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Utility-Connected Solar Power Conditioner Using Edge-Resonant Soft Switching Duty Cycle Sinewave Modulated Inverter Link

[1]Koki Ogura*, [1]Srawouth Chandhaket, [1]Mutsuo Nakaoka,
[2]Haruo Terai, [2]Shinichiro Sumiyoshi, [2]Takeshi Kitaizumi, and [2]Hideki Omori

[1]The Graduate School of Science & Eng., Yamaguchi University, Yamaguchi, Japan
[2]Home Appliance & Housing Electronics Research Lab., Matsushita Electric Industrial Co., Ltd. Osaka, Japan

ABSTRACT

The utility interfaced sinewave modulation inverter for the solar photovoltaic power conditioner with a high frequency transformer is presented for residential applications. As compared with the conventional full-bridge hard switching sinewave PWM inverter with a high frequency link, the simplest single-ended edge-resonant soft switching sinewave inverter with a sinewave duty cycle pulse control scheme is implemented, resulting in size and weight reduction, low cost and high efficiency. *This paper presents a prototype system of the sinewave zero voltage soft switching sinewave inverter for* solar power conditioner, along with its operating principle and unique features. In addition to these, this paper discusses a control implementation to deliver high quality output current. Major design of each component and the power loss analysis under actual power processing is also discussed and evaluated from an experimental point of view. A newly developed utility-connected sinewave power conditioning circuit which achieves 92.5% efficiency under 4kW output is demonstrated.

Keywords: Edge resonant inverter, Zero voltage soft switching, Photovoltaic power conversion system, Utility interfaced power conditioner, High frequency transformer link.

1. Introduction

The Photovoltaic (PV) power energy is an important type of natural energy sources because it is clean, abundant and pollution free. Moreover, it produces no acoustic noise and is available everywhere on earth. Varieties of small scale dispersed PV power conditioners are used today in various applications such as; water pumping, lighting, home power appliances, the mechanical power appliances for air conditioner and refrigerator. In most PV applications, they require a power conversion (DC-DC converter or DC-AC converter).

This paper presents a transformer link utility connected solar power conditioner for the residential PV power *generator system, which delivers the single-phase 50/60Hz* 4kW AC output into the utility AC power grid.

The conventional utility-connected 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 topologies of low frequency AC link and high frequency

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Corresponding Author: ogura@pe-news1.eee.yamaguchi-u.ac.jp, Tel: +81-836-85-9472, Fax: +81-836-85-9401

AC link are advantageous in safety viewpoint due to the function of isolation. On the other hand, the transformer-less AC link topology has the advantages in low cost and small 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 controls the output waveform by using a single-ended edge-resonant zero voltage soft switching inverter in its primary power stage This paper presents the configuration of a new utility-connected sinewave modulated inverter type of power conditioners with a simplified solar power generation Its operating principle as well as its related control scheme are described from a practical point of view

2. Circuit Topology and Operating Principle

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 edge resonant inverter, specially designed leakage transformer, high frequency rectifier circuit, and synchronized polarity switching bridge The leakage transformer T_{HF} provides an equivalent series inductance component to achieve zero voltage soft switching by means of edge-resonant operation in addition to the electrical isolation between the DC input and the 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 inverter. Its operation principle is described below.

Mode 1. During the 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 windings of a leakage transformer. The collector current i_C through Q_1 increases linearly until Q_1 is turned off. Then, this mode is changed to mode 2 by turning off the main switch Q_1

Mode 2: When the switch 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 edge-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 is changed to Mode 3

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

The proposed 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 at the range of

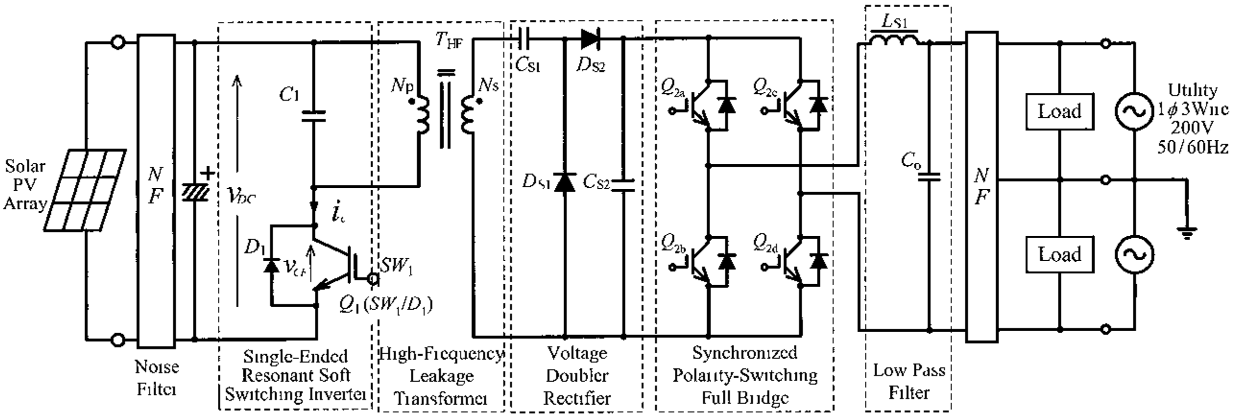
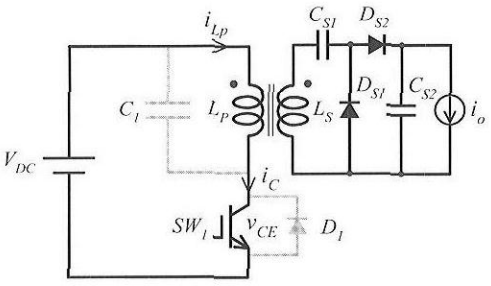
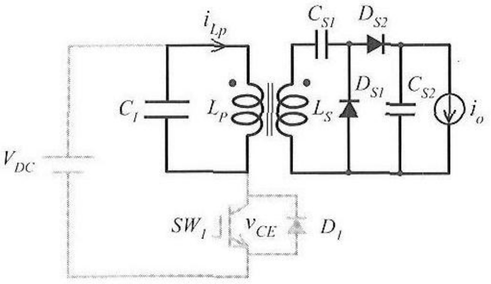


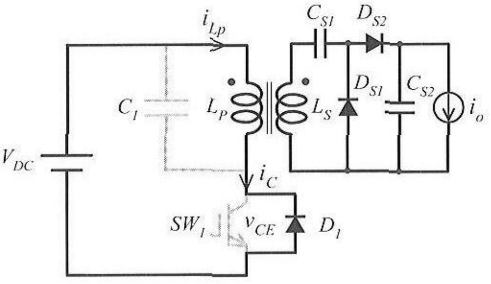
Fig 1 Single-ended edge-resonant utility-connected inverter



(a) Mode 1



(b) Mode 2



(c) Mode 3

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

20-30kHz. Fig. 3 shows the theoretical operating waveforms of the single-ended edge resonant inverter that is displayed in Fig. 2.

While the active power switch SW_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 superpositioned over the transformer voltage. D_{S2} is naturally turned on. This power processing results in a half-wave voltage-doubling high-frequency rectification. The current generated in the resonant inverter treated here is delivered to the output of the voltage doubler rectifier. The AC power processed by the filtered current with a full-wave rectified sinusoidal waveform is delivered into the utility AC power system through the polarity switching low frequency IGBT full bridge inverter.

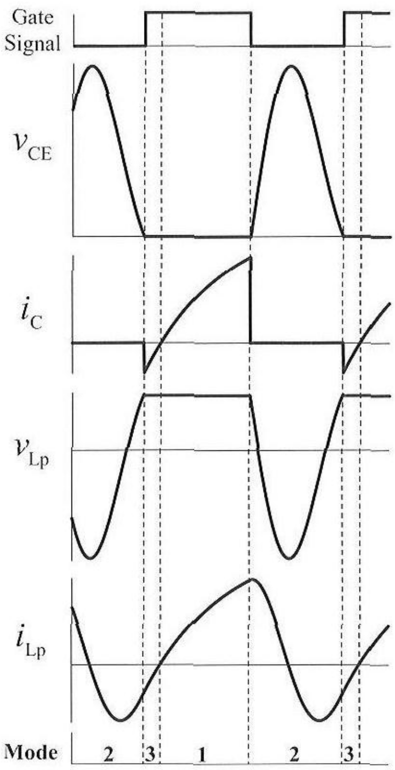


Fig. 3. Theoretical operation waveforms.

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_1 / D_1) 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 noted that the maximum points of v_{CE} and i_C reach 800V and 100A, respectively.

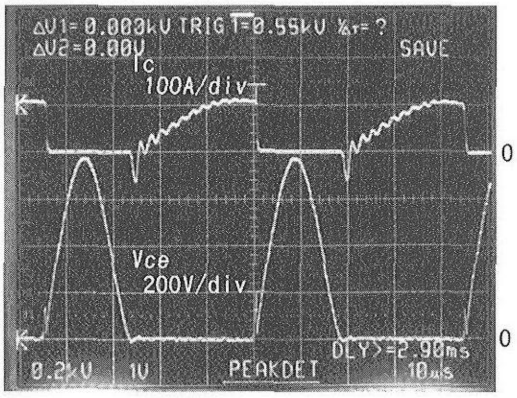


Fig. 4. Voltage and current switching waveforms.

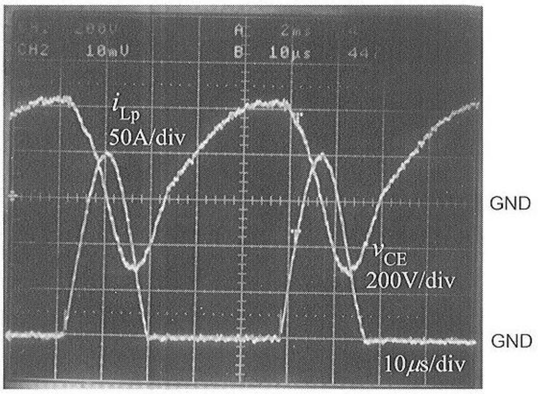


Fig. 5. Experimental waveforms of i_{Lp} and v_{CE}.

Fig. 5 depicts the operating waveforms of the primary side current i_{Lp} of high frequency transformer and voltage across Q_1 (v_{CE}). It is proven that the simulated results have good agreements with the experiment ones.

3. Circuit Topology and Operating Principle

The single-ended edge-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 the solar array panel as the DC input power source. Fig. 6 shows the control system block diagram for delivering sinusoidal output waveform.

T_{on} (Q_1 on-time) command of the single-ended edge-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 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. 7. 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_{DC}=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.

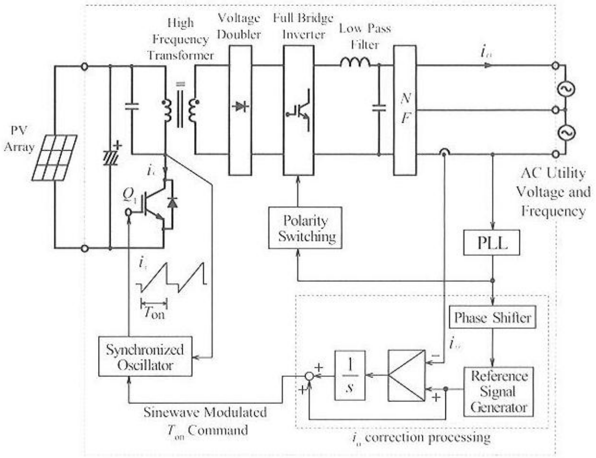


Fig. 6. Block diagram of control system.

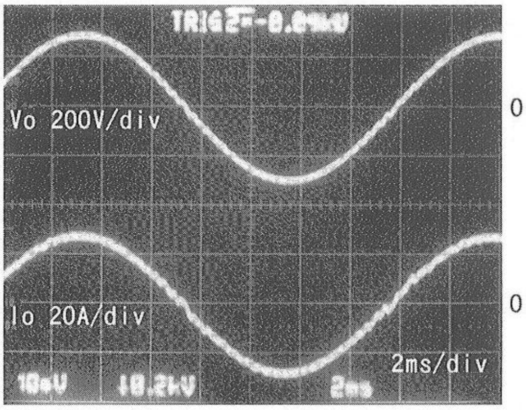


Fig. 7. Output voltage and current waveforms.

Table 1. Specifications of Solar Power Conditioner.

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

4. 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$_{ave}$, the output current i_O; 20A$_{rms}$, and output power

Table 2. Measured Results of Power Loss Analysis.

Circuit Power Component	Symbol	Power Loss
Switching Element in Primary Side	Q_1	78W
Switching Element in Secondary Side	Q_{2a} - Q_{2d}	69W
Rectifying Diode of Voltage Doubler	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

P_O; 4kW. By making the optimal component arrangement on the basis of the power losses obtained, the natural cooling method can be introduced for the utility-connected inverter type power conditioner for 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 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 IGBT with the trench gate structure, two IGBTs are provided as the active switch Q_1 so that its power dissipation is shared and the cooling equipment becomes simple. Table 3 indicates the actual specifications of the 4th generation IGBT used for the edge-resonant inverter switch Q_1 and the polarity switching inverter Q_{2a} - Q_{2d}. And the appearance of the IGBT is shown in Fig. 8.

Because the polarity switching utility-connected inverter is operated under a low frequency (50 or 60Hz) and the switching operation is performed 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 conducting 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 575turns is introduced as the primary and secondary windings. The ferrite core is used for the transformer magnetic circuit to reduce the core losses.

High frequency 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. Fig. 9 shows the whole appearance of high frequency transformer, and the schematic structure of this transformer designed newly is depicted in Fig. 10.

Table 3. 4th Generation IGBT(CT90AM-18) Rating and Performances.

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

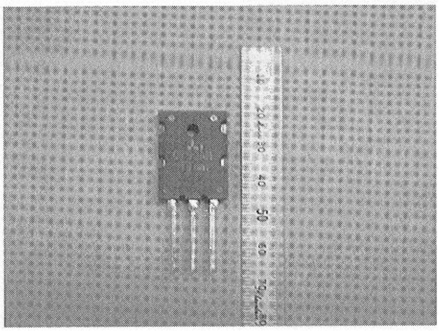


Fig. 8. Physical appearance of Trench-gate IGBT

Table 4. Transformer Specifications.

Item	Specification
Primary side indactance	58 μH
Secondary side indactance	43 μH
Coupling cocficient	0.78

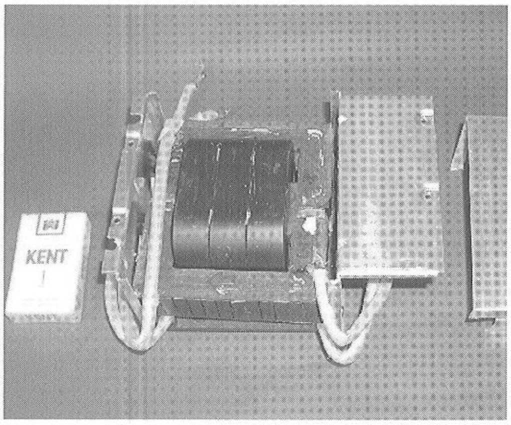
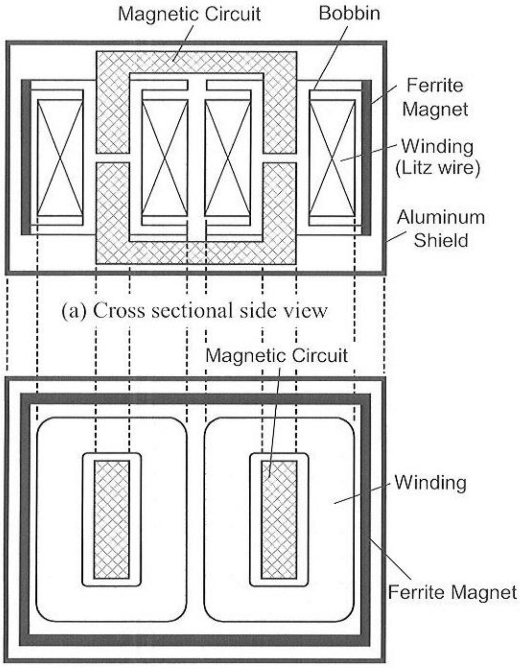


Fig. 9. Appearance of high-frequency transformer.



(a) Cross sectional side view

(b) Top view

Fig. 10. Physical Structure of high-frequency leakage transformer.

5. Conclusions

By applying the high-frequency soft switching inverter linked power conversion conditioning and processing system topology based on the single-ended high frequency soft switching sinewave pulse modulated inverter using a single active power switch which is composed of a high frequency transformer isolation for utility-connected inverter type solar photovoltaic power conditioner, a downsized lightweight and flat sinewave pulse modulated inverter using the latest trench gate IGBTs was demonstrated for small scale and distributed residential applications and evaluated from a practical point of view. The micro computer-based control system was implemented for PLL-connected utility interactive high frequency link solar power conditioner. The excellent performances of this solar power conditioner were actually confirmed through the experimental results obtained from a 4kW prototype breadboard setup designed for small scale distributed utility interactive power supply.

In the future, the other circuit topologies of soft switching sinewave power conditioning and processing converter with high frequency transformer AC link should be studied and evaluated as compared with the single ended soft switching pulse frequency sinewave modulated inverter treated here.

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Koki Ogura was born in Shimane, Japan. He received his B. Eng. and M. Eng. degrees in Electrical and Electronics Eng. from Yamaguchi University, Yamaguchi, Japan in 2000 and 2002, respectively. He is currently doing research in Dept. of Electrical System Engineering, the Graduate School of Science and Engineering, Yamaguchi University, Japan towards his Ph. D. degree. His research interests include the development of high frequency soft-switched resonant power conversion circuits and systems applied to new energy system such as photovoltaic generation system. He is a student member of IEEE, the Institute of Electrical Engineers of Japan , the Japan Society for Power Electronics and the Japan Solar Energy Society.

Srawouth Chandhaket was born in Surin, Thailand. He received his B. Eng. degree in Electronics from Kobe University, Kobe, Japan in 1995 and also his M. S. degree in Electrical Engineering from Virginia Tech in 1998. He is currently a Ph. D. candidate in the Graduate School of Engineering and Science, Yamaguchi University, Yamaguchi, Japan since 2001. His research interests include the soft-switching technology in power electronics and power systems, the stability of power system network and the applications of soft computing in power electronics and power systems. He is a student member of IEEE, the Institute of Electrical Engineers of Japan and the Japan Solar Energy Society.

Mutsuo Nakaoka was born in Hiroshima, Japan. He received his doctoral degree in Electrical Engineering from Osaka University, Osaka, Japan in 1981. He joined in the Electrical and Electronics Engineering Department, Kobe University, Kobe, Japan in 1981. Since 1995, he has been a professor in the Electrical and Electronics Engineering Department, the Graduate School of Engineering and Science, Yamaguchi University, Yamaguchi, Japan. His research interests include circuit and control systems of power electronics, especially in soft-switching areas. Dr. Nakaoka is a member of the Institute of Electrical Engineers of Japan, the Institute of Electronics, Information and Communication Engineers of Japan, the Institute of Illumination Engineering of Japan and a senior member of IEEE.

Haruo Terai was born in Japan, 1949. He received B.S. degree in electrical engineering from Osaka University, Japan, in 1973. Since 1973, he has been with Matsushita Electric Industrial Co., Ltd., where he is currently engaged in the development of electronic control system for household/cooking appliances. He is now in charge of the director of Home Appliance and Housing Electronics Research Laboratory. Mr. Terai is a member of the Institute of System, Control and Information Engineers, the Institute of Electrical Engineers of Japan and the Japan Society for Power Electronics. He was awarded IATC Award of Excellence in 1983 and Ohm Technical Prize in 1999.

Shinichiro Sumiyoshi was born in Kagoshima, Japan, in 1963. He received the B.S. and M.S. degrees in Nuclear Engineering from Kyushu University, Fukuoka, Japan in 1986 and 1988, respectively. Since 1991, joined the Home Appliance Research Laboratory, Matsushita Electric Industrial Co., Ltd. He has been engaged in development research on high frequency inverter applications. Mr. Sumiyoshi is a member of the Institute of Electrical Engineers of Japan and the Japan Society for Power Electronics.

Takeshi Kitaizumi was born in Osaka, Japan, on May 5,1967. He received the B.S. and M.S. degrees in Electronic Engineering from Tohoku University, Miyagi, Japan in 1991 and 1993, respectively. Since 1993, joined the Home Appliance and Housing Electronics Research Laboratory, Matsushita Electric Industrial Co., Ltd. He has been engaged in development research on high frequency inverter applications. Mr. Kitaizumi is a member of the Japan Society for Power Electronics.

Hideki Omori was born in Japan, 1954. He received the B.S., M.S., and Dr.Eng. degrees in electrical engineering from Kobe University, Japan, in 1975, 1977, and 1988, respectively. Since Joining Matsushita Electric Industrial Co., Ltd., in 1977, he has been engaged in developmental research of power electronics. He is now a general manager of Home Appliance and Housing Electronics Research Laboratory, Matsushita Electric Industrial Co., Ltd. Dr. Omori is a member of the Institute of Electrical Engineers, the Institute of Electronics and Communication Engineers of Japan, and the IEEE. He is a councilor of the Japan Society for Power Electronics. He received an Ohm Technical Prize in 1994, and a Minister of Education and Science Award in 2002.