AN2946
Application note

Solar-LED streetlight controller with 25 W LED lamp driver and 85 W battery charger based on the STM32F101Rx

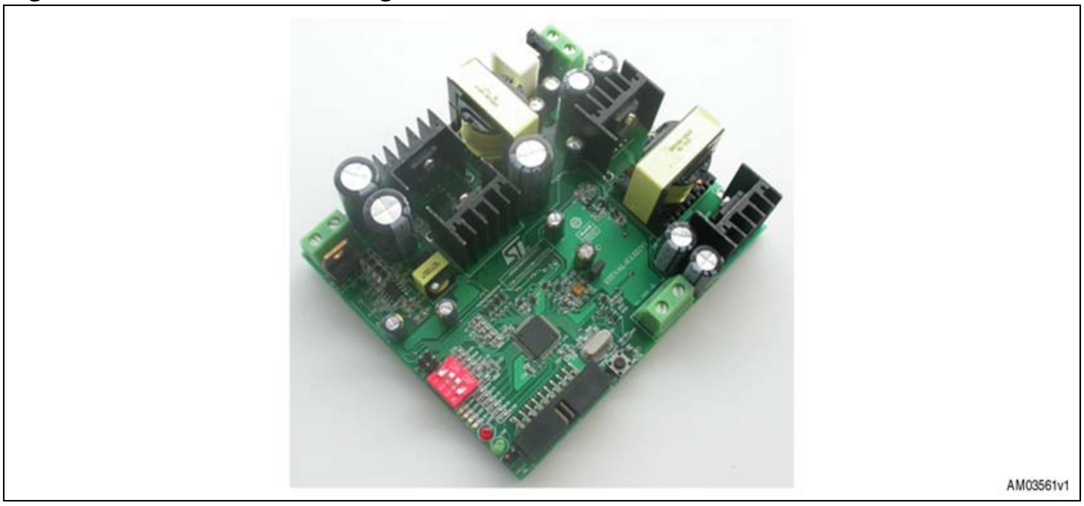
Introduction

The solar-LED streetlight controller described in this application note is designed to achieve an 85 W solar energy battery charger and a 25 W LED lamp driver. During the daytime the controller preserves the electricity energy gathered by the solar module (PV module), then stores it in the battery. In the evening the controller uses the battery energy to power the LED streetlight. When the battery runs out of power after several rainy days, the controller enables the external offline power supply (not included in this system) instead of the battery to power the LED streetlight until the system battery is fully charged again.

Due to the clean nature of solar energy, and the highly efficient energy conversion of the PV module and very long operating life of the LED lamp, the solar-LED streetlight controller, compared to conventional streetlights, can save electricity remarkably, thus abating greenhouse gas (e.g. CO_2) emission.

This application note is based on the solution of solar-LED streetlight controller architecture, including a battery charger and LED lamp driver. The description of the architecture involves hardware and firmware design with design parameter settings. The solar-LED streetlight controller demonstration board is shown in *Figure 1*.

Figure 1. Solar-LED streetlight controller demonstration board



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1 Safety instructions

Warning: **The demonstration board must be used in a suitable laboratory by qualified personnel only who are familiar with the installation, use, and maintenance of electrical systems.**

1.1 Intended use

The demonstration board is a component designed for demonstration purposes only, and shall be used neither for domestic installation nor for industrial installation. The technical data as well as the information concerning the power supply and operating conditions shall be taken from the documentation included with the demonstration board and strictly observed.

1.2 Installation

The installation of the demonstration board shall be taken from the present document and strictly observed. The components must be protected against excessive strain. In particular, no components are to be bent, or isolating distances altered during the transportation, handling or usage. The demonstration board contains electrostatically-sensitive components that are prone to damage through improper use. Electrical components must not be mechanically damaged or destroyed (to avoid potential risks and health injury).

1.3 Electrical connection

Applicable national accident prevention rules must be followed when working on the mains power supply. The electrical installation shall be completed in accordance with the appropriate requirements (e.g. cross-sectional areas of conductors, soldering, and PE connections).

1.4 Board operation

A system architecture which supplies power to the demonstration board shall be equipped with additional control and protective devices in accordance with the applicable safety requirements (e.g. compliance with technical equipment and accident prevention rules).

2 General description

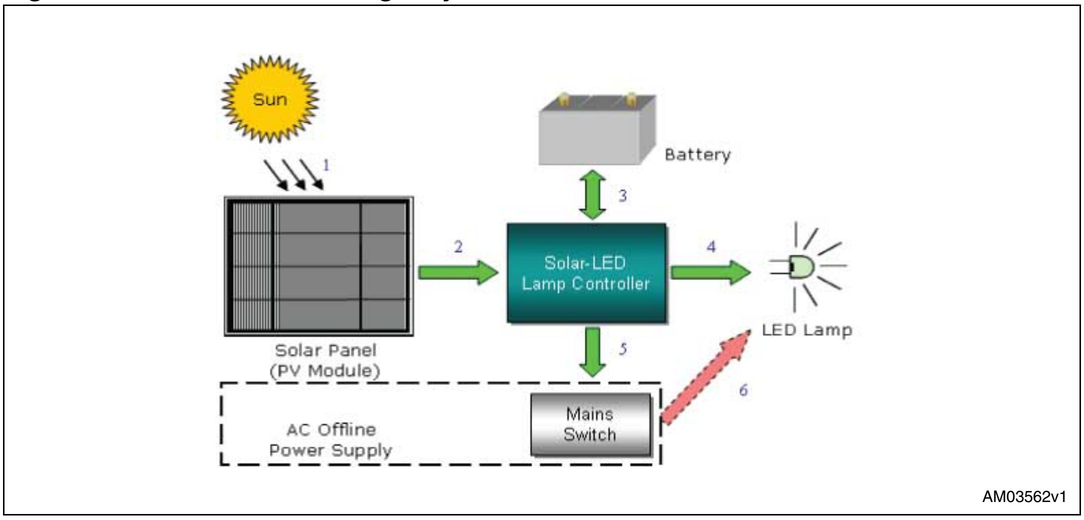
2.1 Controller features

- MPPT maximizes solar module efficacy
- Automatic day and night detection
- Automatic mains switch enable function when battery low
- Constant current control for LED lamp
- Battery charge control
- Optional LED lighting mode
- LED indicators for system status monitoring and debugging status
- Full protection function for OVP, UVP, OCP, and OTP.

2.2 Solar-LED streetlight system architecture

The solar-LED streetlight controller not only controls solar energy storage to the battery, but it also manages the power consumption to the LED streetlight. The system architecture of the solar-LED streetlight system is illustrated in *Figure 2*.

Figure 2. Solar-LED streetlight system



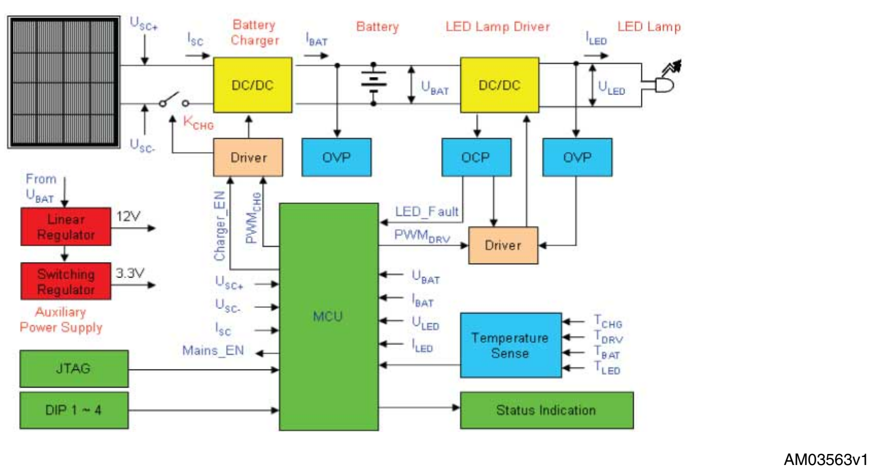
1. The sunlight delivers rays of photons (solar energy) which hit the solar panel (Photovoltaic or PV module). The photons (energy) are absorbed by the PV and electrons are released.
2. The electrons flow along the metal contact of the PV and form electricity.
3. Energy is stored in the battery during daytime and consumed at night.
4. The LED lamp (LED streetlight) is driven to operate by the LED lamp driver. This controller monitors the system and manages the light-on and light-off in day and night time.
5. When the battery goes low, the controller sends an enable signal to the 'Mains switch' which enables the AC offline power supply.
6. The AC offline power supply (not included in this application note) works as a backup source to power the LED streetlight.

2.3 Scope of the solar-LED streetlight controller

The block diagram of the solar-LED streetlight controller is shown in *Figure 3*. The controller consists of the following blocks:

- Auxiliary power supply - supplied from the battery, regulated to 12VDC for driving every MOSFET and then 3.3 VDC for the MCU and its peripherals.
- Battery charger - a DC/DC converter using buck topology. It converts solar energy to electricity and stores the electricity in the battery.
- LED lamp driver - a DC/DC converter using flyback topology in order to drive the LED lamp and provide even illumination.
- Driver - generates gate voltage in order to drive every MOSFET properly in the battery charger and the LED lamp driver including K_{CHG}.
- Protection circuits - OVP, UVP, OCP, OTP (through the temperature sense block) and reverse-connection protection for the battery and the LED lamp.
- MCU - the microcontroller includes the human machine interfaces (HMI), the DIP switch for the selection of the operating time schedule and the indicators of the debugging status. The software routines for OVP, UVP, OCP and OTP are implemented in the MCU.

Figure 3. System block diagram



The MCU implements the sophisticated peripherals as listed in *Table 1*.

Table 1. MCU peripheral allocation

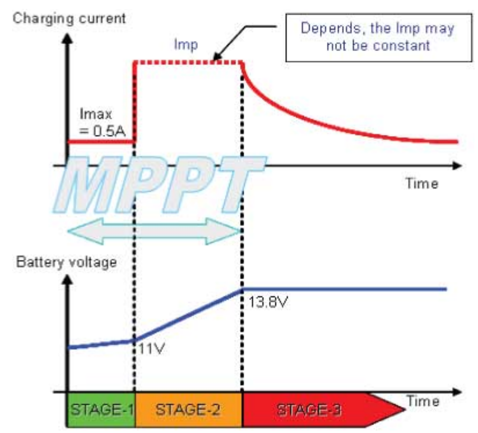
Peripheral	Number	Description	
ADC	11	U_{SC+}, U_{SC-}, U_{BAT}, U_{LED}, I_{SC}, I_{BAT}, I_{LED}, T_{CHG}, T_{BAT}, T_{DRV}, T_{LED}	
GPIO	12	Inputs	DIP1~4 (up to 16 modes) JTAG
		Status indication	Charger_EN for anti-backflow charge Mains_EN for switching to mains supply Battery LED1-2 for indicating battery status Debug LED1-4 for diagnosis (up to 16 messages)
PWM	2	PWM_{CHG}, PWM_{DRV} (100 kHz)	
EXT1	1	LED fault	

2.4 Main functions of the controller

2.4.1 Battery charging management

During the daytime, the battery is charged by PV electricity according to the typical pattern. An MPPT (maximum power point tracing) algorithm is applied to enable the PV module to output as much electricity power as it can. Refer to *Section 4.2* for more information concerning MPPT. The pattern for the 12 V battery system is shown in *Figure 4*. The pattern differentiates the entire charging process into 3 stages. During stage 1 and stage 2, the battery is charged with the solar module maximum power. In stage 3, the battery is charged in constant voltage algorithm.

Figure 4. Battery charging pattern



- Stage 1 (trickle charging): $U_{BAT} < 11$ V. The battery is charged with the maximum power of the PV module. This stage is designed for a battery which is deeply discharged. In order to prolong battery operating life, the charging current is constrained at Imax = 0.5 A.

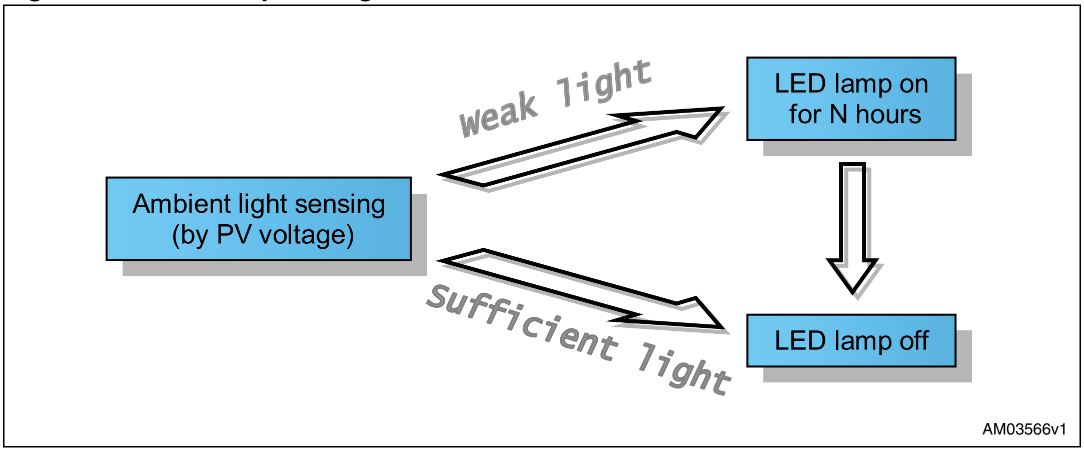
- Stage 2 (high-current bulk charging): 11 V $\leq U_{BAT} < 14.3$ V. In this stage, the battery is charged with the maximum power of the PV module. The charging current (Imp) may not be constant.
- Stage 3 (floating charging): $U_{BAT} \geq 14.3$ V. In this stage, battery is charged at constant voltage (14.3 V).

The voltage values 11 V and 14.3 V define the boundaries of the stages that are based on the characteristics of a typical 12 V lead acid battery. The voltage needed depends on the type of battery.

2.4.2 LED lamp driving management

During nighttime, normally the ambient light is weak, the LED lamp lights for N hours. The determined light-on duration (N hours) can be set by selecting a switch, DIP1~4. The controller turns on/off the LED lamp to automatically correspond to the ambient light. *Figure 5* illustrates how the controller turns on the LED lamp. The DIP switch also provides a test mode to test the LED lamp.

Figure 5. LED lamp driving scheme



2.4.3 System monitoring circuit

The microcontroller (MCU) provides a real-time system monitoring for the controller, including:

- Error detection/protection for solar module output voltage (U_{SC}), battery voltage(U_{BAT}), LED lamp voltage(U_{LED}), battery charging current (I_{BAT}) and LED lamp current(I_{LED})
- Temperature detection for the operating temperature of the battery, MOSFET and LED lamp
- System self-recovery

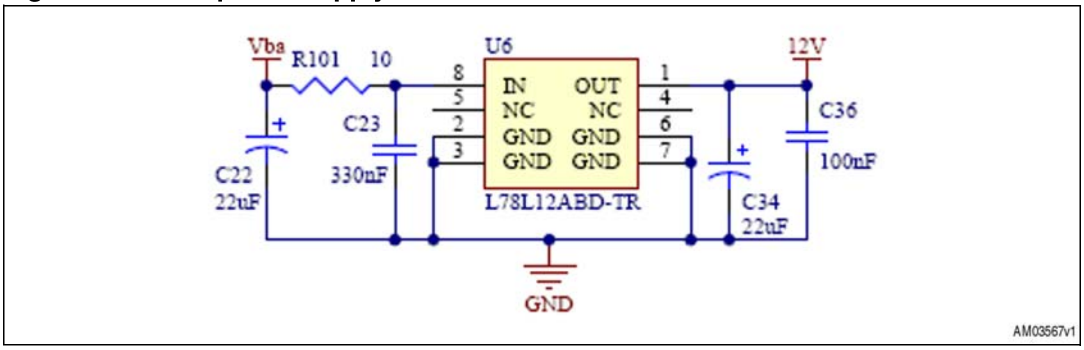
3 Hardware design

3.1 Circuit description

3.1.1 Power supply circuit

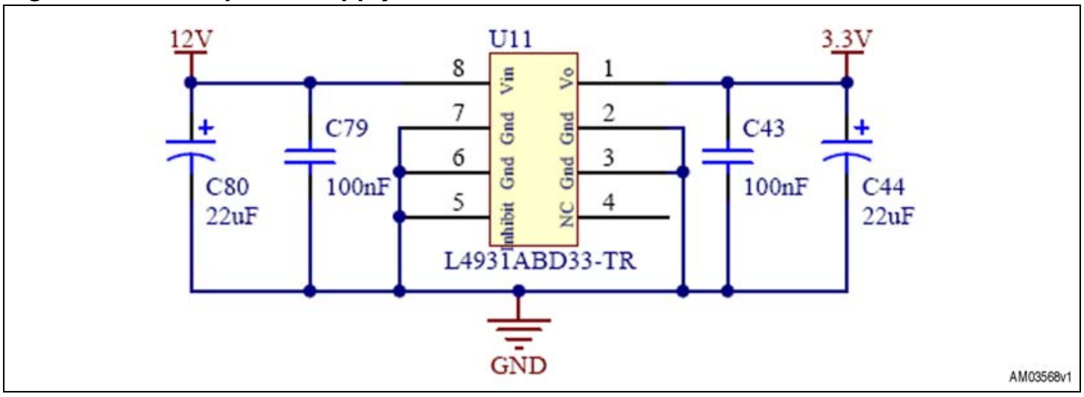
The system auxiliary power supply can be built with a 12 V battery. In order to drive the power MOSFET and some analog ICs perfectly, a regulated 12 V is required. The 12 V power supply schematic is shown in *Figure 6*.

Figure 6. 12 V power supply circuit



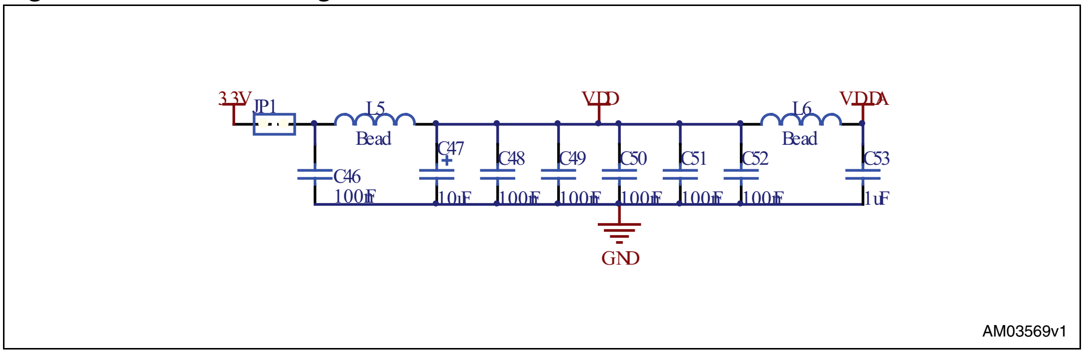
The MCU requires a 3.3 V source which is obtained from the output of the linear regulator (U11), see *Figure 7* .

Figure 7. 3.3 V power supply circuit



Since the 3.3 V supply is mainly for the MCU, a proper filter, which avoids high-frequency switching noise interference between the digital power supply (VDD) and analog power supply (VDDA), is strongly recommended. The filter circuit is shown in *Figure 8*.

Figure 8. Noise filtering circuit for VDD and VDDA

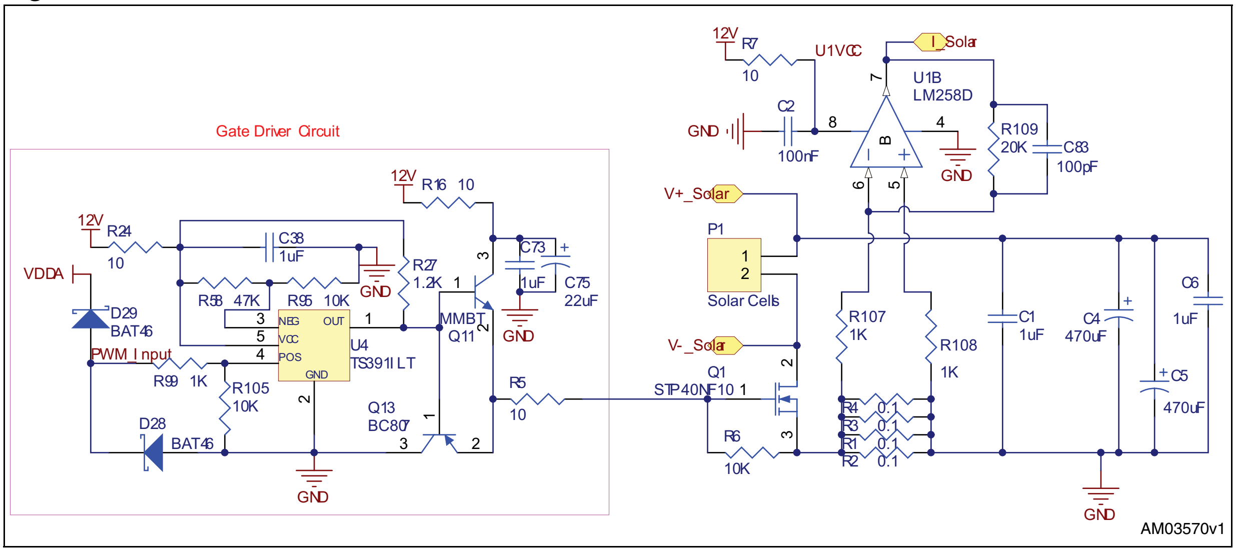


3.1.2 Electricity power collection

In *Figure 9*, C1, and C4//C5//C6 are used to reject the high switching frequency interference from the charger so that only the "clean" current flows through the solar cells (P1). When photons hit the solar cells, P1 releases electrons which flow along the metal contacts and stores electricity to C1 and C4/C5/C6 through R1//R2//R3//R4 and Q1. R1~R4 are current sense resistors which are used to sense the solar module current. An operational amplifier U1 (LM258D) is used to amplify and smooth the sense signal, then feedback to the MCU.

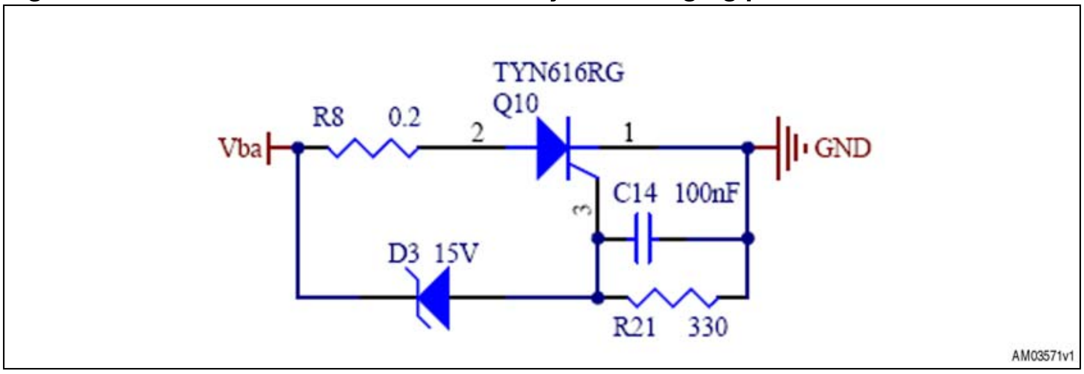
When solar cells charge the battery with high current, Q1 is turned on in order to minimize the power losses. Q1 is turned off if solar cells voltage falls below the battery voltage. Q1 also works as a polarity protection diode, preventing that the solar module is reversely connected. The gate driving signal (PWM_Input) of Q1 is given by the MCU through U4. In order to properly drive Q1, the 3.3 V PWM signal from the MCU must be sent to U4 (comparator TS391). Q11 and Q13 are configured as the push-pull totem to turn on/off Q1 perfectly.

Figure 9. Solar module control circuit



A hardware solution to protect the battery from being overcharged is important. When battery voltage exceeds 15 V (example of 12 V battery in system), D3 in *Figure 10* is triggered and SCR (Q10) is turned on. The battery provides latch-current to Q10 and the fuse (F1 in *Figure 11*) is blown. Then battery is protected.

Figure 10. Hardware OVP circuit for battery overcharging protection



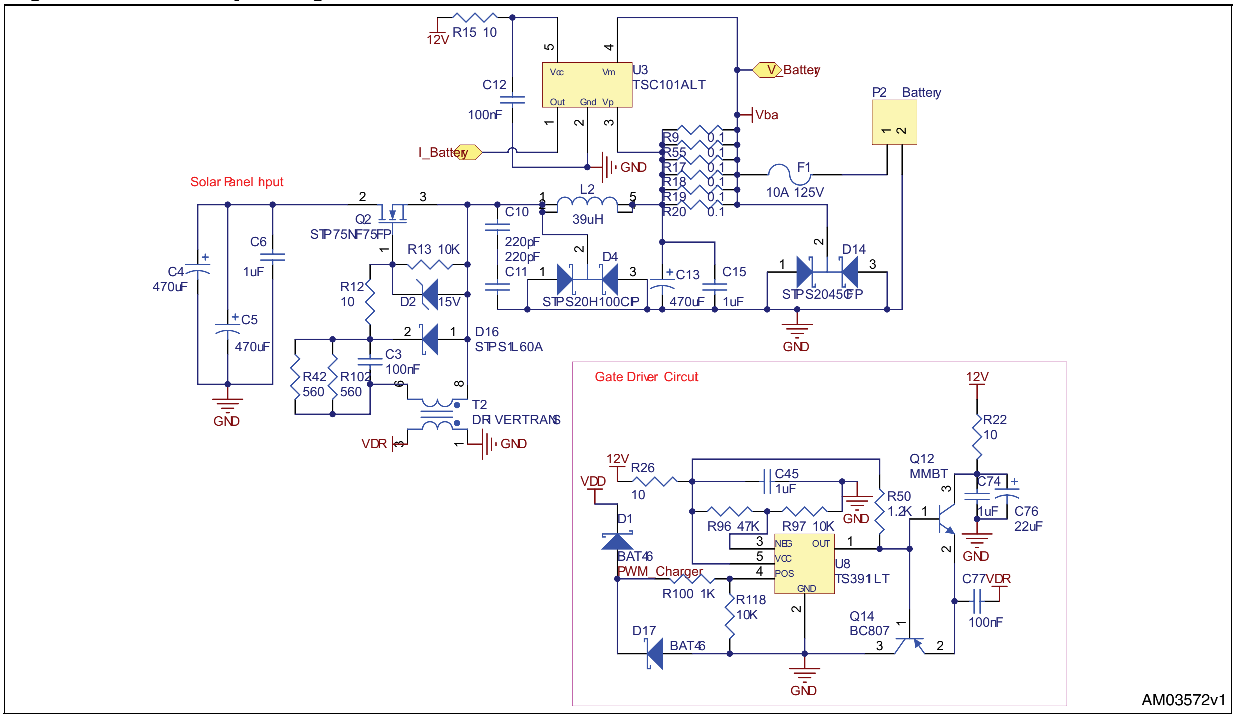
The schematic of the battery charger is shown in *Figure 11* which is based on buck topology. Q2, D4 are the buck MOSFET and diode, respectively. L2 is the inductor and C13 is the output capacitor. The charger operates in a continuous current mode so that small output current ripple is achieved and a small output capacitor can be used. C10 and C11 are used as a snubber to suppress high voltage spikes.

Since Q2 is floating and high-side transformer T2 is used to drive the MOSFET, the gate driving circuit is similar to the one shown in *Figure 9*.

Resistors R9, R17 ~ R20 and R55 are used to sense the charge current to the battery. U3 (TSC101) is the high-side current sensor which amplifies the signal and gives feedback to the MCU.

P2 is the connector to the battery. One fuse (F1) is in series with the battery to prevent catastrophic failure. To prevent reverse connection of the battery, one Schottky diode D14 is added. F1 blows out with D14 if the battery is reversely connected. This helps to protect the rest of the circuits.

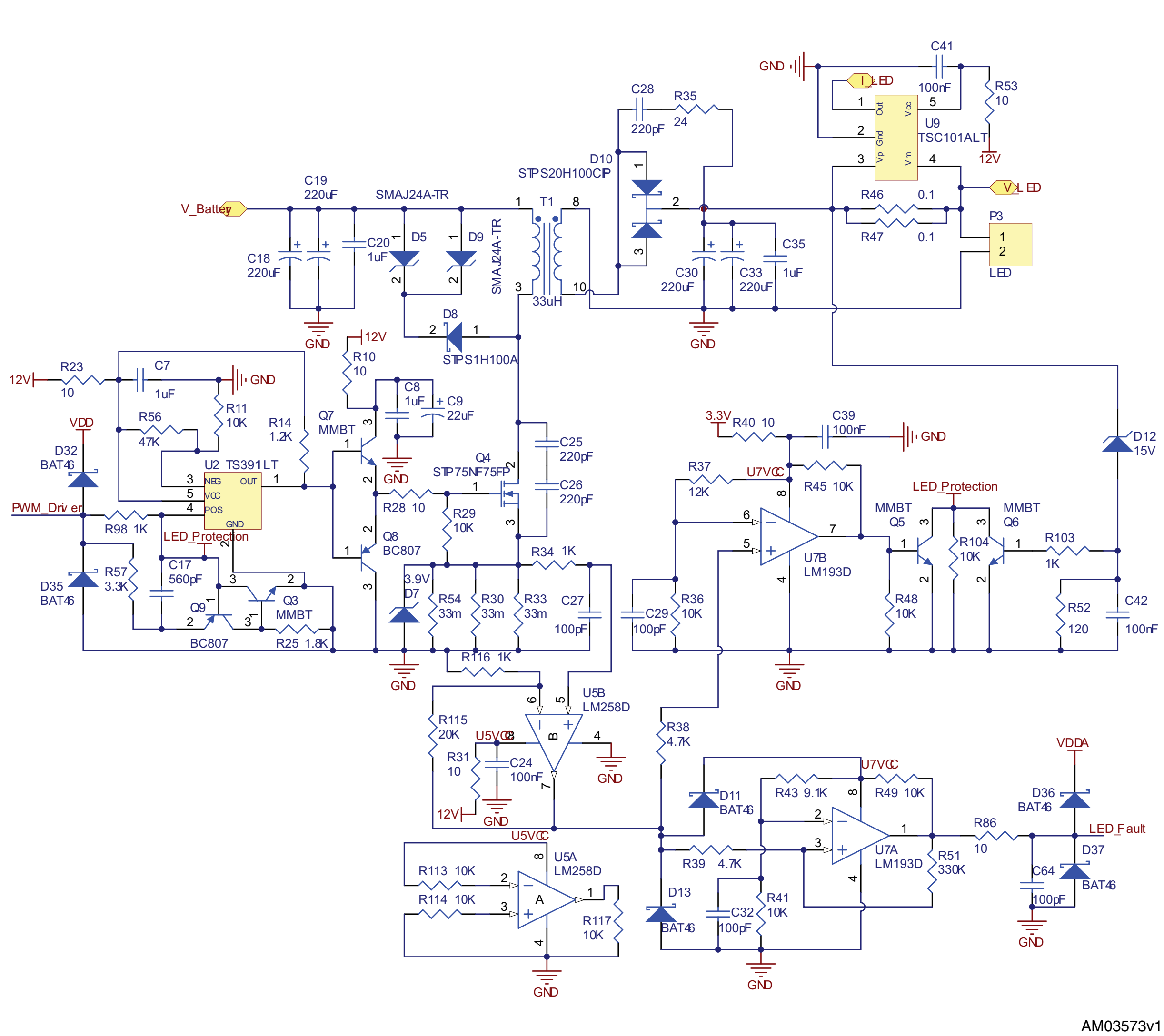
Figure 11. Battery charger circuit



3.1.3 LED lamp driving circuit

The LED lamp driver is designed with flyback topology. No isolation is required in this application. Flyback is suitable for a wide ratio range of output voltage to input voltage. The battery voltage is 11 V ~ 14.3 V while for the LED lamp, which is connected in a 3*7 matrix (3 LED lamps in series and 7 strings in parallel), the maximum LED voltage is defined as 12 V. The flyback converter keeps the LED current constant in the above-mentioned battery voltage range. In *Figure 12*, T1 is the flyback transformer and Q4 is the power MOSFET. D5 and D9 clamp the maximum voltage across Q4 in the off-state. D10 acts as the output rectifier and C30 and C33 are the output capacitors. R46, R47 and U9 are used to sense the LED lamp current and feedback to the MCU for constant current regulation. The PWM signal from the MCU is converted from TTL level to CMOS level via U2 and amplified by Q7 and Q8 to drive Q4. When OCP and/or OVP activate, Q3 and Q9 are used to guarantee a single turn-on within each switching cycle. The MOSFET current is sensed by resistors R30, R33 and R54 and amplified by U5B. The output of U5B is used to achieve OCP. There are two levels of OCP implemented in the LED lamp driver. The MOSFET current is sensed and transferred to comparators U7A and U7B. U7B sets the first current limit which is activated cycle by cycle. R37 and R36 form a voltage divider and set the threshold at the negative input of U7B. Overcurrent in the primary circuit of T1 results in high logic output of U7B, thus pulling down the voltage of the 'LED_Protection' node at the Q5 collector. Consequently, comparator U2 outputs low voltage and forces Q4 to shut down. In case a heavy overload or short-circuit occurs, such as a physical short-circuit of T1 or D10 which might exist for some time, a second level OCP is needed to protect the driver. R41 and R43 form another voltage divider and set a higher threshold. A high current spike from Q4 triggers the threshold and U7A generates 'LED_Fault' interrupt to the MCU. After receiving continuous interrupts, the MCU stops outputting the 'PWM_Driver' signal and waits for a certain time for the next try (refer to *Section 4.4*). Such burst mode operation definitely lowers the voltage stress and current stress on power components. The OVP of the LED lamp is achieved by D12. The principal is similar to that of the first level of OCP.

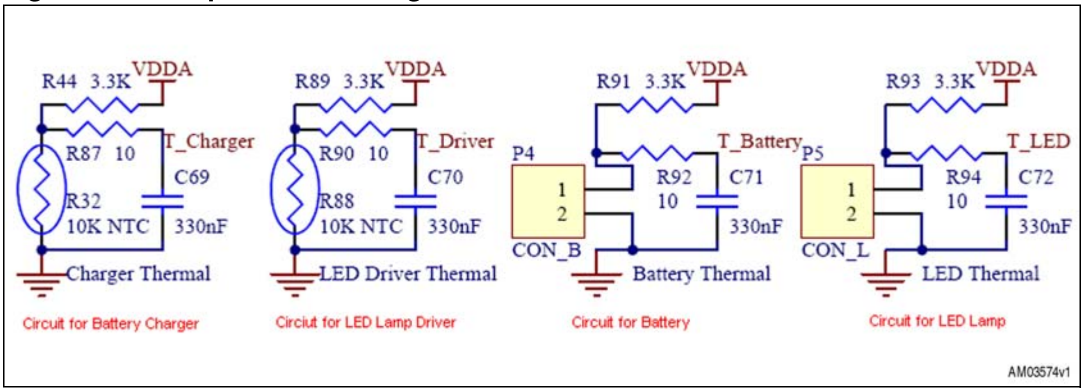
Figure 12. LED lamp driver circuit



3.1.4 Analog signal acquisition circuit

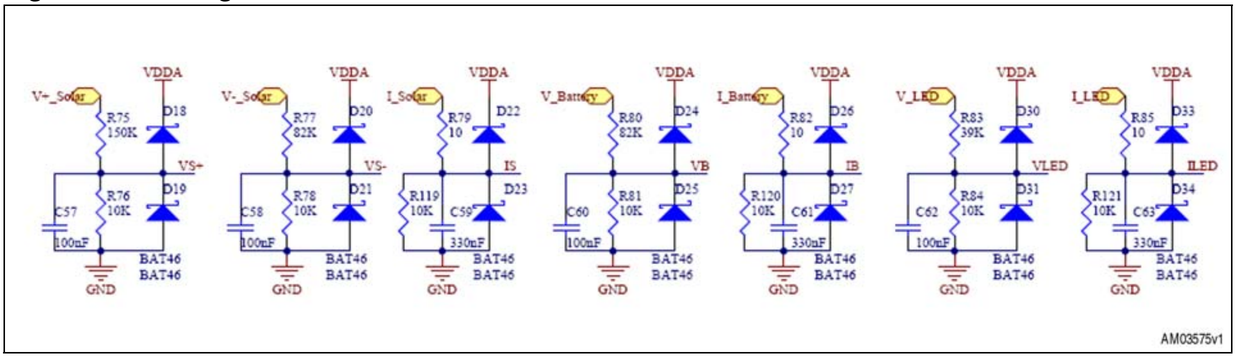
The operating voltage, current and temperature of the battery and LED lamp are monitored by the MCU. The temperature sensing circuits are illustrated in *Figure 13*. The voltage and current sensing circuits are shown in *Figure 14*. For the battery charger and LED lamp driver, NTC(s) is soldered on the heat sink of MOSFET (or rectifier). The operating temperature of the MOSFET (or rectifier) is sensed via NTC(s) and sent to the MCU. These key power components are protected against overtemperature. For the battery and LED lamp, the sensing NTC(s) is applied on the battery case and the heat sink of the LED lamp with wires connected to P4 and P5. For each temperature sensing circuit, a simple RC filter is added before the signal feeds to the MCU. The temperature sensing is not only for protection but also applicable for charge pattern optimization online. The battery life is prolonged.

Figure 13. Temperature sensing circuits



For the LED lamp, if the sensed temperature rises to a certain level, the LED lamp current is reduced to correspond to entering LP (low power) mode. The LED lamp is dimmed then without further increasing temperature, the LED lamp is shut down only when the sensed temperature rises to an even higher level. For all the voltage and current sensing, an RC filter and clamp circuit are added before the signal feeds to the MCU. Track routing of these sensing circuits should be done very carefully to avoid picking up noise, otherwise the noise influences the MCU and results in an unpredictable result.

Figure 14. Voltage and current detection circuit



3.2 Test results

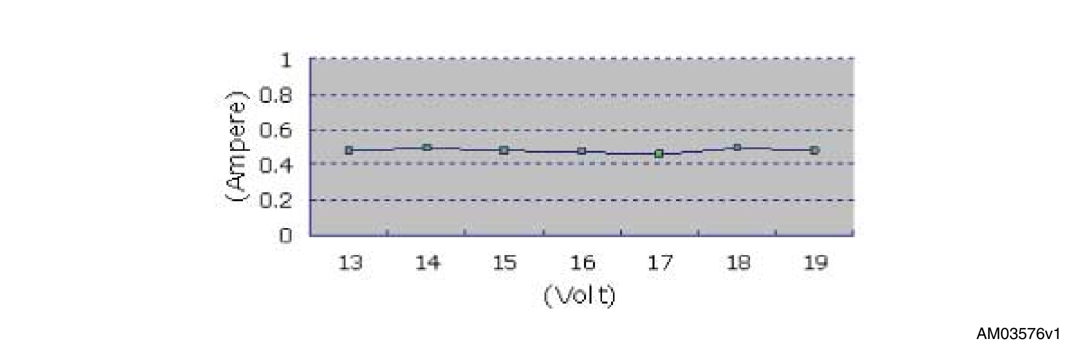
3.2.1 Battery charger

As discussed in *Section 2.4.1*, the battery charger operation is divided into 3 stages. This section shows us the test results for each stage.

- Stage 1:

In this stage, when $V_{BATTERY} < 11$ V, the controller executes the MPPT algorithm with current constraint $I_{BATTERY} < 0.5$ A. The charging current is shown in *Figure 15*.

Figure 15. Charging current versus solar module output voltage



The charging current is measured against different output voltages of the solar module. A DC source is used to simulate the solar module output and when its voltage changes from 13.1 V to 19.1 V, the charging current is limited to around 0.5 A. This demonstrates the proper operation of the first stage.

- Stage 2:

In stage 2, when 11 V < $V_{BATTERY}$ < 14.3 V, MPPT is implemented. To simulate the V-I curve of the solar module, the test method is proposed as shown in *Figure 16* with two important equations below.

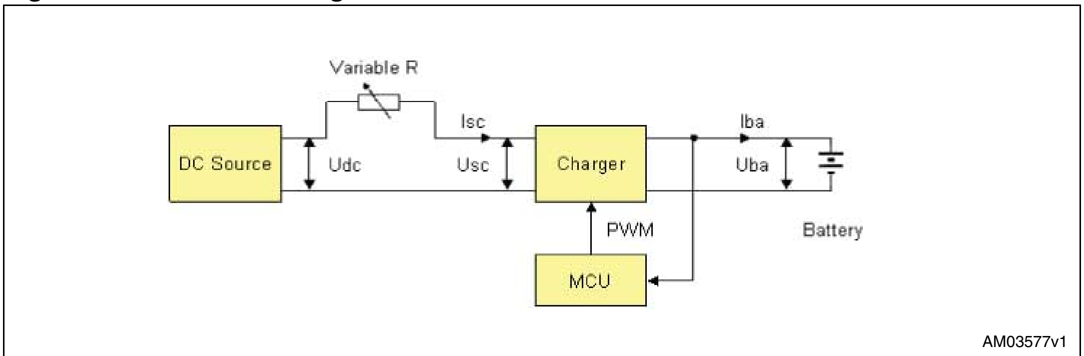
Equation 1

$$Usc = Udc - R \cdot Isc$$

Equation 2

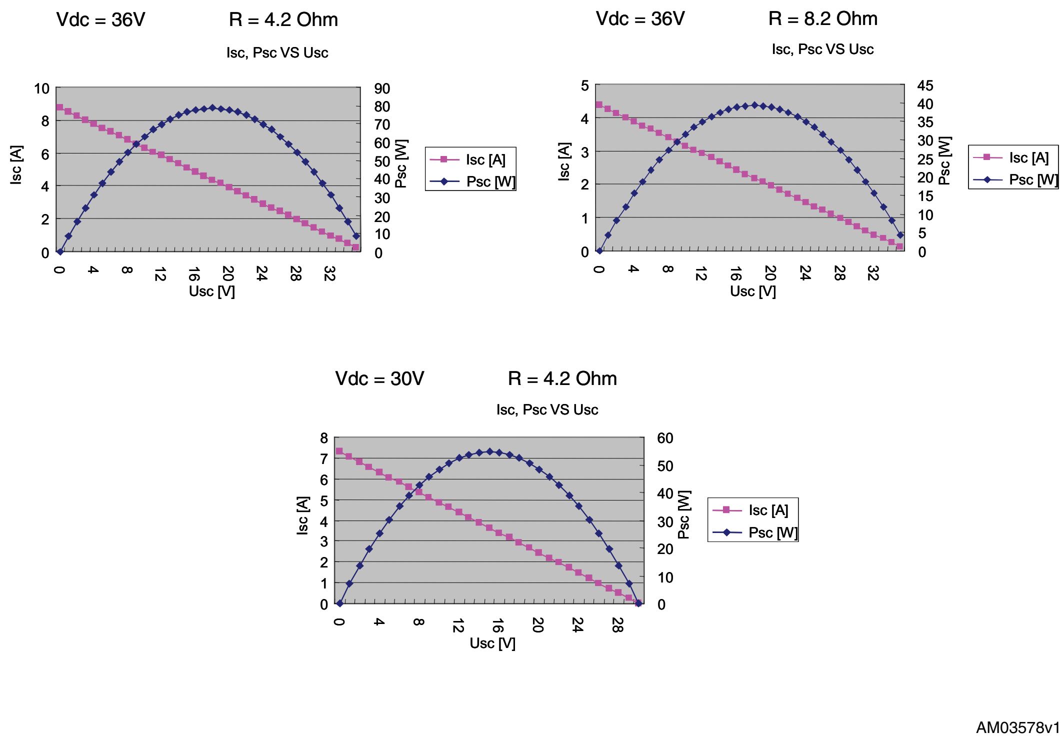
$$Psc = Usc \cdot Isc = (Udc - R \cdot Isc) \cdot Isc$$

Figure 16. MPPT test diagram



The V-I curves of this test system and charger power are shown in *Figure 17*.

Figure 17. V-I curve and P_{SC}



According to *Equation 1* and *Equation 2*, the maximum power point (MPP) occurs at Usc = 0.5 × Udc. A different R value results in different output power at the MPP delivered to the charger. From *Table 2* as long as Udc is 36 V, Usc is kept at18 V no matter what the R value is. *Table 3* shows the result with fixed R and variable Udc. Usc is always half of Udc during steady state. Thus the test diagram shows the way to find the MPP during the test.

Table 2. Test results for different values of R (Vdc = 36 V)

R[Ω]	Usc [V]	Isc [A]	Uba [V]	Iba [A]	Charger efficiency [%]
4.6	18.0	3.90	13.08	5.03	93.7
5.2	18.0	3.45	13.08	4.41	94.0
6.0	18.0	3.00	13.03	3.88	93.6
7.1	18.0	2.53	12.81	3.31	93.1
8.8	18.0	2.05	12.54	2.76	93.8
11.6	18.0	1.55	12.34	2.10	92.9
17.3	18.0	1.04	12.07	1.43	92.2
34.0	18.0	0.53	11.96	0.69	86.5

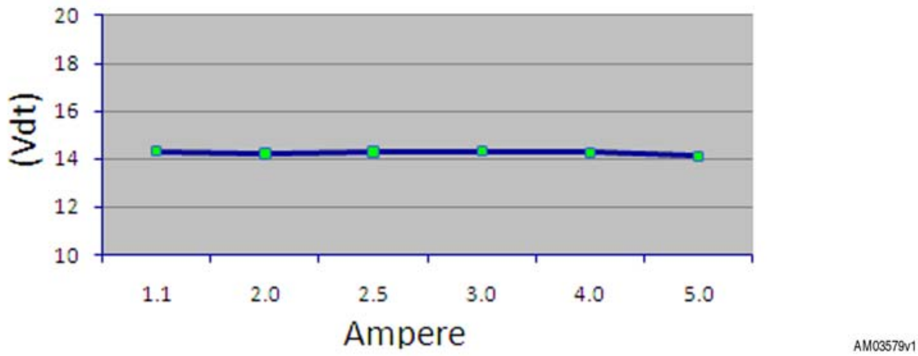
Table 3. Test results for different values of Vdc (R = 4.6 Ω)

Udc [V]	Usc [V]	Isc [A]	Uba [V]	Iba [A]	Charger efficiency [%]
36	18.0	3.90	13.08	5.03	93.7
35	17.5	3.80	12.99	4.79	93.6
34	17.0	3.65	12.90	4.57	95.0
33	16.5	3.50	12.82	4.33	96.1
32	16.0	3.48	12.73	4.12	94.2
31	15.5	3.38	12.65	3.90	94.2
30	15.0	3.30	12.57	3.69	93.7
29	14.6	3.17	12.47	3.48	93.8
28	14.4	2.97	12.39	3.26	94.4

- Stage 3:

In stage 3 when $V_{BATTERY} \geq 14.3$ V, the controller enters into floating charging, and Uba is limited to 14.3 V. *Figure 18* shows the battery voltage (Uba) and charging current (Iba) in this stage.

Figure 18. Battery voltage versus charging current



The result shows that with different charging currents, the battery voltage is kept at around 13.8 V and remains constant. *Figure 19* and *20* show the typical current output from the solar module and the current charged to the battery. Both currents are smooth and no large current ripple is observed. In *Figure 21* the inductor current waveform shows that the buck converter works at continuous current mode. Peak-to-peak current (IL) ripple is around 0.7 A. Such a small current ripple requires a small output capacitor. The turn-off switching voltage spike of the MOSFET (Vds) and diode (Vak) are very small in actuality.

Figure 19. Charger input current (Isc)

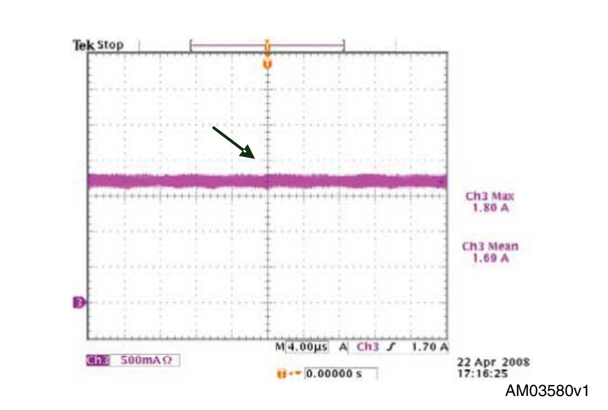


Figure 20. Charger output current (Iba)

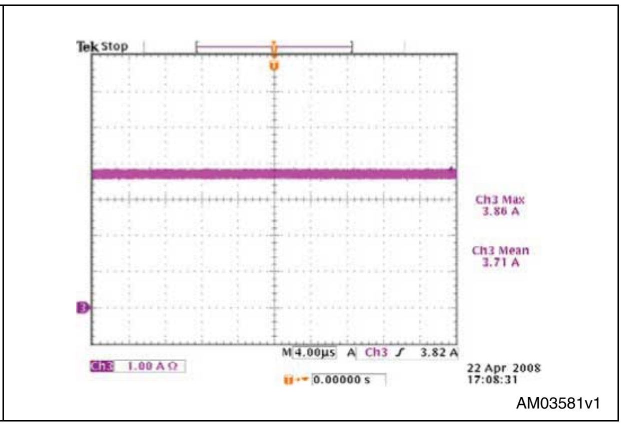
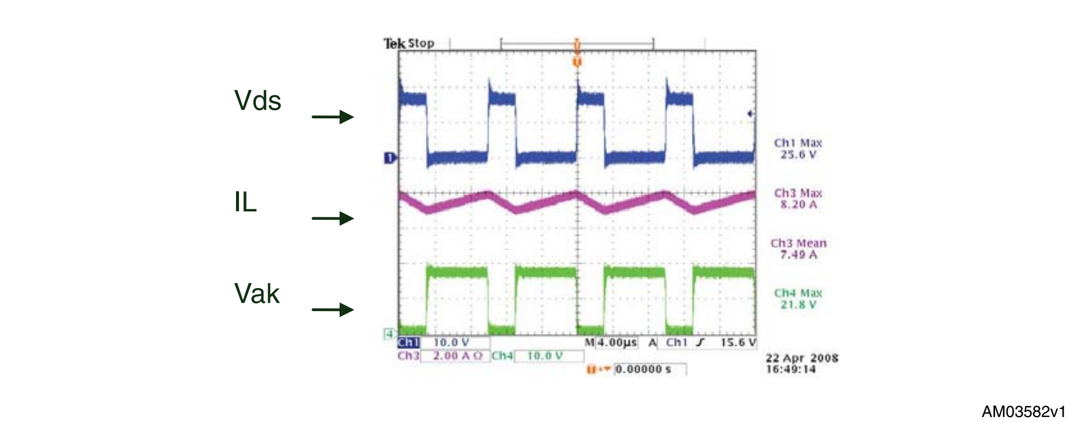


Figure 21. Vds on Q2, current on L2, and Vak on D4



3.2.2 LED driver

The LED driver provides the LED lamp with constant current for different battery and lamp voltages. The LED currents are shown in *Figure 22* and *23*.

Figure 22. LED lamp current, efficiency vs. battery voltage

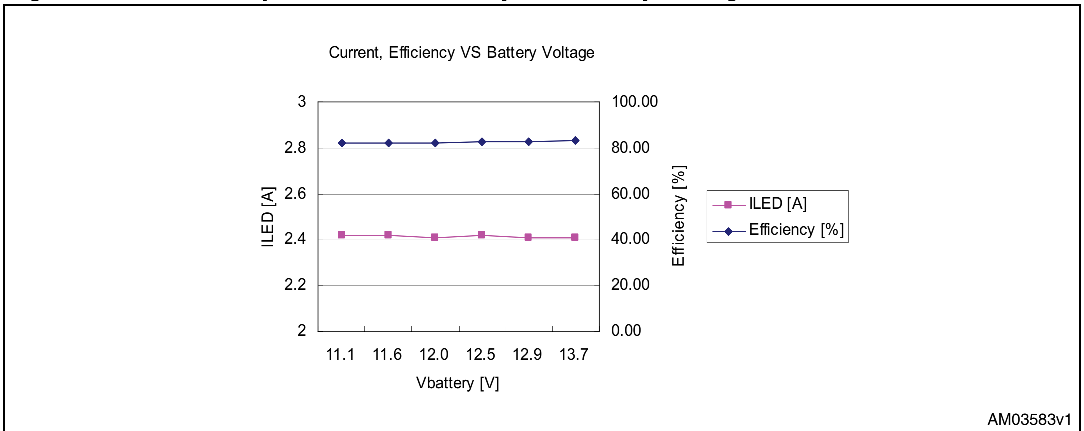
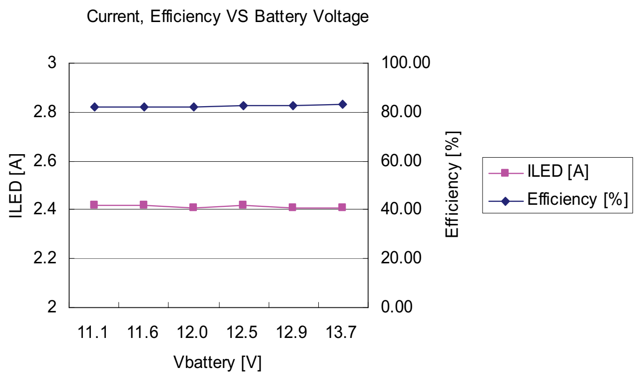


Figure 23. LED current, efficiency vs. LED voltage



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LED current is constantly regulated with different lamp and battery voltages. The measured efficiency is around 82%. The efficiency is not high when compared to a buck converter, but it can keep LED current constant for a large input voltage range. *Figure 24* and *25* show some typical waveforms for LED drivers.

Figure 24. Driver input current

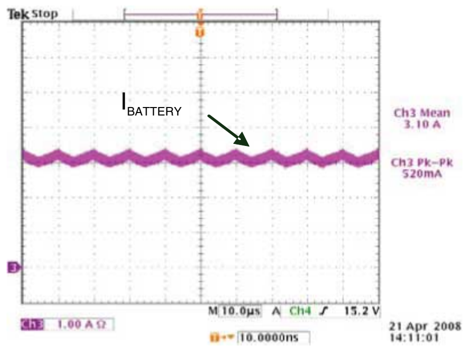

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Figure 25. Driver output current

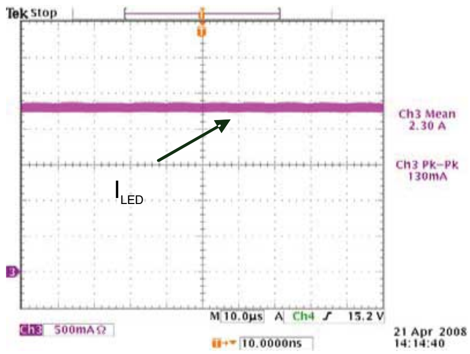

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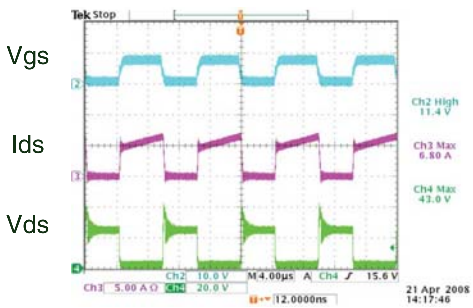
Figure 26. Vgs, Ids, and Vds on Q4



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4 Firmware design

In accordance with the main functions of the controller described in *Section 2.4*, solar-LED lamp controller firmware also consists of the following 3 main modules:

- Battery charging management
- LED lamp driving management
- System monitoring circuit

The main loop in *Section 4.1* coordinates the above 3 function modules. All the reference parameters are listed in *Table 4*.

Table 4. Firmware reference parameters

Parameter	Value	Description
U_{SC}-th1	7.0 V	Lower threshold of solar cell cathode voltage
U_{SC}-th2	15.0 V	Upper threshold of solar cell cathode voltage
U_{SC}th	5.0 V	Solar cell voltage threshold for detecting day and night
U_{BAT}th1	10.0 V	Lower limit voltage for battery
U_{BAT}th2	11.0 V	Empty charge voltage for battery
U_{BAT}th3	13.8 V	Full charge voltage for battery
U_{BAT}th4	14.5 V	Upper limit voltage for battery
U_{LED}th	13.0 V	Upper limit voltage for LED
I_{SC}th	0.5 A	Current threshold for switching on/off K_{CHG}
I_{BAT}th1	0.5 A	Charging current for battery (deep discharge)
I_{BAT}th2	8.0 A	Upper limit of charging current for battery
I_{LED}th1	2.0 A	Current for LED (LP mode)
I_{LED}th2	2.45 A	Nominal current for LED
I_{LED}th3	2.8 A	Upper limit current for LED
T_{CHG}th1	60 ºC	Recovery temperature for battery charger
T_{CHG}th2	90 ºC	Upper limit temperature for battery charger
T_{BAT}th1	30 ºC	Recovery temperature for battery
T_{BAT}th2	45 ºC	Upper limit temperature for battery
T_{DRV}th1	60 ºC	Recovery temperature for LED driver
T_{DRV}th2	90 ºC	Upper limit temperature for LED driver
T_{LED}th1	80 ºC	Threshold temperature to enter LP mode for LED
T_{LED}th2	100 ºC	Upper limit temperature for LED
Timth1	1 sec	Cool down period for recovery
Timth2	1 min	Continuous sensing time for day & night judgment
Timth3	1 ms	Response time of PWM output
Timth4	10 min	MPPT self-calibration time interval

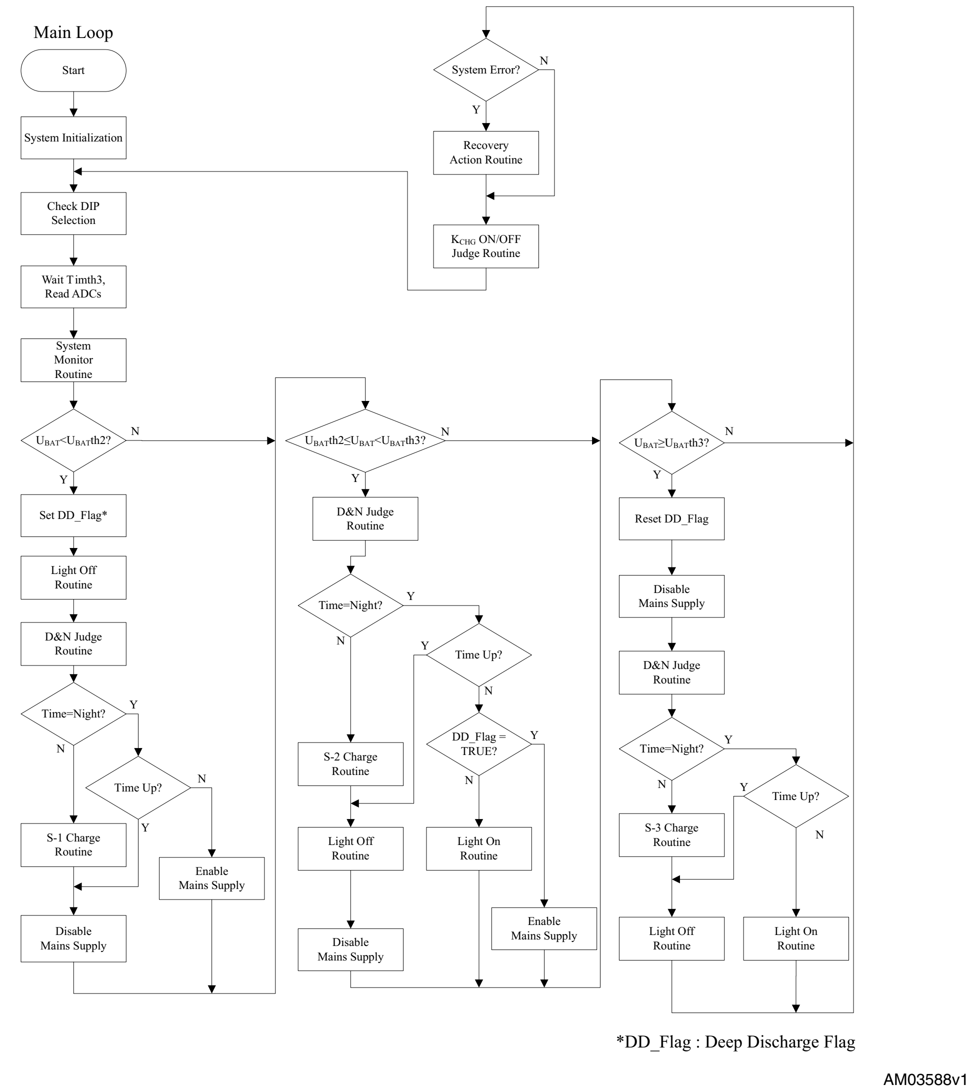
Table 4. Firmware reference parameters (continued)

Parameter	Value	Description
EXTIth	3	Number of times that LED_Fault EXTI has been triggered
Δ	1 system clock cycle (~28 ns)	Step of duty cycle adjustment (may not be constant)

4.1 Main loop

In the main loop in *Figure 27*, the parameter 'Timth3' restricts the execution time of every loop within around 1 ms to make sure system is in steady state after changing the duty cycle of the battery charger or LED lamp driving. A loop speed that is too fast might cause an inaccurate value to be processed by the ADC.

Figure 27. Main loop flowchart



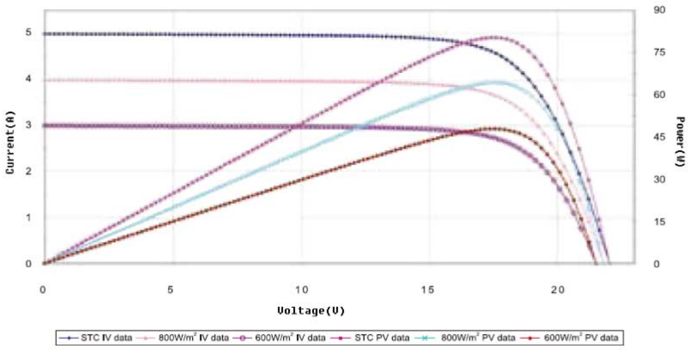
Once the battery is deeply discharged, and the voltage falls below 'U_{BAT}th2', the MCU stops driving the LED lamp immediately. For battery life cycle considerations, the battery cannot be discharged until it is fully charged. DD_Flag is set when $U_{BAT} < U_{BAT}$th2 and is reset when $U_{BAT} \geq U_{BAT}$th3.

4.2 Battery charging management

4.2.1 MPPT principle

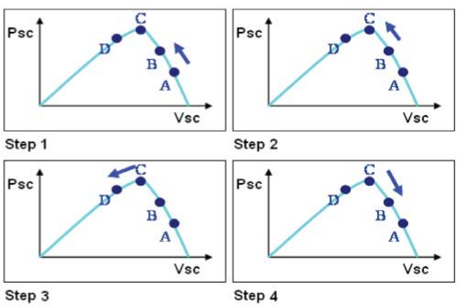
The objective of the MPPT algorithm is to get the maximum battery charging power. Taking into account the charger efficiency, this is the most efficient way to utilize solar energy. In *Figure 28* there exists a maximum power point for each curve.

Figure 28. 80 W solar module I-V and P-V curve



In actual conditions, the I-V curve and P-V curve of the solar module change with different irradiance and temperature which means the charging current cannot remain constant even when the charging voltage is fixed. This kind of state causes the MPPT algorithm to be adaptive and dynamic. The solar-LED streetlight controller adopts one of the MPPTs, i.e. P&O (perturbation and observation) method.

Figure 29. P and O method



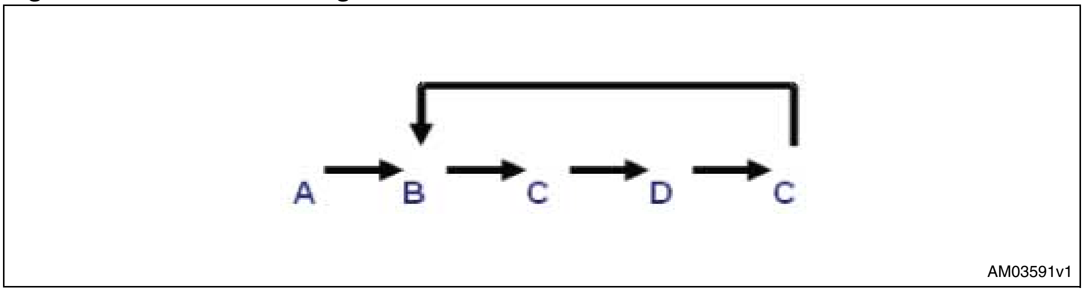
1. Step 1: Suppose the charger is working at point A, the duty cycle is DC(A). At the next step, the MCU increases the duty cycle to DC(B). The charger then moves to point B at

steady state. Since the resulted power at point B is higher than the power at point A, the MCU continues to increase the duty cycle.

2. Step 2: The MCU increases the duty cycle from DC(B) to DC(C). During steady state the charger operates at point C. Because the power at point C is still higher than the power at point B, the MCU keeps the same trend and increases the duty cycle.
3. Step 3: The charger now moves to point D after the MCU increases the duty cycle from DC(C) to DC(D). Since the power at point D is lower than the power at point C, the MCU reverses the direction. At the next step, it decreases the duty cycle and moves to C.
4. Step 4: The MCU keeps decreasing duty cycle from DC(C) to DC(B). After detecting that the power at B point is lower than that at C point, MCU reverses direction again. Then system comes back to step 2.

The P&O tracing route can be described as shown in *Figure 30*. This tracing route explains that the MPPT algorithm is dynamic. The charger does not operate at a fixed point, and it works within a certain range that the maximum power point locates.

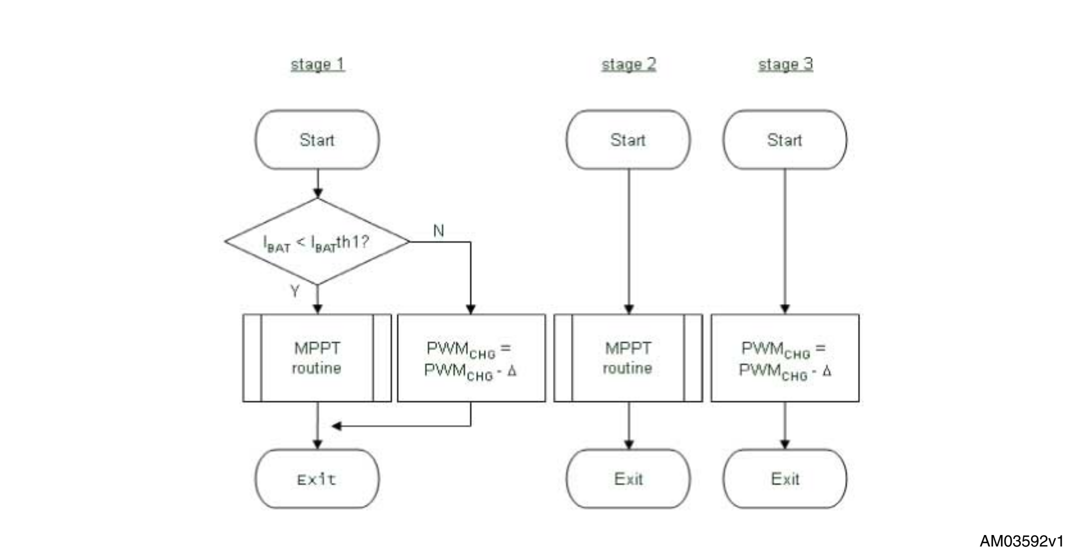
Figure 30. P and O tracing route



The P&O method is based on the fact that the P-V curve remains almost unchanged during a very short time period. Generally, the MCU executes each P&O step in several milliseconds, while the P-V curve drift caused by environmental change usually takes a few seconds or even several minutes, which is much longer. The P&O method is a feasible method to achieve MPP tracking.

4.2.2 Battery charging management

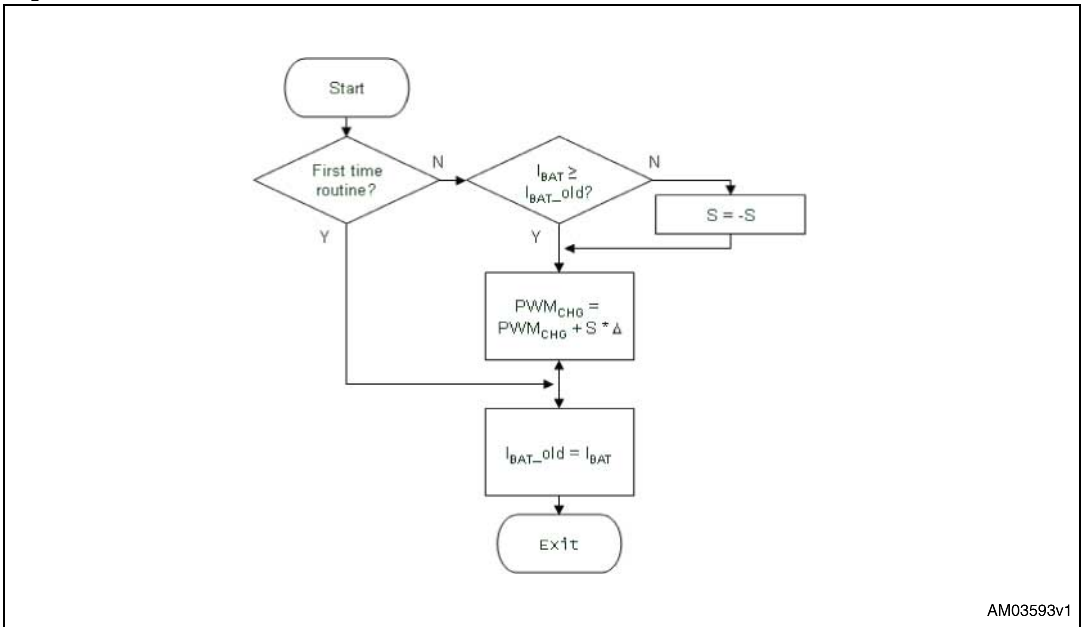
Figure 31. Three-stage charging routine



The battery charging flowchart is illustrated in *Figure 31*. The MPPT algorithm is involved in stage 1 and stage 2 charging. The stage 1 is a current constraint. In stage 3, the charger keeps changing the charging current to maintain a constant charging voltage.

The MPPT algorithm illustrated in *Figure 32*, simplifies the conventional P&O method. Since battery voltage cannot drastically change in a short period, the maximum power point must lie on the maximum current point. This allows the MCU to compare current instead of a power comparison which is more complex for an embedded system.

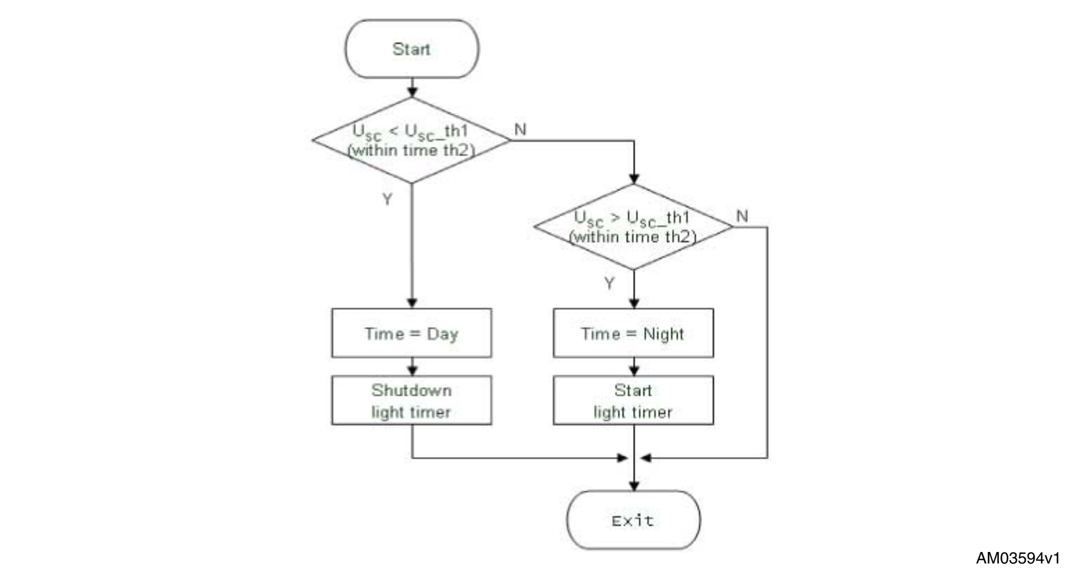
Figure 32. MPPT flowchart



4.3 LED lamp driving management

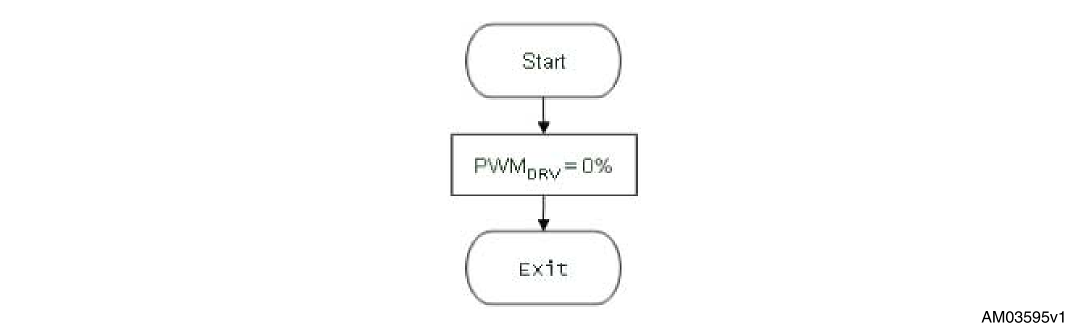
The controller judges whether there is sufficient ambient light (daytime) or weak ambient light (nighttime) by detecting the solar module voltage. When the ambient light becomes weak, the solar module voltage might fall below a certain level. If the voltage does not exceed this level for a period, the controller considers that it is nighttime. The parameter 'Timth2' is used to avoid misjudgment caused by very cloudy weather or a solar eclipse. The day and night judgment routine is illustrated in *Figure 33*.

Figure 33. Ambient light sensing flowchart (day and night judgment)



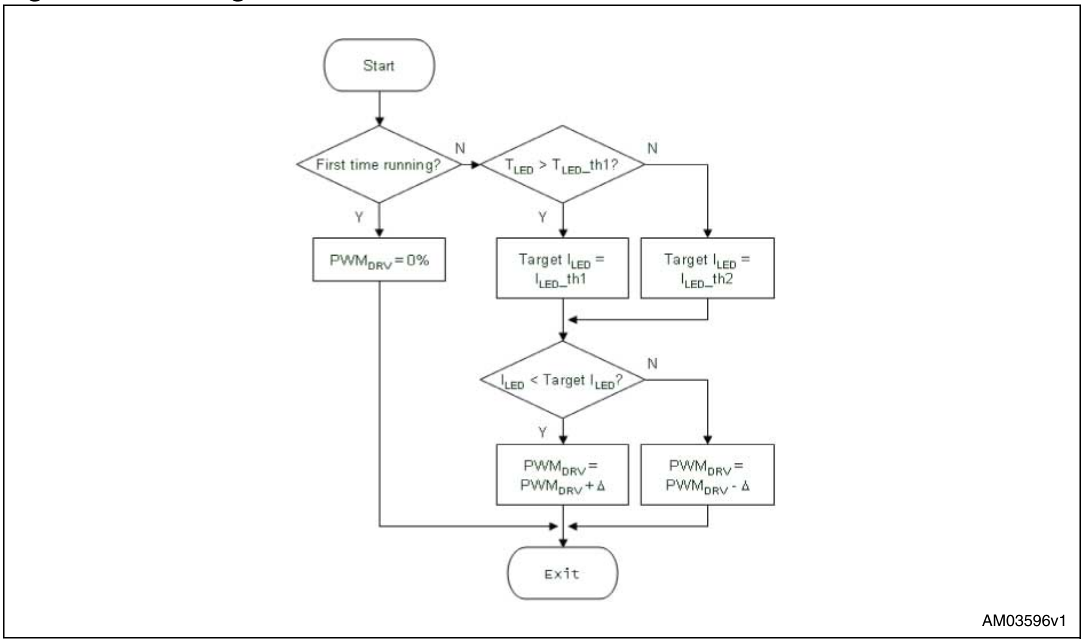
Once the controller detects that it is night and starts to turn on the LED, the light-on routine increases the duty cycle of the LED driver by 'Δ' for every loop. LED driving is implemented by constant current control. Generally, it takes 200 ms ~ 300 ms to reach the nominal current. For streetlight applications, this startup time is acceptable. *Figure 34* shows light-off routines for LED lamp driving. The LED lamp does not turn on if PWM driving is zero.

Figure 34. LED light-off routine



To turn on the LED lamp perfectly, the MCU also detects the LED lamp temperature. In *Figure 35* when the LED temperature exceeds 'T_{LED}th1', the controller reduces the target current to enter LP mode (low power). The LP mode has been introduced in *Section 3.1.4*. This action is to prevent loss of efficiency at a high temperature for the LED and to extend the LED life cycle as well.

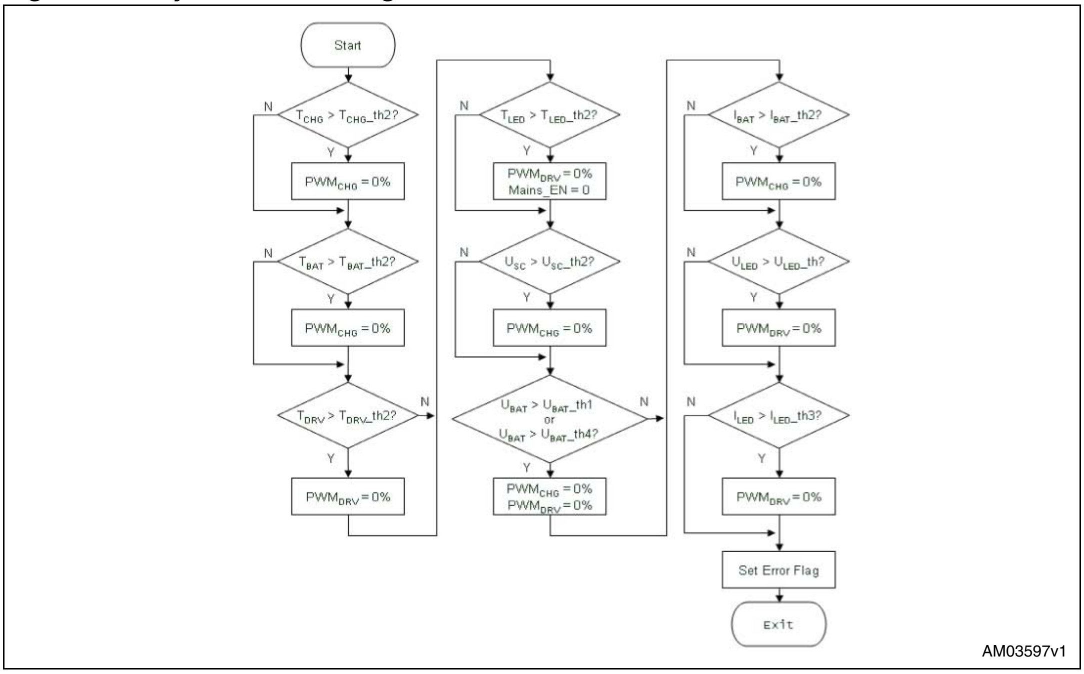
Figure 35. LED light-on routine



4.4 System monitoring management

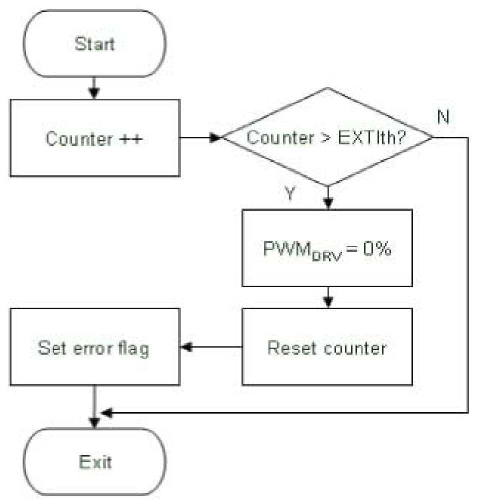
The system monitoring routine is executed at the beginning of every loop. It checks if voltage, current or temperature is abnormal or not. A corresponding protective action is implemented and 'ErrorFlag' is set if any error occurs. The controller maintains the protective action until 'ErrorFlag' is cleared by the system recovery routine. The flowchart is shown in *Figure 36*.

Figure 36. System monitoring flowchart



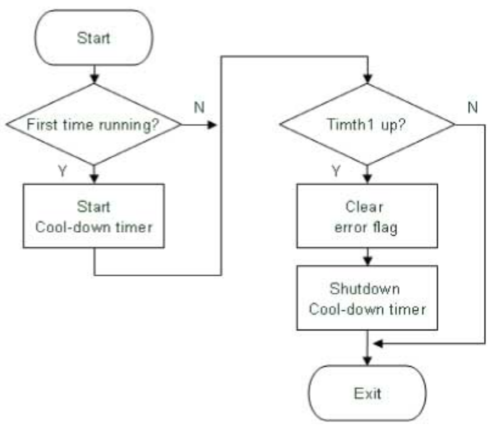
In system monitoring management, LED_Fault IRQ is the only interrupt to trigger the MCU EXTI peripheral which is implemented by the hardware and firmware. In some abnormal situations, the primary current of LED driving might rise radically, and then the pulse-shaped LED_Fault signal is generated by a comparator. Several rising edges of this interrupt in EXTI tell the controller to stop driving the LED and wait for system recovery. The flowchart is shown in *Figure 37*.

Figure 37. LED_fault IRQ flowchart



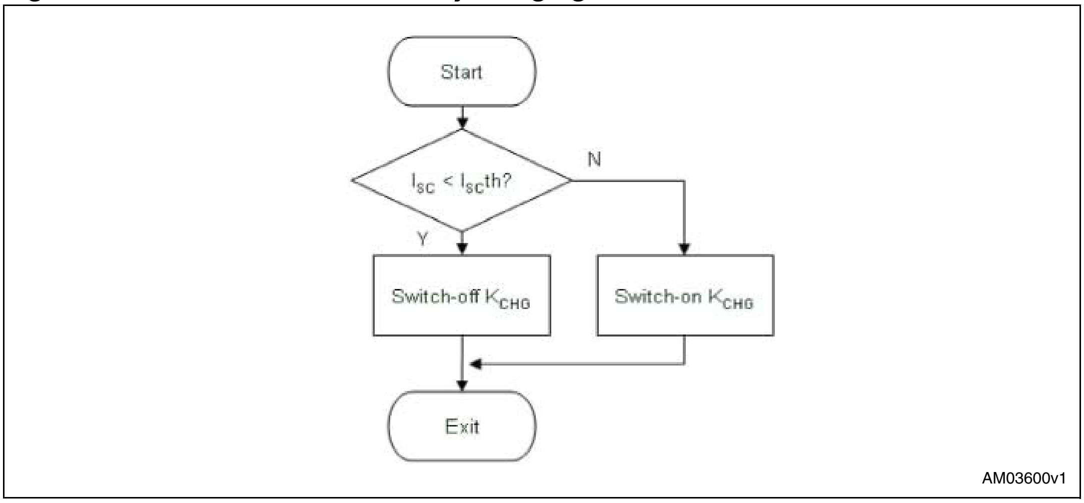
A complete monitoring system should include a self-recovery function. Every second, which is defined by 'Timth1', the controller tries to recover system errors by clearing 'ErrorFlag'. This enables all the error functions paused at the last system monitoring routine to run again. The system self-recovery flowchart is shown in *Figure 38*.

Figure 38. System self-recovery flowchart



To prevent battery power backflow through the charger, K_{CHG} should be turned off when charging current is very low. In normal conditions, K_{CHG} is turned on to reduce power loss in its body diode. The flowchart of anti-backflow for the battery charger is shown in *Figure 39*.

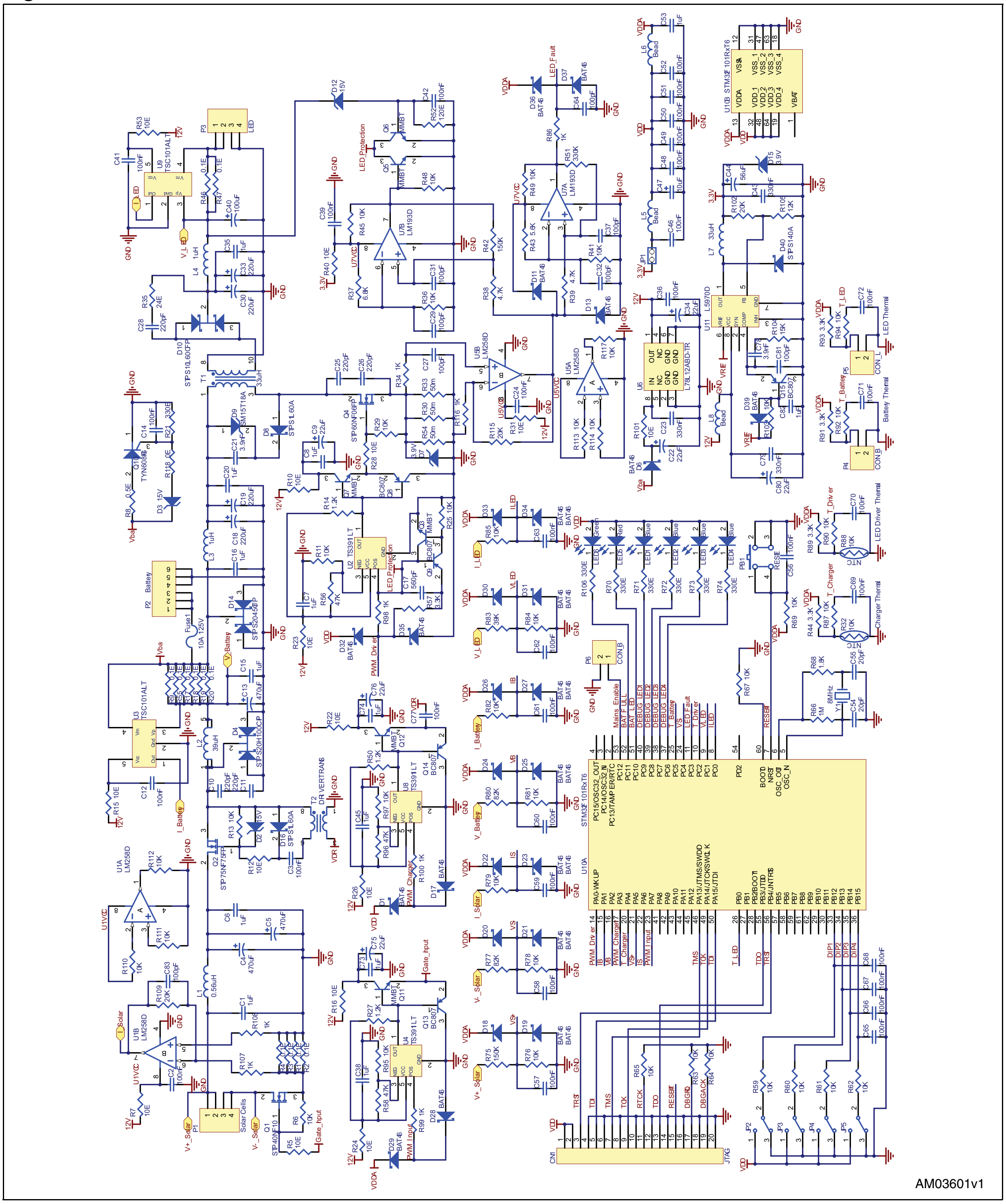
Figure 39. Anti-backflow for battery charging flowchart



5 Overview of demonstration board

5.1 Application schematic

Figure 40. Schematic



5.2 Application board

Figure 41. Top view of demonstration board

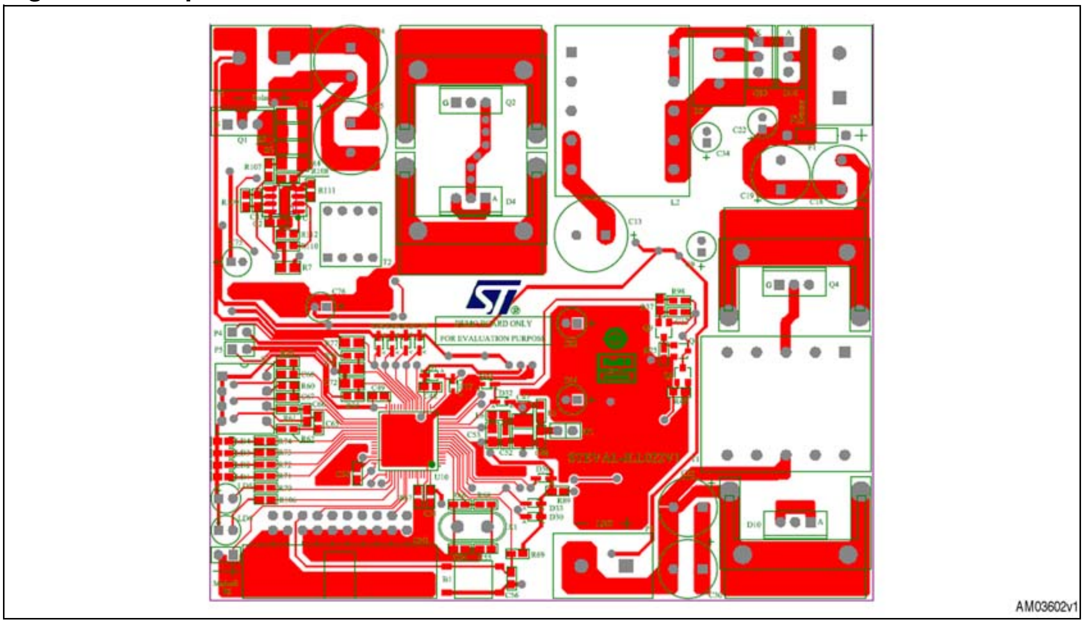
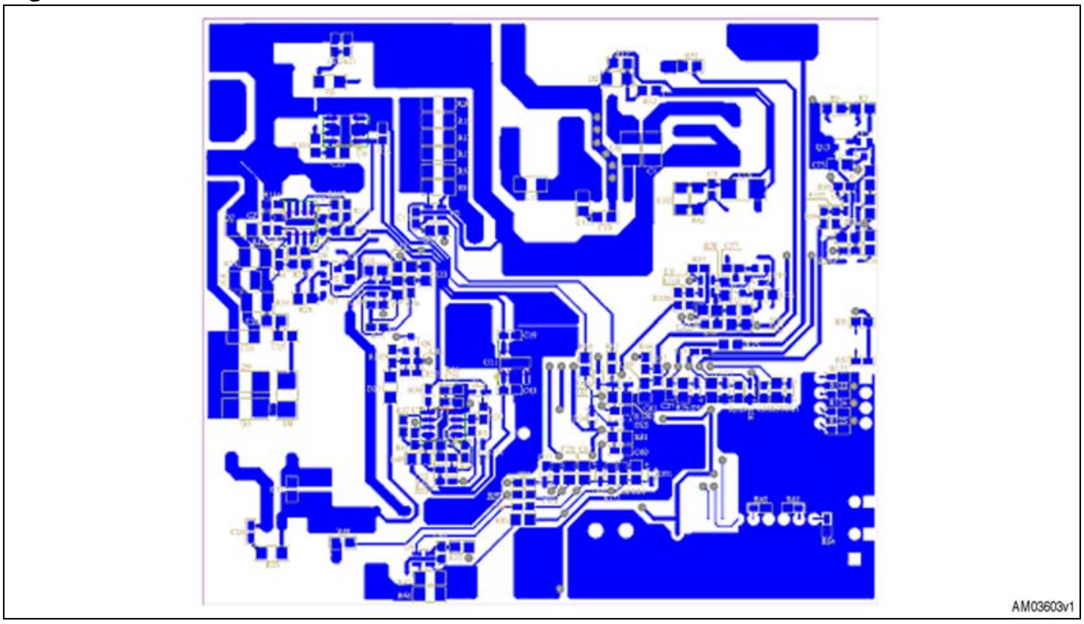


Figure 42. Bottom view of demonstration board



5.3 Bill of material

Table 5. BOM

Name	Value	Rated	Type
B1	One way 6x6 mm	(SMD), 4.3 mm(H), tactile switch	OMRON
C1, C6	1 µF	(1210), 100 V, ceramic capacitor	
C2, C3, C12, C14, C24, C36, C39, C41, C42, C43, C46, C48, C49, C50, C51, C52, C56, C57, C58, C60, C62, C65, C66, C67, C68, C77, C79	100 nF	(0603), 50 V, ceramic capacitor	
C4, C5, C13	470 µF	63 V, Al-cap electrolytic capacitor	Rubycon
C7, C8, C35, C38, C45, C53, C73, C74	1 µF	(0805), 25 V, ceramic capacitor	
C9, C22, C34, C44, C75, C76, C80	22 µF	50 V, Al-cap electrolytic capacitor	Rubycon
C10, C11, C25, C26	220 pF	(0805), 50 V, ceramic capacitor	
C15, C20	1 µF	(1206), 50 V, ceramic capacitor	
C17	560 pF	(0603), 50 V, ceramic capacitor	
C18, C19, C30, C33	220 µF	50 V, Al-cap electrolytic capacitor	Rubycon
C23, C59, C61, C63, C69, C70, C71, C72,	330 nF	(0805), 50 V, ceramic capacitor	
C27, C29, C32, C64, C83	100 pF	(0603), 50 V, ceramic capacitor	
C28	220 pF	(0603), 250 V, ceramic capacitor	
C47	10 µF	(3528-21), 16 V, tantalum	VISHAY
C54, C55	20 pF	(0603), 50 V, ceramic capacitor	
CN1	20-way box header	(Right angle mounting), JTAG connector	Tyco electronics
D1, D11, D13, D17, D18, D19, D20, D21, D22, D23, D24, D25, D26, D27, D28, D29, D30, D31, D32, D33, D34, D35, D36, D37	BAT46JFILM	(SOD323), small signal Schottky diode	STMicroelectronics
D2, D3, D12	15 V	(SOD 80C), Zener diode	
D4, D10	STPS20H100CFP	(TO-220FPAB), power Schottky rectifier	STMicroelectronics
D5, D9	SMAJ24A-TR	(SMA or DO-214AC), 24V 400W Transil™ (TVS)	STMicroelectronics
D7	3.9 V	(SOD 80C), Zener diode	
D8	STPS1H100A	(SMA or DO-214AC), power Schottky rectifier	STMicroelectronics
D14	STPS2045CFP	(TO-220FPAB), power Schottky rectifier	STMicroelectronics

Table 5. BOM (continued)

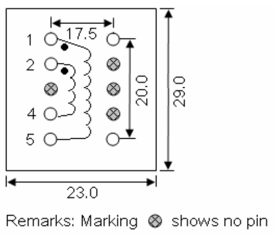
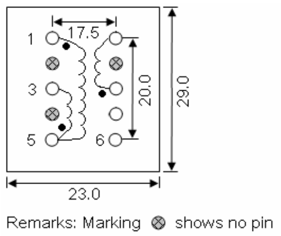
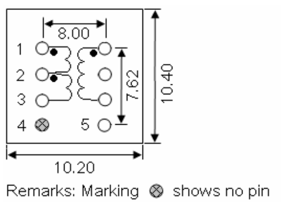
Name	Value	Rated	Type
D16	STPS1L60A	(SMA or DO-214AC), power Schottky rectifier	STMicroelectronics
F1	10 A	(2.54 x 7.2 mm, axial lead), 251 series fuse	Littelfuse®
JP1 (see *Table 6*)	0.64x0.64 mm, 2 way	2.54 mm pitch, Pin strip header	3M
L2 (see *Table 6*)	39 µH	Inductor	BOBITRANS
L5, L6	600 Ω @ 100 MHz	(0603), Chip ferrite bead, 25%, 200mA max.	MuRata
LD1, LD2, LD3, LD4	80 mcd, yellow	(0603), LED	VISHAY
LD5	45 mcd, red	(3.0, diffused, radio lead), LED	VISHAY
LD6	10 mcd, green	(3.0, undiffused, radio lead), LED	VISHAY
P1, P2, P3	Terminal block	2 Terminal, pitch 7.5 mm	DEGSON®
P4, P5, P6	Header, 2 pin	HDR1x2, pitch 2.54 mm	
Q1	STP40NF10	(TO-220), N-channel MOSFET	STMicroelectronics
Q2, Q4	STP75NF75FP	(TO-220FP), N-channel MOSFET	STMicroelectronics
Q3, Q5, Q6, Q7, Q11, Q12	MMBTA42	(SOT-23), NPN bipolar transistor	STMicroelectronics
Q8, Q9, Q13, Q14	BC807	(SOT-23), PNP bipolar transistor	
Q10	TYN616RG	(TO-220AB), Triac	STMicroelectronics
R1, R2, R3, R4, R9, R17, R18, R19, R20, R46, R47, R55	0.1 Ω	(1206), 1%, resistor	
R5, R7, R10, R12, R15, R16, R22, R23, R24, R26, R28, R31, R40, R53, R101	10 Ω	(0805), 1%, resistor	
R6, R13, R29	10 kΩ	(0805), 5%, resistor	
R8	0.2 Ω	(Axial lead), cement, 2 W, resistor	TOKEN®
R11, R45, R48, R49, R59, R60, R61, R62, R63, R64, R65, R67, R69, R95, R97, R104, R105, R110, R111, R112, R113, R114, R117, R118, R119, R120, R121, R122, R123, R124, R125	10 kΩ	(0603), 5%, resistor	
R14, R27, R50	1.2 kΩ	(0805), 5%, resistor	
R21, R70, R71, R72, R73, R74, R106	330 Ω	(0603), 5%, resistor	
R25	1.8 kΩ	(0603), 5%, resistor	
R30, R33, R54	33 mΩ	(1210), 1%, resistor	

Table 5. BOM (continued)

Name	Value	Rated	Type
R32, R88	NTC, 10 kΩ	(0805), NTC resistor	
R34, R107, R108, R116	1 kΩ	(0603), 1%, resistor	
R35	24 Ω	(1206), 5%, resistor	
R36, R41	10 kΩ	(0603), 1%, resistor	
R37	12 kΩ	(0603), 1%, resistor	
R38, R39	4.7 kΩ	(0603), 5%, resistor	
R102	560 Ω	(1206), 5%, resistor	
R43	9.1 kΩ	(0603), 1%, resistor	
R44, R89, R91, R93	3.3 kΩ	(0603), 1%, resistor	
R51	330 kΩ	(0603), 5%, resistor	
R52	120 Ω	(0603), 5%, resistor	
R56, R58, R96	47 kΩ	(0603), 5%, resistor	
R57	3.3 kΩ	(0603), 5%, resistor	
R66	1 MΩ	(0603), 1%, resistor	
R68	1.8 kΩ	(0603), 1%, resistor	
R75	150 kΩ	(0805), 1%, resistor	
R76, R78, R81, R84	10 kΩ	(0805), 1%, resistor	
R77, R80	82 kΩ	(0805), 1%, resistor	
R79, R82, R85, R86, R87, R90, R92, R94	10 Ω	(0603), 5%, resistor	
R83	39 kΩ	(0805), 1%, resistor	
R98, R99, R100, R103	1 kΩ	(0603), 5%, resistor	
R109, R115	20 kΩ	(0603), 1%, resistor	
S1	DIP Switch	4 Position DIP Switch	
T1 (see *Table 6*)	33 µH	EER25.5, transformer	BOBITRANS
T2 (see *Table 6*)	1 mH	Driver transformer	BOBITRANS
U1, U5	LM258D	(SO8 narrow), dual operational amplifiers	STMicroelectronics
U2, U4, U8	TS391ILT	(SO), single voltage comparator	STMicroelectronics
U3, U9	TSC101AILT	(SO), current sense IC	STMicroelectronics
U6	L78L12ABD-TR	(SO8 narrow), positive voltage regulator	STMicroelectronics
U7	LM193D	(SO8), dual voltage comparator	STMicroelectronics
U10	STM32F101RXT6	(LQFP64), 32-bit microprocessor	STMicroelectronics
U11	L4931ABD33-TR	(SO8 narrow), linear regulator	STMicroelectronics
X1	8 MHz	(ϕ3x8) crystal oscillator	Yuechung International Corp.

Note: STM32F101R4, STM32F101R6, STM32F101R8, STM32F101RB, STM32F101RC STM32F101RD, STM32F101RE are all equivalent for this purpose.

Table 6. Pin strip header

Figure	Description
Accessory for JP1	M20 series jumper socket
	L2 – 1: 39 µH +/- 4% (W1//W2 and twisted) – 2: Winding 1: pin 1 to pin 5 (18 turns CCW) – 3: Winding 2: pin 2 to pin 4 (18 turns CCW) – 4: Wire gage: AWG31*20 – 5: Core: EER28-Z-PC40 – 6: Bobbin: BEER28-1110CPFR
	T1 – 1: 33 µH +/- 4% (W1+W3 @ 50 kHz, 1VRMS) – 2: Leakage < 0.1 µH (W2 short-circuit) – 2: Winding 1: pin 1 to pin 5 (5 turns CCW) – 3: Winding 2: pin 8 to pin 10 (10 turns CCW) – 4: Winding 3: pin 5 to pin 3 (5 turns CCW) – 4: Wire gage: AWG31*20 – 5: Core: EER28-Z-PC40 – 6: Bobbin: BEER28-1110CPFR
	T2 – 1: 1 mH (W1+W3 @ 50 kHz, 1VRMS) – 2: Leakage < 10 µH (W2 short-circuit) – 3: No air-gap is required – 2: Winding 1: pin 1 to pin 2 (17 turns CCW) – 3: Winding 2: pin 8 to pin 6 (34 turns CCW) – 4: Winding 3: pin 2 to pin 3 (17 turns CCW) – 4: Wire gage: AWG31 – 5: Core: EE10/11-Z-PC40 – 6: Bobbin: BE10-118CPSFR

6 References

1. "BAT46JFILM, Small signal Schottky diode" (datasheet)
2. "STPS20H100CFP, Power Schottky rectifier" (datasheet)
3. "STPS1L60A, power Schottky rectifier" (datasheet)
4. "STPS2045CFP, power Schottky rectifier" (datasheet)
5. "SMAJ24A-TR, 24 V 400 W Transil^{TM}" (datasheet)
6. "STPS1H100A, power Schottky rectifier" (datasheet)
7. "MMBTA42, NPN bipolar transistor" (datasheet)
8. "STP40NF10, N-channel power MOSFET" (datasheet)
9. "STP60NF06FP, N-channel power MOSFET" (datasheet)
10. "STP75NF75FP, N-channel power MOSFET" (datasheet)
11. "TYN616RG, Triac" (datasheet)
12. "LM258D, Low power dual operational amplifiers" (datasheet)
13. "TS391ILT, Single voltage comparator" (datasheet)
14. "TSC101AILT, current sense IC" (datasheet)
15. "L78L12ABD, positive voltage regulator" (datasheet)
16. "STM32F101RXT6, 32-bit microcontroller" (datasheet)

7 Revision history

Table 7. Document revision history

Date	Revision	Changes
16-Oct-2009	1	Initial release.
28-Sep-2010	2	– For easy mount and better operating life of demo-board, below type of connectors are changed. 1: P1: Solar panel connector 2: P2: Battery connector 3: P3: LED lamp connector – MCU reset switch is renamed as B1. – Battery use only 12VDC. Below figures are renew according to the modification. – *Figure 1*, *6*, *7*, *9*, *10*, *11*, *12*, *13*, *14*, *18*, *40*, *41*, *42* changed – *Table 5* updated