Design of a Battery-Considerate Uninterruptable Power Supply Unit for Network Devices

Martin Pospisilik, Tomas Dulik, Pavel Varacha, Milan Adamek

***Abstract*—** Recently, the importance of the Power on Ethernet (PoE) technology has been increasing significantly. Specifically, the use of standard voltages of 12, 24 or 48 V and construction of the appropriate uninterruptable power supply unit to supply the PoE devices come to the fore. This paper describes construction of a simple but reliable and highly efficient UPS circuit which employs electronic battery connecting, defined battery charging and maintenance currents. The purpose of this construction is to find the means of protecting the battery from excessive wearing off.

***Keywords*—** Power on Ethernet, Uniterruptable Power Source, Electronic Commutation, On-line UPS.

I. INTRODUCTION

OPERABILITY of any electrical appliance powered by means of an electrical network is highly affected by the quality of this network. According to [2] the following power supply network malfunctions occur at most:

- total power network failure (blackout),
- short undervoltage (usually without negative consequences),
- long undervoltage showing the decrease of the power supply voltage by more than 15 %,
- overvoltage,
- short voltage spikes,
- waveform distortion,
- noise,
- electromagnetic interferences.

The statistics published in [2] shows that more than 90 % of power supply network failures are the total power network failure and long undervoltage, resulting in the lack of the supplied power and malfunctions of the powered appliances. This problem has been solved by employing the UPS (Uninterruptible Power Supply source) units that are capable of delivering the power from accumulators in case the power supply network failed. The more sophisticated systems are capable of the voltage spikes and noise on the power line elimination. As the PoE devices are fed with DC current, the quality of the sinusoidal waveform is not critical for applications like this. Generally, three types of the stationary (accumulator based) UPS units are recognized as follows:

- off-line UPS,
- line-interactive UPS,
- on-line UPS.

Further description of the UPS types is provided in the following chapter.

II. STATE OF ART

As mentioned within the introduction, generally three types of UPSs are recognized as described in the following sections.

A. *Off-line UPS*

These systems use a simple switch, usually a relay, to switch between the power network and accumulator source. These UPSs are the most commonly used in undemanding applications. The accumulator is being recharged by an AC/DC converter and at its output a DC/AC converter is utilized to produce the alternating voltage. The reliability of this construction depends mainly on the quality of the switch (relay) and the efficiency is affected by the AC/DC and DC/AC converters. In undemanding applications, mechanical relays are still often employed. As the accumulator can be fully isolated, it is well protected against voltage or current surges. Its lifetime can be high, affected mainly by the quality of the recharging unit.

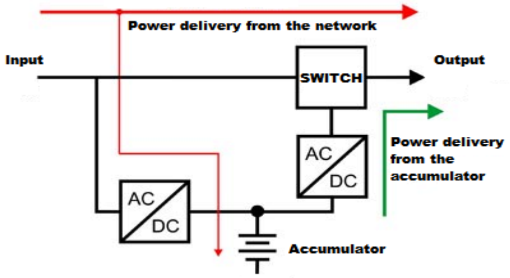

Fig. 1 - Off-line UPS block diagram [2]

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B. *Line Interactive UPS*

The Line-interactive UPSs are more sophisticated, suitable to be used within small servers or workstations. Usually, these devices are equipped with a voltage stabilization that can for example be realized by switching the transformer taps or different power sources (see the “Other power source” in Fig. 2).

Usually, these UPSs can be remotely controlled by means of a computer network that results in the possibility of the accumulator state check etc.

As shown in the Fig. 2, the construction of such UPSs is more complex, not avoiding the use of switches, AC/DC and DC/AC converters. The reliability of the whole system as well as the lifetime of the accumulators are affected by many of the design considerations, quality of the utilized devices (switches) etd.

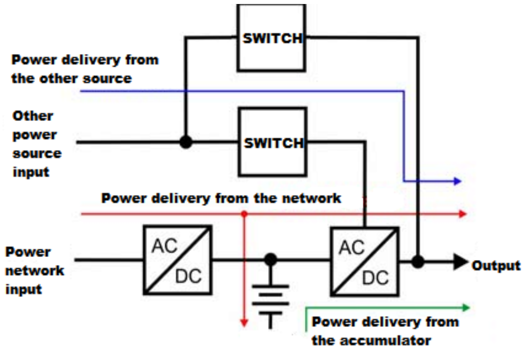

Fig. 2 - Line-interactive UPS block diagram [2]

C. *On-line UPS*

The On-line UPS operates with the accumulator permanently connected between the AC/DC and the DC/AC converter (see Fig. 3). This solution seems to be ideal because it uses no switches and the accumulator acts as a huge capacitor, filtering the interferences penetrating the system from the power supply network. However, the lifetime of the accumulator is decreased because its charging current is not defined and can be quite high when the accumulator is deeply discharged. Moreover, the accumulator is permanently loaded by pulse currents as the power network voltage wobbles or shows voltage spikes.

On the other hand, this approach seemed to be ideal for the construction proposed in this paper, requiring only a few modifications in order the accumulator was protected better.

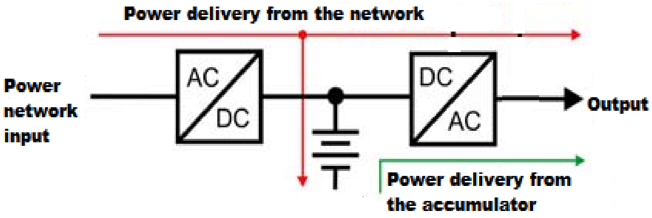

Fig. 3 – On-line UPS block diagram

III. UPS FOR POE DESIGN

As the PoE standard requires DC supply current, there is no need for DC/AC converter at the output of the device. For these purposes the On-line UPS seems to be the most convenient one. The power is delivered mainly from the power network and in case of its failure the accumulator is employed. However the issues on the accumulator lifetime are still a serious issue. Therefore the authors of this paper decided to propose a modification of the On-line UPS structure leading to better protection of the accumulator.

A. *Targets and Expectations*

The main target was to find such configuration of the On-line UPS that would be simple to manufacture, effectively operating, reliable and friendly to the accumulator. The nominal output voltage of 24 V DC was considered with the fact that, if necessary, other voltages can be generated by means of an appropriate DC/DC converter.

Because in each of the powered network devices an individual DC/DC converter is implemented, there is no need for stabilizing the output voltage. Therefore the output stabilizer was omitted in order the efficiency of the supply source was as high as possible. According to the condition of the accumulator, the voltage in the power supply network and the load connected to the output of the power source, the output voltage can vary from 19.6 to 26.0 V considering the 5 % voltage drop at the transformer when it is fully loaded and the power supply voltage fluctuations are as high as ± 12.5 %. The charge current of the accumulator is limited to 0.5 A provided the nominal supply network voltage does not exceed the permitted tolerance of ± 10 %. When fully charged, the accumulator is being charged only with the maintaining current the level of which is limited to 5 mA. The current limits are adjustable according to the capacity of the utilized accumulator.

B. *The improvements*

The block diagram of an improved On-line UPS construction is depicted in Fig. 4. The construction employs a simple toroid transformer 230 / 18.5 V. The voltage delivered by the power supply network is rectified by the B1 rectifier and filtered by a set of capacitors, displayed as the capacitor C1 in the block diagram.

Provided the power supply network is active, the power is delivered to the output through the D1 low-drop Schottky diode. Considering the rectified voltage fluctuates between 19.6 and 26.0 V, the accumulator G1 cannot be carrying the charging current by itself as its voltage (when charged) lies between 25.0 and 27.0 V. This situation can be described by the following equation:

$$V_{OUT} \leq V_{ACC} + V_{CH} + V_D \tag{1}$$

Where:

V_{OUT} - voltage at the output of the UPS,

V_{ACC} - voltage at the terminals of the accumulator,

V_{CH} - threshold voltage of the accumulator that must be exceeded in order the charge current started to flow,

V_D - diode parallel to the Q1 transistor threshold voltage.

In order the proper charge current was applied into the accumulator, the Negative voltage source with current limiting must operate, being fed directly from the output of the B1 rectifier. Now the negative terminal of the accumulator is tied to a potential lower than 0 V and the transistor Q1 is polarized in the nonconductive direction. Moreover, there is a protection diode connected antiparallely to the Q1 transistor that in case of high voltage spike occurring at the input of the circuit seduces this spike to the accumulator, not letting it penetrate into the output.

When the power supply network fails, the Charge pump is activated. This results in opening of the T1 transistor. Now the output is fed by the accumulator and the Negative voltage source is decommissioned, being blocked by the Schottky diode D1.Once the supply network starts to be active again, the Charge pump is switched off and the transistor Q1 is closed as its gate charge is distracted by the R1 resistor.

The charge current is limited by the current limit set on the Negative voltage source. However a situation can occur in which the accumulator is deeply discharged and the power supply voltage is close to the upper limit. In this case the inequality described by (1) is not applicable and the accumulator is fed by the current flowing through the protective diode. However, it is worth mentioning that the threshold voltage of the deeply discharged accumulator is quite high (approximately 1.5 V [3]). Such accumulator also embodies higher internal resistance which keeps the current within the acceptable limits. This is the only situation in which the operation of the improved On-line UPS is comparable to the operation of the basic On-line UPS solution described in Fig. 3. In other cases the accumulator is less stressed.

1) *Accumulator Management*

The improved UPS is also equipped with the Accumulator management circuit that monitors the state of the accumulator. This circuit is based on one quad low-power operational amplifier and is fed directly from the accumulator. Two outputs insulated by optocouplers are provided as follows:

DD (Deep Discharge) is NOT active when the voltage at the accumulator drops below the preset level. This protects the accumulator from the state of the deep discharge. When this situation occurs, the Charge pump is blocked and the Q1 transistor is closed. The power supply is powered off until the power supply network is connected. In this state the only device that consumes the power from the accumulator is the Accumulator management the consumption of which is very low because both optocouplers are inactive.

FC (Fully Charged) is active when the voltage at the accumulator exceeds the preset limit. When this situation occurs, the accumulator is treated as fully charged and is fed only with the maintaining current. This is achieved by switching the feedback in the current limiter of the Negative voltage source by means of the optocoupler.

The optocouplers driven from the Accumulator management block are controlled by comparators with a hysteresis of about 1.5 V in order to prevent the controlling loops from the occurrence of oscillations.

2) *Switching Between Power Sources*

The switching between the power sources is simple. The Charge pump driving the Q1 transistor is blocked by the ***MAINS*** signal wire when the voltage at C1 exceeds the threshold of approximately 19.0 V. This voltage is high enough to keep the network devices in their power-on state and low enough to keep the diode D1 in the closed state because the accumulator voltage is higher than the threshold voltage.

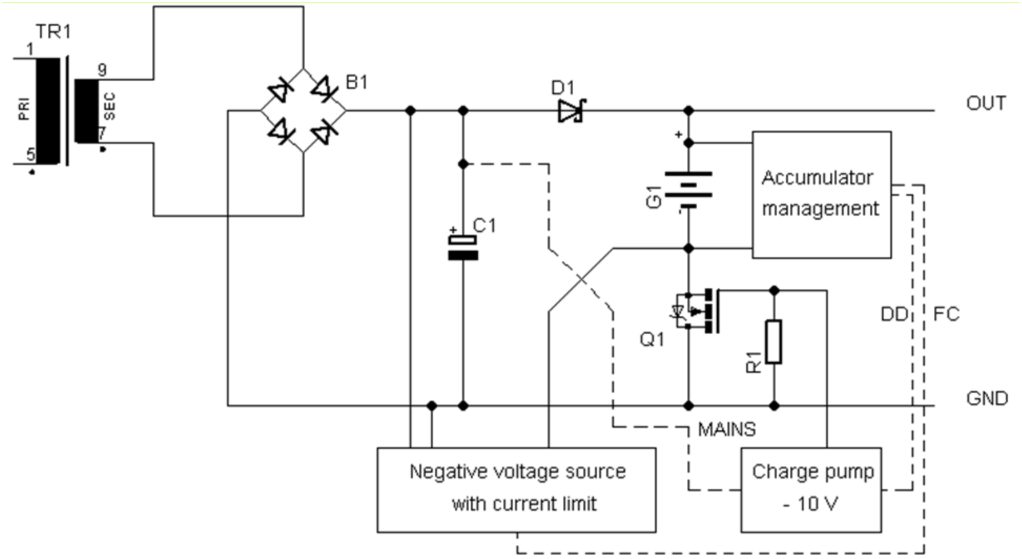

Fig. 4. Block diagram of the proposed circuit arrangement

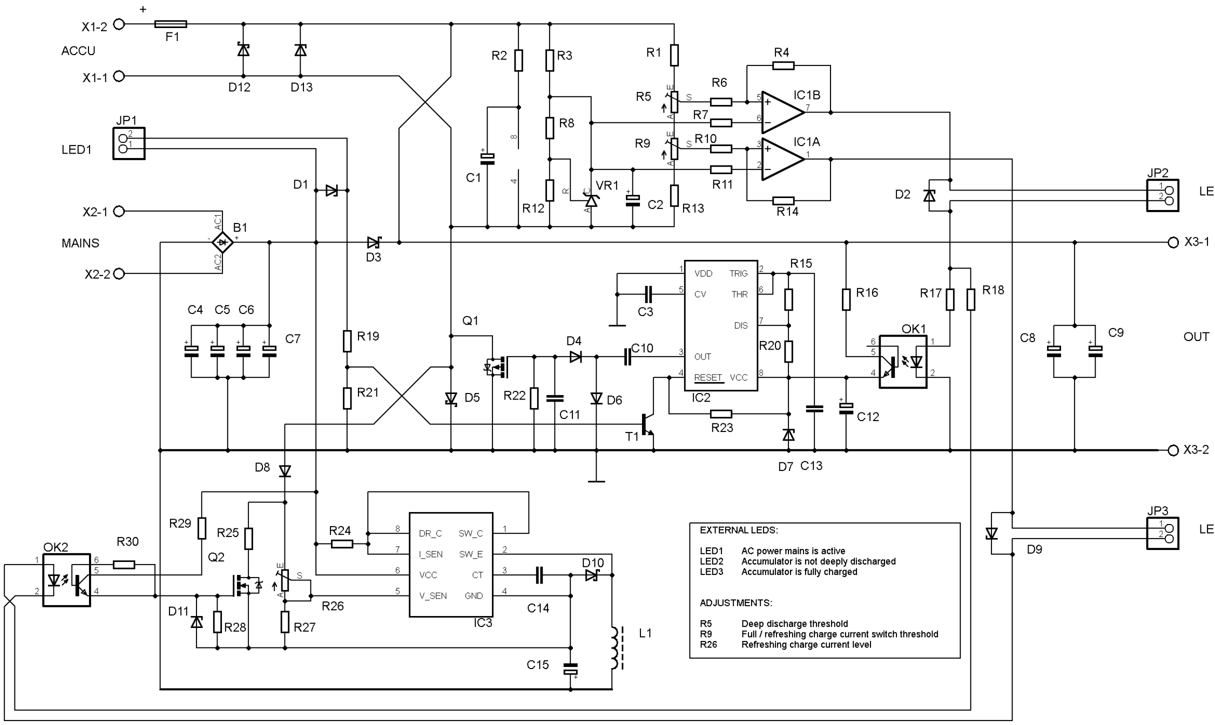

Fig. 5 – Complete circuit diagram

3) Practical Realization

The prototype of the Improved UPS device was constructed according to the block diagram depicted in Fig. 4. A complete circuit diagram is depicted in Fig. 5. The detailed description of the construction is provided below.

The power transformer's output is connected to X2 terminals (MAINS). Its nominal output voltage should be approximately 19.5 V. The pulses at the output of the rectifier B1 are smoothed by means of capacitors C4, C5, C6 and C7. When the mains power delivery is active, the power is delivered to the load connected to X3 terminals (OUT) via the Schottky diode D3 with minimum power losses. The voltage divider consisting of R19 and R21 resistors is set in that way the transistor T1 was opened when the voltage at the smoothing capacitors is approximately 19 V or higher. Then the /RESET pin of IC2 is tied low, resulting in the suspension of the IC2 operation. The Q1 transistor is not activated, but when the input voltage is high enough and the voltage at the accumulator, being connected to X1 terminals (ACCU) is low (discharged accumulator), the current can sink to the accumulator through the D5 Schottky protective diode.

The integrated circuit IC3 is an easy purchasable universal switching regulator MC34063. It is connected as a voltage inverter, producing negative voltage up to – 10 V. Its feedback loop is connected in that way so it maintained a constant current instead of maintaining the constant voltage. The current is sensed by the resistors R25, R27 and the trimming resistor R26. This voltage inverter produces negative voltage that is required to develop the required battery charging current. While the positive battery terminal is connected directly to the main power wire behind the D3 diode, its negative terminal is now kept at a potential below zero in order the defined current through the battery was sunk. When the transistor Q2, driven by the OK2 optocoupler, is switched on, the low resistance of R25 resistor defines the main charging current, which is set to approximately 0.5 A. Higher values are not achievable without using an external switching transistor to drive the L1 inductor the current peaks at which are now up to 1.5 A high. Once the Q2 is switched off, the resistor R25 is disconnected and the charging current is limited to a value that is set by the trimming resistor R26. The current flowing through the accumulator also supplies the battery management consisting of IC1 operating amplifiers. Its volume should be set in order the refreshing current through the battery was between 1 to 3 mA. Because the voltage inverter is connected as the current source, the disconnection of the battery, leading to the opened current loop, would cause inadmissible voltage rise, resulting in destruction of IC3 the maximum operating voltage of which is 45 V. Therefore a protective Zener diode D13 is applied, closing the current loop in case of the battery disconnection. High current protective diode D12 is also applied. Together with F1 fuse it disconnects the battery once the battery terminals are connected in reverse polarity by the operator.

The battery management is very simple. It consists of two comparators IC1A and IC1B. The hysteresis of the comparators is approximately 1.5 V. The appropriate thresholds are set by R5 and R9 trimming resistors. The voltage reference is generated by VR1 voltage regulator the current through which is approximately 1.5 mA. The IC1B comparator generates the DD (Deep Discharge) signal that drives the OK1 optocoupler. In order the power consumption was as low as possible when the Deep Discharge state occurs, the DD signal is negated. Once DD is set to LOW, the optocoupler OK1 disconnects the IC2 multivibrator and the operation of the circuit is disabled until the mains power supply is active again. The detailed information on this state is provided below in this chapter. The IC1A comparator drives the OK2 optocoupler which switches the charging current source between charging and maintenance mode. The optocoupler OK2 is connected between the outputs of IC1A and IC1B. Therefore it is active only when the DD (Deep Discharge) signal is HIGH and the FC (Fully Charged) signal is LOW. Once the voltage at the battery terminals reaches the limit set by the trimming resistor R9, the comparator IC1A switches into HIGH state (generating the FC signal) and the optocoupler OK2 is deactivated, resulting in decreasing of the recharging current to the maintenance value.

Normally the output is intended to be supplied from the mains network (via B1 and D3) and the battery is intended to be recharged or kept in the charged state by the maintenance current. Under these circumstances the optocoupler OK1 is turned on and the astable multivibrator IC2 is supplied with the voltage, but does not oscillate because its /RESET pin is tied low by T1 transistor. Once there is a power network malfunction and the voltage at the smoothing capacitors drop below the threshold that is set by the resistors R19 and R21, the transistor T1 is switched off and the astable multivibrator IC2 starts to oscillate. There is a square wave at its output driving the rectifier with the diodes D4 and D6. This rectifier produces negative voltage that is necessary to drive the transistor Q1. Once the transistor Q1 is switched on, the current flows to the load from the battery. Now the load is operated from the battery and the negative voltage source is not supplied any more as the D3 diode is oriented in the reverse direction. The transistor T1 cannot be driven as well. The capacitors C8 and C9 help to bridge the period in which the switching from the power network to the battery is done. When operating from the battery, two situations can occur:

1. The power network starts to deliver the energy. Once the transistor T1 is driven high, the operation of the astable multivibrator is suspended and the charge at the gate of the transistor Q1 is drained by means of the resistor R22. Battery is disconnected while the load is supplied with the power from the mains network. The battery starts to be charged with the current of 0.5 A until the voltage at its terminals reaches the desired level.
2. The power network has been suspended for too long. The capacity of the battery is exhausted and its terminal voltage dropped to the critical level. The comparator IC1B turns LOW and the astable multivibrator is disconnected from the power supply. The gate of the transistor Q1 is not driven anymore and its charge was drained to ground by means of the resistor R22. The battery is disconnected and the power delivery to the load is switched off as well as the circuitry of the UPS. Only a small current (lower than 2 mA) is still needed to supply the battery management that is connected in parallel with the battery. Once the battery has been discharged, the circuit cannot be turned on again until the power delivery from the power network is resumed.

Between the battery management and the optocouplers there are pins JP2 and JP3 that enable connecting of LEDs that can indicate the states in which the circuit is. The pins JP1 also enable connecting the LED that indicates that the power is delivered by means of the power supply network. The Zener diodes D1, D2 and D9 enable proper operation in case the LEDs are not connected. Alternatively, optocouplers can be implemented instead of the LEDs, providing on-line monitoring via the powered computer network, using standard methods [6], [7], [8].

When the LEDs are connected, the indicated states are as described in Table 1. In the Table 2 the description of the utilized devices is provided.

Table 1 – States indicated by LEDs

LEDs on	**Indicated state**
LED1 + LED2 + LED3	Powered from the supply network, battery is being charged
LED1 + LED2	Powered from the supply network, battery is fully charged
LED2	Powered from battery
LED1	Powered from the supply network, the battery is faulty
-	The battery is exhausted and the power supply delivery from the network is inactive

Table 2 – Circuit devices position

Position	**Value or type**	**Note**
B1	GPBC80X	Rectifier. Low voltage drop and average current at least 15 A is preferred. May need a heatsink.
C1	10 μF / 35 V	Electrolytic
C2	1 μF / 16 V	Electrolytic
C3	100 nF	Ceramic
C4, C5, C6, C7, C8, C9	6.8 mF / 35 V	SNAP-IN Electrolytic
C10	33 nF	Ceramic
C11	33 nF	Ceramic
C12	10 μF / 25 V	Electrolyric
C13	1 nF	Ceramic
C14	680 pF	Ceramic
C15	470 μF / 35 V	Electrolytic
D1	BZX55 - 3.3V	Zener diode, low power dissipation
D2	BZX55 - 3.3V	Zener diode, low power dissipation
D3	SBH1540	Schottky diode, $V_f < 0.5$ V, $P_d > 2$ W, $I_a > 12$ A, $V_r \geq 40$ V
D4	1N4148	
D5	BYV10	
D6	1N4148	
D7	BZX55 – 12V	Zener diode, low power dissipation
D8	1N4004	Or equivalent
D9	BZX55 – 3.3V	Zener diode, low power dissipation
D10	BYV10	

D11	BZX55 – 12V	Zener diode, low power dissipation
D12	SBH1540	Schottky diode, capable of high surge current
F1	10 A	20 x 5 mm fuse
IC1	TL062	Low power dual operating amplifier
IC2	NE555	
IC3	MC34063A	
JP1, JP2, JP3		2.54 mm 2pin jumpers / connectors
L1	330 µH / 2.8 A	Toroid
OK1, OK2	4N35	Or similar
Q1	STP80PF55	Or similar MOSFET, TO220
Q2	IPP096N03LG	Or similar MOSFET, TO220
R1	180 kΩ	Metal-oxide standard R0207
R2	10 Ω	Metal-oxide standard R0207
R3	15 kΩ	Metal-oxide standard R0207
R4	22 MΩ	Metal-oxide standard R0207
R5	10 kΩ	Rotary trimming resistor, RM5, horizontal
R6	330 kΩ	Metal-oxide standard R0207
R7	330 kΩ	Metal-oxide standard R0207
R8	100 kΩ	Metal-oxide standard R0207
R9	10 kΩ	Rotary trimming resistor, RM5, horizontal
R10	330 kΩ	Metal-oxide standard R0207
R11	330 kΩ	Metal-oxide standard R0207
R12	100 kΩ	Metal-oxide standard R0207
R13	39 kΩ	Metal-oxide standard R0207
R14	22 MΩ	Metal-oxide standard R0207
R15	68 kΩ	Metal-oxide standard R0207
R16	680 Ω	Metal-oxide standard R0207
R17	3.3 kΩ	Metal-oxide standard R0207
R18	3.3 kΩ	Metal-oxide standard R0207
R19	4.2 kΩ	Metal-oxide standard R0207
R20	15 kΩ	Metal-oxide standard R0207
R21	150 Ω	Metal-oxide standard R0207
R22	100 kΩ	Metal-oxide standard R0207
R23	47 kΩ	Metal-oxide standard R0207
R24	0.22 Ω	1 W power dissipation
R25	2.2 Ω	Metal-oxide standard R0207
R26	220 Ω	Rotary trimming resistor, RM5, horizontal
R27	33 Ω	Metal-oxide standard R0207
R28	100 kΩ	Metal-oxide standard R0207
R29	330 kΩ	Metal-oxide standard R0207
R30	100 kΩ	Metal-oxide standard R0207
T1	BC546A	Or similar
VR1	TLC431	
X1, X2, X3		Screw terminals, RM5

Table 3 – Comparators setting possibilities

	IC1B	IC1A	IC1B	IC1A
	Trimmed to MIN		Trimmed to MAX	
Flips to LOW	20.5 V	24.5 V	24.6 V	30.8 V
Flips to HIGH	19.3 V	22.9 V	23.1 V	28.2 V
Hysteresis	1.2 V	1.6 V	1.5 V	2.6 V

As obvious from Table 3, the trimming resistors R5 and R9 enable to set the threshold of DD (Deep Discharge) signal from approximately 19 V to approximately 23 V and the threshold of FC (Fully Charged) signal from approximately 25 V to approximately 31 V. The hysteresis is dependent of the trimming resistors' setting, but it is always higher than 1 V.

4) *Efficiency Estimation*

The total efficiency of the presented device depends on the quality of the utilized parts. The design is oriented so as to achieve the highest possible efficiency when operating from the accumulators. This objective was achieved perfectly because only the low-resistance transistor Q1 and the appropriate wires are connected in series with the load. When powered from the power network, the efficiency is decreased by the power dissipation on the rectifier B1 and the Schottky diode D1. However, the B1 rectifier can be replaced by more efficient rectifier, using for example switched transistors. The only reason for using this kind of rectifier was the aim to simplify the construction of the prototype. The estimated power dissipation of the D1 diode is expected to be lower than 3.75 W provided the maximum voltage drop at the diode is not greater than 0.6 V and the maximum power of 150 W is delivered.

5) *Further Improvements*

Provided the stabilization of the output voltage is requested, the authors of this paper propose to connect a step up / step down converter in series with the UPS device. In order the efficiency was improved it is advisable to establish a bypass around the converter that is active when the difference between the delivered and the requested voltage is lower than the prescribed tolerance. This can spare up to 10 W of power dissipation provided the output power is 150 W and the efficiency of the converter is lower than approximately 94 %.
Additional monitoring system can be embedded in the device provided the outputs of the Accumulator management are followed by means of optocouplers. More optocouplers can be connected in series with the ones mentioned in the text above.

When the power network is out of order and the accumulator was discharged under the preset limit, the power delivery to the output of the device is switched off until the power network is available. Provided there is a need to start the power delivery when the power network is disconnected (for example the discharged accumulator was replaced by the charged one) a simple momentary button or other contact can be connected in parallel to the transistor Q1 to enable the substandard launch.

IV. VERIFICATION OF THE PROPER OPERATION

In order to verify the design, the authors constructed the circuit described in this paper and subjected it to testing. As a secondary power source, two 12 V lead-acid batteries were connected in series while the primary power source consisted of a toroid transformer. The output of the circuit was loaded with a set of resistors that simulated ballast consuming approximately 150 W of power.

The testing consisted of several tasks as described in appropriate subchapters below.

A. Reliability of Power Source Commutation

The primary power source was periodically switched on and off. Transient at the power output of the circuit were observed. The source commutation worked in every case, launching the power delivery from the batteries once the output voltage dropped below the intentionally set threshold of 19.0 V.

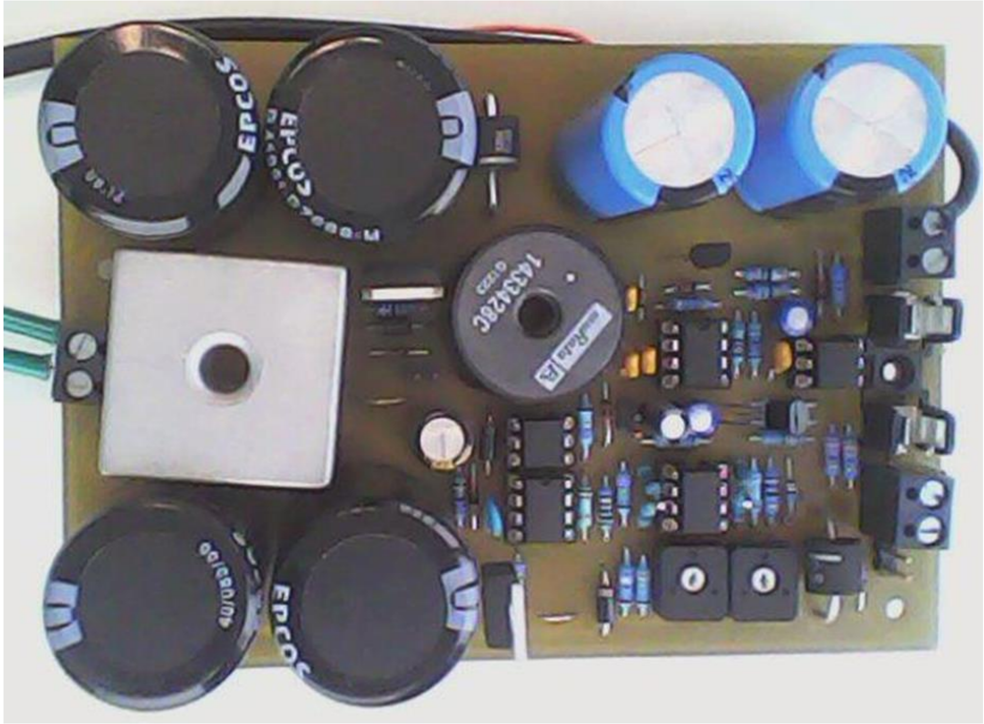

Fig. 6 – Practical realization of the circuit

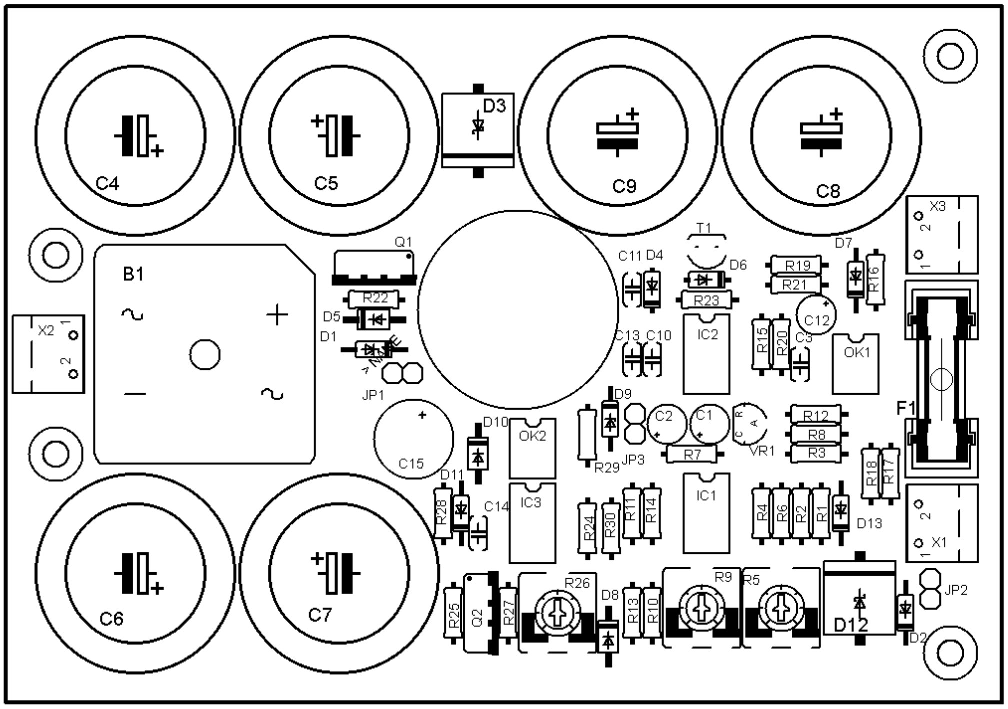

Fig. 7 – Devices displacement

B. *Battery Charging and Maintenance*

The battery charging starts every time the primary power source is on and the voltage across the accumulators is lower than the value set by the user. As default, the threshold of 27 V with at least 1 V hysteresis is advised by the authors. The charging current is approximately 500 mA ± 10 %. Once the voltage threshold is exceeded, the circuit switches into the maintenance mode in which the battery is charged only with a small current from 5 to 10 mA in order its voltage did not drop due to self-discharge.

C. *Undervoltage Protection*

The undervoltage protection is active when the primary voltage source is out of order and the voltage at the secondary power source (battery) drops below the safe value. The authors suggest setting the default undervoltage protection threshold to 22.0 V using the hysteresis of at least 1.75 V. The hysteresis is necessary because once disconnected, the voltage across the battery rises up as a consequence of the internal resistance effects of the battery, causing periodical switching of the secondary power source on and off provided the automatic wake up circuit is implemented.

D. *WakeUp*

The circuit is always put into operation when the primary power source is active. When there is a need to wake the circuit up when powered only from the secondary power source (batteries), a momentary button connected in parallel to the Q1 transistor must be connected, enabling this operation. Optionally, automatic wake up circuit can be implemented. However the authors suggest not using the automatic wake up circuit because it is not necessary to use it. The only need for waking the circuit up when powered from the batteries occurs when the primary power source is disabled for a long time and the person operating the device must replace the exhausted batteries with the fresh ones. In such case a simple button enabling the emergency start of the circuit will work sufficiently. Moreover, the circuit will be prevented from errors that occur when the batteries get faulty, resulting in their voltage fluctuations causing periodical switching on and off of the circuit.

E. *Efficiency*

The efficiency was not measured directly but the temperature of the power devices was checked. It can roughly be claimed that when powered from the batteries, the efficiency of the circuit is high as none of the devices radiate excessive heat even when the output power is approximately 150 W.

When powered from the primary power supply (by means of the power network and a transformer), considerable power dissipation was observed at the devices B1 and D1 although the manufacturers of the devices declared much higher rating. However, in practical realisations it is more convenient to replace the conventional transformer and rectifier by the switching mode power supply unit that better complies to the EMC requirements.

V. CONCLUSION

Within the framework of this paper the authors bring a suggestion on improvements that can be made in the conception of an on-line UPS in order the lifetime of the batteries was increased.

As a very simple-to-implement application they decided to design and create the circuitry of the UPS for PoE devices, because these devices operate with the voltage of 24 V and are not very sensitive to the fluctuations of this voltage. On the other hand, the power consumption of the PoE devices can be high, resulting in high supply currents that must be switched by the circuit. Therefore there was an effort to maximize the efficiency of the switches, simply by using as little transistors as possible.

The constructed circuit, the photography of which is depicted in Fig. 6, underwent several tests as described above in the paper. The results achieved at these tests verified the ideas of the authors.

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