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Research paper

Modeling and controller design for high gain dc-dc converter

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Abstract

This paper presents a mathematical model of a high gain non-isolated dc-dc converter for solar photovoltaic application under closed loop condition. This converter utilizes active switched inductor technology to achieve high gain with reduced voltage stress. All the steady states and transient states are discussed in detail and a suitable PI based voltage mode controller is designed to control the output voltage under various transient conditions. Further the mathematical model is implemented in MATLAB/SIMULINK and performance of the converter is tested.

Keywords: *DC-DC Converter; CCM; Switched Inductor; State Space Averaging; PI Controller.*

1. Introduction

Due to the rapid depletion of fossil fuels and increasing carbon footprint, renewable energy sources like solar photovoltaic, wind, biomass has received attention in recent days [1]. Among all renewable energy sources, solar photovoltaic is most popular due to its easy availability and reliability [2]. But it is essential to interface power electronic devices in between solar photovoltaic and utility to make it usable [3].

As the voltage available from solar photovoltaic is quiet low, so dc-dc boost converters are popular choice to increase the voltage to a standard level [4], [5]. Isolated dc-dc boost converters are not convenient for this application due to its problem related to saturation and bulk in size [6], [7]. Non-Isolated conventional dc-dc boost converter cannot provide very high gain because of the diode reverse recovery issue and limitations related to semiconductor devices [8]. Many boost derived converters are proposed in recent days for high gain application to overcome these problems [9-18]. At the same time, a suitable control topology is essential in order to connect this kind of systems to grid as the voltage available from solar photovoltaic is variable in nature.

Among all boost derived converters, Switched Inductor (S.I) based dc-dc converters are popular due to its simple structure and ability to provide high voltage gain. A passive S.I based dc-dc converter is proposed in [19], but the power switch of this converter suffers from problem related to high voltage stress. This problem is overcome by proposing an active S.I network in [20]; In this converter topology, two inductors are charging in parallel during simultaneous switching on of power switches and are discharging in series during switching off of the power switches in order to provide high voltage gain.

This paper presents a mathematical state space model of the converter proposed in [20], in order to develop a suitable control topology. At first, the steady state operation of the converter is discussed in detail and then a large signal model and small signal model is developed. Further, this converter with close loop controller is implemented in MATLAB/SIMULINK and tested under various dynamic conditions in order to check its performance. All the mathematical models and results confirm that this converter can provide high voltage gain and is stable under various dynamic conditions in closed loop.

Nomenclature	
Symbols used	
S_1,S_2	Switches
L_1,L_2	Inductors
C	Output Capacitor
V_S	Input Voltage
V_0	Output Voltage
I_0	Output Current
I_C	Current through the capacitor
V_C	Voltage across the capacitor
VL_1,VL_2	Voltage across the inductors
IL_1,IL_2	Current through the inductors

2. Circuit diagram

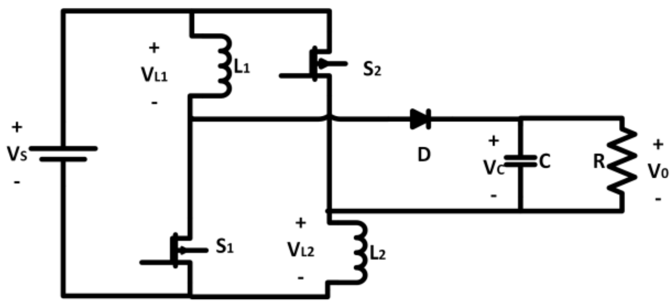

Fig. 1: Circuit Diagram of the Proposed Converter.

Figure 1 shows the proposed converter, the two switches (S_1 and S_2) are triggered simultaneously so that the two inductors (L_1,L_2) charge in parallel and during the off time of the switches the inductors discharge in series to the load through the output diode (D). During the on time period of the switches the load is fed by the output capacitor (C) whereas the capacitor gets charged during the off time period of the switch. Following assumptions are made for easier understanding and analysis of the circuit.

1) All the semiconductor devices and passive elements are ideal.
2) Values of switched inductors (L_1 and L_2) are same.

2.1. Mode-1:- when both the switches (S_1 and S_2) are turned on

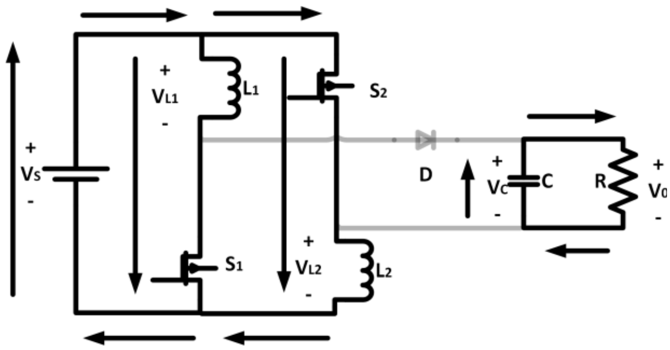

Fig. 2: Equivalent Circuit during the on Time Period of the Switches.

During the on time period of the switches the equivalent circuit is as shown in the figure 2. Both the inductors are connected in parallel with the input source and output capacitor feeds the load. The inductor voltage and output voltage is written as,

$$V_S = V_{L1} = V_{L2} \tag{1}$$

$$V_0 = V_C \tag{2}$$

The equation for output current is written as,

$$I_C = -I_0 \tag{3}$$

2.2. Mode-2:- when both the switches (S_1 and S_2) are turned off

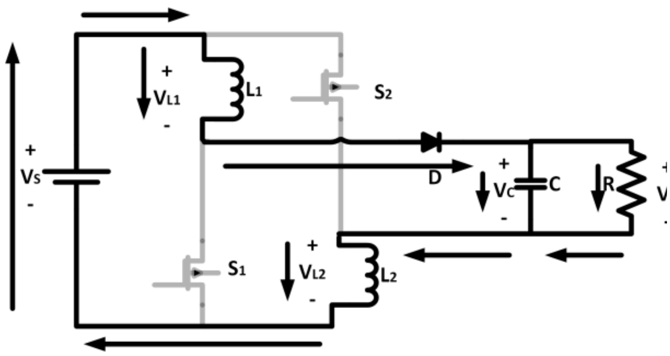

Fig. 3: Equivalent Circuit during the Off Time Period of the Switches.

When the switches are turned off, both the inductors discharge serially to the load and output capacitor through the output diode as shown in figure 3. The voltage equation is written as,

$$V_S - V_{L1} - V_0 - V_{L2} = 0 \tag{4}$$

As L_1 and L_2 are with same values, (4) can be written as,

$$V_S - 2V_L - V_0 = 0 \tag{5}$$

Output current is given by,

$$I_0 = I_{L1} - I_C \tag{6}$$

Output voltage is given by,

$$V_0 = V_C \tag{7}$$

3. Analysis

3.1. Steady state analysis

3.1.1. Voltage gain

Voltage gain during CCM is given by,

$$\frac{V_0}{V_S} = \frac{(1+D)}{(1-D)} \tag{8}$$

3.1.2. Design of inductor

In case of the switched inductor based converter, voltage stress on diode and switches is high. So, in the proposed converter both the inductors (L_1 and L_2) are chosen with equal values. The required value of inductors L_1 and L_2 considering ripple current of inductors (ΔI_L) and switching frequency (f_s) can be found out using,

$$L_1 = L_2 = \frac{V_S}{\Delta I_L f_s} \tag{9}$$

3.1.3. Design of capacitor

The value of capacitor in terms of ripple in capacitor voltage (ΔV_c) and switching frequency (f_s) is given by,

$$C = \frac{V_0 D}{\Delta V_c R f_s} \tag{10}$$

3.2. Transient analysis

Transient analysis is performed to check the performance of the circuit with respect to change in time, output or input parameters like change in load or change in input voltage. With the help of the results obtained from this analysis a proper controller can be designed in order to get the desired output irrespective of change in the parameters. General state space model is represented as,

$$\dot{x(t)} = Ax(t) + Bu(t)$$

$$y(t) = Cx(t) + Du(t)$$

3.2.1. Large signal analysis

Large signal analysis represents the transient behavior of the system over the entire range of the parameters. In short, it is the addition of steady state signal and small signal. The large signal analysis of a converter is done by obtaining the state space model of the converter during the on and off state of the switch separately and then adding them using the large signal averaging method. The large signal averaging is done as,

$$A = A_1 * D + A_2 * (1 - D)$$

$$B = B_1 * D + B_2 * (1 - D)$$

$$C = C_1 * D + C_2 * (1 - D)$$

$$D = D_1 * D + D_2 * (1 - D)$$

The states (x (t)) depend on the number of passive components. Current through the inductor is considered as a state whereas in case of capacitors voltage across a capacitor is considered as state. In the proposed converter there are three passive components (two inductors and one capacitor). Hence the proposed converter has three states which can be represented as I_{L1}, I_{L2} and V_C.
During the on time period of the switch (Ton), using (1) the state equation for the inductors can be written as,

$$L\frac{dI_{L1}}{dt} = L\frac{dI_{L2}}{dt} = V_S \tag{11}$$

The above equation can also be represented as,

$$\dot{I_{L1}} = \dot{I_{L2}} = \frac{V_S}{L} \tag{12}$$

Using (3), the state equation for capacitor can be written as,

$$C\frac{dV_C}{dt} = -V_C \tag{13}$$

The above equation can also be written as,

$$\dot{V_C} = -\frac{V_C}{RC} \tag{14}$$

The state equation for the on time period of switches is represented as,

$$\dot{x(t)} = A_1 x(t) + B_1 u(t)$$

Where

$$A_1 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{-1}{RC} \end{bmatrix}, B_1 = \begin{bmatrix} \frac{1}{L} \\ \frac{1}{L} \\ 0 \end{bmatrix},$$

$$\dot{x} = \begin{bmatrix} \dot{I_{L1}} \\ \dot{I_{L2}} \\ \dot{V_C} \end{bmatrix}, u(t) = V_S$$

Using (2) output of the converter is given by,

$$V_0 = V_C \ (15)$$

The output equation for off time period of the switches is written as,

$$y(t) = C_1 x(t) + D_1 u(t)$$

Where

$$C_1 = [0 \quad 0 \quad 1], D_1 = [0], y(t) = V_0$$

During the off time period of the switch (T_{off}), using (5) the state equation for the inductors can be written as,

$$L\frac{dI_{L1}}{dt} = L\frac{dI_{L2}}{dt} = \frac{V_S - V_0}{2} \tag{16}$$

This equation can be further written as,

$$\dot{I_{L1}} = \dot{I_{L2}} = \frac{V_S - V_0}{2L} \tag{17}$$

Using (6) current through the capacitor is given by,

$$C\frac{dV_C}{dt} = \frac{I_{L1}}{2} - \frac{V_C}{R} \tag{18}$$

This equation can be written as,

$$\dot{V_C} = \frac{I_{L1}}{C} - \frac{V_C}{RC} \tag{19}$$

The state equation for the off time period of switches is be written as,

$$\dot{x(t)} = A_2 x(t) + B_2 u(t)$$

Where

$$A_2 = \begin{bmatrix} 0 & 0 & \frac{-1}{2L} \\ 0 & 0 & \frac{-1}{2L} \\ \frac{1}{C} & 0 & \frac{-1}{RC} \end{bmatrix}, B_2 = \begin{bmatrix} \frac{1}{2L} \\ \frac{1}{2L} \\ 0 \end{bmatrix},$$

$$\dot{x} = \begin{bmatrix} \dot{I_{L1}} \\ \dot{I_{L2}} \\ \dot{V_C} \end{bmatrix}, u(t) = v_S$$

Using (7) output equation of the converter is given by,

$$V_0 = V_C \tag{20}$$

The output equation for off time period of the switches is written as,

$$y(t) = C_2 x(t) + D_2 u(t)$$

Where

$$C_2 = [0 \quad 0 \quad 1], D_2 = [0], y(t) = V0$$

By applying the state space averaging technique, the state space matrices are obtained as,

$$A = \begin{bmatrix} 0 & 0 & \frac{-(1-D)}{2L} \\ 0 & 0 & \frac{-(1-D)}{2L} \\ \frac{1-D}{C} & 0 & \frac{-1}{RC} \end{bmatrix}, B = \begin{bmatrix} \frac{1+D}{2L} \\ \frac{1+D}{2L} \\ 0 \end{bmatrix},$$

$$C = [0 \quad 0 \quad 1], D = [0]$$

The transfer function obtained from MATLAB for output to input (after substituting the values from the Table 1) becomes,

$$T_{FL}(s) = \frac{2.6359e07}{s^2 + 3973*S + 5.983e06} \tag{21}$$

Table 1: Specifications of the Proposed Converter

Parameters	Specifications
Maximum power output , P0	500 W
Input Voltage ,Vin	50 V
Output Voltage,V0	220 V
Switching frequency , fs	50 KHz
Duty Cycle , D	0.63
Inductors , L1,L2	4.4 mH
Output Capacitor , C	2.6 µF
Output Resistance , R	96.8 Ω

3.2.2. Small signal model

Small signal model can be obtained by subtracting the steady state signal from large signal. Small signal model is used to design controllers. The small signal model is represented as,

$$\dot{\widehat{x(t)}} = A\,\widehat{x(t)} + B\,\widehat{u(t)} + [(A_1 - A_2)X + (B_1 - B_2)U]\,\hat{d}$$

$$\widehat{y(t)} = C\,\widehat{x(t)} + D\,\widehat{u(t)} + [(C_1 - C_2)X + (D_1 - D_2)U]\,\hat{d}$$

Where $\widehat{x(t)}$, $\widehat{u(t)}$, $\hat{d}$ are the small signal values

X, U are the steady state values

For the proposed the converter the resulting small signal model can be written as,

$$\begin{bmatrix} \dot{\widehat{I_{L1}}} \\ \dot{\widehat{I_{L2}}} \\ \dot{\widehat{V_C}} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{-(1-D)}{2L} \\ 0 & 0 & \frac{-(1-D)}{2L} \\ \frac{1-D}{C} & 0 & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} \widehat{I_{L1}} \\ \widehat{I_{L2}} \\ \widehat{V_C} \end{bmatrix} + \begin{bmatrix} \frac{1+D}{2L} & \frac{V_C + V_S}{2L} \\ \frac{1+D}{2L} & \frac{V_C + V_S}{2L} \\ 0 & \frac{-I_{L1}}{C} \end{bmatrix} \begin{bmatrix} \widehat{Vin} \\ \hat{d} \end{bmatrix}$$

$$\widetilde{V_0} = [0 \quad 0 \quad 1]\begin{bmatrix}\widetilde{I_{L1}} \\ \widetilde{I_{L2}} \\ \widetilde{V_C}\end{bmatrix}$$

The transfer function for small change in output voltage to small change in duty ratio obtained from MATLAB (after substituting the values from the Table 1 and the value of IL1 was used from the MATLAB/SIMULINK model which comes out to be 6.07Amp) becomes,

$$T_{FS}(s) = \frac{-2.3346e06(s-1872)}{S^2+3973*S+5.983e06} \tag{22}$$

3.2.3. Controller design

Controller is designed for using small signal model. Bode plot for the small signal model shows that there is no need for a derivative controller. Hence the controller designed is a PI controller. Controller was designed for a different set of controller gain values and the best set of values is used for further analysis.

4. Results and discussion

Step response for output voltage to input voltage is shown in figure 4. The plot shows that the output voltage settles for a value of around 4.4 for a duty ratio 0.63 which can be verified from (8).

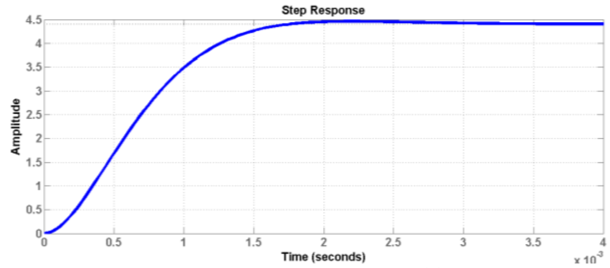

Fig. 4: Step Response To$T_{FL}(S)$.

Step response for small change in output voltage to small change in duty ratio is as shown in figure 5.

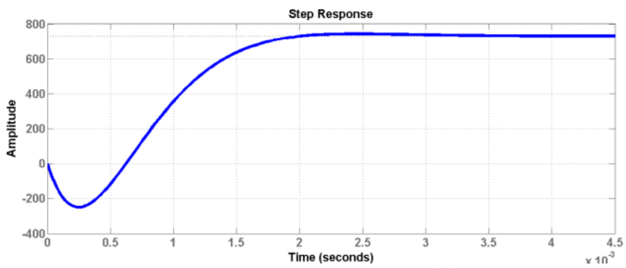

Fig. 5: Step Response For$T_{FS}(S)$.

Root locus plot for small change in output voltage to small change in duty ratio is shown in figure 6.

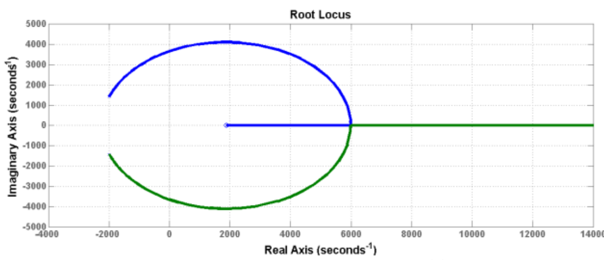

Fig. 6: Root Locus Plot for $T_{FS}(s)$.

Controller was designed for different sets of values and the comparison between them is shown in Table-2.

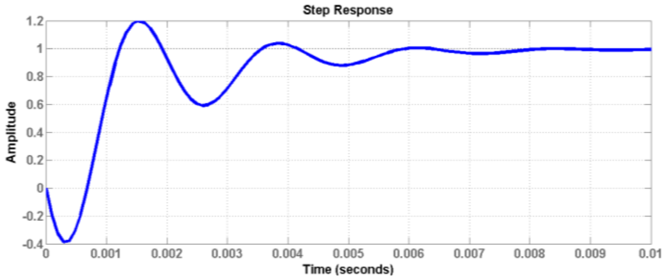

Fig. 7: Step Response of Controller with Set 1 Gain Values.

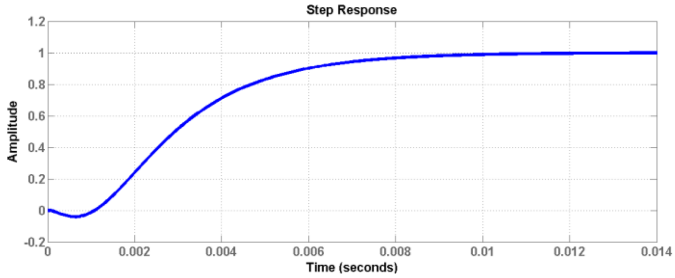

Fig. 8: Step Response of Controller with Set 2 Gain Values.

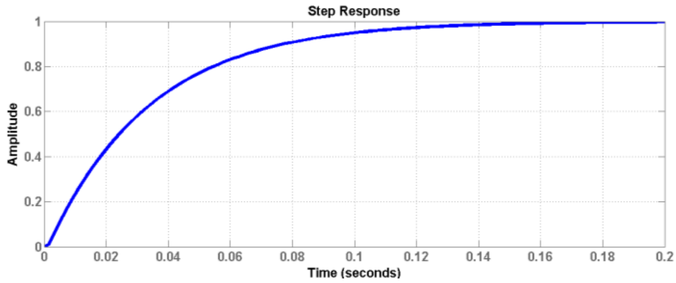

Fig. 9: Step Response of Controller with Set 3 Gain Values.

Considering all the parameters from table 2, set-2 gain values were used for further analysis due to low rise and settling time with no peak overshoot and appropriate gain and phase margin.

Root locus of the entire system with set-2 controller gain and feedback (feedback transfer function is taken as 1) is as shown in figure 10.

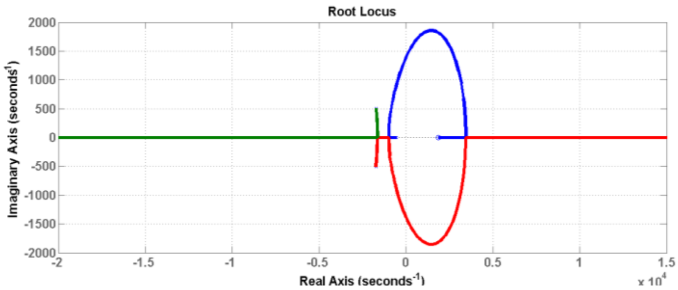

Fig. 10: Root Locus Plot for Set-2 Values of Controller Gain.

Bode plot for entire system with set-2 controller gain is shown in figure 11.

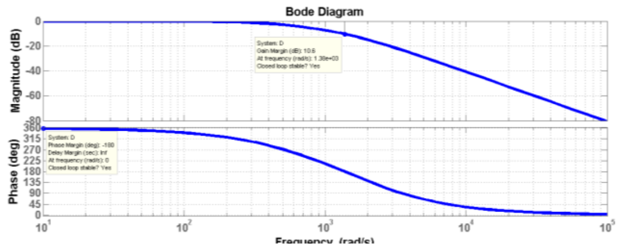

Fig. 11: Bode Plot for Entire System with Set-2 Controller Gain.

A MATLAB/SIMULINK model was designed with set-2 controller gain values for 74V input to get a constant output of 220V with variable load and the schematic is as shown in figure 12.

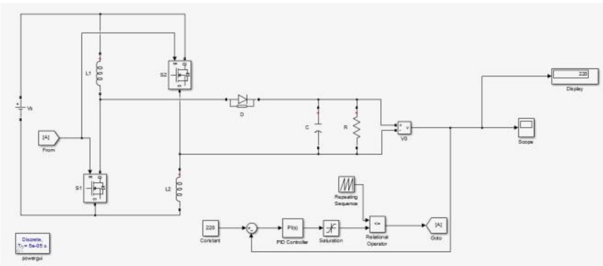

Fig. 12: Matlab/Simulink of the Converter.

The plot for output voltage and output current versus time in seconds is as shown in figure 13 and figure 14 respectively.

Table 2: Comparison between Parameters of Different Sets of Values of Controller Gain

Parameters	Set 1	Set 2	Set 3
Proportional gain, Kp	0.00101	0	0
Integral gain, Ki	0.86314	0.39555	0.039843
Rise time	0.000414 sec	0.00446 sec	0.0728 sec
Settling time	0.00754 sec	0.00889 sec	0.131 sec
Overshoot	19.8 %	0 %	0 %
Peak	1.2	0.999	0.999
Gain Margin	3.17 dB	12.9 dB	32.8 dB
Phase Margin	69 deg	70.1 deg	88 deg
Step Response	Figure 7	Figure 8	Figure 9

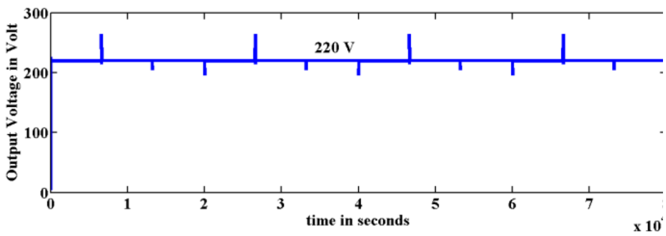

Fig. 13: Plot For Output Voltage Versus Time.

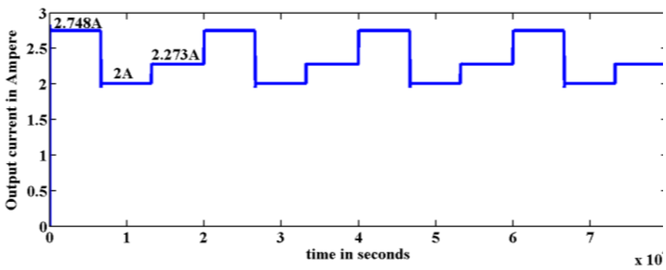

Fig. 14: Plot for Output Current Versus Time.

5. Conclusion

A mathematical model has been developed and a controller has been proposed, designed and implemented for a non-isolated high gain dc-dc converter for solar photovoltaic application. This paper includes the steady state model as well as the dynamic model of the converter. A pole placement technique has been used in order to design the controller. Root locus and bode plot mentioned in this paper confirms that the converter operated stably under various voltage fluctuation conditions. All this features of the converter make it suitable to connect with solar photovoltaic system.

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References

[1] Jacobson, M.Z., Delucchi, M.A., 2011. Providing all global energy with wind, water, and solar power, part I: technologies, energy resources, quantities and areas of infrastructure, and materials. Energy Pol. 39 (3), 1154–1169. https://doi.org/10.1016/j.enpol.2010.11.040.

[2] Bennett, Thomas, Zilouchian, Ali, Messenger, Rogar, 2012. Photovoltaic model and converter topology considerations for MPPT purposes. Sol. Energy 86(7), 2029–2040. https://doi.org/10.1016/j.solener.2012.04.005.

[3] Shuhui, L., Timothy, A.H., Dawen, L., Fei, H., 2011. Integrating photovoltaic and power converter characteristics for energy extraction study of solar PV systems. Renew. Energy 36(12), 3238–3245. https://doi.org/10.1016/j.renene.2011.02.016.

[4] Forouzesh, Mojtaba, Siwakoti, Yam P., Gorji, Saman A., Blaabjerg, Frede, Lehman, Brad, 2017. Step-up DC–DC converters: a comprehensive review of voltage boosting techniques, topologies, and applications. IEEE Trans. Power Electron. 32(12), 9143–9178. https://doi.org/10.1109/TPEL.2017.2652318.

[5] Li, Wuhua, He, Xiangning, 2011. Review of non-isolated high step-up DC/DC converters in photovoltaic grid connected applications. IEEE Trans. Ind. Electron. 58 (4), 1239–1250. https://doi.org/10.1109/TIE.2010.2049715.

[6] Gonzalez, R., Lopez, J., Sanchis, P., Marroyo, L., 2007. Transformerless inverter for singlephase photovoltaic systems. IEEE Trans. Power Electron. 22(2), 693–697. https://doi.org/10.1109/TPEL.2007.892120.

[7] Fathabadi, H., 2016. Novel high efficiency DC/DC boost converter for using in photovoltaic systems. Sol. Energy 125, 22–31. https://doi.org/10.1016/j.solener.2015.11.047.

[8] Mohan N, Undeland TM, Robbins WP. Power electronics: converters, applications, and design. New York, NY: John Wiley & Sons, Inc; 2007, available online: http://refhub.elsevier.com/S1364-0321(16)30490-7/sbref16, last visit: 19.11.2018

[9] B. Sri Revathi, M. Prabhakar. Non isolated high gain DC-DC converter topologies for PV applications – A comprehensive review. Renewable and Sustainable Energy Reviews 66(2016)920–933. https://doi.org/10.1016/j.rser.2016.08.057.

[10] Nilanjan Tewari, V.T. Sreedevi. A novel single switch dc-dc converter with high voltage gain capability for Solar PV based power generation systems. Solar Energy 171 (2018) 466–477. https://doi.org/10.1016/j.solener.2018.06.081.

[11] Sheshidhar Reddy Addula, M.Prabhakar. Coupled Inductor Based Soft Switched Interleaved DC-DC Converter for PV Applications. INTERNATIONAL JOURNAL OF RENEWABLE ENERGY RESEARCH.Vol.6, No.2, 2016:361-374, available online: http://www.ijrer.org/ijrer/index.php/ijrer/article/view/3327/pdf, last visit: 21.11.2018.

[12] CH Hussaian Basha, C. Rani, S. Odofin. A Review on Non-Isolated Inductor Coupled DC-DC Converter for Photovoltaic Grid-Connected Applications. INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH. Vol.7, No.4, 2017:1570-1585, available online:http://www.ijrer.org/ijrer/index.php/ijrer/article/view/6158/pdf, last visit: 21.11.2018.

[13] T. Arunkumari, V.Indragandhi. A Novel Single Switch High Step Up DC-DC Converter for PV Based Application. INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH. Vol. 8, No.2, June, 2018:1085-1097, available online:http://www.ijrer.org/ijrer/index.php/ijrer/article/view/6950/pdf,last visit: 21.11.2018.

[14] YeYuan-mao, ChengKaWaiEric. Quadratic boost converter with low buffer capacitor stress. IET Trans Power Electron 2014; 7(5):1162–70. https://doi.org/10.1049/iet-pel.2013.0205.

[15] Nouri Tohid ,Babaei Ebrahim, Hosseini Seyed Hossein . A generalized ultra step-up DC–DC converter for high voltage application with design considerations. Electr Power Syst Res 2013; 105:71–84. https://doi.org/10.1016/j.epsr.2013.07.012.

[16] Rodrigues J P, Mussa S A, Barbi I, Perin A J. Three level zero-voltage switching pulse-width modulation DC–DC boost converter with active clamping.IET Trans Power Electron 2010;3(3):345–54. https://doi.org/10.1049/iet-pel.2008.0352.

[17] Vighetti St´ephane, Ferrieux JP,Lembeye Yves. Optimization and design of a cascaded DC-DC converter devoted to grid-connected photovoltaic systems. IEEE Trans Power Electron 2012; 27(4):2018–27. https://doi.org/10.1109/TPEL.2011.2167159.

[18] Yang Lung-Sheng, Liang Tsorng-Juu, LeeHau-Cheng, Chen Jiann-Fuh. Novel high step-up DC–DC converter with coupled-inductor and voltage-doubler circuits. IEEE Trans Ind Electron 2011; 58(9):4196–206. https://doi.org/10.1109/TIE.2010.2098360.

[19] Axelrod, Boris, Berkovich, Yefim, Ioinovici, Adrian, 2008.Switched-capacitor/switchedinductor structures for getting transformerless hybrid DC-DC PWM converters. IEEE Trans. Circ. Syst. 55 (2), 687–696. https://doi.org/10.1109/TCSI.2008.916403.

[20] Lung-Sheng Yang, Tsorng-Juu Liang and Jiann-Fuh Chen. Transformerless DC–DC Converters with High Step-Up Voltage Gain. IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL. 56, NO. 8, AUGUST 2009. https://doi.org/10.1109/TIE.2009.2022512.