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Faculty of Transport Engineering

Traction battery charger for teaching railway vehicle

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Bachelor student’s thesis

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Zásady pro vypracování:

Úkolem bakaláře bude navrhnout, vyrobit a oživit funkční výrobek nabíječ olověných trakčních akumulátorů. Nabíječ bude využíván pro nabíjení akumulátorové baterie typu VRLA se jmenovitým napětím 24V a kapacitou 40Ah, jež se stará o pohon výukového kolejového vozidla.
Specifikace zařízení:
Vstupní napětí 230V 50Hz
Výstupní napětí 24V (28,8V)
Výstupní proud do 6A
Kompaktní rozměry
Ochrana proti zkratu na výstupu
Ochrana proti přepólování
Úkoly bakaláře:
Provést rešerši z oblasti Pb akumulátorů a jejich nabíjení
Vybrat vhodnou nabíjecí charakteristiku
Vybrat vhodné řízení a topologii nabíječe
Navrhnout zapojení signálové i výkonové části
Fyzicky zařízení zrealizovat a oživit
Ověřit funkčnost přímo na vozidle

Rozsah grafických prací:

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In Pardubice on 10th January 2018 Mykyta Chabanenko

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ANNOTATION

This bachelor thesis deals with design, implementation and the verification of full functionality of the traction battery charger for the teaching railway vehicle. The first part of the thesis describes not only the teaching railway vehicle but also the working principles of lead-acid batteries with their charging characteristics and information about their construction. The second chapter provides designing and implementation where the proper type of charger is selected, where the operating principle of the integrated charge controller is explained and production with running revealed. The conclusion of the thesis contains a description of the results reached with advantages of the designed charger.

KEY WORDS

linear power supplies, integrated charge controller BQ24550, Lead-acid batteries, railway vehicles

NÁZEV

Nabíječ trakčních akumulátorů výukového kolejového vozidla

ANOTACE

Bakalářská práce se zabývá návrhem, výrobou a ověřením plné funkčnosti nabíječe olověných akumulátorů výukového kolejového vozidla. První část práce je určená k popisu výukového kolejového vozidla, vysvětlení provedení a fungování olověných akumulátorů, a jejich nabíjecí charakteristiky. Druhá kapitola poskytuje návrh a realizaci, ve které je popsán výběr vhodné topologie nabíječe, princip činnosti řídicího obvodu, výroba a oživení nabíječe. Závěr práce se soustředí na popis dosažených výsledků a výhod navrhnutého nabíječe.

KLÍČOVÁ SLOVA

lineární zdroje napětí, integrovaný řídicí obvod BQ24550, olověné akumulátor, kolejová vozidla

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LIST OF ABBREVIATIONS

AGM	Absorbent Glass Mat
DOD	Depth of Discharge
EDA	Electronic Design Automation
ICC	Integrated Charge Controller
ICE	Internal Combustion Engine
PCB	Printed Circuit Board
RMS	Root Mean Square
SLI	Starting-lighting-ignition battery
SMPS	Switch Mode Power Supply
TRV	Teaching Railway Vehicle
UPS	Uninterruptible power supplies
VRLA	Valve-Regulated Lead-Acid

INTRODUCTION

The aim of this bachelor thesis is to design and develop the charger for traction batteries which are installed on teaching railway vehicle. This vehicle is located on the sight of Educational and Research Transporting Center.

Lead-acid batteries are one of the most common electrochemical devices for storing the energy. These secondary batteries are used in a variety of applications, for most people they become associated with installing them in vehicles, where their ability to provide high currents for cranking power is valued. Deep discharge batteries are commonly used for backup power supplies. Unlike car batteries with high starting current which are used to provide energy for very short periods, deep discharge batteries are designed to hold larger amounts of energy for longer time. Although batteries are reliable, they have a limited life. Lead-acid batteries have moderate power density and good response time. Batteries can go from accepting energy to supplying energy instantaneously. Lead-acid batteries are influenced by temperature and must be well maintained to achieve long-lasting life. So for their outstanding value they are worth to have a proper maintenance.

Bachelor thesis will devote time to theoretical subtle aspects in the field of batteries electrochemistry. Then the most common types of chargers and their charging characteristics will be described. Next step is a research in the field of traction battery's chargers, it will provide an answer what is the most suitable option for this application, from all of the existing models on the market.

After choosing a desirable integrated charge controller and estimation of external components, the designed charger will be assembled. In the last chapters the results of powering up of the battery charger will give direct answer about its functionality. So, the battery will be tested, tuned up and prepared to carry out its straight duties.

1 TEACHING RAILWAY VEHICLE

The Department of Electrical and Electronic Engineering and Signalling in Transport designed and assembled teaching railway vehicle (TRV). It is fitted with two DC motors with permanent magnets from the public company ATAS electric motors Náchod. Two traction DC voltage converters from Curtis Instruments, which are suitable for controlling motors mentioned above. Vehicle is also fitted with a contactor made by Albright International, it is used for switching large currents flowing from accumulators to DC/DC converters. As power source two lead-acid batteries had been chosen, bought from CSB Battery, which are suitable for our traction vehicle. Next part of electrical equipment is a distributor, which provides high protection level for all components. Finally, there is a small box on which are placed operating and safety buttons from Eaton's company. The box is used as main controller for manipulating teaching railway vehicle.

1.1 Mechanical and electrical description of TRV

Construction of the main frame of TRV is welded into rectangular shape made with steel profiles. Whole length of the frame, including wooden bumpers, is 1610 mm and width is 1000 mm. There are loops in each corner for lifting vehicle by crane in case of relocation. Middle part of the frame is reinforced with additional steel profile. Total weight of the vehicle is 274 kg.

Undercarriage of the vehicle is made up of two axles which are mounted on pivot shoulders. Drivetrain of TRV contains two-stage gears, mounted on pivot shoulders, for transmission of a large torque at a constant output from DC motors. Usage of sprockets and chain for transmission of torque gives this construction an advantage, because it provides constant rotation without slippage. Each axle has its own transmission mechanism for transferring torque from DC motors shafts. The sprockets ratio is determined by the number of teeth on sprockets. Resulting gear ratio for teaching railway vehicle is 31,6.

Maximum speed of TRV is determined by diameter of wheels, gear ratio and number of rotations on DC motor shaft per minute. Top speed is coming up to 4,87 km per hour.

On Fig. 1.1 main chassis are represented, fully welded, painted and standing on gathered undercarriage, which constituting pivoting shoulders attached to pair of wheelsets.

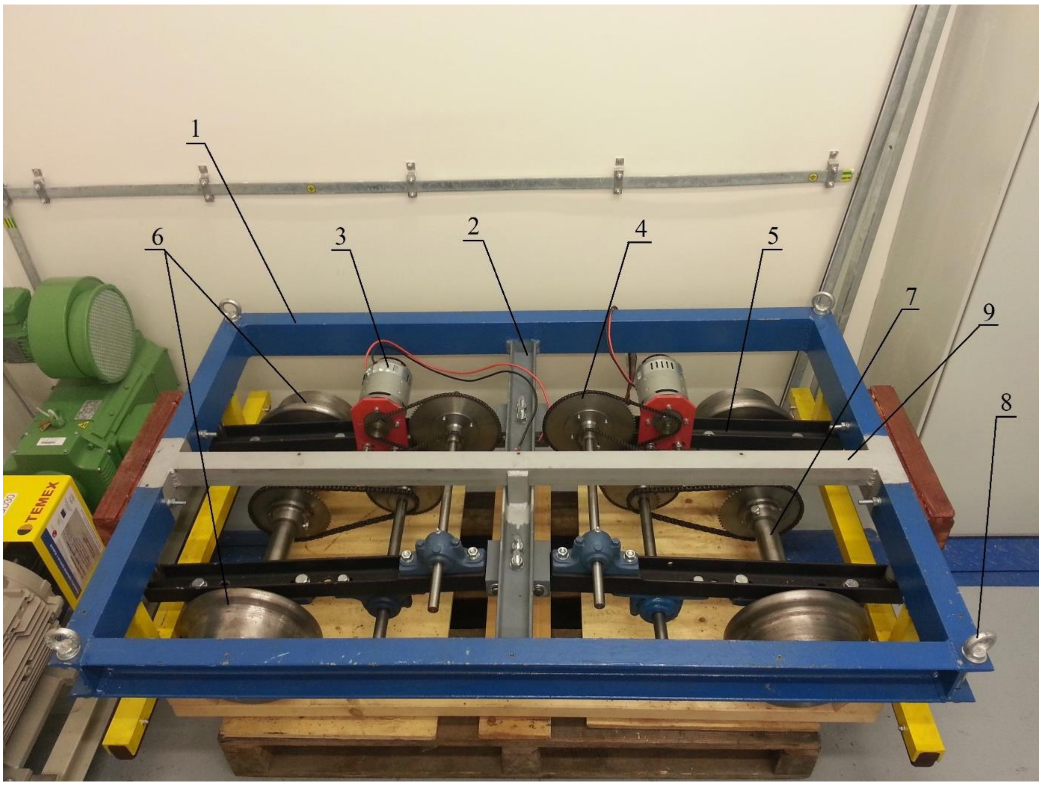


Fig. 1.1 Chassis of TRV [1]

Legend: 1 – Frame, 2 – widthwise steel beam, 3 – DC traction motors, 4 – transmission, 5 – pivoting shoulders, 6 – wheelsets, 7 – axle, 8 – loops, 9 – lengthwise steel profile.

TRV is equipped with two DC motors. Direct current and direct voltage are used to power DC motors. Principle of any motor is to convert electrical energy to mechanical energy. DC motors are ones of the oldest types and widely used in industry and transportation. Theirs excellent traction properties serve the purpose in locomotives and trams. In TRV are used DC motors with permanent magnets type P2XR492 made by ATAS electric motors Náchod. This traction motors have benefits for teaching installation, because lead-acid batteries can be used as a power supply to provide energy to DC motors. Each motor is used to drive one of two transmission mechanisms connected to wheelsets.

Contactor is the next electrical equipment used in this vehicle, mostly it is used to control electric motors, lighting, heating, capacitor banks and other electrical loads. It is designed to switch on and off high-current load devices such as installed DC motors. The main working element in contactor is coil, when voltage is connected to coil terminals, electric current starts to pass through the coil. Passing through electric current creates magnetic field, which attracts the moving core of the contractor. The force developed by electromagnet holds contacts which were pulled together. When no magnetic field produced, gravity or spring, depending on construction of contactor, returns electromagnet core to basic position and disconnects the contacts. Contactor Albright SD150LA-1 had been chosen, because it is compatible to work with lead-acid batteries as power source. It is designed for fast disconnection from battery if some unexpected situations occur. There are two options how to operate in such situations. First is red button, which could be pressed manually, or second method is electrical one, shutting down voltage from coil contacts with further disconnect of power contacts. Also, contactor has a lock on button, when locked it prevents from accidental switching on main contacts so vehicle is secured from spontaneous movement.

Curtis model 1228 had been chosen as permanent magnet motor speed controller. Ideal for applications on three or four wheeled mobility aids, such as scooters and light industrial equipment, such as sweepers and scrubbers. The advantage of this DC voltage converter is that it is easy to operate, to adjust and it has functions of complete diagnostics in conjunction with personal computer. Connecting 100 kΩ potentiometer to converter allows to set vehicle’s speed limit, so when maximum allowed speed is achieved vehicle stops further acceleration. Second potentiometer is installed on control panel and it is used to manage the speed of the vehicle. Fig. 1.2 represents all electrical components illustrated block scheme of TRV is illustrated.

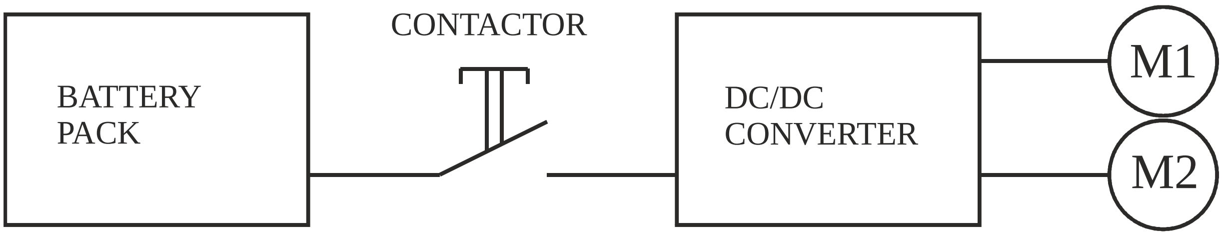


Fig. 1.2 Block scheme of TRV

1.2 Specification of power source on railway vehicle

Two lead-acid batteries are placed on TRV as power supply. CSB EVX 12400 batteries are designed especially for electric vehicles, such as electric golf cart, electric wheelchair, mower, dust collector, scooter, bike and etc. It has high cycling life, high efficiency and long service life [2]. These maintenance-free batteries are sealed and do not require watering, they can be used in any orientation. These batteries are designed as

Absorbed glass mat (AGM) batteries. In AGM batteries the spaces between the cells is replaced by a glass fiber mat soaked in electrolyte. Glass mat greatly reduces evaporation, so this combination of features allows the battery to be completely sealed. The advantage of this technology is high durability to repeated deep discharge, which occurs for example with traction vehicles where the battery is the only power source and could be completely discharged. These batteries are in the category of valve-regulated lead-acid (VRLA) batteries. When battery is in charging status the oxygen at the positive electrode occurs, which reacts with the lead on the negative electrode. While lead sulfate is created, negative electrodes are getting gradually chemical discharging. Hydrogen is produced, and it should be controlled by pressure valves. Produced hydrogen, together with the oxygen recombine back into water so no gas leakage will be outside the accumulator. Therefore, the batteries can be used in confined spaces. Another advantage is their small internal resistance, so the battery could be loaded with large discharge currents [3]. Detailed information is represented in Tab. 1.

Fig. 1.3 CSB EVX 12400 battery [2]

Tab. 1 SVX 12400 product specification [2]

Cells per unit	6
Nominal voltage	12V
Maximum voltage	14,7V
Equalization and Cycle Service	14,4 to 15,0 VDC/unit at 25°C
Float Charging Voltage	13,5 to 13,8 VDC/unit at 25°C
Capacity	40 Ah
Maximum charge current	12 A
Maximum discharge current	400A/5sec
Internal resistance	8,2mΩ
Design life	
400 cycles	100%DOD at 25°C
1800 cycles	30%DOD at 25°C
Operating temperature range	
Nominal operating temperature	25 °C
Discharge	-15 °C – 50 °C
Charge and Storage	-15 °C – 40 °C
Weight	13,2 kg
Dimensions	
Length	197 mm
Width	165 mm
Height	170,4 mm

Previously for charging EVX 12400 batteries ordinary laboratory power supply was used. Such power supplies do not have any intelligent charging logic, so constant current and constant voltage were charging lead-acid batteries. Laboratory power supply is not so suitable for charging due to absence of float mode, it is needed to keep the charging process under observation. The question of creating a reliable and precise lead-acid battery charger came up. Main objective was stated, and practical solution is reviewed in this bachelor student’s thesis.

2 LEAD-ACID BATTERIES

In 1859 French physicist Gaston Planté invented the lead-acid battery, it was the first battery that could be recharged. Such batteries had very low energy-to-weight ratio which means that amount of storable energy in this battery was too low compared to its weight, but battery cells possessed with relatively large power-to-weight ratio and they were able to supply high surge currents. These features, altogether with their low cost and recyclability, make them affordable for use in vehicles with internal combustion engine (ICE) to supply the high current required by automobile starters.

2.1 Electrochemistry and working principles

The lead–acid battery was the first rechargeable battery (secondary power source) that could have its capacity replenished from an external source. The electrochemical reaction that produced current was reversible, allowing electrical energy and chemical energy to be interchanged as needed. Electrolyte solution consists of a mixture of water and acid. The water-acid mixture of electrolyte used today consists of 30% acid and 70% water and its density comes up to 1,28 g/cm^3. Left uncharged battery could have one problem, is that acid will crystallize within the lead plates of the battery rendering it useless [4].

The positive and negative plates when discharged, both become lead(II) sulfate ($PbSO_4$), and the electrolyte loses much of its dissolved sulfuric acid and becomes primarily water. The discharge process is driven by the conduction of electrons from the negative plate back into the cell at the positive plate in the external circuit [5].

In the formula (2.1) negative plate reaction is described. It shows release of two conducting electrons gives lead electrode a net negative charge.

$$Pb(s) + HSO_4^-(aq) \rightarrow PbSO_4(s) + H^+(aq) + 2e^- \qquad (2.1)$$

As electrons accumulate they create an electric field which attracts hydrogen ions and repels sulfate ions, leading to a double-layer near the surface. The hydrogen ions screen the charged electrode from the solution which limits further reactions unless charge is allowed to flow out of electrode. On positive plate discharging process is followed by dissolving sulfuric acid from electrolyte and it becomes water. This reaction is written below in formula (2.2).

Positive plate reaction:

$$PbO_2(s) + HSO_4^-(aq) + 3H^+(aq) + 2e^- \rightarrow PbSO_4(s) + 2H_2O(l) \qquad (2.2)$$

The total reaction can be written as:

$$Pb(s) + PbO_2(s) + 2H_2SO_4(aq) \rightarrow 2PbSO_4(s) + 2H_2O(l) \quad (2.3)$$

When the battery is fully charged, the negative plate consists of pure lead, and the positive plate consists of lead dioxide, when the electrolyte becomes a concentrated sulfuric acid. Overcharging with high voltages causes electrolysis of water so oxygen and hydrogen gases are generated. During winter, when temperature is below zero, a discharged battery's electrolyte is more likely to freeze, because when battery is discharged the concentration of sulfuric acid decreases.

Lead–acid batteries lose the ability to accept a charge when discharged for too long, this process is called sulfation, the crystallization of lead sulfate. Cells generate electricity through a double sulfate chemical reaction. Lead and lead dioxide, the active materials on the battery's plates, react with sulfuric acid in the electrolyte to form lead sulfate. Through numerous discharge and charge cycles, some lead sulfate is not recombined into electrolyte and slowly crystallizes and settles on the bottom of the battery and no longer dissolves on recharging. It is believed that large crystals physically block the electrolyte from entering the pores of the plates. This means that the battery plates will never fully restore their lead structure, and the amount of active material used in reaction for electricity generation declines over time.

Sulfation also occurs when the battery is insufficiently charging during normal operation. It impedes recharging; sulfate deposits ultimately expand, breaking the plates and destroying the battery. To avoid sulfation the battery should be fully recharged immediately after discharging cycle. Sulfation also affects the charging cycle, resulting in longer charging times, less efficient and incomplete charging, and higher battery temperatures [5].

2.2 Construction

The design of the battery could slightly differ, but for most types of automotive and motorcycle batteries it is the same. The battery is made of a plastic container. At the top of the container there are positive and negative poles of battery, there could be valves with plugs for refillable old versions of batteries and sometimes the charge status indicator. Inside the battery, there are individual cells that are connected in series. Number of cells form a system of positive and negative lead plates which have grid structure, they are separated from each other and immersed into diluted sulfuric acid. The active material of the positive grid is fine-grained and porous lead oxide; negative grid is formed by sponge-like lead. The rechargeable battery with a rated voltage of 12 V contains 6 cells.

There could be small construction differences in individual accumulators of each manufacturer. Solutions in configuration and features of lead grids or separators would ensure particularly extension of the battery life, reducing internal resistance, self-discharging and improving start capabilities even behind low temperatures.

2.3 Types

Lead accumulators can be divided into 2 basic categories:

1. batteries requiring maintenance;
2. maintenance-free batteries.

Batteries which require maintenance are the oldest ones. Such a battery can be easily identified by refilling plugs on the container's lid also called inspection plugs which serves to control the electrolyte's level and further replenishment of distilled water if needed, because during the operation activity the electrolyte's level decreases with the natural evaporation, gasification and electrolysis. The lack of electrolyte is compensated with distilled water. However, modern lead-acid batteries, due to their design, show lower water losses and so the inspection of electrolyte level is carried out in the range of 3 to 12 months depending on the type, design and operating mode of the battery.

Second category is a maintenance-free battery. It does not need any special attention or maintenance operations as the first type. The main feature of this battery is that it is enclosed, except one small hole. This vent-hole is made to provide safety precaution to avoid explode of the battery, which can be caused by overcharging with further gasification of electrolyte.

Closed battery concepts have lead compound grids doped with calcium to reduce the evaporation of water, which also contributes to the reduction of gassing and boiling of electrolyte. The batteries are working on the principle of so-called oxygen recombination, when the free oxygen released in later phases of charging passes through the porous separator from positive electrode to negative where it is reduced to water. This process reduces the amount of generated gaseous oxygen and hydrogen during recharging process. That is how practically hermetically sealed construction of lead-acid batteries has been achieved. It is designed so that it does not allow the air to penetrate the surrounding air environments into the battery compartment.

The maintenance of batteries cannot be limited with measuring the level of the electrolyte, but it is advisable to check from time to time the state of the electrodes called the terminals. Their oxidation is a defect, as it limits the charging process or the energy output, especially when high current is demanded. Maintenance can also include regular charging battery.

Battery with flooded electrodes. It is so-called a semi-maintenance-free battery. This is particularly achieved by alloying grids with calcium. Earlier technology used grids exclusively antimony-doped. Such solution was chosen to ensure sufficient stiffness of the grids. Today construction is changed, it uses calcium on both negative and positive grids. Dotting grids with calcium, gives a positive effect on evaporation of water, which is now minimal. The level of electrolyte slightly decreases and is kept on safe level over a long life of the battery [6].

One of the progressive solutions is the AGM battery. The actual AGM battery cell consists of many positive and negative electrodes that are separated by special glass fiber separators dotted with boron. Such separator has excellent ion conductivity, allowing for rapid gas penetration and thus effective recombination to the negative electrode and an excellent ability to bind the electrolyte. In accumulators of this type, the electrolyte is just bound in the separator. The advantage of AGM accumulators is the high output power at low temperatures, high shock resistance, increased capacity while weight reduction. Absolute maintenance-free no need in distilled water filling, no care to electrolyte level and slow self-discharge [6].

Gel battery. AGM batteries are often mistakenly referred as gel batteries. Information about gel cell construction is not publicly available, so many rumors are made. However, the design of the gel accumulator is similar to any other battery. It contains a set of positive and negative grids separated with a common separator. However, gel battery is filled with a gelified electrolyte, the sulfuric acid is mixed with added fumed silica, which makes the resulting mass gel-lice and immobile [3]. The advantage of the gel concept is the lower sensitivity to higher operating temperature. Gel batteries have decreased the risk of stratification practically to zero due to the suspended electrolyte acids. As AGM type, they are maintenance-free, they have increased capacity at reduced weight with low self-discharge level. Gel batteries can better withstand elevated temperatures and deeper discharge.

2.4 Application

Compared to newer technologies, lead–acid batteries are inexpensive and widely used. Starting, lighting, ignition batteries (SLI) and car lead-acid batteries continue to be widely used in automobile industry. They are widely used for storage in backup power supplies in cell phone towers, high-availability settings like hospitals, and stand-alone power systems [5].

Stand-by batteries, which are based on wet cell technology, are designed for deep discharge and commonly used for hospitals, telephone and computer centers, energy grid storage and off-grid household electric power systems. They are called to provide reserve power supplies in stationary applications. Lead–acid batteries are used in emergency lighting and to power sump pumps in case of power failure [5].

Traction batteries are used in golf carts and other battery electric vehicles. VRLA batteries are used in back-up power supplies for alarm and smaller computer systems, particularly in UPS, marine applications, electrified bicycles and motorcycles [5].

3 CHARGERS AND CHARGING CHARACTERISTICS OF LEAD-ACID BATTERIES

In technical publications dedicated to chemistries of batteries and their charging properties are always determined different types of charging characteristics. Charger, which acts as source of constant voltage even with wide range of charging current and small internal resistance is symbolized with U letter. Charger, which works as source of constant current with high inner resistance is marked with I letter. Charger with decreasing current and increasing voltage is named W charger with current limiting resistance.

3.1 Most used charging characteristics of lead-acid batteries

Interrelation between output voltage and charging current is called volt ampere characteristic of the charger. In this part the most common characteristics are described.

3.1.1 U charging characteristic

Constant charging voltage characteristic is voltage, whose value is set from 14,4 V to 14,8 V for 12 V battery, it means 2,4 to 2,46 V per cell. After connecting a charger of this type, it will start charging the battery with a very high current, it's rate depends on the depth of discharge of the battery. For example, the value of charging current corresponds to a value from 0,5 to 1 times the nominal capacity of the battery. As the battery voltage increases during charging, the charging current decreases. The final charge current reaches about 0,002 times the nominal capacity of the battery. Of course, current charging ratio depends on condition of the battery and on the output voltage tolerance of the charger. These values are only orientative and can vary with specifications of the charger. Discharged battery is fully charged from 10 to 15 hours, however, within first 1 to 2 hours the battery is charged to 80% of its nominal capacity. Because of big charging currents a considerable amount of heat is produced and it is recommended not to exceed 40 °C temperature. Advantage of U charging characteristic is the short time of charging.

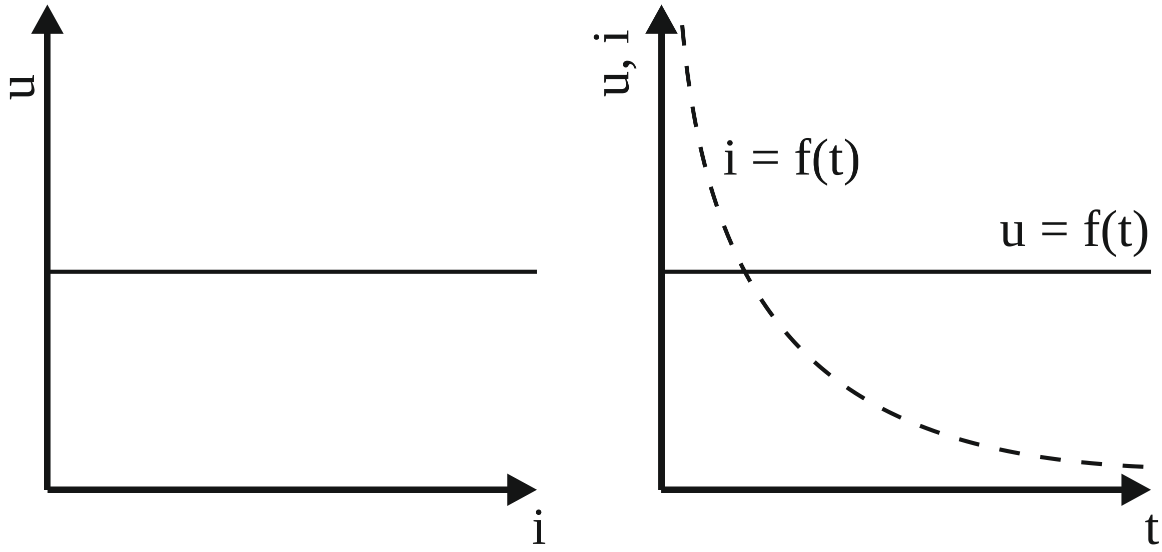


Fig. 3.1 Charging characteristics with constant voltage on the left, on the right how charging voltage and current change over time

3.1.2 I charging characteristic

When charging the battery using constant current characteristics the value of charging current is set from 0,08 to 0,1 times the nominal capacity of the battery. Full charging process is done after 10 up to 14 hours. Comparing this charging characteristics to the previous, there is no quick charge effect. After charging the same accumulator for 2 hours the capacity of the battery will be maximum 20% of its total capacity. The advantage of this type of charger is the evaluable value of the supplied charge. The disadvantage is that the charging current is all the same during the whole period of charging, it creates danger of overcharging. So the charger needs to be equipped with a full charge monitoring circuit, or at least a time switch. Perfect variant is when charger is equipped with dual level charging current, when it is higher at the beginning and smaller to the end of the charging process.

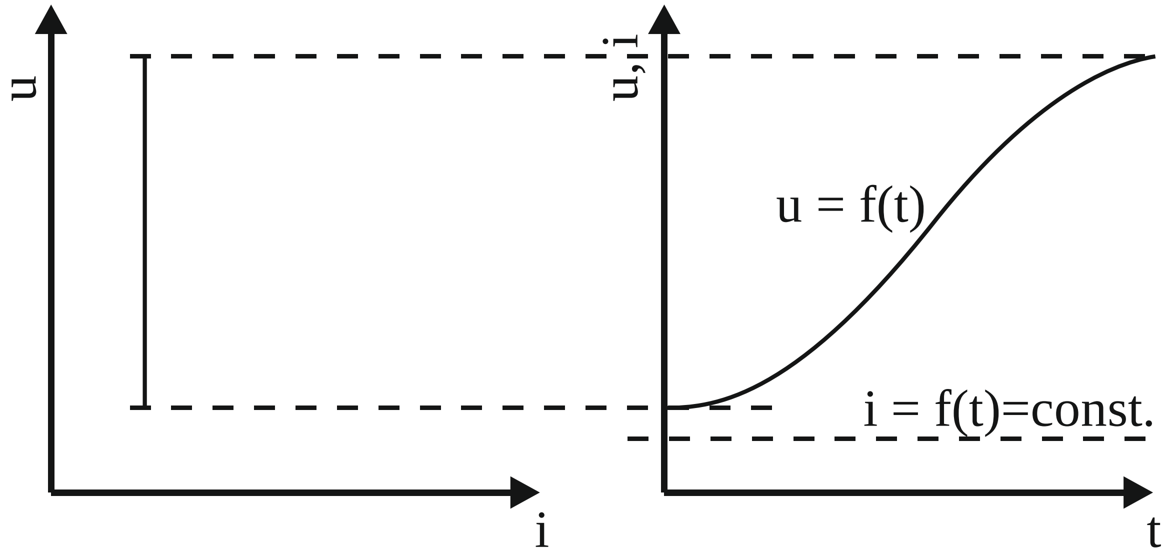


Fig. 3.2 Characteristics of charger with constant current is shown on the left plot, right plot represents how charging voltage's level is changed during charging process

3.1.3 W charging characteristic

Charging with increasing voltage and decreasing current. The charger's voltage increases during charging. Increasing batteries inner voltage decreases charging current. Chargers with this characteristic charge faster as they work with relatively large currents during the entire charging process.

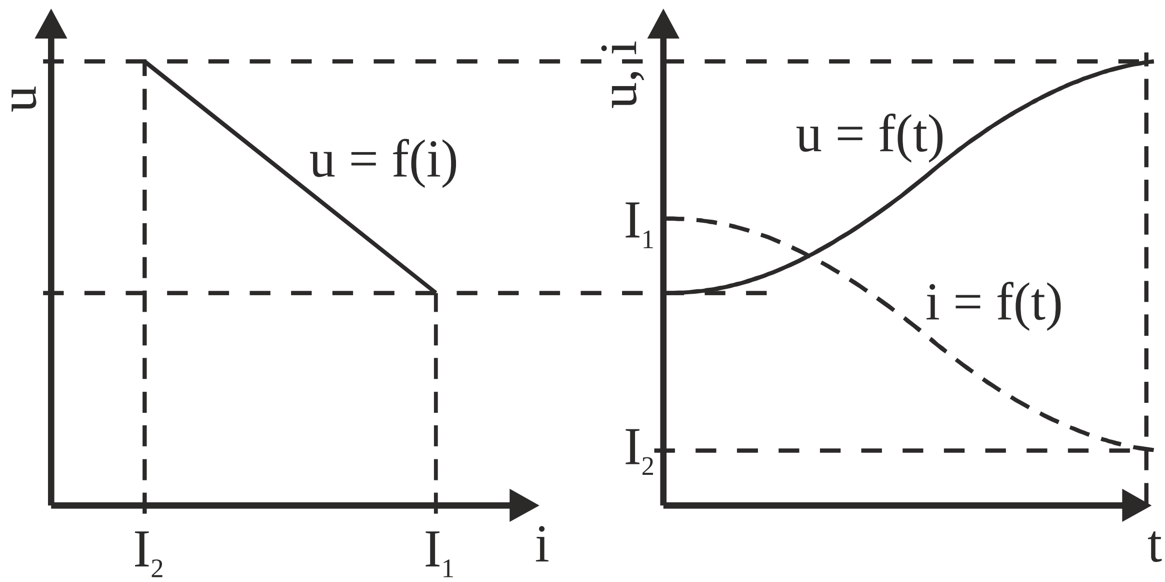


Fig. 3.3 Plot on the left represents charging characteristics with decreasing current, plot on the right describes reliance of charging voltage and current on time

3.2 Most common types of chargers

Construction of the charger must be defined by design of the battery which require to be charged. Chargers for traction batteries come in different design varieties. Chargers that are rated up to two amperes may be used to maintain charge of the battery when it is not used. Charger rated a few amperes to ten amperes is for maintenance of traction batteries or to recharge a vehicle battery that has accidentally discharged.

3.2.1 Battery charger with unsymmetrical alternating current

This type of charger is also called pulsating charger. Half-wave rectification of a pulsating charging current. After charging interval when positive half-wave occurs, comes negative half-wave where the battery is partially discharged by 1/10 of the charging current. The discharge current has certain depolarizing effect. Surface of the electrodes is getting changed it is caused by electrolysis reaction when current flowing through electrolyte. Charging efficiency is also slightly increasing. This charge affects sulfated batteries, it could restore the capacity of the battery, in case when the active material on grids of cells is not depleted or degraded. In one period of time the battery is charging, in the next one it discharges with a fraction of the charging current and so on to fully charged battery [7]. The schematic of unsymmetrical alternating current charger is illustrated on Fig. 3.4. The logic of this schematic shows that transformer is reducing voltage to desired level and then is rectified by half-wave rectifier. One half of the input waveform reaches limiting power resistor which used to regulate charging current. In half period when charging voltage occur battery is charging, then the negative half-wave is blocked by diode and no current flows to the battery at this moment battery is discharged in reverse because load in the form of light bulb is connected. The waveform of charging and discharging currents is illustrated on Fig. 3.5. This type of charger is very easy, cheap and effective in production.

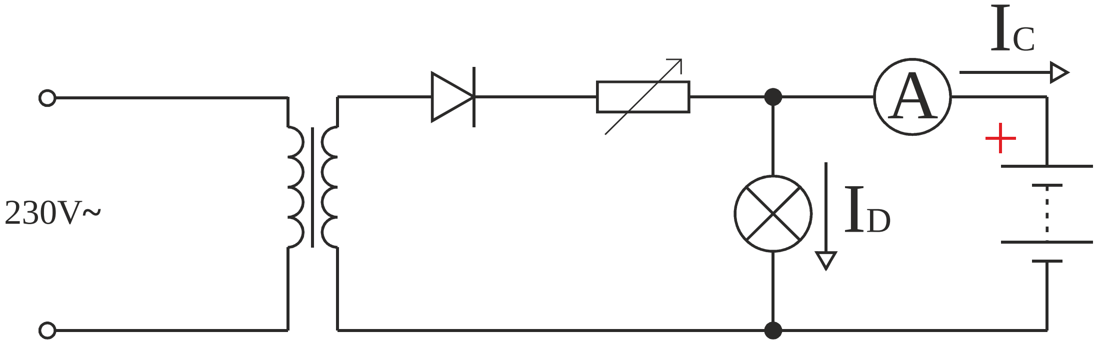


Fig. 3.4 Scheme of unsymmetrical alternating current charger

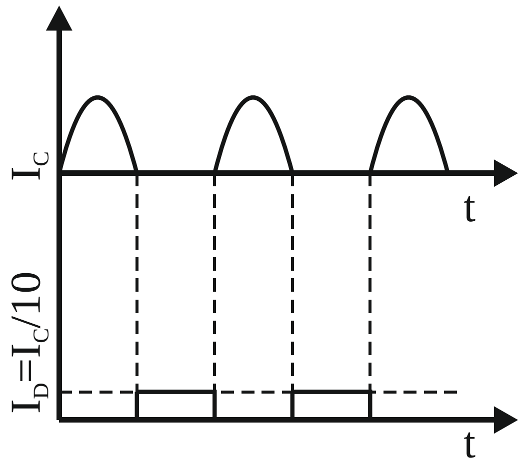


Fig. 3.5 Shapes of charging I_C and discharging reverse I_D currents

3.2.2 Battery charger with LM317

Battery charger circuit with LM317 which is able to charge 12 V 4,5 Ah lead-acid batteries. The schematic is very simple and using only few components. Integrated controller LM317T is the heart of the circuit. This battery charger is automatic so when the battery will become full charge it will stop charging.

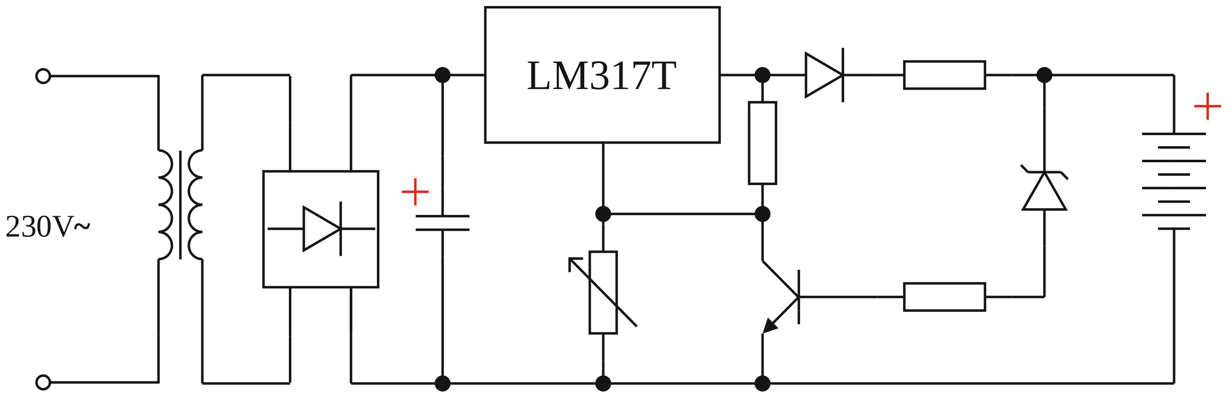


Fig. 3.6 Charger with LM317T

3.2.3 Switching battery charger

The LT3652 is a complete monolithic step-down battery charger that operates over a 4,95 V to 32 V input voltage range. The LT3652 provides a constant current and constant voltage charge characteristic, with programmable charge current up to 2A. The charger can be programmed with a resistor divider for float voltage up to 14,4 V.

It employs an input voltage regulation loop, which reduces charge current if the input voltage falls below a programmed level, set with a resistor divider.

The LT3652 can be configured to terminate charging when charge current falls below 1/10 of the programmed maximum (C/10). Once charging is completed, the LT3652 enters a low-current 85 µA standby mode. An auto-recharge feature starts a new charging cycle if the battery voltage falls 2,5 % below the programmed float voltage. It also contains a programmable safety timer, used to terminate charging after a desired time is reached. This allows top-off charging at currents less than C/10.

Applications:

- Solar powered applications,
- remote monitoring stations,
- $LiFePO_4$ (lithium phosphate) applications,
- portable handheld instruments,
- 12v to 24v automotive systems.

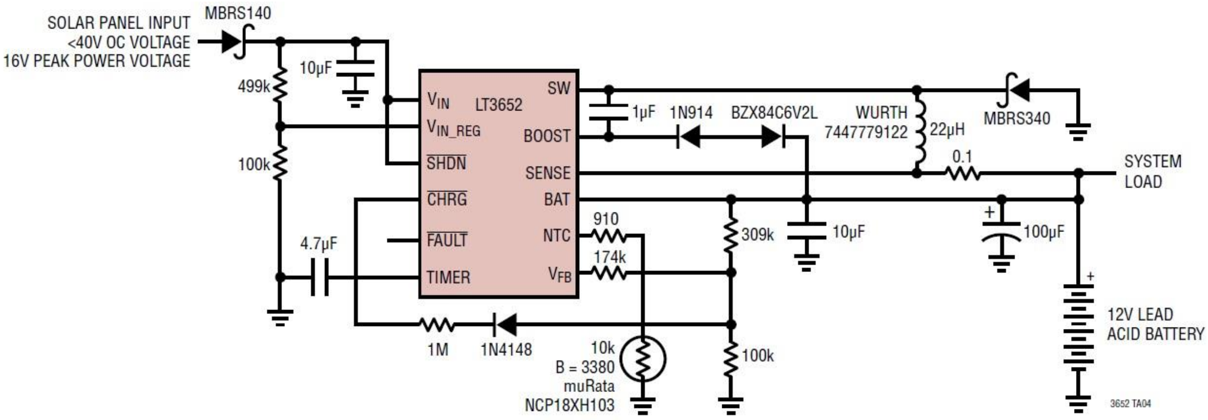


Fig. 3.7 Power tracking 2 A battery charger

4 PLACED DEMANDS ON TRV TRACTION BATTERY CHARGER

Defining main purposes of the lead-acid charger is an important step to plan further design and production. Such parameters as usage conditions, weight, portability and operating temperature are considered to determine construction of the charger for TRV.

After TRV was fully assembled the question of charging has raised. For charging the power source of the vehicle which consists of two lead-acid batteries ordinary laboratory power supply was used. Such power supply was very easy to get, because the Department of Electrical and Electronic Engineering has all needed equipment to provide easy and simple power source to charge batteries. But it has a disadvantage that it does not have any automatic controller to monitor and regulate charging voltage and current, so charging current and voltage were supplying lead-acid batteries constantly. As it was described above such charging characteristics could lead to gasification of electrolyte which could damage the whole battery if voltage and current levels are not measured and adjusted in time. Average time of charging for these batteries is around 6 hours, it is not very convenient for the operator to check stages all the time. While designing and assembling the battery charger all stated requirements put by experience of exploitation were taken into account.

First demand put on the battery charger is that it should be portable and could have optimal weight-to-size ratio. It is therefore that the charger need to consume power from electrical grid as it is the most common source of energy and can be found in every socket of every household in Europe. So, input voltage from the grid is 230 V with 50 Hz frequency. Output characteristics of the lead-acid charger are determined by the batteries, as they are connected in series the voltage of the batteries is summarized and evaluates 24 V so minimum output voltage from the charger must be supplied on the level of 28,8 V. As the charging current per battery unit is defined by datasheet as 12 A, the convenient value for charging current had been chosen as 5 A. Parameters corresponding for proper charging and maintaining of the battery are listed in Tab. 2. The charger must take care of batteries and monitor state of charging current and voltage and adjust them when necessary to maintain maximum life span to galvanic cells of each unit.

Battery charger will take care of the batteries while charging them, but human factor cannot be fully eliminated on the beginning of this operation. That is why concept of protection and construction must be defined. When the batteries are going to be connected to the charger, the polarity of the terminals could be connected oppositely then short circuit could occur, so the logic of the battery charger must be protected. The battery charger will be also equipped with indication which will show status of the charger or even detect and show errors in operating stage. All components of the main charging and protection circuits should be assembled in one box to create a solid construction which can be connected fast, has intuitive interface and will be easy to grasp by the user.

Tab. 2 Specification of TRV battery charger

Charging current up to	5 A
Float voltage up to	27,75 V
Full charge voltage up to	29,5 V

5 PROPER TOPOLOGY FOR THE BATTERY CHARGER

For the charging application the switching mode or linear mode charger can be used. Switching mode charger could be a good choice when the compact size plays key role in the application, but it is much harder to design and assembling process with verification activities could last for a season, so it does not meet a requirement to build a battery charger for quickest availability. But there are also imperfections in the circuitry, does not matter which type to use in assemble and it can cause electrical noise problems to the whole application.

Linear power supplies are ideal for low power applications so when a higher power is needed, the disadvantages become more apparent. These disadvantages include high heat loss and lower efficiency when compared to a SMPS. Much power is needed than much bigger will be the linear power supply because it requires a large transformer and other components as diodes and capacitors to handle the power. So, the overall weight and size of the battery charger increases.

High power output creates high heat loss because of efficiency of the linear power supply. The high output current must pass through the transformer, rectifier and power transistor. This thermal expansion demands that the linear power supply should be placed in a well-ventilated box with big cooling grills and use a heat sink to dissipate for the escaping heat.

According to placed demands on traction battery charger the linear integrated charge controller (ICC) for lead-acid batteries model bq24550 had been chosen. As this topology controller is close to previous series of UC3906 battery charger controllers. It contains all the necessary circuitry to optimally control the charge and hold cycle for sealed lead-acid batteries [9].

This controller can be used in many applications where needed continuous power supply to the DC load and simultaneously charge the connected batteries.

Application:

1. Emergency Lighting Systems
2. Security and Alarm Systems
3. Telecommunication Backup Power
4. Uninterruptible Power Supplies

6 FUNCTIONAL DESCRIPTION OF INTEGRATED CHARGE CONTROLLER

The bq24450 contains all the necessary circuitry to control the charging operation of VRLA batteries in the optimum way. At the same time the ICC controls the charging current and the charging voltage. It is made to ensure safe and efficient supply of the charge to the battery, maximizing both capacity and life of the battery. Depending on the application and when it is necessary, the ICC can be limited and configured as a simple constant voltage float charge controller or a dual-voltage float and boost charge controller.

The built-in precision voltage reference is especially temperature-compensated to track the characteristics of lead-acid cells, and maintains optimum charging voltage over an extended temperature range without using any external components. The ICC is a very low current consumer, which allows to monitor the temperature of itself and minimize self-heating effects.

Charging currents are limited only by the selection of the external pass transistors, the ICC supports both NPN and PNP types and provides at least 25 mA of base current. It can support a wide range of battery capacities and provide a wide range of the charging voltages.

In addition, the ICC has built in comparators to monitor the charging voltage and current. Some these comparators are brought out at external pins and made available status signals. These comparators feed into an internal state machine that sequences the charge cycle. These status and control pins can be connected to a signaling and informative indication, or they can be connected up in flexible ways for standalone applications [10].

Features:

- Regulates both voltage and current during charging
- Precision temperature-compensated reference
    - Maximizes battery capacity over temperature
    - Ensures safety while charging over temperature
- Optimum control to maximize battery capacity and life
- Supports different configurations
- Minimum external components
- Available in 16-pin SOIC

Normally the power is supplied to the battery by the Float Charger. To keep the battery healthy, the ICC could also supply it with trickle charge. Boost charger is switched ON when the level of If the charging current under Float Mode exceeds a set level, it supplies quick charging current to the battery. On battery reaching the set value, the Boost Charger is switched OFF.

For our application there are two main charger circuits suggested by manufacturer:

1. A Simple Dual-Level Float-Cum-Boost Charger
2. An Improved Dual-Level Float-Cum-Boost Charger with Pre-Charge

The problem with the charger circuit mentioned as a first application method is that even with deeply discharged batteries, charging process will start at maximum current level $I_{MAX\text{-}CHG}$. It is very hazardous, because gassing of the batteries electrolyte could be resulted.

With a second application ICC bq24450 is configured with pre-charge mode of the battery. Pre-charge current level will hold till the voltage levels rise to levels safe enough to permit charging at $I_{MAX\text{-}CHG}$.

In the circuit of Fig. 6.1, the CE pin is used to detect the battery voltage, comparing voltage this pin with V_{REF} which equals 2,3 V, if the voltage at the CE pin is below 2,3 V, permitting a pre-charge current I_{PRE} to flow from the PRE-CHG pin through R_T into the battery.

Once the battery voltage rises above a safe threshold V_{TH} in Fig. 6.2 at point 2, the enable comparator turns off internal transistors and enabling base current on DRVC pin. External transistor Q_{EXT} provides $I_{MAX\text{-}CHG}$ to the battery and then circuit performs bulk charge to the battery terminals.

As $I_{MAX\text{-}CHG}$ flows into the battery, the battery voltage increases. The voltage at the VFB pin is the battery voltage scaled by the numerous of resistors. At the point when the voltage on the VFB pin exceeds 0,95 V_{REF}, then STAT2 turns ON, it indicates initiation of boost mode. This moment is illustrated on Fig. 6.2 when the battery voltage reaches level of V_{BI}.

The addition of D_{EXT} as shown on Fig. 6.1 fixes the reverse current problem. Returning the voltage feedback to the PGOOD pin instead of GND ensures that the divider does not conduct any current when the input supply is not present.

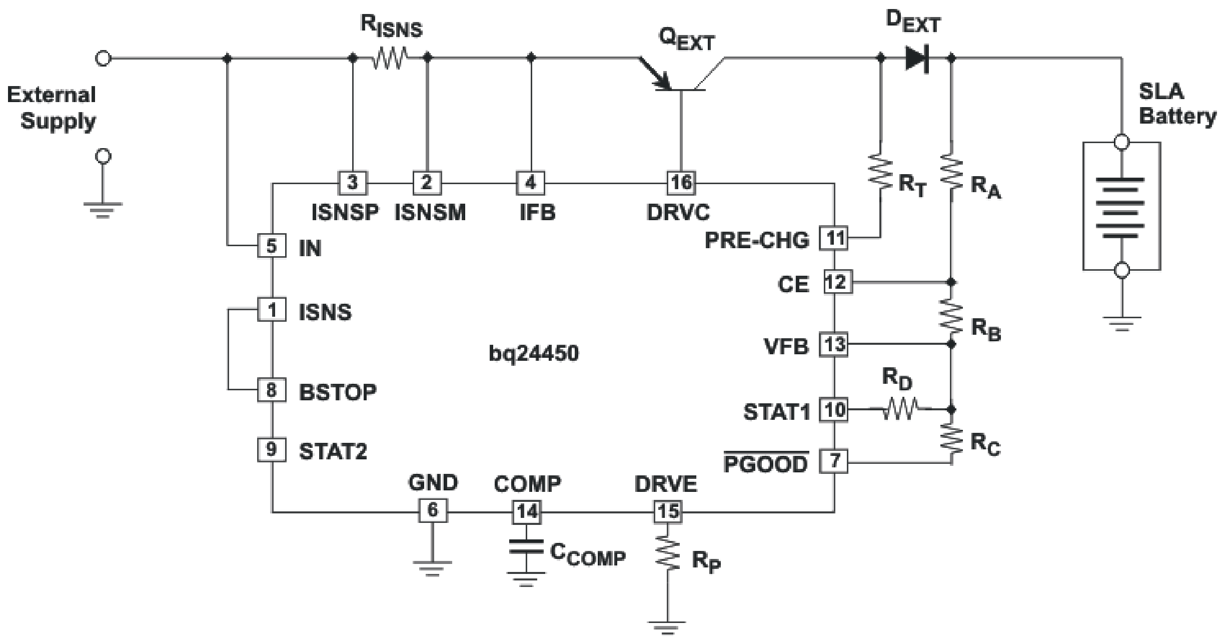


Fig. 6.1 Typical application schematic of BQ24450 [10]

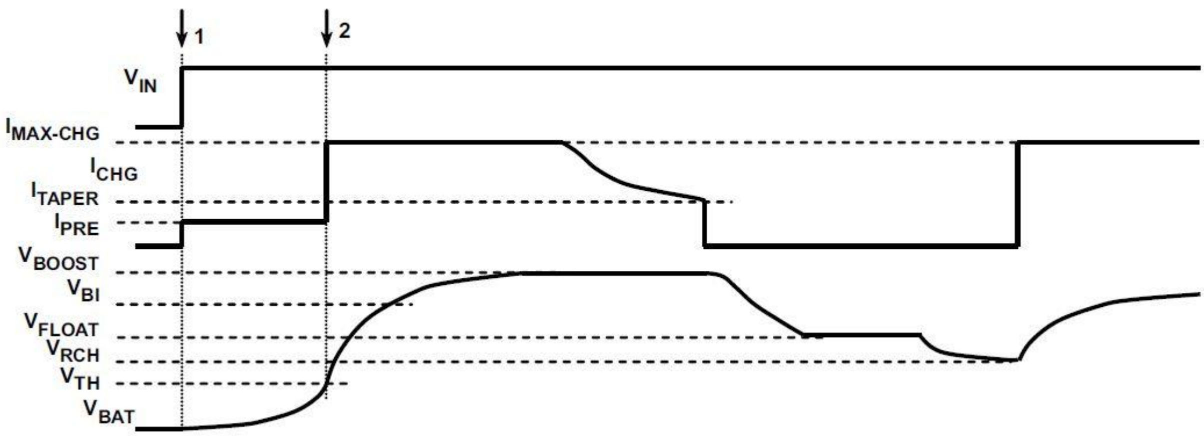


Fig. 6.2 Charging characteristics of BQ24450 [10]

7 PROJECT INSTALLATION AND DIMENSIONING

At the moment, when the main functions of the ICC are considered, it is time to calculate important parameters to implement the working prototype of the battery charger. This process will be attended by full description of stages of development of the circuitry. On Fig. 7.1 the block scheme of the battery charger is illustrated, its call is to provide the concept of the charger and to show approximate component layout.

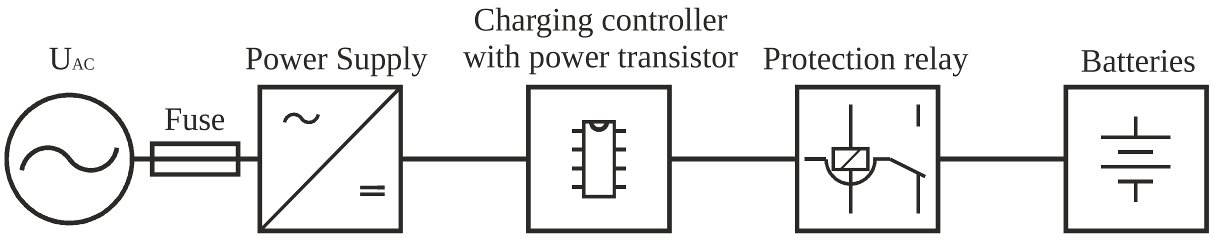


Fig. 7.1 Block scheme of the battery charger

In previous chapter the type of AC to DC converter was demonstrated. For the installation, linear mode power supply will be used. It will supply the charger controller for lead-acid battery with direct current and voltage. Fuses will be connected in front of the most powerful circuitry parts as transformer and bridge rectifier, so fuse will provide safety for that power devices with overcurrent protection.

7.1 Power supply

For powering the ICC and provide charging voltage to the battery, input supply is taken form energy grid. Alternating voltage of 230 V is used and is converted to DC voltage. To rectify AC voltage in the battery charger application a full-wave rectifier will be designed and installed in front of the circuitry with the ICC.

A full-wave bridge rectifier converts the whole of the input waveform to one of constant polarity (positive or negative) at its output. Full-wave rectification converts both polarities of the input waveform to pulsating DC, and yields a higher average output voltage [8]. To make a full-wave rectifier a transformer and four-diode bridge are needed. Four single semiconductor diodes are connected to create a diode bridge or four diodes in a bridge configuration, are manufactured as single components. A full-wave rectifier also called Graetz bridge rectifier is using four diodes which form diode bridge and illustrated on Fig. 7.2.

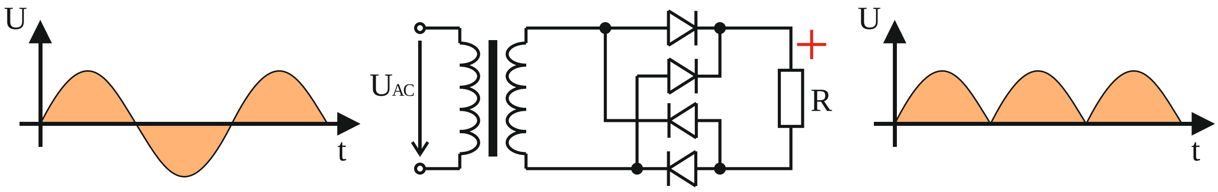


Fig. 7.2 Graetz bridge rectifier

A full-wave rectifier connected to a transformer transforms AC voltage into rippled DC voltage, so adding a proper capacitor, the signal will be filtered, and proper DC voltage will be reached for further supply of the ICC. The configuration of transformer, bridge rectifier and capacitor makes an electronic power supply usually called linear mode power supply, but the right linear power supply uses for the output voltage stabilization linear stabilizer. Linear power supplies were the normal standard before switch mode power supplies were invented.

This type of power supply was chosen for the application because of its advantages. It is very uncomplicated to calculate and assemble, it is very reliable and it is a low noise power supply because there are no switching parts inside. The cost to performance ratio is also justifiable for the compact and portable battery charging application.

These power supplies require few components making them easy to design and to work with. Its design makes it more reliable. Commonly, linear power supplies have a low output voltage ripple this reduces overall level of noisemaking, so they can be used where noise sensitivity is essential. And finally, linear power supplies overall are cost-effective because they do not contain lots of components, so making them a preferred power supply, when such solution suits the requirements of application. The schematic diagram of power supply for the battery charger is presented on Fig. 7.3.

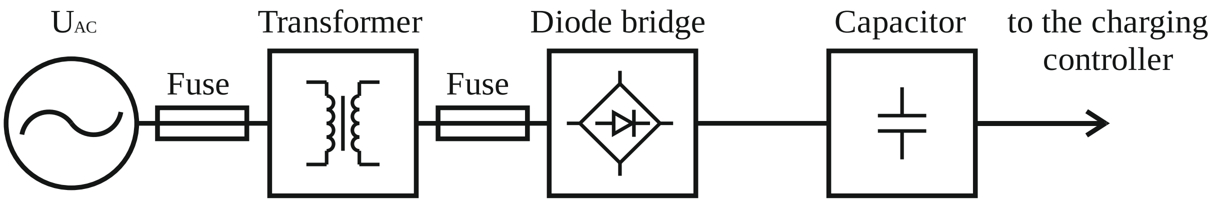


Fig. 7.3 Schematic diagram of the linear power supply

Power supply consists of three elements. First part is toroidal transformer. It is used to step down the input voltage to give the ICC the value of voltage in the range in which it would not destroy the internal structure of the ICC. Toroidal transformer is desired, because copper wire is coiled around ferrite core, such transformer is more efficient than the laminated E-shaped transformers and they are compact in size, so it is best choice for the installation.

There is a wide array of choices on the market, unfortunately there was no transformer which could provide us precise voltage level as desired. According to the datasheet, the range of input voltage for the ICC is from 0,3 to 40 V, but taking into account the maximum charging voltage to the buttery summing it up with losses on Schottky diodes, transistor and rectifying bridge the voltage level approaches 34 V plus reducing voltage level on transformer his own when it is loaded, so the nominal stepped down voltage should be near 39 V to 40 V value.

The only one toroidal transformer fits our design is INDEL TST200/006. It has pair of secondary windings each has stepped down voltage to a level of 14 VAC and each coil can provide 7 A of current. Two secondary coils are connected into series and it gives us 28 VAC on output.

Next, the rectifying bridge is chosen. Mostly, four-diode bridges are packaged in one case which makes possible to put a radiator on it to dissipate heat. DC COMPONENTS BR251 is a good one because it has 70 V of maximum RMS bridge input voltage and 25 A of maximum average forward rectified output current. It is more than enough to supply our batteries.

The last but not least important is capacitor which filters output waveform pulse voltage from the bridge. Nichicon UVZ1J332MRD is an electrolytic capacitor which can hold 63 VDC its capacitance is 3 300 μF. From the calculations below will be stated that connection of two capacitors in parallel is needed for filtering the waveform with 38,4 V peak. To calculate the maximum output voltage from the transformer, the formula (7.1) is used.

$$V_{MAX} = V_{ef} \cdot \sqrt{2} \tag{7.1}$$

where:

V_{MAX} the maximum value of rectified voltage [V],

V_{ef} the effective value of rectified voltage [V].

$$V_{MAX} = 28 \cdot \sqrt{2} = 39{,}6\, V$$

Using formula (7.2) to calculate the capacitance of needed filtering capacitor.

$$C = \frac{k \cdot I_{OUT}}{p \cdot V_{DC}} \tag{7.2}$$

where:

I_{OUT} the output current of the load [mA],

V_{DC} the output voltage [V],

k constant for full-wave rectification equals 300,

p ripple factor, 0% means perfectly smoothed voltage [%].

$$C = \frac{300 \cdot 5000}{10 \cdot 37{,}2} = 4\,032{,}48\ \mu F$$

To ensure that the capacitor will not fail high voltages and current the capacitance will be raised to 120 % of already calculated value.

$$C_{120\%} = C \cdot 1{,}2 = 4032{,}48 \cdot 1{,}2 = 4\,848{,}97\ \mu F$$

7.2 Integrated charging controller

The ICC part of the whole battery charger consists number of additional features as LED indication to make the charger more informative to user. Also, a protection relay is added to the circuitry to ensure the battery and the charger against short circuits which could be occasionally achieved by connecting contacts to the terminals of the battery in wrong polarity.

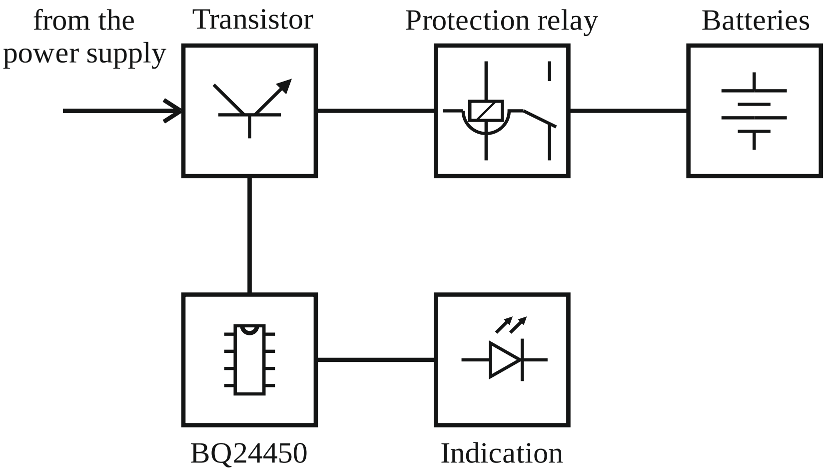


Fig. 7.4 Schematic diagram of integrated charging controller

7.2.1 Voltage dividers

To design BQ24450 periphery the first step is to decide on the value of the current in the voltage divider resistor string in FLOAT mode. This should be substantially higher than the input bias current in the CE and VFB pins and the leakage current in the STAT1 pin, but low enough such that the voltage on the PGOOD pin does not introduce errors. A value of 50 μA is suitable. In FLOAT mode, STAT1 is OFF, so there is no current in R_D. The voltage on the VFB pin V_{REF} is 2,3 V. Other parameters needed to provide the calculation of electric components are inserted to the Tab. 3.

Tab. 3 Parameters of the battery

	Per cell	Per 2 batteries	
$V_{BAT-MIN}$		14 V	Minimum level discharged
V_{TH}	1,75 V	21 V	Final discharge voltage
V_{BULK}	2,19 V	26,25 V	Bulk voltage
V_{BOOST}	2,45 V	29,4 V	Boost voltage
V_{FLOAT}	2,31 V	27,75 V	Float voltage
V_{PRE}	2 V		Voltage drop across the internal transistor and the internal diode
V_{REF}	2,3 V		Reference voltage level
$I_{PRE-CHG}$	500 mA=1/10 $I_{MAX-CHG}$		Pre-charge current
$I_{MAX-CHG}$	5 A		Maximum charge current

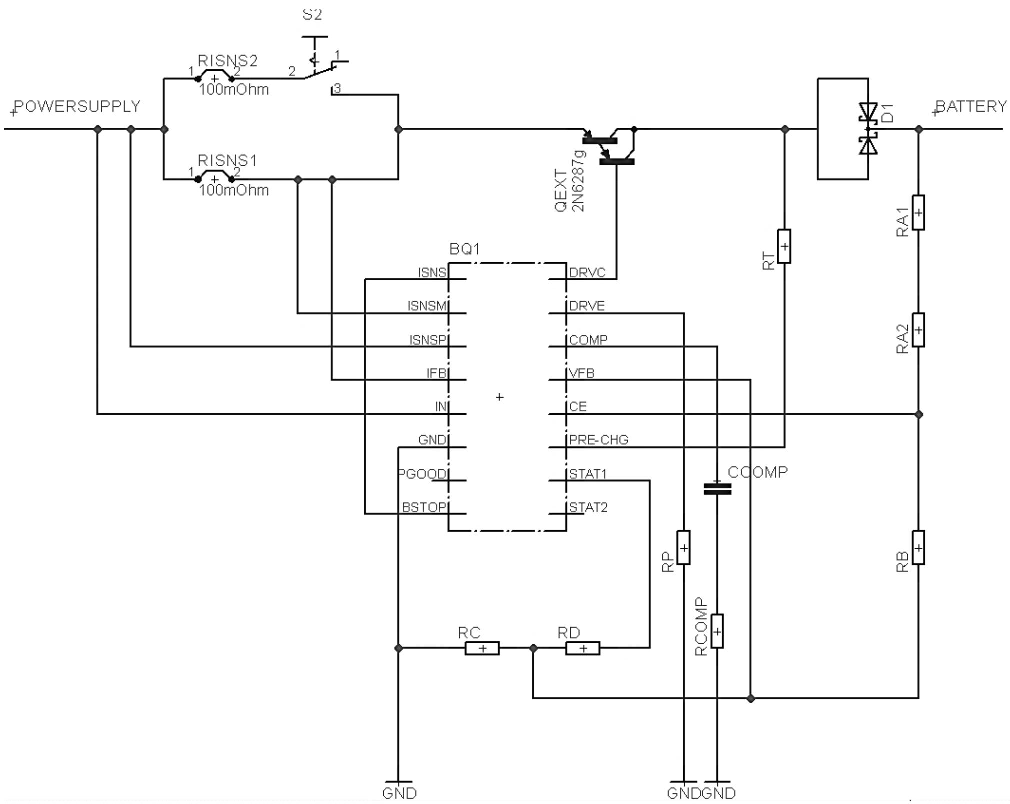


Fig. 7.5 Eagle schematic of voltage dividers for BQ24450

The charger is required to operate from a supply voltage of 31,4 V to 38,2 V. Firstly, from all the voltage dividing components the resistive divider R_C will be calculated using formula (7.3).

$$R_C = V_{REF} \div I_{IFB} \tag{7.3}$$

where:

R_C resistor [Ω],

I_{FB} input bias current [μA].

$$R_C = 2{,}3\,V \div 50\,\mu A = 46\,k\Omega$$

The closest 1% value is 46,4 kΩ. After getting the value of R_C using the formula (7.4) the total resistance of R_A and R_B is defined.

$$V_{FLOAT} = V_{REF} \times (R_A + R_B + R_C) \div R_C \tag{7.4}$$

where:

R_A, R_B resistors [Ω].

$$R_A + R_B = \left(\frac{V_{FLOAT}}{V_{REF}} - 1\right) \cdot R_C = 513{,}43\,k\Omega$$

The next step is to calculate resistance of R_D using boost voltage. To perform calculations in formula (7.5) total resistance of R_A and R_B will be plugged in.

$$V_{BOOST} = V_{REF} \times (R_A + R_B + R_C//R_D) \div R_C//R_D \tag{7.5}$$

where:

$R_C//R_D$ parallel connected resistors [Ω],

V_{BOOST} boost voltage [V].

$$R_C//R_D = \frac{R_C \cdot R_D}{R_C + R_D} \tag{7.6}$$

$$R_D = \frac{1}{\dfrac{\dfrac{V_{BOOST}}{V_{REF}} - 1}{R_A + R_B} - \dfrac{1}{R_C}} = 715{,}68\,k\Omega$$

Resistor R_D equals 715,68 kΩ. Pick the closest 1% value of 715 kΩ. From this part it is left to calculate R_B and R_A resistors. Firstly, resistor R_B will be calculated from formula (7.7).

$$V_{TH} = V_{REF} \times (R_A + R_B + R_C//R_D) \div (R_B + R_C//R_D) \tag{7.7}$$

where:

V_{TH} threshold voltage [V].

$$R_B = \frac{(R_A + R_B) - R_C//R_D \cdot \left(\dfrac{V_{BOOST}}{V_{REF}} - 1\right)}{\left(\dfrac{V_{BOOST}}{V_{REF}} - 1\right) + 1} = 17{,}43\,k\Omega$$

The closest precise value of R_B available on the market is 17,4 kΩ. So now it is left to subtract R_A from R_A+R_B value from formula (7.8) below.

$$R_A = (R_A + R_B) - R_B \tag{7.8}$$

$$R_A = 513\ k\Omega - 17{,}43\ k\Omega = 495{,}99\ k\Omega$$

There is no closest standard value for R_A which equals almost 496 kΩ, so it will be made with two connected in series resistors with values of 470 kΩ and 27 kΩ.

Now it is time to calculate the rest of additional parts, which are used to sustain proper voltage dividing. The pre-charge current flows from PRE-CHG pin through the resistor R_T into the battery. It is calculated by (7.9) formula.

$$I_{PRE} = (V_{IN} - V_{PRE} - V_{DEXT} - V_{BAT}) \div R_T \tag{7.9}$$

where:

V_{Dext} forward voltage drop [V].

$$R_T = \frac{38{,}2\ V - 2\ V - 0{,}4\ V - 14\ V}{0{,}5\ A} = 43{,}6\ \Omega$$

The value of R_T is selected in closest tolerance of 43 Ω. To calculate input of the current-sense comparator resistor the formula (7.10) is used.

$$I_{MAX-CHG} = V_{ILIM} \div R_{ISNS} \tag{7.10}$$

where:

R_{ISNS} input of the current-sense comparator resistor [Ω],

V_{ILIM} current limit amplifier voltage [mV].

$$R_{ISNS} = 250\ mV \div 5\ A = 0{,}05\ \Omega = 50\ m\Omega$$

As the resistor for comparator R_{ISNS} were chosen two open air resistors 100 mΩ connected in parallel with the power rating of 5 W.

7.2.2 External transistor and diode

For external transistor Q_{EXT}, ON SEMICONDUCTOR 2N6287G is suitable. It is Darlington bipolar transistor as ICC supplies DRVC pin with relatively small base current 25 mA, external transistor should have high DC current gain. For external diode D_{EXT} was chosen a Schottky VISHAY MBR2060CT-E3/45 its purpose is to fix reverse current problem. Its forward voltage value during charging is about 0,4 V to 0,5 V and is very good for ICC, because after charging cycle is completed, battery could be disconnected from the charger later than the power supply is switched off. This situation could lead to reverse current flow which is not desired, as in cases where there are no securing components in the circuitry nothing could block voltage flowing in opposite direction from batteries to ICC.

The choice of the external pass transistor and the configuration of the internal driver transistor coupled with the high charging voltage influence the ICC's power dissipation and thus its self-heating. The ICC typically has a thermal resistance of 100 °C/W. An external resistance R_P can be added to share some of the power dissipation and reduce the ICC's self-heating, the calculation step is provided based on formula (7.11).

$$R_P = (V_{IN(MIN)} - 1{,}4\,V) \div I_{MAX-CHG} \times h_{FE(min)} \tag{7.11}$$

where:

R_P resistor [Ω],

$h_{FE(min)}$ DC current gain.

$$R_P = (31{,}4\,V - 1{,}4\,V) \div 5\,A\,x\,750 = 4500\,\Omega = 4{,}5\,k\Omega$$

Picking 4,64 kΩ resistor from the standard values with 1% tolerance.

Also, the ICC is affected by the minimum and maximum practical charging current. The open-loop gains of the current and voltage loops, and hence the value of the compensation capacitor at the COMP pin. In battery charging applications, dynamic response is not a requirement, and the values of C_{COMP} given below should give stable operation under all conditions. C_{COMP} capacitor is selected with a value of 0,1 µF it is interconnected with R_{COMP} resistor. Value of R_{COMP} is taken from datasheet and equals 470 Ω. These components are in series connected to ground.

7.2.3 Indication circuits

The call of the LED indication circuit is to inform a user of the traction battery charger about working stages and charging modes of the charger in real time. The indication circuit consists of four LEDs:

1. Power ON/OFF status (green),
2. Wrong polarity connection (red),
3. State1 LED (green) which corresponds to Bulk charging mode,
4. State2 LED (orange). Boost mode is initialized after battery is charged to a level of V_{BI} in Bulk charging mode. State2 LED beams simultaneously with State1 LED.

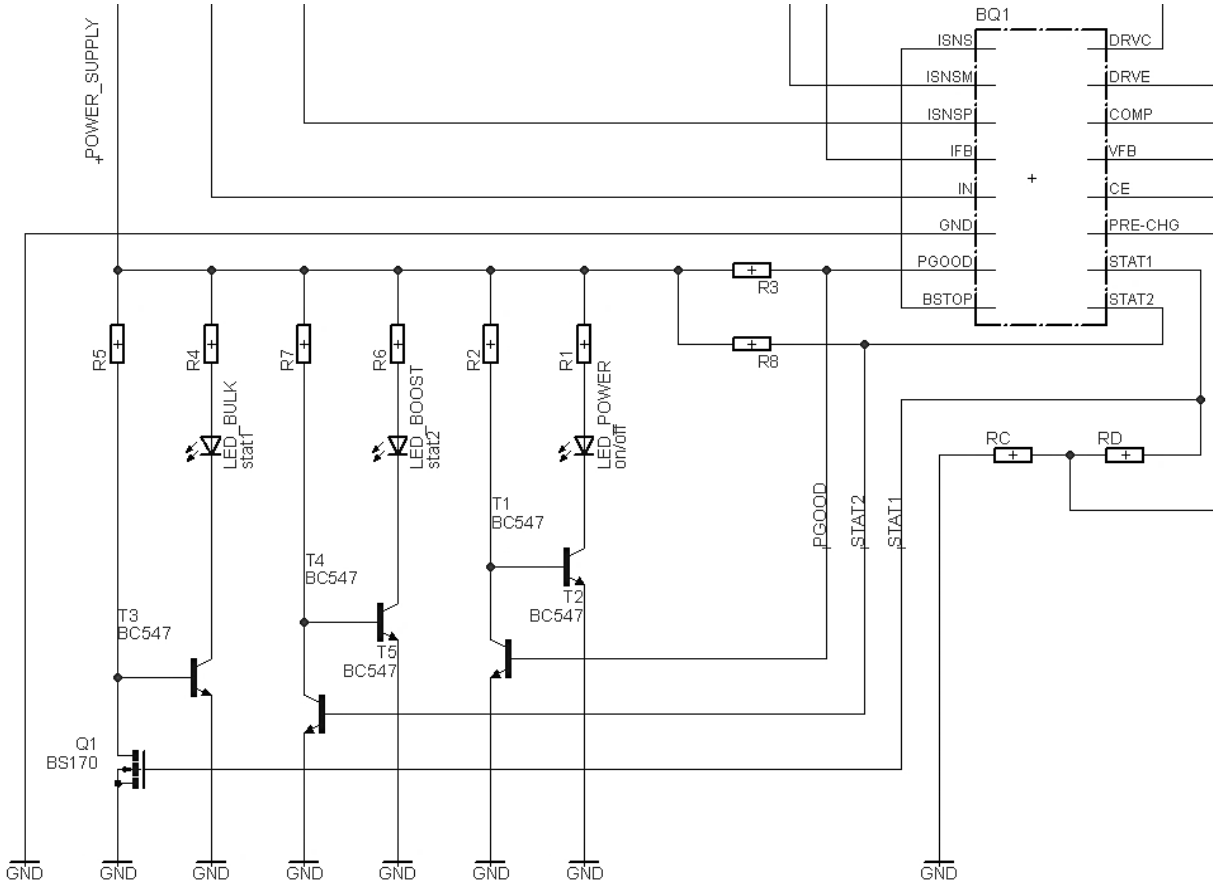


Fig. 7.6 Eagle schematic of LED indication circuits for BQ24450

7.2.4 Output protection

Output protection is necessary to take care of the ICC, when the batteries are going to be connected to the charger, the polarity of the terminals could be connected oppositely then short circuit could occur, so the logic of the battery charger must be protected.

A relay is selected to operate with the reverse-polarity voltage. In this case, a 24 VDC relay for the battery with a reverse voltage of 24 V. An electromagnetic relay Relpol RM50-3011-85-1024 has a very short operation time 10 ms with switching current up to 15 A. When correct polarity is applied to the ICC's terminals, the relay remains off. Then connect the battery terminals opposite to the polarity of the relay, so current flows to the protection circuit. Diode blocks power to the relay, and the protection circuit dissipates no power.

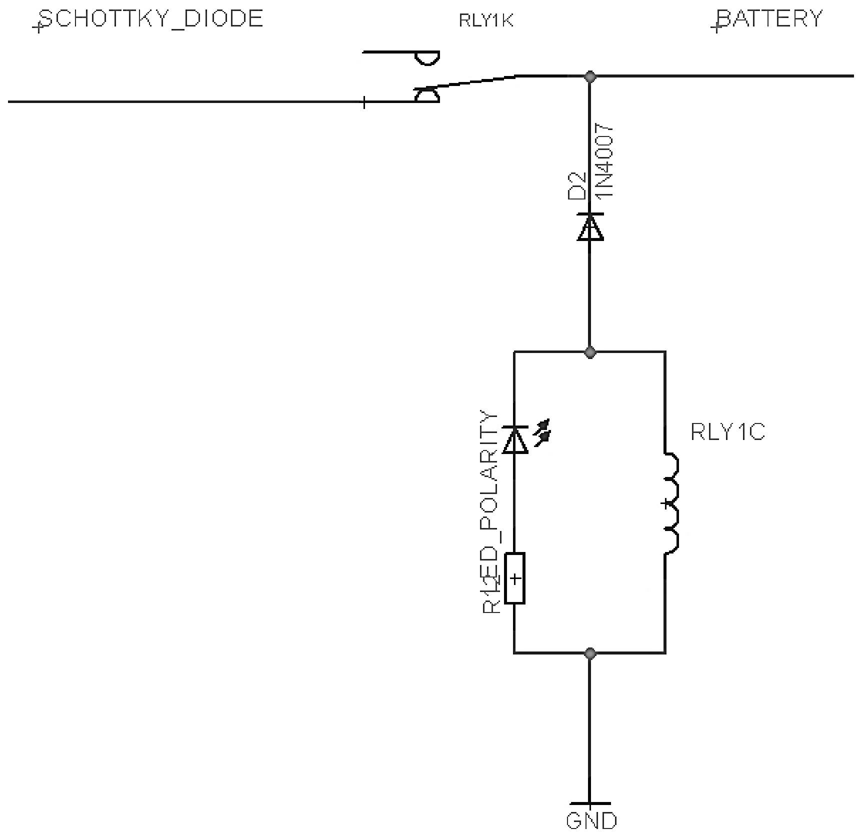


Fig. 7.7 Eagle schematic of relay based protection of BQ24450

8 MANUFACTURING PROCESS

From the previous chapter the values of the desired components were calculated. So the process of designing had been initialized. The defined parts of voltage divider, indication circuit for ICC, external transistor and output protection were processed in electronic design automation (EDA) application called Eagle, developed by Autodesk. This program allows to create a schematic capture of the desired circuitry with further working out of printed circuit board (PCB) layout. The project circuit board for traction battery charger is illustrated on the Fig. 8.1.

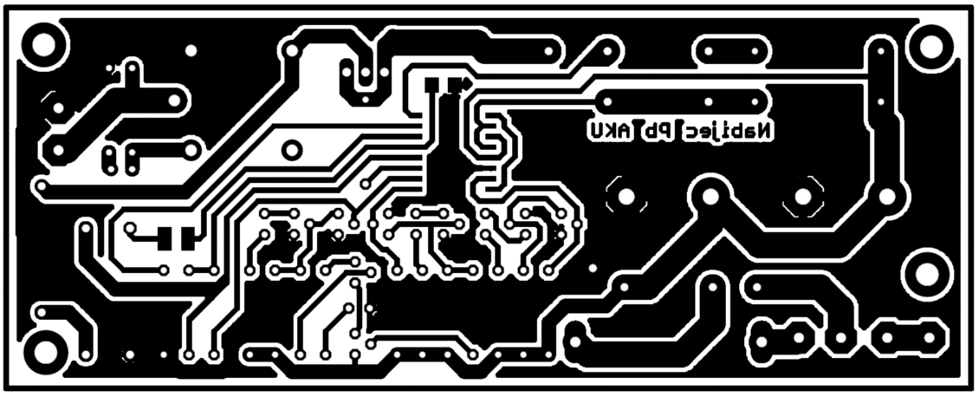


Fig. 8.1 Eagle project in PCB view

After the project was completed, the stage of etching comes. The solution of iron(III) chloride was used to etch the circuitry from the board covered with thin layer of copper. The completed PCB with drilled holes is demonstrated on Fig. 8.2.

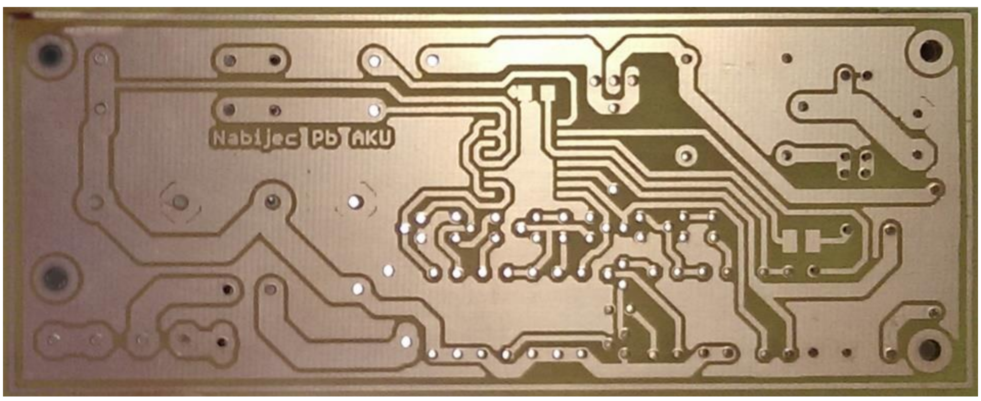


Fig. 8.2 Produced PCB with drilled holes

Most of all components were soldered on the PCB, except transistor and bridge rectifier as they must be fastened on the enclosure's radiators to dissipate power efficiently and extend their life span. To make the charger compact and ready to use all of the circuitry was placed in aluminum enclosure which was taken from the old mechanical facilities used to supply the radio station with electric power. Toroidal transformer was fixed on the rack and

PCB was placed near the transformer. Indicating LEDs were brought out on the same panel with switchers, fuse sockets and cable plug in. On Fig. 8.3 the whole construction is shown, it should be noticed, that toroidal transformer was reeled with additional copper wire but connected in opposite polarity so as to reduce voltage level at the secondary coil. Because when transformer was run idly its output voltage was bigger than absolute maximum input voltage which could cause permanent damage to the ICC. There were 9 loops coiled on the transformer, each loop reduced output voltage for 0,3 V. After all adjustments were completed. The working characteristics were measured in the laboratory tests.

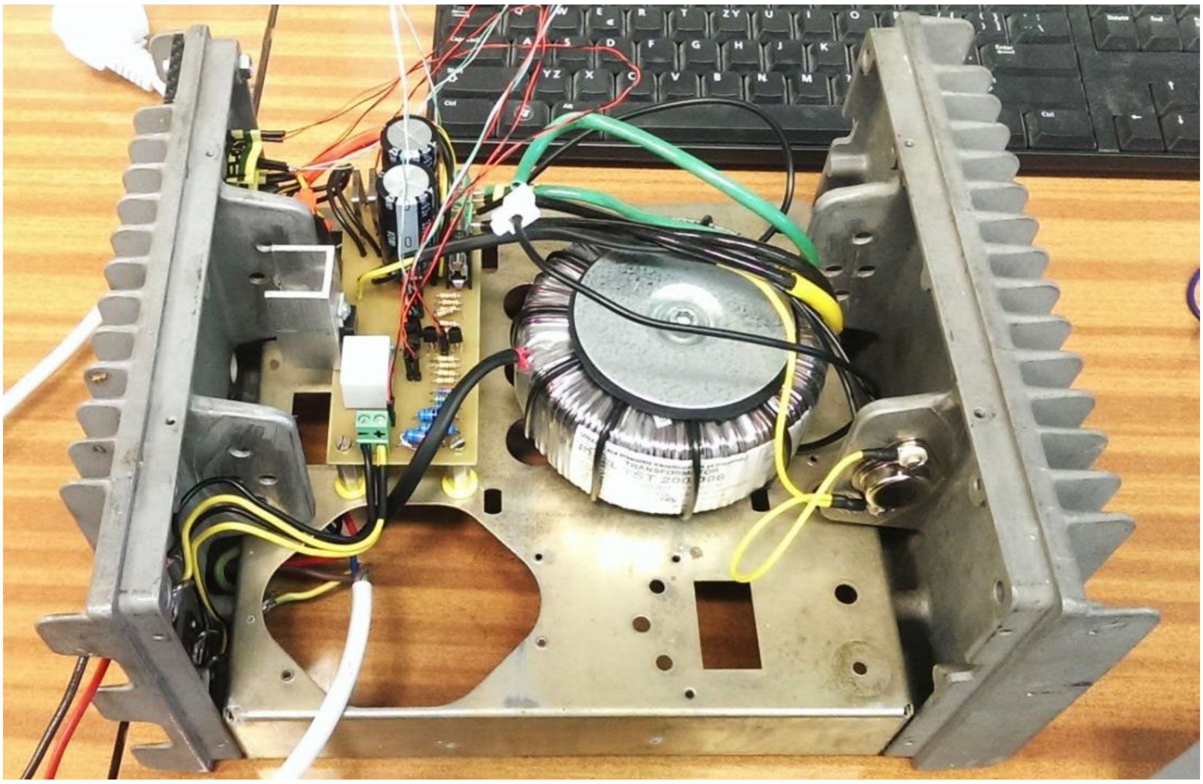


Fig. 8.3 Inside room of an aluminum rack with placed circuitry

9 VERIFICATION OF FUNCTIONALITY AND MEASUREMENTS

The object of the verification of functionality is to compare real measured data with data stated in datasheet. It is needed to understand if the volt ampere characteristics are relatively similar to each other. On the Fig. 9.1 is illustrated circuit diagram for measuring power losses on external transistor Q_{EXT} and Schottky diode D_{EXT}. A thermocouple is attached to a collector of the transistor to measure its heating during charging process.

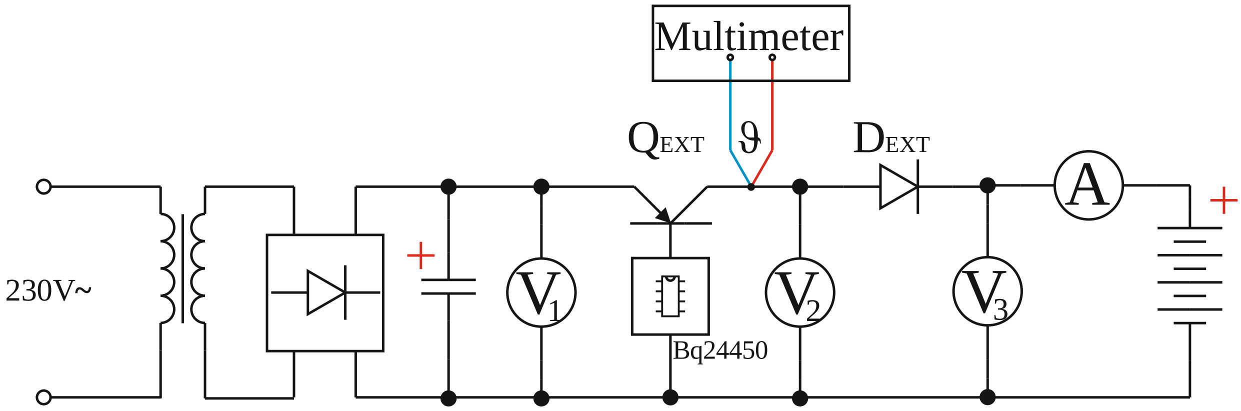


Fig. 9.1 Diagram for laboratory measurements

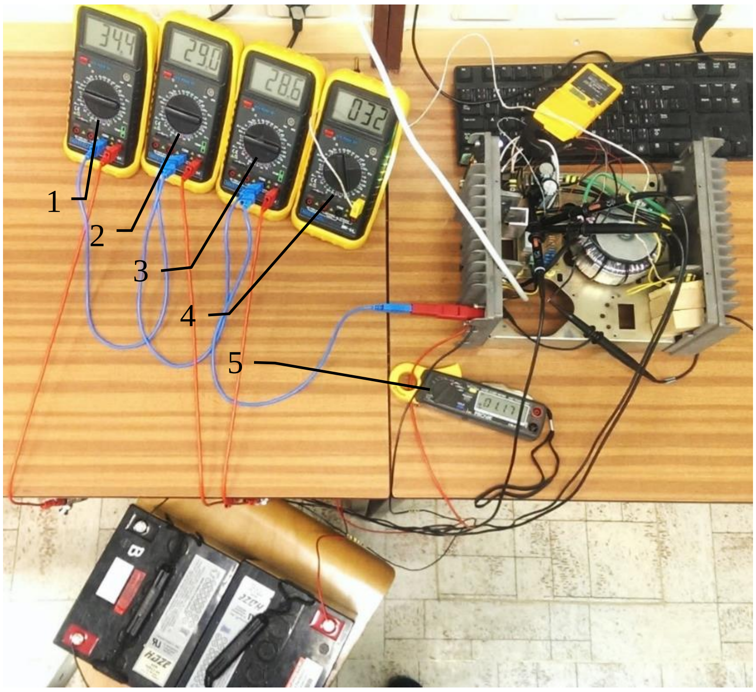
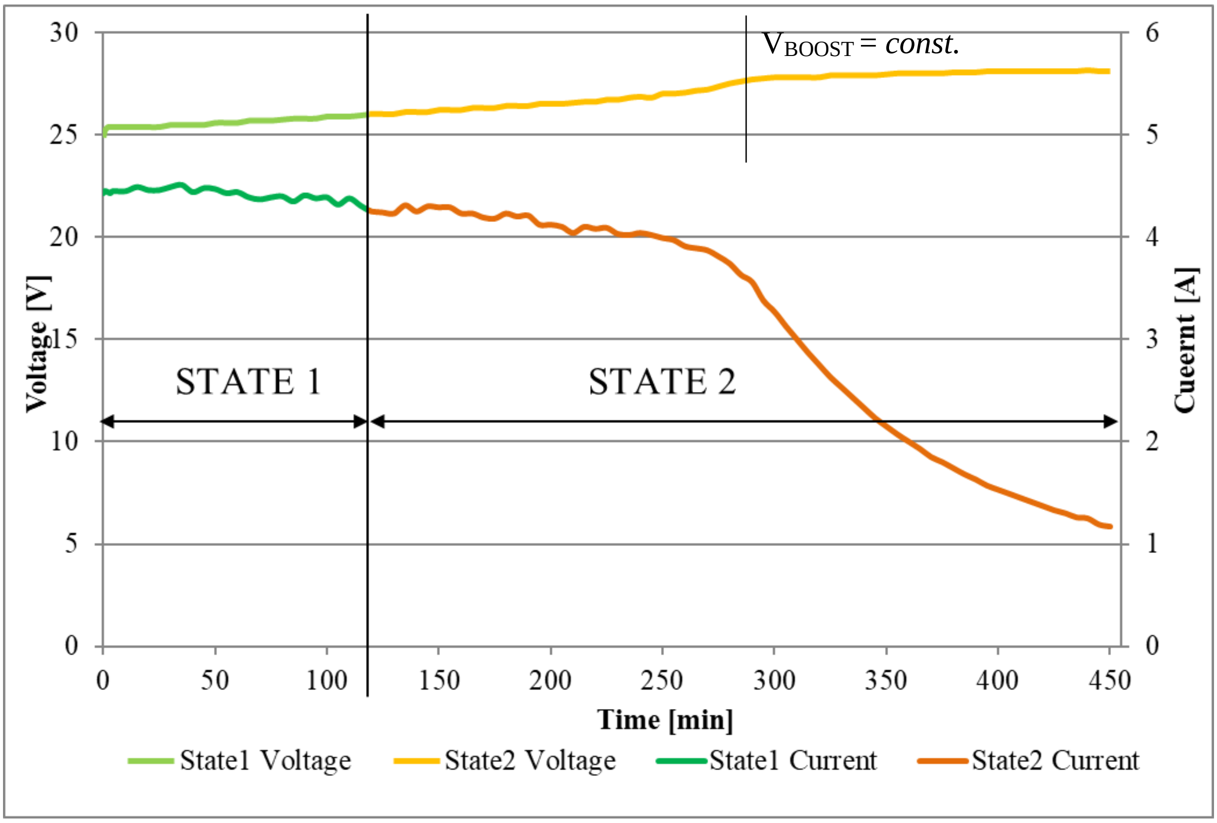


Fig. 9.2 Battery charger in process of measurement

Legend: 1 – Voltmeter#1, 2 – Voltmeter#2, 3 – Voltmeter#3, 4 – thermocouple, 5 – current clamps.

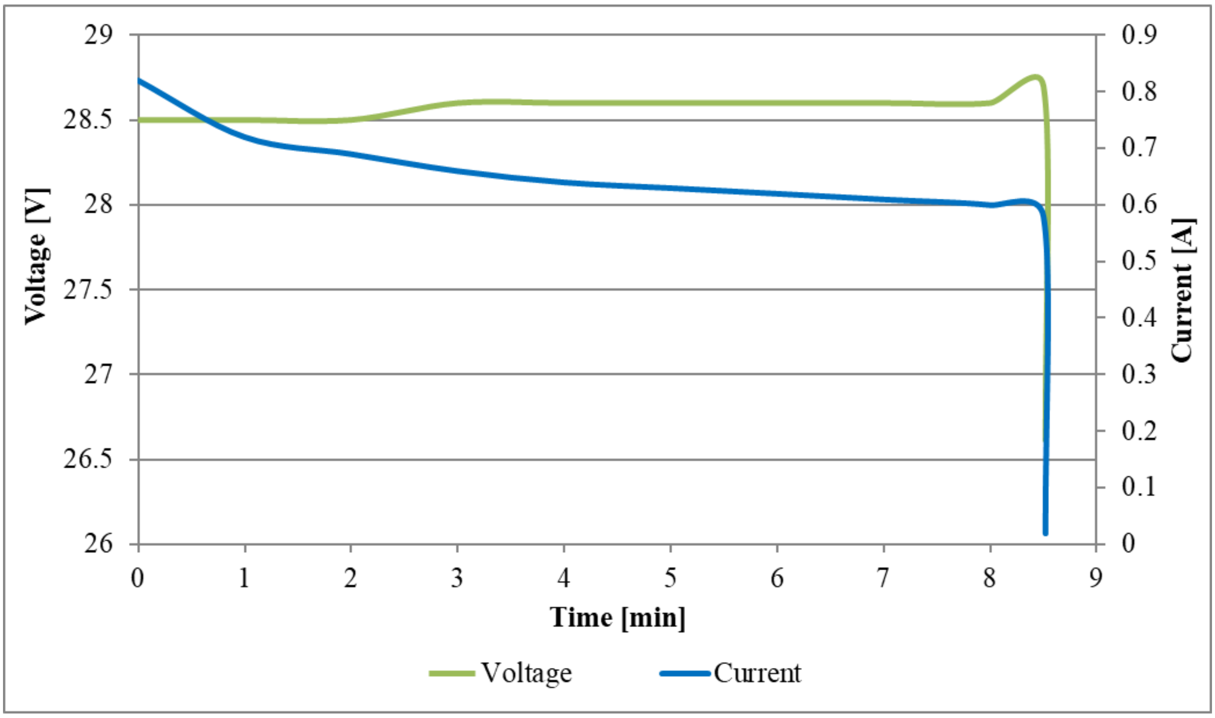
The table of laboratory measurements is attached to the thesis in annex A. Using data from that table the Plot 9.1 was constructed. It represents courses of current and voltage flowing to the battery. The State2 is preceded by State1 which objectify bulk charging mode with maximum charging current. When voltage on the VFB pin exceeds 0,95 V_{REF}, the battery voltage V_{BI} at this point when State2 indicates boost mode. This point is shown on the Plot 9.1 as a vertical line, separating State1 from State2.

As charging proceeds, the voltage at VFB pin increases further to $V_{REF.}$ The voltage regulating amplifier prevents the voltage at the VFB pin from rising further, maintaining the battery voltage at V_{BOOST}. I_{CHG} keeps flowing into the battery. As the battery approaches full charge, the current into the battery decreases, while the battery terminal voltage is maintained at V_{BOOST}.



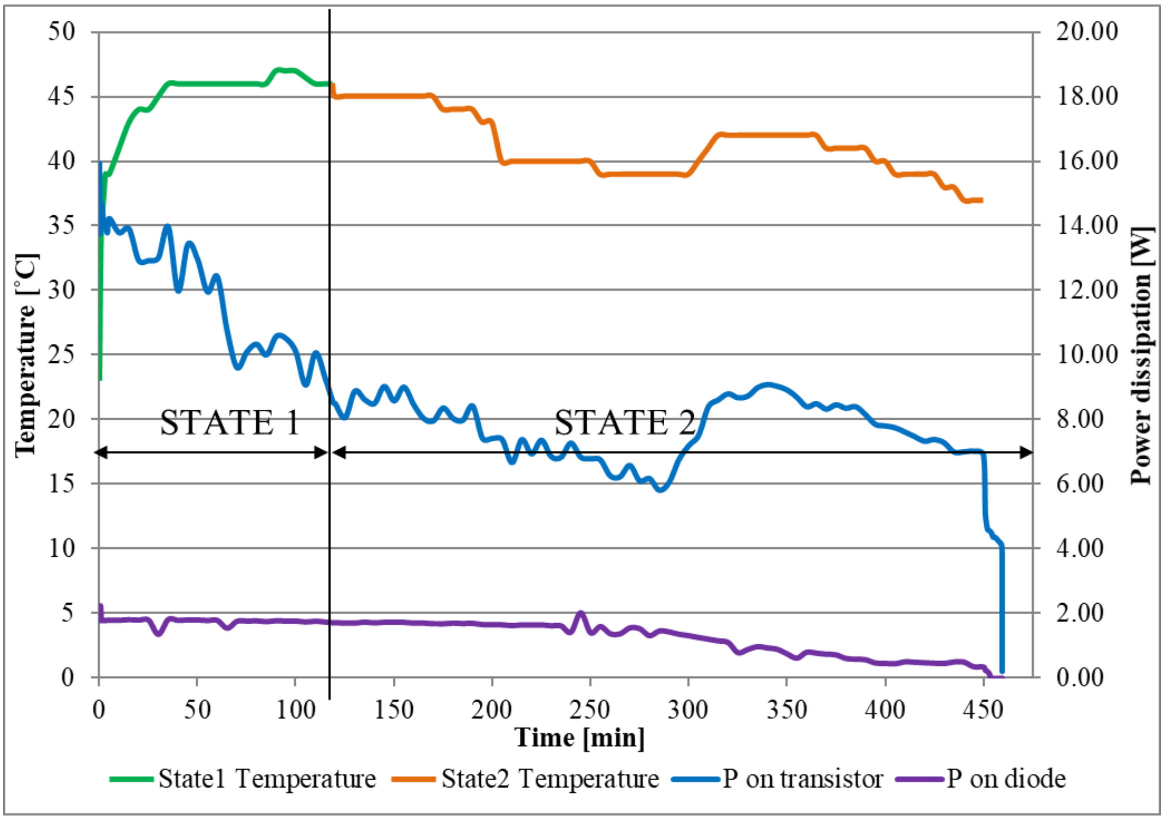
Plot 9.1 Charging characteristics in State1 and State2

Plot 9.2 represents transition between State2 and State3. Float mode is the third level of battery charging mode. The battery is fully charged when the current drops to a low level. The float voltage is reduced. Float charge compensates for self-discharge that all batteries possessed with.



Plot 9.2 Charging characteristics in State2 with transition to State3

Next step is to evaluate the losses of power on external transistor and diode and create a course of warming characteristic using a thermocouple attached to a transistor enclosure which is technically represents collector of the transistor. From the Plot 9.3 it is seen that the dissipated power on the diode is a relatively linear as it forward voltage fluctuates within the boundaries of 0,4 to 0,5 V. Apparent changes are observed when the V_{BOOST} is maintained on its maximum but constant level. As the battery approaches full charge, the current into the battery decreases, thus gradually reduces the load of transformer. The difference of the voltage at the output of power supply and input at the battery increases dramatically. Therefore, the transistor must to sustain the same level of the charging voltage on the collector but holds more of voltage on the emitter which eventually ascends power dissipation. This is why the courses of the temperature and transistor dissipating power have a hilly shape.



Plot 9.3 Warming characteristics

Fig. 9.3 illustrates the heating processes in the charging circuitry. Compared to the temperature of the surrounding environment the most heated parts are transformer as it steps down the voltage from 220 VAC to 28 VAC. Also, there was actively heated fuse installed between transformer and bridge rectifier. This can be solved by selecting fuse with bigger amperage.

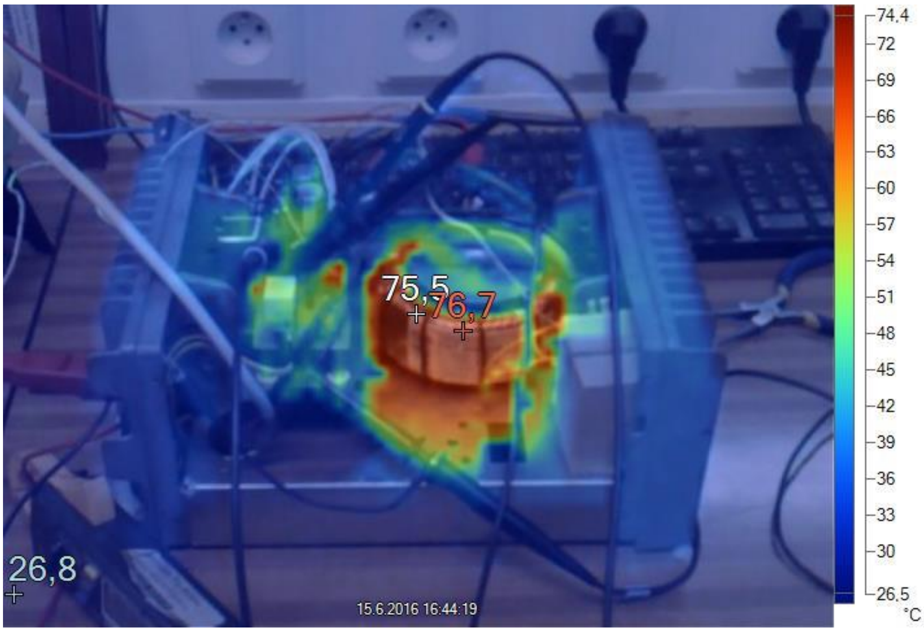
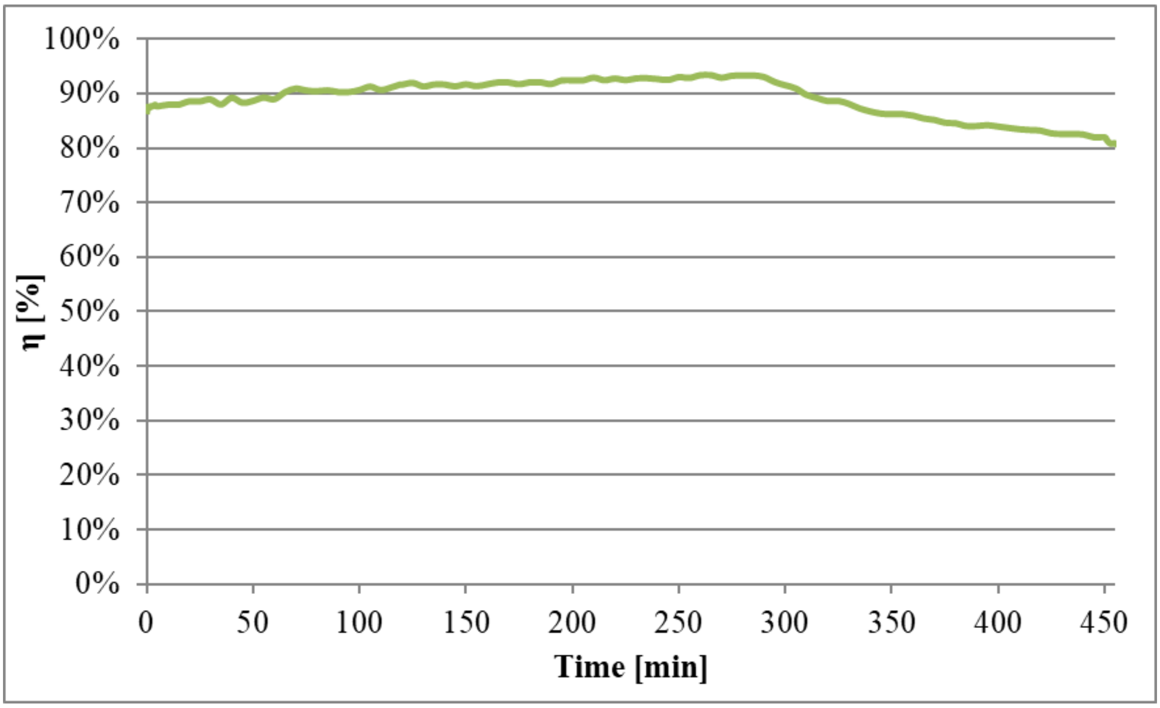


Fig. 9.3 Thermal image of working battery charger

Plot 9.4 represents energy conversion efficiency of the charger it was measured in between the output of the power supplier and battery terminals. The energy conversion efficiency is described separately.



Plot 9.4 Energy conversion efficiency

From the measured data it is possible to calculate the capacity which was charged to the battery. It is proceeded according to formula (9.1).

$$C = \frac{1}{n}\sum_{i=1}^{n}\left(I_{Charge}\right) \cdot t \qquad (9.1)$$

where:

C capacity [A/h],

n number of measured values,

I_{Charge} charging current [A],

t total charging time [h].

$$C = 3{,}495\ A \cdot 450\ min \div 60 = 26{,}215\ Ah$$

The total capacity charged to the battery was 26,2 Ah. Comparing to the nominal capacity of the battery the conclusion is that the battery was not deeply discharged and battery charger just tops up the battery.

The next calculation is almost the same as previous, but it evaluates the added energy, which is now stored in the battery. Energy is calculated as by following (9.2) formula.

$$E = \frac{1}{n}\sum_{i=1}^{n}(V_3) \cdot \frac{1}{n}\sum_{i=1}^{n}(I_{Charge}) \cdot t \qquad (9.2)$$

where:

E energy [W/h],

V_3 voltage [V].

$$E = 26{,}748\ V \ \cdot\ 3{,}495\ A \cdot\ 450\ min \cdot 60 = 2{,}524\ GJ = 0{,}7\ kW/h$$

Total energy provided by traction battery charger is 0,7 kW/h. This value can be used to calculate possible running time of TRV to the next charging.

Energy conversion efficiency of the power supply was not measured altogether with ICC's efficiency. So, this step will provide measurement which gives aggregate picture of efficiency of the charger. Functional diagram of measurement is shown on Fig. 9.4.

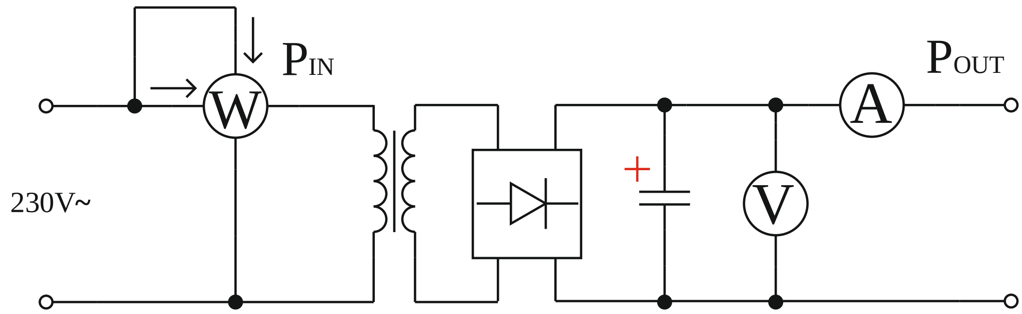


Fig. 9.4 Diagram of power supply for measurement of energy conversion efficiency

Input and output powers of the power supply are calculated in figures (9.3) and (9.4). These values are then divided in the figure (9.5) to get the level of energy conversion of the power supply.

$$P_{Input} = V_{Input} \cdot I_{Input} \qquad (9.3)$$

$$P_{Input} = 240\ V \cdot 0{,}687A = 165\ W$$

$$P_{Output} = V_{Output} \cdot I_{Output} \qquad (9.4)$$

$$P_{Output} = 29{,}5\ V \cdot 4{,}6A = 135{,}7\ W$$

$$\eta_{Power\ supply} = P_{Output} \div P_{Input} \qquad (9.5)$$

$$\eta_{Power\ supply} = 135{,}7\ W \div 165\ W = 0{,}822 = 82{,}2\ \%$$

When the energy conversion efficiency of power supply was defined, it is possible to calculate total efficiency of the traction battery charger, it comes from formula (9.6).

$$\eta_{total} = \eta_{Power\ suply} \times \frac{1}{n} \sum_{i=1}^{n} (\eta_{ICC}) \qquad (9.6)$$

$$\eta_{total} = 0{,}822 \times 0{,}891 = 0{,}732 = 73{,}2\%$$

The last important point of verification of charger's functionality is to evaluate how chosen capacitors filter rectified output DC current. On Fig. 9.5 is shown captured screenshot of filtered DC current.

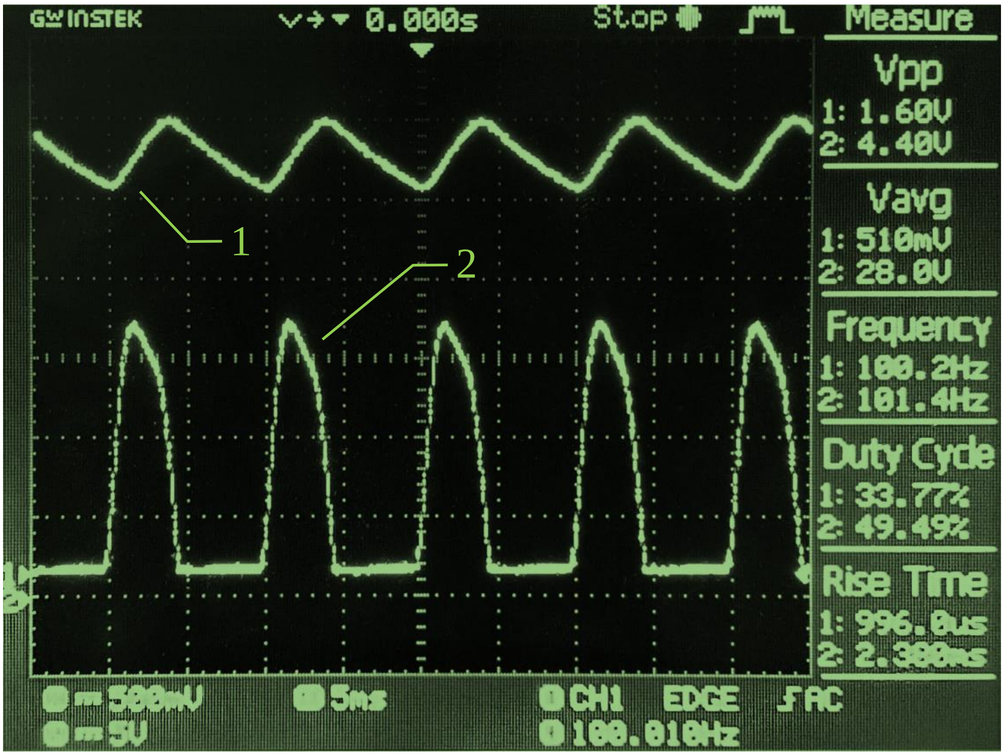


Fig. 9.5 Screenshot from oscillator

Legend: 1 – course of filtered voltage, 2 – course of current.

Formula (9.7) is determined for calculation of waving coefficient.

$$k_{wave} = V_{Peak\ to\ peak} \div V_{AVG\ output} \qquad (9.7)$$

$$k_{wave} = 4{,}4\ V \div 28\ V = 0{,}157 = 15{,}7\ \%$$

In conclusion, from the measurement can be stated, that the ripple factor of 10% which was chosen to smooth voltage is inaccurate for 5,7 %, which is not so much and determined by tolerance of capacitors.

CONCLUSION

In the bachelor thesis I have designed, implemented and verified full functionality of the traction battery charger for the teaching railway vehicle. Whole thesis was divided into two parts, theoretical and practical. In theoretical part of the thesis I have described that the purpose of the battery charger is to supply teaching railway vehicle batteries. After I explained working principles of lead-acid batteries, electrochemistry, types of batteries, construction information and application where they are used. The next chapter provides information about most usable charging characteristics and what topology is commonly is taken to design battery chargers.

Practical part is responsible one. Here was the question how to meet main targets of the thesis — design and assemble traction battery charger. Firstly, I have described and explained functionality of integrated charge controller. Thereafter, main parameters needed for dimensioning and project installation were divided into categories in accordance with their direct purpose and then calculated.

The next step after calculations were completed, manufacturing process was initialized. Printed circuit board was designed, etched and components were soldered on.

The final chapter of the thesis contains evaluation process of efficiency of the battery charger, description of the reached results with advantages of the designed charger.

As a result of the bachelor thesis functional and ready to use battery charger will be used to supply traction batteries. It is assembled, functionality is verified and charging states are switching properly. This charger is a good complement to a laboratory power supply.

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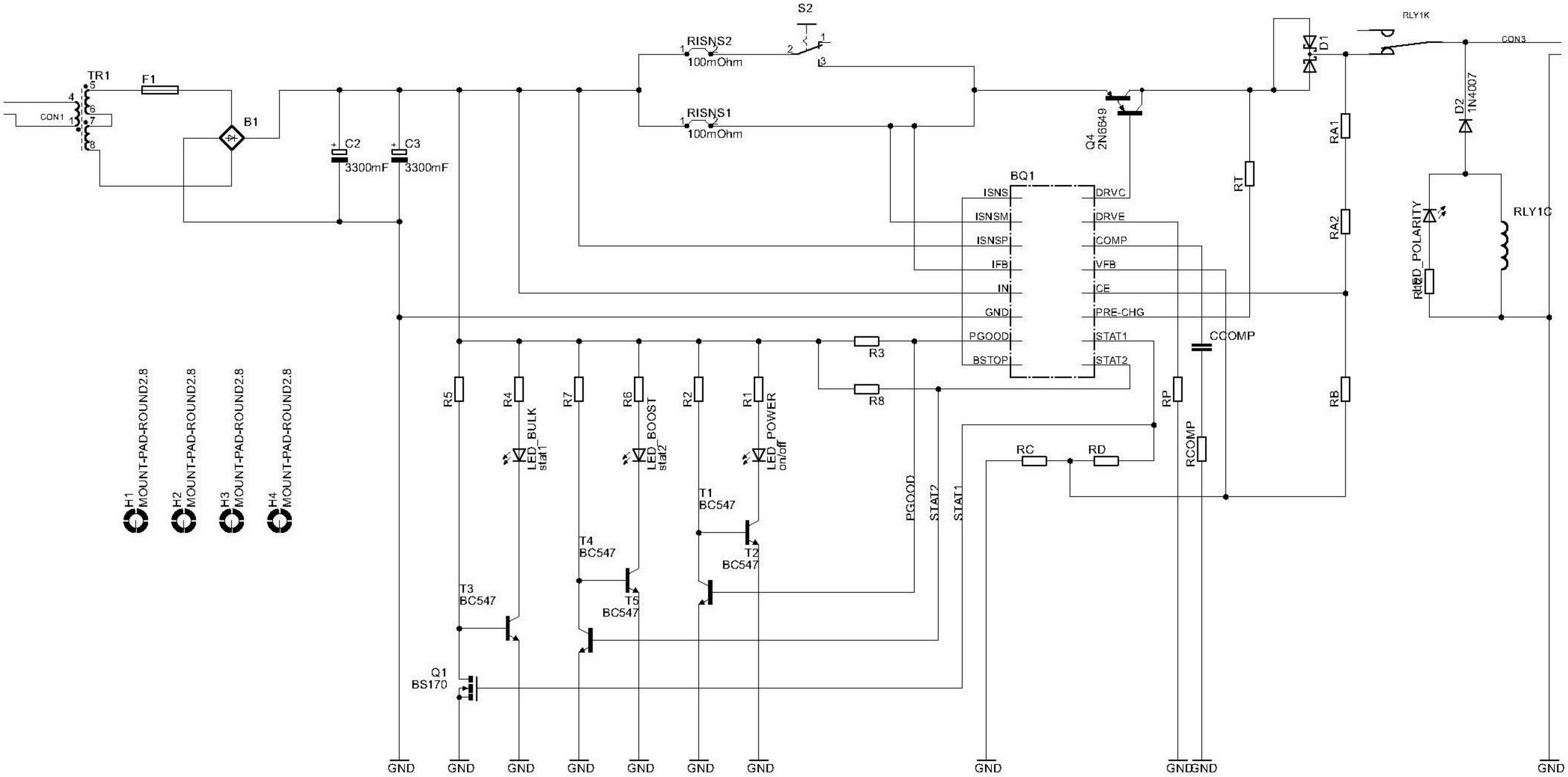
ANNEX A. SCHEMATIC CIRCUIT DIAGRAM OF THE TRACTION BATTERY CHARGER



ANNEX B. TABLE OF LABORATORY MEASUREMENTS

t [min]	U_1 [V]	U_2 [V]	U_3 [V]	T [°C]	I_{Charge} [A]	P_{Qext} [W]	P_{Dext} [W]	P_{input} [W]	P_{output} [W]	η [%]
State1										
0	28.9	25.3	24.9	23	4.43	15.95	1.77	128.03	110.31	86
0.5	28.8	25.7	25.2	31	4.45	13.80	2.23	128.16	112.14	88
1	29	25.7	25.3	35	4.45	14.69	1.78	129.05	112.59	87
2	29	25.8	25.4	37	4.44	14.21	1.78	128.76	112.78	88
3	29	25.8	25.4	39	4.43	14.18	1.77	128.47	112.52	88
4	28.9	25.8	25.4	39	4.45	13.80	1.78	128.61	113.03	88
5	29	25.8	25.4	39	4.45	14.24	1.78	129.05	113.03	88
10	28.9	25.8	25.4	41	4.45	13.80	1.78	128.61	113.03	88
15	28.9	25.8	25.4	43	4.49	13.92	1.80	129.76	114.05	88
20	28.7	25.8	25.4	44	4.46	12.93	1.78	128.00	113.28	89
25	28.7	25.8	25.4	44	4.46	12.93	1.78	128.00	113.28	89
30	28.7	25.8	25.5	45	4.49	13.02	1.35	128.86	114.50	89
35	29	25.9	25.5	46	4.51	13.98	1.80	130.79	115.01	88
40	28.6	25.9	25.5	46	4.44	11.99	1.78	126.98	113.22	89
45	28.9	25.9	25.5	46	4.48	13.44	1.79	129.47	114.24	88
50	28.9	26	25.6	46	4.47	12.96	1.79	129.18	114.43	89
55	28.7	26	25.6	46	4.43	11.96	1.77	127.14	113.41	89
60	28.8	26	25.6	46	4.44	12.43	1.78	127.87	113.66	89
65	28.5	26.05	25.7	46	4.39	10.76	1.54	125.12	112.82	90
70	28.3	26.1	25.7	46	4.37	9.61	1.75	123.67	112.31	91
75	28.4	26.1	25.7	46	4.39	10.10	1.76	124.68	112.82	90
80	28.5	26.15	25.75	46	4.4	10.34	1.76	125.40	113.30	90
85	28.5	26.2	25.8	46	4.35	10.01	1.74	123.98	112.23	91
90	28.6	26.2	25.8	47	4.41	10.58	1.76	126.13	113.78	90
95	28.6	26.2	25.8	47	4.38	10.51	1.75	125.27	113.00	90
100	28.6	26.3	25.9	47	4.39	10.10	1.76	125.55	113.70	91
105	28.4	26.3	25.9	46.5	4.32	9.07	1.73	122.69	111.89	91
110	28.6	26.3	25.9	46	4.38	10.07	1.75	125.27	113.44	91
115	28.5	26.35	25.95	46	4.31	9.27	1.72	122.84	111.84	91
State2										
119	28.4	26.4	26	46	4.26	8.52	1.70	120.98	110.76	92
120	28.4	26.4	26	45	4.25	8.50	1.70	120.70	110.50	92
125	28.3	26.4	26	45	4.24	8.06	1.70	119.99	110.24	92
130	28.5	26.4	26	45	4.23	8.88	1.69	120.56	109.98	91
135	28.5	26.5	26.1	45	4.31	8.62	1.72	122.84	112.49	92
140	28.5	26.5	26.1	45	4.25	8.50	1.70	121.13	110.93	92
145	28.6	26.5	26.1	45	4.3	9.03	1.72	122.98	112.23	91
150	28.6	26.6	26.2	45	4.29	8.58	1.72	122.69	112.40	92
155	28.7	26.6	26.2	45	4.29	9.01	1.72	123.12	112.40	91
160	28.6	26.6	26.2	45	4.23	8.46	1.69	120.98	110.83	92
165	28.6	26.7	26.3	45	4.23	8.04	1.69	120.98	111.25	92

170	28.6	26.7	26.3	45	4.19	7.96	1.68	119.83	110.20	92
175	28.7	26.7	26.3	44	4.18	8.36	1.67	119.97	109.93	92
180	28.7	26.8	26.4	44	4.23	8.04	1.69	121.40	111.67	92
185	28.7	26.8	26.4	44	4.2	7.98	1.68	120.54	110.88	92
190	28.8	26.8	26.4	44	4.21	8.42	1.68	121.25	111.14	92
195	28.7	26.9	26.5	43	4.12	7.42	1.65	118.24	109.18	92
200	28.7	26.9	26.5	43	4.12	7.42	1.65	118.24	109.18	92
205	28.7	26.9	26.5	40	4.1	7.38	1.64	117.67	108.65	92
210	28.6	26.95	26.55	40	4.04	6.67	1.62	115.54	107.26	93
215	28.8	27	26.6	40	4.1	7.38	1.64	118.08	109.06	92
220	28.7	27	26.6	40	4.08	6.94	1.63	117.10	108.53	93
225	28.9	27.1	26.7	40	4.09	7.36	1.64	118.20	109.20	92
230	28.8	27.1	26.7	40	4.03	6.85	1.61	116.06	107.60	93
235	28.9	27.2	26.8	40	4.02	6.83	1.61	116.18	107.74	93
240	29	27.2	26.85	40	4.04	7.27	1.41	117.16	108.47	93
245	29	27.3	26.8	40	4.02	6.83	2.01	116.58	107.74	92
250	29.05	27.35	27	40	3.99	6.78	1.40	115.91	107.73	93
255	29.1	27.4	27	39	3.97	6.75	1.59	115.53	107.19	93
260	29	27.4	27.05	39	3.91	6.26	1.37	113.39	105.77	93
265	29.1	27.5	27.15	39	3.89	6.22	1.36	113.20	105.61	93
270	29.3	27.6	27.2	39	3.87	6.58	1.55	113.39	105.26	93
275	29.35	27.75	27.35	39	3.81	6.10	1.52	111.82	104.20	93
280	29.5	27.85	27.5	39	3.74	6.17	1.31	110.33	102.85	93
285	29.6	28	27.6	39	3.63	5.81	1.45	107.45	100.19	93
290	29.8	28.1	27.7	39	3.56	6.05	1.42	106.09	98.61	93
295	30.15	28.15	27.75	39	3.38	6.76	1.35	101.91	93.80	92
300	30.4	28.2	27.8	39	3.27	7.19	1.31	99.41	90.91	91
305	30.6	28.2	27.8	40	3.13	7.51	1.25	95.78	87.01	91
310	31	28.2	27.8	41	3	8.40	1.20	93.00	83.40	90
315	31.2	28.2	27.8	42	2.87	8.61	1.15	89.54	79.79	89
320	31.4	28.2	27.8	42	2.75	8.80	1.10	86.35	76.45	89
325	31.5	28.2	27.9	42	2.63	8.68	0.79	82.85	73.38	89
330	31.7	28.25	27.9	42	2.53	8.73	0.89	80.20	70.59	88
335	32	28.3	27.9	42	2.43	8.99	0.97	77.76	67.80	87
340	32.2	28.3	27.9	42	2.33	9.09	0.93	75.03	65.01	87
345	32.35	28.3	27.9	42	2.23	9.03	0.89	72.14	62.22	86
350	32.45	28.3	27.95	42	2.15	8.92	0.75	69.77	60.09	86
355	32.5	28.3	28	42	2.07	8.69	0.62	67.28	57.96	86
360	32.6	28.4	28	42	2	8.40	0.80	65.20	56.00	86
365	32.8	28.4	28	42	1.93	8.49	0.77	63.30	54.04	85
370	32.9	28.4	28	41	1.85	8.33	0.74	60.87	51.80	85
375	33.1	28.4	28	41	1.8	8.46	0.72	59.58	50.40	85
380	33.2	28.4	28.05	41	1.74	8.35	0.61	57.77	48.81	84
385	33.4	28.4	28.05	41	1.68	8.40	0.59	56.11	47.12	84
390	33.4	28.4	28.05	41	1.63	8.15	0.57	54.44	45.72	84

395	33.4	28.4	28.1	40	1.57	7.85	0.47	52.44	44.12	84
400	33.5	28.4	28.1	40	1.53	7.80	0.46	51.26	42.99	84
405	33.6	28.4	28.1	39	1.49	7.75	0.45	50.06	41.87	84
410	33.7	28.45	28.1	39	1.45	7.61	0.51	48.87	40.75	83
415	33.75	28.45	28.1	39	1.41	7.47	0.49	47.59	39.62	83
420	33.8	28.45	28.1	39	1.37	7.33	0.48	46.31	38.50	83
425	34	28.45	28.1	39	1.33	7.38	0.47	45.22	37.37	83
430	34.05	28.45	28.1	38	1.3	7.28	0.45	44.27	36.53	83
435	34.05	28.5	28.1	38	1.26	6.99	0.50	42.90	35.41	83
440	34.15	28.55	28.15	37	1.25	7.00	0.50	42.69	35.19	82
445	34.3	28.4	28.1	37	1.19	7.02	0.36	40.82	33.44	82
450	34.3	28.4	28.1	37	1.17	6.90	0.35	40.13	32.88	82