

High Step up DC-DC Converter with PID Controller for Photovoltaic Applications

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Abstract—From the literature survey, it is observed that the need of ac photovoltaic modules in photovoltaic (PV) power-generation market has increased. However, the important aspect is a requirement of a high voltage gain converter for the module's grid connection through a dc-ac inverter. A high step up dc-dc converter using PI controller is proposed and presented in this paper. Further, the converter proposed in this paper employs a floating active switch, which is designed to isolate the dc current from the PV panel when the ac module is off-grid as well as in the non-operating condition. This isolation will ensure the operation of the internal components without any residential energy being transferred to the output or input terminal. The PI controller is used in feedback in order to speed-up the response. The converter achieves a high step-up voltage-conversion ratio without extreme duty ratio and the numerous turns-ratios of a coupled inductor. The leakage inductor energy of the coupled inductor is efficiently recycled to the load. The proposed converter model along with PI controller is modeled using SIMULINK and the simulation results are presented in this paper to authenticate the proposed scheme.

Keywords: PID Controller, Single switch, AC module, coupled inductor, High step up voltage gain.

1. INTRODUCTION

Solar energy is growing at double-digit rates worldwide. And it will continue to do so in coming years across all its different applications be them residential, in small and large buildings, or in power plants. They have made it a prime source of clean, renewable energy that is making a major contribution to reducing the carbon footprint and building the environmental sustainability of power generation. The compelling advantage of PV generation systems is how versatile and convenient they are. They can be used in standalone applications and installed in places that are difficult and uneconomical to supply with traditional power lines. A conventional centralized PV array is a serial connection of numerous panels to obtain higher dc voltage [1], [2]. Unfortunately, once there is a partial shadow on some panels; the system's energy yield becomes significantly reduced [3]. An ac module is a microinverter configured on

the rear bezel of a PV panel [4]; this alternative solution not only immunizes against the yield loss by shadow effect, but their efficiency levels are lower than those of conventional PV inverters. However, employing a high step-up dc-dc converter improves power-conversion efficiency. Previous research on various converters for high step-up applications has included analyses of the switched-inductor and switched-capacitor types[5], the boost type integrating with the switched-capacitor technique[6], the voltage-lift type, the capacitor-diode voltage multiplier type, and the transformer less dc-dc converters[7]. In these converters the voltage gain is not enough to convert to a suitable ac source as a model micro source, in case of extremely high voltage gain is required, to using series connection of converter is able to reach much higher voltage gain. As known, the efficiency and voltage gain of dc-dc boost converter are restrained by either the parasitic effect of power switches or the reverse-recovery issue of diodes. However in the proposed converter without extreme duty ratios and the numerous turns-ratios of a coupled inductor, this converter achieves a high step-up voltage-conversion ratio. The conventional converter [8] it consist of converter that employs a floating active switch is designed to isolate the dc current from the PV panel, when the ac module is off-grid as well as in the non operating condition. This isolation ensures the operation of the internal components without any residential energy being transferred to the output or input terminals, which could be unsafe. This particular design protects installers and users from electrical hazards. Without extreme duty ratios and the numerous turns-ratios of a coupled inductor, this converter achieves a high step-up voltage-conversion ratio.

2. PROPOSED CONVERTER

The proposed converter, shown in Fig. 1, is comprised of a coupled inductor T1 with the floating active switch S1. The primary winding N1 of a

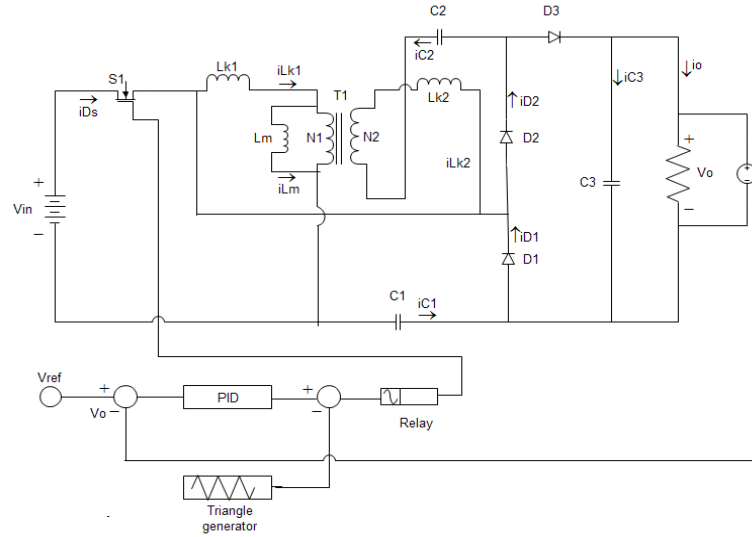


Figure 1 Circuit of proposed converter

coupled inductor T1 is similar to the input inductor of the conventional boost converter, and capacitor C1 and diode D1 receives leakage inductor energy from N1. The secondary winding N2 of coupled inductor T1 is connected with another pair of capacitors C2 and diode D2, which are in series with N1 in order to further enlarge the boost voltage. The rectifier diode D3 connects to its output capacitor C3. A PID controller is a generic control loop feedback mechanism widely used in industrial control systems. A PI controller attempts to correct the error between a measured process variable and a desired set point by calculating and then outputting a corrective action that can adjust the process accordingly. The proportional term makes the change in output that is proportional to the current error value. The proportional response can be adjusted by multiplying the error by a constant value, K_p called as proportional gain. The integral term causes the steady-state error to reduce to zero, which is not the case for proportional-only control in general. The integral term is proportional to both the magnitude of error and the duration of the error. The magnitude of the contribution of the integral term to the overall control action is determined by the integral gain K_i . The output voltage and the reference voltage are summed together and it is given to the PI controller. The proposed converter has several features:

- 1) The connection of the two pairs of inductors, capacitor, and diode gives a large step-up voltage-conversion ratio.
- 2) The leakage-inductor energy of the coupled inductor can be recycled, thus increasing the

efficiency and restraining the voltage stress across the active switch

3) The floating active switch efficiently isolates the PV panel energy during non-operating conditions, which enhances safety. The ideal version of the PID controller is given by the formula.

$$u(t) = k_p e(t) + k_i \int_0^t e(t) dt + k_d \frac{d}{dt} e(t) \quad (1)$$

Where

u = Control signal.

e = Control error ($e = r - y$).

r = Reference value, is also called the set point

y = Input signal

K_p = Proportional gain

K_i = Integral gain

K_d = Derivative gain

t = time

4. OPERATING PRINCIPLES OF THE PROPOSED CONVERTER

In this section the five operating modes of the proposed converter are explained in brief

MODE – I

The FIG 3(a) shows circuit operation in mode 1. When S1 is in ON state the magnetizing inductor L_m continuously charges capacitor C2 through T1. The source voltage V_{in} crosses the magnetizing inductor L_m and primary leakage inductor L_{k1} . The magnetizing inductor L_m transfers its energy through coupled inductor T1 to charge switched capacitor C2. As a result the current i_{Lm} is decreases. In this Mode the charging current i_{D2} , i_{C2} , decreases. The Mode Ends When $i_{Lk1} = i_{Lm}$.

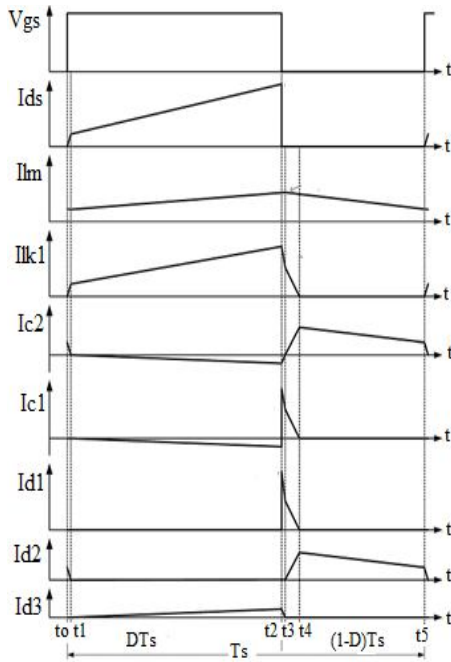


Figure 2 Typical waveforms of proposed converters

MODE – II

The FIG 3(b) shows circuit operation in mode 2. The source voltage V_{in} crosses the magnetizing inductor L_m , primary leakage inductor L_{k1} and Primary winding N_1 and acts series with secondary winding N_2 of coupled inductor T_1 , Capacitor C_1, C_2 . Magnetizing inductor L_m is also receiving energy from V_{in} . The energy is finally discharged to Output Capacitor C_3 and Load R . This mode ends when switch S_1 are turned OFF.

MODE – III

The FIG 3(c) shows circuit operation in mode 3. As the switches S_1 is in OFF state. Energy of secondary leakage inductor L_{k2} is series connected with C_2 to charge output capacitor C_3 and the load R . Energy stored in Primary leakage inductor L_{k1} flows through diode D_1 & D_3 to charge capacitor C_1 & C_3 . I_{lm} are increasing because magnetizing inductor L_m and L_m is receiving energy from L_{k1} . Diode D_1 and D_3 are conducting. This Mode ends when Leakage Current I_{Lk2} decreases to zero.

MODE – IV

The FIG 3(d) shows circuit operation in mode 4. The leakage energy from the Leakage inductor L_{k1} & L_{k2} flows through the diodes D_1 and keeps charging capacitor C_1 as a result Currents I_{Lk1} , and I_{D1} , are continually decreasing. The L_m is delivering its energy through T_1 and D_2 to charge

capacitor C_2 . Diodes D_1, D_2 , are conducting. The energy stored in output capacitor C_3 is constantly discharged to the load R . These energy transfers result in decrease of I_{Lk1} and I_{Lm} but increases in I_{Lk2} . This mode ends when current I_{Lk1} reaches zero.

MODE – V

The FIG 3(e) shows circuit operation in mode 5. Magnetizing inductor L_m are constantly releasing its energy to C_2 . Diode D_2 is conducting. The magnetizing inductor energy flows through the secondary winding of the coupled inductor N_2 and D_2 continues to charge capacitor C_2 . As a result the i_{Lm} is decreasing. The energy stored in capacitor C_3 is constantly discharged to the load R . This mode ends when switch S_1 is turned ON.

5. DESIGN OF PROPOSED CONVERTER

In this section the Circuit design of the proposed converter with electrical specification are presented.

Input voltage $V_{in}=15V$

Output voltage $V_{out}=200V$

Switching frequency $F_s=50 \text{ kHz}$

Duty cycle (D) is given by equation given below

$$D = 1 - \frac{V_{in}(1+n)}{V_{out}} \quad (2)$$

Where n represents turns ratio, $n = 6$

Substituting the input and output voltage in (2)

$$D = 1 - \frac{15(1+5)}{200}$$

We get duty cycle $D = 0.55$ or 55% .

The normalized magnetizing inductor time constant τ_L is defined as

$$\tau_L = \frac{L_m F_s}{R} \quad (3)$$

The normalized magnetizing inductor time constant τ_{LB} to be depicted as

$$\tau_{LB} = \frac{D(1-D)^2}{2(1+n)^2} \quad (4)$$

Substituting the duty cycle D and turns ratio n in (4)

$$\tau_{LB} = \frac{0.5(1-0.5)^2}{2(1+5)^2}$$

$$\tau_{LB} = 1.547 \times 10^{-3} \mu H$$

The actual magnetizing inductance L_m can be found by rearranging the equation 2

$$L_m = \frac{\tau_L}{F_s} R \quad (5)$$

Substituting the Switching frequency load resistance and magnetizing inductor time constant in (5)

$$L_m = \frac{1.547 * 10^{-3} * 800}{50k}$$

$$L_m = 24.75 \mu H$$

The actual magnetizing inductance L_m is equal to 24.75uH.

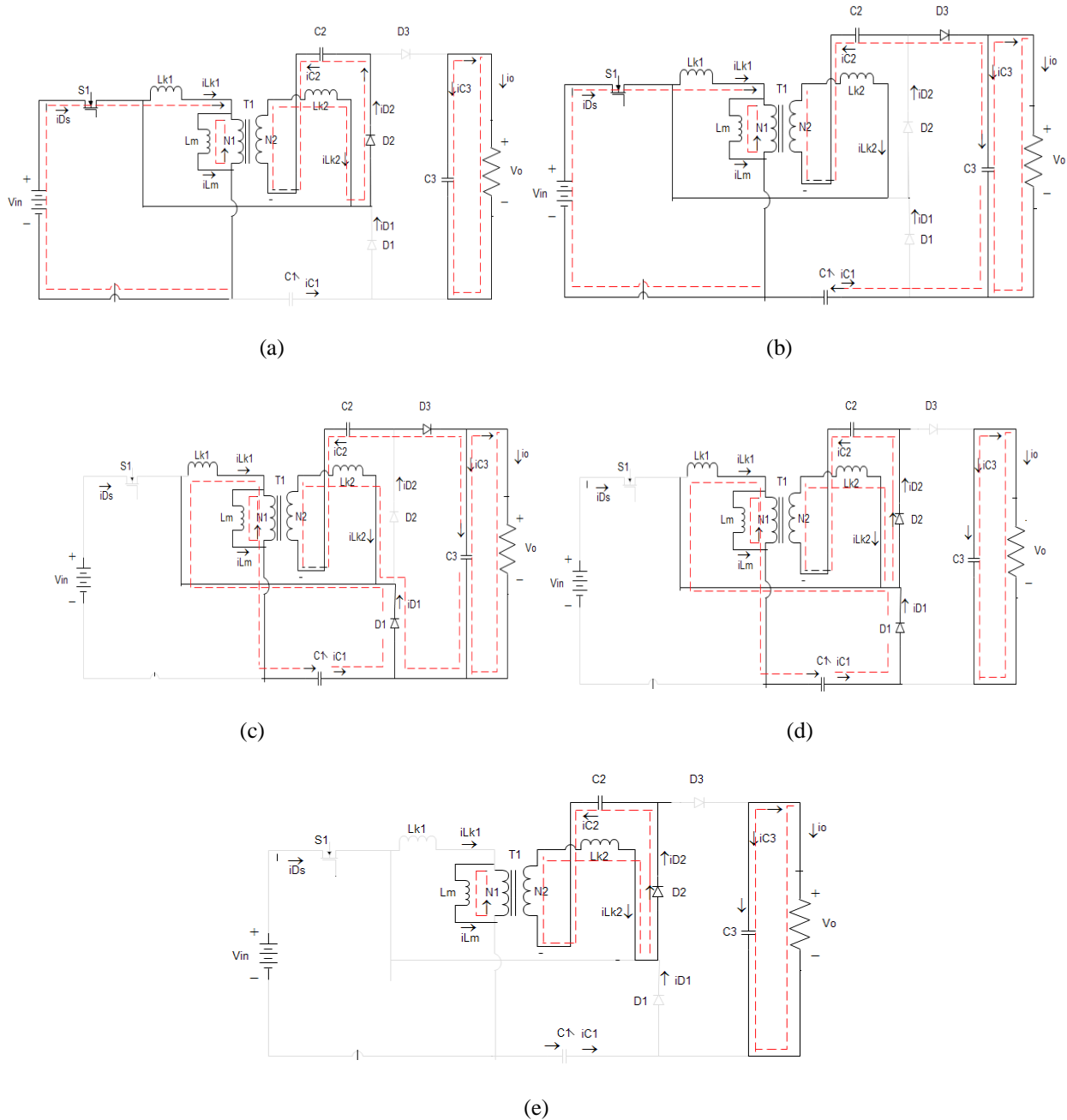


Figure 3 Operating modes of the proposed converter (a) mode 1 (b) mode 2 (c) mode 3(d) mode 4 (e) mode 5

6. SIMULATION MODEL OF PROPOSED CONVERTER

The Simulink model of proposed converter is shown in Fig. 4. It consists of the windings N1 and N2 are primary and secondary windings of a coupled inductor T1 is similar to the input inductor of the conventional boost converter, and LK1 LK2 are leakage inductors and Lm is magnetizing inductance. And the diodes D1 D2 D3 and capacitor C1 C2 C3 are present. Capacitor C1 and diode D1 receives leakage inductor energy from N1. The secondary winding N2 of coupled inductor T1 is connected with another pair of capacitors C2 and diode D2, which are in series with N1 in order to further enlarge the boost voltage. The rectifier diode D3 connects to its output capacitor C3. The output of the converter is summed with reference voltage and the resulting error is fed to the pi controller. The output of the pi controller is summed with triangle pulse and later it is fed as gating pulse for the mosfet switch. The Powergui block is necessary for simulation of any Simulink model containing SimPowerSystems™.

blocks. It is used to store the equivalent Simulink circuit that represents the state-space equations of the model. Here the powergui used is in continues form. IT also consists of voltage measurement and current measurement block measures the instantaneous voltage and current between two electric nodes. The output provides a Simulink® signal that can be used by other Simulink blocks.

7. RESULTS

The electrical specifications are

$$V_{in} = 15 \text{ V},$$
$$V_o = 200 \text{ V.}$$
 $F_s = 50 \text{ kHz},$
$$RL = 1000\Omega.$$
$$C1 = C2 = 47\mu F, C3 = 220\mu F.$$
$$N = 6,$$

D is derived as 55%

P=0.003

I=0.001

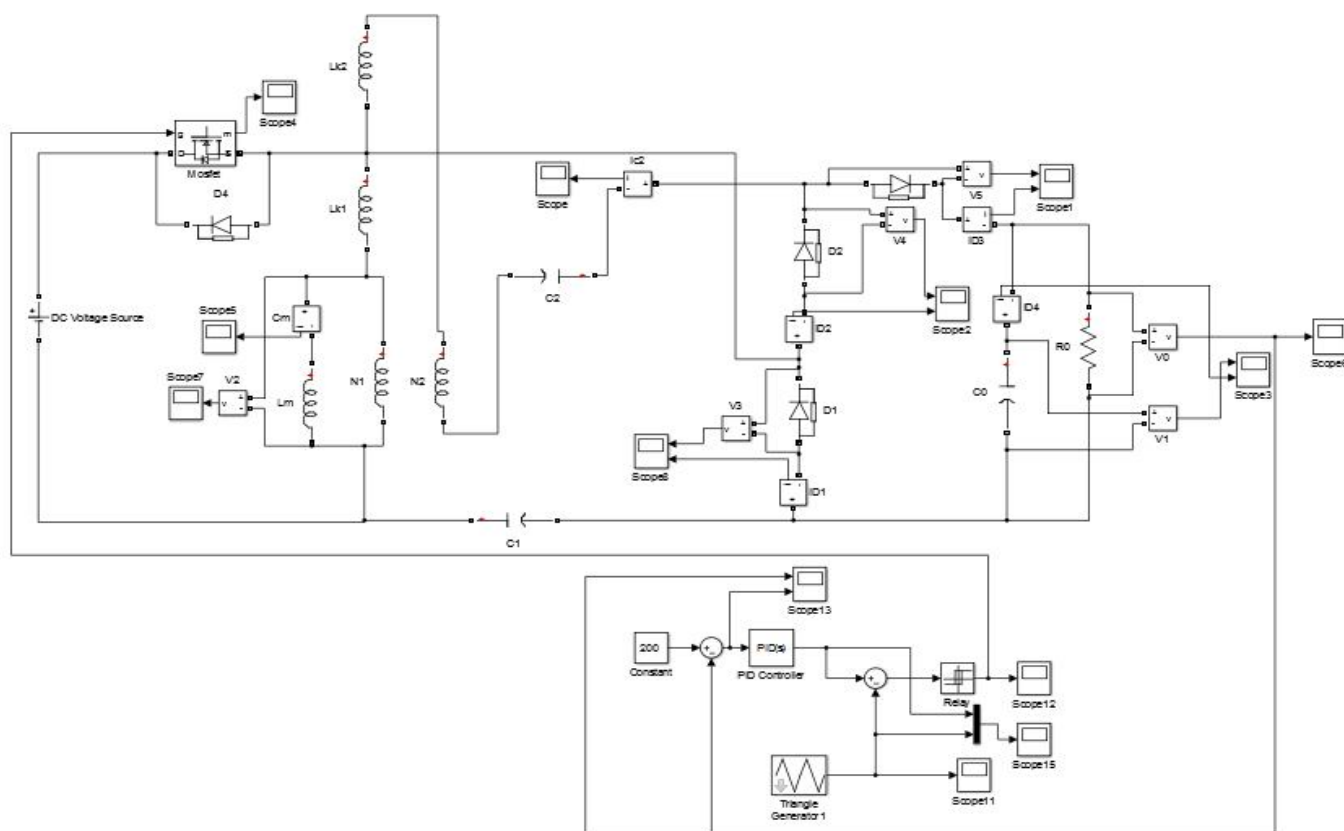


Figure 4 Simulink model of proposed converter

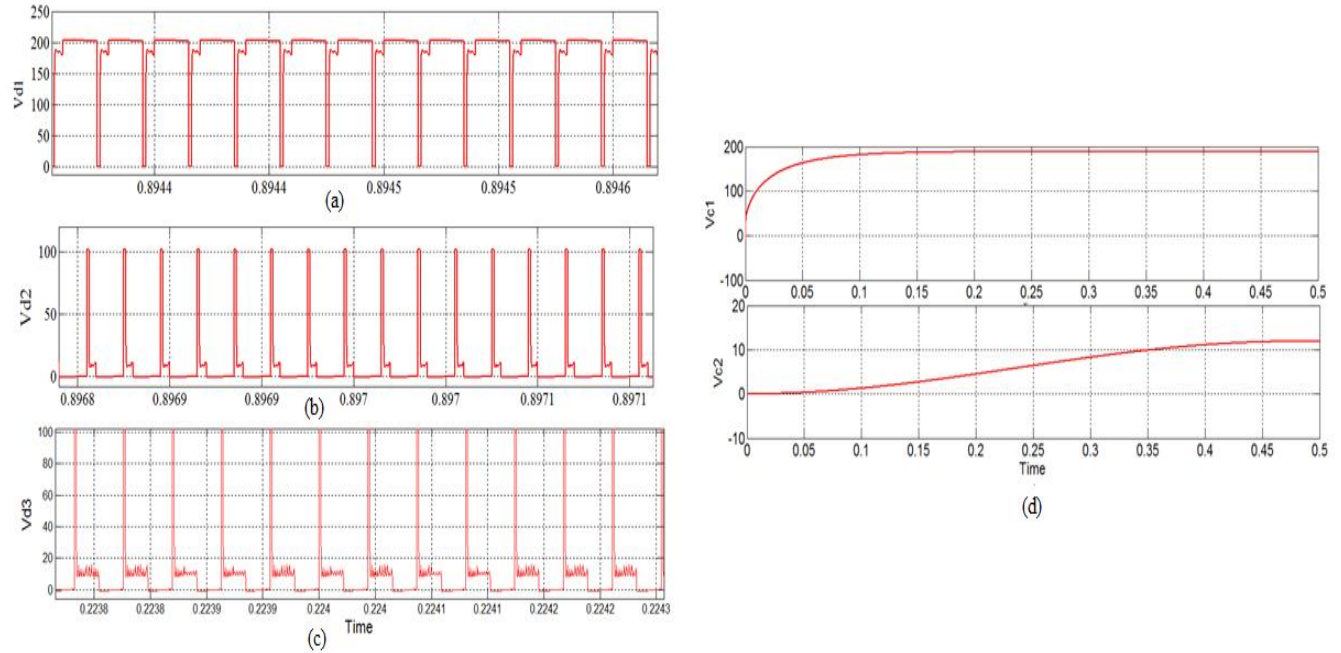


Figure 5 voltage across diode d1, d2, d3, capacitors C1 and C2.

Voltage across diodes ,switches and capacitors are calculated from below equations

$$V_{ds} = V_{D1} = \frac{nV_{in}}{1-D} = 200 \quad (6)$$

$$V_{D2} = V_{D3} = nV_{IN} \frac{D}{1-D} = 100 \quad (7)$$

$$V_{C1} = \frac{nV_{in}}{1-D} = 180V \quad (8)$$

$$V_{C2} = \frac{DV_{in}}{1-D} = 15V \quad (9)$$

The voltage waveforms across the diodes D1, D2 & D3 are shown in Fig.5 From Fig. 5(a), it is observed that voltage across diode D1 is 200 volt Similarly, from Fig.5 (b) it is observed that the voltage across diode D2 is 100 volt and from Fig 5(c) it can observe that voltage across diode D3 is 100 volt. from Fig. 5(d), it is observed that voltage across capacitor C1 is 180 volt similarly; from Fig.5 (d) it is observed that the voltage across capacitor C2 is 15 volt.

The Fig 6 shows output voltage on y axes and time on x axes . In Fig 6 the blue line represents the converter output with pid controller and red line represents without pid controller .From the Fig 6 it is concluded that 15 volt dc input voltage to the converter has been stepped up to 200 volt dc output voltage and it can be observed that rise time (tr) of

the voltage without pid controller is 0.35 and with pid controller it is 0.15.

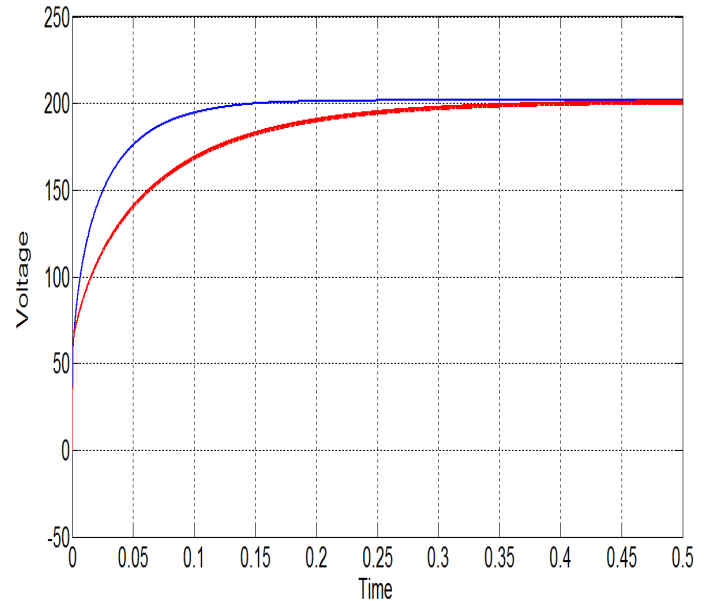


Figure 6 Converter output with and without PID controller

TABLE 1
Converter output comparison

Converter output	Without PID controller	With PID controller
Rise time	0.35	0.15
Steady state error	2v	0.2v

From Table 1, it is evident that the transient and steady state response of the system is improved using PID controller. The voltage gain and efficiency of the converter are calculated by using (6) & (7) respectively.

$$\text{Voltage gain} = \frac{V_{out}}{V_{in}} = \frac{1+n}{1-D} \quad (6)$$

$$\text{Voltage gain} = \frac{V_{out}}{V_{in}} = \frac{1+6}{1-0.5}$$

$$\text{Voltage gain} = 14$$

$$\text{efficiency} = \frac{P_{out}}{P_{in}} = \frac{P_{in} - P_{loss}}{P_{in}} \quad (7)$$

$$\text{efficiency} = \frac{P_{out}}{P_{in}} = \frac{40.5}{41.6} = 97\%$$

Thus it is observed from equation (6) without extreme duty ratios and the numerous turns-ratios of a coupled inductor, this converter achieves a high step-up voltage-conversion ratio; the leakage inductor energy of the coupled inductor is efficiently recycled to the load and they is very low ripple content in the output .

7. CONCLUSION

Since the energy of the coupled inductor's leakage inductor has been recycled, the voltage stress selected across the active switch S1 is constrained, which means low ON-state resistance RDS (ON) can be selected. Thus, improvements to the efficiency of the proposed converter have been achieved. The switching signal action is performed well by the floating switch during system operation; on the other

hand, the residential energy is effectively eliminated during the non operating condition, which improves safety to system technicians. From the converter, the turns ratio $n=6$ and the duty ratio D is 55%; thus, without extreme duty ratios and turns ratios, the proposed converter achieves high step-up voltage gain, of up to 13 times the level of input voltage and also reduction in the rise time and steady state error is achieved due use of PID controller in feedback. The experimental results show the efficiency of the converter is 97 %.

8. REFERENCE

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