A NOVEL APPROACH OF A SINGLE-INPUT MULTI-OUTPUTS CONVERTER FOR A MODIFIED DC NANOGRID WITHIN AN OPEN ENERGY SYSTEM

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Abstract: A DC nano-grid is typically designed as a reliable system that can supply power from the distributed renewable energy sources to the local loads. Traditional nano-grid employs two-stage ac–dc power converter/inverter sets to feed both ac and dc loads respectively. But, modified nano-grid utilizes only one single-stage converter. This system is based on a power-electronic single-input multi-output converter which interfaces the source with the average load demands. This paper deals with a switched boost inverter (SBI) applicable for solar photovoltaic system (PV) as its renewable energy source. SBI is a single-stage power converter that can supply both dc and ac loads simultaneously from a single dc input voltage source. The SBI can also produce an ac output voltage either greater or lower than its dc input voltage. This converter exhibits better Electro Magnetic Interference (EMI) noise immunity as compared to the two stage-power converter. Also, this converter operation allows shoot-through of the inverter legs without damage to its IGBT- switches. So, this paper discusses the advantages, structure, steady-state analysis, and PWM control technique for the SBI especially, when produces a high-rating dc-output voltage from a very-low input-voltage of a PV- solar array to establish its verification. Matlab/Simulink-based simulation is performed for several cases of operations – with PV-mathematical model- to test the robustness of this converter against the supply fluctuations. Also, the harmonic spectrum analysis for the load current is also computed and plotted for a 5-Kw proposed nanogrid.

Keywords: Renewable Energy Source (RES), DC nanogrids, Switched Boost Inverter (SBI), Z-Source Inverter (ZSI), Open Energy System (OES)

1. Introduction

The electrical power crisis became a huge problem that faces the most of world countries. So, the Renewable Energy Sources (RES) penetrate widely. The renewable energy is generated from natural processes that are continuously replenished, such as: sunlight, geothermal heat, wind, tides, water, and various forms of biomass. These sources cannot be exhausted, constantly renewed, and environmental friendly. But most of them need power converters and inverters for transferring the generated power to the consumable loads. Also, these resources face many problems when interconnected with the traditional grid. So, many researches and studies concerned with one of the smart-grid system’s classification which called an Open Energy System (OES) [1]. OES is a new type of scalable and bottom-up distribution network approach which represented by building blocks of a flexible number of dc nanogrids, as well as interconnected such subsystem via a local dc power grid and controlled in a distributed way to make an OES. Nanogrid - as the name implies - is a small rating system that can serve a single building or a group of residential buildings with ratings from 1.5 KW to 5 KW. Nanogrids can be seen as smaller and technologically simpler microgrid but it provides less number of voltage levels with a high quality and reliability [2]. Also, nanogrids limited some of the microgrids drawback and complexity such as they reduce a huge amount of heating and power losses due to the transmission and distribution lines. In addition, the nanogrids are closed proximity to the end user /they help bring good electricity services to developing countries and they are more secure and safety [3]. But, there are some drawbacks were appeared in the conventional nanogrid such as: it contains several inverter/converter sets. This needs a separate and isolated control and protection techniques. Dependently, the overall cost and losses will be increased. Also, the noise due to interconnections between elements causes many problems such as
interference and increase the probability of the fault occurrence which cause personal hazard. So, the researchers started to intensify their efforts to overcome these problems by studying and designing a modified nanogrid with a single input multi-output converter. This converter has a unique input, i.e. the renewable dc source, and produces both dc/ac supplies required to feed the dc and ac loads.

Two special converters were proposed for this purpose: Z- and switched boost inverters (SBI) [4]. The Z-inverter has many disadvantages – compared with SBI- because of using many passive elements to give the required outputs which cause the system operates with lower efficiency, bulky and costly [5-7]. The advantages of SBI encourage researchers to study it within the modified nanogrids - as in [9-11,14].

Adda et al. [8,12-13,15], presented a review for the SBI operation techniques, its comparison with the traditional two stage conversion system and analyzed it including pulse width modulation (PWM) control strategy with its applicability on a low-rating application. But also, it still needs for modification to be used for high power rating applications. So, this manuscript represents an extensive study for the SBI modeling, analysis and simulation by applying the PWM control strategy on high rating power applications. Also, the research will focus on the features of this inverter with open-loop modified PV-nanogrid, mathematical models, and Matlab/Simulink simulation.

This paper will be organized as follows: Section 1 introduction, Section 2 presents a detailed review for the proposed system and a comparison between the Z-source/SBI inverters showing the SBI advantages. Section 3 discusses the SBI topology, its principles, and analysis at a steady-state operation by using its PWM strategy followed by section 4 which described the simulation results for the whole system. Section 5 presents some concluded results for this paper.

2. The Proposed modified nano-grid

The proposed modified PV-nano grid is shown in figure 1. It implies PV-solar panels, SBI, and both dc and ac outputs feeding the load demands.

2.1. The Photovoltaic (PV) Mathematical Model:

PV cell is a semiconductor p-n junction that transforms the sunlight to electrical power. While modeling a solar cell, the effect of different factors must be taken into considerations, such as (open circuit voltage \( V_{oc} \), maximum power voltage \( V_{mp} \), short circuit current \( I_{sc} \), maximum power current \( I_{mp} \), efficiency, and fill factor (FF).

The PV module consists of a set of PV cells, while the PV array is a set of PV modules which are connected in series or in parallel to achieve the desired power and voltage [16].

2.2. Equivalent circuit of a PV cell

In the approximated model, the PV efficiency is insensitive to the variation of the shunt resistance \( R_{sh} \) so it can be neglected. On the other hand, a small variation in the series resistance \( R_s \) will significantly affect the PV output power. Then, the approximated model of PV solar cell with suitable complexity is shown in figure 2 [16, 17].

The PV cell output current \( I_o \) can be calculated from the following equations

\[
I_o = I_{PH} - I_D = I_{PH} - I_s \left[ \exp \left( \frac{q(V_o + I_o R_s)}{kT_e} \right) - 1 \right]
\]

The photo current:

\[
I_{PH} = [I_{sc} + K_1(T_c - T_{ref})]G
\]

And the cell’s saturation current \( I_s \) is given from the following eqn.

\[
I_s = I_{ref} \left( \frac{T_c}{T_{ref}} \right)^3 \exp \left( \frac{qV_{ref} + q/2}{kT_{ref}} \right)
\]
The reverse saturation current ($I_{RS}$)

$$I_{RS} = \frac{I_{sc}}{[\exp(qV_{oc}/kT_{ref})]-1}$$  \hspace{1cm} (4)

Where, $q$ is an electron charge ($=1.6 \times 10^{-19}$ C), $R_{sh}$ is the shunt leakage resistance in ($\Omega$), $T_{c}$ is the cell’s working temperature (K), $T_{ref}$: The cell’s reference temperature (Kelvin), $A$: An ideal factor, $K$: Boltzmann’s constant ($=1.38 \times 10^{-23}$ J/K), $v$: the PV output voltage (volt) $N$:The number of series cells, $G$: The solar insulation in kw/m², $I_{sc}$: Short circuit current (A), $E_{G}$: The bang-gap energy of the semiconductor of the cell and $V_{oc}$: Open circuit voltage (V).

The power generated from a single module may be not sufficient enough to meet the load power requirements applications. So the modules are arranged in different ways in series and parallel to form a PV array for our desired power and voltage. The PV modules are arranged in a different manner such that the series connection to obtain the suitable voltage and the parallel connection to obtain more required currents. Also, the array construction is suitable to obtain the desired power according to equation.

The array current:

$$I_{arr} = I_{ph}N_p - N_p I_s \cdot [\exp(q(v+IR_a)/kT_cA) - 1]$$  \hspace{1cm} (5)

Where $N_s$, $N_p$ represented the number of series and parallel cells respectively.

3. Switched boost inverter topology

Both the SBI and Z-source inverters were become more popular due to their capability for serving a dc and ac loads simultaneously from a single dc input source. The SBI was constructed in such a way to overcome the z-source problems as it reduced the number of the passive components [4]. So, this paper uses the SBI as it made the system had better performance in reducing the whole system size and weight with a huge enhancement in the system efficiency. Moreover, it improves the system reliability with an integrated-small size power-electronics module which exhibits better electromagnetic interference noise immunity when compared to the traditional voltage source inverter. These inverters can be operating with very high skills in low-voltage ac-load applications, such as fans and blowers….etc. This inverter operation also provides the shoot-through to the inverter limbs without causing any damage to the inverter switches and it also doesn’t required to the dead time compensation circuits which cause a reduction in the probability of faults occurrence and the personal hazards.

Figure 3 shows the schematic circuit of the SBI that implies a boost converter and an inverter in a single power stage [13]. It contains five active switches ($S, S_1, S_2, S_3, S_4$), two passive components (one inductor ($L$) and one capacitor ($C$)), and two diodes $D_a$and $D_b$ as shown. A low pass LC filter is connected across the output of the inverter bridge to mitigate the harmonics and improve the output waveform of the ac-fundamental sinusoidal component.

3.1 The operation principles of the SBI.

SBI has two modes of operations: non-shoot through state and shoot through state modes [15], as shown in figures 4 (a) and (b). The first mode of operation, the inverter is in non-shoot through state and switch ($S$) is turned off, the inverter bridge is represented by a current source in this interval, as shown in the equivalent circuit in figure 4 (a). Now the grid input voltage ($V_g$) is greater than the inductor voltage ($V_L$), so the diode ($D_a$) is forward biased. As
a result, the \( V_L \) will increase gradually exceeds the capacitor voltage \( V_C \) which also made the diode \( D_a \) forward biased. The current will flow through the inductor storing energy through it. The inductor current \( i_L \) will exceed linearly equal the capacitor charging current added to the dc load current and the inverter input current (assuming the inductor current to be sufficient enough for the continuous conduction) for the interval \( t_{off} \).

The second mode of operation, the inverter is in shoot through state and switch \( S \) is turned on, the inverter bridge is represented as a short circuit (zero state mode) in this interval, \( t_{on} \), as shown in figure 4(b). Now by the help of the stored energy in the inductor, the capacitor voltage \( V_C \) exceeds the grid voltage \( V_g \), so the diodes \( (D_a \) and \( D_b) \) will be reversed biased. The inductor current equals the capacitor discharging current subtracted by the dc load current.

Where: the switch-off time \( t_{off} = (1 - D).T_s \)
The switch-on time \( t_{on} = D.T_s \) and \( D \) is the duty cycle.

From figures 4(a) and (b):

The instantaneous inductor voltage:
\[
V_L(t) = \begin{cases} 
    v_{DC}(t), & 0 < t < D.T_s \\
    V_g - v_{DC}(t), & D.T_s < t < T_s 
\end{cases}
\] (6)

The instantaneous capacitor current:
\[
i_C(t) = \begin{cases} 
    -i(t) - i_{DC}(t), & 0 < t < D.T_s \\
    i(t) - i_{DC}(t) - i_c, & D.T_s < t < T_s 
\end{cases}
\] (7)

The instantaneous dc link voltage:
\[
v_I(t) = \begin{cases} 
    V_{DC}(t), & 0 < t < D.T_s \\
    V_{DC}(t), & D.T_s < t < T_s 
\end{cases}
\] (8)

By using a small ripple approximation for the pervious equations (1)-(3) can be rewritten as:

The instantaneous inductor voltage:
\[
V_L(t) = \begin{cases} 
    v_{DC}(t), & 0 < t < D.T_s \\
    V_g - v_{DC}(t), & D.T_s < t < T_s 
\end{cases}
\] (9)

The instantaneous capacitor current:
\[
i_C(t) = \begin{cases} 
    -i(t) - i_{DC}(t), & 0 < t < D.T_s \\
    i(t) - i_{DC}(t) - i_c, & D.T_s < t < T_s 
\end{cases}
\] (10)

The instantaneous dc link voltage:
\[
v_I(t) = \begin{cases} 
    V_{DC}(t), & 0 < t < D.T_s \\
    V_{DC}(t), & D.T_s < t < T_s 
\end{cases}
\] (11)

Under steady state, the average voltage across the inductor should be zero so according to equation (1)
\[
\frac{V_{DC}}{V_g} = \frac{1}{1-2D} \] (12)

Similarly the average current of the capacitor should be zero so according to (7)
\[
I_L = \frac{1}{1-2D}.I_{DC} + \frac{1}{1-2D}.I_l \] (13)

From (8) the average dc link voltage \( V_I \) can be calculated as:
\[
V_I = V_{DC}.(1 - D) \] (14)

### 3.2 The PWM control strategy for SBI

The SBI operation utilizes the shoot through interval for the H-bridge to invoke the boost operation for the input voltage \( V_g \). So, the traditional sine-triangle pulse width modulation technique should be modified [11]. The modified technique has been illustrated in figure 5 during the positive and negative half cycles of the sinusoidal modulation signal \( v_m(t) \).

### 3.3 The SBI gating signals

During the positive half cycle of the sine wave \( v_m(t) > 0 \), as shown in figures 5(a),(b) and (c),the gating control signal \( GS_1, GS_2 \) for switches \( (S_1, S_2) \) are generated by comparing the sinusoidal reference modulation signal \( \pm v_m(t) \) with a high frequency \( f_0 \) triangular carrier wave \( v_{tri}(t) \) of amplitude \( V_p \). The carrier wave frequency \( f_0 \) has to be chosen such that \( f_0 \ll f_0 \) which cause the
Fig. 5 (a) Sinusoidal modulation signals $v_m(t)$ and $-v_m(t)$. (b) The sinusoidal (reference) wave with the triangular (carrier) wave. (c) Schematic of the PWM control circuit when $v_m(t) > 0$. (d) Generation of gate control signals for SBI when $v_m(t) > 0$. (e) Schematic of the PWM control circuit when $v_m(t) < 0$. (f) Generation of gate control signals for SBI when $v_m(t) < 0$.

The sinusoidal reference wave at $v_m(t)$ is assumed to be approximately constant in figure 5(b) [12-15]. While the other three gating control signals ($G_{S3}, G_{S4}, G_{S}$) are generated by comparing the triangular $v_{tri}(t)$ with two constant voltage levels $V_{s1}, -V_{s1}$ to generate ST1 and ST2 respectively. The purpose of these two signals is to insert the required shoot-through interval $D.T_{s}$ in the PWM signals of the inverter bridge. The gating control signals for switches S3, S4, and S can be obtained using these expressions (as shown in figure 5(d)):

$$G_{S3} = G_{S2} + ST_1; \quad G_{S4} = G_{S1} + ST_2;$$
$$G_{S} = ST_1 + ST_2$$
Similarly during the negative half cycle of the sine wave \((v_m(t) < 0)\), as shown in figure 5(e), (f), the gating control signal \(G_{S_3}, \ G_{S_4}\) for switches \((S_3, S_4)\) can be generated. The gate control signals for switches \(S_1, S_2, \ \text{and} \ S\) can be obtained using these expressions:
\[
G_{S_1} = G_{S_4} + ST_1; \quad G_{S_2} = G_{S_3} + ST_2; \\
G_S = ST_1 + ST_2.
\]

Noted that: The sum of shoot-through duty ratio \((D)\) and the modulation index \((M)\) is less than or equal to unity to reduce the harmonics that may happen in the Inverter’s output voltage.
\[
M + D \leq 1 \quad (15)
\]

The values of \(M\) and \(D\) can be chosen to give the desired peak value for the ac output voltage \(V_{AC}\) where:
\[
V_{AC} = M.V_{DC} = M.((1-D)/(1-2.D)).V_g \quad (16)
\]

4. Simulation Results

MATLAB Simulink software package [18] is used to verify the proposed modified PV-nano grid system. The PV-system specifications are taken from a module (IS4000P) that its data is tabulated in appendix 1. The characteristic curves for the module are given in figures 6 (a), (b), (c) and (d). Figures 6 (a) and (b) describe the P-V and I-V curves with the temperature variation for the 5.4 Kw PV-array. In addition, figures 6 (c) and (d) demonstrate the same curves with the variation of the PV insolation. The Matlab/Simulink model for the SBI is shown in figure 7. The SBI is represented by five IGBTs switches with a small internal resistances \(10^{-3}\) ohm and with an LC filter to minimize the harmonics in the AC output voltage.

The main parameters for the inverter are designed and modeled with those final selected values:
\[
L = 5 \ \text{mH}, \ C=100 \ \text{μF}, \ L_f = 4.6 \ \text{mH}, \ C_f = 10 \ \text{μF} \\
R_{dc} = 25 \ \Omega \ \text{and} \ R_{ac} \ \text{ranging from} \ 20 \ \Omega \ \text{to} \ 100 \ \Omega.
\]

4.1 Open loop control of the switched boost inverter

There are eight cases to ensure the validity of the switched boost inverter with an open loop control for either bucking or boosting the output voltage of the ac loads than the dc input voltage \((V_g)\). In the 1st six cases, the input dc voltage is represented by a constant dc voltage source for testing the system’s control signals validity while cases (7 and 8), the dc input voltage \((V_g)\) is taken from a real-PV system model.

Fig. 6 P-V and I-V curves with the temperature and irradiance variations for the selected PV-module
The 1st four cases show the relation between ac-rms output and the input voltage \( V_g \) by changing the control signal voltage \( V_{ST} \) and the duty ratio (D) according to the Table I.

In cases 1 and 4, the ac-rms output voltage values are selected as double to the dc input one \( (V_g) \) to test the system ability to take the boosting action.

While in the opposite side, cases 2 and 3, the ac-rms output voltage values are selected to be half the dc input one for testing the system ability to work on the bucking mode.

The 1st four cases can be calculated according to the following relations:

\[
V_g = \text{Constant} \tag{17}
\]

\[
V_{ac(rms)} = \text{required to be halved or doubled} \tag{18}
\]

\[
V_{ac(peak)} = \sqrt{2} \cdot V_{ac(rms)} \tag{19}
\]

\[
M = \frac{V_m}{V_P} = \frac{1}{2} = 0.5 \tag{20}
\]

From equations (19 and 20) the dc output voltage can be calculated according to the following equation:

\[
V_{DC} = \frac{V_{ac(peak)}}{M} \tag{21}
\]

So the duty ratio can be computed from equations (12, 17 and 21), then the control signal voltage \( V_{ST} \) can be calculated according to:

\[
V_{ST} = (1 - D) \cdot V_P \tag{22}
\]

In cases (5 and 6) shows the change in the ac output voltage \( V_{ac(rms)} \) and \( V_{ac(peak)} \) by changing the value modulation index \( (M) \) according to the equations (20 and 21)

\[
M = \frac{0.7}{2} = 0.35
\]

In cases (7 and 8) the PV modules are connected together to form a PV array such that case 7 uses a real PV-array model. The input dc voltage \( V_g = 37.6V \) which represent (1 series and 18 parallel modules). While case 8, uses \( V_g = 75.2V \) which means that 2 series and 9 parallel modules are connected to each other.

Table I shows the parameters of the previous eight cases.

4.1.1. Cases 1 and 4 (Boosting mode \( V_{ac} = 2V_g \))

Those cases show that the ability of the switched boost inverter for boosting the AC output voltage than the DC input voltage as shown in the table I. Figure 8 describes the input dc voltage, output dc-voltage at transient and steady state (ss) and finally, the ac-output voltage that its rms value is equal to the double of SBI-input dc voltage. Also, the ripples and total harmonic distortion (THD) can be computed as follow [19-22]:

\[
\text{Percentage of Ripples} \% = \left( \frac{V_{max} - V_{min}}{V_{nominal}} \right) \times 100 \%
\]

The THD can be computed from the relation:

\[
\text{THD} \% = \sqrt{\frac{V_2 + V_3 + V_4 + \ldots + V_n}{V_1}} \times 100 \tag{23}
\]

Where, \( n \) is the harmonic order.

Case 1 uses the dc input voltage equal to 75.2 V and the ac-rms output voltage equal double of its input value (i.e., 150.4 V). But, case 4 uses \( V_g = 37.6V \) and the output \( V_{ac} = 75.2V \) as shown in table I and also figures 8 and 12 demonstrate the waveforms for both dc output voltage at transient and steady states and in addition the ac-output voltage. Figure 9 is a spectrum analyzing for the ac-load current to focus on the harmonics and computing THD. Also, it can be noted the dc-output with its high rating. The average dc value is approximately equal 425 V.

![Fig.7 Matlab simulink model for the proposed system](image-url)
Table I The parameters of the eight cases

<table>
<thead>
<tr>
<th>Cases</th>
<th>$V_g$</th>
<th>$V_{ac (rms)}$</th>
<th>$V_{ac (peak)}$</th>
<th>$V_{dc}$</th>
<th>$D$</th>
<th>$V_{st}$</th>
<th>$V_P$</th>
<th>$M$</th>
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<tr>
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Fig. 8 Case 1 waveforms for both dc input and output voltages, and the ac-output voltage

Fig. 9 Case 1: spectrum analysis for harmonics of load current and its THD
Fig. 10 Case 2 waveforms for both dc-ac input and output voltages ($V_g=75.2$ V and $V_{ac} = 37.6$ V)

Fig. 11 Case 3 waveforms for both dc-ac input and output voltages ($V_g=37.6$ V and $V_{ac} = 18.8$ V)

Fig. 12 Case 4 waveforms for both dc-ac input and output voltages ($V_g=37.6$ V and $V_{ac} = 75.2$ V)
Fig. 13 Case 5: waveforms for both dc-ac input and output voltages (Modulation Index (M=0.35))

Fig. 14 Case 6: waveforms for both dc-ac input and output voltages (Buck mode (M=0.35))

Fig. 15 Case 7: waveforms for both dc-ac input and output voltages actual PV-model ($V_p = V_{ac} = 37.6\ V$)
4.1.2. Cases 2 and 3 (Bucking mode $V_{ac} = \frac{1}{2}V_{g}$)

Case 2, the grid voltage input to the SBI is 75.2 V and need to reduce it to half value (i.e, the output of the SBI is approximately 37.6V) as shown in figure 10. Also, figure 11 describes the output voltage ($V_{ac}=18.8V$) when the input is doubled (i.e., $V_{g}=37.6V$). It can be noticed that the ripple of the output dc voltage of the SBI is reduced in bucking mode because of the low voltages for both input and dc/ac outputs.

The first 4th cases use the same modulation index (i.e., M=0.5). To study the effect of the modulation index to both dc and ac outputs of the SBI, the next two cases (5 and 6) will use another value for the modulation index (i.e, M=0.35), as in table I.

4.1.3. Cases 5 and 6 (M changed from 0.5 to 0.35)

All parameters are kept constant or not changed except the modulation index that reduced to 0.35 and test the inverter in bucking mode as in cases 2 and 3. From figures 13 and 14, both the output dc and ac voltages are affected by changing the modulation index especially in an open-loop control that needs to change the control signal ($V_{st}$). As demonstrated in table I, the value of $V_{st}$ is changed from 1.0969583 to 1.54681816 to adapt the required output. Due to the narrow range for changing this control signal required to adapt the duty cycle ($D = 1$ to $1.5$), the control process is very sensitive.

4.1.4. Cases 7and 8 (with real model for PV-array)

The final two cases are testing the real PV-model. In case 7, only one PV-module is connected in series and 18 modules are in parallel to form the array. In case 8, $N_s = 2$ and $N_p = 9$, to form the array with 76.2 V output voltage. As shown in figures 15 and 16, there are so many ripples in simulation results due to high-frequency switching simulation sample that is selected equal to 0.1 μs for each sample.

5. Conclusion

This paper is a novel-approach for SBI as a single input multi output power electronics technique used in a modified nano-grid within an OES. It is a single stage power converter that can supply both dc and ac loads simultaneously from the same dc input source.

This research introduces a software package for modeling, designing and simulation of SBI. This package includes a PWM control technique with its control gating signals strategy which is suitable for this inverter to the best performance. This paper contributes towards raising the output dc-link voltage of the inverter to high-rating values. Also, this technique allows to the ac output voltage to be higher or lower than the dc input voltage by operating the SBI in either bucking or boosting mode of operation.

This package for simulation is prepared with the help of the MATLAB/ SIMULINK program and simulation results are obtained for several cases.

References


**Appendix 1: PV module specifications (IS4000PS)**

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<thead>
<tr>
<th>P&lt;sub&gt;max&lt;/sub&gt;</th>
<th>235Wp</th>
<th>240Wp</th>
<th>245Wp</th>
<th>250Wp</th>
<th>255Wp</th>
</tr>
</thead>
<tbody>
<tr>
<td>I&lt;sub&gt;mp&lt;/sub&gt;</td>
<td>7.74A</td>
<td>7.87</td>
<td>7.96A</td>
<td>8.07A</td>
<td>8.14A</td>
</tr>
<tr>
<td>I&lt;sub&gt;sc&lt;/sub&gt;</td>
<td>8.26A</td>
<td>8.31A</td>
<td>8.43A</td>
<td>8.47A</td>
<td>8.54A</td>
</tr>
<tr>
<td>V&lt;sub&gt;oc&lt;/sub&gt;</td>
<td>36.6V</td>
<td>36.8V</td>
<td>37.0V</td>
<td>37.2V</td>
<td>37.5V</td>
</tr>
<tr>
<td>V&lt;sub&gt;mp&lt;/sub&gt;</td>
<td>30.4V</td>
<td>30.5V</td>
<td>30.8V</td>
<td>31.0V</td>
<td>31.3V</td>
</tr>
<tr>
<td>η&lt;sub&gt;s&lt;/sub&gt;</td>
<td>16.2%</td>
<td>16.4%</td>
<td>16.8%</td>
<td>17.0%</td>
<td>17.4%</td>
</tr>
<tr>
<td>η&lt;sub&gt;fm&lt;/sub&gt;</td>
<td>13.8%</td>
<td>14.1%</td>
<td>14.4%</td>
<td>14.7%</td>
<td>15.0%</td>
</tr>
</tbody>
</table>

STC: 1000 W/m² .25 C° , AM 1.5