Power Conditioning Inverter Controlled by Sinewave Tracking Boost Chopper without DC Smoothing Capacitor Stage

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Abstract- This paper presents a novel circuit topology of a high efficiency single-phase power conditioner. This power conditioner is composed of time-sharing sinewave absolute pulse width modulated boost chopper with a bypass diode in the first power processing stage and time-sharing sinewave pulse width modulated full-bridge inverter in the second power processing stage operated by time-sharing dual mode pulse pattern control scheme. The unique operating principle of the two power processing stage with time-sharing dual mode sinewave modulation scheme is described with a design example. This paper proposes also a sinewave tracking voltage controlled soft switching PWM boost chopper with a passive auxiliary edge-resonant snubber. The new conceptual operating principle of this novel power conditioner related to new energy utilization system is presented and discussed through the experimental results.

Keywords: Time-sharing sinewave modulation, dual mode control, boost chopper with bypass diode, full-bridge inverter, PWM, soft switching, high efficiency power conversion, new energy utilization system

1. Introduction

The small scale distributed solar photovoltaic (PV) and fuel cell (FC) power generation conditioning system for residential power applications has been become more and more popular from the earth environmental point of view.

In recent years, for the further practical and cost effective requirements as much higher efficiency, smaller on physical size and lighter weight for small scale stand-alone or utility interactive sinewave power conditioner, some new conceptual power conditioners based on power electronic circuit controller is developed[1]~[4]. In general, the non-isolated single-phase sinewave inverter topologies have practical advantages such as lower cost, smaller size, higher power density and higher efficiency power generation systems. Of these, non-isolated sinewave inverter used for new energy generation systems composed of two cascaded power processing stages; a high frequency PWM boost chopper required for boosting a low DC voltage from PV modules or FC stacks in addition to sinewave modulated inverter connected to commercial utility AC power grid or stand-alone power utilizations. However, the conventional power conditioner has some disadvantages as poor power conversion efficiency especially in the low output power setting ranges due to switching and conduction losses in boost chopper type DC-DC converter cascaded sinewave full-bridge (FB) inverter topology. Furthermore, the bulky and temperature dependent unreliable electrolytic DC smoothing capacitor bank, which includes a little short life time, impossible recycle easiness is actually required for constant voltage regulation based on the PWM controlled boost chopper. Moreover, this electrolytic capacitor bank in DC link have sufficiently high capacitance, relatively large volumetric size, heavy weight and high frequency ripple current related power loss due to its equivalent series resistance. Therefore, it is more difficult to implement the cost-effective, compact solar PV or FC power generation system acceptable for miniaturization in size and light in weight.

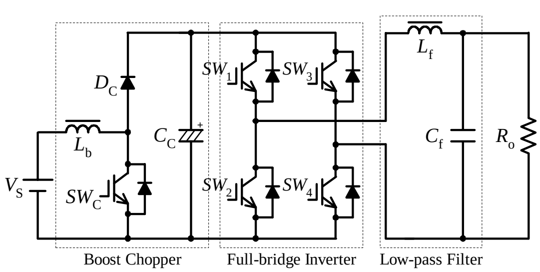
In this paper, a novel prototype of power conditioner with time-sharing sinewave absolute modulated boost chopper with a bypass diode is presented, which can especially achieve high efficiency power conversion processing for wide range power setting requirements[5][6]. In addition, its DC link capacitor between the first and the second power conversion processing stages can be largely reduced. Finally, this paper also proposes a soft switching boost chopper with an auxiliary edge-resonant passive snubber with bypass diode. The operating principle of this novel power conditioner with time-sharing sinewave pulse width modulation is evaluated and verified experimentally with a practical design model in terms of its switching voltage and current waveforms, *v-i* switching trajectory and actual power conversion efficiency as compared with the conventional one from an experimental point of view.

2. Conventional Power Conversion Configuration of Boost Chopper Cascaded Single-Phase Power Conditioner

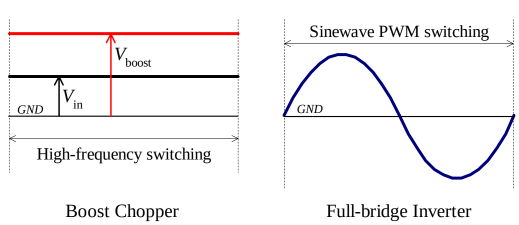
The basic system configuration of single-phase power conditioner for PV or FC power generation system is schematically shown in Fig. 1(a). This power conditioner consists of the boost chopper type DC-DC converter in addition to full-bridge (FB) single-phase sinewave inverter with low-pass filter in parallel with load. Its operating principle is also depicted in Fig. 1(b).

The boost chopper in the first power processing stage is used to boost low DC voltage from PV module array or FC stacks up to a constant output voltage (DC 350~400V). The active power switch SW_C in this boost chopper always operate at high frequency switching modulation to keep a constant output voltage in accordance with the fluctuation voltage from new energy sources. In general, the boost chopper stage causes switching losses and conduction losses because of high frequency switching. And the output side of this boost chopper needs the bulky large-volumetric electrolytic DC capacitor. It is actually impossible to implement smaller and lighter power conditioner. In addition to these, the bulky electrolytic DC capacitor provides lower reliability such as power loss of ESR based on ripple current, degradation and a little short lifetime.

The FB inverter in the second power processing stage is to make utility AC $200V_{rms}$ under sinewave carrier-based high frequency PWM. In actual, the active power switches (SW_1~SW_4) in the full-bridge inverter occur switching losses and conduction losses because of high frequency switching sinewave carrier-based PWM. As a result, the total system efficiency of this power conditioner can be reduced because of these power losses.



(a) Circuit configuration



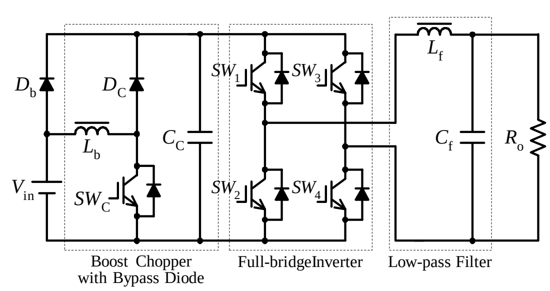
(b) Operating principle

Fig. 1 Conventional single-phase power conditioner.

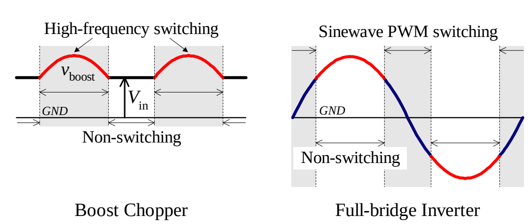
3. Proposed Power Conversion Configuration of Boost Chopper Cascaded Single-Phase Power Conditioner

Fig. 2(a) shows the proposed time-sharing dual mode controlled PWM single-phase power conditioner composed of time-sharing sinewave pulse width modulated boost chopper with a new bypass diode D_b assisted boost chopper and complementary sinewave FB inverter. This sinewave power conditioner includes partially commutated sinewave PWM boost chopper used for converting intermediate input side DC link voltage to quasi sinewave AC absolute value in the first power processing stage, and partially controlled sinewave PWM FB inverter with low-pass filter in the second power processing stage with time-sharing dual mode control scheme.

The unique operating principle of this single-phase power conditioner with a bypass diode assisted sinewave absolute PWM boost chopper is basically shown in Fig. 2(b). Observing the operating principle, when the sinewave instantaneous tracking boost chopper operates under a condition of time-sharing sinewave absolute modulation, the single-phase FB inverter is designed for non-operation. When the FB inverter operates under a condition of sinewave PWM, the boost chopper is also designed for non-operation. As the proposed sinewave inverter is not necessary to operate both power processing stages like conventional power conditioner in Fig. 1, which consists of boost chopper converter in addition to FB sinewave inverter, the total number of switching operation times in the power conditioner can be reduced. Therefore, the switching losses and conduction losses of two power processing stages can be substantially reduced.



(a) Circuit configuration



(b) Operating principle

Fig. 2 Proposed single-phase power conditioner with time-sharing sinewave modulation.

Moreover, this time-sharing controlled sinewave PWM boost chopper with a bypass diode is not necessary to keep constant output voltage, so the large-volumetric electrolytic DC capacitor bank between the first and the second power processing stages is unnecessary in practice. The small film capacitor for high frequency can be employed in place of the electrolytic DC capacitor. The capacitance of reduced scale film capacitor is about 1/1000 as compared with that of conventional electrolytic capacitor for DC smoothing. The film capacitor as a non-smoothing DC link can realize small and thin size, low power losses in system, high reliability and long lifetime.

4. Unique Control Strategy of Proposed Power Conditioner

4.1 Circuit Operation

The dual mode control strategies for the proposed time-sharing dual mode single-phase power conditioner with time-sharing sinewave absolute modulated boost chopper in Fig. 2(a) are summarized as follows;

<u>(i) Operation mode of boost chopper stage</u>

When the input DC voltage V_{in} is less than the absolute of the required sinewave output voltage v_{out}, the switch SW_C in the boost chopper operates at high frequency switching mode for boosting and producing quasi sinusoidal pulse modulated waveform. On the other hand, the switches (SW_1~SW_4) in the FB inverter is commercial frequency- based synchronous polarity switching; for example, when the positive sinewave of output voltage is required, the switches SW_1 and SW_4 are only in on-state. When the negative sinewave of output voltage is required, the switches SW_2 and SW_3 are only in on-state.

<u>(ii) Operation mode of full-bridge inverter stage</u>

When the input DC voltage V_{in} is greater than or equal the absolute of the required sinewave output voltage v_{out}, the switch SW_C in the boost chopper is always off state in this mode, and the switches (SW_1~SW_4) in the FB inverter operate at high frequency switching sinewave carrier-based PWM switching mode. In this case, the input current from DC supply does not flow through the boost inductor L_b and free wheeling diode D_C, but it flows through the bypass diode D_b. Therefore, the conduction losses of boost inductor L_b and diode D_C do not occur in this mode.

4.2 Time-Sharing Sinewave Modulation of Boost Chopper

A steady-state voltage conversion characteristic of the boost chopper can be represented by

$$v_{out} = \frac{V_{in}}{1-D} \tag{1}$$

where D; the duty ratio of boost chopper switch SW_C, V_{in}; the input voltage, v_{out}: the output absolute voltage (absolute value of desired sinusoidal output voltage) obtained from the boost chopper. Rearranging (1), the duty cycle of the boost chopper can be given by

$$D = 1 - \frac{1}{v_{out}/V_{in}} \tag{2}$$

By using (2), the duty ratio D of switch SW_C can be specified from the input voltage V_{in} and absolute value of desired sinusoidal output voltage v_{out}. Fig. 3 illustrates the steady state boosted voltage ratio (v_{out} / V_{in}) versus duty ratio characteristics. This operating characteristic is used for experimental set up.

Fig. 4 shows the block diagram of time-sharing sinewave modulation. When $V_{in} < |v_{out}|$, boost chopper operates for boosting and producing quasi sinusoidal pulse modulated waveform with duty ratio characteristics of Fig. 3. FB inverter operates by comparing a triangular carrier signal with a reference signal waveforms, where the modulation index was designed with a value more than 1.

The gate voltage pulse sequences of proposed power conditioner are depicted in Fig. 5. When the FB inverter operates, the boost chopper does not operate. When the boost chopper operates, the FB inverter operates under commercial frequency-based synchronous polarity switching. Therefore, the switching cycles of the proposed power conditioner can be decreased.

4. 3 Unique Features of Proposed Single-phase Power Conditioner

Unique features and excellent advantageous of the time-sharing single-phase power conditioner can be summarized in the following points.

First, when the FB inverter-side power switches operate, the boost chopper-side power switch does not operate. On the other hand, when the boost chopper-side power switch operates, the FB inverter-side power switches operate only under a condition of commercial frequency-based synchronous polarity switching. However, in the conventional power conditioner shown in Fig. 1, it is noted that the boost chopper as well as the FB inverter always operate at high frequency sinewave PWM switching conditions. The switching cycles of the proposed type are substantially decreased as compared with the conventional one. As a result, the newly-proposed single-phase power conditioner can suppress the switching losses and conduction losses at time-sharing partially controlled sinewave PWM switching scheme.

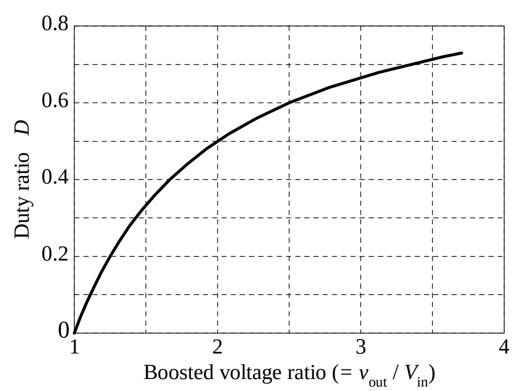


Fig. 3 Boosted voltage ratio vs. duty ratio characteristics of boost chopper.

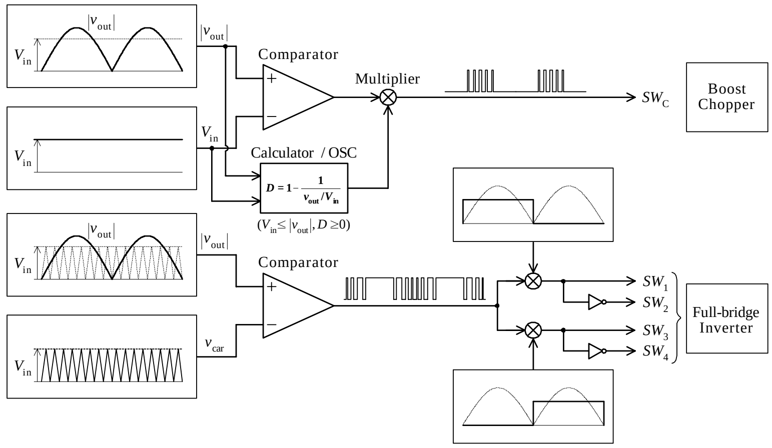


Fig. 4 Block diagram of time-sharing sinewave modulation.

Second, the time-sharing sinewave operated FB inverter operates under a condition of zero or low current value. Therefore, the switching losses and conduction losses of FB inverter stage are kept to be low compared to the conventional one.

Third, the smoothing DC link capacitor stage between boost chopper and FB inverter is not required for using the large-volumetric electrolytic capacitor. The total of PV or FC power generation systems can achieve downsizing and light weight in addition to long lifetime and higher reliability operating due to the possibility of the film capacitor usage as the DC link capacitor instead of unreliable and bulky type electrolytic DC smoothing capacitor bank.

Fourth, at the operation mode of the of FB inverter, the input current does not flow through the boost inductor L_b and diode D_C, but it flows through the bypass diode D_b. Therefore, the conduction losses of boost chopper can be reduced.

5. Soft Switching Boost Chopper

5.1 Circuit Configuration

Fig. 6 shows the proposed time-sharing dual mode controlled PWM single-phase power conditioner composed of time-sharing sinewave soft switching boost chopper and complementary sinewave FB inverter. This soft switching boost chopper is based on the boost chopper in Fig. 2(a), which also includes an passive auxiliary resonant snubber circuit composed of a resonant inductor L_r, a resonant capacitor C_r, a lossless snubber capacitor C_S, and auxiliary diode D_1~D_3. This soft switching boost chopper operates ZVS in turn-off transition.

5.2 Circuit Operation

The mode transitions of soft switching boost chopper are depicted in Fig. 7. The gate voltage pulse sequence of the active power switch SW_C is indicated in Fig. 8, the operating voltage and current waveforms of each component are shown in Fig. 8, too. The operating principle in mode transitions of this boost chopper is explained as follows;

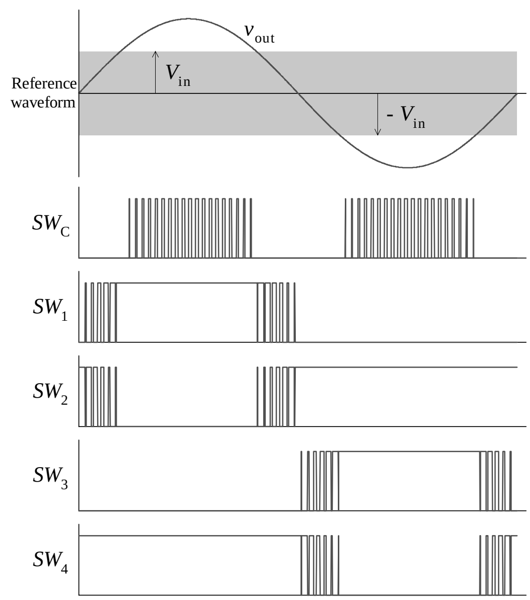


Fig. 5 Gate pulse sequences of proposed power conditioner.

Mode 0

The stored energy of the boost inductor L_b and input voltage V_{in} is transferred to the load side. When the power switch SW_C is turned on, Mode 0 shifts to Mode 1.

Mode 1

When the power switch SW_C is turned on, the current begins to flow in the passive auxiliary resonant snubber circuit. The resonant current flows through the resonant inductor L_r, the resonant capacitor C_r and the lossless snubber capacitor C_S. In this mode, the resonant capacitor C_r is charging, the lossless snubber capacitor C_S is discharging, respectively. The switch SW_C is turned on with hard switching commutation because the voltage and current of switch SW_C have rapid *dv/dt* and *di/dt*.

Mode 2

When the voltage across the snubber capacitor C_S becomes zero and the resonant capacitor C_r is equal to

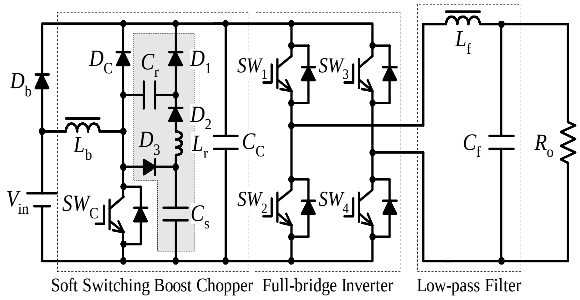


Fig. 6 Proposed time-sharing sinewave modulated power conditioner with soft switching boost chopper.

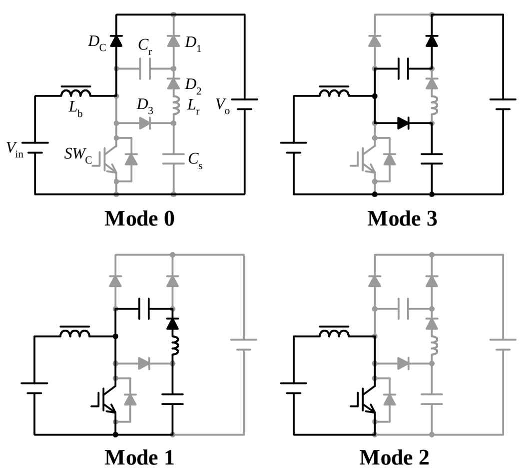


Fig. 7 Mode transitions and equivalent circuits.

the output voltage, the auxiliary diode D_2 is turned off. So the resonant current flowing through the inductor L_r and the capacitor C_r, C_S becomes zero. All the circuit operations are identical to the conduction state of the conventional boost chopper with stored mode of boost inductor L_b.

Mode 3

When the power switch SW_C is turned off with ZVS, the current flowing through the boost inductor L_b flows through the snubber capacitor C_S and the resonant capacitor C_r. Therefore, the lossless snubber capacitor C_S starts charging, and the voltages across it increases gradually, and the resonant capacitor C_r starts discharging. When the voltage across the lossless snubber capacitor C_S is equal to the output voltage V_o and the voltage across the auxiliary resonant capacitor C_r becomes zero, the diode D_1 and D_3 are naturally turned off. At the same time, the diode D_C is turned on and Mode 3 shifts to Mode 0.

6. Experimental Results and Evaluations

6.1 Design Specifications

The experimental design specifications and circuit parameter constants of proposed single-phase power conditioner with time-sharing sinewave absolute modulated soft switching boost chopper are listed in Table 1.

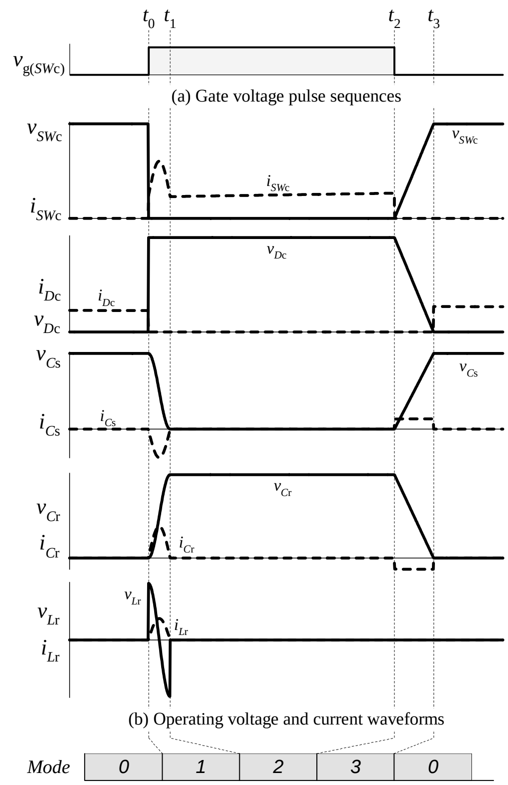


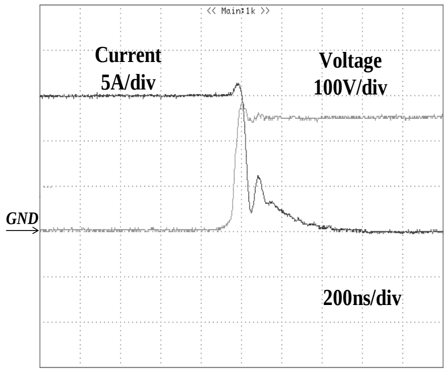
Fig. 8 Operating modes and operating waveforms during one switching period.

Table 1 Design specifications and circuit constants.

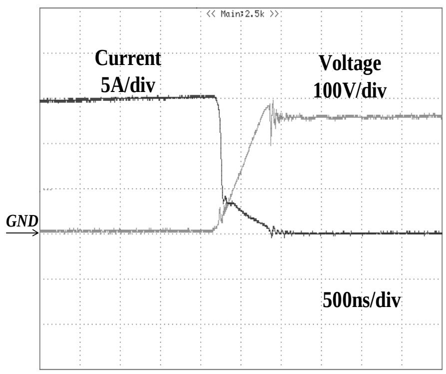
Item	Symbol	Value	
		Conventional	Proposed
DC Input Voltage	V_{in}	160V	160V
AC Output Voltage	v_{out}	$200V_{rms}$	$200V_{rms}$
Switching Frequency	f_S	20kHz	20kHz
Boost Inductor	L_b	1mH	1mH
Intermediate Capacitor	C_C	3,900μF	2.2μF
Snubber Capacitor	C_S	–	12nF
Resonant Inductor	L_r	–	7μH
Resonant Capacitor	C_r	–	12nF
Filter Capacitor	C_f	10μF	10μF
Filter Inductor	L_f	1mH	1mH

6.2 Switching Operating Waveforms

Figs. 9 and 10 illustrate the voltage and current operating waveforms and and *v-i* trajectory in case of turn-off commutation of the power switch SW_C of the boost chopper under hard switching and soft switching commutation conditions, respectively. From the voltage and current switching waveforms at turn-off commutation under hard switching commutation as



(a) Hard switching



(b) Soft switching

Fig. 9 Switching waveforms at turn-off transient of boost chopper switch SW_C.

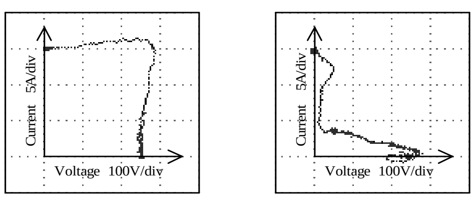


Fig. 10 *v*-*i* trajectory at turn-off transient of SW_C.

depicted in Fig. 9(a), there is an overlapped region of voltage and current switching waveforms. Moreover, observing the *v*-*i* trajectory in Fig. 10(a), it spreads out in the first quadrant in the *v*-*i* plane, which increases the switching power losses.

On the other hand, observing the switching voltage and current operating waveforms shown in Fig. 9(b) under soft switching commutation conditions, except the overlapping period of the switching voltage and falling current during the turn-off period and tail current during the tail period of IGBT, there is no overlapping region. Also, the relevant *v*-*i* trajectory illustrated in Fig. 10(b) is nearly moving along the voltage axis and current axis of *v*-*i* plane. Therefore, under a soft-switching, the switching power losses of the power switch SW_C can be essentially reduced compared with that of the hard switching conditions.

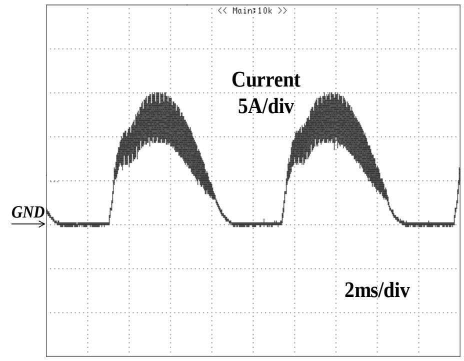


Fig. 11 Current waveform through boost inductor L_b.

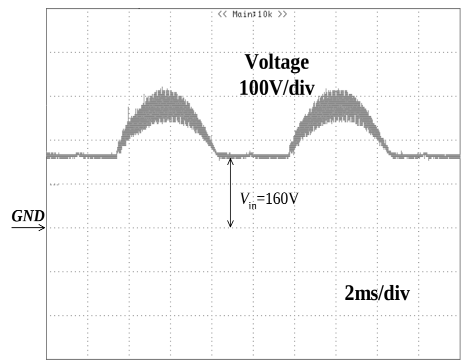


Fig. 12 Voltage waveform across intermediate capacitor C_C.

6. 3 Operating Waveforms and Actual Efficiency

Fig. 11 shows the time-sharing sinewave tracking current waveform through the boost inductor L_b. Fig. 12 depicts the voltage waveform across the intermediate DC link capacitor C_C. As shown in Figs. 11 and 12, the boost chopper operates when the input DC voltage V_{in} is less than the required sinewave output voltage v_{out}.

Fig. 13 illustrates the time-sharing dual mode sinewave modulated voltage waveforms of proposed power conditioner in the input side of the low pass filter stage. Observing this waveform, when the desired sinusoidal AC output voltage v_{out} is greater than the input DC voltage V_{in}, the boost chopper operates under a condition of partially controlled sinewave PWM scheme and the FB inverter operates only under a condition of commercial frequency- based synchronous polarity switching. On the other hand, if the desired sinewave output voltage v_{out} is less than the input DC voltage V_{in}, the boost chopper does not operate and the FB inverter operates with partially controlled sinewave PWM strategy.

The output current and voltage waveforms of proposed inverter are shown in Fig. 14. The AC output voltage and current waveforms can produce high quality sinewave with the maximum total harmonic current distortion (THD) 3% or less.

Fig. 15 depicts the comparative actual power conversion efficiency of conventional and proposed types, respectively. Observing the data in Fig. 15, the

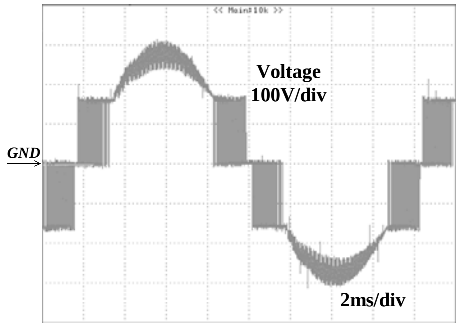


Fig. 13. Voltage waveform across full-bridge inverter.

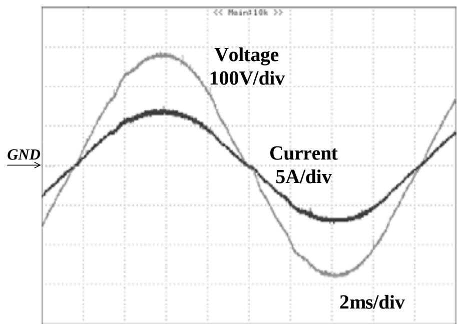


Fig. 14. Output current and voltage waveforms.

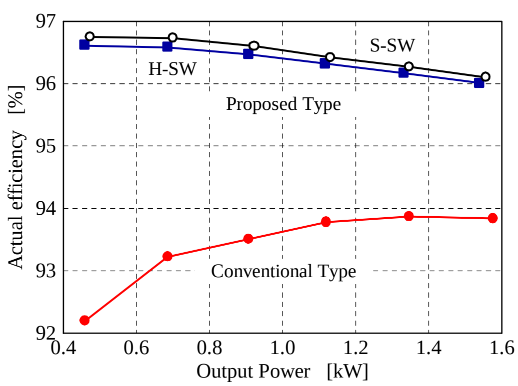


Fig. 15. Output power vs. actual efficiency

actual efficiency of the proposed type is higher than that of conventional one for all the required output power ranges. Especially, for low output power setting condition, proposed power conditioner operating at time-sharing dual mode sinewave PWM control scheme can realize higher efficiency characteristics as as well as high power density. Moreover, the actual efficiency of the soft switching is higher than that of hard switching for all output power range.

7. Conclusions

In this paper, a novel prototype of time-sharing dual mode single-phase power conditioner controlled by time-sharing sinewave absolute pulse width modulated boost chopper with a bypass diode has been proposed for the small scale PV or FC power generation system. The unique operating principle of the proposed power conditioner has been described and discussed in experiment point of view. The paper also has introduced a front stage soft switching boost chopper with a passive configuration auxiliary edge-resonant snubber to achieve further high efficiency power conversion. The practical effectiveness of the proposed single-phase power conditioner was proved as compared with conventional one on the basis of experimental results.

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