Low Cost PLC Uninterrupted Power Supply for use on AGVs with a Removable Battery Banks

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***Abstract*—When it comes to electrical AGVs, downtime due to charging batteries is a significant hurdle. This is often dealt with in numerous ways; including opportunistic charging, mobile charging, quick charging, etc. This paper will focus on the difficulties of using exchangeable "power units", which entails making the entire battery system (including the battery management system) removable from the host machine. This eliminates downtime, due to charging, as the entire power plant is replaced with a "fresh" one. The depleted power unit can then be recharged at a sustainable (from a battery lifespan perspective) rate. The major disadvantage of this strategy is that with the power plant removed from the AGV, all control systems are unpowered thus deactivated. Hence the focus of this paper on creating a "control system UPS" to keep the control systems powered even when the main power unit is down and thus solving one of the major problems with a removable battery system.**

Keywords—DC UPS, UPS, Uninterrupted Power Supply, AGV, Automatic Guided Vehicle, Lead Acid, Battery

I. INTRODUCTION

An Automatic Guided Vehicle (AGV) is an intelligent self-driving vehicle used to perform repetitive fetch, carry and deposit tasks in industry. These machines often use electrical power trains as opposed to more traditional internal combustion engines (ICs), due to concerns about greenhouse gasses and newer European Union laws[1]. The use of an electrical power train has quite a few advantages over IC systems such as a lower carbon footprint (provided the electricity is cleanly sourced) and fewer mechanical components (most electrical motors consist of primarily a rotor and some form of commutation ring as their only moving parts, compared to the hundreds of moving parts of an IC engine)[2]. There are however some disadvantages, the most prominent and the one focused on in this paper, is that of the charge time of the system's batteries[3]. The recharge time of such a system using batteries is excessively long when compared to the near instantaneous "recharge" of an IC engine (which simply requires its fuel supply to be topped up). There are numerous proposed solutions to deal with this issue some include:

- Opportunistic charging – Charging while the AGV is performing a stationary task [3]
- Mobile charging – Using special lanes/tracks between nodes that have a charging system integrated for in-motion charging [4]
- Quick charging – Using super capacitors to store a massive instantaneous charge and slowly charge the batteries with this energy during operation [5]
- Wireless Charging – A possible future technology (currently range to small ~1m in ideal circumstances) [6]
- Exchangeable power units – Battery and battery management system removable from host machine [7]

The AGV that this paper will focus on will implement a number of these strategies however this paper will specifically focus on the last point "exchangeable power units" and the difficulties they introduce; specifically the loss of power the host system, AGV, will experience when the main power unit is removed.

II. JUSTIFICATION

The implementation of the removable "power module" (battery and battery management system (BMS)) has already been implement on the subject AGV. The problem is keeping the control system active when the main power bank is removed. The main control system must be active when the AGV is exchanging batteries for the following reasons. Firstly, the AGV must continually communicate to a higher control network. Secondly, the AGV takes part in the "power module" exchange action; by locking the battery bank in place and closing a solid-state relay that allows power to flow to the rest of the system. Lastly, the AGV has an onboard Industrial PC (IPC), these systems state time to reboot (5 to 10 minutes) and can easily be damaged it power is suddenly cut [8].

III. SYETEM OVERVIEW

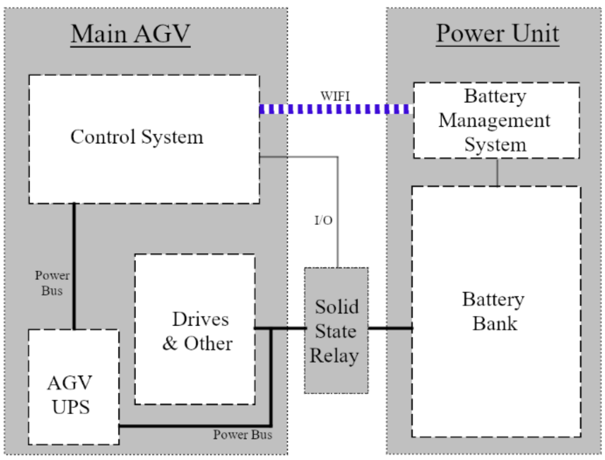

fig. 1. AGV and Power Unit Layout

As illustrated in fig. 1, the AGV is broken into two parts, the "main AGV" and the "power unit. Power is transferred to the "main AGV" from the "power unit" via a solid-state relay. The purpose of the solid ate relay is to prevent arcing on the power unit's terminals during battery exchange. The relay is controlled by the AGV's control system. All communication between the battery management system (BMS) and AGV control system is done via WIFI communication to reduce the number of physical connections. fig. 1 also clearly indicates the position of the uninterrupted power supply (UPS) on the main AGV's body. It is to be noted that when the AGV is exchanging batteries the main drive chain and any auxiliary electronics will be unpowered.

IV. AGV PLC UPS REQUIREMENTS

Since this UPS system is supply power to a Programmable Logic Controller (PLC), Siemens Industrial PC (IPC) and industry standard distributed peripherals (DP) The UPS will need to provide a nominal voltage of 24 Vdc however this can vary between 19.2 Vdc and 28.8 Vdc [9], which is the tolerable range of the Siemens range of equipment used for the AGV control system.

The largest concern for this UPS is cost. Ideally this system should be as cost effective as possible. Originally an off-the shelf unit was to be used, an example of this is the TRACOPOWER TSP-BCMU360, which is available from RS Components. At the time of creating this design the cost of this unit was R 3,347.86, this price excludes batteries [10].

Ideally this system should have only one battery attached to it. Since 24 Vdc batteries do exist, this battery would seem like the ideal choice; however, they tend to be cost prohibitive to implement when compared to using two 12 Vdc batteries, this is illustrated in TABLE I.

TABLE I. BATTERY COST FROM NELSON MANDELA UNIVERSITY SUPPLIERS

Battery Type	**Battery Cost Analysis**			
	Supplier	***Number of Batteries Needed to make 24V @ 7Ah***	***Single Battery Cost[a]***	***Total Cost to Implement 24VDC @ 7Ah***
24VDC 7Ah	RS Components[10]	1	R 6,364.58	R 6,364.58
12VDC 7Ah	RS Components	2	R 435.33	R 870.66
24VDC 4.5 Ah	Mantech[11]	2	R 487.36	R 974.72
12VDC 7Ah	Mantech	2	R 179.52	R 359.04

a. Prices taken September 2019

Thus, it was decided to use two 12 Vdc batteries rated at 7 Ah to give at total rating of 24 Vdc @ 7 Ah when in series as opposed to the 24 Vdc equivalent. Although it is possible to use a 12 Vdc battery and boost the DC voltage up to the required 24 Vdc, this strategy was decided against due to the added complexity a buck-boost converter would add.

The next concern for the system, is the total load drawn from the battery and the length of time the backup battery will last for. This was determined by first calculating the total load of the system when in the low powered "power module" removal state (i.e. what systems are active during this state) then comparing maximum allowable current draw of the batteries.

TABLE II below excludes any system not active or **not in use** during the power module removal state as many of the distributed I/O output systems can still be theoretically driven during this state from the UPS, however would quickly max out the UPS's current limit. These I/O will be software interlocked to prevent operation during the "power module" removal state.

TABLE II. POWER CONSUMPTION DURING LOW POWER STATE[B]

Item	**Power Usage**		
	Current Draw (A)	***Quantity***	***Total Current***
Siemens S7-1500 PLC	0.6A	1	0.6A
Siemens Ditrabuted I/O Inputs	0.09A	16 total (4 modules)	0.36A
Siemens Distrabuted I/O Outputs	0.5A	6 total (4 modules)	3A
SICK Saftey PLC	0.3	1	0.3A
Siemens IPC (max)	4A	1	4A
Battery Bank Eject Motor **(not connected through UPS only to UPS battery)**	4A	1	4A

B. Data taken from Siemens[12] and Sick[13] website

Thus, from TABLE II the total power drawn by the control system during the low power state through the UPS is 8.26 A, while an additional 4 A will be drawn directly from the UPS batteries for the "power module" eject system motor. The eject motor does not need to have uninterrupted power characteristics as it will only operate when the AGV's main "power module" is disconnected.

It was decided that in a worst-case scenario, where a manual battery exchange occurs, the maximum amount of time that the main "power module would be disconnected from the core AGV would be no longer than 5 minutes. Thus, the UPS battery should be able the sustain a maximum current of 12.26 A (sum of UPS draw of 8.26 A and eject motor draw of 4 A) for at least 5 minutes.

The battery selected to make up the UPS battery bank was thus a RITAR RT1270B. Two of these batteries in series would produce a 24 V battery bank of 7 Ah. Since these are lead acid batteries it is not recommended to discharge the batteries at a C_{rate} value higher than 4 [14]. The C_{rate} value of a battery relates its discharge current to its total capacity, see (1):

$$I_{discharge} = C_{rate}C \quad (1)$$

Where $I_{discharge}$ is the discharge current in amperes (A) and C is the capacity of the battery in amp-hours (Ah).

The RT1270B can provide the needed current of 12.26 A if a C_{rate} of 2 is used (At $2C_{rate}$ the discharge is 14 A). Shown in fig. 2 (Note the $2C_{rate}$ is estimated as a line of best fit) the battery will reach a voltage of 11.5 Vdc at approximately 7.02 minute mark. 11.5 Vdc is chosen as the cutoff voltage (i.e. battery is "flat") as this corresponds to a depth of discharge (DoD) of 50% for this battery (see fig. 3), which for lead acid batteries is often stated as the best compromise between total lifespan and usable capacity[15].

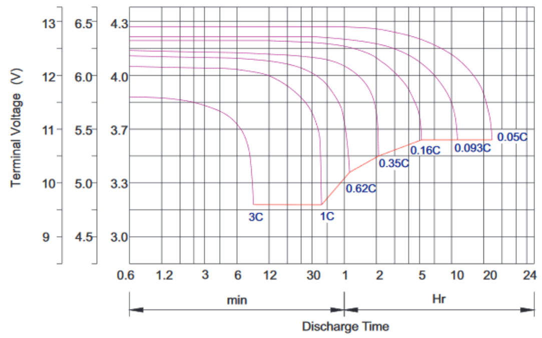

fig. 2. RT1270B Discharge Characteristic Curve[16]

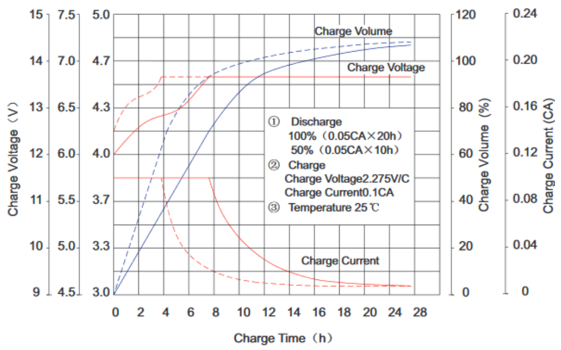

fig. 3. RT1270B Charge Characteristic Curve[16]

As for the UPS the industry standard for switching speed seems to be between 3 ms and 10 ms. Though there are "high efficiency double conversion" UPS's that take between 1 ms and 3 ms to switch in [17]. Thus, ideally the UPS should be able to switch over faster than 8 ms.

V. Working Principal Of The UPS

Since this UPS is operating on a DC system a redundant DC power supply topography [18] can be used. The principal of operation of this system is shown below, in fig. 4.

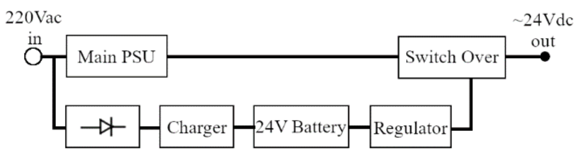

fig. 4. Block Diagram Operation of UPS System

As illustrated in fig. 4, the AGV does contain a 220 Vac bus. This is generated by an inverter from the main "power module". The inclusion of this AC bus simplifies matters considerably when generating multiple, high current, DC voltages, eliminating the need for DC-DC converters. When the main "power module" is present in the AGV the 24 Vdc is generated for the control systems via a standard AC to DC power supply unit (Main PSU) at the same time the backup battery for the system (24 V Battery) is charged. When the "power module" is removed from the AGV the 230 Vac with shut off, at this point the backup battery will be switched in (Switch Over) automatically. The voltage generated by the backup battery will be regulated by a regulator, see fig. 4, to ensure it voltage is stable.

VI. Working Principal Of The UPS

The UPS system was designed with the aid of National Instruments Multisim 12.0 and consists of the following parts:

- Charger
- Regulator
- Switch Over

A. Charger

The charger is a constant current type charger and. This means that the charger's current fed to the battery is uniform regardless of the battery's voltage. This strategy is ideal as a low-cost strategy for charging battery's that are cyclically discharged and have a relatively long recharge time available [19]. Constant current charging also has the advantage of significantly reducing the imbalance charge state of cells, when compared to other charging strategies. This also reduces the need for a BMS on the backup battery bank which would add extra cost and complexity to the system [20].

To achieve the afore mentioned goals the LM317 variable voltage regulator from Texas Instruments was used with a Fairchild BC547B NPN transistor. A reference circuit for a constant current lead acid battery is provided for in the LM317 documentation and is illustrated in fig. 5.

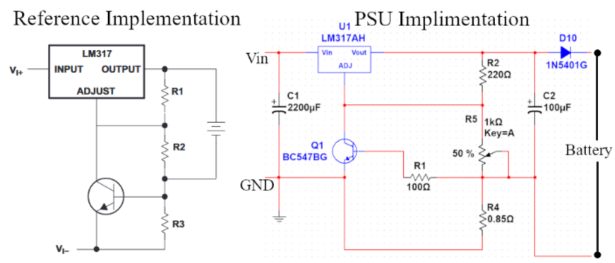

fig. 5. Implementation of The LM317 as a Current-Limited Charger

fig. 5 shows the reference implementation of the LM317 as current limited charger along with the implementation in the AGVs PSU circuit. In the PSU Implementation (all component labels will refer to the PSU implementation) resistor R2 and potentiometer R5 are used to set the charging voltage for the system. Ideally this will be calibrated to 30 Vdc, the battery will only see 28.8 Vdc due to the 1.2 V drop over D10, this will correspond to a cell charge voltage of 2.4 V (for a 24 V system).

The constant current value is set using resistor R4 which at 0.45Ω corresponds to a charging current of 1.37 A. This charging current is approximately equal to the 0.2C (or 0.2*7Ah = 1.4A) recommended by the RT1270B data sheet.

Constant current charging is achieved as follows. If the current through R4 increases, the resultant voltage over the resistor will increase. As this voltage approaches 0.7 V, the base to emitter junction of transistor Q1 will begin to conduct. This effectively reduces the resistance of R5 by sinking extra current from the adjustment pin of the LM317 voltage regulator (U1) and thus lowers the output voltage of the regulator to maintain a constant current over the battery.

The capacitor C1 is used as smoothing capacitor from the bridge rectifier, it is also needed by the voltage regulator to maintain stability. C2 is used to improve transient response.

B. Regulator

The regulator portion of the UPS is used to maintain a constant voltage output to the control system. This is necessary as the voltage of the battery will vary with its level of charge.

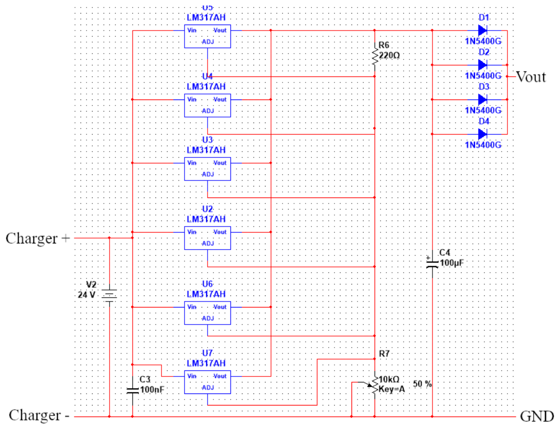

fig. 6. UPS Regulation Circuit

The regulation circuit of UPS system, fig. 6, relies on a parallel array of LM317 variable voltage regulators. The parallelization is done to increase the maximum current that can be drawn from the system the LM317 has a maximum output current rating of 1.5 A. Thus 6 in parallel will be able to provide 9 A in total. This exceeds the 8.26 A needed by the system by 8.2%. The output voltage of the regulator bank and is set to 21 V using resistors R6 and R7. This value corresponds to 2 V less than the minimum battery voltage (when at 50% DoD) of 23 V. The regulators cannot be set at 23 V as the regulators have a voltage minimum differential of 2 V between Vin and Vout. Once the current has flown through Schottky diodes D1 to D4, the voltage will drop to 20.475 V. This is still within the tolerable range of the components in the control system.

C. Switch Over

Due to the inclusion of the Schottky diodes D1 to D4 in fig. 6, the UPS can be directly attached to the control system, with the diodes acting as the changeover as the 21 V at the diodes will always be reverse biased against the main PSU's 24 V. Thus, changeover will occur when the voltage from the main PSU drop to zero and diodes D1 to D4 become forward biased.

D. Full Schemtic

The full schematic diagram of the AGV UPS system can be found in fig. 7. The AC to DC rectification is done using a 230 Vac to 35 Vac (T1), full bridge rectifier consisting of four 1N5401 (D6 to D9) which can provide 3 A to the battery charger circuit. Smoothing of the half wave AC produced by the bridge rectifier is done using a 2200 uF electrolytic capacitor. This produces peak of ~47.94 V a minimum of ~47.91 V with a ripple of 3 mV.

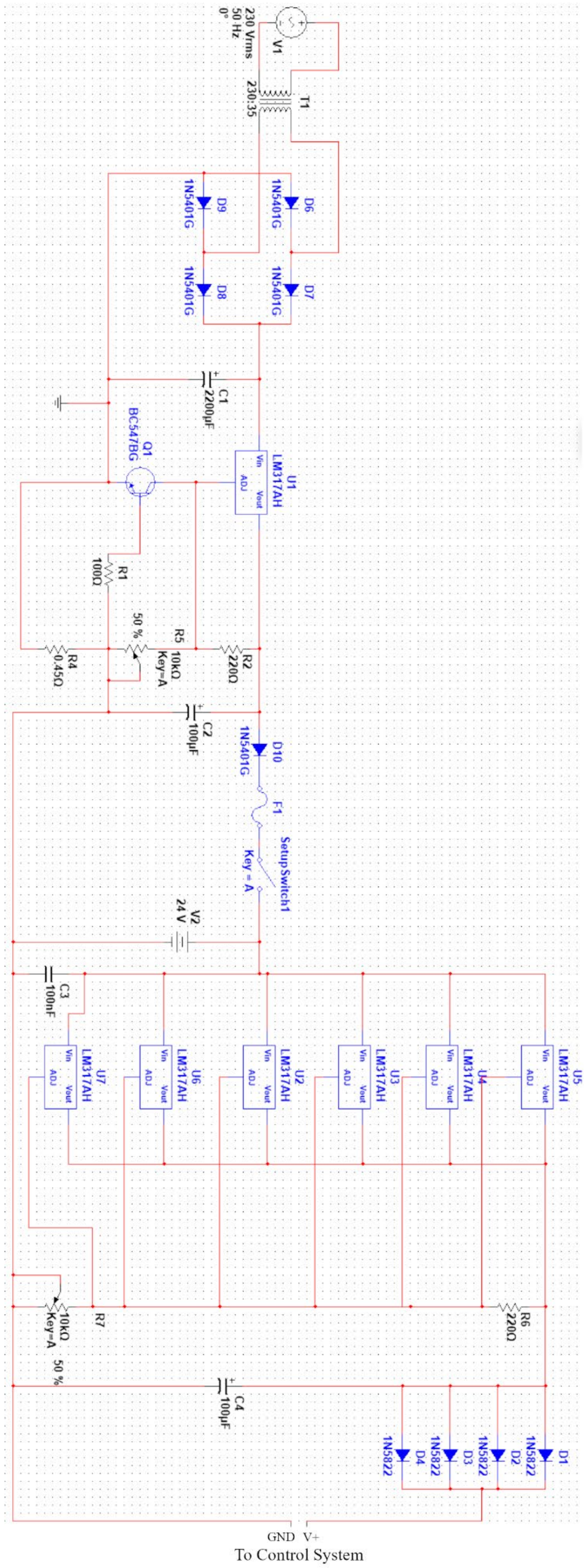

fig. 7. Full Mutism Schematic of AGV UPS System

Also, of note in the main schematic, fig. 7, is the inclusion of a 1.5 A fuse (F1) between the battery charger and battery. This is to prevent an accidental overcurrent draw if the battery is depleted, the charger is still connected to the powered AC bus and the main DC PSU, see fig. 4, is not running. Since control system would then attempt to draw the full 12.26 A from the charger, which is only capable of supplying maximum 1.5 A. (LM317 limitation).

The “SetupSwitch1”, in fig. 7, is used to calibrate the charge voltage of the charger portion of the UPS. When calibrating the charger, the switch is opened. The open voltage is measured using a multimeter connected between ground and the output of D10. This voltage should be set to 28.8 Vdc using potentiometer R5 (50% will be the ideal starting point).

VII. PRINTED CIRCUIT BOARD DESIGN

The design of the UPS was built such that the entire system fits on one Printed Circuit Board (PCB). The PCB is illustrated in fig. 8.

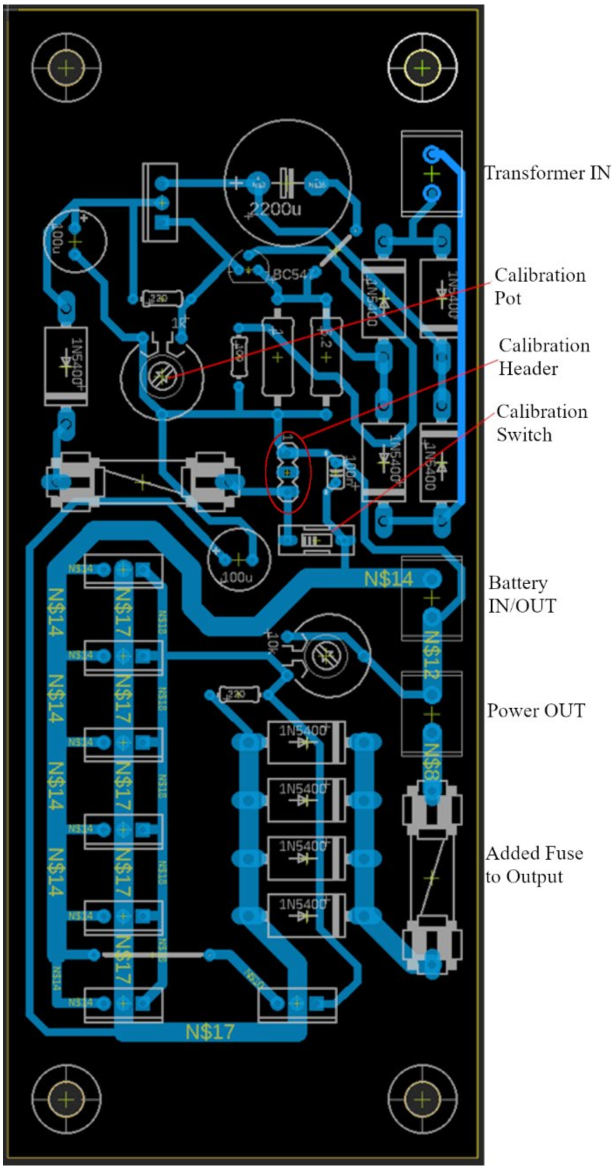

fig. 8. Printed Circuit Board for PLC UPS

The PCB is a single sided PCB to save cost, with the components mounted on the opposite face to the traces. Components that cannot be attached to the PCB include the battery bank and transformer. The transformer is attached directly to the AC bus and its output is attached to the “transformer IN” screw terminal of the PCB. The battery bank is attached via the “Battery IN/OUT” screw terminal and finally the “Power OUT” is connected to the same DC bus the main 24V dc PSU of the AGV is connected to.

The “Calibration Header” in fig. 8 can be used to attach a multimeter to set the correct charge voltage for the charging circuit of the UPS. When this is done “calibration switch” must be switched to the off position and the “Calibration Pot” is used to set the correct charging voltage of 28.8 Vdc.

There is one discrepancy between the schematic diagram shown in fig. 7 and the PCB shown in fig. 8, that is the inclusion of a second fuse for the output of the UPS, this is labeled as “added fuse to output” on fig. 8. This fuse is rated at 9A and prevent overloading the voltage regulator or more commonly shorting out the leads when connecting the UPS in, when the battery is attached.

VIII. CONCLUSION & FUTURE IMPROVEMENTS

This AGV PSU was very hastily put together, to get a low-cost PSU system for an existing AGV. However, it works surprisingly well. Some improved that could be made to future iteration of this system include the removal of the LM317 based voltage regulation segment and replacing this with a true buck-boost converter able to produce an output voltage of approximately 23.48 V due to the voltage drop over the Schottky diodes used for switching in the UPS.

This System should not be implemented on any electrical system that requires more stringent 24 Vdc adhesion due to the manner it does the switching, via biased diodes. Even with the afore mentioned improved voltage regulation segment the voltage between using the AGV’s main PSU and back up UPS will differ by 0.52 V. As the system stands, without the improved voltage regulation system, the voltage drop between the main PSU and UPS is 3.525 V or a 14.7% voltage drop.

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