

2 Design of an Efficient Non- Separately Operated Cells Multi-Cell System

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Abstract

In this work, improving the conversion efficiency (η_n) related to non-separately operated cells multi-cell system is the responsibility of the way by which the system cells are electrically arranged. Optically, cells are arranged similar to the well-known multi-cell system arrangement. Electrically, cells are connected into several parallel branches, each branch consists of several series connected cells. Branch cells are chosen to as much as possible satisfy: first, equality of all currents generated in a branch; second, Equality of all parallel branch voltages. A relative comparison of the values of η_n (multi-cell system with non-separately operated cells) with those of the optimal one, η , (multi-cell system with separately operated cells) reveals the interest that may grow in the use of only single load and single controller. Theoretical calculations under air mass zero (AM0) solar spectrum and concentration ratio (X) of 10^3 result in an efficiency (η_n) of up to 52.52%, 44.88% at 300K, 400K, respectively.

Keywords: Solar cells, multi - cell system.

المخلص

في هذا البحث ، يعود تحسين كفاءة التحويل في منظومة الخلايا- المتعددة ذات الخلايا غير المستقلة وظيفياً إلى الطريقة التي رتبنا بواسطتها كهربائياً خلايا المنظومة . بصرياً ، لا يختلف ترتيب الخلايا عن الترتيب المؤلف في منظومات الخلايا المتعددة . كهربائياً ، تم ربط خلايا المنظومة في فروع متوازية ، يحتوي كل فرع على عدد من الخلايا المربوطة على التوالي . يقع اختيار خلايا الفروع ، قدر الإمكان ، لتحقيق التالي : أولاً ، تساوي كل تيارات خلايا الفرع وثانياً ، تساوي الجهد في كل الفروع المتوازية . يجعل التقارب النسبي المتحصل عليه بين الكفاءتين (η_n) وتلك المثلى (η) المتعلقة بالخلايا المستقلة وظيفياً من الممكن وبالتالي من المفيد عدم استخدام أكثر من حمل وأكثر من متحكم. أظهرت النتائج النظرية لثمان خلايا تعمل عند كثلة هواء (AM0) ونسبة تركيز ($X=10^3$) كفاءات تحويل (η_n) ، 52.52% ، 44.38% عند درجات حرارة 400K ، 300K .

1. INTRODUCTION

The maximum theoretical conversion efficiency of a single-junction solar cell is limited by the trade-off between increased voltage and lower current as the band gap is increased [Chenming, Richard, 1983 and Geoffrey, 1988]. As a solution to low conversion efficiency, multi-cell systems (cascade or spectrum-splitting) show a higher

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efficiency but at the expense of the number of cells used [Gokcen and Lofersky, 1979]. Spectrum-splitting has a slightly higher theoretical conversion efficiency as compared to cascaded-cells because the requirement of an equal current is not imposed on the cells when operated separately [Mitchel, 1987]. Monolithic cascade has a reduced current and large voltage since cells are non-separately operated and internally connected in series [Salah, Sunil, 1980 and Sze, 1981].

The main reason that makes separately operated cells multi-cell system more efficient than the non-separately operated multi-cell system is that the problem of minimum current and minimum voltage does not exist, but this is at the expense of some extra system requirement such as: more than one controller, inverter, and load.

Regarding all these problems, this paper introduces the solution when it offers an electrical way of connection (current / voltage branching method) that makes possible obtaining a conversion efficiency (η_n) that reasonably approaches in its value that of the conversion efficiency (η) obtained from the familiar multi-cell system in which the system cells are separately operated.

2. DESIGN ANALYSIS

Consider an eight cells (non- separately operated) multi-cell system shown in Fig. (1), in which the system cells are represented by their band gaps (E_{g1} through E_{g8}). Optically, cells are arranged as familiar in a sequence of $E_{g1} > E_{g2} > \dots > E_{g8}$.

Electrically, narrowest and widest band gap solar cells may be serially connected and thus forming a branch independent of their optical arrangement.

Cells those generating an equal currents are included in each of these three branches: (E_{g1}, E_{g5}), (E_{g2}, E_{g4}), and ($E_{g3}, E_{g6}, E_{g7}, E_{g8}$).

2.1 Branch Current Equations

In multi-cell system, the short circuit current is given by [Wolf 1960].

$$I_{sc}(E, E_g) = I_{sc}(E_g) - I_{sc}(E) \quad (1)$$

Cell current generated in each branch when each branch cell is separately operated is:

Branch (A)

$$I_{1A} = I_{sc}(0, E_{g1}) = I_{sc}(E_{g1}) \quad (2)$$

$$I_{5A} = I_{sc}(E_{g4}, E_{g5}) = I_{sc}(E_{g5}) - I_{sc}(E_{g4}) \quad (3)$$

Branch (B)

$$I_{2B} = I_{sc}(E_{g1}, E_{g2}) = I_{sc}(E_{g2}) - I_{sc}(E_{g1}) \quad (4)$$

$$I_{4B} = I_{sc}(E_{g3}, E_{g4}) = I_{sc}(E_{g4}) - I_{sc}(E_{g3}) \quad (5)$$

Branch (C)

$$I_{3C} = I_{sc}(E_{g2}, E_{g3}) = I_{sc}(E_{g3}) - I_{sc}(E_{g2}) \quad (6)$$

$$I_{6C} = I_{sc}(E_{g5}, E_{g6}) = I_{sc}(E_{g6}) - I_{sc}(E_{g5}) \quad (7)$$

$$I_{7C} = I_{sc}(E_{g6}, E_{g7}) = I_{sc}(E_{g7}) - I_{sc}(E_{g6}) \quad (8)$$

$$I_{8C} = I_{sc}(E_{g7}, E_{g8}) = I_{sc}(E_{g8}) - I_{sc}(E_{g7}) \quad (9)$$

Where the current subscripts in eqns (2) - (9) represent cell number, and branch, respectively.

Current equality condition is satisfied when currents generated by cells of certain branch are equal to each other, that is:

$$I_{1A} = I_{5A}, I_{2B} = I_{4B}, \text{ and } I_{3C} = I_{6C} = I_{7C} = I_{8C} \quad (10)$$

Shockley equation for each current in eqns. (2 to 9) is given by the form:

$$I = I_0 \left(\frac{qV}{kT} - 1 \right) - I_{sc}(Eg) \tag{11}$$

where I_0 is the reverse saturation current given by:

$$I_0 = 6.03 \times 10^9 e^{-E_g / kT} \tag{12}$$

The maximum current is given by:

$$I_{mp} = \frac{qV_m / kT}{1 + (qV_m / kT)} (I_{sc}(E, Eg) + I_0) \tag{13}$$

2.2 Branch Voltage Equations

Voltage across branches (A, B and C) are given by

$$\sum V_A = V_1 + V_5, \quad \sum V_B = V_2 + V_4 \text{ and } \sum V_C = V_3 + V_6 + V_7 + V_8 \tag{14}$$

and the maximum voltage is given by:

$$e^{qV_m / kT} (1 + \frac{qV_m}{kT}) = \frac{I_{sc}(E, Eg)}{I_0} + 1 \tag{15}$$

2.3 Maximum Power and Conversion Efficiency Equations

Since branch cells are connected in series, the maximum voltage (V_m) related to eqn. (14) are given by:

$$\sum V_m = \frac{kT}{q} \ln \left[\prod_{i=1}^n \left(\frac{I_{sc} + I_0 - I}{I_0} \right) \right] \tag{16}$$

where n is the number of branch cells connected in series .

The maximum current generated from all parallel branches is given by :

$$\sum I_m = I_m A + I_m B + I_m C \tag{17}$$

and the maximum power is:

$$P_m = (\sum V_m)(\sum I_m) \tag{18}$$

Thus the conversion efficiency (η_n) is given by:

$$\begin{aligned} \eta_n &= \frac{(\sum V_m)(\sum I_m)}{(Pin)(X)} = \frac{(\sum V_m A)(I_m A) + (\sum V_m B)(I_m B) + (\sum V_m C)(I_m C)}{(Pin)(X)} \\ &= \frac{(V_{m1} + V_{m5})(I_m A) + (V_{m2} + V_{m4})(I_m B) + (V_{m3} + V_{m6} + V_{m7} + V_{m8})(I_m C)}{(Pin)(X)} \end{aligned} \tag{19}$$

According to voltage equality equation, that is:

$$\sum V_{mA} = \sum V_{mB} = \sum V_{mC} = \sum V_m \tag{20}$$

Eqn. (19) can be written as:

$$\eta_n = \frac{(\sum V_m)(I_m A + I_m B + I_m C)}{(Pin)(X)} \tag{21}$$

where P_{in} is the input solar power.

3. RESULTS AND DISCUSSIONS

In this work, calculations are carried out under AM0 solar insulation at concentration ratios of 1, 10^2 , and 10^3 and temperatures of 300K and 400K, for up to an eight-cell non-separately operated cells multi-cell system.

The variation of efficiency with the number of cells at T=300K, 400K are shown in Figs. (2 and 3).

Table (1), shows the variations of the conversion efficiency (η_n), branch current, and branch voltage with the number of cells (N) at temperature of 300K.

Cell sets selected may not be identical to those cells [Wolf, 1960] optimized to the maximum power in separately operated cells multi-cell system. Consider the three cells multi-cell system illustrated in Table (1), (2.4 eV, 1.6 eV, 1.1 eV) at X=10 .There are two branches (A and B); Branch (A) consists of a single cell of 2.4 eV while Branch (B) consists of two series-connected cells (1.6 eV and 1.1 eV). Both branches are then connected in parallel . Branch currents and voltages are obtained by using data [Wolf, 1960] related to AM0. Maximum branch voltages $\sum V_{mA}$, $\sum V_{mB}$ are 1.77V, 1.52V respectively and maximum branch currents I_{mA} , I_{mB} are 11.24 mA, 19.60 mA, respectively, since the smallest maximum branch voltages and currents are the predominant . Conversion efficiency (η_n) of 34.62% is obtained. When cells in this set (2.4 eV, 1.6 eV, 1.1 eV) are separately operated cells then three separate loads and controllers are required that leads into an economic problem to be arises regardless what maximum is efficiency is obtainable, (η_n), 37.42%. The variation of efficiency (η_n), branch currents, and branch voltages at temperature of 400K with the number of cells (N) is shown in Table (2).

Both Tables (1 and 2) show an increase in η_n with increasing N and X.

Tables (3) and (4) show a comparison between the value of (η) and (η_n) at N=3 and

X of 10^2 and 10^3 at 300K, 400K, respectively. A ratio $\left(\frac{\eta_n}{\eta}\right) \times 100\%$ of about 95% and

93% are obtained at 300K, 400K, respectively. From tables (3) and (4) it is also obvious how could the efficiency related to separately operated cells multi-cell system be decreased when cells are directly connected in series.

Cell sets used by this work should not be far in their band gaps from those cells optimized to the maximum power [Wolf, 1960], but at the same time calculations should move around the point that ensures maximum current to flow through a branch.

Table (1): Variation of conversion efficiency with the number of cells at T=300K

Number of cells (N)	X	Branch (A) cells (eV)	Branch (B) cells (eV)	Branch (C) cells (eV)	$\sum I_m$ (mA)	$\sum V_m$ (V)	η_n (%)
3	1	2.4	1.6, 1.1	-	30.84	1.519	34.62
5	1	2.6	2.1, 1.2	1.7, 1.4	27.57	1.876	38.23
6	1	2.6	2.1, 1.2	1.7, 1.4, 0.9	27.57	1.967	40.08
7	1	2.6, 1.5, 1.3	2.1, 1.8, 1.1, 0.9	-	15.83	3.455	40.4
8	1	2.6, 1.5, 1.3	2.1, 1.8, 1.1, 0.9, 0.7	-	15.829	3.5405	41.42
3	10 ²	2.4	1.6, 1	-	3090.26	1.7518	40.01
5	10 ²	2.6	2.1, 1.2	1.7, 1.4	2763.528	2.081	42.50
6	10 ²	2.6, 2.1	1.8, 1.5, 1.3, 1.1	-	1606.68	3.669	43.57
7	10 ²	2.6, 1.3	2.1, 1.1, 0.9	1.8, 1.5	2649.61	2.301	45.06
8	10 ²	2.6, 1.3	2.1, 1.5	1.8, 1.1, 0.9, 2.7	2618.26	2.5805	49.93
3	10 ³	2.4	1.6, 1	1.7, 1.4	30929.13	1.8673	42.690
5	10 ³	2.6	2.1, 1.2	-	2760.88	2.14	43.67
6	10 ³	2.4, 2.5	2.1, 1.7, 1.4, 1.2	1.8, 1.5	13700.28	4.451	45.07
7	10 ²	2.6, 1.3	2.1, 1.1, 0.9	1.8, 1.5	26536.44	2.4177	47.428
8	10 ²	2.6, 1.3	2.1, 1.5	1.8, 1.5, 0.9, 0.7	26242	2.708	52.52

Table (2) : Variation of conversion efficiency with the number of cells at T=400K.

Number of cells	X	Branch (A) cells (eV)	Branch (B) cells (eV)	Branch (C) cells (eV)	$\sum I_m$ (mA)	$\sum V_m$ (V)	η_n (%)
5	1	2.6	2.1, 1.3	1.8, 1.5	25.41	1.687	31.606
6	1	2.6	2.1, 1.3	1.8, 1.5, 1.1	24.67	1.76	32.2
7	1	2.6, 1.3, 1.1, 0.9	2.1, 1.8, 1.5	-	16.3246	2.732	32.963
8	1	2.6, 0.9	2.1, 1.5	1.8, 1.3, 1.1, 0.8	24.39	1.857	33.475
5	10 ²	2.6	2.1, 1.3	1.8, 1.5	2562.575	1.9155	36.28
6	10 ²	2.6, 1.3, 1.1	2.1, 1.8, 1.5	-	1667.775	3.0365	37.43
7	10 ²	2.6, 1.3, 1.1, 0.9	2.1, 1.8, 1.5	-	1647.075	3.324	39.13
8	10 ²	2.9, 2.5, 0.9	2, 1.7, 1.4, 1.2, 1	-	1328	4.0677	39.925
5	10 ³	2.6	2.1, 1.2	1.7, 1.4	27356.71	1.9566	39.561
6	10 ³	2.6, 1.3, 1.1	2.1, 1.8, 1.5	-	16518.21	3.265	39.86
7	10 ³	2.6, 1.3, 1.1, 0.9	2.1, 1.8, 1.5	-	16518.21	3.6251	44.25
8	10 ³	2.9, 2.5, 0.9	2, 1.7, 1.4, 1	-	13506.524	4.4465	44.387

Table (3): comparison between separately, non-separately (Series- connected) ,and the approach efficiencies N=3,T=300K .

Separately-operated cells			Series - connected non- separately operated cells		The Approach			
X	η (%)	Cell set (eV)	X	η (%)	X	Cell branches		η_n (%)
						A(eV)	B(eV)	
10^2	42.52	2.3,1.5,0.9	10^2	31.18	10^2	2.4	1.6,1	40.01
10^3	45.37	2.2,1.4,0.8	10^3	32.85	10^3	2.4	1.61	42.685

Table (4): comparison between separately , non-separately (series-connected), and the approach efficiencies at N= 3 ,T=400K

Separately-operated cells multi-cell system			Series - connected non- separately operated cells multi-cell system 2.3 eV ,1.6eV, 1eV		The Approach			
X	η (%)	Cell set (eV)	X	η (%)	X	Cell branches		η_n (%)
						A(eV)	B(eV)	
10^2	35.86	2.3,1.61	10^2	28.59	10^2	2.3	1.7,1.3	33.2
10^3	39.14	2.3,1.6,1	10^3	30.79	10^3	2.4	1.7,1.2	36.2

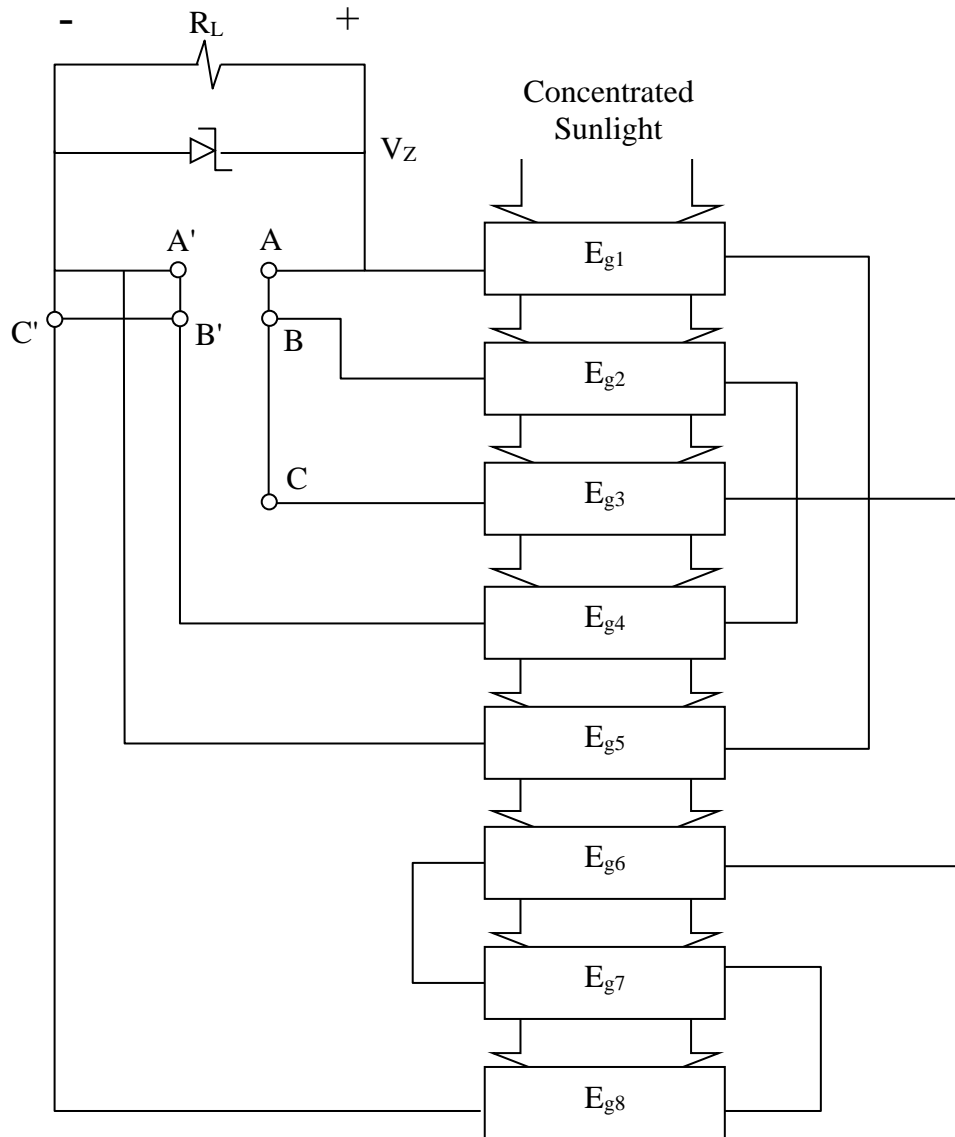


Fig. (1): Eight cells multi - cell system connection.

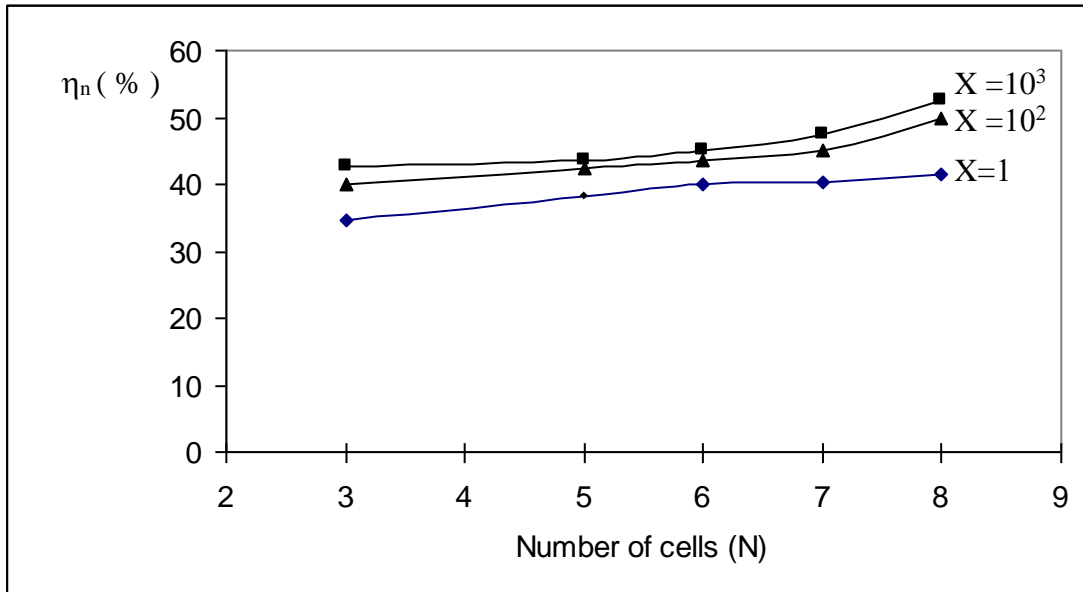


Fig. (2): Variation of efficiency (η_n) with the number of cells (N) at T=300K

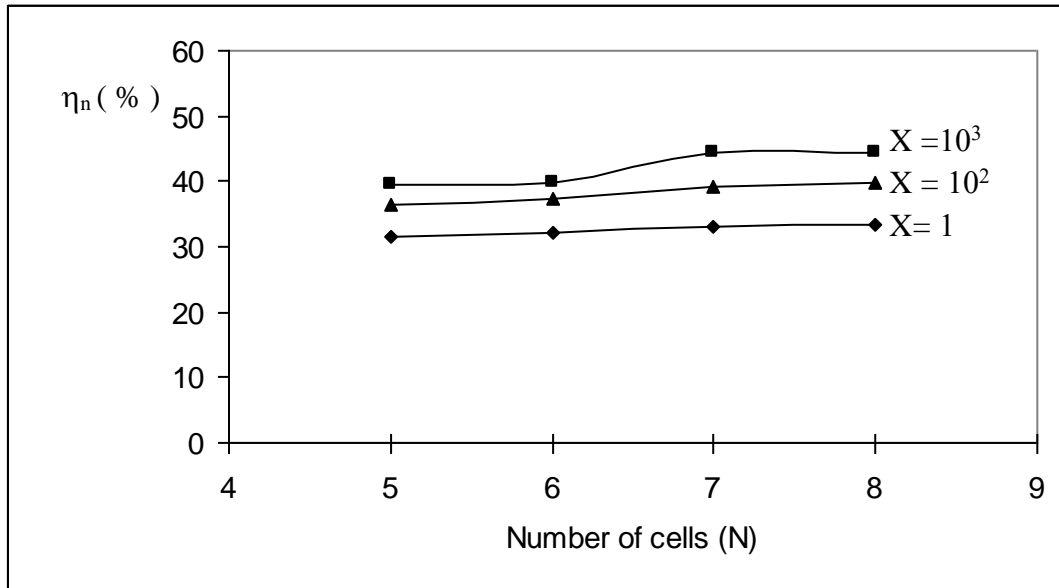


Fig. (3): Variation of efficiency (η_n) with the number of cells (N) at T=400K

4. CONCLUSIONS

From this work it is concluded that:

- 1- Improving the conversion efficiency (η_n) depends on how far is the minimum current from the maximum current in a branch, and also on how far is the minimum voltage from the maximum voltage across branches, since minimum currents and voltages are the predominant parameters.
- 2- Separately operated cells multi-cell system when applied to this design may show a lower conversion efficiencies unless their band gaps are tuned following this design rules.
- 3- This design provides an efficiency comparable with the optimal one obtained from separately operated cells-multi-cell system, for the same number of cells, with only single load and controller .
- 4- This design is more suitable for monolithic cascaded cells where it introduces a reasonable solution to the minimum current problem. Also, it provides flexibility of choosing the system cells so that the lattice matching problem between semi-conducting materials may be solved.

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