Utility Interactive Solar Power Conditioner with Zero Voltage Soft Switching High frequency Sinewave Modulated Inverter Link

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Abstract–**The utility interactive sinewave modulated inverter for the solar photovoltaic (PV) power conversion and conditioning with a new high frequency pulse modulated link is presented for domestic residential applications. As compared with the conventional full-bridge hard switching PWM inverter with a high frequency AC link, the simplest single-ended quasi-resonant soft switching sinewave modulated inverter with a duty cycle pulse 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 sinewave inverter for solar power conditioner and its operating principle. In addition, this paper proposes a control system to deliver high quality output current. Major design of each component and the power loss analysis under actual power processing is also discussed from an experimental point of view. A newly developed interactive sinewave power processor which has 92.5% efficiency at 4kW output is demonstrated. It is designed 540mm-300mm-125mm in size, and 20kg in weight.**

Index Terms– **A quasi-resonant inverter, Zero voltage soft switching, Photovoltaic power conversion system, Utility interactive power generator, High frequency transformer link**

I. INTRODUCTION

The Photovoltaic (PV) power energy is more important energy resource because of clean, abundant, pollution free, no acoustic noise and distributed through the earth. A variety of small scale dispersed PV power conditioners are used today in many applications such as; water pumping, lighting, home power appliances, the mechanical power appliances for air conditioner and refrigerator. In most power applications, they require a power conditioner (DC-DC converter or DC-AC converter).

This paper presents the utility connected solar power conditioner for the residential PV system which is converted to the single-phase 50/60Hz 4kW AC output and is connected to the utility AC power grid.

The conventional utility interactive power conditioner is classified into three different types; an isolated low frequency transformer link, an isolated high frequency transformer link, and a transformer-less direct link. The low frequency AC link and high frequency AC link topologies are advantageous in excellent safety viewpoint due to the transformer isolation. On the other hand, the transformer-less AC link topology has the advantages in cost and physical size.

In recent years, the authors have developed a high frequency transformer linked utility interactive inverter system for the small scale PV power generator that controls the output waveform by using a single-ended quasi-resonant zero voltage soft switching inverter in its primary power stage. This paper presents the configuration of a new utility interactive sinewave modulated inverter type power conditioner with a simplified solar power generation. Its operating principle as well as its related control scheme are described from a practical point of view.

II. CIRCUIT TOPOLOGY AND OPERATING PRICIPLE

The basic circuit configuration of the voltage-fed single-ended soft switching inverter developed for solar power regeneration system is depicted in Fig. 1. The main circuit consists of the single-ended resonant inverter, specially designed leakage transformer, high frequency rectifier circuit, and synchronized polarity switching

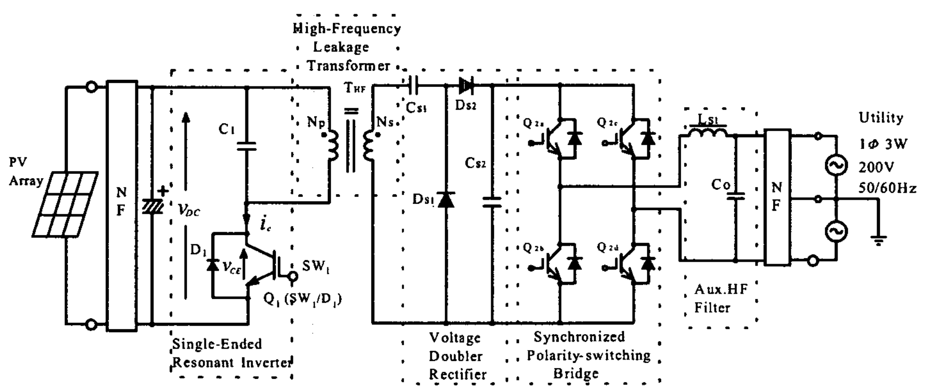
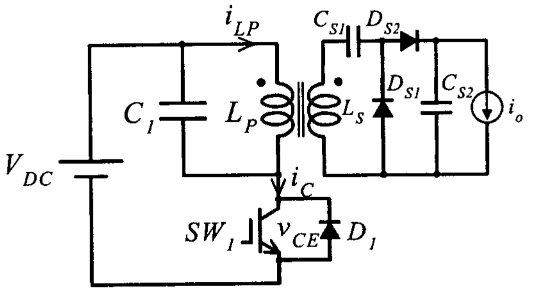


Fig. 1 Single-ended quasi-resonant utility interactive inverter

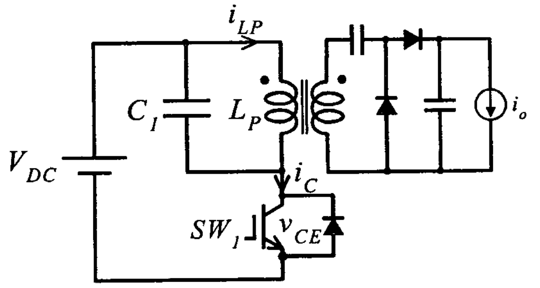
bridge. The leakage transformer T_{HF} provides an equivalent series inductance component to achieve zero voltage soft switching by means of the quasi-resonant operation in addition to the electrical isolation between the DC input and the AC output. This zero voltage soft switching inverter operation is able to be achieved by connecting a resonant capacitor C_1 in parallel to 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 inverter. Its operation principle is as follows.

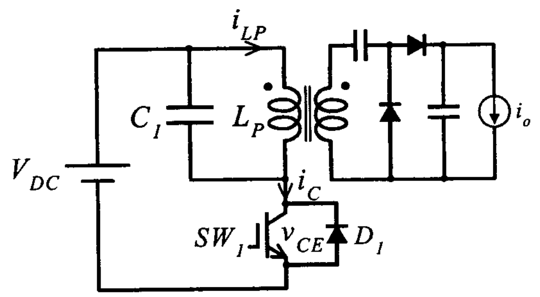
Mode 1: During a time interval in mode 1, when the active power switch Q_1 (SW_1/D_1) is turned on with ZVS & ZCS, the current flows through the primary windings of a leakage transformer. The collector current i_C of Q_1 increases linearly until Q_1 is turned off. This mode moves to mode 2 by turning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



(a) Mode 1



(b) Mode 2



(c) Mode 3

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

Mode 2: When Q_1 is turned off with ZVS, the current accumulated into the equivalent 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 form resonant waveform. When the voltage returns to zero again, the circuits in mode 2 moves to Mode 3.

Mode 3: When the voltage v_{CE} reaches to zero, the flywheel diode D_1 becomes a conduction state and the power is fed back into the input DC side of the inverter. During this period, the gate signal of active power switch Q_1 is on. And Mode 3 shifts to Mode 1.

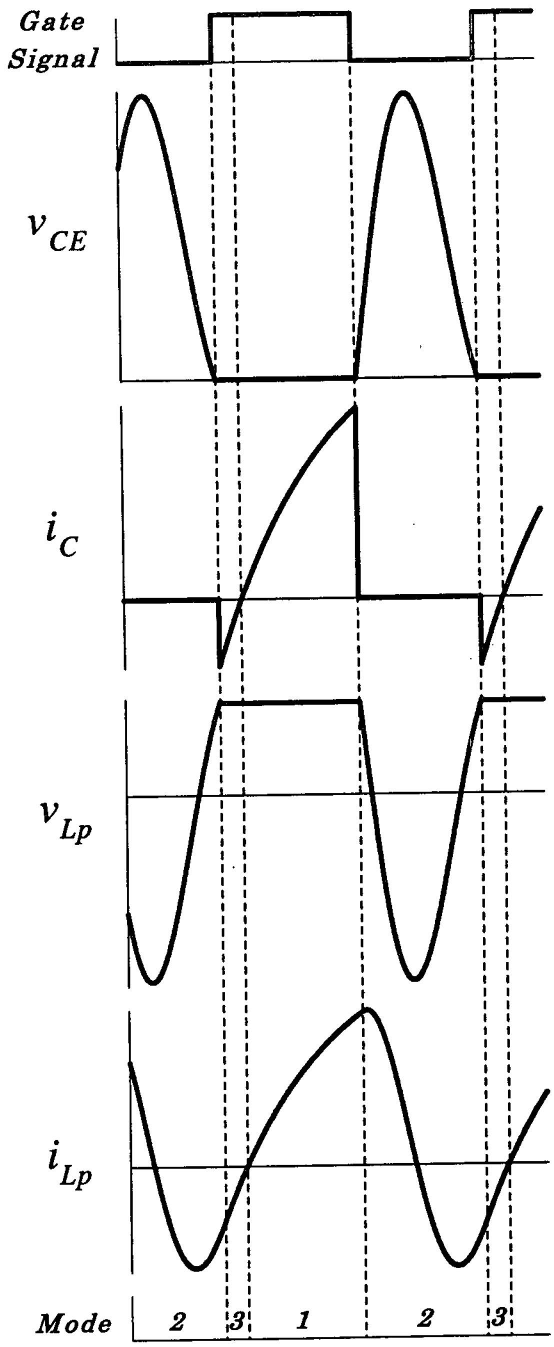


Fig. 3 Theoretical operating waveform

The inverter circuit repeats the interrupted operation described above. To avoid the audible noise and to reduce the power losses of the inverter, the operating frequency of this inverter is optimized so as to design for 20-30kHz. Fig. 3 shows the typical theoretical operating waveforms of the single-ended resonant inverter shown 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 conducted and C_{S1} is charged. While SW_1 is on, the voltage across C_{S1} is superpositioned over the transformer voltage, D_{S2} is conducted. This power processing results in a half wave voltage-doubler type high freque ncy rectification, and the current generated in the resonant inverter treated here is delivered to the output st age 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 system through the low frequency IGBT full bridge inverter.

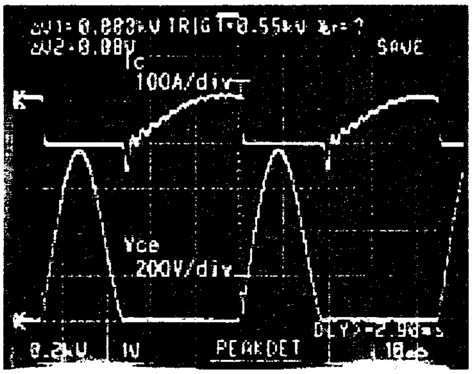


Fig. 4 Voltage and current switching waveforms

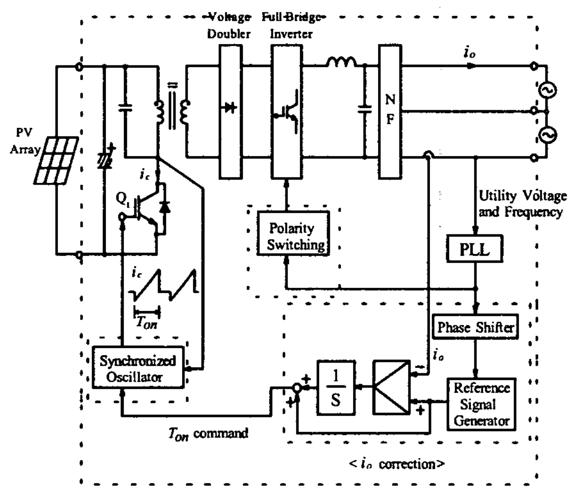


Fig. 5 Block diagram of waveform control system

The IGBT full bridge type low frequency inverter consisting of four devices is to be operated in synchronization with the utility 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 inverter achieves the zero voltage switching of Q_1 as can be seen from the operating waveforms in Fig. 4. It is also seen that the maximum of v_{CE} and i_C reach 800V and 100A, respectively.

III. Control System Implementation

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

T_{on} (Q_1 on-time) command 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 accordance with an error signal between the output current i_O and the reference signal. This correction is not only made instantaneously but also synchronized in every cycle of the utility voltage.

TABLE I

SPCIFICATIONS OF SOLAR POWER CONDITIONER

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

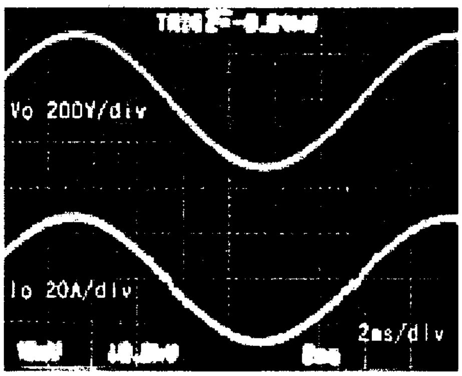


Fig. 6 Output voltage and current waveforms

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; P_O=4kW, V_O=200V_{rms}, and V_{DC}=200V_{ave}, respectively. The total harmonic distortion 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.

IV. POWER LOSS ANALYSIS AND EVALUATIONS

Table. 2 indicates the measured power losses of each component in actual operation under the input voltage V_{DC}; 200V_{ave}, output current i_O; 20A_{rms}, and output power P_O; 4kW. By making the optimum component arrangement on the basis of the result of power losses obtained, the natural cooling can be introduced for the utility interactive inverter type power conditioner in the solar power generation.

The switching power semiconductor devices for hard switching inverters cause the power losses of approximately 130W for a 4kW power conditioner.

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 IGBT with a trench gate structure, two IGBTs are provided as the active switch Q_1 so that the power dissipation is shared and the cooling equipment becomes simple. Table. 3 indicates the actual specifications of the 4th generation IGBT used for the quasi-resonant inverter switch Q_1 and the polarity switching inverter Q_{2a} - Q_{2d}. And the appearance of the IGBT is shown in Fig. 7.

Because the polarity switching utility interactive inverter operates under a low frequency (50 or 60Hz) and performs the switching operation when the utility AC grid voltage remains in almost zero, the majority of the power losses in Q_{2a}-Q_{2d} are produced on the conduction state. Since the high frequency resonant inverter operates at 20kHz or more, high frequency current flows through the transformer windings.

To suppress increase of 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 used as the primary and secondary windings. The ferrite core is used for the transformer magnetic circuit to reduce core loss.

TABLE II
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 III
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

TABLE IV
TRANSFORMER SPECIFICATIONS

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

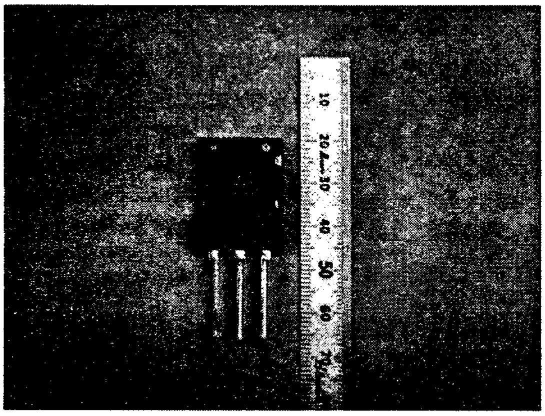


Fig. 7. Physical appearance of IGBT

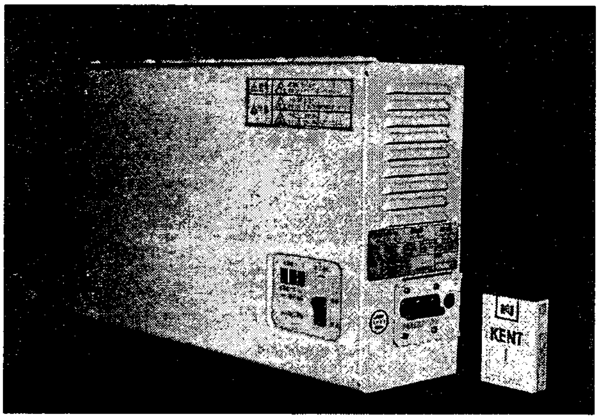


Fig. 8. Appearance of utility-interactive inverter for solar photovoltaic power generator

The high frequency transformer has a gap in the core to obtain the reasonable equivalent series 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.

V. CONCLUSIONS

By applying the system topology of the single-ended high frequency soft switching inverter for a high frequency transformer isolation linked utility interactive 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 for consumer . The excellent performances were confirmed through the experimental results obtained from a 4kW prototype breadboard setup.

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