A 97.0% Maximum Efficiency, Fast Response, Low Voltage Ripple KY Boost Converter for Photovoltaic Application

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***Abstract*— This project designed and implemented a high-performance DC-DC KY boost converter for photovoltaic application. Targeting at the growing solar energy market, the proposed PV generation system is used to directly transfer the power from PV panel to AC power grid. The system adopted a topology of DC-DC converter called KY converter to step up DC voltage to a suitable level. Its characteristics include high efficiency, fast transient response, and small output voltage ripple, in comparison with the traditional DC-DC boost topologies. With feedback control circuits with digital signal processor (DSP), system can adjust the output level immediately. After the correctness of the system, the design was verified by simulation for both continuous conduction mode (CCM) and discontinuous conduction mode (DCM) of KY boost converter; experiments for CCM was conducted, which showed a peak efficiency of 97.0% in 1.2kW load condition, with 0.5% low voltage ripple and transient response time within 25ms.**

***Keywords*— KY converter, DC-DC boost converter, efficiency, pulse-width-modulation (PWM) control.**

I. Introduction

This project targets on solar energy since related applications have become increasingly important. In practice, a DC-DC boost converter is usually connected with photovoltaic (PV) panel output, and it is possible to transfer the power directly to AC power grid through its connection to a DC/AC inverter as shown in Fig. 1. With few components, such a PV generation system allows the absorbed energy to be used by countless appliances which are connected with the power grid.

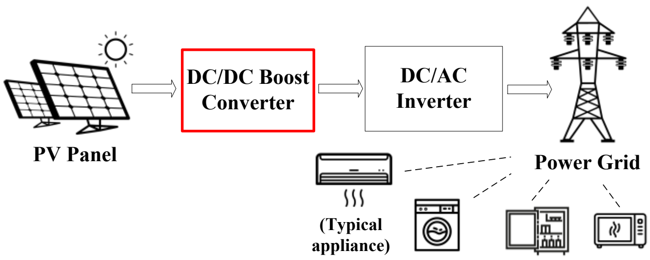


Fig. 1. Typical PV generation system with DC-DC boost converter

Recent research of the project is focused on designing a DC-DC boost converter with low output voltage ripple, fast transient response, and high-power efficiency by adopting a new topology called KY boost converter [1]. Traditional inductor based boost converter generates pulsating current in output, which causes high voltage ripple. In consequence, large power loss will also have appeared. KY converter generates continuous output current, which makes it superior than traditional topology in terms of voltage ripple level and power efficiency. Moreover, when converter is working in CCM, KY converter shows better system stability and faster transient response as shown in Fig. 2.

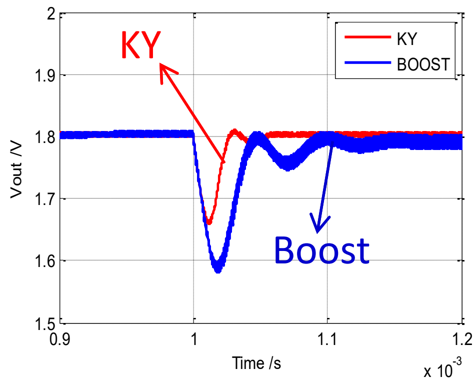
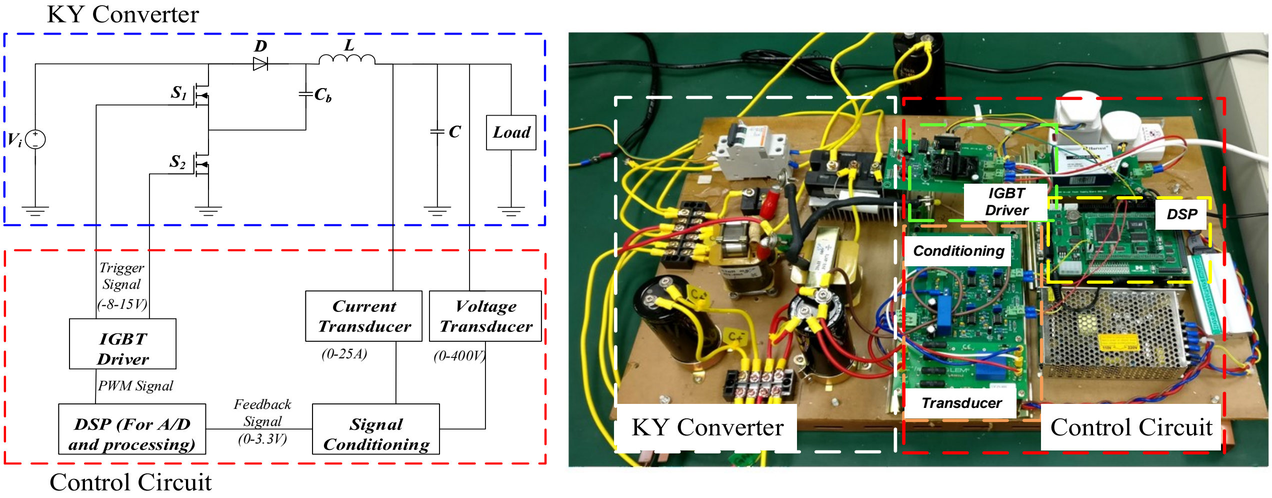


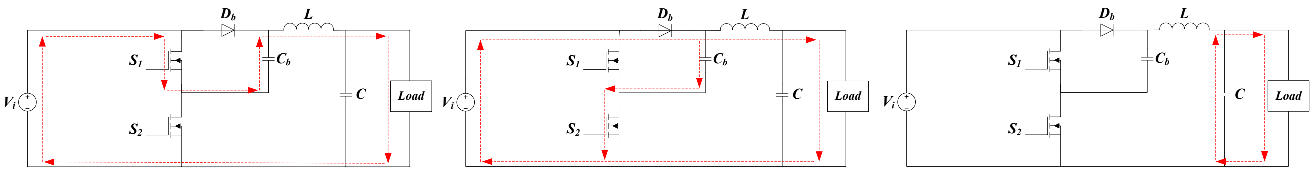
Fig. 2. Output voltage transient waveform of KY and transitional boost converters

In order to keep the system running properly under different situations, close-loop control circuit is designed with controller in proportional–integral–derivative (PID). According to the transfer functions of converter power stage and desired phase margin being reached on the overall system, controller is designed, and corresponding parameters are calculated by a DSP. After theoretical analysis is verified by simulation, an experimental prototype is built up as shown in Fig. 3 along with a simplified schematic. From current experimental results in CCM, system shows its characteristics of fast transient response, low voltage ripple and high-power efficiency.



(a) (b)

Fig. 3. (a) Schematic and (b) hardware photos of KY boost converter experimental prototype with closed-loop control



(a) (b) (c)

Fig. 4. Energy flow of KY boost converter: (a) charging period, (b) discharging period and (c) discontinuous period in DCM operation

II. Operation Principle of KY Converter

This section describes the working principle of KY converter, which boosts up the input voltage from PV panel to suitable level to fit the power grid. In general, the converter is controlled by pulse-width-modulation (PWM) technique. By variating the duty ratio of two power switches S_1 and S_2, output voltage level can be controlled. An important consideration of the performance of KY boost converter is the inductor current during a single switching period: (a) if the inductor current remains above zero for the full duration of switching period, the converter is working in CCM. On the other hand; (b) if it falls to zero and remains still for a portion of each period, the operation is known as DCM. Within one switching period, three circuit operations are possibly occur as shown in Fig. 4, which will be discussed in the following parts.

A. Continuous Conduction Mode (CCM)

Converter will operate as (a) and (b) in Fig. 4 during CCM. In (a), S_1 will open and S_2 will maintain off. Flying capacitor C_b will be charged to input level within a short period. Inductor will absorb energy and inductor current will increase. In (b), S_1 will switch off S_2 and will be on. Inductor will release its energy to output capacitor, and inductor current will decrease. After the analysis of both large and small signal model, transfer function in CCM can be represented as (1), which neglects the ac part since it has limited effect on system characteristic. D represents the duty ratio of S_1 in each switching cycle. On the contrary, S_2 will be turned on for (*1-D*) in every cycle.

B. Discontinuous Conduction Mode (DCM)

KY converter will be possibly dropped into DCM in light load situation. In discharge period, inductor current will drop to zero before the duration reaches (1-D). Hence, extra switching logic is needed for S_2 to be switched off when inductor current touches the zero edge. Otherwise, if the inductor current flows in reverse direction, it will cause large power loss. Furthermore, an extra conduction period exists in DCM as shown in Fig. 4(c). Its duration varies from inductance L and switching frequency f of converter, and load resistance R. Correspondingly, transfer function in DCM becomes (2). Based on (1), (2), the KY boost converter's transfer function characteristic can be plotted as Fig. 5.

C. PID Controller

In feedback circuit, after the error signal $e(t)$ is generated by comparison between actual and reference output, it will pass through a PID controller for performance improvement. Based on (1) and (2), useful parameters can be retrieved for designing a type III compensator to improve the phase margin of overall system. PID gain of controller can be obtained from compensator's transfer function as represented in (3), and be applied into simulation and experiment.

For a digital processor, it need to be transformed into discrete time domain to perform integration and differentiation by numerical calculation. In (4), T represents the sampling period. $u[k]$ in (5) represents the kth error calculation result. In practical, number for this iteration k is decided by digital signal processor (DSP) overall calculation capability. It will be chosen as big as possible to realize better accuracy for these mathematical computations.

$$T_{CCM} = \frac{V_o}{V_i} = 1 + D \quad (1)$$

$$T_{DCM} = \frac{V_o}{V_i} = \frac{\left(1 - \frac{D^2}{k}\right) + \sqrt{1 + \frac{D^4}{k} + \frac{6D^2}{k}}}{2}, \quad (2)$$

$$k = \frac{2fL}{R}$$

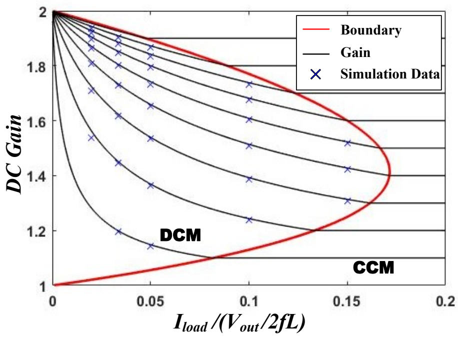


Fig. 5. DC voltage gain of KY boost converter versus normalized load current

$$G_c(t) = K_p \cdot e(t) + K_i \cdot e(t)dt + \frac{K_d \cdot de(t)}{dt} \quad (3)$$

$$\begin{cases} t \approx mT, m = 0,1,2,... \\ \int_0^t e(t)dt \approx \sum_{j=0}^{k} e(jT) = T\sum_{j=0}^{k} e(j) \\ \frac{de(t)}{dt} \approx \frac{e(kT) - e[(k-1)T]}{T} = \frac{e[k] - e[k-1]}{T} \end{cases} \quad (4)$$

$$u[k] = K_p \cdot e[k] + K_i \cdot \sum_{j=0}^{k} e(j) + K_d \cdot (e[k] - e[k-1]) \quad (5)$$

III. Simulation Result

Based on theoretical analysis, system's parameters are shown in Table I. The simulation results performed in PSCAD EMTDC, as shown in Fig. 6, indicates that the system is capable of maintaining the output in setting reference after load condition sudden changes in both CCM and DCM. After the controller is applied, the system performance of the KY boost converter can be improved in terms of transient response time, undershoot level and steady-state error. As the simulation results verify the idea, the same system parameters will be adopted in the experimental circuit design.

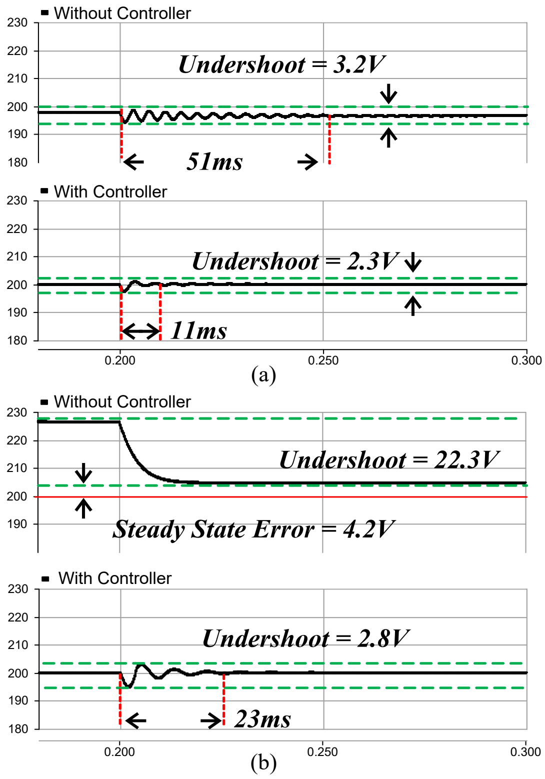


Fig. 6. Simulation validation for load transient from 2A to 6A, 130V input and 200V output in (a) CCM and (b) DCM for KY boost converter

IV. Experimental Result

Experiments are conducted by using a DC power supply and variable loads as shown in Fig. 7, to emulate the operating environment of PV generation system. The control circuit shown in Fig. 3(b) consists of IGBT driver, DSP and a signal conditioning circuit

DSP-TMS320F2812 is adapted here to control the overall hardware platform. Fig. 8 shows a simplified program flow. Two timers in DSP are used for PWM signal generation and A/D signal acquisition. After the error signal is processed by PID algorithm, a value for relative compare logics will be assigned to generate two PWM signal for switches.

TABLE I. SIMULATION AND EXPERIMENT'S CONVERTER PARAMETER

System Parameters	Physical Values	
Input Voltage (V)	120 – 150	
Output Voltage (V)	180 – 200	
Inductor (mH)	***Small Load Transient***	***Large Load Transient***
	0.22	0.5
Output Capacitor (mF)	1	
Flying Capacitor (mF)	1	
Switching Frequency (kHz)	15	
Load Resistance (Ω)	25 - 100	

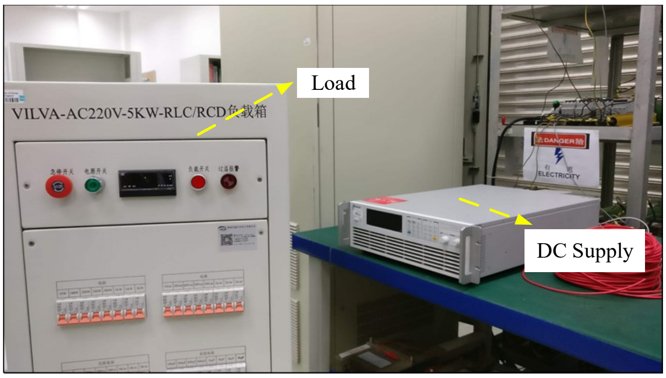


Fig. 7. DC power supply and variable load

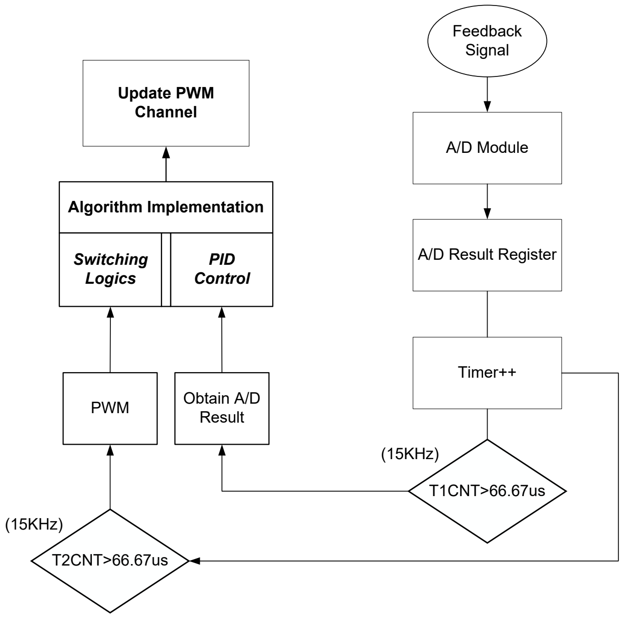


Fig. 8. Program flow in DSP for KY boost converter

Experimental result of the KY boost converter operating in CCM is presented. Load regulation for various input and output level is shown in Fig. 9, which shows the system is capable of maintaining the setting reference voltage level under different input/output conditions. The system efficiency under different load conditions are given in Fig. 10.

In Fig. 11(a), the load transient response waveform is captured from the loading current change from 4A to 5A. In order to obtain a larger CCM operation region, a larger inductance with L=0.5mH is used to test the load transient response waveform with a wider range of 2A to 6A, of which Fig. 11(b) shows the corresponding experimental results.

Table II shows the KY boost converter performance comparison with the other boost converter that works for PV generation system, which shows its high power conversion efficiency, low output voltage ripple, fast load transient response time characteristics. It can be effectively applied for the PV generation system.

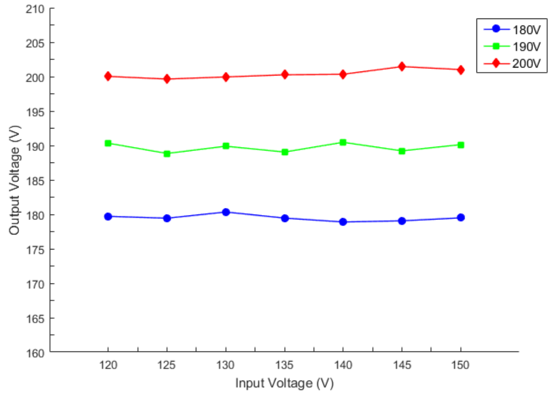


Fig. 9. Load regulation with 120-150V input, setting output as 180-200V

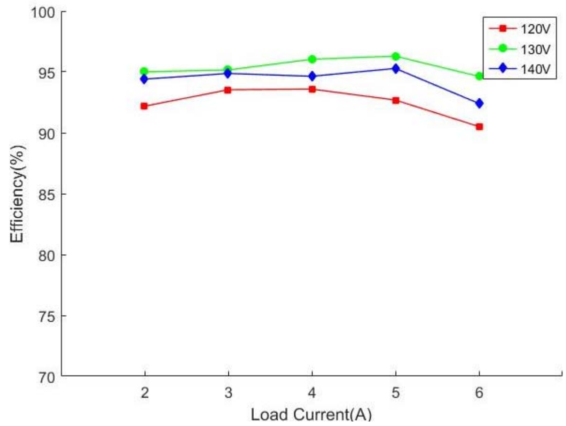


Fig. 10. System efficiency versus load current

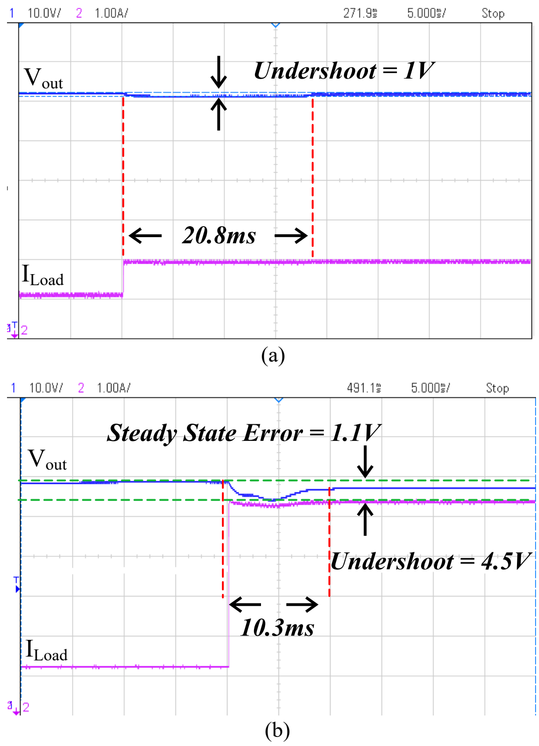


Fig. 11. Load transient response when load changes from (a) 4A to 5A and (b) 2A to 6A

TABLE II. PERFORMANCE COMPARISON

	[2]	[3]	[4]	[5]	This work
Input voltage (V)	303.5 – 378.8	200	48	48	130
Output voltage(V)	600	400	380	380	200
Freq. (kHz)	100	20	50	50	15
L (mH)	0.56	0.1875	0.11	0.052	0.5
C (mF)	470	0.16	0.12	0.47	1
Load transient step (A)	0-3	10-20*	-	2-3*	2-6
Vo undershoot / overshoot (V)	6	10*	-	10*	4.5
Settling time (ms)	75*	<5*	-	100*	**<25**
Voltage ripple (%) (max)	1	5*	-	5*	**0.5**
Maximum Output Power (W)	2,500	19,000	3,500	200	1,200
Peak efficiency (%)	92.5	97.25	94.65	90.1	**97.0**

*: Estimated from figure

V. Conclusion

The simulation and hardware design of a DC-DC KY boost converter for PV generation system is presented in this paper. The experimental results show that the system provides high power efficiency up to 97.0% in 1.2kW, output voltage ripple of 0.5% and load transient response time under 25ms, which are comparable with the other works in PV generation system.

ACKNOWLEDGMENT

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