JPE 7-2-4

Selective Dual Duty Cycle Controlled High Frequency Inverter Using a Resonant Capacitor in Parallel with an Auxiliary Reverse Blocking Switch

Bishwajit Saha†, Ki-Young Suh*, Soon-Kurl Kwon*, Tomokazu Mishima** and Mutsuo Nakaoka*

†* Department of Electrical Engineering, Kyungnam University, Masan, Korea
** Kure National College of Technology, Hiroshima, Japan

ABSTRACT

This paper presents a new ZCS-PWM high frequency inverter. Zero current switching operation is achieved in the whole load range by using a simple auxiliary reverse blocking switch in parallel with series resonant capacitor. Dual duty cycle control scheme is used to provide a wide range of high frequency AC output power regulation that is important in many high frequency inverter applications. It found that a complete soft switching operation can be achieved even for low power setting ranges by introducing high-frequency dual duty cycle control scheme. The proposed high frequency inverter is more suitable for consumer induction heating (IH) applications. The operation and control principle of the proposed high frequency inverter are described and verified through simulated results.

Keywords: high frequency inverter, ZVZCS, reverse blocking switched resonant capacitor, induction heated load, dual duty cycle control

1. Introduction

With great advances in high frequency power electronics, electromagnetic eddy current based induction heating (IH) technology has become more acceptable for consumer food cooking and processing appliances such as rice cookers, warmers, hot water producer, along with super heated steamer. Currently variety of IH equipments not only fill up demands of safety and cleanliness, but also has excellent advantages; such as very high thermal conversion efficiency, rapid heating, local spot heating, direct heating, high power density, high reliability, low running cost and non-acoustic noise. Aforementioned IH appliances using high frequency inverters make use of eddy current based Joule's heat and Faraday's electromagnetic induction law. The high frequency inverters of induction heating applications can supply high frequency power to IH load, which consists of working coil and eddy current based heating materials. Some high frequency inverters operating over power frequency ranges from 20 kHz to several MHz need to be cost effective, high efficiency and high power density. There is various high frequency inverter circuit topologies, such as full bridge, half bridge, single-ended push-pull, center tap push-pull and boost half bridge. Of these, the voltage source type ZCS (zero current switching), ZVS (zero voltage switching), SEPP (Single-Ended Push Pull)

Manuscript received Dec. 4, 2006; revised Feb. 9, 2007
†Corresponding Author: bsaha@ieee.org
Tel: +82-55-2633, Fax: +82-55-242-2683, Kyungnam Univ.
*Department of Electrical Engineering, Kyungnam Univ.
**Kure National College of Technology

resonant and quasi-resonant hybrid high frequency inverter has unique features; such as simple configuration, high efficiency and wide soft commutation range. The proposed inverter is configured by IGBTs and evaluated by simulation diagrams.

As we know, induction heating appliances are employed in our family, this concept can be simplified as follows: Firstly, convert the utility AC voltage into smoothing or non-smoothing DC use rectifier, then connected to high frequency switching circuit to supply high frequency current to the working coil.

There are several types and topologies of high frequency inverter used in consumer induction heating appliances. The newly developed high frequency inverter consists of half bridge series resonant converter and bypass switch. The advantages of half-bridge series resonant converter are stable switching, low cost and streamlined design.

2. ZVZCS-PWM High Frequency Inverter

2.1 Circuit Configuration

Figure 1 shows the newly developed duty cycle ZVZCS PWM high-frequency inverter circuit topologies using the latest trench gate IGBTs and operating with constant frequency PWM control strategy. This voltage-fed PWM high frequency inverter circuit consists of two main switches reverse conducting IGBTs Q_1 (SW_1/D_1) and Q_2 (SW_2/D_2), a single reverse blocking auxiliary switch Q_3 (SW_3/D_3). The IH load modified topology of the proposed inverter is illustrated in Fig. 2. The resonant circuit comprises of resonant inductance (L_0) and resonant capacitance (C_r). The capacitors, C_1 and C_2, are the lossless turn-off snubbers Q_1 and Q_2.

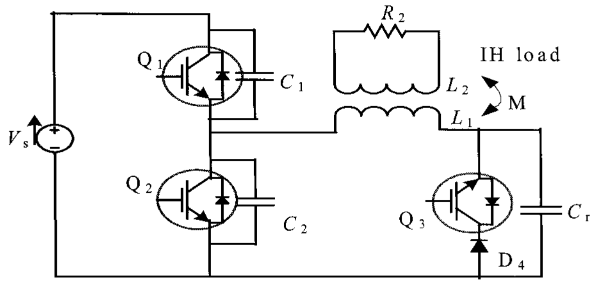


Fig. 1 Proposed soft-switching high frequency inverter for induction heated load

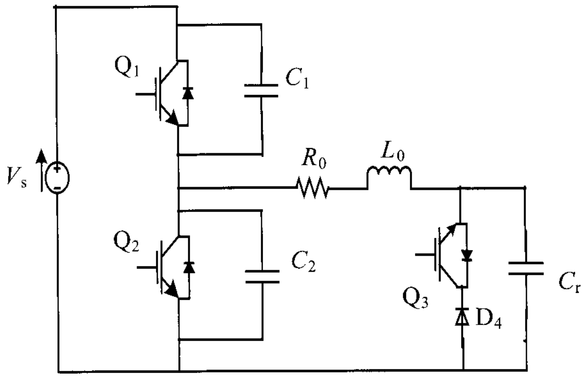


Fig. 2 Modified topologies of inverter circuit shown in Fig. 1

2.2 Gate Pulse Timing Sequences

The high frequency AC output power of the proposed inverter circuit, delivered to the IH load as IH cooker, can be continuously regulated by a constant frequency asymmetrical PWM duty cycle control scheme under a condition of zero voltage-current switching commutation modes. The proposed gate voltage pulse timing PWM sequences for the active power switches Q_1, Q_2 and the auxiliary power switch Q_3 are shown in Fig. 3.

2.3 HFAC Power Regulation Scheme

The output high-frequency AC effective power of the proposed soft-switching high frequency inverter circuit in Fig.1 can be continuously regulated by a constant frequency dual duty cycle PWM control scheme under a condition of zero voltage-current transition soft switching principle. The PWM gate pulse timing sequences are illustrated in Fig.3. Constant frequency asymmetrical PWM control scheme, which is based on varying the time ratio of total conduction times T_{on} of Q_1, Q_2 and Q_3 to the operating switching period T of high-frequency, the proposed high-frequency inverter circuit can control the high-frequency output power continuously. The conduction time T_{on1} of Q_1 (SW_1/D_1) and the conduction time T_{on3} of Q_3 can be varied. As a control variable in the proposed dual duty cycle PWM schemes, selective duty cycle is defined as

$$D_1 = \frac{T_{on1}}{T} \tag{1}$$

$$D_2 = \frac{T_{on3}}{T} \tag{2}$$

2.4 Induction Heating Equivalent Load

The high frequency inverter circuit with IH loads includes non-magnetic conductive stainless steel plate or vessel via ceramic spacer, which is magnetically coupled with a spiral planar, rectangular or cylindrical working coil. The IH load circuit of the proposed resonant inverter consists of the working coil composed of litz wire and IH metal-based object (pan or vessel) represented by the transformer equivalent circuit model (Load time constant $\tau = L_2/R_2$ [R_2: Equivalent effective resistance due to a frequency dependent skin effect of the heated material itself, L_2: the eddy current induced side self inductance].

The electro-magnetic coupling coefficient (k) is given by $k = M / (L_1L_2)^{1/2}$ where L_1 is the self-inductance of the working coil, with loosely-coupled mutual inductance M. The equivalent effective resistance R_0 and inductance L_0 is derived from the working coil side of a variety of IH loads as the following equations (3) and (4) respectively. The current stored into the equivalent inductive component is required to achieve ZCS in main power switch Q_1, Q_2 and ZVS in the high side subsidiary power switch Q_3. The inductor makes resonance in accordance with the resonant capacitor C_r. The auxiliary power switch Q_3 is in parallel with the resonant capacitor C_r that creates induction-heated load for the resonance.

$$R_0 = \frac{\omega^2 M^2 R_2}{R_2^{\,2} + \omega^2 L_2^{\,2}} + R_{L1} \tag{3}$$

$$L_0 = L_1 - \frac{\omega^2 M^2 L_2}{R_2^{\,2} + \omega^2 L_2^{\,2}} \tag{4}$$

2.5 Remarkable Features

The outstanding features of the newly developed soft switching high frequency inverter are summarized below:

The DC component of the high frequency current through the working coil is zero because the series capacitor compensated resonant tank.

The ZVS soft switching commutation range becomes much wider because dual mode duty cycle.

The effective efficiency of this high frequency inverter is much higher over wider power regulation range from high power settings to low power settings because selective dual duty cycle mode PWM control scheme.

Constant frequency operation can be implemented.

3. Principle of Operation

3.1 Circuit Operation

The current flow and equivalent circuits of this inverter in steady state are illustrated in Fig. 4. The operating modes of proposed soft-switching high frequency inverter are divided into six modes:

Mode 1: This mode starts when Q_2 begin conducting, current flows through R_0, L_0, C_r until D_4 is forward biased as shown in Fig.4a.

Mode 2: In this mode D_4 begin to conduct, the current passing through R_0, L_0, D_4, Q_3, and Q_2 until Q_3 is turned off as depicted in Fig. 4b.

Mode 3: This current circulates in C_r, L_0, R_0, and Q_2 until Q_2 is turned off as shown in Fig. 4c.

Mode 4: In this mode, D_2 conducts due to energy stored in L_0 until Q_2 start conducting as in Fig. 4d.

Mode 5: Main switch Q_1 is turned on, the supply current passing through Q_1 divided between (C_r+ R_0+ L_0) and C_2 as shown Fig. 4e.

Mode 6: After the voltage across C_2 exceeded its maximum value, D_1 now is conducting as in Fig. 4f.

3.2 Operating Voltage and Current Waveforms

The corresponding switching modes, voltage and current waveforms and the proposed high frequency inverter in steady state during one switching cycle are shown in Fig. 5. The switches of ZCS resonant converter

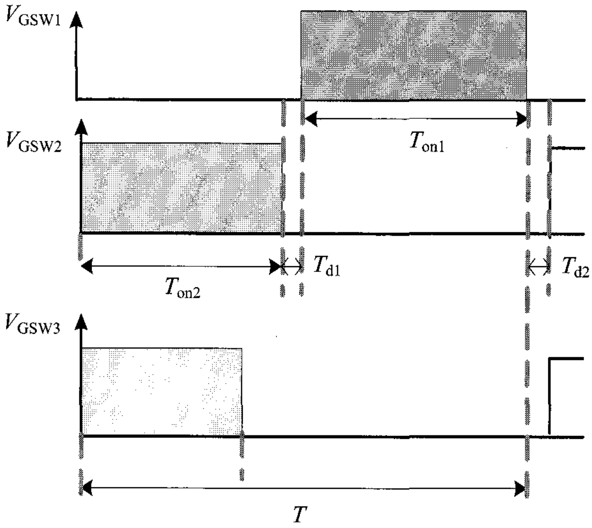
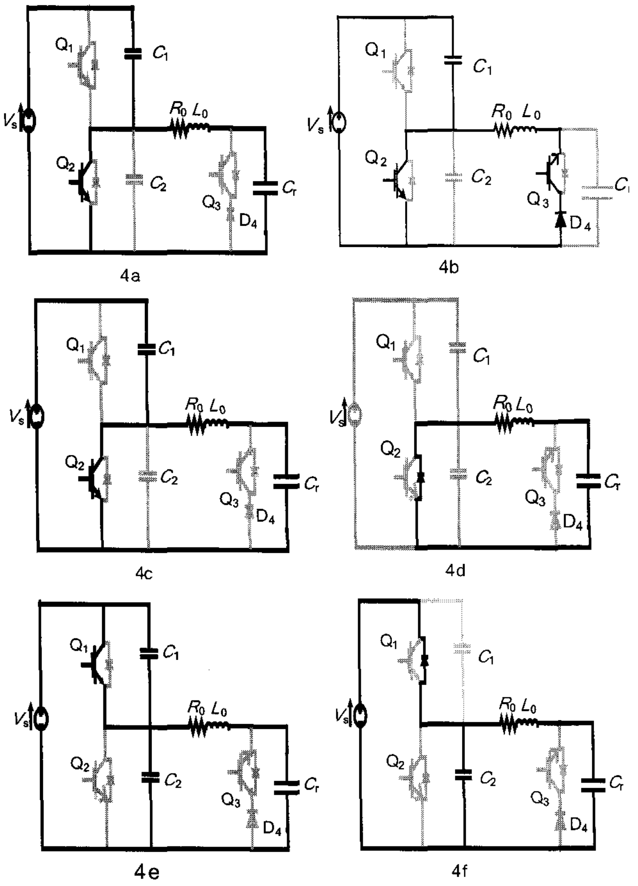


Fig. 3 Gate pulse timing sequences pattern of dual duty cycle

turn on and off at zero current. The capacitors are connected in parallel with Q_1, Q_2, and Q_3 to achieve ZVZCS. The internal switch capacitance is added to the capacitors and it affects only the resonant frequency, thereby contributing no power dissipation in the switch. These switches are implemented by Q_1, Q_2 with anti parallel diode D_1, and D_2. So, the voltage across capacitors is clamped by D_1, D_2 and these switches operate in half wave configuration, the voltage across C_r is clamped by D_3. If diode D_4 is connected in series with Q_3 the voltage across C_r will be oscillate freely and the switch will operate in a full wave configuration.

4. High Frequency AC Power Regulation Characteristics and Performances

Output power vs. duty cycle characteristics for the proposed voltage source type dual duty cycle high frequency inverter with PWM control scheme using the trench gate IGBTs is depicted Fig. 6. In the high-frequency inverter circuit proposed here, the input power of this inverter can be regulated approximately from 0.2 kW to 3.4 kW at switching frequency 20 kHz under a principle of soft-switching commutation. The soft-switching operating range is relatively large in the proposed PWM dual duty cycle high frequency inverter.



4a 4b 4c 4d 4e 4f

Fig. 4 Operating modes and current commutation equivalent circuits

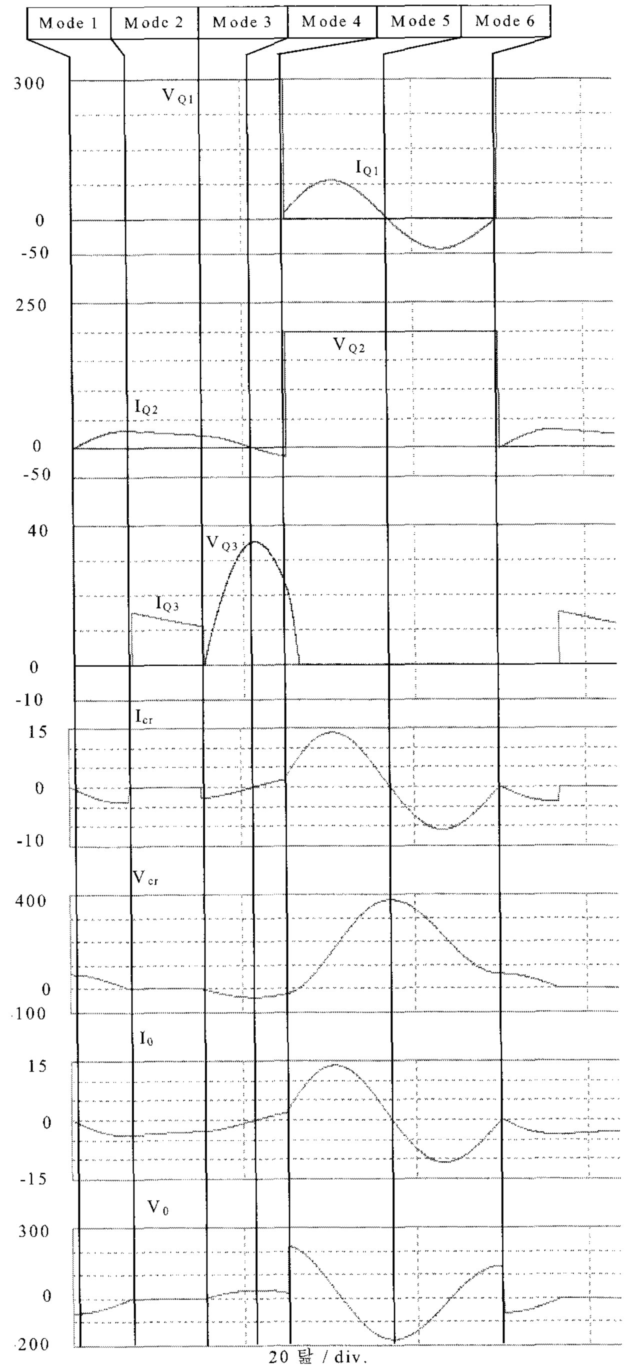


Fig. 5 Relevant voltage and current waveforms

The diagram of output power vs. auxiliary control duty cycle has shown in Fig. 7. This diagram depicts the output power regulation affected by the auxiliary control at certain values of the main control scheme. Figure 8 depicts the output illustrated power regulation characteristics of the proposed high frequency inverter.

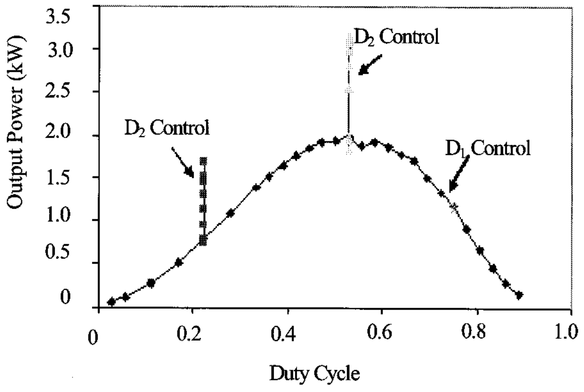


Fig. 6 Output power regulation characteristics

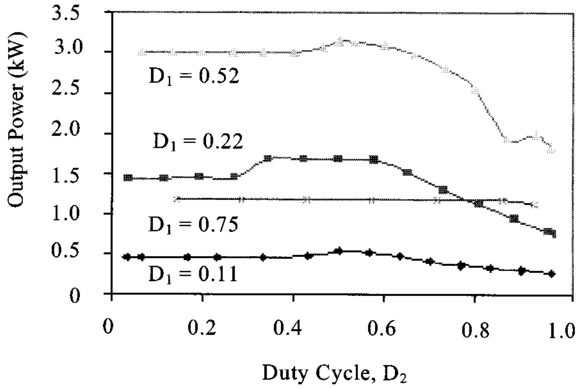


Fig. 7 Output vs. auxiliary control duty cycle

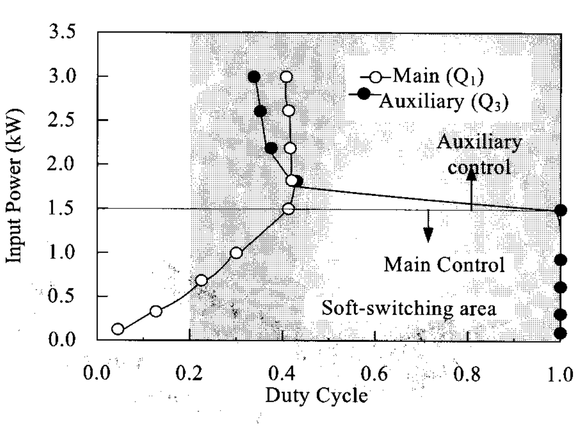


Fig. 8 Comparative power regulation characteristics

5. Conclusions

In this paper, a new circuit topology of a dual duty cycle controlled soft-switching high frequency inverter with single auxiliary reverse blocking switch in parallel with resonant capacitor. The operation principle and the power characteristics of the newly developed high frequency inverter circuit were illustrated and evaluated on the basis of simulation results. Through these simulations, complete soft switching operation can be achieved even for low power setting ranges by introducing high-frequency dual duty cycle control scheme.

Therefore, it was proved that the proposed ZVS soft switching PWM high-frequency inverter can actually achieve high efficiency, high performance and obtain wider soft switching range in selective dual duty cycle PWM control scheme. For commercial IH cooking appliances, the practical effectiveness of the proposed voltage source ZVZCS-PWM dual duty cycle high frequency inverter evaluated on the basis of simulation results.

Acknowledgment

Ministry of Commerce, Industry and Energy (MOCIE) financially supported this work through Industry and Energy Research Center (IERC) program.

References

[1] Muhammad H. Rashid, Power Electronics Circuits, Devices and Applications, Third Edition (International)

[2] H. S. Choi, B. H. Cho, "Improved Zero Current Switching (ZCS) PWM Switch Cell with Minimum Additional Conduction Losses", Journal of Power Electronics (KIPE), Vol.1, No.2, pp 71-77, October 2001.

[3] L. Gamage, T. Ahmed, H. Sugimura, S. Chandhaket and M. Nakaoka," Series Load Resonant Phase Shifted ZVS-PWM High frequency Inverter with a Single Auxiliary Edge Resonant AC Load Side Snubber for Induction Heating Super Heated Steamer", Proceedings of International Conference on Power Electronics and Drive Systems (PEDS), Singapore, November, 2003 Vol. 1, pp. 30-37.

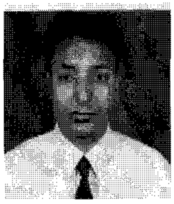
[4] H. Ogiwara, M. Itoi and M. Nakaoka, PWM-controlled soft-switching SEPP high-frequency inverter for induction-heating applications" IEE Proceeding- Electric

Power Applications, Vol. 151, No. 4, July 2004.

[5] H. Tanimatsu, H. Sadakata, T. Iwai, H. Omori, Y. Miura, E. Hiraki, H. W. Lee, M. Nakaoka," Quasi-Resonant Inductive Snubbers-Assisted Series Load Resonant Tank Soft Switching PWM SEPP High-Frequency Multi Resonant Inverter with Auxiliary Switched Capacitor" Proceeding of 6th International Conference on Power Electronics (ICPE), Busan, Korea, October, 2004 pp II-299.

[6] W. S. Choi, N. Ju Park. D.Y. Lee, D. S. Hyun. "A New Control Scheme for Class D inverter with induction Heating Jar Application by Constant Switching Frequency", Journal of Power Electronics, Vol. 5, No. 4, October 2005, pp272-281.

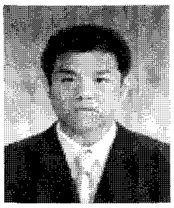
[7] B. Saha, H. W. Lee and M. Nakaoka, "Utility Frequency AC to High Frequency AC Power Converter with Boost-Half Bridge Single Stage Circuit Topology" Proceedings of IEEE-ICIT, 15-17 Dec 2006, Mumbai, India.



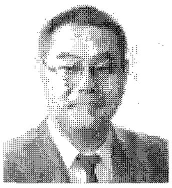
Bishwajit Saha received B.Sc. degree in Electrical and Electronics Engineering in 2004 from Dhaka University of Engineering & Technology, Bangladesh. He is now studying toward Ph.D. degree in the Department of Electrical & Electronic Engineering, Electric Energy Saving Research Center, Kyungnam University, Masan, Republic of Korea. His research interests are development of DC-DC power converter topologies, high frequency inverters applications and renewal energy related power conditioners. He is a student member of IEEE-USA and IEB-Bangladesh.

Ki-Young Suh received B.S., M.S., and Ph. D degrees in the Dept. of Electrical Engineering from the Han Yang University, Seoul, Korea, in 1965, 1980 and 1987, respectively. He is currently a professor in the department of Electronic and Electrical Engineering at Kyungnam University, Masan, Korea. He is an active member of KIEE, KIPE, KIIEE, and IEEJ

Soon-Kurl Kwon received Ph. D (Dr-Eng) degree in Electrical Engineering from Young-Nam University, Daegu, Republic of Korea. He joined the Electrical Engineering Department of Kyungnam University, Masan, Republic of Korea, in 1983 as a professor. He was a visiting professor of Virginia Polytechnic Institute and State University, USA in 1997. His research interests include application developments of power electronics circuits and system. He is a member of the KIEE and KIPE.



Tomokazu Mishima received B.E, M.S., and Dr-Eng. Degrees, all in Electrical and Electronics Engineering, from the University of Tokushima, Japan in 1999, 2001 and 2004, respectively. Since 2003, he has been with Kure National College of Technology, Hiroshima, Japan, as a research associate in the Department of Electrical Engineering and Information Science. His research interests include design and analysis of soft switching DC-DC converter topologies, power conditioners of renewable energy storage devices and their control systems. He received the 2001 Paper Award from IEEJ. He is a member of IEEE (PELS, IES, and IAS), IEEJ, and JIPE.



Mutsuo Nakaoka received Dr-Eng. degree in Electrical Engineering from Osaka University, Osaka, Japan in 1981. He joined the Electrical and Electronics Engineering Department of Kobe University, Kobe, Japan in 1981 and served as a professor in the Dept. of Electrical and Electronics Engineering, Graduate School of Engineering, Kobe University, Kobe, Japan. Since 1995, he has been a professor in the Electrical and Electronics Engineering Department, Graduate School of Science and Engineering, Yamaguchi University, Yamaguchi, Japan and Hyogo College of Industrial Technology, Hyogo, Japan. His research interests include application developments of power electronics circuits and systems. He received the 2001 Premium Prize Paper Award from IEE-UK, 2001/ 2003 IEEE-IECON Best Paper Award, the third paper award in 2000 IEEE-PEDS, 2003 IEEE-IAS James Melcher Prize Paper Award, Best Paper Award in the International Appliance Technical Conference, as well as other numerous awards. He is now a chairman of IEEE Industrial Electronics Society Japan Chapter. He is an active member of the, IEE-J, IEICE-J, Solar Energy Institute of Engineers, European Power Electronics Association, IEIE-J, KIPE, JIPE and IEEE.