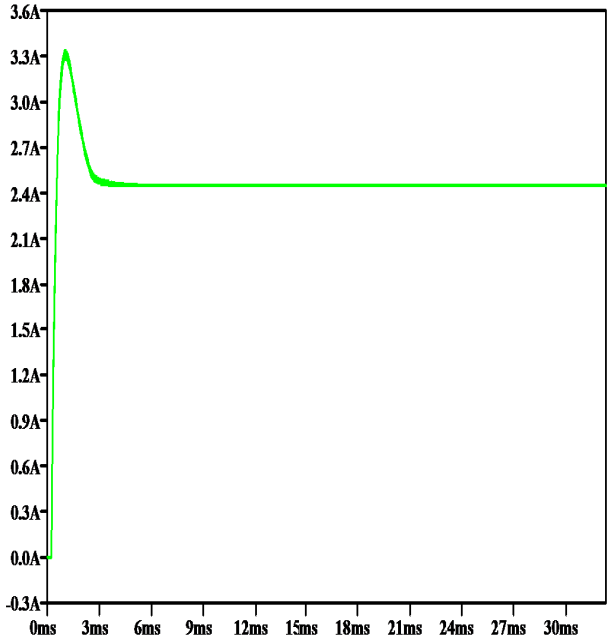

Figure 9: Charging current is stabilised at 2.5A

Table 1 shows the performance parameters of the charger circuit. All the results are in the acceptable ranges and support the commercial use of the charger.

Table 1: Performance parameters of the charger circuit

Efficiency	99%
Form Factor	1.001
Ripple Factor	0.0447
Crest Factor	0.9

Figure 10 shows the prototype of 42V charger. AC signal of 230V is first stepped down to 12V and then 12V DC, obtained from rectification, is applied to the charger.

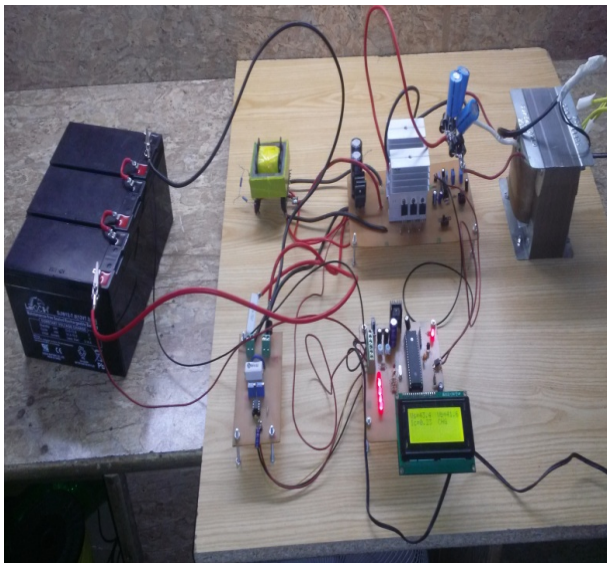

Figure 10: Prototype of 42V charger

Table 2 shows the charging and discharging voltages of three 12V, 7AHr batteries. Charging is done for three hours. Average charging voltage across each battery was 13.9V which verifies the simulation results.

Moreover, the input power factor was 0.9.

Table 2. Experimental results of charging/discharging the three batteries in series

Battery	Charging voltage	Discharging voltage
1	14	12.6
2	13.8	12.58
3	13.8	12.58

V. CONCLUSION

Switch mode-based 42V on/off - board battery charger is designed for new generation vehicles. Push-pull topology is utilized along with PWM based feedback circuitry. The charger is connected across three batteries, of 12V, 7AHr each, connected in series. Simulation and experimental results support each other. Besides the high efficiency, the DC signal of the charger is of high quality with respect to the ripple, crest and form factors. The output of the charger was regulated at 41.6V. This gives an average of 13.9V across each battery, which is recommended charging voltage.

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