2019 IEEE International Conference on Power, Electrical, and Electronics and Industrial Applications (PEEIACON)
29 November - 01 December, 2019, Dhaka, Bangladesh.

Design Optimization of Self-Driven Boost Converter for CZTSSe Indoor Photovoltaic Device Based Low-Power Electronic Application

Khandaker Akramul Haque
Department of Electrical and Electronic Engineering
Bangladesh University of Engineering and Technology
Dhaka, Bangladesh
kahd.unplugged@gmail.com

Md Zunaid Baten
Department of Electrical and Electronic Engineering
Bangladesh University of Engineering and Technology
Dhaka, Bangladesh
mdzunaid@eee.buet.ac.bd

***Abstract*—In this work we optimize the performance characteristics of a Meisner oscillator based DC-to-DC boost converter circuit which is desinged to drive low-power electronic devices when operated under indoor lighting conditions. A $Cu_2ZnSn(SSe)_4$ or CZTSSe-based thin-film photovoltaic (PV) device is considered as the energy harvesting source considering illumination by an experimentally measured white light emitting diode (LED). Output of the CZTSSe device, which is estimated by numerically solving Poisson's and continuity equations under optical generation-recombination conditions, is taken as input to the boost converter on the basis of the device's equivalent circuit model. Steady-state and transient analyses indicate that a trade-off needs to be conceded while trying to maximize both output voltage and efficiency of the boost converter. Output characteristics of the converter is mainly governed by the load resistance and capacitance, rather than by the RC time constant of the oscillator circuit. By adjusting these values, an output voltage of ∼6V can be attained with ∼22% operating efficiency. This efficiency value can be ramped up to ∼36% if the output voltage is compromised down to about 2V. This study, which to the best of our knowledge is the first of its kind, offers an approach towards designing and optimizing an indoor PV device based standalone up-converter circuit suitable for driving low-power electronic devices.**

***Index Terms*—internet of things, energy harvesting, indoor lighting conditions, self-driven**

I. Introduction

Indoor photovoltaics has been an area of extensive research over recent years. In particular with the ever-expanding network of cyberphysical systems and internet of things (IoTs), there has been a growing demand for non-exhaustible, clean sources of energy which would be able to drive low-power electronic components of cyberphysical systems comprising of wired or wireless sensors, actuators and communication nodes. Indoor photovoltaic (PV) devices have garnered considerable attention in this regard primarily because of the proven track-record of the solar-cell technology and also because of the relatively low material cost of thin-film PV devices compared to conventional first-generation solar cells. Moreover, whereas the maximum efficiency limit of a single- junction thin-film solar cell is limited to about 33.7%, under indoor lighting conditions this value can theoretically exceed 60% depending on the illuminating light source [1]–[3].

Motivated by these auspices, significant research efforts have been dedicated towards the development of indoor PV devices employing different material systems, such as GaAs, silicon, CdTe, GaInP, perovskites, organics and dye sensitized materials [4]–[8]. Very recently a low-cost abundant earth Kesterite compound $Cu_2ZnSn(SSe)_4$, commonly known as CZTSSe, has been reported as a prospective candidate for harvesting energy from commercially available white light-emitting diode (LED) sources [9]. However, in spite of such intensive studies on indoor photovoltaics, an aspect rather overlooked in this area of research is the design and optimization of appropriate power-electronic converter circuits which would be ultimately driving the low-power electronic component. This is particularly important from a practical point of view as the output voltage coming from a single PV cell is not high enough to drive a full-scale electronic node. Hence, energy harvesting with photovoltaic sources will fail to meet its truest potential unless enough keen observation is given to the research concerning the realization of suitable power electronic converter circuit so as to deliver voltage high enough for driving IoT components.

In this work, we present design optimization of a DC-to-DC boost converter circuit for driving low-power electronic devices employing a CZTSSe-based indoor photovoltaic device. By numerically solving Poisson's and continuity equations under optical generation-recombination conditions, output characteristics of the CZTSSe device is derived considering operation under an experimentally measured white LED source. Taking the CZTSSe device output as input to the driver circuit, performance characteristics of a Meissner oscillator based boost converter circuit is optimized using SPICE simulation such that it can be practically utilized for driving electronic devices requiring operating voltages up to 6 V. The underlying reasons behind the observed performance characteristics have also been explained based on steady-state and transient analysis.

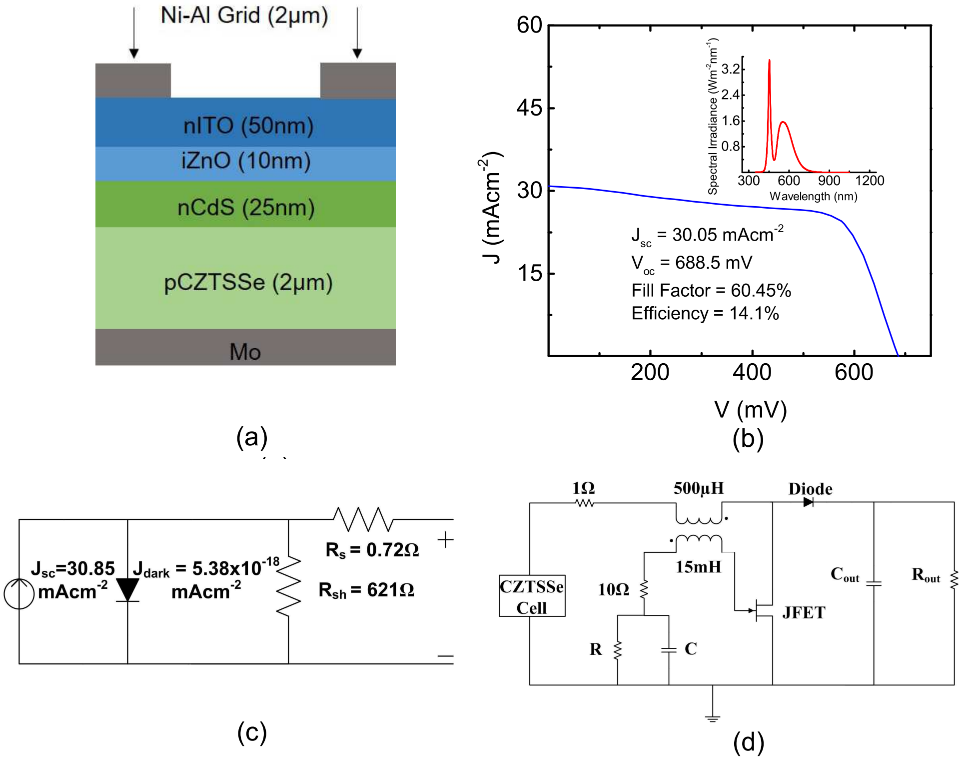

Fig. 1: (a) Schematic diagram of a CZTSSe-based PV device; (b) Current density and power density as a function of voltage for CZTSSe-based PV device under white LED illumination [inset shows the measured LED spectra]; (c) Equivalent circuit diagram of the CZTSSe-based PV device; (d) Circuit diagram of the oscillator based DC-to-DC boost converter

II. Performance Characteristics of the Indoor PV Device

The CZTSSe-based low cost indoor photovoltaic device considered in this work had earlier been reported in [9] as a suitable candidate for low-power electronic applications under indoor lighting conditions. A schematic of the considered device heterostructure is shown in Fig. 1(a). Output characteristics of this device is obtained by numerically solving the Poisson's and continuity equations under optical generation-recombination conditions [10]. The indoor light source considered here is a commercially available white LED source, which was measured using an optical spectrometer at room temperature. Measured spectra of this illuminating source and the resultant current density (J) vs voltage (V) characteristics of the PV device are shown in Fig. 1(b). As can be observed, the efficiency of the PV device under this condition is 14.1%, which is higher than highest reported efficiency of CZTSSe-based PV-devices [11]. Equivalent circuit of this indoor PV device is shown in Fig. 1(c) along with the relevant circuit parameters. The series and shunt resistance values used here are in accordance with experimentally reported values of the champion CZTSSe PV-device [11], whereas the short circuit current density (J_{sc}) and dark current density (J_{dark}) are extracted from the numerical simulation results shown in Fig. 1(b). Output of this equivalent circuit is taken as input to the boost converter, the design and optimization of which is discussed in the next section.

III. Design and Optimization of the Up-converter Circuit

The boost converter (Fig. 1(d)) is based on the topology of the Meissner oscillator [12]–[14]. Existence of the oscillator ensures that the boost converter itself is a self-driven circuit and hence no additional circuitry is required to drive the switching element used herein. In the present design, the oscillator circuit takes power from the transformer's secondary side, the polarity of which is opposite to that of its primary side. Alternately, mutual inductance or an inductor having the same inductance from the side with alternate polarity could also have been connected in series with the switch. The concept of using the alternate polarity is to provide the switching signal to the converter. In the present study, a JFET is used as the switching element. Though JFET is usually not suitable for high power and high frequency operation, the Meissner oscillator based design ensures that switching frequency of the JFET remains at around 1kHz. The low power nature of the application at hand also supports the use of JFET as the switching element. Another underlying reason behind using JFET in this design lies in its capability to conduct under its natural state and thereby work as a normally ON device. This ensures that the device can be turned off only by applying a negative voltage at the gate. Hence in lieu of the JFET, a depletion type MOSFET could have also been used as the switching element in this design.

In order to optimize performance characteristics of the

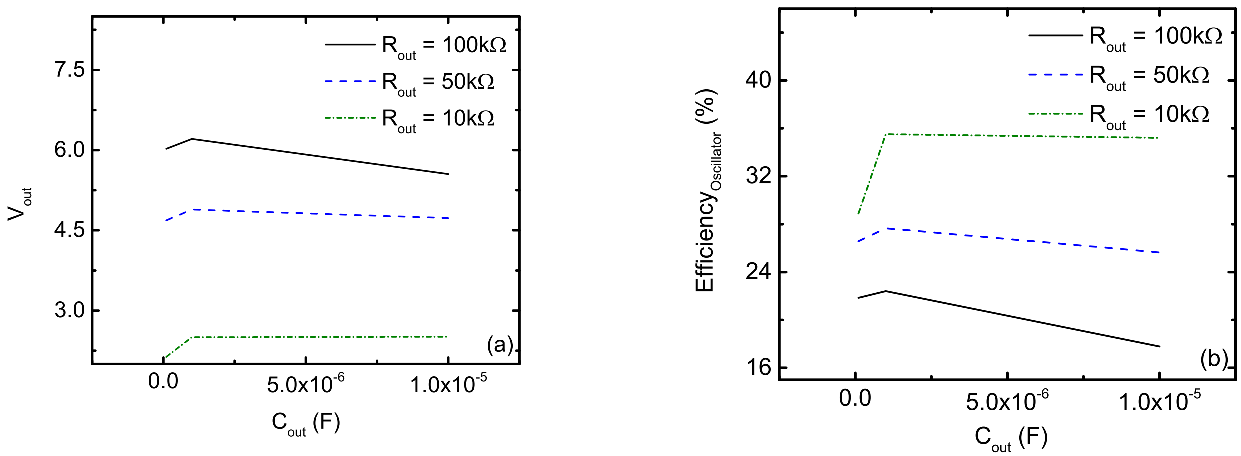

Fig. 2: (a) V_{out} as a function of ripple capacitor C_{out} and (b) Efficiency as a function of ripple capacitor C_{out} of the converter circuit

boost converter being operated with the CZTSSe PV device as the input source, its output voltage (V_{out}) and efficiency are taken as the two figures of merit. Detailed SPICE-based simulation and analysis indicates that there are primarily two pairs of circuit elements in this design which determine these performance metrics. These are the resistor and capacitor of the tank oscillator circuit (denoted as R and C respectively), and resistor and capacitor of the output load (denoted as R_{out} and C_{out} respectively). Here C_{out} can also said to be the ripple capacitor of the circuit. In Fig. 2, the output voltage and efficiency of the boost converter are shown as a function of the ripple capacitor C_{out}. As can be observed in Fig. 2, the output voltage increases at the cost of lower efficiency and vice versa as the load resistance R_{out} increases. Hence there is a tradeoff depending on whether higher output voltage or efficiency is required at the output of the boost converter. It is also noteworthy that with higher ripple capacitor, the output voltage increases at first but later decreases for high values of load or becomes more or less constant for low values of the load. The efficiency profile exhibits the opposite trend, i.e. with low values of R_{out} the output efficiency increases and becomes more or less constant with the increase of ripple capacitor. Based on simulation results, the optimized value of the ripple capacitor can be taken to be $5x10^{-6}$F whereas the choice of R_{out} depends on whether higher efficiency or output voltage is required.

In order to have further insight into the design and optimization of the boost converter, its transient characteristics are analyzed and illustrated in Fig. 3. The results shown here correspond to highest and lowest values of the output voltage obtained in Fig. 2(a). As can be observed from Fig. 3(a), when the choice of resistance-capacitor combination results in the highest output voltage, changing the value of R and C of the oscillator circuit negligibly influences both the magnitude and shape of V_{out}. The output steady state voltage remains at about 6V in this case. Comparison between Fig. 3(a) and 3(b) however indicates that changing the values of R_{out} and C_{out} has significant impact on the shape of the transient characteristics and thereby on the output voltage level. In spite of the small ripple voltage, the steady state output voltage is only about 2V in this case. It is also noteworthy that changing the values of R and C of the oscillator circuit has comparatively more significant influence on the transient and steady-state output voltage when the load resistance is reduced 10 times for the case shown in Fig. 3(b), in comparison with the case considered in Fig. 3(a). Hence reducing the load resistance value results in greater dependence of the output voltage characteristics on the R-C tank oscillator circuit. The resistance-capacitor combinations considered in Fig. 3(a) though result in high output voltage, the output efficiency remains low at about $\sim$22% in comparison with the $\sim$36% efficiency obtained for the case considered in Fig. 3(b). This can be attributed to the high ripple voltage obtained for the case of Fig. 3(a), which is much smaller for the case considered in Fig. 3(b). Finally, transient characteristics of the transistor current (I_L) are shown in Fig. 3(c)-(d) for the R_{out} , C_{out} and R, C values considered in Fig. 3(a), (b). This reveals that the specific shape of the output voltage transient emanates from the particular shape of the currents, which are both quantitatively and qualitatively different when R_{out} and C_{out} are changed. Changing the values of R and C components of the oscillator circuit appears to have negligible effect on the shape and value of the transient currents. Hence in terms of both output voltage and switching current, the load resistor and capacitor combination appears to have dominant role in the circuit under consideration and therefore they serve as the main design parameters as far as design optimization is concerned.

IV. Conclusion

In conclusion, the design of a self-driven DC-to-DC boost converter circuit has been analyzed to optimize its performance characteristics when a CZTSSe-based PV device is considered as the energy harvester under indoor illumination. Results of the analysis indicate that output voltage and efficiency of

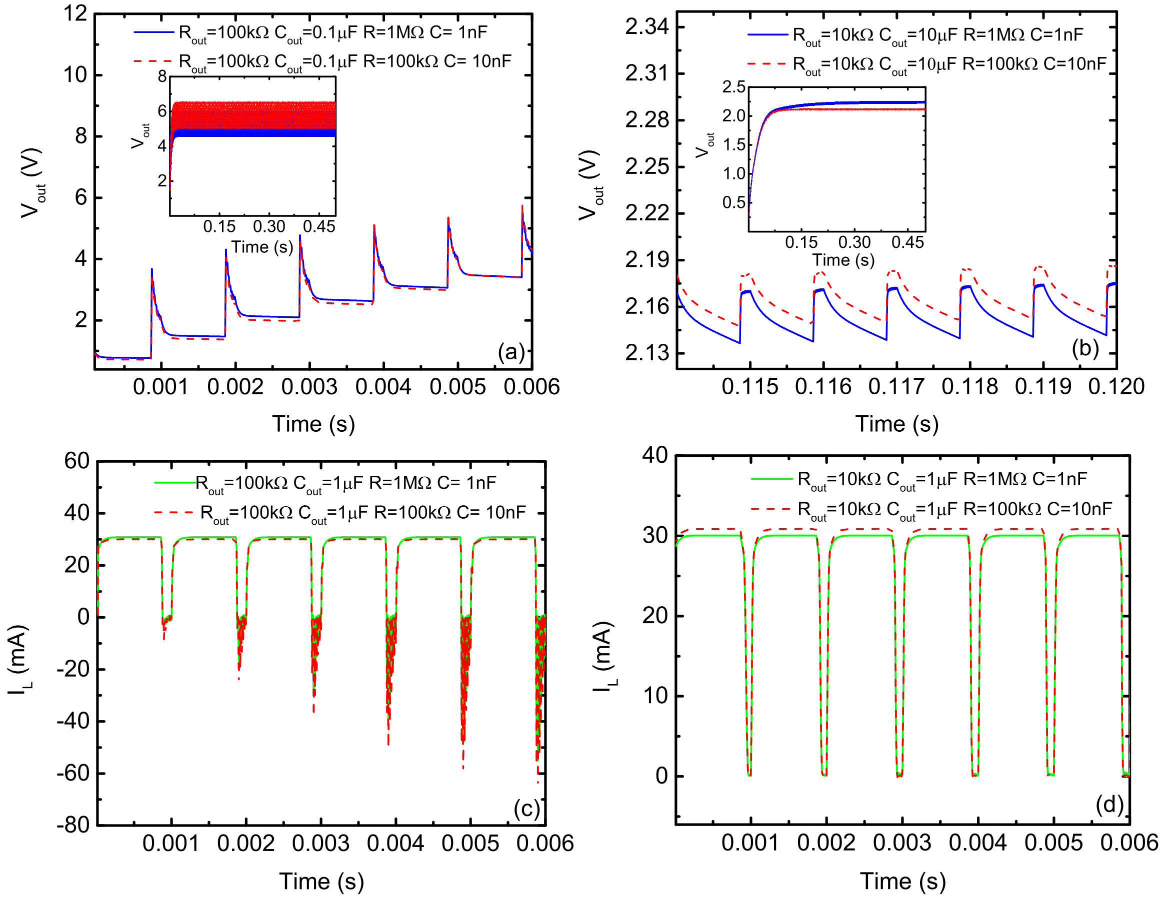

Fig. 3: (a) Transient value of V_{out} with R_{out} at the highest optimized value, C_{out} at the lowest optimized value and varying R, C [inset: steady state value of V_{out}]; (b) Transient value of V_{out} with R_{out} at the lowest optimized value, C_{out} at the highest optimized value and varying R, C [inset: steady state value of V_{out}]; (c)Transient value of transistor current (I_L) with R_{out} at the highest optimized value, C_{out} at the lowest optimized value and varying R, C; (d) Transient value of transistor current (I_L) with R_{out} at the lowest optimized value, C_{out} at the highest optimized value and varying R, C

this particular converter is primarily dependent on the load resistance and capacitance of the converter circuit. By systematically adjusting these circuit parameters, output voltages ranging from 2V to 6V can be obtained with output efficiency varying over the range of 22% to 36%. The combination of PV device and boost converter therefore offers a standalone, self-sustained source for driving low-power electronic devices which are expected to be integral to the successful operation of IoT devices and components of cyberphysical systems.

References

[1] A. S. Teran, J. Wong, W. Lim, G. Kim, Y. Lee, D. Blaauw, and J. D. Phillips, "AlGaAs photovoltaics for indoor energy harvesting in mm-scale wireless sensor nodes," *IEEE Transactions on Electron Devices*, vol. 62, no. 7, pp. 2170–2175, July 2015.

[2] W. Shockley and H. J. Queisser, "Detailed balance limit of efficiency of p-n junction solar cells," *Journal of Applied Physics*, vol. 32, pp. 510 – 519, Apr 1961.

[3] M. Freunek, M. Freunek, and L. M. Reindl, "Maximum efficiencies of indoor photovoltaic devices," *IEEE Journal of Photovoltaics*, vol. 3, no. 1, pp. 59–64, Jan 2013.

[4] J. Randall and J. Jacot, "Is AM1.5 applicable in practice? Modelling eight photovoltaic materials with respect to light intensity and two spectra," *Renewable Energy*, vol. 28, pp. 1851–1864, Oct 2003.

[5] J. Manser, J. Christians, and P. Kamat, "Intriguing optoelectronic properties of metal halide perovskites," *Chemical reviews*, vol. 116, pp. 12 956–13 008, June 2016.

[6] J. Nelson, "Polymer: Fullerene bulk heterojunction solar cells," *Materials Today*, vol. 14, pp. 462–470, Oct 2011.

[7] B. O'Regan and M. Graetzel, "A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO_2 films," *Nature*, vol. 353, pp. 737–740, Oct 1991.

[8] C. S. Tao, J. Jiang, and M. Tao, "Natural resource limitations to terawatt-scale solar cells," *Solar Energy Materials and Solar Cells*, vol. 95, no. 12, pp. 3176 – 3180, Dec 2011.

[9] K. Haque and M. Z. Baten, "On the prospect of CZTSSe-based thin film solar cells for indoor photovoltaic applications: A simulation study," *AIP Advances*, vol. 9, no. 5, p. 055326, 2019.

[10] R. Varache, C. Leendertz, M. Gueunier-Farret, J. Haschke, D. Muñoz, and L. Korte, "Investigation of selective junctions using a newly developed tunnel current model for solar cell applications," *Solar Energy Materials and Solar Cells*, vol. 141, pp. 14–23, Oct 2015.

[11] W. Wang, M. T. Winkler, O. Gunawan, T. Gokmen, T. K. Todorov, Y. Zhu, and D. B. Mitzi, "Device characteristics of CZTSSe thin-film solar cells with 12.6% efficiency," *Advanced Energy Materials*, vol. 4, May 2014.

[12] P. Spies, M. Pollak, and L. Mateu, *Handbook of energy harvesting power supplies and applications*. CRC Press, 2015.

[13] N. Mohan, *Power electronics: a first course*. Wiley, 2011.

[14] M. Pollak, L. Mateu, and P. Spies, "Step-up DC-DC-Converter with coupled inductors for low input voltages," *Fraunhofer IIS*, vol. 86, pp. 625–632, 2008.