Charger for NiMH Batteries
Based on Buck DC/DC Converter

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Abstract: In this paper is presented charger for NiMH battery types AA. Charger is realized by Buck DC/DC converter and microcontroller. Microcontroller controls the work of Buck DC/DC converter by pulse width modulation and by measuring the current of battery charging. The current of charging is held constant by power electronics, and the time of charging is set by the user dependent of capacity of the battery. Standard battery chargers enable the recharge of NiMH battery for few hundred times, because termination of charging is done when voltage drop on the battery is detected. The aim of this paper is to create charger which enables that NiMH battery is charged 1000 times.

Keywords: Buck DC/DC converter, Pulse width modulation, Microcontroller.

1   Introduction

Rechargeable nickel metal hydride (NiMH) battery has minimum 1000 charging and discharging cycles. Numerous literatures give out this affirmation [1]. Producers of rechargeable NiMH batteries give information that one of their rechargeable batteries can replace 150 alkaline batteries [2]. Besides batteries they also sell chargers. All these mean that it is possible to charge NiMH battery 150 times by commercial chargers. NiMH battery, which has more than 150 cycles of charging and discharging, is possible to be charged but not with standard commercial chargers.

Standard commercial chargers of NiMH batteries charge battery with the constant current and the termination of battery charging happens when A/D converter detects voltage drop on the battery [3]. This voltage drop is equal 10 mV to NiMH batteries and is equal 30 mV to NiCD (nickel cadmium) batteries [4]. This voltage drop happens when battery is charged and further charging would produce overcharging of battery and decrease of battery lifetime. A lifetime of battery is defined by the number of charging and dicharging cycles. However, the problem occurs because voltage drop can exist if the battery is relatively old. During the charging of battery, which has more

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than few hundred cycles of charging and discharging, voltage drop on battery occurs at the begining of charging and standard chargers immediately stop battery charging. Besides that, very often happens that NiMH battery has false peaks in early the charging cycle, and so the charger will terminate too soon [5]. In that way the battery, which has more than few hundred of charging and discharging cycles, remains discharged and for user it is useless.

In case that A/D converter does not registrate voltage drop on the battery, standard chargers have safety timer which stops battery charging. The second disadvantage of standard commercial battery chargers is that they enable charging of only one determined capacity of battery. The time of safety timer of standard charger is fixed and is set to respond to only one determined capacity of battery. It means that battery, which capacity is higher than capacity dedicated to that charger, could not be charged until its nominal capacity. It happens because safety timer turns off battery charging before detection of voltage drop on battery.

Standard commercial chargers of NiMH batteries must terminate battery charging when A/D converter detects voltage drop on the battery. If termination of battery charging is done only by period of time, some user can charge battery again after battery is charged without discharging. If user does it for several times they can ruin the battery and after that can prosecute producer of charger or producer of battery and demand the money for damage. For that reason, all commercial chargers terminate battery charging when A/D converter detects voltage drop on the battery.

Charger, which enables that NiMH battery can be charged 1000 times, is presented in this paper. Realized charger charges NiMH battery with constant current and the termination of charging is done by programmable timer. In that way is avoided that the termination of charging of NiMH battery is done by detection of voltage drop from battery which provides that NiMH battery has 1000 cycles of charging and discharging. As termination of charging of this charger is done after period of time, than it is necessary that NiMH battery is fully empty, before charging, so over charging battery can be avoided. This realized charger is dedicated for extending lifetime of the battery.

Realized charger has possibility of asserting time of battery charging and in that way it is possible to charge batteries of various capacities. Battery charging is done with constant current until 120 % of battery capacity. It is necessary to charge battery more than its nominal capacity so battery can be used with its nominal capacity. It is established by experimental way that voltage drop on the battery during the charging happens when battery is charged until its 120% of nominal capacity [4].

For charger which is constructed and presented in this paper, the time of the battery charging is determined by capacity of battery ″C″ and by current of battery charging ″I″ which is presented in next equation:

$$t = \frac{1.2C}{I}.$$ (1)

NiMH batteries do not have ″memory effect″. NiCd batteries have ″memory effect″ and they must be fully discharged before charging. Memory effect is the appearance of battery capacity decreasing which exists if NiCd battery is not discharged to its end. If NiCd battery has 20% capacity before charging, it can have maximum 80% of nominal capacity after charging and it cannot ever reach full nominal capacity. The advantage of NiMH batteries in reference to NiCd batteries is that NiMH batteries do not have ″memory effect″ and NiMH batteries have much more capacity than NiCd batteries. The only advantage of NiCd batteries is low cost. Charger, which is constructed and presented in this paper, can be used for charging NiMH and NiCd batteries (Fig. 1).
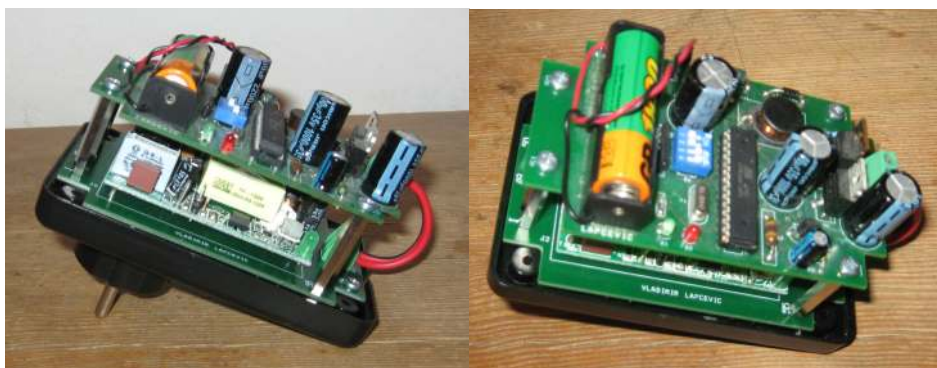

Fig. 1 – *Charger for NiMH batteries type AA (side view and top view).*

Realized charger of the NiMH battery is consisted of:
- Buck DC/DC converter;
- microcontroller ATMEGA 8 [6] which controls work of Buck DC/DC converter;
- 3 switches by which time of battery charging is asserted;
- power supply.

Nowadays NiMH batteries are the most used rechargeable batteries. They have high energy density, low price, no toxicity and safety [7]. The disadvantage of NiMH batteries is that they have full capacity only in positive temperature's range from 0°C to 50°C. It is possible that NiMH batteries work

in the negative temperature's range, but in the negative temperature's range capacity of NiMH batteries decreases with temperature decreasing.

2 Buck DC/DC Converter

Buck DC/DC converters are used in case when there is necessity to decrease input voltage and when there is no need for galvanic isolation. As Buck DC/DC converter does not have galvanic isolation, than it does not have transformer. That enables simple production and low cost. Buck DC/DC converter has high efficiency. By its simple and low cost realization, Buck DC/DC converters have great applying in wide range of power. The most powerful Buck DC/DC converters are used for regulation of rolling speed of motors like in electric vehicles (battery's locomotive, forklifts).

In Fig. 2 is shown electric scheme of Buck DC/DC converter together with accompanied electronics for measurement and regulation of current of battery charging.
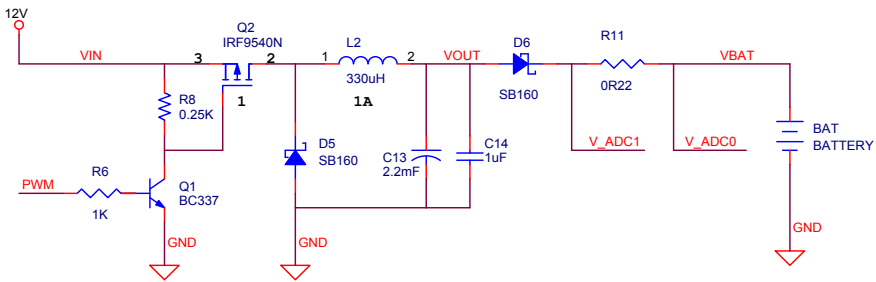

Fig. 2 – *Buck DC/DC converter with accompanied electronics for measurement and regulation of current of battery charging.*

On the input of Buck DC/DC converter occurs Meanwell's voltage source of 12 V. Transistors Q_1, Q_2 and resistors R_6, R_8 from Fig. 2 present switch of Buck DC/DC converter. Microcontroller controls work of this switch in that way that it generates sequence of control pulses of constant frequency 20 kHz, but with variable time relation of pulse/period. The resistors R_6, R_8 and bipolar NPN transistor BC337 are used to turn on P-MOSFET transistor IRF9540N. When the bipolar NPN transistor Q_1 conducts, than current streams through resistor R_8 and on the junction source-gate of P-MOSFET transistor Q_2 creates positive voltage by which it conducts. When used P-MOSFET transistor conducts, it works in the linear mode and than it behaves as the resistor of a very small resistance which is equal to 0.12 Ω. In that way, losses of dissipation on P-MOSFET transistor are decreased.

During existing logic one of control signals t_{ON}, transistors Q_1 and Q_2 conduct, and diode D_5 do not conduct and in that case the battery charging is done from voltage source of 12 V. During existing logic zero of control signals t_{OFF}, transistors Q_1 and Q_2 do not conduct, and diode D_5 conducts and than battery charging is done from accumulated energy of inductor.

During t_{ON} switch of Buck DC/DC converter is turned on and during t_{OFF} switch of Buck DC/DC converter is turned off. The sum of times turning on t_{ON} and turning off t_{OFF} of switch of Buck DC/DC converter presents period of controlled signal T_S:

$$T_S = t_{ON} + t_{OFF} . \tag{2}$$

Ratio of time t_{ON} and period of control signal T_S is called duty cycle and it is defined by equation:

$$D = \frac{t_{ON}}{T_S} . \tag{3}$$

The output voltage V_{OUT} of Buck DC/DC converter is regulated by only one variable D. In continual mode of work, the output voltage V_{OUT} is linear dependent on input voltage V_{IN} [8]:

$$V_{OUT} = DV_{IN} . \tag{4}$$

Diode D_6 is needed to prevent the stream of current from battery to Buck DC/DC converter. Diodes D_5 and D_6 which are used in Buck DC/DC converter are shotky diodes SB160. Shotky diodes are used because they have less voltage than standard diodes. In that way dissipation of charger is decreased. Resistor R_{11} is used for measurement of battery charging current I_{OUT}. Its resistance is very small and is equal to 0.22 Ω, so power losses can be reduced. As resistance of resistor R_{11} is known, by measuring voltages on its ends, current measures which streams through it. This current of the charging holds constant by changing duration of logic one of pulses which controls work of switch of Buck DC/DC converter. Dissipation on resistor R_{11} is given by equation:

$$P_D = R_{11} I_{OUT}^2 . \tag{5}$$

As current of battery charging is constant and is equal to 900 mA, dissipation on the resistor R_{11} is 178 mW.

3   Microcontroller Operation of Buck DC/DC Converter

Microcontroller ATMEGA 8 controls the work of whole electronics in charger (Fig. 3). Program for microcontroller is written in C program language.

In microcontroller ATMEGA 8 generator of pulse width modulation is integrated. This generator of pulse width modulation consists of 8-bits timer TCNT2, 8-bits register for comparing OCR2 and 8-bits comparator. The

frequency of modulated pulses is determined by frequency of timer's clock f_{CLK} and by started value of timer. The value of duty cycle D is set by writing value in register for comparing OCR2. The value of timer TCNT2 increases on clock and compares with the value of register OCR2 by 8-bits comparator. Logic one or logic zero appears on the output of 8-bits comparator as the result of comparing of value of timer TCNT2 and value of register OCR2. The output of comparator is inverted by setting appropriated bit in control register. The output from comparator is connected to the output pin PB3 of microcontroller, inside of microcontroller. Control pulses are sent to switch the Buck DC/DC converter, from the output pin PB3 of microcontroller.

Fig. 3 – *Microcontroller ATMEGA 8 and line connections*
with the rest of electronics in battery charger.

After the time of timer is elapsed, subroutine occurs in which is possible to correct duty cycle by changing value of register for comparing OCR2. In this subroutine, its started value is again written in timer. In realized charger, frequency of control pulses f_S is set to 20 kHz. It is done by setting frequency of timer's clock on 2 MHz and by setting started value of timer TCNT2 to 156. As timer TCNT2 is 8-bits, it is necessary to pass 100 pulses of clock of 2 MHz until subroutine happens. Subroutine of microcontroller, which is referent on pulse width modulation, occurs at the end of every period of control signal T_S. Period of control signal is defined by equation:

$$T_S = \frac{1}{f_S} = \frac{100}{f_{CLK}}. \tag{6}$$

For control signal of frequency 20 kHz, time priod T_S is equal to 50 μs. Time spent in subroutine is maximum 10 μs, which means that time for execution of the rest of program is equal to 40 μs, what is quite enough. Microcontroller has 10-bits A/D converter with successive approximation by which measures voltages at the ends of resistor R_{11} through which current of battery charging streams. Voltage V_{ADC0} is equal:

$$V_{ADC0} = \frac{d_0}{1023} V_{REF} \, . \tag{7}$$

In the last equation d_0 presents digital value of A/D conversion on channel 0 and V_{REF} presents referent voltage of A/D converter. Voltage V_{ADC1} is equal:

$$V_{ADC1} = \frac{d_1}{1023} V_{REF} \, . \tag{8}$$

In the last equation d_1 presents digital value of A/D conversion on channel 1.

Voltage on the resistor R_{11} is equal to the difference of voltages at its ends:

$$U_{R11} = V_{ADC1} - V_{ADC0} \, . \tag{9}$$

Taking in observation (7) and (8), the last equation can be written:

$$U_{R11} = \frac{(d_1 - d_0)}{1023} V_{REF} \, . \tag{10}$$

As current of battery charging streams through resistor R_{11}, voltage on it is:

$$U_{R11} = R_{11} I_{OUT} \, . \tag{11}$$

The battery charging current is held constant by algorithm which flowchart is shown in Fig. 4.

In order to be the current of battery charging constant and equal to 900 mA, voltage on resistor R_{11} must be constant and equal to 198 mV. When measurement of voltage is done, than this measured value compares with asserted value of $U_{ASR} = 198$ mV. After this comparing, correction of duty cycle D is done in subroutine for pulse width modulation.

If measured voltage is higher than asserted voltage, duty cycle D decreases for 1. If measured voltage is lower than asserted voltage, duty cycle D increases for 1. If measured voltage is equal to asserted voltage, duty cycle D remains unchanged. Measurement of voltage U_{R11} is done by averaging 10 values of voltages V_{ADC1} and V_{ADC0}. In that way precision of measurement is increased because influence of ripple of battery charging current on measured values of voltages V_{ADC1} and V_{ADC0} is decreased. A/D conversion starts every 1 ms and takes time of 116 μs. The value of ripple of battery charging current can be computed by next equation [9]:

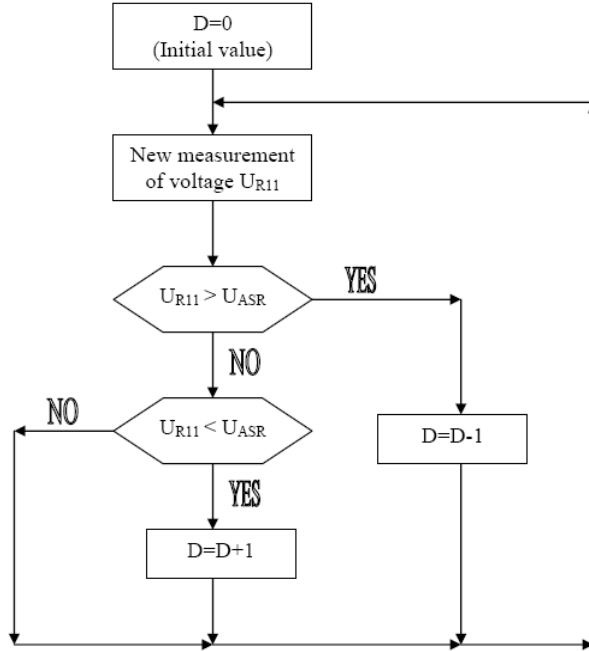$$\Delta I_{OUT} = \frac{(V_{IN} - V_{OUT})V_{OUT}}{2Lf_S V_{IN}} .$$ (12)

Fig. 4 – *Flowchart for generating constant current of battery charging.*

Output voltage of Buck DC/DC converter V_{OUT} is equal:

$$V_{OUT} = V_{D6} + R_{11}I_{OUT} + V_{BAT} .$$ (13)

Very soon from the begining of battery charging, voltage on battery is increased to value which is higher than nominal value. Voltage on schottky diode D_5 is 0.5 V when current of 900 mA streams through it. Voltage on resistor R_{11} is constant and is equal to 198 mV. If it takes that voltage of battery is equal to 1.55 V during charging, and when all of these values are replaced in (13), the approximate value of output voltage of Buck DC/DC converter can be obtained:

$$V_{OUT} \approx 2.25\,\text{V} .$$ (14)

As inductivity of used inductor is 330 μH, frequency of controlled signal is 20 kHz and input voltage in Buck DC/DC converter is 12 V, applying (12), ripple of current can be computed:

$$\Delta I_{OUT} = 138\,\text{mA} .$$ (15)

The condition of work of Buck DC/DC converter in continual mode of work is given by next equation:

$$I_{OUT} \geq \Delta I_{OUT} . \tag{16}$$

As average current of battery charging is 900 mA and ripple of current is 138 mA, it is approved that Buck DC/DC converter works in continual mode and that it was justifed to use transfer charasteristics given by equation (4) which defines work of Buck DC/DC converter in continual mode. Ripple of charging current expressed in percents is:

$$\delta = \frac{\Delta I_{OUT}}{I_{OUT}} 100 \, [\%] = 15\% . \tag{17}$$

It can be seen from equation (12) that current ripple can be decreased by increasing inductivity of inductor L or increasing frequency of control signal. Inductor of higher inductivity and higher allowed current has higher dimensions. As space on printed board is limited, inductor with inductivity of 330 μH with maximum allowed current of 1 A is used. It is very practical and nice looking to put charger in the box with AC power plug. All comercial boxes with AC power plug have small dimension and because of that space on printed board is limited. Increasing frequency of control signal depends on semiconductor physics of used transistors which present controlled switch of Buck DC/DC converter and time that remains to microcontroller for doing other operations after going out from subroutine which is referent on pulse width modulation. In this case limiting factor for choosing frequency of controlled signal, which is 20 kHz, is time necessary for microcontroller for doing other operations after going out from subroutine.

Time of battery charging can be asserted by 3 switches. Every switch is connected to ground by one end, and by the other end is connected to pull up resistor and pin of microcontroller (Fig. 5). Forth switch is not used. These switches present digital inputs. Microcontroller reads digital values on their inputs during the initialisation and asserts time of battery charging by read values. If switch is in position ON, microcontroller will read logic zero on its input. If switch is in position OFF, microcontroller will read logic one on its input. One timer, which is integrated in microcontroller ATMEGA 8, is dedicated to time measurement of battery charging. After asserted time is elapsed, microcontroller sets logical zero on its output pin PB3 which is used for work controlling of switch of Buck DC/DC converter. After that, Buck DC/DC converter stops to charge battery.

Microcontroller controls work of green and red LED diodes by 2 output pins. When green LED diode is lit on, it means that microcontroller has needed 5 V for its work. When red LED diode is lit off, than charging battery is going on. When red LED diode is lit on, than battery charging is finished.

Microcontroller gets outside clock from crystal quartz which frequency is 16 MHz. This high frequency is chosen to provide high speed of microcontroller's work, which in this case is unnecessary. Positions of switches for different values of battery capacity and appropriated times of charging are shown in **Table 1**.
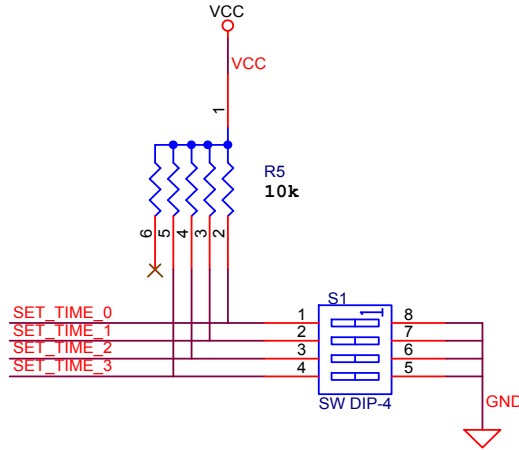

Fig. 5 – *Switches for asserted time of battery charging.*

Table 1
Positions of switches in battery charger.

C [mAh]	S3	S2	S1	$t = \dfrac{1.2C}{I} [\min]$
1800	ON	ON	ON	144
2100	ON	ON	OFF	168
2300	ON	OFF	ON	184
2500	ON	OFF	OFF	200
2700	OFF	ON	ON	216
3000	OFF	ON	OFF	240
3300	OFF	OFF	ON	264
3600	OFF	OFF	OFF	288

Time diagrams of charger are shown in the Fig. 6. The state of switch is determined by the output pin PB3 of microcontroller which presents PWM signal. In Fig. 6 are also shown voltage of inductor U_L and current of inductor I_L, which present current of battery charging, current of switch I_S and current of diode I_D.

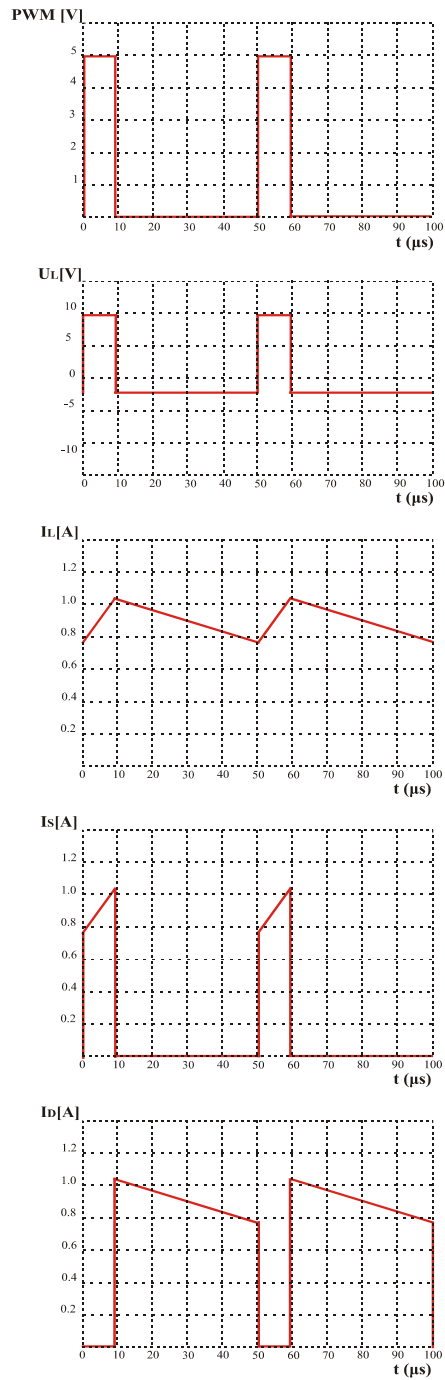Charger for NiMH Batteries based on Buck DC/DC Converter

Fig. 6 – *Time diagrams of charger.*

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4 Power Supply

Battery charger is connected to alternate low voltage net of 230 VAC. The main power supply in charger presents Meanwell's AC/DC converter NFM-1502 [10]. This power supply of 12 VDC has power of 15 W and can give the maximum current of 1.25 A. It has stable 12 V on its output for wide range of input voltage in range from 85 VAC to 264 VAC. Buck DC/DC converter is supplied from this voltage source of 12 V. Besides that, this voltage source of 12 V is used for getting 5 V for microcontroller's work and for generating referent voltage of A/D converter. This quality of voltage source is necessary to provide a high current of battery charging and at the same time to enable enough current for microcontroller's work. Buck DC/DC converter demands power supply of high current capacity because switching of current is done on the input of DC/DC converter. In case that voltage source of 12 V with less power is used, current limit would exist by which microcontroller would go in reset state. If microcontroller goes in reset state, at the same moment switch of Buck microcontroller would be turned off and battery charging would be finished. In Fig. 7a is shown power supply of 5 V, which is necessary for microcontroller's work, realized by LM7805.
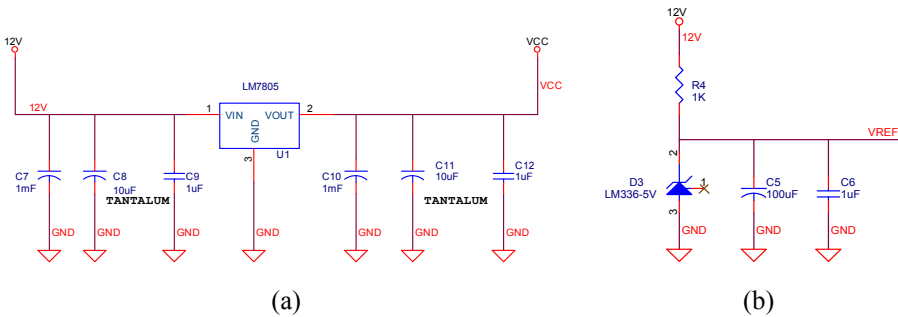

(a)   (b)

Fig. 7 – (a) *Power supply of* 5 V; (b) *Referent voltage source of* A/D *converter*.

Referent voltage of 4.95 V is realized by integrated circuit LM336-5V in battery charger. This voltage source is used as referent voltage source of A/D converter. Integrated circuit LM336-5V gives stable voltage of 4.95 V on its output when the current in range from 0.6 mA to 10 mA streams through it. The current of 7 mA, which streams through integrated circuit LM336-5V, is asserted by voltage source of 12 V and resistor R_4 which resistance is 1 kΩ (Fig. 7b). It is better to use another voltage source for referent voltage of A/D converter than voltage source which supplies microcontroller. It is because at high frequency superposition of noise and voltage of microcontroller's supplying is possible. That noise can cause improper measurement.

5   Comparison of Realized Battery Charger with other Chargers

There are three modes of work of battery charger dependent on ratio between current of the battery charging and capacity of the battery [11]:

- slow charge (current of battery charging is up to 0.1 C/hour)

- quick charge (current of battery charging is from 0.3 C/hour to 0.5 C/hour)

- rapid charge (current of battery charging is equal or higher than 1 C/hour).

Nowadays almost all chargers work in quick charge mode or rapid charge mode. The aim is that battery can be charged for a very short time. The very small number of chargers works in slow charge mode. Charger, which works in rapid charge mode, must have sensor of temperature because high current of charging can produce battery heating. Battery heating can decrease lifetime of battery. Besides sensor of temperature, this charger has timer and measures speed of changing temperature dT/dt. If parameter dT/dt exceeds limit value than battery charging is finished. This limit value is from 1ºC/min to 2ºC/min [4]. Also if temperature of battery exceeds 45ºC, charging is finished [4]. The temperature control of charging increases complexity and price of charger. Only small number of rapid chargers have sensor of temperature. It is desirable, but not necessary, that chargers which work in quick charge mode have temperature control. There is not need that chargers, which work in slow charge mode, have temperature control. Charger, which is realized and presented in this paper, charges batteries which capacity, is from 1800 mAh to 3600 mAh with the current of 900 mA. It means that current of charging is in the range from 0.25 C/hour to 0.5 C/hour and it works in quick charge mode.

Here will be presented 2 chargers which producer is the famous company VARTA which produces rechargeable batteries and chargers. First charger, which will be presented here, is LCD charger "VARTA 57070" [2]. This charger can charge 4 batteries type AA. If two batteries are charged, current of charging is 1.4 A. If four batteries are charged, current of charging is 0.7 A. As this charger is dedicated to batteries which capacity is 2400 mAh, it means that this charger works in quick charge mode. Charger "VARTA 57070" has few ways of termination of charging:

- − minus delta V method (detection of voltage drop on the battery);

- − temperature control (measurement temperature T and speed of changing temperature dT/dt);

- − timer cut-off.

Disadvantage of this charger is that battery of higher capacity than 2400 mAh can not be charged by this charger because safety timer will cut off charging after asserted time is elapsed. Time of safety timer is fixed and can not be changed.

Second charger, which will be presented here, is plug charger "VARTA 57667" [2]. This charger works in slow charge mode. It charges battery with the constant current of 350 mA. The termination of charging is done only by timer. Timer is set on 8 hours. Charger is dedicated to battery which capacity is 2100 mAh. Disadvantage of this charger is that battery of higher capacity than 2100 mAh can not be charged enough by this charger because safety timer will cut off charging after asserted time is elapsed and the battery of lower capacity than mAh will be overcharged.

6   Conclusion

The main contribution of this paper is to indicate that realized charger enables NiMH battery to have 1000 charging and discharging cycles. The second contribution of this paper is that realized charger enables charging batteries of various capacities by matching time of programmable timer as opposed to standard commercial chargers which have fixed time of safety timer. By standard commercial chargers it is possible to charge only one determined capacity of battery. The third contribution of this paper is the possibility of easy modification of this charger in a way that it can charge the NiMH batteries of other types, not only type AA. For example, it can be easily changed to charge NiMH battery of 9 V. It would be enough to change current of battery charging and time of battery charging in that modification.

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