Comparative Study on Solar Powered Interleaved Boost Converter

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Abstract
Solar energy is an important source of renewable energy. But, it is unpleasant that, only partial amount of energy can be extracted from the Solar cells by our conventional DC-DC Boost converters. A comparative study on solar powered Interleaving Boost converters (ILBCs) is initiated. A novel Solar powered, Series-Inductor ILBC with less current ripple than the conventional ILBC is proposed. A comparative study on single-stage, two-stage and three-stage ILBCs are done. The comparison of ripple reduction of output voltage is tried with ‘C’, ‘Pi’ and Cascade Filters. The results have been applied to R-Load and motor load. The input of 150V is fed to the ILBC from the solar cell and compared for the ripple. The proposed solar powered series inductor ILBC has reduced ripple than the conventional ILBCs. Comparison table of performance and simulation results of these aforementioned solar powered ILBCs have been exhibited in this paper.

Key words: Boost Converter, Comparison Study, Interleaving, Solar Power

1. Introduction
To enable the solar cell and to use sunlight efficiently, a DC-DC converters are used for the solar power generation. But, the fact is that 100% energy cannot be extracted from the solar cell by the conventional DC-DC converters. Though, many technique have been invented and implemented still, there is a lag and restrictions in the research of boost converters. While commencement of interleaving technique in the converters being an evolving technique, it can be a solution for the aforementioned problem.

2. Design of a Photovoltaic Panel
The efficiency of a solar cell depends mainly on Short circuit current (Isc), open circuit voltage (Voc), Fill factor (FF). FF is nothing but the squareness of the I-V curve Figure 2, which is related to the resistive losses of the solar cell. Best value of a good solar cell should be ≥ 0.80.

\[
FF = \frac{V_{oc} - \ln(V_{oc} - 0.72)}{V_{oc} + 1}; \quad V_{oc} = \frac{kT}{q} \left[ \ln(I/I_0) + 1 \right];
\]

Where, \( I_0 \) → Recombination current in the material due to the electron-hole pair; \( I_L \) → Light generated current; \( V_{oc} \) → Maximum voltage obtained when solar cell is left open; \( I_{sc} \) → Maximum current when the solar cell terminals are shorted.

The material with a large band gap energy will absorb less number of Photon for recombination. \( I_{sc} \) will increase with decrease in band gap energy of the material of solar cell. Therefore \( V_{oc} \) and \( I_{sc} \) increases with decreases in \( I_0 \).

Therefore, the model of a solar cell shown Figure 1 is designed with all losses into account. The optical loss of the solar cell is represented by the input current source (I0). The recombination losses are represented by diode (D) which connected parallel to \( I_0 \) and the ohmic losses are represented by the shunt resistance (Rsh) and series resistance (R). Rs should be as low as possible because it is nothing but the sum of all resistance in the current path. Rsh should be as high as possible and it is referred as the leakage path of the current in the cell, so it is connected in parallel with...
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Figure 1. Solar model.

Figure 2. I-V Curve.

current source. Where, \( k \) → Boltzmann constant, \( q \) → quantity of electronic charge and \( T \) → solar cell surface absolute temperature. The ideal I-V equation of a solar cell is given by

\[
J = I_s - D (\exp (qv/kT) - 1);
\]

This series and shunt resistance have effect on Fill factor (FF), which in turn have effect on efficiency of the solar cell. So, care should be taken to select the value of \( R_s \) and \( R_{sh} \) in order to maintain the squareness of the curve shown on Figure 2. The relationship between the \( R_s \), \( R_{sh} \) and FF is given by the following equations. While, \( R_{ch} \) → Characteristic resistance and \( FF_0 \) → Ideal FF.

\[
FF = FF_0 - \left(1 - r_s\right); \quad FF = FF_0 - \left(1 - 1/r_{sh}\right); \quad r_s = \left(R_s / R_{ch}\right); \quad r_{sh} = \left(R_{sh} / R_{ch}\right);^2.
\]

In this paper we have designed a solar cell for an output voltage of 150V is designed which is shown in the Figure 3 and the pulse generated by the solar cell have been shown in the Figure 4.

3. Comparison of Solar Powered Interleaved Boost Converters

3.1 Conventional Interleaved DC-DC Boost Converter

3.1.1 Working of Single-Phase Converter

A boost converter is one which gives increased output than the given input. All the converter shown in this paper is a solar cell, which is designed to produce an output voltage of 150V. In Figure 5, a simple boost converter is shown where, the input of the converter is a solar cell. The output of the solar cell is given as input to the converter. The converter has an inductance \( L_1 \) connected in series with the Input, a MOSFET \( S1 \) connected in parallel with the input, diode \( D1 \), capacitor \( C \) is also connected along with \( R \) load at the end. The operation is as follows,

Mode (a): (t0 < T < t1)
S1 in ON, by applying gate pulse; L1 stores energy from input (during T\textsubscript{ON}); D1 is reverse biased, output stage is isolated from input side.

Mode (b): (t\textsubscript{1} ≤ T ≤ t\textsubscript{2})

- S1 is OFF; D1 forward biased; both input and stored L1 energy is supplied to the load side.

Therefore, now the current is supplied through L, D, C and R load\textsuperscript{1}. The input voltage of 150V is applied from the solar

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**Table 1. Comparison of solar powered interleaved DC-DC boost converters**

| Parameter                          | Single Phase | Two Phase ILBC | Three Phase ILBC |
|------------------------------------|--------------|----------------|------------------|
|                                    | Conventional | Conventional   | Conventional     | Proposed | Proposed |
| Input Voltage (V)                  | 150          | 150            | 150              | 150      | 150      |
| Output Voltage (V)                 | 300          | 621            | 1010             | 920      | 1430     |
| Output current (A)                 | 0.6          | 1.2            | 1.8              | 1.84     | 2.86     |
| Output Power (W)                   | 185          | 770            | 1818             | 1700     | 4090     |
| Output voltage ripple (V)          | 2            | 1.5            | 1                | 0.11     | 0.09     |
| Output Current ripple (A)          | 0.004        | 0.0001         | 0.0002           | 0.0002   | 0.00001  |
| Voltage Gain (V\textsubscript{o}/V\textsubscript{i}) | 2            | 4.14           | 6.77             | 6.13     | 9.53     |
| Inductor ripple current ΔI=L/V\textsubscript{o}V\textsubscript{i} | 3.33  | 1.6            | 0.5              | 1.05     | 0.56     |
| Inductor current (A)               | I\textsubscript{L1}=6A; I\textsubscript{L2}=20A; | I\textsubscript{L1}=13A; I\textsubscript{L2}=6A; | I\textsubscript{L1}=110A; I\textsubscript{L2}=110A; | I\textsubscript{L1}=20A; I\textsubscript{L2}=10A; |
| Voltage stress across the Diode (V) | V\textsubscript{d1}=800V; V\textsubscript{d2}=600V; | V\textsubscript{d1}=350V; V\textsubscript{d2}=350V; | V\textsubscript{d1}=900V; V\textsubscript{d2}=900V; | V\textsubscript{d3}=900V; V\textsubscript{d3}=900V; | V\textsubscript{d1}=150V; V\textsubscript{d2}=400V; V\textsubscript{d3}=5V; |

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**Figure 5.** Single-phase boost converter.

**Figure 6.** Two-phase interleaved boost converter.

**Figure 7.** Results of single phase boost converter Time(sec).

- S1 in ON, by applying gate pulse; L1 stores energy from input (during T\textsubscript{ON}); D1 is reverse biased, output stage is isolated from input side.

Mode (b): (t\textsubscript{1} ≤ T ≤ t\textsubscript{2})

- S1 is OFF; D1 forward biased; both input and stored L1 energy is supplied to the load side.
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3.1.2 Working of Two Phase Interleaved Converter

In two phase conventional interleaved converter, two single phase converters are connected in parallel shown in Figure 6. The two converters works at same frequency but with a phase difference of $360^\circ/n$. Where, $n$→ number of phase. In this case, it is $360^\circ/2 = 1800$. With duty cycle of 0.5. The operation is as follows.

Mode (a): ($t_0 \leq T \leq t_1$)

- S1 is ON, by applying gate pulse; L1 stores energy from input (during $T_{ON}$); D1 is reverse biased, output stage is isolated from L1.

Mode (b): ($t_1 \leq T \leq t_2$)

- S1 is OFF; S2 is ON, by applying gate pulse; L2 stores energy from input (during $T_{ON}$); D1 is forward biased, D2 is reverse biased, output stage is isolated from L2; L1 releases the stored energy which is stored during mode (a).

Mode (c): ($t_2 \leq T \leq t_3$)

- S2 is OFF; S1 is ON, by applying gate pulse; L2 releases the energy which is stored during mode (b); L1 stores energy from input, same as mode (a); D1 is reverse biased; D2 is forward biased.

Thus, both the converters feed the output continuously which results in continuous current. The input voltage of 150V is applied from the solar cell and simulation results of output voltage (621V), output current (1.2A), output current ripple (0.001A) and output power (770W) is shown in Figure 8.

3.1.3 Working of Three Phase Interleaved Converter

Three phase interleaved conventional boost converter is shown in Figure 9. the operation is similar to that of the two phase conventional converter (explained in sec: 3.1.2). Since, three phase are employed, each phase works at $360^\circ/n=1200$, (i.e.) at 120° phase difference. With duty cycle of 0.3. The gate pulse applied to the switches S1, S2, S3 accordingly. The input voltage of 150V is applied from the solar cell and simulation results of output voltage (920V), output current (1.84A), output current ripple (0.0002A) and output power (1700W) is shown in Figure 11.

Therefore, each converter has a switch, diode and an inductor. It is assumed that the parallel converters are symmetrical and operate in continuous conduction mode.

The above literature does not compare various solar powered interleaved converters. This work proposes comparison of various converters in order to find the best converter.
3.2 Proposed Interleaved DC-DC Boost Converter

3.2.1 Working of Proposed interleaved DC-DC Converter

The series-inductance, single switch boost converter is shown in the Figure 10, the input voltage of 150V is given from a solar cell. Three inductors are connected in series with the input and diodes D1, D2, D3 are placed in between them, capacitors C1 and C2 are connected in parallel to the R load5. The operation of the converter is as follows. Modes of operation6–11 of the converter is shown in Figure 13 to Figure 17 respectively. The simulation results are displayed in Figure 12.

The input voltage of 150V is applied from the solar cell and simulation results of output voltage (1430V), output current (2.86A), output current ripple (0.0001A) and output power (4090W) is shown in Figure 12.

Mode (a): (t₀ ≤ t ≤ t₁)
- S1 is ON; S2, S3 are OFF; D1, D2, D3 are reverse biased; Inductor L1, L2, L3 store energy from input during (T₁); output stage is isolated from L1, L2, and L3. C1, C2 gets charged.

Mode (b): (t₁ ≤ t ≤ t₂)
- S1, S2, S3 is OFF; D1, D2, D3 is forward biased output stage is connected to L1, L2, L3; Inductor L1, L2, L3, C1, C2 releases the energy which is stored during mode (a) to the C0 and Load;

Mode (c): (t₂ ≤ t ≤ t₃)
- S2 is ON; S1, S3 are OFF; D1, D3 are forward biased; D2 is reverse biased; Inductor L1; store energy from input during this mode; output stage is isolated from L1 and C1 gets charged.

Mode (d): (t₃ ≤ t ≤ t₄)
- S1, S2, S3 are OFF; D1, D2, D3 is forward biased output stage is connected to L1, L2, L3; Inductor L1, L2, L3, C1, C2 releases the energy which is stored during the previous mode to the C0 and Load;
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- **Figure 13.** Mode (a): \((t_0 < T < t_1)\).

- **Figure 14.** Mode (b): \((t_1 < T < t_2)\).

- **Figure 15.** Mode (c): \((t_2 < T < t_3)\).

- **Figure 16.** Mode (e): \((t_4 < T < t_5)\).

- **Figure 17.** Mode (e): \((t_4 < T < t_5)\).

- **Figure 18.** Single phase ILBC with motor.

Mode (e): \((t_4 < T < t_5)\)

- S3 is ON; S1, S2 are OFF; D2, D3 are forward biased; D1 is reverse biased; Inductor L1, L2 store energy from input during this mode; output stage is isolated from L1, L2 and C2 gets charged.
Mode (f): ($t_6 < T < t_7$)

- $S_1, S_2, S_3$ are OFF; $D_1, D_2, D_3$ is forward biased output stage is connected to $L_1, L_2, L_3$; Inductor $L_1, L_2, L_3, C_1, C_2$ releases the energy which is stored during the previous mode to the $C_0$ and Load;

4. Comparison of Solar Powered Interleaved Boost Converters with Motor Load

4.1 Single Phase Boost Converter with Motor Load

The operation of single phase boost converter has been already explained in the section 3.1.1.

The same converter has been tried with motor load as shown in Figure 18. The simulation results are shown in Figure 19 and the results are presented in the Table 2. The speed and torque are shown in the Figure 19.

4.2 Two Stage Interleaved Boost Converter with Motor Load

The operation of two stage boost converter have been already explained in the section 3.1.2. The same converter has been tried with motor load is shown in Figure 20. The simulation results for speed and torque are shown in Figure 21 and the results are displayed in the Table 2.

4.3 Three Stage Interleaved Boost Converter with Motor Load

The operation of single phase boost converter has already explained in the section 3.1.3. The same converter has been tried with motor load Figure 22. Simulation results are shown in Figure 23 and the results are displayed in the Table 2. The comparison shows that the torque and speed are higher in the case of three phase ILBC system.

| Table 2. Comparison of solar powered ILBC’s with motor load |
|-------------------------------------------------------------|
| **Parameter** | **Single Phase ILBC** | **Two Phase ILBC** | **Three Phase ILBC** |
| Input voltage (V) | 150 | 150 | 150 |
| Speed of the Motor (rpm) | 300 | 621 | 1180 |
| Torque (NM) | 0.6 | 1.2 | 2.3 |
5. Comparison of Solar Powered Interleaved Boost Converters with Different Filters

5.1 Three Phase ILBC with ‘C’ filter at the Output Side

The solar powered three phase interleaved DC-DC boost converter with ‘C’ filter shown in the Figure 3 and the simulation results are shown in the Figure 5.

5.2 Three Phase ILBC with Cascade Filter at the Output Side

Three phase ILBC with cascade filter Shown in Figure 24 and the simulation results are shown in Figure 26.

5.3 Three Phase ILBC with Cascade Filter at the Output Side

Three phase ILBC with cascade filter Shown in Figure 25 and the simulation results are shown in Figure 27.

The comparison indicates that the output voltage ripple is minimum in the case of ‘Pi’ filter system.

Table 3. Comparison of solar powered ILBC with different types of filters

| Parameter            | ‘C’ Filter | Cascade Filter | ‘Pi’ filter |
|----------------------|------------|----------------|-------------|
| Input Voltage (V)    | 150        | 150            | 150         |
| Output Voltage (V)   | 920        | 920            | 920         |
| Output current (A)   | 1.8        | 1.8            | 1.8         |
| Output Power (W)     | 1690       | 1690           | 1690        |
| Output voltage ripple(V)| 0.13      | 0.04           | 0.07        |
| Output current ripple (A)| 0.002     | 0.0002         | 0           |
6. Conclusion

An investigation on solar powered Interleaving Boost converters (ILBC) is done. A Solar powered, Series-Inductor ILBC with less number switches than the conventional ILBC is simulated. A comparative study on single-stage, two-stage and three-stage ILBCs are done. The proposed converter gives reduced ripple. The comparison ILBCs with different types of filters like ‘C’, ‘Pi’ and Cascade Filters is done. Where, the ‘Pi’ filter performs best in ripple reduction. The results have been applied to R-Load and motor load. Comparison table of performance and simulation results of these aforementioned solar powered ILBCs have been exhibited in this paper. The circuit are simulated using MATLAB/Simulink.

Collectively, the results are provided, we propose further study of multiphase interleaved boost converters in future.

7. References

1. Ku C, Chen D, Huang C, Liu C. A novel SFVM-M3 control scheme for interleaved ccm/dcm boundary-mode boost converter in PFC applications. IEEE Trans Power Electron. 2011 Aug; 26(8).

2. Solanki CS. Solar photovoltaics: fundamentals, technologies, and applications. 2nd ed. Eastern economy edition. PHI Publications.

3. Pahlevaninezhad M, Das P, Member, Drobnik J, Jain PK, Bakhshai A. ZVS interleaved boost AC/DC converter used in plug-in electric vehicles. IEEE Trans Power Electron. 2012 Aug; 27(8).

4. Bharathi ML, Kirubakaran D. PIC Based implementation of ZV ZCS interleaved boost converter. Modern achievements and developments in manufacturing and industry. Adv Mater Res. 2014; 1031. ISSN-13:978-3-03835-148-1.

5. Sivachidambaramathan V, Dash SS. Simulation of half bridge series resonant PFC DC to DC converter. IEEE International Conference on Recent Advances in Space Technology Services & Climate Change – 2010, (RSTS&CC-2010); 2010 Nov 13-15; 146–148.

6. Pushpavalli M, Bharathi ML. Comparison of interleaved two &three stages buck converter. ICICES-13; ISBN; 978-1-4673-5786-9. IEEE digital library Pages. 1081–87.

7. Singh MD, Khanchandani KB. Power electronics-electrical & electronics engineering Series. 2nd ed. TATA McGRAW HILL Publications.

8. Luo FL, Ye H. Advanced DC-DC converters. 2004; CRC Press LLC; CRC Press.

9. Shin HB, Park JG, Chung SK, Lee HW, Lipo TA. Generalised steady-state analysis of multiphase interleaved boost converter with coupled inductors. In: Proc. IEE Electronics Power Application; 2005; 152(3): p. 584–94

10. Pushpavalli M, Abirami P, Vasanth K. Performance of fuzzy controlled negative KY boost converter. Indian J Sci and Technol. 2014 Aug; 7(8):1049–59.

11. Jayaprakash S, Ramakrishnan V. A new single-stage solar based controlled full-bridge DC-DC Converter. Indian J Sci and Technol. 2014 Sep; 7(9):1382–86.