Optimized reconfigurable solar PV battery charger using relay switch matrix

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***Abstract*—PV array reconfigurable battery charger has been reported in literature. It had three components: a four module PV array, switch matrix and batteries for charging. The switch matrix, a logically connected 9 SPST relays, would reconfigure array to any of 4x1(series), 2x2, 1x4(parallel) configurations dynamically. Hereafter, this number is referred as switch count. This paper presents an optimized reconfigurable solar PV battery charger design using SPDT relays. Its main contribution is reduction of switch count from 9 to 8. Not requiring a continuous control for configuring the array to 4x1 is the unique operational design feature. Hence, in case of complete control circuit failure, this unique feature allows it charge the battery continuously with array configured permanently to 4x1. Adding, the simplified algorithm implementation requires comparator ICs only and not micro-controller. Compared to prior design, this work reduces the conduction loss, cost of investment and size of PV charger circuitry. Experimental tests have been conducted to verify the proposed design and control algorithm.**

***Index Terms*—PV array reconfiguration(PVAR),solar photovoltaic charger,SPDT relay,switch matrix.**

I. Introduction

Storage batteries play intrinsic role in any electrical circuitry of a large application system. Importantly, for ignition starting of automobiles, satellite communication, cellular mobile communication, house lighting etc., are few notable examples dependent on battery power. For increasing the access of such devices to remote village and satellites, circuits that take solar Photovoltaic(PV) power and convert it to useful battery charge were developed. In literature, these are familiar as PV battery charging circuits [1]–[3] .

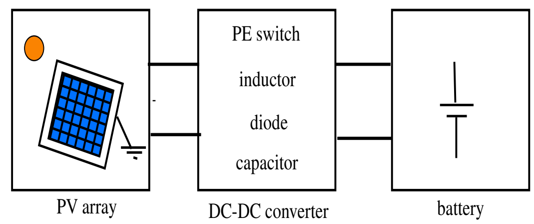

Fig. 1: Schematic diagram of fixed array type PV battery charger.

PV battery chargers can be classified in to two: fixed and reconfigurable array type. In case of former the PV array would be in one configuration permanently and in case of latter it would be reconfigured dynamically. Many works of PV battery charger reported in literature are of fixed configuration type [2] [3]. They make use of a dc-dc converter to match the various battery charging voltages.

Reconfigurable PV battery charger is a novel concept reported in [1]. It had three components mainly: a four module PV array, switch matrix and batteries. Switch matrix is critical component of complete charging system. A total of 9 logically connected switches, hereafter this number would be referred as switch count, form the switch matrix. Upon sensing the battery voltage, micro-controller would trigger switch matrix to alter the configuration from and to any of 4x1,2x2 and 1x4 configurations. It changes in to trickle charging mode once the state of charge (SOC) reaches a predefined level. This helps to avoid overcharging and overheat issues of battery.

Compared to dc-dc based PV chargers as shown in Fig. 1, reconfigurable type is simple and easy for

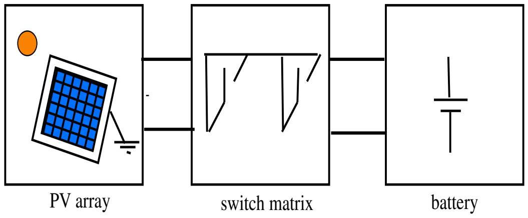

Fig. 2: Schematic diagram of reconfigurable type PV battery charger.

implementation. Reliability studies have highlighted that 70% failures of PV systems are mainly due to electronics circuitry [4]. Further, not having the high end circuit components make it highly reliable for remote village installations [5]. Not involving any storage elements as shown in Fig. 2 make it highly sensitive and non-sluggish to battery parameter changes. Absence of high frequency requirements and related operation give high reliability and can last for longer duration. This uniqueness make it highly qualified for the product commercialization and daily usage. Finally, all the above would lead to a less cost of investment to realize it.

This paper presents reconfigurable type PV battery charger. In comparison to [1], it presents following new features

(1) For first time in literature, single-pole double-throw(SPDT) type relay has been used for PV battery charger purpose

(2) in effect, the switch count of four module PV switch matrix has been reduced from 9 to 8

(3) for controlling and smooth operation of charger require comparator ICs only and not micro-controller

(4) In [1] control circuit shall generate and hold the trigger signal continuously for having the array in any of 4x1,2x2,1x4 configurations. Proposed switch matrix doesn't require continuous control for having the array permanently in 4x1 configuration and

(5) In case of complete control circuit failure, prior art in [1] fails to operate. However, proposed switch matrix continuous to function with the PV array configured permanently to 4x1 configuration.

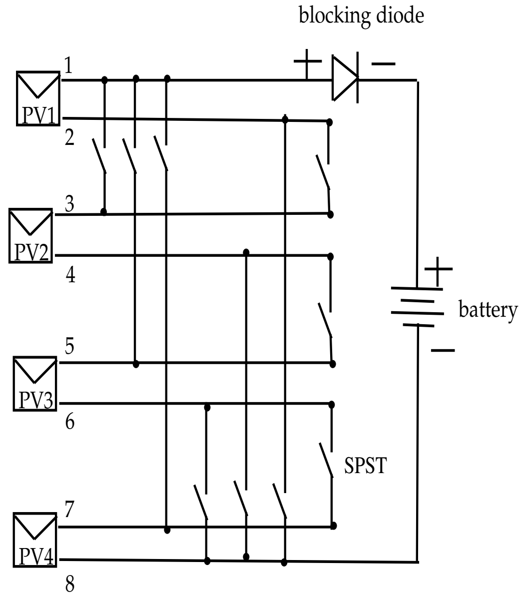

Fig. 3: Schematic diagram of reconfigurable type PV battery charger as in [1] using SPST relay.

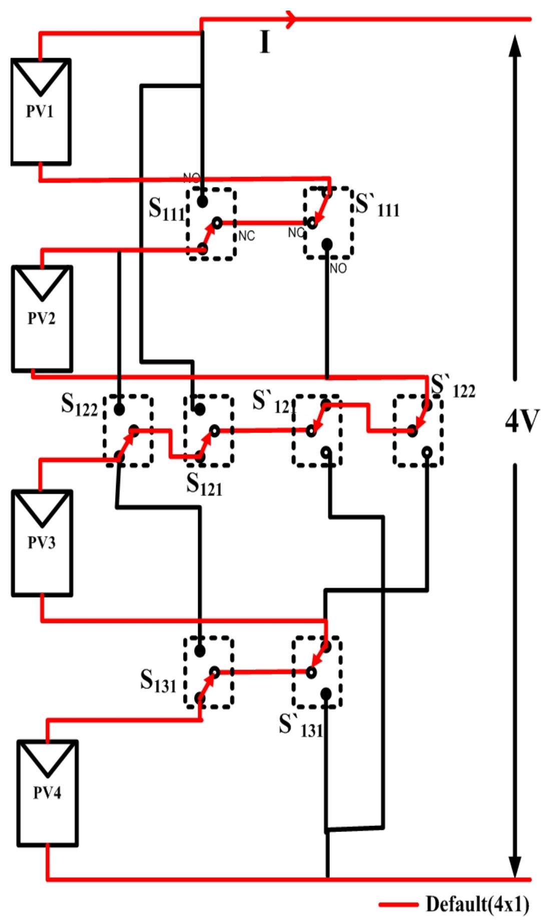

Fig. 4: Schematic diagram of proposed reconfigurable type PV battery charger using SPDT relay with array in 4x1 by default.

TABLE I: COMPARISON OF RECONFIGURABLE SWITCH MATRIX DESIGN

Switching configurations	Four module switch matrix design in [1]	in this paper
Switch count	9	8
Switch type	SPST	SPDT
	Number of switches triggered	
4x1 all in series	3	0
2x2 all in series-parallel	4	2 (S_{122}),(S'_{122})
1x4 all in parallel	6	8 (S_{111}),(S'_{111})(S_{121}),(S'_{121}) (S_{122}),(S'_{122})(S_{131}),(S'_{131})

II. Description of SPDT switch matrix and algorithm working

A. Switch matrix

SPDT relay has three power terminals and a coil to control the relay contacts. Among three, one is movable and other two are fixed terminals. In default state, one fixed and movable terminal are connected forming a contact called normally close(NC). Similarly, not connected second terminal would form a normally open(NO) contact with the movable terminal. Hence, an SPDT relay in normal state has 1 NC and 1 NO contact respectively. Once triggered, movable terminal changes its position to second fixed terminal. This results in NC becoming open contact and NO becoming closed contact.

Figure 4 shows the proposed switch matrix design where NC contacts of 8 SPDT relays have been effectively used to realize 4x1 configuration. In the sense, proposed design configures array to 4x1 by default and no control signal would be required for the purpose. Hence, in case of complete control circuit failure, where relays remain untriggered, would cause the array remain in 4x1 configuration permanently.

Triggering two relays viz., S_{122},S'_{122} of Fig. 4 would reconfigure the array to series-parallel 2x2 configuration. Similarly, triggering all relays of Fig. 4 would reconfigure the array to parallel 1x4 configuration. The control algorithm shall decide the suitable configuration for given battery such that charging takes place in less time effectively.

B. PV array and battery VI characteristics

The PV array having specifications as in Table II has been used for simulation and experimental tests conducted. Assuming the array as interconnection of a number of cells N_{se} in series per string and a number of parallel strings N_{pa}. Its characteristics equation is given by

$$V = 0.0731\ N_{se}\ ln(\frac{I_{ph} - I_L + 0.0005\ N_{pa}}{0.0005\ N_{pa}}) - 0.005\ N_{pa}\ I_L \tag{1}$$

where I_{ph} is photo current (= 0.7005x10^{-3}xϕ) in A, ϕ is insolation level in W/m^2 and I_L is load current in A. The N_{se}, N_{pa} values of various configurations are listed in Table II. Three typical batteries each having a nominal voltage of 15V, 30V and 60V are used to test the scheme. For experimental purpose, assume that at full SOC the batteries voltage would be same as its nominal voltage. The VI curve interaction of PV array and three batteries are shown in Fig. 5. For 1000 W/m^2 insolation, it is to be noted that, operating 15V battery in 1x4 is suitable to track maximum power point(MPP) and for effective charging. This interaction would result in operating point A_1 in close vicinity of P_1 MPP of array.

In case of 30V battery, configuring array to 2x2 would charge the battery quickly by drawing higher current that other two configurations would fail to provide. This interaction results in A_2 operating point in close vicinity of P_2 MPP of PV array. In case of 60V battery, configuring array to 4x1 can charge the battery at fast rate. This results in A_3 operating point in vicinity of P_3 MPP of PV array.

TABLE II: PV ARRAY SPECIFICATIONS

Particulars	at STC and 1000W/m^2		Array	
	cell	module	Particulars	Quantity
OC voltage	0.58 V	21 V	total	4 modules
SC current	0.70 A	0.70A	total cells	144
V_{MPPT}	0.45 V	16.40 V	4x1N_{pa},N_{se}	1,144
I_{MPPT}	0.61 A	0.61 A	2x2N_{pa},N_{se}	2,72
$I_{ph}^{@}$	0.71 A	0.71 A	1x4N_{pa},N_{se}	4,36
rsc*	0.23 mA	0.23mA	configurations	3

@ photo current;* reverse saturation current

C. Control algorithm

Figure 6 demonstrates the working of proposed algorithm. Type of configuration suitable for a given

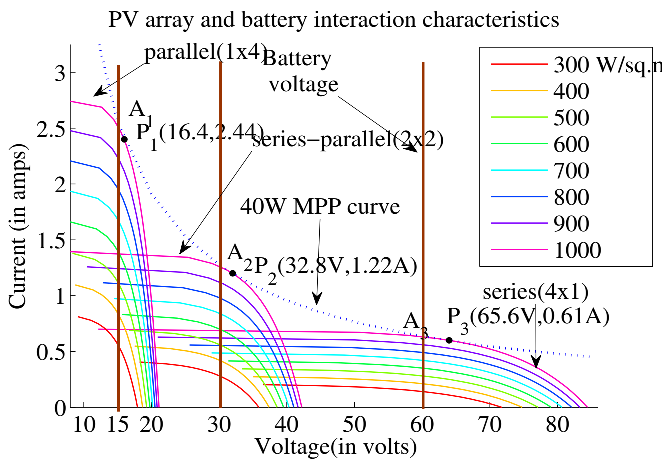

Fig. 5: Simulation response of PV array and battery VI characteristics interaction.

battery is discussed above. Unlike the motor or light load, battery is an active load. When charged, its voltage changes to higher value and from which its SOC is estimated. The SOC increases in charging or decreases in discharging or floats in trickle charging mode. In default state, the array is configured to 4x1. Hence, irrespective of voltage, the battery starts charging and builds the voltage. The algorithm senses battery voltage continuously so as to confirm the type of battery connected and it would quickly reconfigure array if another battery replaces it.

Identifying right boundary voltages such that (a) type of battery connected can be identified and (b) at all insolation conditions the PV array operates near its MPP. For this purpose, the voltage at which 4x1, 2x2 curves of a particular insolation level would interact is considered to be $V_{j-1}(\phi)$ boundary between 4x1, 2x2. Similarly, for 2x2, 1x4 the $V_{j-2}(\phi)$ would be the boundary voltage. Substituting N_{pa},N_{se} in above (1) for each of 4x1,2x2 configurations and solving these two equations would give the boundary voltage $V_{j-1}(\phi)$. Similarly, substituting 2x2,1x4 parameters in (1) and solving them gives the next boundary voltage $V_{j-1}(\phi)$. For the operating point to be in vicinity of MPP, it is advised to select PV modules that can match 3 range of batteries. This increases the efficient use of PV panels and reduces net cost of investment involved.

D. Trickle charging phenomena

Once the battery reaches the required SOC, battery be charged at reduced rate of current. For this

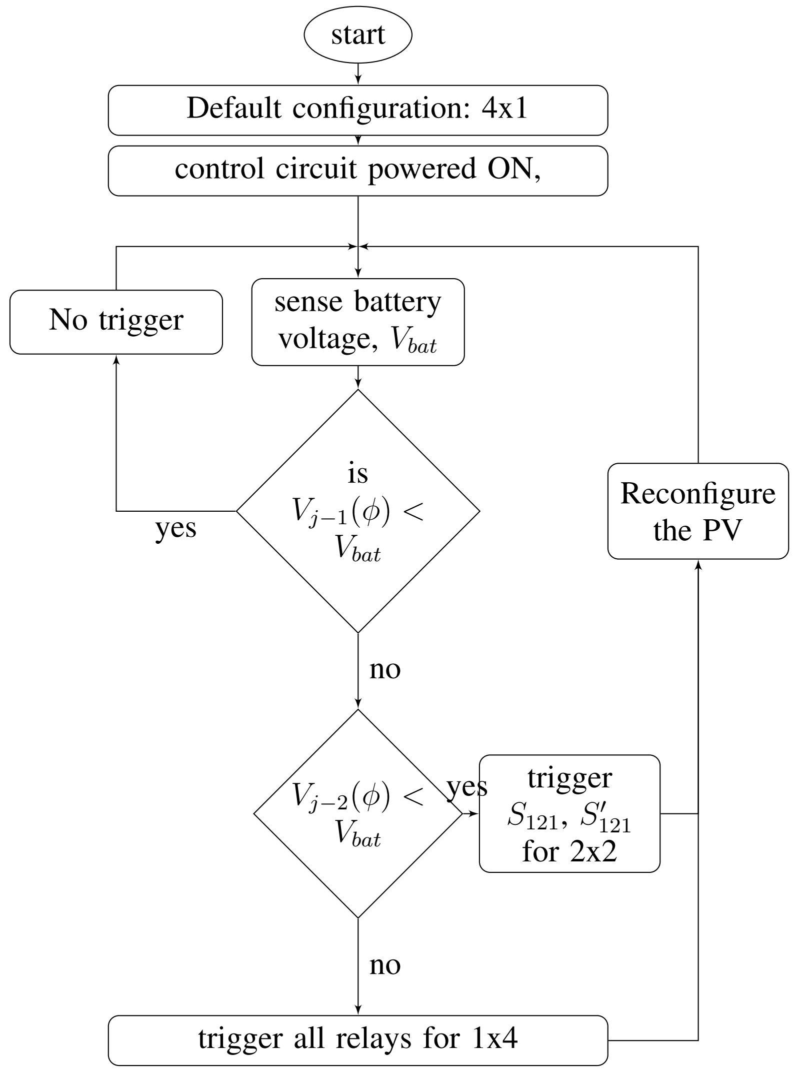

Fig. 6: Reconfigurable PV array battery charger algorithm for all insolation and battery conditions.

purpose, the configuration at which the battery was originally charged shall be altered to next high voltage configuration. For example, a battery originally charged at 1x4 shall be reconfigured to 2x2 once full SOC reached. This causes reduced rate of current charging and power transfer. This can be achieved by setting boundary voltages $V_{j-1}(\phi)$, $V_{j-2}(\phi)$ to match the SOC voltage of two types of batteries viz 15V, 30V. Once charged to full SOC, algorithm would alter the configuration for trickle charging.

III. Experimental Results

The objective of experiments is to verify the working of proposed algorithm. For this purpose, three batteries each having a nominal voltage of 15V, 30V, 60V have been used. The boundary voltage V_{j-1},V_{j-2} are set at 35V, 20V respectively. PV array, battery and control algorithm all have been simulated on a real time digital simulator OPAL-RT, as shown in Fig. 7, depicting a practical experiment. A Digital storage oscilloscope(DSO) TPS2404B of Textronix was connected to output port of simulator. Recorded experimental results are shown in Fig. 8.

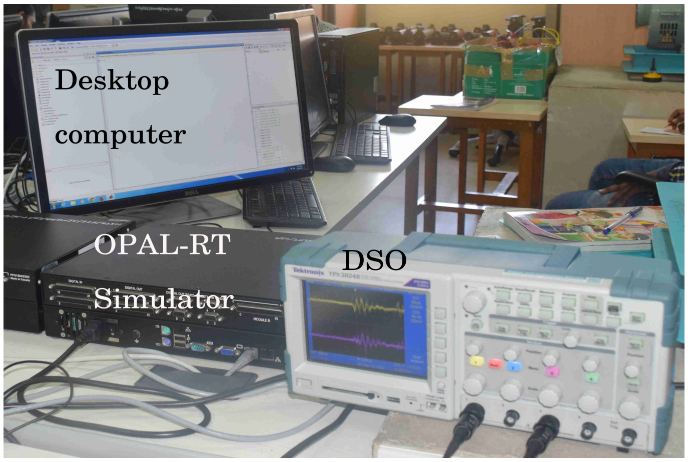

Fig. 7: Experimental set up consisting desktop computer, OPAL-RT simulator and DSO to record waveforms

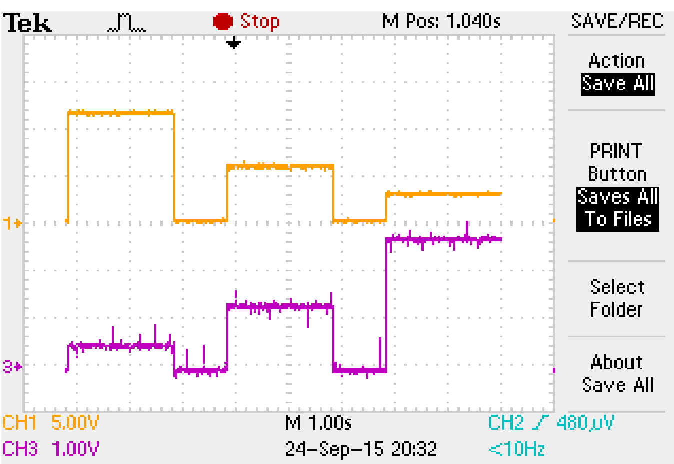

Fig. 8: Experimental voltage (yellow coloured), current(purple coloured) waveforms when PV charger connected to a battery of 60V during 1-3s, 30V during 4-6s and 15V during 7-9s.(Scale:axis x-1div=1s, CH1-1div=5Vx6 (M factor), CH3-1div=1A)

Figure 8 is the array voltage, current response wrt to time when three batteries are connected individually at different times of operation. When a 60V battery was connected at end of 1s, the algorithm senses 60V voltage which is above the voltage V_{j-1} of 35V, V_{j-2} of 20V respectively. This satisfies 4x1 configuration condition. Hence, by not triggering any of relays, algorithm allows the array to remain in 4x1 configuration. This results in battery charging at 0.62A current while operating at A_3 point as shown in Fig. 5 which is near the array MPP.

When 30V battery was connected during 4-6s, algorithm senses a battery voltage V_{bat} of 30V. It is above the boundary voltage V_{j-2} of 20V and below the V_{j-1} of 35V. This satisfies 2x2 configuration condition. Immediately, the algorithm triggers S_{122}, S'_{122} relays reconfiguring array from 4x1 to 2x2. As shown in Fig. 8, battery charges at 30V and 1.3A current. It operates at A_2 point as shown in Fig. 5 which in vicinity of array MPP.

When 15V battery is connected, algorithm senses battery voltage V_{bat} of 15V which is less than boundary V_{j-2} voltage of 20V. This condition satisfies 1x4. Hence, the algorithm will trigger all 8 relays and would reconfigure the array quickly to 1x4 configuration. This allows battery to charge at 2.5A current, highest the array can supply. In turn, array operates at A_1 point as shown in Fig. 5 near the array MPP.

It is to be noted that, PV array having MPP voltage in vicinity of battery voltages has been selected. In effect, array operates in close vicinity of its MPP. This completes the verification of algorithm working for three different battery voltages.

IV. Conclusion

This paper presents an optimized reconfigurable PV battery charger using a relay switch matrix. For first time, SPDT relay has been used in reconfigurable PV battery charger. Compared to prior art, the design has reduced the switch count from 9 to 8. A simplified control algorithm senses the connected battery voltage and configures array accordingly such that charging takes place effectively. Its implementation require comparator ICs and not the micro-controller or storage elements. Hence, this reduces size of circuitry and increases the PV charger reliability. Proposed design configures the array to 4x1 configuration by default. This unique feature empowers it to charge battery even when control circuit fails completely. Adding, configuring array to 4x1 require no control signal and this results in reduced circuit power consumption. In comparison to prior art, proposed PV battery charger has optimized the switch count, operational requirements and increased system reliability.

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