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Photovoltaic Battery Charge Controller

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A charge controller is one of the main components of a solar battery charging system (Fig. 1). Its main function is to fully charge a battery without permitting overcharge or reverse current flow (generally during night). If a solar array is connected to a lead-acid battery with no overcharge protection, the battery life is adversely affected.

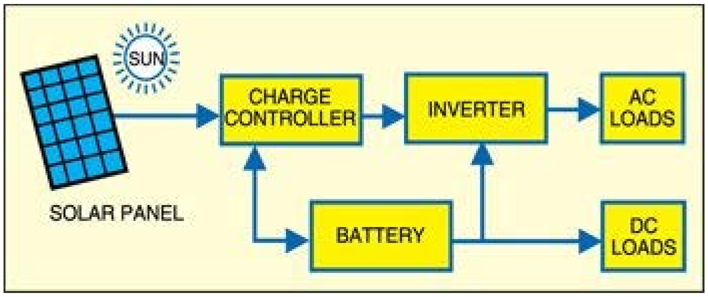

Fig. 1: Block diagram of a typical solar battery charging system

Ordinary controllers consist of a relay that opens the charging circuit when a preset high-voltage point is reached and closes the circuit again when a preset low-voltage limit is reached, allowing charging to continue. More sophisticated controllers utilise pulse-width modulation (PWM) or maximum power-point tracking (MPPT) to ensure that the battery is being fully charged in the most efficient manner.

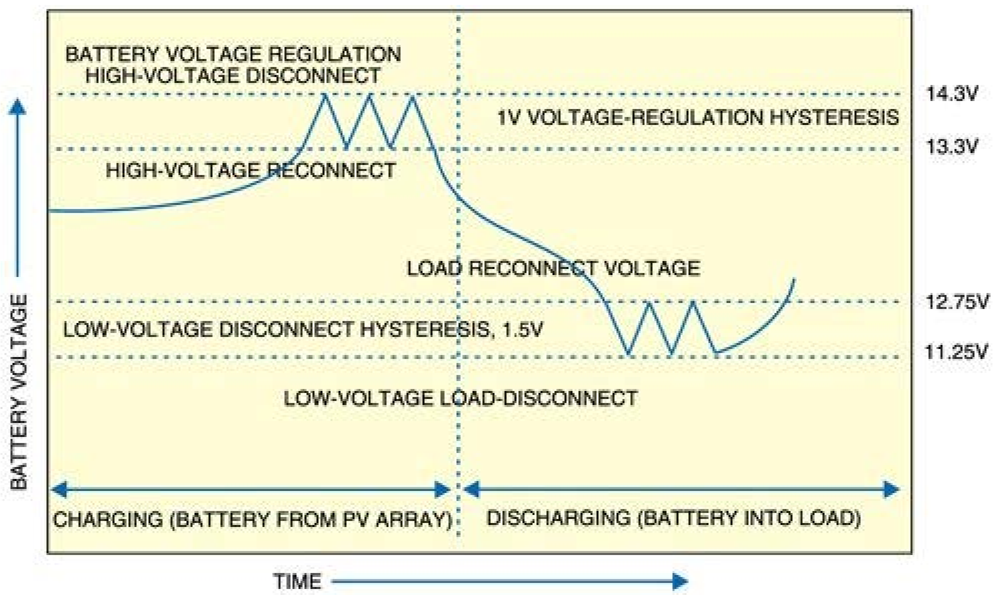

Fig. 2: Charging and discharging set points at 25°C

The charge controller design described here incorporates the following features:

1. Based on PWM technique
2. Battery temperature compensation
3. Battery charge/discharge mode indication (through LED)
4. Reverse-current protection for the PV module
5. Limited protection against lightning and wrong polarity

6. Over-current protection (fuse and automatic load disconnect)
7. Low-voltage load-disconnect indication
8. Load-on indication (through LED)

PV panel selection

A photovoltaic (PV) panel or module comprises a number of PV cells in various series-parallel combinations in order to generate the required power (voltage×current). Typically,a PV cell built using a 9×9cm2 (81cm2) wafer, when subject to sunlight, could produce around 0.5V, which could source around 2.5A of current into a load. Note that a PV cell or module is not damaged when its terminals are shorted. Key specifications of a PV panel are:

- PMAX: Maximum power in watts (PMAX = VMP × IMP)
- VOC: Open-circuit voltage (maximum voltage with module output open circuit)
- VMP: Voltage at which the module produces the highest power (also called operating voltage)
- IMP: Current at which the module produces the highest power (also called operating current)
- ISC: Short-circuit current (maximum current with output shorted)

Typical Rating of a PV Module

Electrical parameters	PM80
Maximum power rating $P_{max.}$ (Wp)*	80.0
Minimum power rating $P_{min.}$ (Wp)*	75.0
Rated current I_{MPP} (A)	4.6
Rated voltage V_{MPP} (V)	17.5
Short-circuit current I_{SC} (A)	5.0
Open-circuit voltage V_{OC} (V)	21.5
Physical parameters	**Values**
Number of cells	36
Physical dimension (mm) (L×W×T)	1200×550×35
Weight (kg)	7.5

Note: 1. There will be 8-10 per cent increase in power after lamination using high-transmission iron-free glass and ethylene vinyl acetate (EVA).
2. Standard test condition (STC)—Solar irradiation: AM 1.5; Intensity: 100 milliwatts/cm^2; Cell temperature: 25°C (within the measurement tolerance of ±5 per cent)

Minimum acceptable VMP voltage rating. To charge a 12V battery, a PV module with higher VMP in the range of 17.5V-18.5V will provide improved MPPT and battery charging performance. For 24V or 48V batteries, these voltages should be multiplied by 2 and 4, respectively.

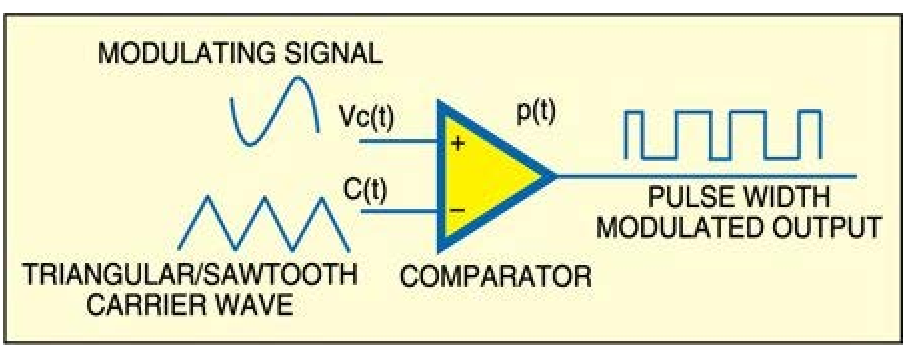

Fig. 3: Basic conventional PWM circuit

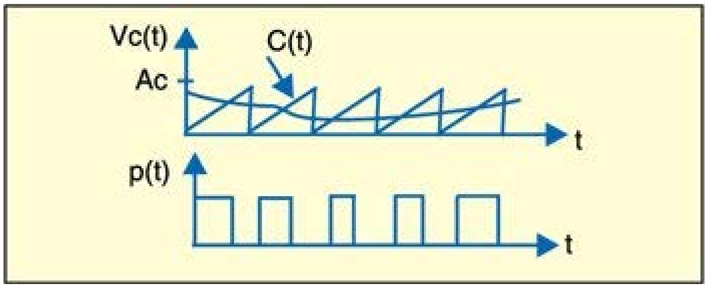

Fig. 4: Variable duty ratio generation using PWM

Minimum acceptable IMP current rating. A preferred rule of thumb is that there should be at least 3 amperes of IMP per 100 amp-hours of battery capacity for proper battery charging. Thus it will be safe to select a PV module of 70W-80W PMAX rating to get an IMP of 4 to 4.5 amperes.

PV solar panel orientation

The parameters of a PV panel are specified by the manufacturer at 20oC cell temperature for the condition that each one square metre of its area receives 'peak sun' power of 1000W, thus providing 1000 Wh per m^2 (1 kWh/m^2)—representing the solar energy received in one hour on a cloudless summer day when the PV panel is directed towards the sun. In practice, the power output of a photovoltaic solar panel is affected by its orientation with respect to the sun and atmospheric conditions.

The best tilt angle is usually equal to the latitude of the installation site. For example, New Delhi is at latitude 28°-36' North and if solar panels are tilted at 28°-36' (with respect to the horizon), these would be perpendicular to the sun twice a year. As the Indian sub-continent is towards north of the equator, the PV panel should face towards south in the azimuth. When you have a large number of PV panels, some of them may be tilted within a range of ±15° of the site-latitude, depending on whether a slight winter/summer bias is desirable in the system.

Insolation. This term is used for sunlight intensity in relation to the solar PV panel and is measured in equivalent full or peak sun hours (as explained above) during the day (24 hours). Even if the sun is in the horizon for a period exceeding twelve hours in a day, your PV panel may receive full sunlight only for four to seven hours or so. This is due to the fact that the panel will not be perpendicular to the sunrays most of the time and also there is earth atmospheric absorption.

PARTS LIST

Semiconductors:

IC1	- 78L05, 5V regulator
IC2, IC5	- LM358 dual operational amplifier
IC3	- LM339 quad comparator
IC4	- TL494 pulse-width modulation control chip
IC6	- LM319 dual comparator
IC7	- LM35DZ centigrade temperature sensor
T1, T2	- IRF9530 p-channel power MOSFET
T3, T4	- 2N7000 n-channel enhancement MOSFET
T5	- BC548 npn transistor
T6, T7	- TIP120 npn Darlington transistor
T8	- TIP125 pnp Darlington transistor
D1, D2	- MBR20045 Schottky rectifier diode
D3	- 1N4007 rectifier diode
D4, D5	- 1N4148 signal diode
LED1-LED3	- 5mm LED
MOV1	- 14D431K varistor
PVM1	- PM80 80 watt solar module

Resistors (all ¼-watt, ±5% carbon unless stated otherwise):

R1, R2, R13, R22	- 1M
R3, R4, R15, R29, R30, R31, R41, R42, R43, R44	- 100-kilo-ohm
R5, R6	- 0.1-ohm, 5W
R7, R23, R25	- 2.2-kilo-ohm
R8, R9, R14	- 1-kilo-ohm
R10	- 8.2-kilo-ohm
R11, R12, R16, R17, R19, R20, R24, R27, R34, R50	- 10-kilo-ohm
R18, R32, R46	- 47-kilo-ohm
R39	- 51-kilo-ohm
R21	- 27-kilo-ohm
R26	- 22-kilo-ohm
R28	- 470-kilo-ohm
R33	- 20-kilo-ohm
R35	- 33-kilo-ohm
R36	- 18-kilo-ohm
R37, R38	- 510-ohm
R40	- 5-kilo-ohm
R45	- 15-kilo-ohm
R47	- 1.5-kilo-ohm
R48	- 75-ohm
R49	- 1.2-kilo-ohm
R51	- 4.7-kilo-ohm
R52	- 5.6-kilo-ohm
VR1	- 1-kilo-ohm, preset
VR2	- 100-kilo-ohm, preset

Capacitors:

C1, C2, C4, C5, C6, C9	- 0.1 µF ceramic
C3	- 100µF, 25V electrolytic
C7, C8	- 10µF, 25V electrolytic
C10	- 0.01µF ceramic
C11	- 2.2µF, 16V electrolytic
C12	- 1µF, 16V electrolytic

Miscellaneous:

Batt.	- 12V, 80Ah battery
F1	- 10A Fuse
S1	- On/off switch
S2, S3, S4	- Tactile switch
Coaxial cable	- 75-ohm
	- Jumper connectors
	- Berg strips

Most of the Indian subcontinent receives full sunlight for about five hours a day. (Refer to the map at www.solar4power.com/map14-global-solar-power.html). Taking the conversion efficiency of the system into account, a PV panel rated for Pmax of 75 watts will be able to supply you 75 watts of power for just five hours per day. Thus you would be able to draw only 75W×5 hours = 375 watt-hours of energy per day from the PV panel.

If you desire to run your appliance for a longer duration, you will have to install more number of PV panels and connect them in series/parallel for increasing the combination's voltage/current rating.

In India, various companies like Central Electronics Ltd (CEL), Bharat Electronics Ltd (BEL), Bharat Heavy Electricals Ltd (BHEL), Moser Baer Photovoltaic, TATA-BP Solar and Maharishi Solar Technology are making solar panels using indigenous and imported technologies. A PV module such as the PM80 from CEL, Sahibabad, having the specifications as shown in the table on previous page, could be used for our example case.

Battery selection

The selected PV module should be able to support an energy supply of 375 watt-hours per day. That means if you have an appliance rated at 40 watts which is supplied power from an inverter (with power conversion efficiency of, say, 80 per cent), you would be able to use the appliance for an aggregate of 7.5 hours (40W×7.5 hours× 100/80 = 375 watt-hours).

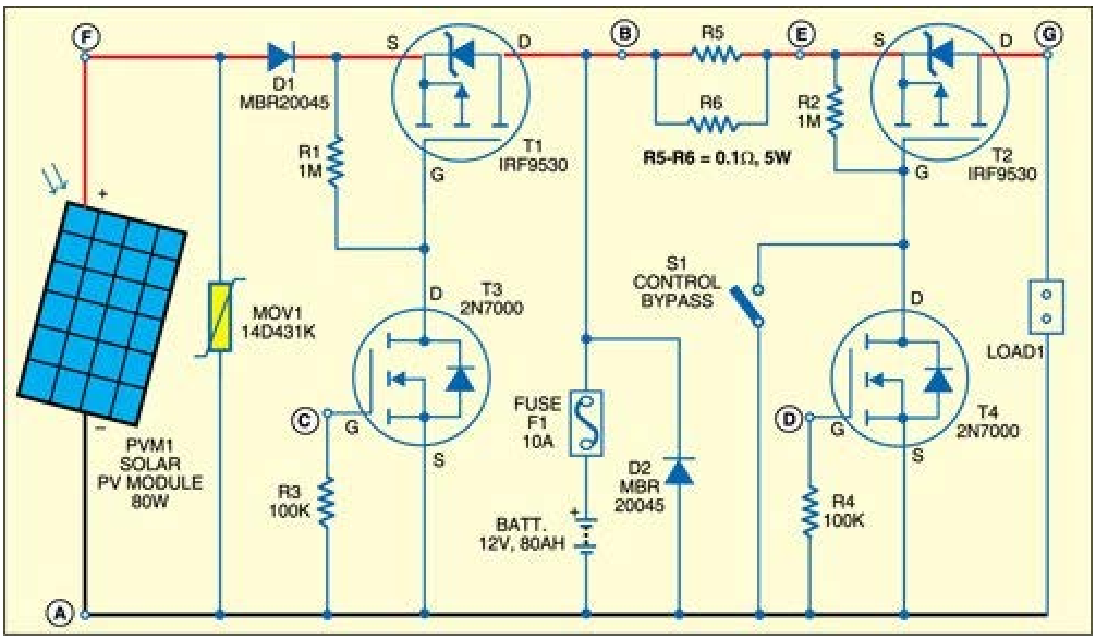

Fig. 5: Main charger circuit

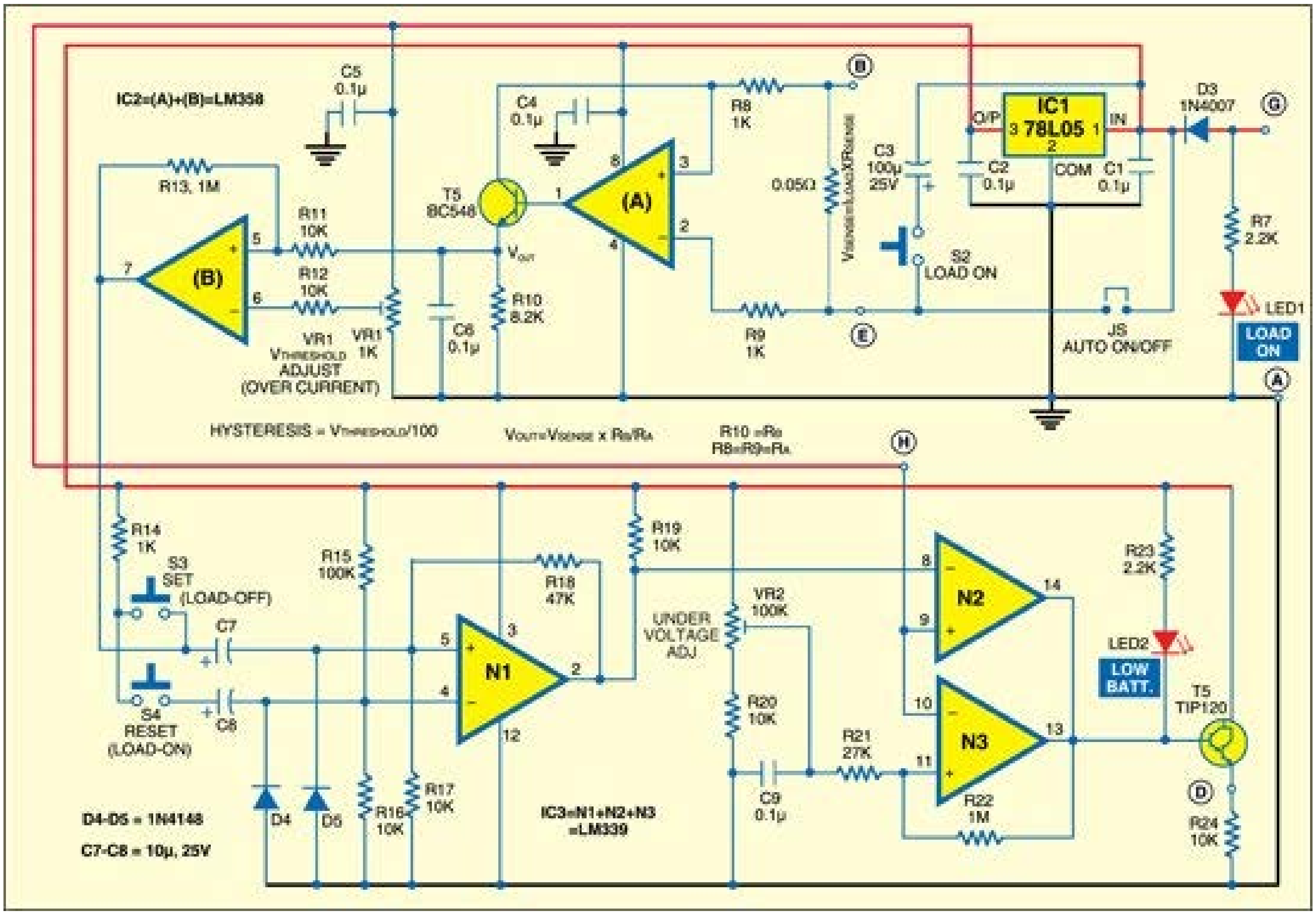

Fig. 6: Over-load cum low-battery control section

As per the recommendations of International Energy Agency, one should draw not more than 40 per cent of the rated energy capacity (VAh) of a battery during a 24-hour period. Accordingly, your battery should be rated for at least 375×100/40 = 937.5 watt-hours of energy. With the battery terminal voltage of 12V, its capacity should be around 80 Ah (energy capacity=12V×80 Ah=960 Ah). Tubular-type battery is the preferred choice for a longer life as this application needs batteries having deep discharge capability.

Wire sizing. The voltage drop between PV modules and batteries may not be allowed to exceed 2 per cent of the 12V battery terminal voltage. For 5A IMP, the maximum length (in metres) of various two-conductor copper wires is given below:

SWG	#16	#14	#12	#10	#8	#4	#2
Metre	2.5	4	6	10	15	24	40

For other PV module amperage, you may refer the chart at www.solar4power.com/solar-power-volt_drop.html#Volt%20Drop%20Chart

Important terms. Important terms used in relation to a PV charge controller for an open or vented lead-acid battery are explained below:

Main charge. It refers to charging the battery up to a voltage level when gassing starts and the voltage rises. (The voltage limit is 2.39V at 25°C and 2.33V at 40°C.) For a 12V battery, these limits work out to be 14.34V at 25°C and 13.98V at 40°C. Extra care needs be taken to ensure that a gel-cell 12V battery is not charged above 14.1 volts.

Top-up charge. It means raising the charge to reach the 100 per cent state from a 90-95 per cent level.

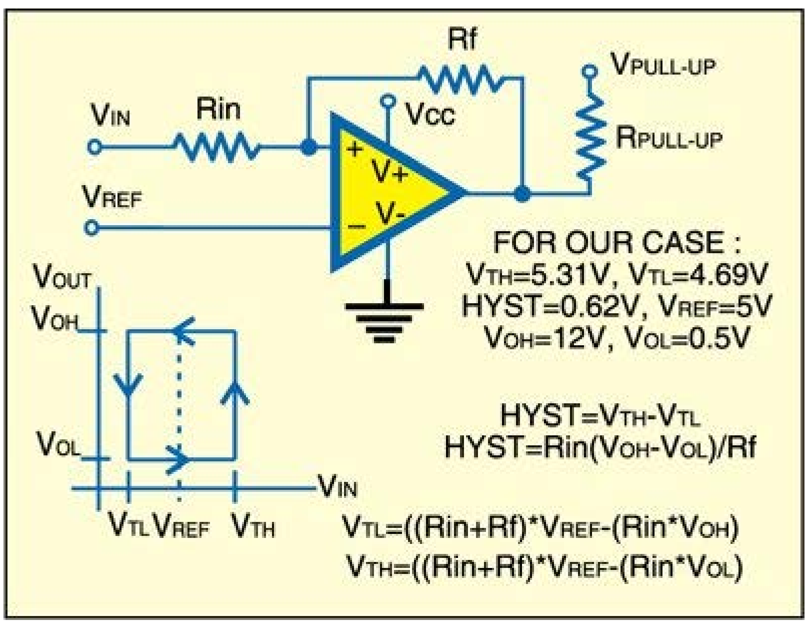

Fig. 7: Single supply for non-inverting comparator hysteresis

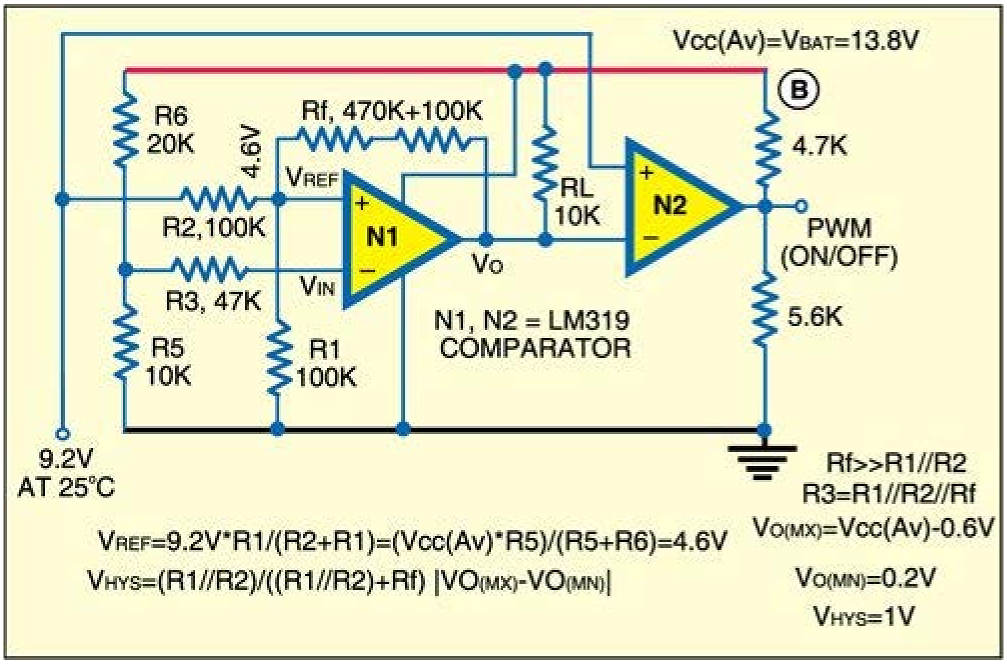

Fig. 8: Single supply for inverting comparator hysteresis

Equalisation charge. It refers to equalising the capacity of the individual cells in a multicell battery. This is an important issue for improving the battery life, but requires a special controller mode to create it in a system charged by PV panels. (It involves increasing the voltage to 2.5-2.6V/cell for a short time period (0.5-1 hour) at regular intervals, say, once a week.) It can be termed as forced overcharge interval after the main charge sequence.

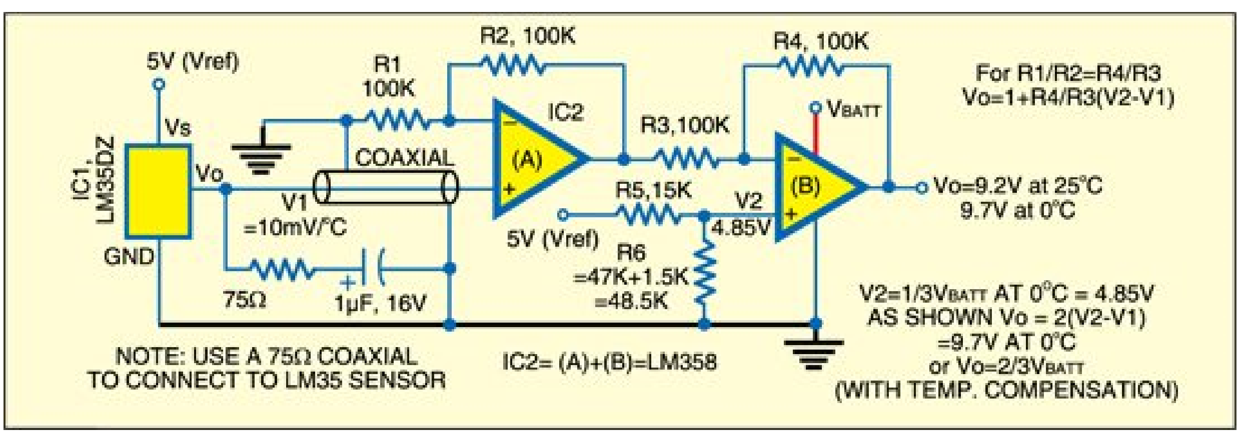

Fig. 9: Temperature-dependant reference-voltage generation circuit

Generally, the voltage ranges for six-cell (12V) lead-acid batteries are:

1. Open-circuit voltage after full charge: 12.6-12.8V
2. Open-circuit voltage after full discharge: 11.8-12.0V
3. Loaded at full discharge: 10.5V
4. Float charging: 13.8V for gelled and 13.4V for wet cells
5. Typical (daily) charging: 14.2-14.5V
6. Equalisation charging (for wet lead-acid): 15-16V

Note. Above voltages are at 25°C, and need to be adjusted for temperature changes.

Charge controller design

Fixing the set points (Fig. 2). The battery voltage levels at which a charge controller performs control or switching functions are called the controller set points. Four basic control set points are defined for most charge controllers that have battery overcharge and over-discharge protection features. High-voltage array disconnect (HVD) and high-voltage array reconnect (HVR) refer to the voltage set points at which the PV array is connected and disconnected from the battery. For our example, charger HVD=14.3V and HVR=13.3V. These two set points are also referred to as voltage regulation (VR) and low voltage reconnect (LVR), respectively.

Low-voltage load-disconnect (LVD) and load-reconnect voltage (LRV) refer to the voltage set points at which the load is disconnected/reconnected from/to the battery to prevent over-discharge.

Temperature compensation. The battery capacity (Ah) is defined for cell temperature of 27°C (80°F). If the battery temperature is higher than the design condition, it will slightly increase its Ah capacity. But, this will also increase the water loss and decrease the number of cycles in the battery life. The battery life is halved if the temperature rises to 35°C (95°F) from 25°C (77°F), and at 45°C (113°F), it drops to one-quarter.

A widely accepted value of temperature compensation for lead-acid batteries is -5 mV/°C/cell. For a 12V battery, this amounts to -30 mV/°C. It is important to note that the temperature compensation (TC) coefficient is negative, meaning that temperature increase requires a reduction in the charge regulation voltage (HVD) and vice versa.

Technology choice. PWM technology is well suited for solar battery chargers. When the battery voltage reaches the regulation set point (HVD in Fig. 2), the PWM algorithm slowly reduces the charging current to avoid heating and gassing of the battery, but the charging continues to return the maximum amount of energy to the battery in the shortest time. The result is a higher charging efficiency, rapid recharging and a healthy battery at full capacity. Hence our obvious choice is the use of PWM method. It is an effective means for constant-voltage battery charging. With PWM regulation, the current from the solar array tapers off in accordance with the battery's condition and recharging needs.

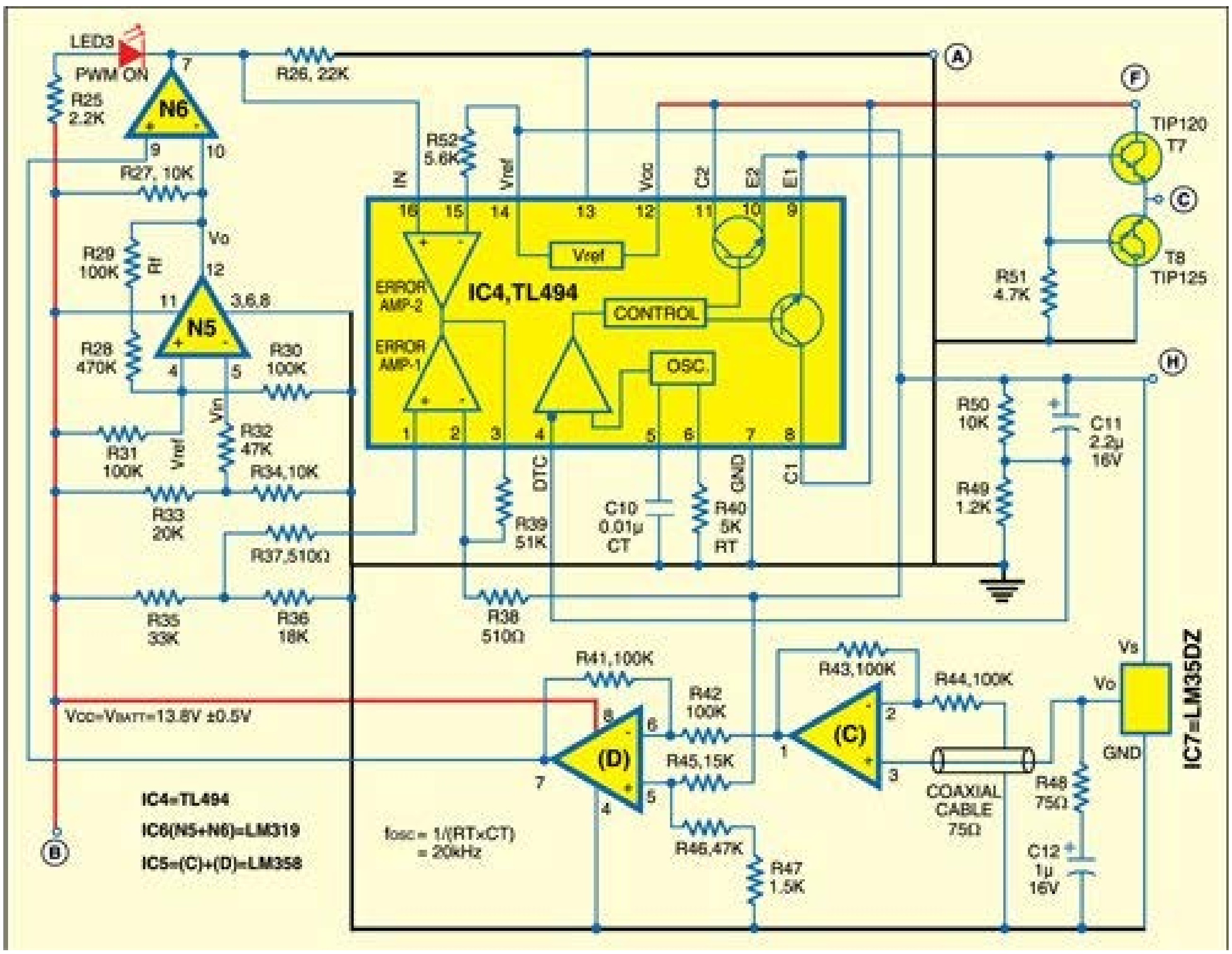

Fig. 10: pwm control section

Fig. 3 shows the basic functional diagram of a conventional constant-frequency PWM circuit. The triangular or sawtooth carrier signal c(t) is compared with modulation signal vc(t) to generate duty ratio D in a switching cycle resulting in pulse-width-modulated output p(t).

At the beginning of a switching cycle, output pulse p(t) is set to high. It is reset to low when c(t)=vc(t). Duty ratio D in a switching cycle is defined as the ratio of the time interval when p(t)=1 to the switching period. In order to get a controllable duty ratio, the amplitude of modulation signal vc(t) must satisfy the following condition:

$$0 \leq vc(t) \leq AC$$

The input and output waveforms and amplitudes against the time axis are shown in Fig. 4.

Circuit description

Fig. 5 shows the circuit of the PWM-based charge controller with main peripheral components. The over-current cum low-battery load-disconnect block whose output is to be connected to point D (and ground) and main charge-control PWM block whose output is to be connected to point C (and ground) are shown in separate figures (Figs 6 and 10, respectively) for the sake of clarity. Inputs/outputs to/from these two circuit blocks are connected to the circuit in Fig. 5 using circled points labeled ‘A’ through ‘G’. An emergency provision is made to bypass the control circuit (Fig. 6) and switch on the load directly by closing switch S1 in Fig. 5. However, bypassing the safety control circuit (Fig. 5) is not advisable under normal circumstances.

Over-load cum low-battery load-disconnect circuit. Fig. 6 shows the overload cum low-battery load-disconnect circuit. The output of this circuit is connected to point D in Fig. 5. As long as point D is at high voltage (> low-battery-voltage cut-off limit), n-channel MOSFET T4 (2N7000) will conduct to extend ground to the gate of p-channel MOSFET T2 (IRF9530). Thus MOSFET T2 also conducts and the battery/PV-module output is connected to the load. LED1 connected across the load through a 2.2-kilo-ohm resistor lights up to indicate that the load is ‘on.’

To prolong the battery life, there is a pro-vision to activate this circuit only when the load is switched on with the help of a push switch S2. It would remain ‘on’ until a low-battery condition or overload is detected by this circuit. Alternatively, to keep the circuit active all the time, the battery can be permanently connected to the circuit using a shorting link (JS). With this arrangement, the load will automatically switch on/off in accordance with the set points (refer Fig. 2). Additionally, manual switching on/off arrangements have been incorporated. The detailed description of the circuit (Fig. 6) follows.

This circuit uses a low-current (100mA) 5V regulator (78L05), a single-supply dual op-amp (LM358) and a quad comparator (LM339), apart from a few passive/active components as shown in Fig. 6. Assuming that presently over-current or low-battery conditions do not exist, the load should be 'on' if JS link is closed.

If JS is open and the load is not 'on,' regulator 78L05 connected across the load terminal (point G in Fig. 5) via 1N4007 diode will not activate and the remainder of the circuit too will not function and output D will be in high-impedance state. Pressing switch S2 momentarily applies battery voltage from point E to the regulator input as well as the remainder of the circuit via a 100µF capacitor for a brief period, causing point D to go high. As a result, it connects the battery to the load by activating the complementary pair of MOSFETs T2 and T4. Thereafter, the circuit remains latched in this state unless over-current or low-battery conditions are encountered. This will become clear to you once you go through further description of the circuit that follows.

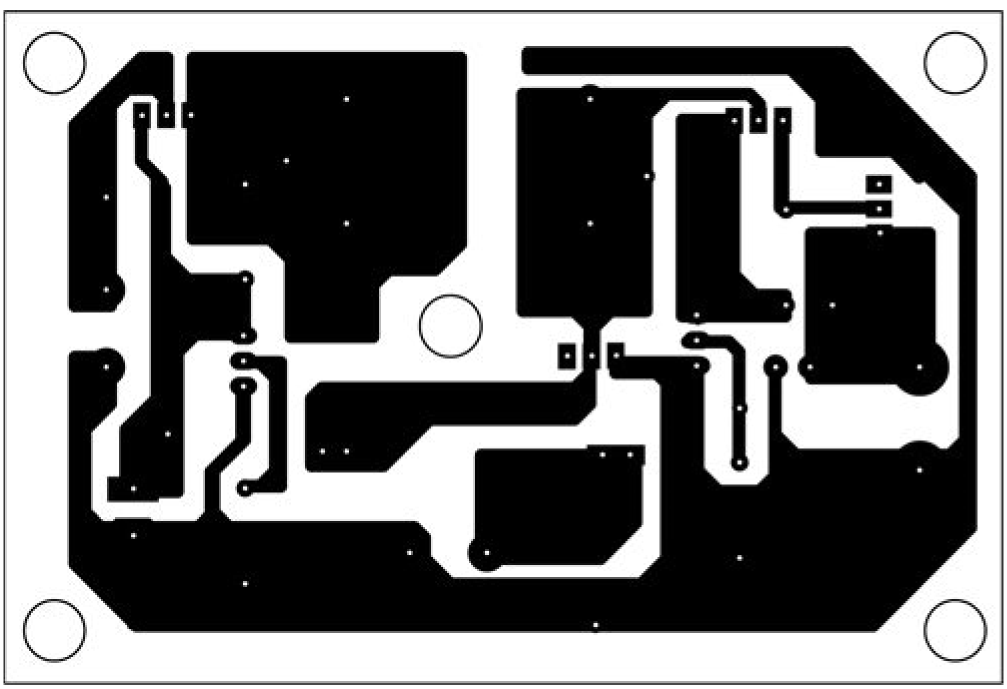

Fig. 11: An actual-size, single-side PCB for the main charger circuit shown in Fig. 5

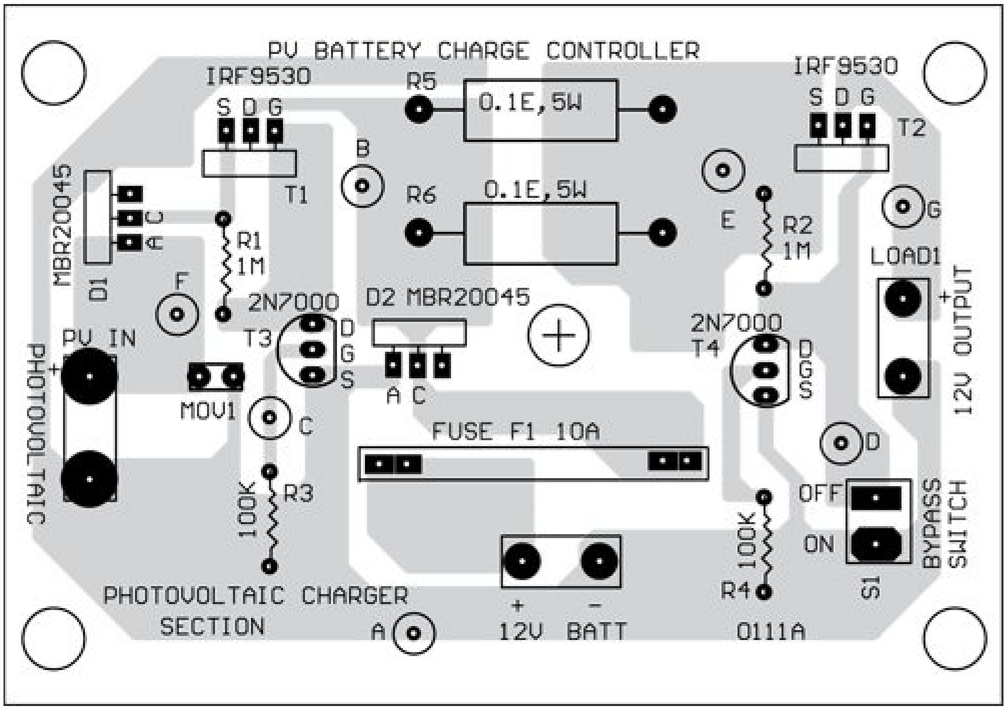

Fig. 12: Component layout for the PCB in Fig. 11

In the circuit, op-amp LM358(A) is connected as a high-side current monitor. The differential input for this op-amp is the sense voltage (VSense=ILoad×RSense) developed across the 0.05-ohm resistor (RSense), which is connected across points B and E in Fig. 5. Out-put voltage Vo developed across resistor RB is given by the relationship:

Vo = VSense × RB/RA

(In the circuit, RA = 1 kilo-ohm and RB = 8.2 kilo-ohms)

If we assume the maxi-mum permissible load current as 8A, then:

VSense = 8x0.05V= 0.4V and Vo = 0.4x8.2 = 3.28V

Thus if you want the load to trip when current exceeds 8A, you should set the inverting pin of LM358(B) (connected as Schmitt trigger) at 3.28V. When the output voltage across RB (connected to its non-inverting pin) exceeds 3.28V, a positive pulse is generated at its output. This positive pulse sets comparator N1 (connected as a bistable) to high output state. (Note that N1 is initially reset to low output state because of slightly positive bias applied at its inverting pin with the help of resistive voltage divider formed by resistors R15 and R16). The high output of N1 is inverted by gate N2. Irrespective of the output state of comparator N2, point D is pulled low to switch off the load. Thus once overload occurs, the battery is disconnected from the load.

Unless the cause of overload is traced and fault removed, you will not be able to switch on the load. Once the overload fault is rectified, you can switch on the load by momentarily pressing switch S2 (if link JS is kept open) or by pressing RESET switch S4 (if link JS is kept closed). Push switch S3 is provided to manually switch off the circuit by setting the output of bi-stable N1 high.

A single comparator (N3) is used for battery voltage monitoring. With link JS closed, it monitors the battery-voltage and switches the load off when the battery voltage falls below 11.25V and switches it on again when the battery voltage reaches 12.75V in accordance with the set points as referred in Fig. 2.

Regulated 5V DC, used as reference volt-age, is applied to the inverting pin of comparator N3. A proportionate sample of the battery volt-age is applied to the non-inverting pin of comparator N3 via potmeter VR2. At 12V battery voltage, the potmeter is set to provide 5V at the non-inverting pin. With the component values selected, you get the required switching on/off threshold points of 5V±0.325V, which corresponds to the battery voltage of 12V±0.78V or a cut-off voltage level of 11.22V and switch-on level of 12.78V. Those interest-ed in the mathematical analysis may follow the relationships given in Fig. 7.

The output of comparator N2 is used for load-off indication. It lights up LED2 when the load is cut-off. The outputs of N2 and N3 form a wired-OR junction. Thus if any of these comparator outputs is low, the output at the junction point is low. Conversely, both the outputs need to be high so that the output at the junction is high.

Overload-current comparator N1 acts as a bistable latch. Hence once set to high state due to overload, the reset button (switch S4) must be pressed to reset it after removal of any fault that caused the overload. To drive the MOSFET (T4 in Fig. 5), a high rate of change of current for gate drive is needed. Hence the wired-OR output of comparators N2 and N3 is passed through Darlington transistor T5 for driving MOSFET T4 connected at point D.

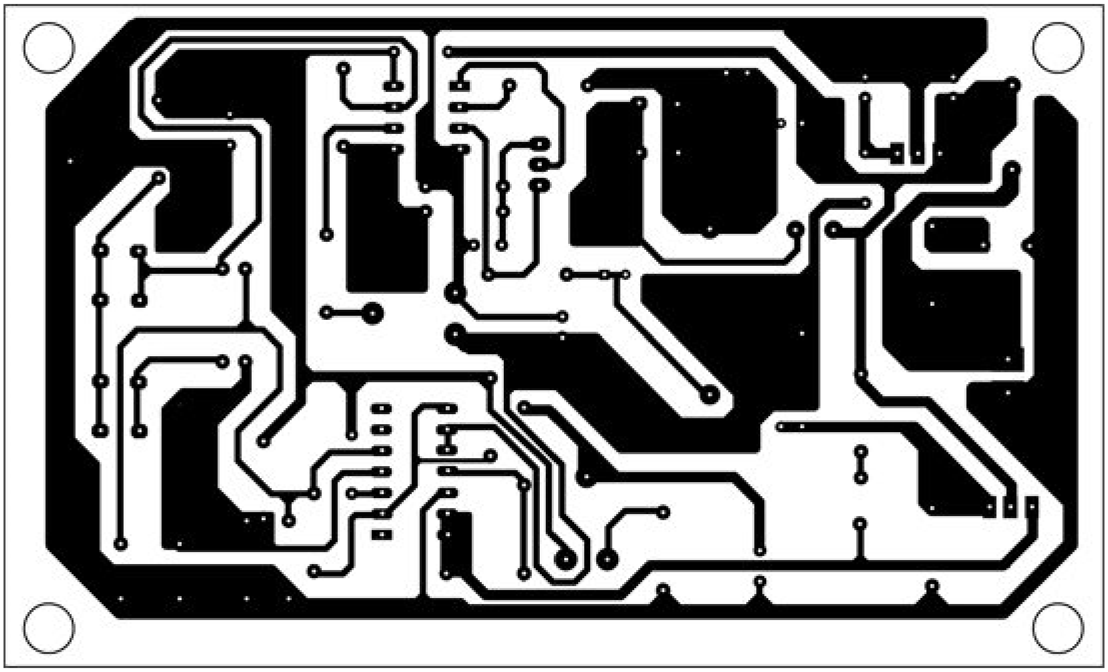

Fig. 13: An actual-size, single-side PCB for the over-load cum low-battery load-disconnect circuit shown in Fig. 6

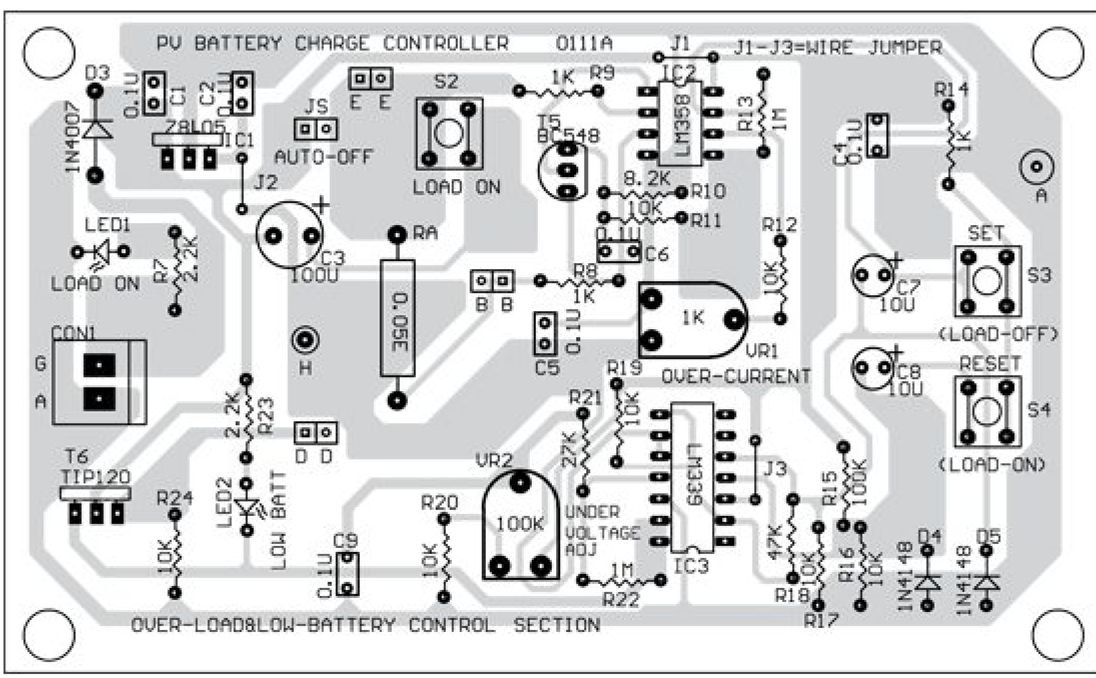

Fig. 14: Component layout for the PCB in Fig. 13

PWM charging circuit. Commonly available PWM controller IC TL494, which is widely used in PC SMPS and costs less than an ordinary op-amp, is used for this circuit.

PWM on/off circuit. Error amplifier-2 is employed as enable/disable control to cut off the PWM output of TL494 when the battery voltage reaches the upper set limit of 14.3V (13.8V+0.5V) and enable it again when the battery reaches the lower set limit of 13.3V (13.8V–0.5V). This function is realised with the help of the circuit shown in Fig. 8. The first comparator provides the necessary cut-off/cut-on points, while the second comparator is used as a simple inverter. Necessary formulae and parameters used for design are shown in Fig. 8 itself. This circuit is interfaced to error amplifier-2 of TL494 after integration with temperature compensation.

Temperature-dependant reference voltage generation circuit. A careful look at Fig. 8 shows that VREF has been obtained from a temperature-dependant reference volt-age (9.2V at 25°C) and one-third of the average VBATT value has been used for comparison with VREF. Variation of VREF shifts the upper and lower threshold points used for switching on/off the PWM output. The circuit used for generation of temperature-dependant reference voltage is shown in Fig. 9.

We had earlier stated that for a 12V lead-acid battery, a 30mV/°C negative temperature correction is required to be applied for the battery voltage set points as shown in Fig. 2. The average charging volt-age at 25°C is indicated as 13.8 volts. This means that the average charging voltage at 0°C should be higher by 0.75V (30mV ×25) or it would be 14.55V (13.8+0.75) at 0°C.

National Radio's LM35DZ temperature sensor IC provides 10 mV/°C. It is one-third of 30 mV/°C required for correction of the 12V battery. Thus we use one-third of the battery voltage (14.55/3=4.85V) as reference voltage at 0°C and subtract from it 10 mV/°C using a DC difference amplifier formed from LM358 IC as shown in Fig. 9. The 4.85V is derived from 5V reference (generated by TL494 IC) using a resistive divider. This circuit provides a temperature-corrected reference voltage of 9.7V at 0°C (or 9.2V at 25°C and so on). This reference output voltage is two-third the battery charging voltage at any given temperature. It is halved (4.6V) using a resistive divider in Fig. 8. Thus the resultant reference voltage equals one-third of the average battery charging voltage at a given temperature. Accordingly, the battery voltage is also divided by '3' before application to the main PWM circuit configured around TL494 IC (Fig. 10).

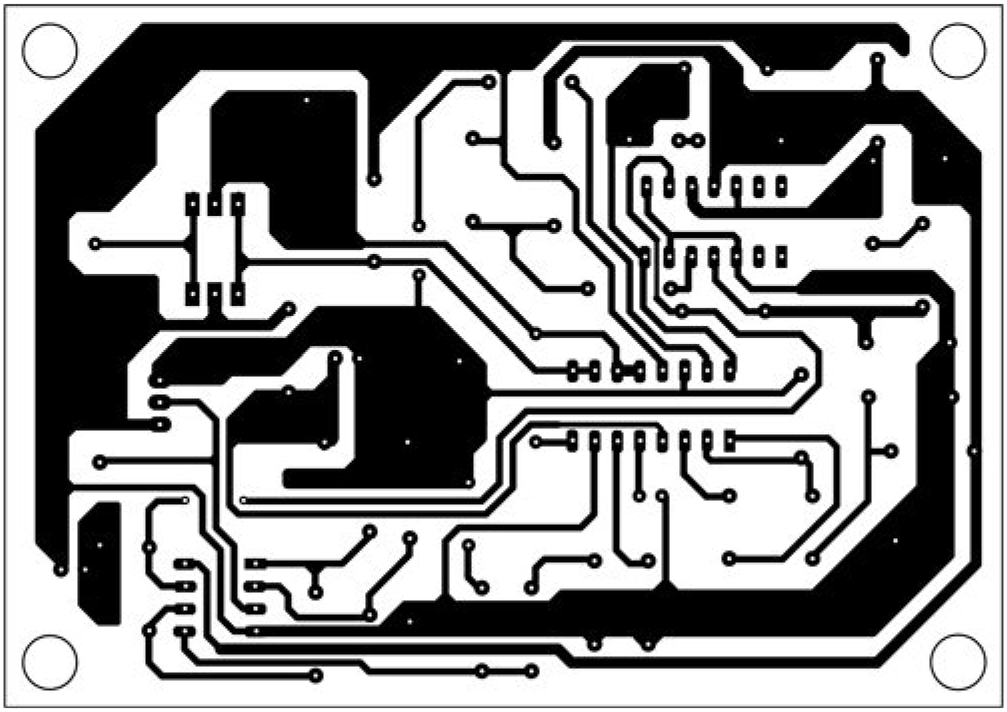

Fig. 15: An actual-size, single-side PCB for the pwm control circuit shown in Fig. 10

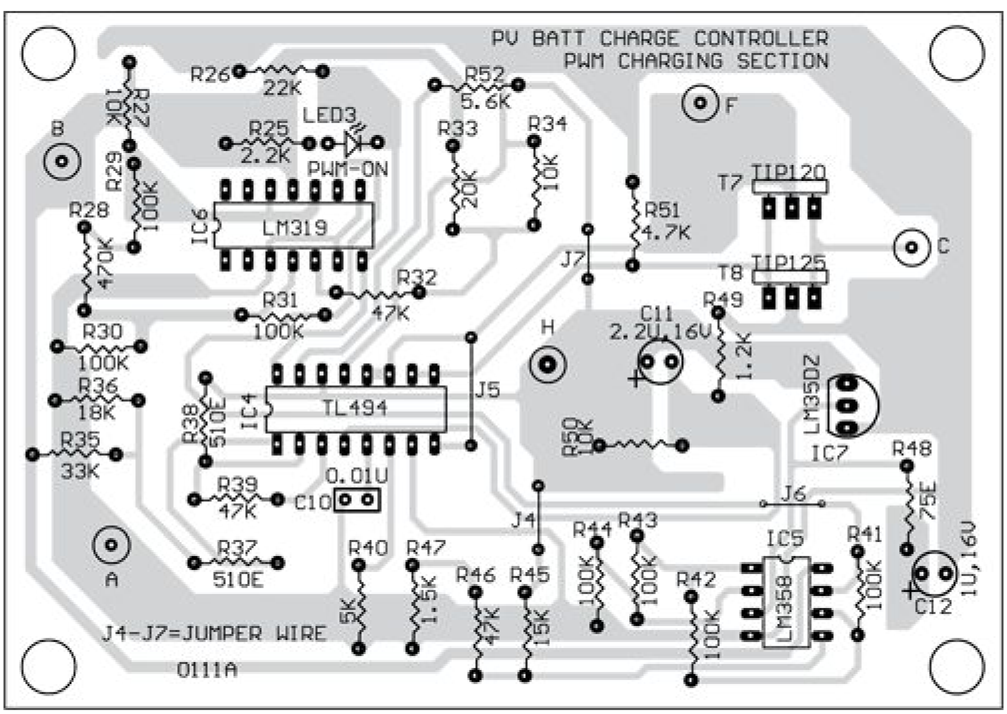

Fig. 16: Component layout for the PCB in Fig. 15

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Input of hysteresis circuit of Fig. 9. Thus we uniquely produce temperature-compensated set points for enabling/disabling the PWM output. (Note that the temperature sensor should be positioned in the vicinity of the battery to measure its temperature and the output from the temperature sensor to the differential op-amp should be conveyed using a properly grounded (both ends) 75-ohm coaxial cable.) Circuits shown in Figs 8 and 9 have been integrated into the main PWM circuit (Fig. 10) configured around TL494 IC.

PWM error-amplifier circuit. PWM control is exercised through error amplifier-1 of TL494. The gain of error amplifier-1 is fixed at 100 using feedback resistor R39 of 51 kilo-ohms, while resistor R38, in series with reference voltage of 5V, is selected as 510 ohms. The sample voltage is derived from the battery using a resistive divider comprising resistors R35 and R36 to provide 5V for the non-inverting terminal of error amplifier-1, corresponding to the maxi-mum battery voltage limit of 14.3 volts.

The output of TL494 is configured for single-ended operation by grounding its control pin 13. The common emitter output developed across R51 is fed to the totem-pole amplifier comprising complementary Darlington pairs of transistors T8 and T9 for driving the MOSFET connected at point ‘C’ in Fig. 5. The various circled points in Fig. 10 are connected to identical points in Fig. 5. This completes the description of the complete PV charge controller circuit.

An actual-size, single-side PCB for the main charger circuit of Fig. 5 is shown in Fig. 11 and its component layout is shown in Fig. 12. Various points for connections to other circuits are shown with encircled alphabets A through G.

The actual-size, single-side PCB for the over-load cum low-battery load disconnect circuit of Fig. 6 is shown in Fig. 13 and its component layout in Fig. 14. The actual-size, single-side PCB for the PWM control section of Fig. 10 is shown in Fig. 15 and its component layout in Fig. 16. Before you start charging the battery, all the connecting points, as indicated in the PCB layout as per the schematic diagrams, should be connected to respective points A through H. The

LM35DZ temperature sensor should be attached to the battery (to be charged) using quick fix glue by extending the connection from the PCB (Fig. 16) to the battery using coaxial cable.

The author is ex-Technical Editor, EFY magazine, and author of some very interesting books