Comparison of High Boost Ratio Hybrid Transformer DC-DC Converter with Multistage Converter

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***Abstract*—Energy of Photovoltaic is one of energy resource that potential to be developed in Indonesia. Output power of Photovoltaic is changing according to changes of sunirradiance. Energy sources that produce DC low voltage require a step-up converter to increase the voltage before it is converted into AC voltage.To optimize the system, step-up converters must have a high voltage ratio and high efficiency at all of loading level and wide voltage input range. In this research will be compared betweem multistage converter and high voltage ratio boost converter that utilizes combination of pulsewidth modulation (PWM) operating mode and a resonant mode.This converter only requires one switch, so it's easier in the controlling. This researh results showed with same duty cycle and voltage input, transformer hybrid method can produce power output greater than multistage. The voltage output of hybrid transformer can also achieve steady state faster than using a hybrid converter.So the hybrid converter transformer has the better ability than multistage converter and can be implemented in alternative energy resources that produce a low DC voltage such as photovoltaics.**

Keywords*— *Photovoltaic; high voltage ratio boost converter; multistage converter; hybridtransformer.

I. INTRODUCTION

Photovoltaic is one of the alternative energy resources that can reduce dependence of fossil fuels. Photovoltaic has a high potential to be developed in Indonesia considering the geography is at the equator. Photovoltaic has a low voltage DC output and varies according to changes in sun irradiance. The power generated was also changing. Low DC voltage requires a step-up converter to increase the voltage before it is converted into AC voltage. To optimize the system, the step-up converter should have high voltage ratio in order to can work on a wide voltage input range and has high efficiency at all of load range.

At previous research produced clamp-mode coupled-inductor buck-boost converter [1]. Leakage energy of converter that comes from reprocessed coupled-inductor which leads to reduced losses of the converter. But stress on the diode such as the fly back converter is greater than the DC voltage output. In this converter also has a high ripple currents on the input side.

Multistage Converter is a DC-DC converter modification between conventional boost converter with the use of capacitors switching to obtain a higher voltage output by using a single switch. Multistage Converter has a huge conversion rate while not using the large duty cycle and without a transformer compared conventional boost converters. The level of converter can be changed without changing the main circuit in the boost converter.

In phtovoltaicApplications, the converter should have high voltageratio and high efficiency to the wide rangeof load voltage input. Therefore, proposed high-boost ratio hybrid transformer topology by utilizing the hybrid operation mode [4], [5]. Hybrid operating mode is a combination of pulse width modulation (PWM) and a resonant mode.

With the use of hybrid transformer, the energy transfer through a two-state transformer, that's as a common transformer and as a coupled-inductor, so the magnetic component can be used effectively. The continuous input current cause small current ripple than the topology that uses a coupled-inductor. Conduction losses in the transformer is getting smaller due to the reduced value of the RMS current input that passes through the primary of transformer. The voltage stress on the switch is always on a low voltage level and not affected by changes of the voltage input when the voltage output is maintained. turn-off current on the switch is reduced because of the resonance section. With the reduction of the RMS value of current input and a reduced turn-off current on the switch, then the converter has high efficiency at low load. Capacitor resonance make voltage stress on the diode below the voltage output and is not affected by changes of the voltage input when the voltage output is maintained [3]. With this topology obtained a high voltage ratio can work on a wide input voltage range and has high efficiency at all levels of loading.

II. RESEACH METHODOLOGY

A. *Multistage Converter Topology*

Multistage Converter is a DC-DC converter modification between conventional boost converter with the use of switching capacitors to obtain a higher voltage output by using single switching. Multistage Converter component consists of one inductor (L), 1 switch (S), 2N-1 diode (D) and 2N-1 capacitors (C). N is the number of levels used in multilevel boost converters.

Lowerest circuit of Multistage Converter is a conventional boost converter circuit, with C1 voltage is the voltage of the conventional boost converter. So the voltage output ofmultistage converter is Vc1xN. N is the number of converter levels.

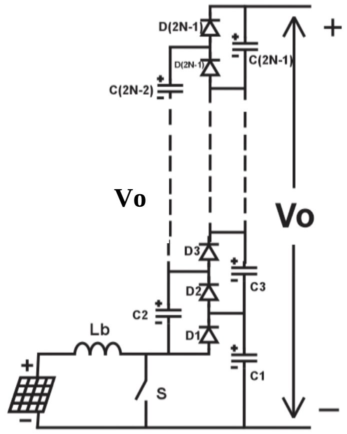


Figure 1. Multistage ConverterTopology

If the switch is on, the voltage of the inductor (Lb) equal to the voltage input (Vi), If the voltage on the capacitor C1 is greater than C2 voltage, then C2 capacitorvoltage will increase because the capacitor C2 charged by the voltage across the capacitor C1 through D2 and S. If the voltage C2 + C4 lower than the voltage of C1 + C5, the voltage across the capacitor C2 + C4 will increase as charged by the voltage across the capacitor C1 + C3 through D4 and S. in the same way, the C, C3 and C5 capacitorscharge the voltage to the capacitor C2, C4 and C6.

If the switch is off, the inductor current turn on D1 and cause voltage capacitor C1 charged. In the same condition, the capacitor C1 + C3 will be charged by the voltage of the capacitor C2 + Vi + VLB through D3. In the same way, Vi + VLB + Vc2 + Vc4 will charge the voltage on the capacitor C1, C3 and C5 until the most level voltage charge.voltage output level is also affected by the duty cycle (D). Duty cycle is the ratio between the time at on (t_on) and switching period (T).

$$D = \frac{t_{on}}{T} \tag{1}$$

$$T = t_{on} + t_{off} \tag{2}$$

Maka didapat :

$$t_{on} = D.T \tag{3}$$

$$t_{off} = (1\text{-}D).T \tag{4}$$

With the assumption that current through inductor is constant, then obtained equation at time at on condition (t_{on}) following:

$$\Delta i(t_{on}) = \frac{Vi.(D.T)}{Lb} \tag{5}$$

$$L = \frac{Vi.(D.T)}{\Delta i(t_{on})} = \frac{Vi.(D)}{\Delta i(t_{on}).f} \tag{6}$$

Sedangkan pada saat keadaan t_{off}:

$$\Delta i(t_{off}) = \frac{(V_{c1} - Vi).(1-D).T}{Lb} \tag{7}$$

$$\Delta i(t_{on}) = \Delta i(t_{off})$$

$$\frac{Vi.(D.T)}{Lb} = \frac{(V_{c1} - Vi).(1-D).T}{Lb}$$

$$V_{c1} = \frac{Vi}{(1-D)} \tag{8}$$

The equation of voltage output is following:

$$Vo = V_{c1} + V_{c3} + V_{c5} + V_{c7} \tag{9}$$

$$Vo = N.V_{c1} \tag{10}$$

$$Vo = \frac{N.Vi}{(1-D)} \tag{11}$$

So, Gain obtained:

$$G = \frac{Vo}{Vi} = \frac{N}{(1-D)} \tag{12}$$

To get the capacitance value of each capacitor is:

$$C = \frac{Vo.D.N}{R.(\Delta Vo).f} \tag{13}$$

B. *Boost Converter with Hybrid Transformator Topology*

Boost converter with a hybrid transformer is circuit circuit to increase voltage with the ratio of input and output voltage is high enough. This converter uses a hybrid transformer, inductor resonance and three diodes as clamping diode, diode resonance and output diode,a switch, four capacitors as capacitor input, clamping capacitors, resonance capacitor and capacitors output[1]. This converter circuit topology as shown in Figure 1.

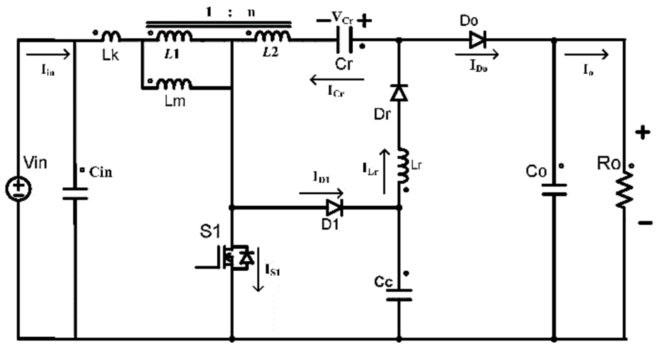


Figure 2. Boost Converter with Hybrid Transformer Topology

Capacitorinput (C_{in}) is used to reduce ripple of the voltageinput. Hybrid transformer (HT) modeled using the ideal transformer with magnetizing inductance include (L_m) and leak inductance (Lk) on the primary of the transformer. Hybrid transformer turns ratio is 1: n. Switch (S1) is a metal oxide semiconductor field effect transistor (MOSFET). Clamping diode (D1) is a clamping diode that serves as the trajectory of energy from leaking inductance originating from hybrid transformer when the switch is off. Resonancediodes (Dr) used in order to the current flow is in one direction when the circuit is in resonance mode, when the charging process energy at resonance capacitor (Cr). D_o is diode outputthat on track to transfer energy to the output side. The capacitor output(C_o) as a filter to reduce ripple voltage on the output side. R_o is the resistance outputrepresents a resistive load.

In one switching period, this converter has five modes of operation [3]. This operation mode describes the working principle of converter topologies. In a simplification to facilitate understanding, it is assumed that the DC voltageinput on the topology of a DC source which is fixed.The loads are resistors and all of diodes and the switches are in an ideal condition.

At t_0-t_1, switch $S_1$is on,magnetizing inductance (L_m) charged by the voltage input (V_{in}). Magnetization current gradually rise linearly. In this mode, resonant circuit is work. Resonant circuit formed by the secondary of the hybrid transformer, C_c, L_r, D_r dan C_r. In this mode, the clamping capacitor (C_c) assumed in fully charged condition. secondary side Voltage of the transformer is$nxVLm$. Resonant capacitor (Cr) charged by the secondaryof transformer and clamping voltage on the capacitor (Cc) by the switch, diode resonance and inductor resonance.

At t_1-t_2, swith $S_1$is off. Current on the primary side and secondary side of the transformer began to charge the parasitic capacitor located on the switch. When the voltage on the switch is higher than the voltage on clamping capacitor (C_c) then clamping diode (D_1) is on. Energy from leakage inductance (Lk) is transmitted to the clamping capacitor (C_c) through the clamping diode (D_1).

At t_2-t_3, in this period diode output(D_o)is on. At this time a series circuit formed between V_{in}, V_{lk}, V_{Lm}, V_{L2}, V_{cr} dan V_{co}. The stored energy in the magnetizing inductance (L_m) and a resonance capacitor (C_r) forwarded to the load. Clamping diode (D1) stay active for clamping capacitor (C_c)is charging.

At t_3-t_4, $D_1$is off.The current flow to the output side during this period, but the magnitude is reduced gradually. The stored energy in the magnetizing inductance and resonance capacitor (C_r) be forwarded simultaneously to the load.

At t_4-t_0, switch $S_1$is on. Because of the effects of leakage of hybrid transformer, output current (I_o)keep flow for a short time, then a diode output is off at t_0 and the next switching period begins again.

The value of conversion ratio determined by this following equation (14).

$$M = \frac{Vo}{Vin} = \frac{(2+n)}{(1-D)} \quad (14)$$

Voltage stresson switching and *clamping*diode (D_1) happened on operation mode 1 (t_0-t_1) and operation mode 2 (t_1-t_2).Whereas, the value of voltage stresson diode output (D_o) dan resonance diode (D_r) can be seen at operation mode 1 (t_0-t_1) dan operation mode 3 (t_2-t_3).

$$V_{DS} = V_{D1} = V_{Cc} = \frac{V_{out}}{(n+2)} \quad (15)$$

$$V_{Do} = V_{dr} = V_o - V_{Cc} = \frac{(n+1)V_o}{(n+2)} \quad (16)$$

Resonant periodand resonant frequency of converter determined by (17) and (18) equation.

$$T_r = 2\pi\sqrt{L_{r\_tot}C_r} \quad (17)$$

$$f_r = \frac{1}{T_r} \quad (18)$$

In implementation, leakage inductor value (Lk) of transformer should be calculated. L_{kp} is leakage inductanceof primary side and $L_{ks}$is leakage inductace of secondary side.

$$L_{r\_tot} = L_r + (L_{ks} + n^2L_{kp}) \quad (19)$$

$$\Delta v_{Cr} = \frac{I_{Lm\_sec}T_{off}}{2C_r} \quad (20)$$

$$I_{lm\_sec} = \frac{I_o}{1-D} = \frac{P_o}{V_o}\frac{1}{1-D} \quad (21)$$

Δv_{Cr} shows the value of voltage ripple on resonance capacitor.$I_{lm_sec}$is the magnetization current average referenced from the secondary side of the transformer.

$$\Delta i_{Lr} = \pi . f_r . T_s . I_o \quad (22)$$

Δi_{Lr}shows the value of current on resonance inductor.

III. Analysis of Design Configuration

A. Design ofMultistage Converter

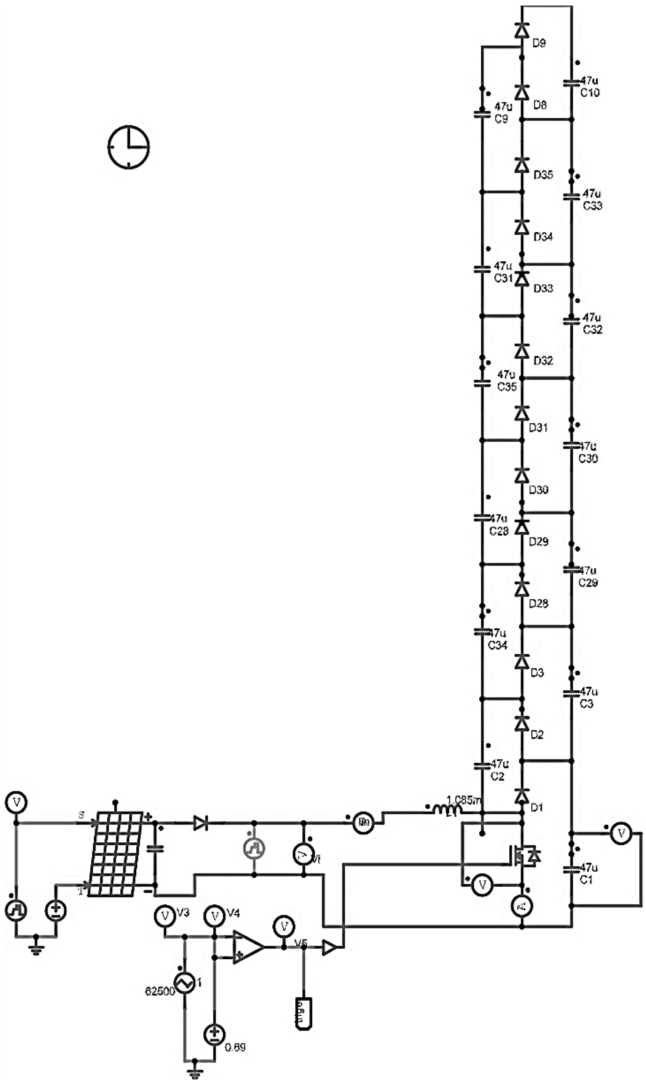


Figure 3. Simulation of Multistage Converter

To calculate the parameters that have not determine can using (8) equation:

$V_{c1} = \frac{Vb}{Nb} = \frac{400}{7} = 57{,}14285$ volt

$D_1 = 1 – (\frac{Vi}{V_{c1}}) = 1 – (\frac{14}{57{,}143}) = 0{,}755 = 75{,}5\%$

$D_2 = 1 – (\frac{Vi}{V_{c1}}) = 1 – (\frac{17{,}24}{57{,}143}) = 0{,}6983 = 69{,}83\%$

the inductance value of L_1 inductor is determined by the greatest value from the multistage converter calculation at maximum input of power of photovoltaic (50 W), From(6)equation we will get:

$I_i = \frac{P}{Vi} = \frac{50}{17{,}24} = 2{,}9$ A

ΔI_i = Ii.20% = (2,9).(6,64%) = 0,192 A

$L_{L1} = \frac{(\mathrm{Vi}_{\min}).D_1}{\mathrm{f}.\Delta \mathrm{Ii}} = \frac{(14).(0{,}755)}{62500.(0{,}192)} = 0{,}88$ mH

$L_{L2} = \frac{(\mathrm{Vi}_{\max}).D_2}{\mathrm{f}.\Delta \mathrm{Ii}} = \frac{(17{,}24).(0{,}6983)}{62500.(0{,}192)} = 1$ mH

So, The minimum value of $L_L$inductor used is 1 mH.

$R_c = \frac{Vc^2}{P} = \frac{96^2}{5} = 184{,}32\ \Omega$

$L_{c21} = \frac{(1-D_1).R}{2.f} = \frac{(1-(0{,}6983)).(184{,}32)}{2.(62500)} = 0.448$ mH

$L_{c22} = \frac{(1-D_2).R}{2.f} = \frac{(1-(0{,}755)).(184{,}32)}{2.(62500)} = 0{,}361$ mH

$R = \frac{Vo^2}{P} = \frac{400^2}{50} = 3200\ \Omega$

$C_1 = \frac{(D_1.V.N)}{R.\Delta Vb.f} = \frac{(0{,}6983).(57{,}143).(7)}{(3200).(0{,}04).(62500)} = 34{,}9\ \mu$F

$C_2 = \frac{(D_2.V.N)}{R.\Delta Vb.f} = \frac{(0{,}755).(57{,}143).(7)}{(3200).(0{,}04).(62500)} = 37{,}75\ \mu$F

The capacitor value is taken from the largest value of the capacitor that is 37.75 μF. Cùk multilevel converter using sum of stage for the operation in order to the voltage output is 96 V. It can be determined from the follow equation:

$N_c = ((\frac{Vo}{Vi}).(1-D)) + (1-D)$

$N_c = ((\frac{96}{17.24}).(1-0{,}6983)) + (1-0{,}6983)$

$N_c = (1{,}68) + (0{,}3017) = 1{,}9817 \approx 2$

B. Design of High Boost Ratio Hybrid Transformer DC-DC

The design of the converter circuit is intended to adjust circuit parameters with the laboratory's equipment. Based on ration conversion equation [14] with the voltage input interval from 20 V up to 30 V, so the duty cycle is 0.4 up to 0.6. If the design of output power is 40 W, the output current(I_o) should be 0,2667 A and the output resistance (R_o) is 562,5 Ω. The input current is affected by load changing and voltage input. In designing, the efficiency of the converter is 100 %, the current input interval from 1,34 A up to 2A. The magnetization current average in secondary side can determine by follow equation (2.20):

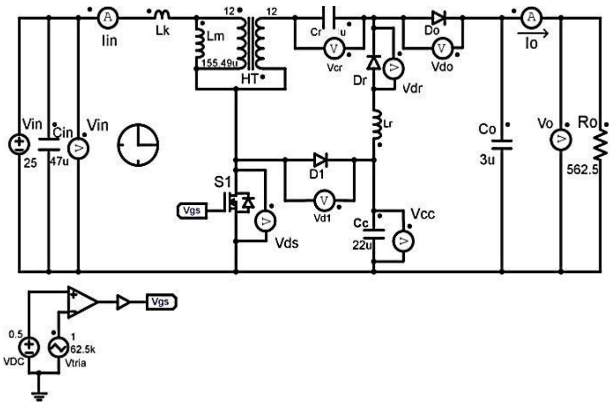


Figure 4. Simulation of High Boost Ratio Hybrid Transformer DC-DC Converter

Δv_{Cr}= 1,422 % . 150V = 2,133 V

From (7) equation, the value of $C_r$is

$C_r = \frac{I_{Lm_sec}T_{off}}{2\Delta v_{Cr}} = \frac{0{,}5334\ .\ 8\ 10^{-6}}{2\ .\ 2{,}133} = 1\ \mu$F

In order to the voltage stress on the switch can be equal or the voltage clamping capacitor (C_c), then the value of the resonant capacitor (Cr) should be smaller than the value clamping capacitor(C_c). With this assumption, the value clamping capacitor (C_c) determined by 22 μF. The period of resonant can be determined by the (17)equation andL_{r_tot}can be determined by the (17)equation.

$T_r = \frac{1}{f_r} = \frac{1}{62500} = 16\ \mu$s

$L_{r_tot} = \frac{\left(\frac{T_r}{2.\pi}\right)^2}{C_r} = \frac{\left(\frac{16\ 10^{-6}}{2.\pi}\right)^2}{1.10^{-6}} = 6{,}4846\ \mu$H

In design of transformer the value of leakage inductance (L_k) assumed 1,7 μH, So the value of inductor resonant can be determined by (22) equation:

L_r= 6,4846 – (1,7) = 4,7846 μH

The value of $\Delta i_{Lr}$is

$\Delta i_{Lr} = \pi\ .\ 62500\ .\ 16\ 10^{-6}\ .\ 0{,}2667 = 0{,}84$ A

Voltage stress on switch and clamping diode (D_1) calculated by (15) equation:

$V_{DS} = V_{D1} = \frac{150}{(1+2)} = 50$ V

IV. Simulation Of System

The easy way to designing the converter circuit, the circuit parameters adjusted to the equipment in the laboratory and components in the market. The design is done by determine multiple variables as shown in Table 1.

Tabel 1.Specification ofHigh Boost Ratio Hybrid Transformer DC-DC Converter with Multistage Converter

No	Parameters	Value
1	Switching Frequency	62,5 *kHz*
2	Power Output(P_o)	50 *W*
3	Voltage*output*	400*V*
4	Voltage*input* (MIN)	20 V

5	Voltage*input* (MAX)	30 V

To produce output voltage of 400 volts, it is necessary to adjust the duty cycle. The duty cycle is influenced by the size comparison of the input voltage and the output voltage at a ratio converter. In the converter hybrid transformers, to get the output voltage of 400 volts, the parameters are changed only duty cycle and input voltage. While the value of L and C others remain. In multistage converter, to get the output voltage of 400 V, the parameters modified are duty cycle, input voltage, and inductance values.

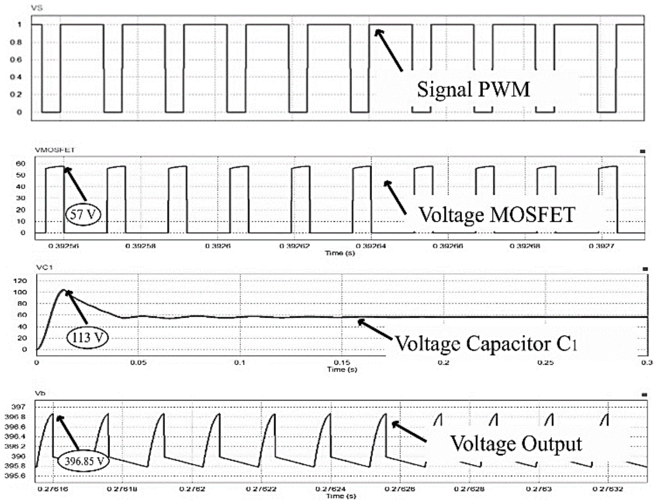


Figure 5.The voltage wave form of Multistage Converter Simulation

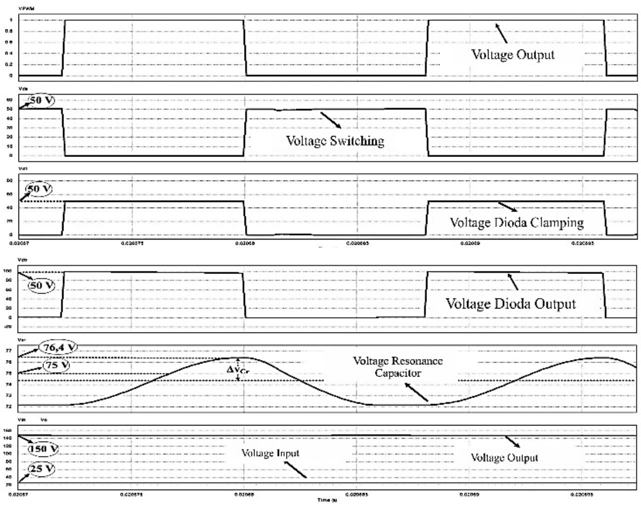


Figure 6.The Voltage wave form of High Boost Ratio Hybrid Transformer DC-DC simulation

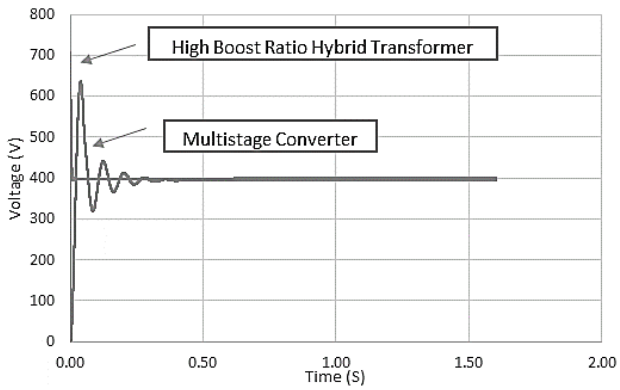
Table 1, Table 2, and Figure 7 show that the converter transformers hybrid capable of producing a minimum efficiency of 88% when given input voltage 21 volts. However, the resulting maximum efficiency of 101.7% when given an input voltage of 30 V. The converter multistage can produce a minimum efficiency of 97.84% at an input voltage of 22 V and 23 V. The resulting maximum efficiency of 98.07% with an input voltage of 25 V.

Table 2.*Comparison between the input voltage and Duty Cycle*

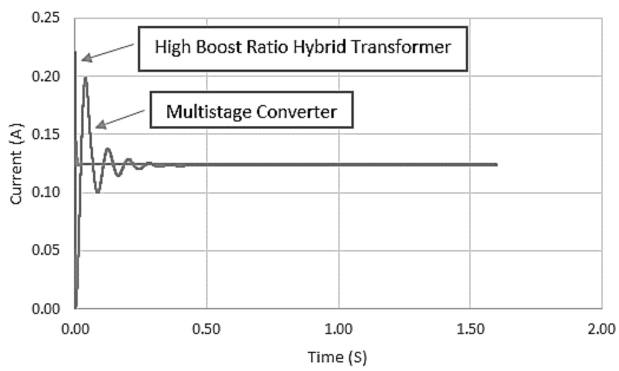
Vin (V)	Vout (V)	Pout (Watt)	Ro (Ω)	D
20	400	50	3200	0.60
21	400	50	3200	0.58
22	400	50	3200	0.56
23	400	50	3200	0.54
24	400	50	3200	0.52
25	400	50	3200	0.50
26	400	50	3200	0.48
27	400	50	3200	0.46
28	400	50	3200	0.44
29	400	50	3200	0.42
30	400	50	3200	0.40

Table 3.Comparison between the input voltage and efficiency

Vin (V)	Hybrid Transformer			Multistage Converter		
	Vout (V)	Iout (A)	Efficiency (%)	Vout (V)	Iout (A)	Efficieny (%)
20	398	0.124	99.2	396	0.123	98%
21	375	0.117	88	395	0.123	97.96
22	389	0.121	94	395	0.123	97.84
23	398	0.124	99.18	395	0.123	97.84
24	398	0.124	99.14	395	0.123	97.88
25	398	0.124	99.23	396	0.123	98.07
26	397	0.124	98.94	396	0.123	98
27	397	0.124	98.76	395	0.123	97.98
28	397	0.124	98.76	396	0.123	98.06
29	397	0.124	98.62	395	0.123	98
30	403	0.126	101.7	396	0.123	98.06



(a)



(b)

Figure 7.Comparison of Voltage wave form (a) and Current wave form (b) between Simulation of High Boost Ratio Hybrid Transformer DC-DC and Multistage Converter

V. CONCLUSION

1. The output voltage *High Boost Ratio Hybrid Transformer DC-DC Converter* can attain steady state more rapidly than multistage converter.
2. The same Duty cycle and voltage input, *High Boost Ratio Hybrid Transformer DC-DC Converter* method can produce output power greater than multistage converter.
3. The boost converter circuit with *High Boost Ratio Hybrid Transformer DC-DC Converter* had a high conversion ratio in this research. Therate conversion can be increased easily by raising the value of transformer winding ratio (n).
4. *High Boost Ratio Hybrid Transformer DC-DC Converter* can operate on a wide range of input voltage.

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