Interconnection and Optimization Issues of Multijunction Solar Cells - A New Mitigation Approach using Switching Power Converters

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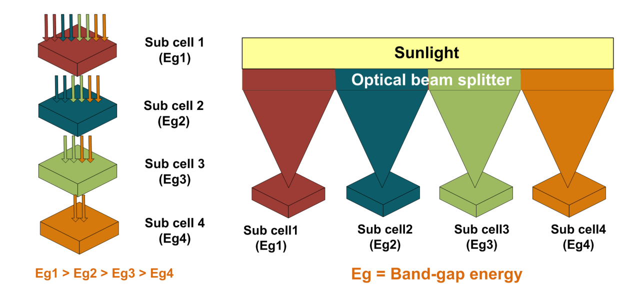
***Abstract*—A multijunction solar cell can extract higher solar energy compared to a single junction solar cell using the spectrum splitting technique. Extensive research on efficiency enhancement of the solar cells to achieve near theoretical limit is in place. However, there are limited research activities to identify the optimum interconnection methods and necessary power electronics solutions for multijunction solar cell systems. A detailed study to identify the optimum interconnection method for various multijunction solar cells is revealed in this paper. The authors believe that the conducted research in this area is very limited and an effective power electronics solution could substantially improve the efficiency and utilization of a PV power system constructed from multijunction solar cells. A multiple input dc-to-dc boost converter has been used to demonstrate the advantage of the proposed interconnection technique. Both Simulation and experimental results have been attached to show the practicality and the potential benefit of the proposed concept.**

I. INTRODUCTION

Only a fraction of the incident spectral energy can be converted into electrical energy by using a single junction solar cell. Depending on the band-gap energy of the material used, a significant portion of the solar spectra is either not absorbed or converted into heat. On the other hand, the concept of multijunction (MJ) solar cell is evolved to extract higher energy from the solar spectrum [1]-[24]. Depending on the spectrum splitting technique and orientation of the intermediate junctions, multijunction solar cells could be categorized into two main types: vertical multijunction (VMJ) solar cell and lateral multijunction (LMJ) solar cell [6], as illustrated in Fig. 1. In VMJ solar cells, beam splitting is performed by the sub cells itself and the efficiency can be as high as 40.7% under concentrated illumination [2]. In LMJ solar cells, optical splitter such as dichroic beam splitting is used to split the beam. VMJ solar cells are in general very expensive compared to single junction cells due to expensive fabrication involved in growing layers of materials having significant lattice mismatch. Strain and interface defects have significant effects over the fabrication yield and performance of the solar cell [16]. Moreover, sub cells in a VMJ solar cell are usually connected in series and suffer from current mismatch. On the other hand, the LMJ solar cell provides greater flexibility in fabrication and inter-connection of sub cells, allows multiple material choices and is able to achieve compatible efficiency [1] [17] [18]. However, the research in LMJ cell fabrication is in very early stage, and the optimum interconnection technique needs to be identified.

II. LMJ SOLAR CELL INTERCONNECTION

The design of the sub cells in LMJ solar cell can be independent [6][13]-[16] or interconnected as explained in [5]. LMJ solar cell is fabricated with $Zn_xCd_{1-x}S_ySe_{1-y}$ and a spatial composition grading is achieved across a single wafer (x = 0~1, y= 0~1). This resulted in a band gap from ~ 1.7eV (CdSe) to ~ 3.6 eV (ZnS). As the beam splitting is performed by the optical instruments, the LMJ solar cell is free from lattice and current mismatches. The absorption efficiency could be as high as 69 percent for three sub cells and this figure is astonishingly 86% for ten sub cells. As the efficiency does not increase in proportion with the number of sub cells, a compromise is made between the efficiency and $/W. However, the lateral splitting is more feasible in space applications, if combined with solar flux concentration techniques [14]. Due to the logarithmic relationship between



(a) VMJ solar cell structure (b) LMJ solar cell structure

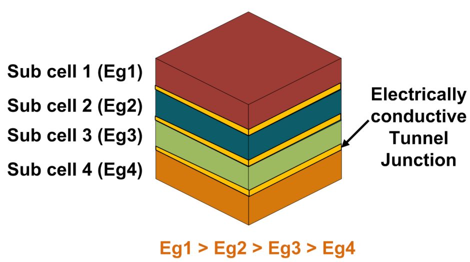
Fig. 1. Different MJ solar cell structures

the absorption efficiency and solar concentration, it is possible to achieve reasonably high efficiency with the same number of sub cells even at low concentration (between 10x and 100x) [12]. In this case, the optical splitter may be integrated with the static solar concentrator [6]. In addition, the need for any tunnel junction is eliminated as the sub cells in the LMJ solar cell can be connected independently. Therefore, the design complexity is substantially reduced. Despite of these advantages, the interconnection technique for LMJ solar cell is not optimized yet. In [15][23], an interconnection technique is proposed where sub cells of same materials are connected in series strings and string of different sub cell materials are connected in parallel to achieve nearly voltage matched interconnection. However, a complete optimal solution with an efficient power electronic solution has not been reported yet.

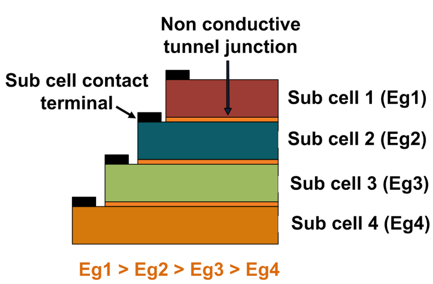
III. VMJ SOLAR CELL INTERCONNECTION

VMJ solar cells can be realized in two different ways, either mechanically or monolithically as shown in Fig. 2 [19][20]. In mechanically stacked MJ solar cells, multiple sub cells of different materials are manufactured on separate substrates, and they are stacked vertically, resulting in a multiple terminal device. Therefore, the sub cells are not electrically connected. Monolithically grown VMJ solar cells have a series of sub cells directly grown on one substrate and electrically series connected through tunnel junctions [1]-[4][7][8][10]. A monolithically grown VMJ solar cell can be either lattice matched or metamorphic in design [2][7][8]. The metamorphic structure provides higher current matching among the different sub cells in a VMJ solar cell. However, better current matched structure has been reported to be an inverted metamorphic structure in [10]. Despite of the above facts, a complete current matching is unattainable because the sub cells are connected in series. It is apparent that the mechanically stacked structure provides more flexibility in terms of material selection and inter-connection of sub cells where maximum power point (MPP) can be achieved for individual sub cells. Thus, this arrangement would be more efficient than the monolithic structure at the expense of greater system complexity [19][20]. The complex fabrication of mechanically stacked VMJ solar cells and recent advancement in the fabrication processes for monolithically stacked cells have led the researchers towards the monolithic structures. However, the mechanically stacked VMJ solar cell is still a promising technology, and the sub cells can be connected in a similar fashion as in LMJ sub cells. This is how the optical splitter could be excluded although maintaining several favorable features of an LMJ structure [6].

Combining the advantages of both LMJ and VMJ solar cells, a hybrid structure is proposed in [12][17][22][23]. In these structures the beam splitting may be performed in two stages as shown in Fig 3. The hybrid structure provides the leverage of optimizing the monolithically grown VMJ solar cells and the optical elements separately. As optical losses and the fabrication constrains are optimized in this hybrid structure, the efficiency can be as high as 50% [12]. Moreover, the system-level interconnection can also be optimized with

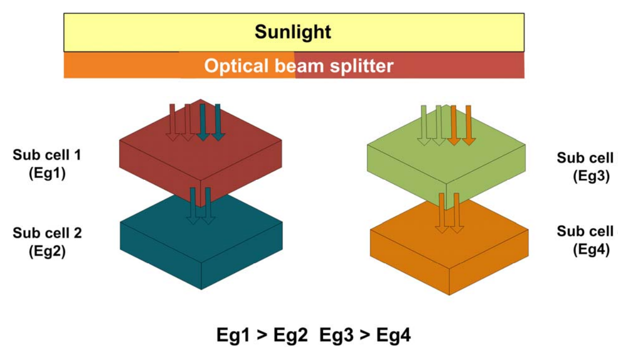


(a) Monolithically stacked

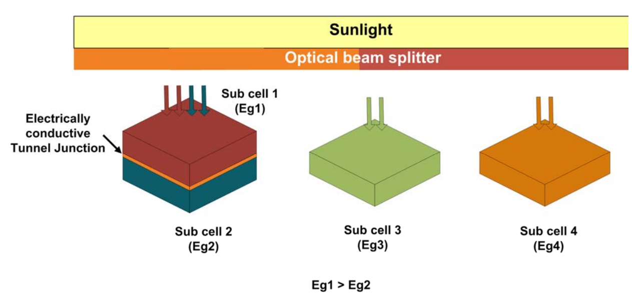


(b) Mechanically stacked

Fig. 2. VMJ structures



(a) Mechanically stacked VMJ solar cells with optical beam splitter used as LMJ structure



(b) Monolithically stacked VMJ solar cell with optical beam splitter used as LMJ structure

Fig. 3. Hybrid MJ structures

mechanically stacked sub cells [22].

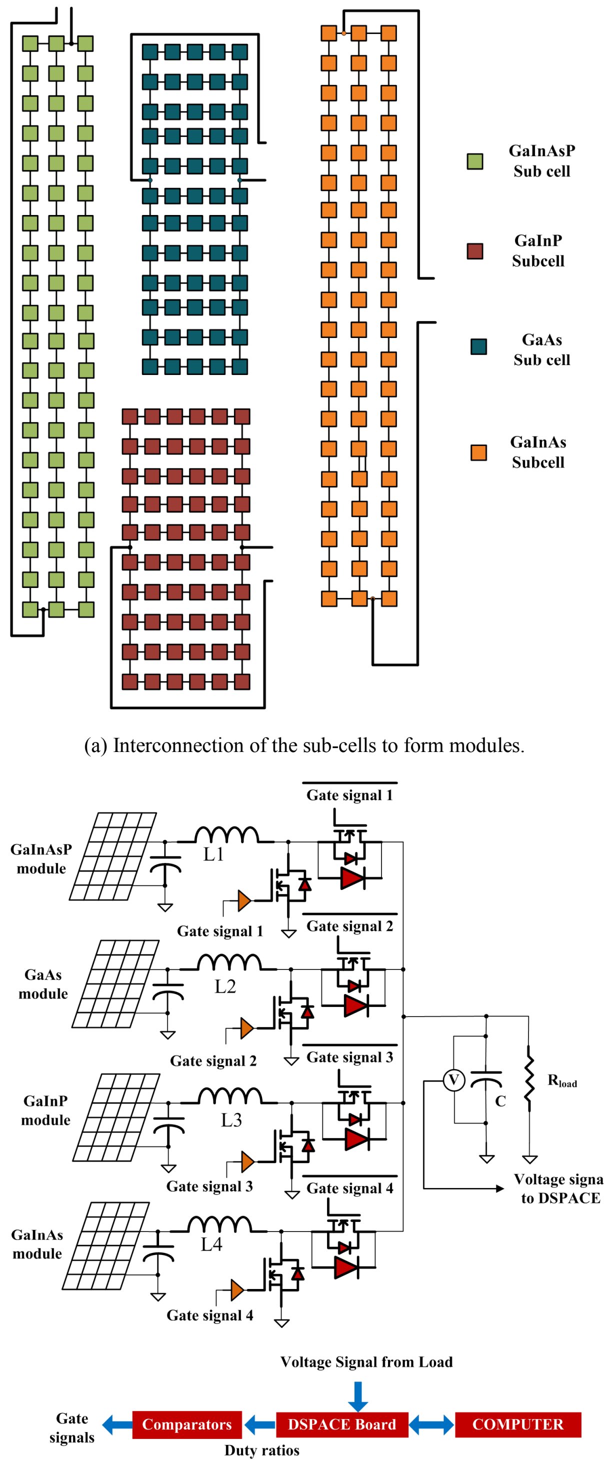
Although a substantial effort is in place to improve the efficiency of multijunction solar cells, only a few initiatives were taken to identify the most efficient interconnection of the sub cells as well as interconnection of the MJ solar cells. Multijunction solar cells having independently connected sub cells provide the leverage of accomplishing a completely matched interconnection. Multiple sub cells having same group of materials can be connected in series to form a string to build up the voltage for suitable power electronic conversion. In addition, identical strings can be connected in parallel to increase the power output. In this paper, a MJ solar cell with four different sub cells consists of GaInP, GaAs, GaInAsP, GaInAs is considered. A completely matched interconnection in terms of terminal voltage and string current is proposed in this paper that requires a multiple input dc-to-dc converter for voltage boosting operation. Although the dc-dc converter was designed to accommodate only four specific sub cell materials, it is scalable to interface with any number of sub cells.

IV. Proposed Interconnection Technique

The individual sub cell characteristics of a multi-junction cell can be found in [22]. Based on this reference and considering 20 cm^2 surface area of each sub cell, Table I has been populated. If all these sub cells with different band gap energies are connected in series, current mismatch will reduce the efficiency and will result in very low short circuit (I_{SC}) current of the system. In addition, connecting all sub cells in parallel will cause voltage mismatch, and the cell will produce very low output voltage for any power conversion. In order to avoid current mismatch and to achieve higher terminal voltage, the sub cells constructed from the same material can be connected in series to form a string and the strings with similar i-v characteristics can be connected in parallel without any mismatch, and therefore a module can be formed. This interconnection will end up having completely matched modules. Moreover, a highly parallel configuration is desired [25] to compensate the effect of partial shading. Therefore, similar modules should be connected in parallel for higher power output. Then these modules are connected to four separate dc-dc converters as shown in Fig 4. Similar interconnection systems for connecting conventional solar panels have been discussed in [26]-[30] and they are termed as multi-string systems. However, the interconnection of the sub cells of a MJ solar cell has not been reported yet.

V. Maximum Power Point Tracking (MPPT)

The power output from a solar cell varies with temperature, illumination and electric load connected with it. Therefore, maximum power point tracking (MPP) is unavoidable [30] for an efficient solar cell system. Separate MPPT circuits are usually implemented for each dc-dc converters in conventional MPP tracking systems, and dc-dc converter requires individual current and voltage sensing. In order to reduce the cost and complexity of the system, only one MPPT circuit can be used for a four-input dc-dc converter assisted by a special algorithm. Here, a simple interleaved perturb and observe (P&O) algorithm is used, and the flowchart of the algorithm is shown in Fig. 5.



(a) Interconnection of the sub-cells to form modules.

(b) Overall system

Fig. 4. Proposed interconnection

TABLE I

SUB-CELL MATERIALS, BAND GAP ENERGY AND SUMMERY OF THE INTERCONNECTION

Sub-cell	Band gap (eV)	Current density of each sub-cell (mA/ cm^2)	Open circuit voltage V_{oc} Of each sub-cell (V)	Number of sub-cells in series in a string	Number of parallel strings in a module	Ideal Open circuit voltage of the module (V)	Ideal Short circuit current the module (A)	Fill Factor (%)
GaInP	1.91	13.5	1.384	10	6	13.84	1.62	84
GaAs	1.42	14.5	0.959	12	5	11.508	1.45	83
GaInAsP	0.98	18.2	0.598	20	3	11.96	1.092	75.6
GaInAs	0.74	8.08	0.336	20	3	6.72	0.4848	72.7

VI. SIMULATION RESULTS

Simulation is performed for four solar modules in PSIM using the functional models stated in Table I. The maximum power point voltages and currents are estimated by matching the fill factor of the corresponding sub cells. The MPPT algorithm is written in C inside PSIM using the simplified C block. The obtained results are shown in Fig. 6. The step size for updating duty ratio duty ratio was 0.02. As shown in Fig. 6. (a), the output power increases with the change of duty ratio of the converters. At steady state, the output power always oscillates near the maximum point due to the inherent nature of the P&O algorithm [31]. This is also true for the variation of duty cycle of the converters as shown in Fig. 6. (b). The magnitude of oscillation might be reduced by decreasing the step size of the duty ratio of the converters. However, the system will have slower response for smaller step size.

VII. EXPERIMENTAL SETUP

As a proof of concept, a prototype was built in the laboratory to demonstrate the benefits of the proposed interconnection. Because a of the unavailability of a physical four-junction MJ solar cell system, four benchtop linear power supplies with series resistors emulating solar cell strings were used in place of the MJ cell system. This arrangement is shown in Fig. 7, and this arrangement is consistent with the MPP characteristics of individual modules stated in Table I. The algorithm was implemented in dSPACE 1104 system, and the switching frequency of the converters was set at 5 kHz. The duty ratio of each converter was updated every 0.2

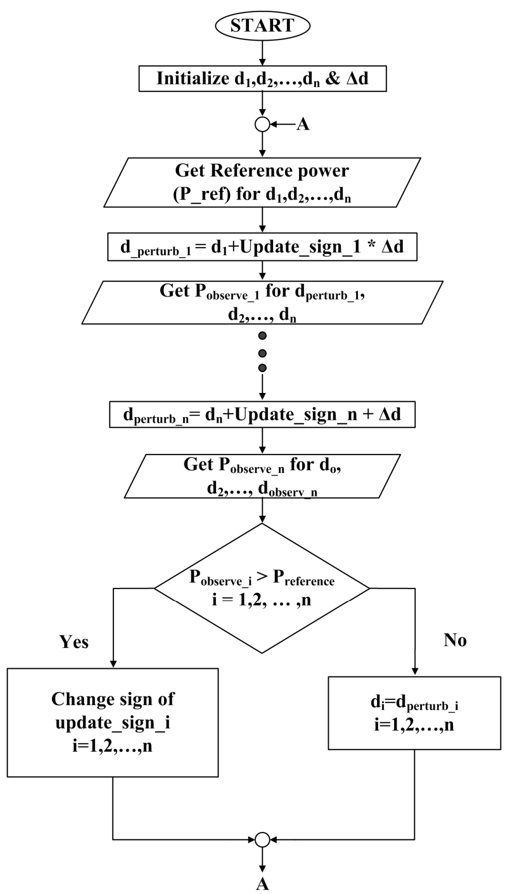
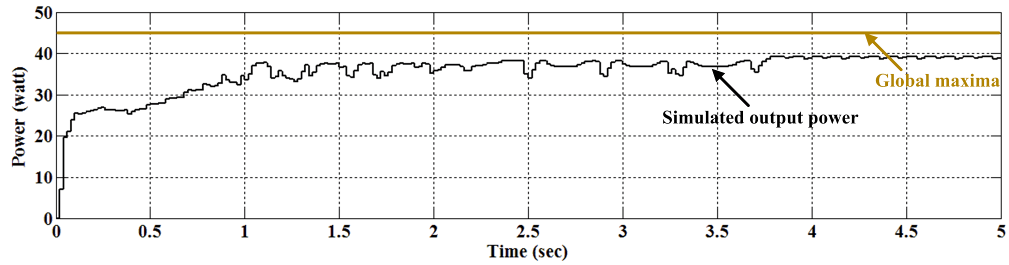
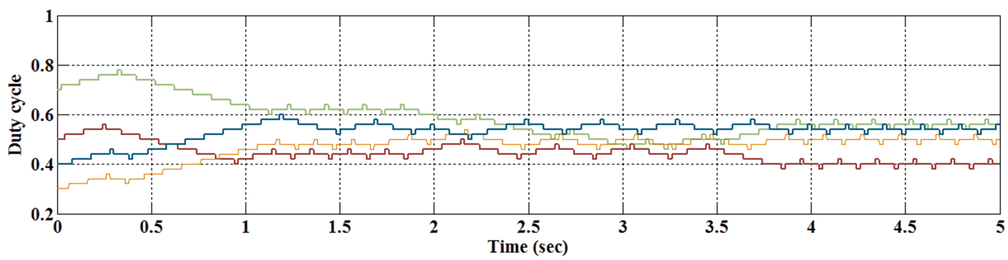


Fig. 5. Interleaved P&O algorithm to obtain global maxima.



(a) Variation of power with time



(b) Variation of duty cycle of four converters with time

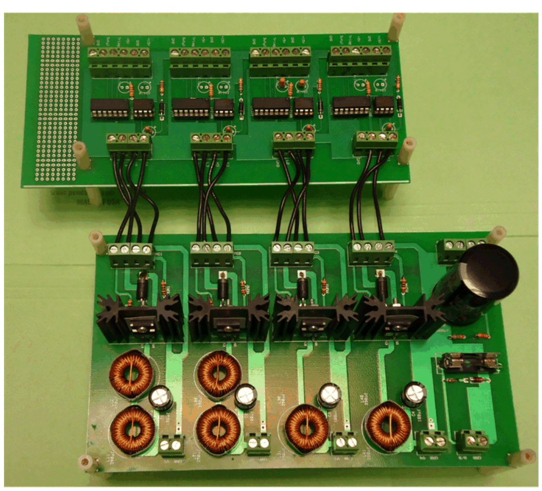
Fig. 6. Simulation data

seconds, and the obtained experimental results are shown in Fig 8.

Synchronous rectification was used to minimize the power loss across the diode of the boost converters. The converters were constructed from discrete components, and the total output power was 40.80 watts with the global MPP (summation of individual MPPs) located at 44.9 watt level. Therefore the overall efficiency of the proposed interconnection is 90.86%., and these results are consistent with the simulation results.

VIII. Comparison with Conventional Interconnection Techniques

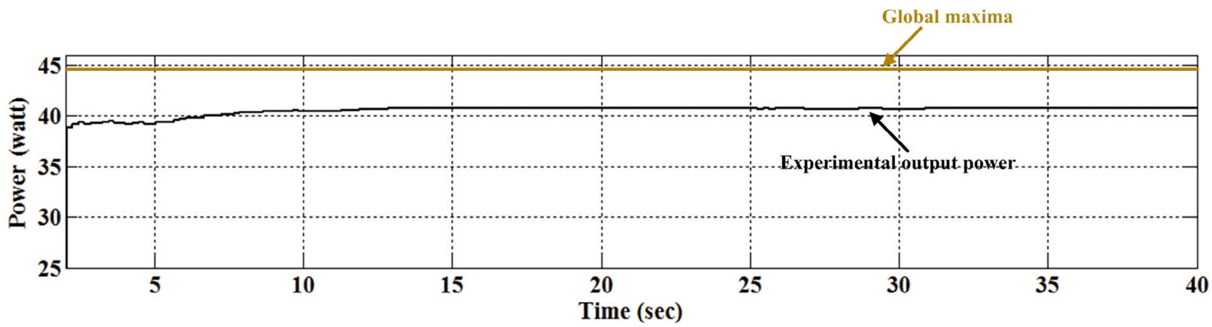
A comparative study was performed to justify the use of this proposed technique with MJ solar cell. If all the sub-cells stated in Table I are connected in series, the open circuit voltage at the terminals would be 196.62 volts with short circuit current 0.1616 amperes. Assuming 80 percent fill factor, the maximum power output from the module will be 25.42 watts. On the other hand, the power output from the proposed interconnection is 40.8 watts. Therefore, the proposed interconnection results in achieving 60.3% power



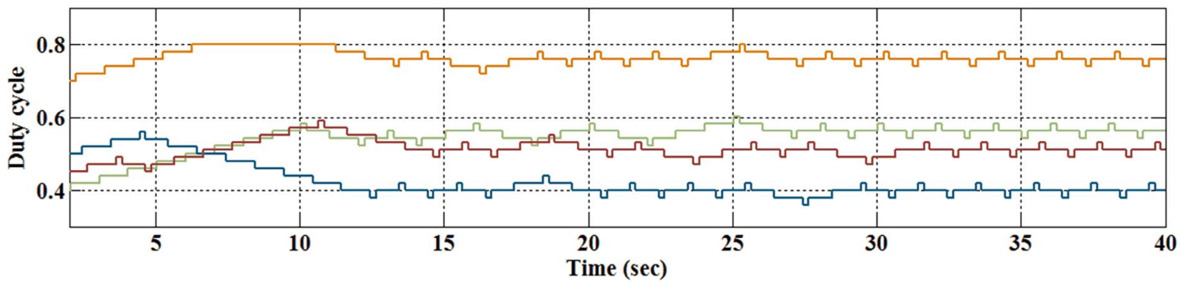
(a) Prototype for the experiment

(b) Experimental setup

Fig. 7. Experimental setup



(a) Variation of power with time



(b) Variation of duty cycle of four converters with time

Fig. 8. Experimental data

gain. Considering 6 hours of average insolation, it will result in approximately 750 kWh energy gain per year for a 1kw unit.

IX. Conclusion

The efficiency of a multi-junction solar cell is much higher than single junction counterpart. However, MJ cells are already very expensive, and even a small amount of efficiency gain could result in substantial savings. The use of MJ cells is gradually increasing due to new material combinations, advancement in concentrator materials and optical splitting techniques, and advancement in fabrication processes. Due to higher price, the application of MJ solar cell is limited to aerospace application and concentrated photovoltaic (CPV) power generation [32][33]. Therefore, the ongoing research in MJ solar cells is primarily focused to efficiency enhancement at the cell level. To the knowledge of the authors, there is no significant work on the optimal interconnection of MJ solar cell systems using efficient power electronics solutions. The identification of the optimum interconnection for multi-junction solar cells is the main consideration of this work, and the overall efficiency enhancement of such a system is also discussed. It has been shown that the proposed interconnection will result in achieving substantial efficiency gain and can yield a completely matched system..

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