Small Scale Utility-Connected Solar Photovoltaic Power Conditioner using Soft Switching High-Frequency Sinewave Modulated Inverter Link for Residential Applications

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Abstract **–** The utility-interfaced sinewave modulated inverter for the solar photovoltaic power conversion conditioning and processing with a high frequency transformer isolated AC link is presented for residential applications. As compared with the conventional full-bridge hard switching-based PWM inverter with a high frequency AC link, the simplest single-ended quasi-resonant soft switching-based sinewave modulated inverter with a duty cycle pulse frequency control is implemented, resulting in size and weight reduction and low-cost. This paper presents a prototype circuit of the single-ended zero voltage soft switching inverter-based sinewave power processor for solar power conditioner in addition to its operating principle. This paper also proposes a control system to deliver high quality output current. The power loss evaluation under actual power processing is discussed from an experimental point of view. A newly-developed sinewave power processor which has 92.5% efficiency at 4kW output is demonstrated for small scale utility-connected power aplications.

Key Words: *Zero voltage soft switching, High frequency inverter, High frequency transformer link, Utility interfaced solar power conditioner, High frequency transformer link*

1. Introduction

The Solar photovoltaic (PV) power energy is an effective type of natural energy resources because it is clean, abundant and pollution free. Moreover, it produces no acoustic noise and is distributed under on-site power generator everywhere on earth. A variety of small scale dispersed PV power conditioners are presently used in various power applications such as water pumping, lighting, home power appliances, the mechanical power appliances for air conditioner and refrigerator. Most PV power applications require high efficient power conversion processing system such as DC-DC converter and DC-AC converter[1), 3)~7)].

The conventional utility-connected power conditioner is generally classified into three different types; an isolated low frequency transformer link type, an isolated high frequency transformer link type, and a transformer-less direct AC link type. The system topologies of low frequency transformer AC link type and high frequency transformer AC link are both advantageous in safety viewpoint due to the transformer type electrical isolation. On the other hand, the transformer-less direct AC link topology has the practical advantages in low cost, high efficiency, and small volumetric physical size.

In recent years, the authors have developed a high frequency transformer linked utility-connected inverter system for the small scale PV power generator that can control to produce the sinewave output waveform by using a single-ended quasi-resonant zero voltage soft switching high frequency inverter with a transformer in its primary power stage. A novel type of high frequency transformer link utility- connected solar power conditioner using a new soft switching inverter is suitable for the residential PV power generator system, which delivers the single-phase 50/60Hz 4kW AC output into the utility AC power grid.

This paper presents a new utility- connected sinewave modulated inverter type solar power conditioner with a high frequency transformer link, which is composed of the new generation trench-gate IGBTs for low saturation voltage design. Its operating principle and its related control scheme are illustrated and evaluated described from a practical point of view.

2. Circuit Description and circuit operation

The basic circuit configuration of the voltage-source single-ended soft switching high frequency sinewave modulated inverter developed for solar power regeneration system is depicted in Fig. 1. The main circuit consists of the single-ended quasi-resonant inverter, specially-designed leakage transformer, high frequency voltage doubler rectifier circuit, and synchronized polarity switching bridge inverter connected to the utility power source. The leakage transformer T_{HF} provides an equivalent series inductance component to achieve zero voltage soft switching of this inverter by means of the quasi-resonant operation in addition to the electrical isolation between DC input and AC output. The operation of this zero voltage soft switching inverter is able to be achieved by connecting a resonant capacitor C_1 in parallel with the primary winding of the high frequency leakage transformer and resonating the collector-emitter voltage across the power semiconductor device Q_1 (SW_1/D_1).

Fig. 2 shows the equivalent circuit for three operating modes of the single-ended resonant high frequency inverter. Its operation principle is described below[2].

<u>Mode 1</u>: During a time interval in mode 1, when the active power switch Q_1 (SW_1/D_1) is turned on with ZVS and ZCS, the current flows through the primary winding of a leakage transformer. The collector current i_C through Q_1 increases linearly until Q_1 is turned off. Then, this mode moves to mode 2 by turning off the main power switch Q_1.

<u>Mode 2</u>: When Q_1 is turned off with ZVS, the current stored into the equivalent leakage inductance in the primary winding N_p of the high frequency transformer begins to flow through the quasi-resonant capacitor C_1, and the voltage v_{CE} across collector-emitter of Q_1 gradually builds up from zero to establish the resonant waveform. When the voltage returns to zero again, the operating mode moves to Mode 3.

<u>Mode 3</u>: When the voltage v_{CE} reaches zero, the flywheel diode D_1 naturally becomes a conducting state. Thus, the power is regenerated into the input DC side of this inverter. During this period, the gate signal of the active power switch Q_1 is on. And Mode 3 shifts to Mode 1.

The soft switching high frequency inverter circuit repeats the interrupted switching operation described above. To protect the acoustic noise and to reduce the power losses of the inverter, the operating frequency of this inverter is optimized in the range of 20-30kHz. Fig. 3 illustrates the theoretical operating waveforms of the single-ended resonant inverter in Fig. 2.

While the active power switch SW_1 of Q_1 is off, in the secondary side of the transformer, D_{S1} is conductive and C_{S1} is electrically charged. While SW_1 is on, the voltage across C_{S1} is boosted over the transformer voltage. D_{S2} is naturally turned on. This power processing results in a half-wave voltage-doubler type high frequency rectification, and the current generated in the quasi-resonant high frequency inverter treated here is delivered to the output stage of the voltage doubler rectifier. The AC power processed by the filtered current with a full-wave rectified sinusoidal waveform is delivered to the utility AC power grid through

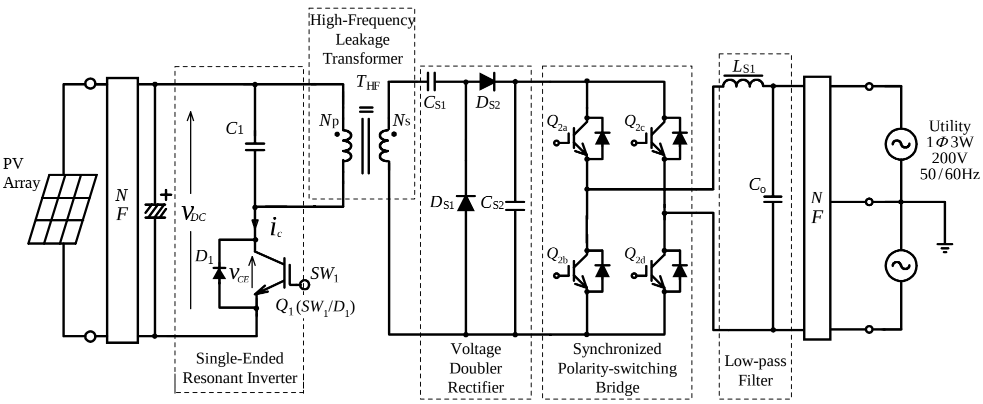
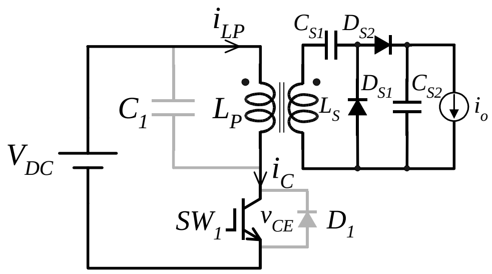
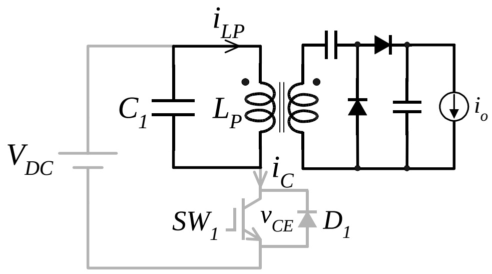


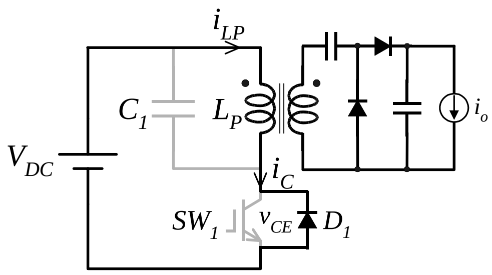
Fig. 1 Single-ended quasi-resonant utility-connected inverter



(a) Mode 1



(b) Mode 2



(c) Mode 3

Fig. 2 Mode transition of single-ended quasi-resonant inverter in equivalent circuit

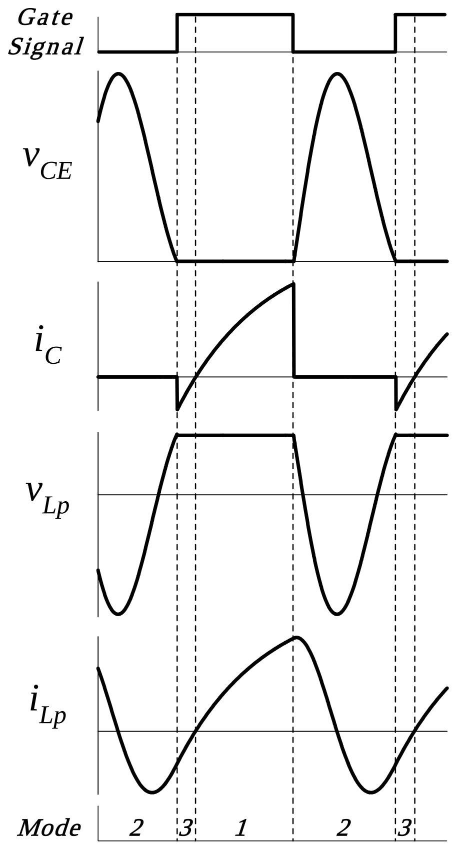


Fig. 3 Theoretical operating waveform

the polarity switching low frequency IGBT full bridge inverter using IGBT power module.

The full bridge type low frequency inverter is to be operated in synchronization with the utility power AC grid voltage. Fig. 4 illustrates the operating waveforms of Q_1 (SW / D) under the condition with maximum utility voltage v_o (v_o=282V). This sinewave inverter system achieves the zero voltage switching of Q_1 as can be seen from the operating waveforms in Fig. 4. It is noted that the maximum points of v_{CE} and i_C reach 800V and 100A, respectively.

3. Control System Implementation

The single-ended quasi-resonant soft switching high frequency inverter performs duty cycle control based PFM (Pulse Frequency Modulation) control in synchronization with the utility AC voltage in order to deliver high quality sinusoidal output current from the solar array panel as the DC input power source. Fig. 5 shows the control system block diagram required for delivering sinusoidal output waveform.

T_{on} (Q_1 on-time) command signal of the single-ended quasi-resonant soft switching inverter for controlling the output current waveform is able to be obtained by adjusting the synchronized oscillator with sinusoidal reference signal that is synchronized with the utility AC grid voltage. Since non-linearity exists between T_{on} and i_o due to the resonant switching operation, the T_{on} command is corrected in

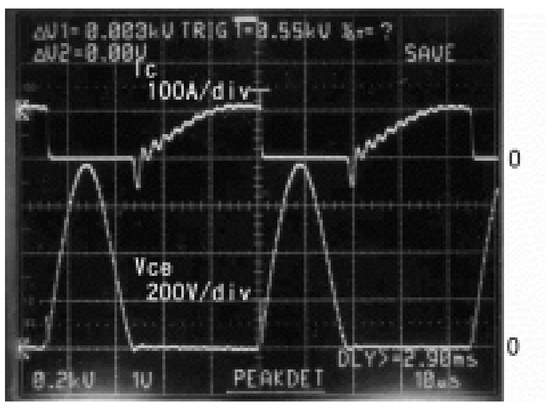


Fig. 4 Voltage and current switching waveforms

accordance with an error signal between the output current i_o and the reference signal. This correction is conducted after every cycle of the utility grid voltage.

The experimental operating waveforms of the AC output current and the output voltage of this inverter are displayed in Fig. 6. The output power P_o, the DC voltage and the utility voltage V_o are designed for; P_o=4kW, V_o=200V$_{rms}$, and V_{in}=200V$_{ave}$, respectively. The total harmonic distortion (THD) of the output current i_o in this case is 3% or less. The major design specifications of the developed solar power conditioner using DC-AC power conversion processing are listed in Table 1.

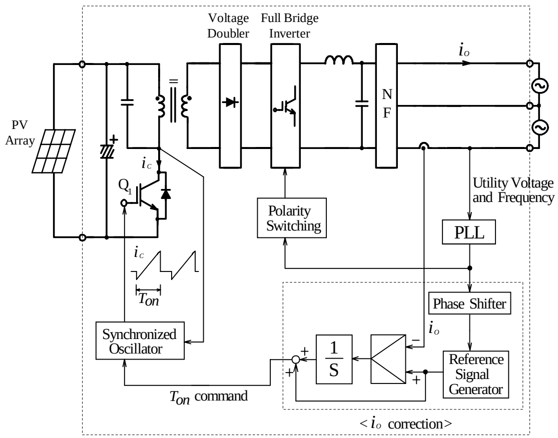


Fig. 5 Block diagram for sinewave modulated control system

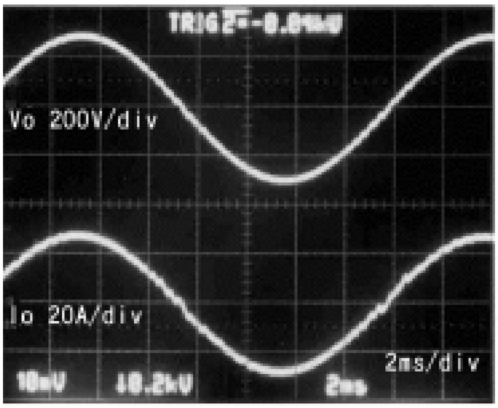


Fig. 6 Output voltage and current waveforms

Table 1 Specifications of solar power conditioner

Item	Specification
Efficiency	92.5%
Dimensions	W 540mm × D 300mm × H 125mm (20 liters)
Weight	20kg

4. Power Loss Analysis and Evaluations

Table 2 indicates the measured power losses of each component in actual operation under the input voltage V_{in}; 200V$_{ave}$, the output current i_o; 20A$_{rms}$, and output power P_o; 4kW. By making the optimal component arrangement on the basis of the power losses obtained, the natural air cooling method can be introduced for the utility-connected sinewave inverter type power conditioner for the solar power generation.

The switching power semiconductor devices for hard switching PWM inverters cause the power losses of approximately 130W for a 4kW power conditioner in the residential applications. On the other hand, the proposed sinewave modulated inverter type power conditioner with 40% power loss reduction using an efficient resonant switching circuit topology and the 4th generation low saturation voltage type IGBT with a trench gate structure, two IGBTs are provided as the active power switch Q_1 so that its power dissipation is shared. As a result, the cooling equipment becomes simple. Table. 3 indicates the actual specifications of the 4th generation IGBT used for the quasi-resonant high frequency inverter switch Q_1, and Q_{2a} - Q_{2d} for the polarity switching inverter. And the appearance of the IGBT is shown in Fig. 7.

Because the polarity switching utility-connected low frequency inverter is operated under a low frequency (50 or 60Hz) and the operation of switching is performed when the utility AC grid voltage remains in almost zero state, the majority of the power losses in Q_{2a}-Q_{2d} are produced for the conducting state. Since the high frequency resonant inverter operates at 20kHz or more, high frequency current flows

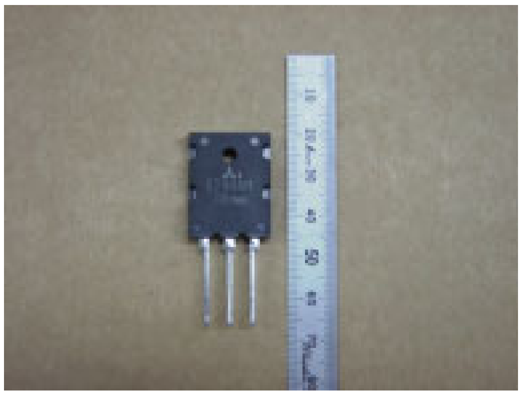


Fig. 7 Physical appearance of Trench-gate IGBT

Table 2 Measured results of power loss analysis

Component	Symbol	Loss
Switching element (primary)	Q_1	78W
Switching element (secondary)	Q_{2a} - Q_{2d}	69W
Rectifying diode	D_{S1}, D_{S2}	30W
Resonance capacitor	C_1	5W
Voltage doubler capacitor	C_{S1}	10W
Filter capacitor	C_{S2}	4W
Output choke coil	L_{S1}	5W
High frequency transformer	T_{HF}	65W
Control circuit		28W
Others		30W
	Total	324W

Table 3 The 4th generation IGBT(CT90AM-18) rating and performances

	Item	Symbol	Specification
Rating	Collector - Emitter voltage	V_{CES}	900V
	Collector current	I_C	60A
	Gate - Emitter voltage	V_{GES}	±25V
	Collector loss	P_C	250W
Performance	Collector - Emitter saturation voltage	$V_{CE\ (sat)}$	1.55V
	Fall time	t_f	0.3μs

through the transformer windings.

To suppress increase of the copper losses produced in the transformer windings due to a skin effect under the high frequency operation, Litz wire with a diameter of 0.14mm and 575 turns is introduced as the primary and secondary windings. The ferrite core is used for the transformer magnetic circuit to reduce the core losses.

The high frequency AC link transformer has a little gap in the magnetic circuit to obtain the reasonable equivalent series leakage inductance, and thus the transformer produces leakage flux outside of the transformer. This leakage flux may result in the radiation noise. To reduce this power loss, the transformer is covered with an aluminum sheet as a low permeability material. This arrangement effectively prevents power loss generation caused by a coupling with the steel chassis that forms the cabinet. Table. 4 indicates the major specifications of the high frequency transformer.

Table 4 Transformer Specifications

Item	Specification
Primary indactance	58μH
Secondary indactance	43μH
Coupling coefficient	0.78

5. Conclusions

By applying the system topology of the single-ended high frequency soft switching sinewave pulse modulated inverter with a high frequency transformer isolation for utility-connected inverter type power conditioner, a downsized lightweight sinewave modulated inverter for a solar photovoltaic power conditioner using the trench gate IGBTs was demonstrated and evaluated from a practical point of view. The excellent performances of this power conditioner were confirmed through the experimental results obtained from a 4kW prototype breadboard setup for residential applications.

Reference

1) S. Sumiyoshi, H. Terai, T. Kitaizumi, T. Okude, H. Omori, Y. Nishida and M. Nakaoka, "Practical Evaluation of Single-Ended Resonant Utility Interactive Inverter", *Proc. of International Power Electronics Conference (IPEC-Tokyo)*, Vol. 3, pp. 1680-1685, March, 2000.
2) I. Hirota, H. Omori and M. Nakaoka, "Practical evaluations of a ZVS-PFM quasi load-resonant high-frequency inverter using a new generation IGBT for an induction-heated cooking appliance", *International Journal of Electronics*, Vol. 80, No. 2, pp. 329-340, 1996.
3) K. Hirachi, and M. Nakaoka, "Improved control strategy on single-phase current-fed interactive inverter", *International Journal of Electronics*, Vol. 88, No. 1, pp. 115-126, 2001.
4) J. A. Gow and C. D. Manning, "Photovoltaic converter system suitable for use in small scale stand-alone or grid connected applications", *IEE Trans. on Electr. Power Appl.,* Vol. 147, No. 6, pp. 535-543, Nov. 2000.
5) B. K. Bose, P. M. Szczesny and R. L. Steigerwald, "Microcomputer Control of a Residential Photovoltaic Power Conditioning System", *IEEE Trans. on Ind. Application*, Vol. IA-21, No. 5, pp. 1182-1191, Sep./Oct. 1985.
6) H. Terai, S. Sumiyoshi, T. Kitaizumi, K. Ogura, S. Chandhaket and M. Nakaoka, "Utility Interactive Solar Power Conditioner with Zero Voltage Soft Switching High frequency Sinewave Modulated Inverter Link", *Proc. of International Conference on Power Electronics (ICPE '01)*, pp. 668-672, Oct. 2001.
7) Y. Konishi, S. Chandhaket, K. Ogura and M. Nakaoka, "Utility-Interactive High-Frequency Flyback Transformer Linked Solar Power Conditioner for Renewal Energy Utilizations", *Proc. of IEEE International Conference on Power Electronics and Drive Systems (PEDS 2001)*, Vol. 2, pp. 628-632, Oct. 2001.

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