Single Switched Non-isolated High Gain Converter

Lopamudra Mitra[1], Ullash Kumar Rout[2]
[1,2] Department of Electrical Engineering, KIIT University, India.

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ABSTRACT

This paper presents a new single switched inductor- capacitor coupled transformer-less high gain DC-DC converter which can be used in renewable energy sources like PV, fuel cell in which the low DC output voltage is to be converted into high dc output voltage. With the varying low input voltages, the output of DC-DC converter remains same and does not change. A state space model of the converter is also presented in the paper. This constant output voltage is obtained by close loop control of converter using PID controller. High voltage gain of 10 is obtained without use of transformer. All the simulations are done in MATLAB-SIMULINK environment.

Corresponding Author:

Lopamudra Mitra,
Department of Electrical Engineering,
KIIT University,
Patia, Bhubaneswar 751024, India.
Email: mitralopa2011@gmail.com

1. INTRODUCTION

As there is a steep rise in costs and limitation on availability of non-renewable energy sources, has led to the development of renewable energy sources such as photovoltaic (PV) modules, wind energy systems, fuel cells etc. Power conditioning systems (PCS) become an integral part of renewable energy systems. As these sources are not dispatch able and the power output cannot be controlled. As the different output voltages are obtained from the PV panel due to varying irradiance and temperature, it would be beneficial to have a system with a high efficiency over the entire PV voltage range to maximize the use of the PV during different operating conditions. Another important part a PV system is the dc-dc converter for which should not only increase the voltage but also be able to implement maximum power point tracking (MPPT). The ability to implement MPPT for an individual PV panel would ensure that a large number of PV could maintain maximum power output from each panel without interfering with the other panels in the system. In this paper operation of a single switched transformer-less dc–dc converter with PID controller is presented to achieve constant output voltage over wide input voltage ranges, as controller forms an integral part of such systems.

2. DESIGN OF THE PROPOSED DC-DC CONVERTER

Nowadays, PV systems has high power rating which has 200 MW and increasing. This requires power converters with a higher power rating and higher voltage level, so high boost ratio converters are required. So a single switched inductor capacitor coupled high-voltage-gain DC/DC converter is proposed as a solution in this paper [1],[5]. Theoretically, a boost converter is able to provide high-voltage-gain with extremely high duty cycle. In practice, however, the voltage gain of the boost converter is limited because of the losses associated with the power devices and the passive elements such as the inductor and the capacitor.

Moreover, high duty cycle results in serious reverse-recovery problems and increases the rating of devices. In order to deal with conversion efficiency and the voltage gain issue of the boost converter, a relatively large variety of high-voltage-gain converter topologies has been proposed [1],[6],[7]. There are many topologies where it uses high frequency transformer and many switches having high switching stress. Again the use of high frequency transformer for high voltage gain has some limitations as parasitic capacitance can be a large source of loss in transformer. The leakage inductance of a transformer often causes voltage spikes during switching events and which increases with increase in operating voltage. Voltage drops across leakage reactance often results in undesirable supply regulation with varying transformer load.

In addition, reducing the size of magnetic material through higher operating frequency is hindered for higher voltage applications due to insulation requirements. A transformer-less converter should be considered to avoid the difficulties of high voltage transformer [8]-[16]. The proposed converter is shown in Figure 2 which consists of *S*1 is the MOSFET switch; *D*1 is the clamping diode, which provides a current path for the inductor Lm when *S*1 is OFF, *Cc* captures the leakage energy from the inductor Lm and transfers it to the resonant capacitor *Cr* by means of a resonant circuit composed of *Cc* , *Cr* , *Lr* , and *Dr* ; *Lr* is a resonant inductor, which operates in the resonant mode; and *Dr* is a diode used to provide an unidirectional current flow path for the operation of the resonant portion of the circuit. *Cr* is a resonant capacitor. *Do* is the output diode and *Co* is the output capacitor. *Ro* is the equivalent resistive load.

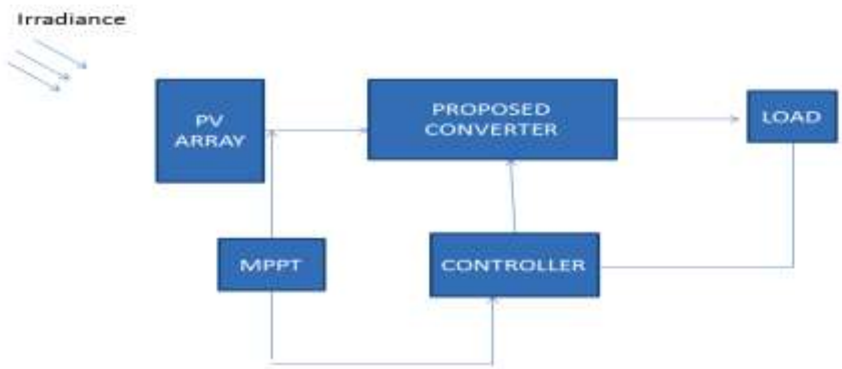

Figure 1. The complete system

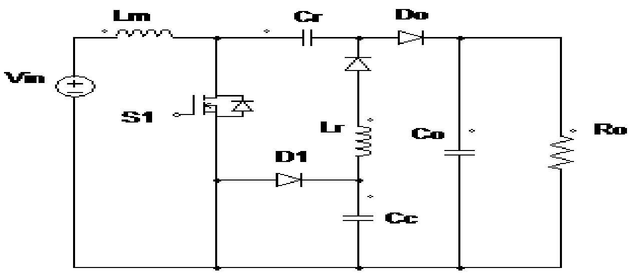

Figure 2. Single Switched Inductor Capacitor Coupled Converter

2.1. Modes of Operation

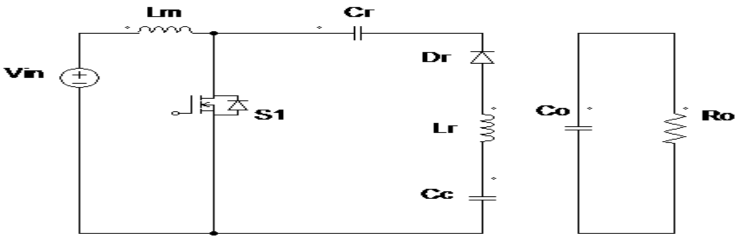

Figure 3. Mode-I

In this mode, MOSFET *S*1 is switched ON, the inductor is charged by input voltage, *Cr* is charged by *Cc*. The energy captured by *Cc* is transferred to *Cr*, which in turn is transferred to the load during the off-time of the MOSFET. The resonant current together with the inductor current forms the current in the switch.

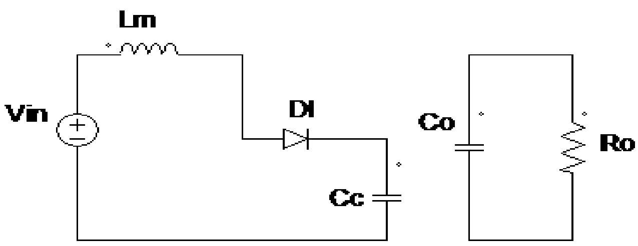

Figure 4. Mode-II

In mode-II MOSFET *S*1 is turned OFF, the clamping diode *D*1 is turned ON by the leakage energy stored in the inductor during ON time of the switch and the capacitor *Cc* is charged which causes the voltage on the MOSFET to be clamped.

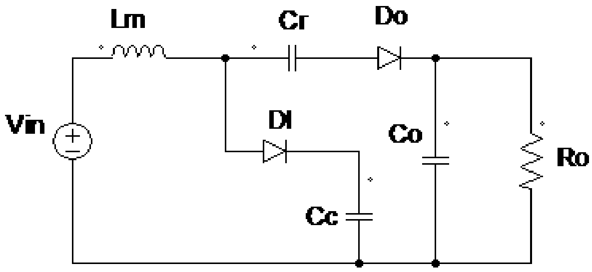

Figure 5. Mode- III

In mode-III as the capacitor Cc got charged so that the output diode Do is forward biased. The energy stored in the inductor and capacitor Cc is being transferred to the load and the clamp diode D1 continues to conduct while Cc remains charged.

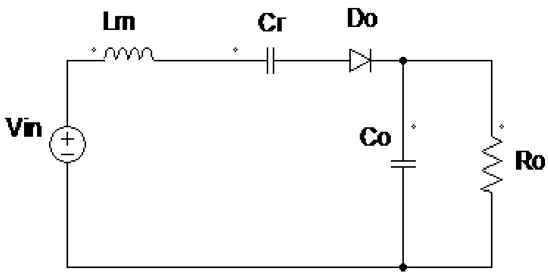

Figure 6. Mode-IV

In mode-IV diode D1 is reversed biased and as a result, the energy stored in inductor and in capacitor Cr is simultaneously transferred to the load. The capacitor Cr is charged to satisfy the balance of the charge in steady state operation.

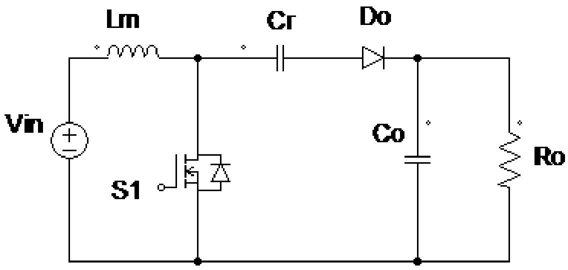

Figure 7. Mode-V

In mode-V the MOSFET S1 is turned ON again and the output diode Do will be reversed biased at the end of this mode then the next switching cycle starts.

3. STATE SPACE MODEL OF THE PROPOSED CONVERTER

When the switch is ON

$$V_{in} - L_m \frac{dI_1}{dt} = 0 \quad (1)$$

State space representation

$$q_1 = x_1$$
$$I_1 = \dot{q}_1 = \dot{x}_1 = x_2$$
$$\dot{I}_1 = \dot{x}_2$$
$$q_2 = x_3$$
$$I_2 = \dot{q}_2 = \dot{x}_3 = x_4$$
$$\dot{I}_2 = \dot{x}_4 = x_5$$

So equation (1) becomes,

$$I_1 = \frac{V_{in}}{L_m}$$

$$\Rightarrow \dot{x}_1 = \frac{V_{in}}{L_m} \quad (2)$$

Let Cc=C1, Cr =C2, Co= C3, Ro=R2 and inductor L2 connected with load (assumption for calculation)

$$\frac{1}{C_1}\int I_1 dt - L_1\frac{dI_1}{dt} - \frac{1}{C_2}\int I_1 dt - L_m\frac{dI_1}{dt} = 0$$

$$\Rightarrow \frac{q_1}{C_1} - L_1\frac{dI_1}{dt} - \frac{q_1}{C_2} = 0$$

$$\Rightarrow \frac{q_1}{C_1} - \frac{q_1}{C_2} - L_1\frac{dI_1}{dt} = 0$$

$$\Rightarrow \frac{dI_1}{dt} = \frac{q_1}{C_2L_1} - \frac{q_1}{C_1L_1} \quad (3)$$

$$\Rightarrow \dot{x}_2 = \frac{C_2 - C_1}{L_1 C_2 C_1} \quad (4)$$

$$\frac{1}{C_3}\int I_2 dt + L_2 \frac{dI_2}{dt} + R_2 I_2 = 0 \quad (5)$$

$$\Rightarrow \frac{q_2}{C_3} + L_2 \dot{x}_4 + R_2 x_4 = 0$$

$$\Rightarrow L_2 \dot{x}_4 = -\frac{x_3}{L_2 C_3} - \frac{R_2 x_4}{L_2}$$

$$\Rightarrow \dot{x}_4 = -\frac{x_3}{L_2 C_3} - \frac{R_2 x_4}{L_2} \quad (6)$$

The output Y is

$$Y = I_2 R_2$$

$$\Rightarrow Y = R_2 x_4 \quad (7)$$

When the switch is OFF, Let R is the resistance of the inductor Lm

$$Vin - RI_1 + L_m \frac{dI_1}{dt} - \frac{1}{C_2}\int I_1 dt - \frac{1}{C_3}\int (I_1 - I_2) dt = 0$$

$$\Rightarrow Vin - RI_1 + L_m \frac{dI_1}{dt} - \frac{q_1}{C_2} - \frac{(q_1 - q_2)}{C_3} = 0$$

$$\Rightarrow Vin - Rx_2 + L_m \dot{x}_1 - \frac{x_1}{C_2} - \frac{1}{C_3}(x_1 - x_2) = 0 \quad (8)$$

$$\Rightarrow \dot{x}_1 = \frac{Vin}{L_m} + \left(\frac{1}{L_m C_2} + \frac{1}{L_m C_3}\right) x_1 + \left(\frac{-1}{L_m C_3} + \frac{R}{L_m}\right) x_2$$

$$\Rightarrow \dot{x}_1 = \frac{Vin}{L_m} + \left(\frac{C_3 + C_2}{L_m C_2 C_3}\right) x_1 + \left(\frac{RC_3 - 1}{L_m C_3}\right) x_2 \quad (9)$$

$$-L_2 \frac{dI_2}{dt} - I_2 R_2 - \frac{1}{C_3}\int (I_2 - I_1) dt = 0 \quad (10)$$

$$\Rightarrow -L_2 \dot{x}_4 - R_2 x_4 - \frac{q_2}{C_3} - \frac{q_1}{C_3} = 0$$

$$\Rightarrow -L_2 \dot{x}_4 - R_2 x_4 - \frac{x_3}{C_3} - \frac{x_1}{C_3} = 0$$

$$\Rightarrow L_2 \dot{x}_4 = -R_2 x_4 - \frac{x_3}{C_3} - \frac{x_1}{C_3}$$

$$\Rightarrow \dot{x}_4 = -\frac{R_2 x_4}{L_2} - \frac{x_3}{L_2 C_3} - \frac{x_1}{L_2 C_3} \tag{11}$$

The output Y is

$$Y = I_2 R_2$$

$$Y = R_2 x_4 \tag{12}$$

So, the state space model during ON condition is,

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \frac{(C_2 - C_1)}{(L_1 C_1 C_2} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & \frac{-1}{L_2 C_3} & \frac{-R_2}{L_2} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} \frac{1}{L_m} \\ 0 \\ 0 \\ 0 \end{bmatrix} V_{in} \tag{13}$$

$$Y = [0 \quad 0 \quad 0 \quad R_2] \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \tag{14}$$

The state space model during OFF condition is,

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} \frac{(C_3 + C_2)}{C_2 C_3 L_m} & \frac{RC_3 - 1}{L_m C_3} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ \frac{-1}{L_2 C_3} & 0 & \frac{-1}{L_2 C_3} & \frac{-R_2}{L_2} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} \frac{1}{L_m} \\ 0 \\ 0 \\ 0 \end{bmatrix} Vin \tag{15}$$

$$Y = [0 \quad 0 \quad 0 \quad R_2] \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \tag{16}$$

The above state model is used to for design of PID controller by sSate Space Averaging Technique.

3.1. State Space Averaging Technique

The state space model is used in design of the converter [17]-[20]. By using the state space averaging (SSA) technique the averaged matrices are obtained as

$$A = A1 \times d + A2 \times (1-d)$$
$$B = B1 \times d + B2 \times (1-d)$$
$$C = C1 \times d + C2 \times (1-d)$$
$$D = D1 \times d + D2 \times (1-d)$$

The control transfer function is defined as the ratio of output voltage to duty ratio and it is obtained as

$$\frac{Vo(s)}{d(s)} = C \times (SI - A)^{-1}(A1 - A2)X \quad (16)$$

Where $X = -A^{-1} \times B \times V_{in}$ (17)

From the state space representation of the model by using MATLAB Program the root locus plot of the converter is obtained and from the root locus plot critical gain K_c and critical time period T_c was obtained. Ziegler Nichols method is used to tune parameters of the PID controller. The Ziegler–Nichols tuning method is a heuristic method of tuning a PID controller. A MATLAB/.m file program is written to obtain the root locus plot of the proposed converter using SSA technique.

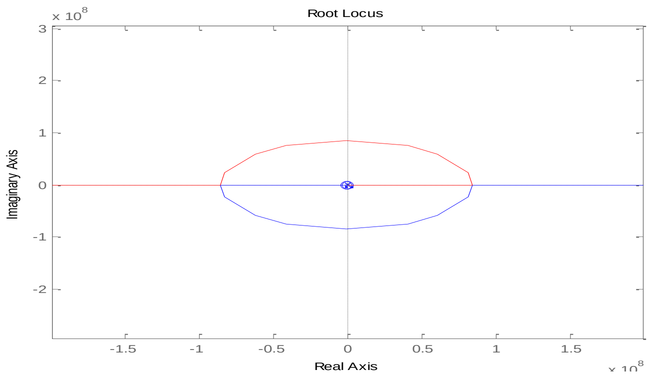

Figure 8. Root Locus Plot of the converter without controller

Ziegler and Nichols suggested rules for tuning PID controllers required to set values of Kp, Ti, and Td [18]-[20].

Table 1. Table for tuning of parameters of controller By Ziegler Nichols Method

Type of Controller	K_p	T_i	T_d
P	0.5 Kc	∞	0
PI	0.45Kc	0.82Tc	0
PID	0.6 Kc	0.5Tc	0.125 Tc

Where K_c is the critical gain. Here for the proposed converter we will use PID controller. So, the parameters are

$$K_p = 0.6K_c$$

$$T_i = 0.5T_c$$

$$\Rightarrow T_i = 0.3685 \times 10^{-7} \text{ seconds.}$$

$$T_d = 0.125\,T_c$$

$$\Rightarrow T_d = 0.0921 \times 10^{-7} \text{ seconds.}$$

$$K_i = \frac{K_p}{T_i}, K_d = K_p T_d$$

4. SIMULATION AND RESULTS

From the voltage balance equation of the converter the parameters are obtained. These parameters are used for the design of the converter. The simulation result shows a voltage gain of 10 is obtained for different in voltages. The output voltage waveforms are also shown with and without controller.

V_{in} =30V, L1=2.2x10^{-6} H, C1=20x10^{-6} F, C2=1x10^{-6}F, C3=33x10^{-6}F, Lm=18x10^{-6} H

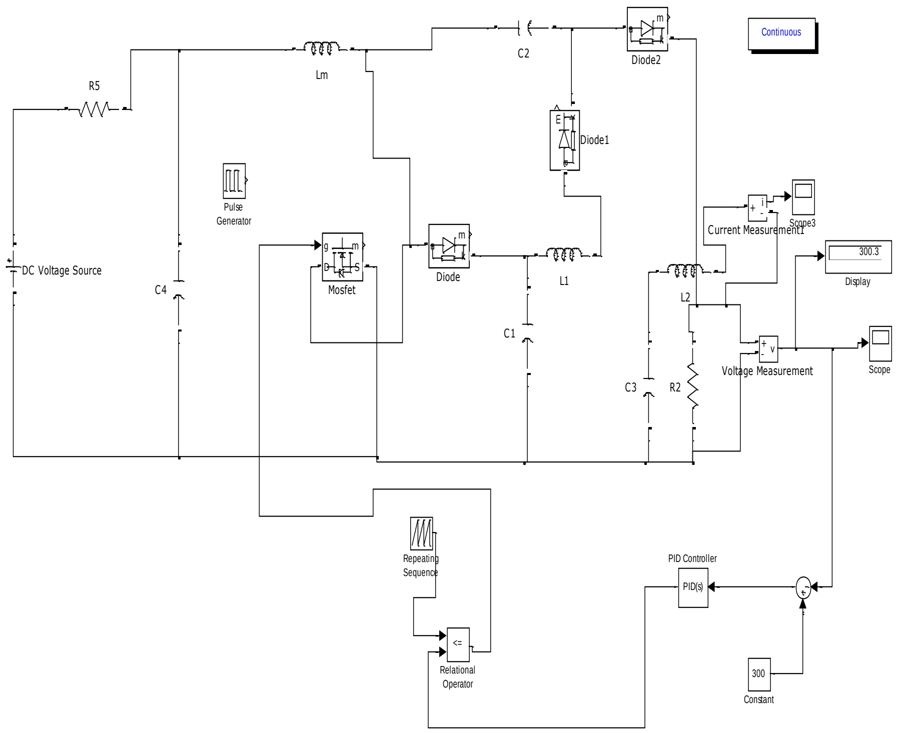

Figure 9. Simulation Diagram of the complete System

In this work PID controller is used to keep the output voltage constant, without controller high voltage gain of 10 is obtained for different inputs, which is shown in the above simulation results in Figure 10 to 12. The following simulation results show the output voltage of the proposed converter for different input voltage using PID controller.

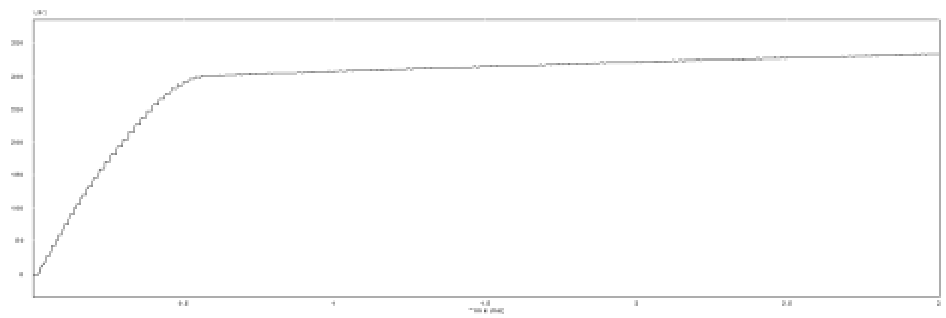

Figure 10. Output Voltage of the converter is 300V for input voltage of 30 V without controller

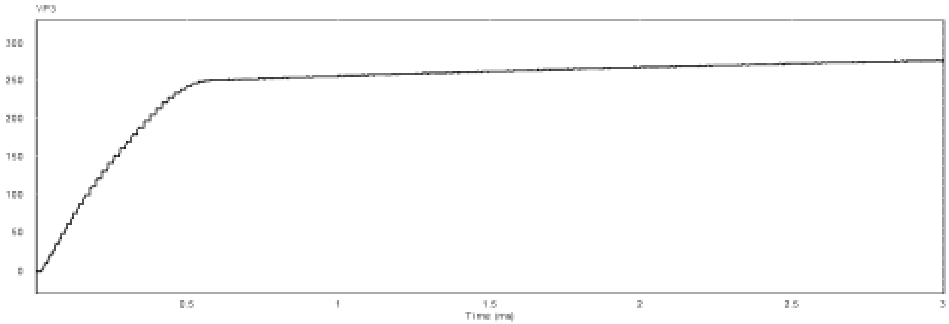

Figure 11. Output Voltage of the converter is 250 V for input voltage of 25 V without controller

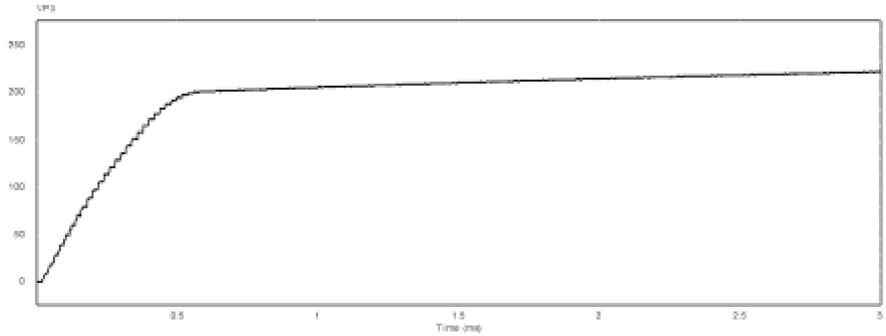

Figure 12. Output Voltage of the converter is 200V for input voltage of 20 V without controller

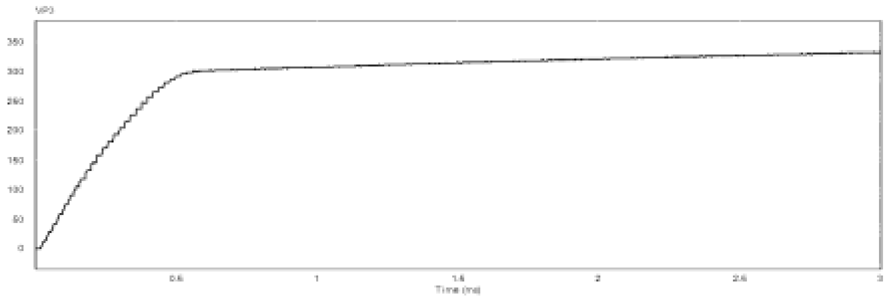

Figure 13. Output Voltage of the converter is 299.8V for input voltage of 30 V with controller

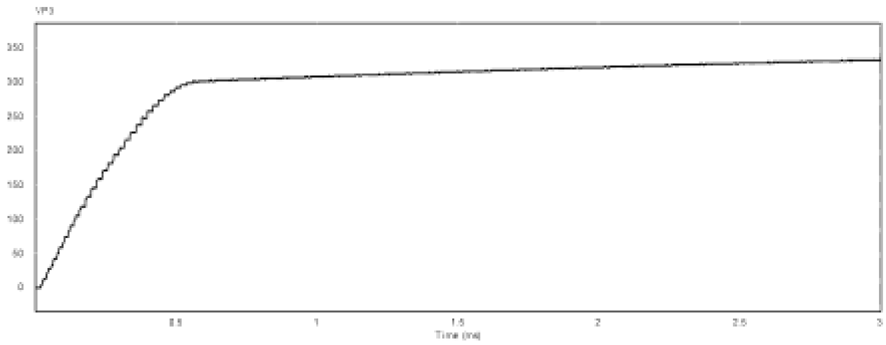

Figure 14. Output Voltage of the converter is 299.8V for input voltage of 25 V with controller

Table 2. Output Voltage of the Converter with variation in input voltage

Sl. No.	Input voltage of the Converter	Output voltage of the Converter
1	30V	299.8V
2	25V	299.8V
3	20V	299.3 V

5. CONCLUSION

In this work a new high voltage gain dc- dc converter is proposed which can be used with PV array to get high output voltage of 299.8V for low input voltage. The new topology uses only one switch hence reduces the switch stress as well as it doesn't use any high frequency transformer for high voltage gain and all the limitations of high frequency transformers are overcome. In order to keep the output voltage constant a controller has been designed. For any change in the input voltage, the output voltage remains constant, so the design of the PID controller is found to be optimum. As a high voltage gain is obtained this can be coupled with a PV array and output voltage is maintained constant with the help of the controller, hence the proposed converter can be used in different standalone applications specially where output voltage variations is not required. Most of the high gain dc-dc converters employ high frequency transformer to achieve the voltage gain leading to the increase of size, weight and cost of the converter. Many topologies also combine two topologies with a resonant circuit to achieve high gain as well as high efficiency at the expense of number of switches. Some topologies also use multiplier cells to increase the voltage transformation ratio with increase of switch count. Other topologies also use interleaved technology and overlapping gating signals which leads to the complexity of the gating circuits. In two transformer topology, two transformers are used to increase the voltage gain and efficiency hence increasing the volume and reducing the power density.Hence the proposed high gain converter with single switch can be employed to PV systems to obtain high voltage.

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BIOGRAPHIES OF AUTHORS

Ms. Lopamudra Mitra is a Research Scholar in the School of Electrical Engineering, KIIT University, Bhubaneswar. She received her B.Tech in Electrical and Electronics Engineering from National Institute of Science and Tecnology and M.Tech with specialization in Power Electronics and Drives from KIIT University, Bhubaneswar.Presently carrying her research in the area of Power Electronics and Renewable Energy Systems.

Dr. Ullash Kumar Rout is currently working as Professor in School of Electrical Engineering, KIIT University, Bhubaneswar.He received his B. Tech. in Electrical Engineering from Utkal University, M. Tech. in Power System from IIT Kanpur, and Ph.D. in Energy System from University of Stuttgart, Germany.He has around 11 years of research experience in energy system modelling and 7 years in teaching. His research interest includes energy system and power system.