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Dual Mode Phase-Shifted ZVS-PWM Series Load Resonant High-Frequency Inverter for Induction Heating Super Heated Steamer

Hisayuki Sugimura*, Hidekazu Muraoka*, Tarek Ahmed†, Srawouth Chandhaket*,
Eiji Hiraki*, Mutsuo Nakaoka*, and Hyun-Woo Lee**

*Division of Electrical and Electronics Eng., The Graduate School of Science and Engineering,
Yamaguchi University, Yamaguchi, Japan
**The Electric Energy Saving Research Center, Kyungnam University, Masan, Korea

ABSTRACT

In this paper, a constant frequency phase shifting PWM-controlled voltage source full bridge-type series load resonant high-frequency inverter using the 4th generation IGBT power modules is presented for innovative consumer electromagnetic induction heating applications, such as a hot water producer, steamer and super heated steamer. The bridge arm side link passive capacitive snubbers in parallel with each power semiconductor device and AC load side linked active edge inductive snubber-assisted series load resonant tank soft switching inverter with a constant frequency phase shifted PWM control scheme is evaluated and discussed on the basis of the simulation and experimental results. It is proved from a practical point of view that the series load resonant and edge resonant hybrid high-frequency inverter topology, what is called, DE class type, including the variable-power variable-frequency regulation function can expand zero voltage soft switching commutation area even under low output power setting ranges, which is more suitable and acceptable for newly developed induction heated dual pack fluid heaters. Furthermore, even the lower output power regulation mode of this high-frequency load resonant tank inverter circuit is verified so that this inverter can achieve ZVS with the aid of the single auxiliary inductor snubber.

Keywords: Series load resonant tank high-frequency inverter, Active auxiliary resonant AC load resonant inductor snubber, Lossless capacitive snubbers, Voltage-fed full brige inverter, Zero voltage soft switching, Induction heating, Dual pack fluid heater as a heat exchanger, Consumer power electronics

1. Introduction

With tremendous modern advances in the present Si-based power semiconductor switching devices such as MOSFETs, IGBTs, IEGTs, MCTs, SITs and IGCTs in addition to the promising SiC-based power semiconductor switching devices SiC-SBD, SiC-MOSFETs and SiC-SITs, high performance voltage source and current source types of the high-frequency series or parallel load resonant tank series and parallel hybrid tank inverters for large current induction-heating power supplies have been widely applied for the forging, brazing, sealing, welding, melting and heat treatment processing in industrial power

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†Corresponding Author: tarek@pe-news1.eee.yamaguchi-u.ac.jp
Division of Electrical and Electronics Eng, Yamaguchi Univ.
Tel: +81- 836-85-9472, Fax: +81-836-85-9401
* Division of Electrical and Electronics Eng, Yamaguchi Univ.
**The Electric Energy Saving Research Center, Kyungnam Univ.

processing plants. On the other hand, the induction heating technologies have attracted special interest for consumer power and energy applications such as induction heating cooking burners, rice cookers and warmers, hot water producers, steamers and super heated steamers.

In recent years, the electromagnetic induction eddy current based heat energy processing appliances and equipment in the industrial, automotive and consumer pipeline systems as well as cogeneration pipeline systems have attracted special interest which incorporate the voltage-fed series resonant type, the current-fed parallel resonant type, the voltage and current hybrid source-fed multi-resonant type, the edge-resonant type and auxiliary resonant high-frequency load resonant inverter circuit topologies using the latest IGBT power modules packages (CSTBTs) and intelligent power switch module (IPS) and intelligent power module (IPM). These high frequency resonant inverters have some advantageous points such as high efficiency, high reliability, high safety, cleanliness, compactness in volumetric physical size, lighter weight, rapid temperature control responses as well as stable temperature tracking and precise temperature controllability and multi-functionability. The new consumer products of the induction heating appliances using the voltage source high-frequency edge resonant ZVS-PWM inverters operating under the conditions of the soft-switching commutation manner have been previously developed by the authors [1][2], which are effectively applied for cooking pans, rice cookers and warmers, hot water producers, steamers and super heated steamed dryers and cleaners, and floor and wall heating boilers in promising household and business uses in consumer power electronics.

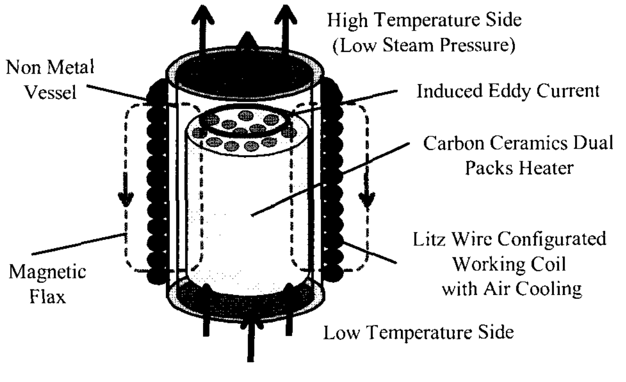


Fig. 1. System configuration of electromagnetic induction eddy current heater termed as dual packs fluid heater appliance developed newly.

Under these technological backgrounds, some attractive electromagnetic induction eddy current based flow-through metal assembly package fluid-heating appliances using the voltage-fed edge resonant ZVS-PWM control type series load resonant tank high-frequency inverter circuit topologies operating at a constant frequency variable power regulation (CFVP) scheme has originally been proposed so far by the authors [2]-[5].

This paper presents a prototype of the voltage source type ZVS-PWM series load resonant high-frequency inverter with an active auxiliary edge resonant snubber in AC load side in addition to the auxiliary passive lossless capacitive snubbers in bridge arm side for the electromagnetic induction eddy current-based fluid heater, or dual pack fluid heater and dual pack steam heater as an induction heated heat exchanger in pipeline plants. Its operation principles and unique features of the newly-developed electromagnetic induction eddy current-based dual pack fluid heater which is composed of using the proposed voltage source soft switching series load resonant inverter using IGBT power modules are evaluated and discussed on the basis of simulation and experimental results from an application point of view.

2. Electromagnetic Induction Eddy Current-Based Dual Packs Fluid Heater

Figure 1 shows a schematic configuration of the new conceptual electromagnetic induction eddy current-based continuous fluid (liquids or gasses, vapor, powder) heater or induction heating (IH) dual pack fluid heater as a small scale IH boiler or IH heat exchanger [6]-[8]. This flow-through IH dual pack heater used as a high efficiency IH heat exchanger is driven by the active voltage-clamped resonant edge and the passive capacitive snubber-assisted ZVS-PWM high-frequency inverter using IGBTs. These IGBTs can operate with the phase-shifted PWM control strategy capable of extending the zero voltage soft switching commutation operating range.

In general, this innovative electromagnetic induction-heated fluid-heating appliances or dual pack fluid heaters including high-frequency series load resonant inverters with the series compensation capacitor, which are used for the industrial, chemical, mechanical energy processing and consumer pipeline systems is basically composed of a single-phase diode rectifier with a non-smoothing DC capacitor filter link, an active voltage-clamped edge-resonant ZVS-PWM high-frequency inverter with CFVP (Constant Frequency Variable Power) function, and specially-designed induction heating dual pack fluid heater shown in Fig.2.

Figure 2 illustrates the eddy current dual pack fluid heater using the high temperature carbon ceramic cylinder with many thin axial tubes. In this carbon ceramics developed as a new material, which is called semi-coke, the various types of ceramics are compounded, mixed and grounded on the basis of a special approach in cold isotonic pressing to many type of shapes, then burned and sintered more than 1500 degree centigrade. The new ceramics material produced newly are able to be made into several forms to suit best for the new application specific composite material such as electromagnetic induction eddy-current based heater operating at a high temperature.

The carbon ceramic characteristics are the increased strength, the variable electrical resistance, the wetting resistance due to lower water absorption, the oxidation resistance, the high temperature strength and the high erosive resistance.

The turbulence fluid flowing through this IH dual pack fluid heater appliance put tightly into the non-metal vessel or chamber serves to exchange efficient heat energy due to the electromagnetic induction eddy current based fluid heating energy processing.

This continuous moving fluid-heating appliance using carbon ceramic cylinder with many axial thin tubes as the fluid channel, which allocates the non metal vessel with the working coil through high-frequency resonant inverter is more suitable and acceptable for fluid heat energy transfer and delivery utilization. This IH dual pack fluid heater in the vessel is driven by the high-frequency inverter, which is able to be realized for a prototype of compact and efficient steamer as IH heat exchanger and super heated steam producer used for a variety of fluid pipeline systems. This fluid heating based on induction heating principle should be implemented and discussed on the unique features of this dual pack fluid heater including compactness, cleanliness, high efficiency, quick temperature responses, stable and precise temperature control characteristics, excellent dynamic controllability in temperature tracking, high reliability, safety and handy on-site fluid heat energy utilizations.

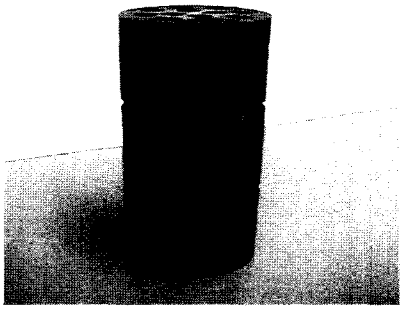
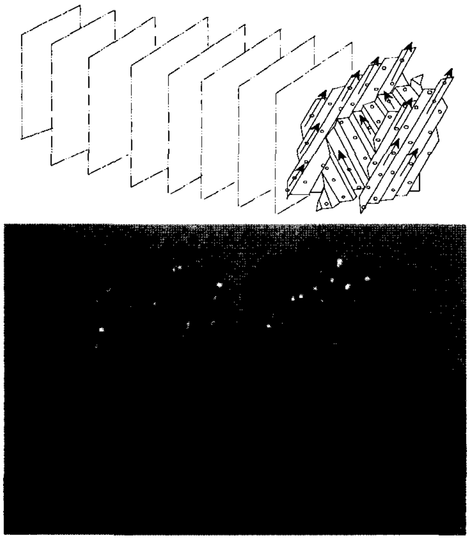


Fig. 2. Divided fluid-through carbon ceramics heating devices termed as induction heating dual packs fluid heater developed newly.

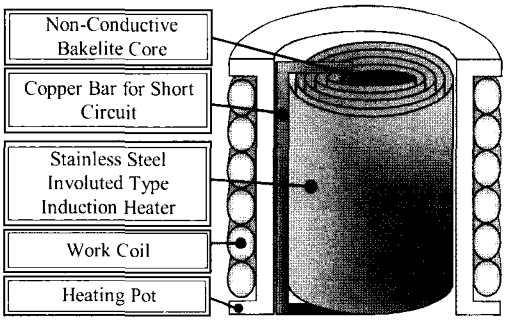
It is practically noted that a new conceptual induction-heated dual pack fluid heating appliance using the previously developed voltage-clamped edge-resonant ZVS-PWM inverter and the lossless capacitive snubber-assisted voltage source type series load resonant ZVS-PWM high-frequency inverter using the trench gate IGBT power modules can be more cost effective and convenient from an effective energy utilization point of view.

In addition, the structure of a specially designed metallic laminated assembly to generate turbulence is shown in Fig.3 (a). This new prototype of induction heating fluid heater, which is made of the electromagnetic induction heated type fluid-through thin metallic layer laminated assembly with many random spots and mechanically processed triangular wavelike channel slits in order to generate natural moving fluid turbulence in all kinds of pipeline systems. This thin metal layer package consists of thin conductive and non magnetic metal sheet heating bodies with a large amount of eddy current-based induction heating surface area, which is incorporated into the high-temperature proof ceramic vessel with non water-cooled working coil connected to the high-frequency inverter treated here. Another induction heating spiral heater developed newly by the authors is shown in Fig.3 (b-1) and top view appearance of induction heating spiral heater represented in Fig.3 (b-2). It is composed of the spiral assembly and each outside edge point is directly connected to the inside edge point by the low resistance copper bar. In this technique, it is possible to achieve unity in temperature distribution of an electromagnetic induction eddy current-based induction heated type dual pack heater as the compact heat exchanger.

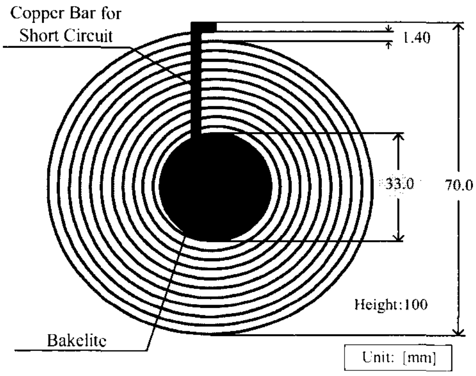
In general, it is difficult to form the spiral structure



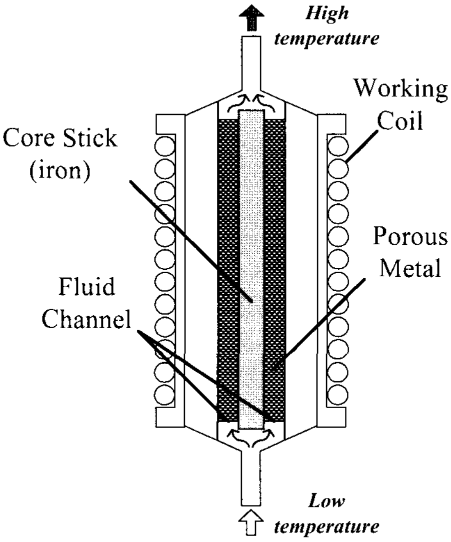
(a) Specially-designed metallic laminated assembly dual packs heater to generate turbulence



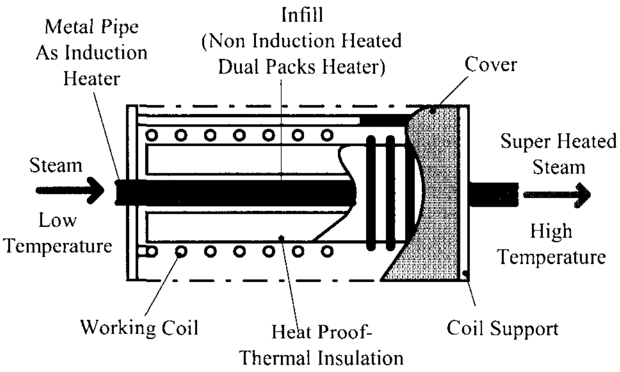
(b-1) Electromagnetic Induction eddy current-based stainless plate involute type spiral heater as the dual packs heater.



(b-2) Top view appearance of electromagnetic induction eddy current-based involute spiral dual packs heater



(c) Porous metal type dual packs heater



(d) Internal metal tube type dual packs heater

Fig. 3. Dual packs heater as the IH boiler

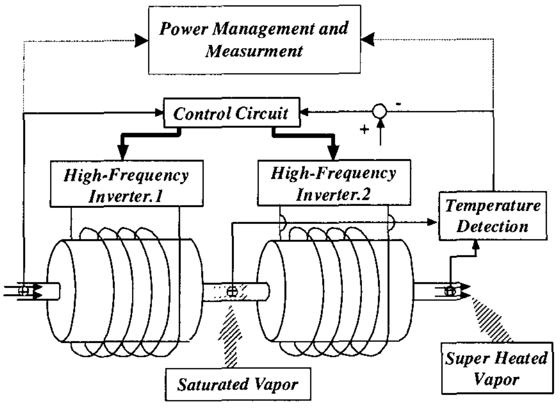


Fig. 4. Super heated steam producer system

toward its center axis. In case of rolling up to its center axis, effective increment of the heating surface could not actually expect to increase in the vessel. However, if no obstacle is inserted toward the center of spiral metal assembly of the vessel, heat exchanger efficiency of this induction heater decreases because a large majority of heated liquid flows through the center of the heater. To improve the reduced heat exchange efficiency, the cylindrical polycarbonate material is inserted toward the center of the vessel. The size and shape of this induction heater is designed as illustrated in Fig.3 (b-2)[9][10]. The other induction heated dual pack heater structures as the IH boiler are shown in Fig.3(c)(d) and these are called porous metal type and internal metal tube type [11].

Figure 4 shows a schematic prototype of induction heated electromagnetic induction eddy current-based fluid heating appliance designed for the super heated steamer producer. The first stage saturated vapor producer called No.1 IH boiler can connected and the second stage fluid heater called No.2 IH boiler can produce super heated steam over temperature ranging from approximately 100-500°C; in some cases, ranging from 200°C to 800°C.

The moving fluid temperature in the pipeline systems is detected at three points in the IH fluid heating appliance shown in Figure 4 and is able to be regulated by an intelligent Fuzzy Logic-based PI controller available commercially. The first and second stage electromagnetic induction fluid heaters controlled individually by two high frequency inverters are distributed by introducing the voltage source type high-frequency soft switching resonant inverter using the IGBT power modules.

3. Phase Shifted ZVS-PWM High-Frequency Series Load Resonant Inverter

3.1 Circuit Description

Figure 5 shows a lossless capacitive snubber-assisted series load resonant high-frequency soft switching inverter as the class D-E type circuit topology which is used for the electromagnetic induction eddy current-based fluid-heating appliance for consumer power and energy processing. This inverter can operate under a condition of stable zero voltage soft switching (ZVS) commutation. As stated below, the constant high-frequency soft switching phase shifted PWM control strategy is introduced to regulate its output power. The gate voltage pulse timing sequences to drive the IGBTs in the high frequency inverter shown in Fig.5 are schematically depicted in Fig.6. The equivalent circuits for its operating mode are respectively shown in Fig.7. The induction heating (IH) dual pack fluid heater (DPH)

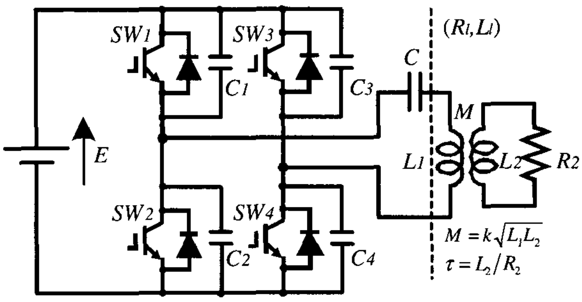


Fig. 5. Phase shifted ZVS-PWM controlled high-frequency series load resonant inverter with lossless snubbing capacitors using IGBT power modules.

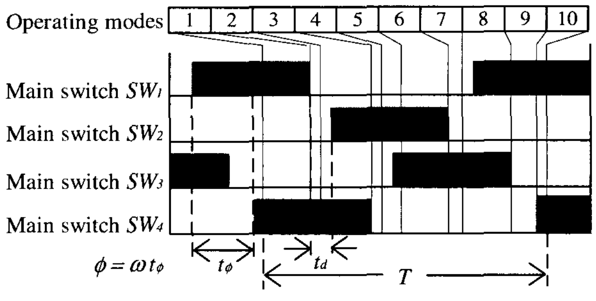
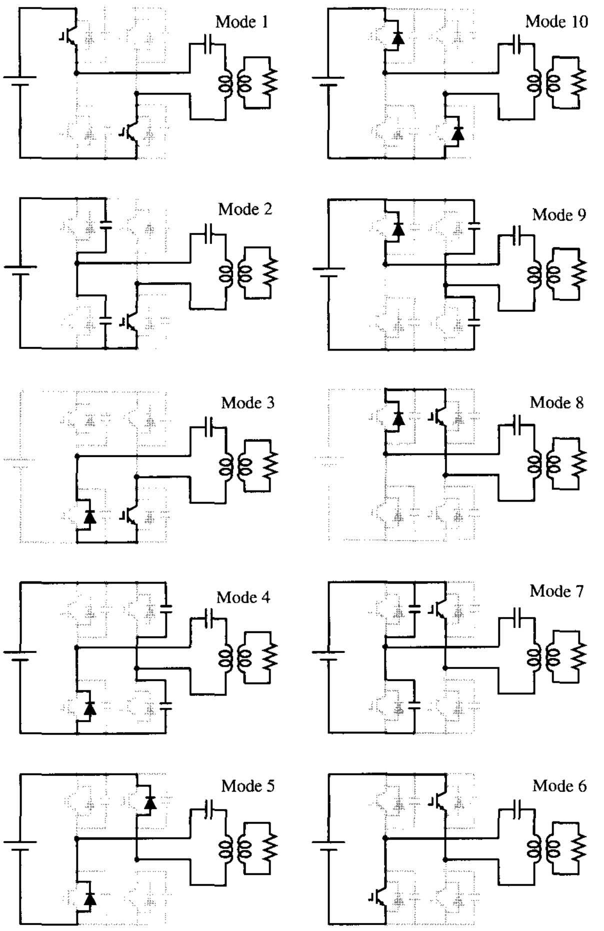


Fig. 6. Phase shifted mode gate voltage pulse signal sequences and circuit operating modes



ig. 7. Switching operation mode transitions and equivalent circuits

stablished previously by the authors. The IH-DPH ppliances are driven by the full bridge high-frequency nverter with bridge arm linked lossless capacitive nubbers as shown in Fig.5. However, the series ompensated resonant capacitor in series with the nduction heating load with highly inductive circuit or quivalent series inductive load R_l-L_l in a work coil side s connected to keep series tuned load resonant tank ondition at a full power setting. The switching frequency r output frequency of this high frequency resonant nverter is designed so as to operate under the 20kHz requency bands over the audible frequency ranges. The quivalent induction heated resonant tank load between he working coil terminals of the electromagnetic nduction heating type dual pack fluid heater appliance is lepicted by a transformer (mutually-coupled inductor) nodel represented by two measured circuit parameters of electromagnetic coupling coefficient $k = M/\sqrt{L_l L_2}$ between the working coil as the primary winding and dual pack heater as the secondary circuit, and the secondary side load circuit time constant $\tau = L_2/R_2$ determined by the skin effect-based resistance which is dependent on the inverter frequency.

3.2 Gate Pulse Pattern Sequences

The output power regulation which is based on a constant frequency phase-shifted PWM control scheme can be implemented by the high-frequency load resonant tank inverter circuit shown in Fig.5. The voltage clamping operation is possible to take the voltage specified by a DC power source applied to the active power switches (*SW1-SW4*) in the H type full bridge inverter topology. The low saturation voltage type power semiconductor device (IGBT) such as the trench gate IGBT; (CSTBT) and planer gate IGBTs produced by Mitsubishi Electric, Co., Ltd. can be effectively incorporated into the series load resonant inverter. On the other hand, the active voltage clamped type edge resonant high-frequency inverter cannot be used actually for the utility AC 200V-rms voltage source. The left side bridge leg with power switches (*SW1&SW2*) of the inverter bridge circuit (see Fig.5) is termed as the standard phase. In addition to this, the right side bridge leg with active power switches (*SW3&SW4*) is termed as the control

Table 1. Design specifications and circuit parameters

Item	Symbol	Parameter Constant
DC Source Voltage	E	140 V
Switching Frequency (Inverter Operating Frequency)	f	20 kHz
Capacitance of Power Factor Series Compensated Resonant Capacitor	C	2.9 μF
Inductance of Working Coil	L_l	31.0 μH
Coupling Coefficient between L_l and L_2	k	0.632
Load Time Constant specified by R5	τ	8.1μs
Capacitance of Lossless Snubber Capacitors	C_s	0.1 μF
Effective Resistance at Working Coil Side	R_l	0.78Ω
Effective Inductance at Working Coil Side	L_l	24.7μH

Remarks:

R_l; Resistance component of working coil, $R_l \cong 0$

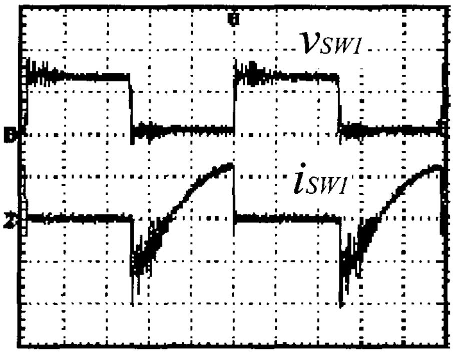
$k = M/\sqrt{L_l L_2}$

M; Mutual inductance between L_l and L_2

L_2; Secondary-side self inductance

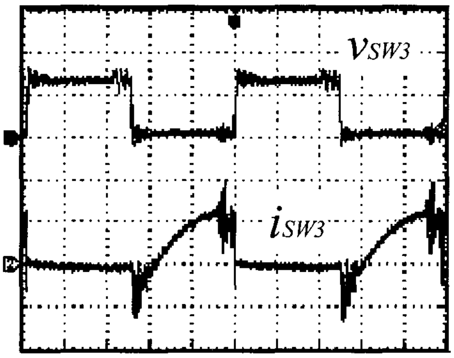
$\tau = L_2/R_2$

R_2; Skin effect related resistance which varies in accordance with the inverter operating frequency phase. In accordance with shifting the retarded phase difference determined by the control phase with respect to the standard phase, the effective output power of this high-frequency load resonant inverter shown in Fig.5 can be continuously adjusted from full power to low power. However, under a condition of the soft switching operating range in the low power setting, it is impossible to regulate the output voltage or output power of the voltage source type full bridge series resonant PWM inverter. The phase retarded difference as a control variable in this high frequency inverter can be roughly varied from 0° to 180°. The gate pulse signal timing sequences in case of delayed phase is shown in Fig.6. The control IC for the switching regulator of the fixed frequency phase shifted PWM due to the driver for phase-shifted PWM gate voltage pulse generation (ML4828CP made by Micro Linear) is used for this high frequency resonant inverter. Table 1 indicates the design specifications and resonant circuit constants in series with the induction heating load in the high-frequency inverter shown in Fig.5.



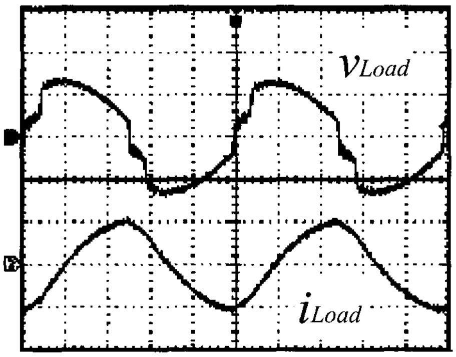
(10μs/div, 100V/div, 50A/div)

Fig. 8. Measured voltage and current waveforms across SW_1 in the standard phase of the bridge leg in case of phase difference ϕ=30°.



(10μs/div, 100V/div, 50A/div)

Fig. 9. Measured voltage and current waveforms across SW_3 in the control phase of the bridge leg in case of phase difference ϕ=30°.



(10μs/div, 100V/div, 50A/div)

Fig. 10. Measured voltage and current waveforms of induction heated load in case of phase difference ϕ=30°.

3.3 Inverter Circuit Operation

The mode transitions of the full bridge voltage source type phase shifted PWM high-frequency soft switching series load resonant inverter circuit with the active power switches in parallel with lossless snubber capacitors are shown in Fig.7. Observing Fig.7, the steady stage operation of this high frequency resonant inverter is divided into 10 operating sub modes during one period,

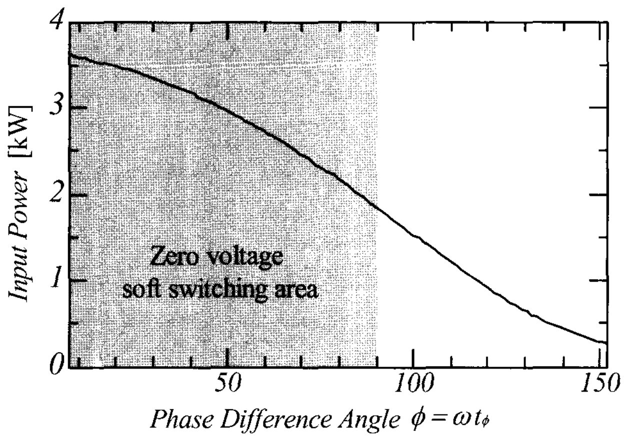
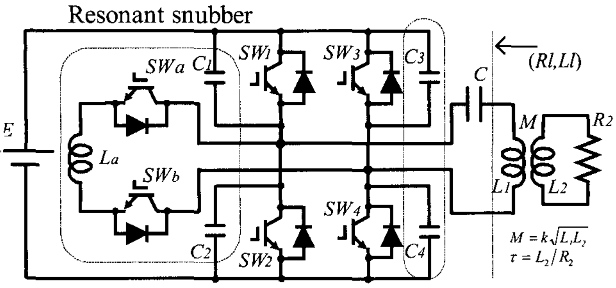


Fig. 11. Input power vs. phase difference characteristics



ig. 12. The proposed dual mode full bridge phase shifted ZVS-PWM controlled high-frequency series load resonant inverter with auxiliary bridge arm passive capacitive snubbers and auxiliary active edge resonant AC link load side snubber

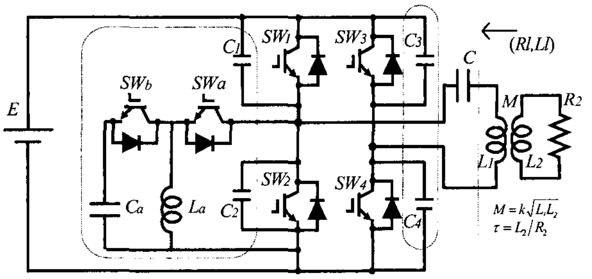
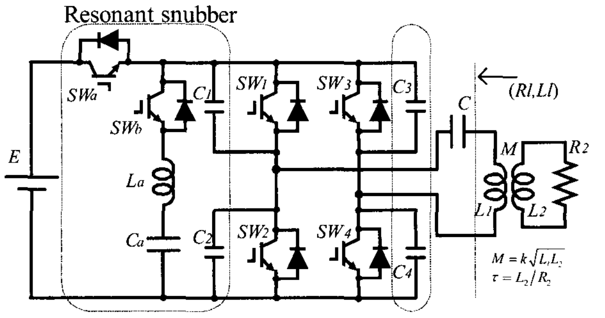
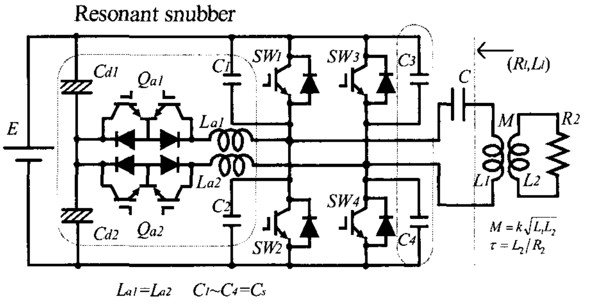


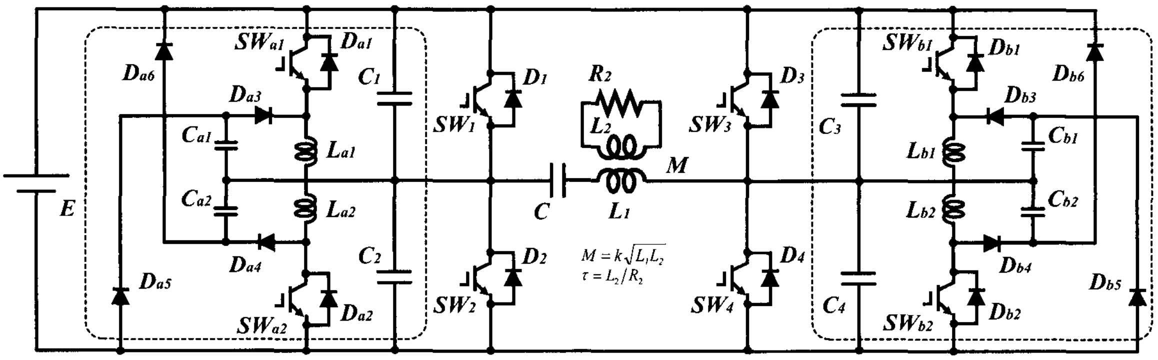
Fig. 15. Active Auxiliary bridge arm link snubber assisted high frequency series load resonant soft switching inverter



ig. 13. Auxiliary resonant DC link soft commutation snubber-assisted high-frequency series load resonant soft commutation inverter



(a) Divided capacitor type



(b) Chemical capacitorless type

Fig. 14. Auxiliary resonant commutation bridge leg snubber-assisted high-frequency series load resonant soft switching inverter

and these operating modes are repeated periodically. In a phase difference angle $\phi = 30^\circ$ setting, the measured switching voltages across *SW1* and *SW2* in addition to their current waveforms are respectively displayed in Fig.8 and Fig.9. The measured operating waveforms of voltage and current for the induction heated load circuit with a series compensated capacitor are also shown in Fig.10. The input power characteristics of the series load resonant high-frequency inverter with bridge arm link lossless capacitor snubbers are shown in Fig.11 for phase shifted PWM control scheme.

The power switch *SW3* or *SW4* could not actually achieve the soft switching commutation for phase difference angle in the vicinity of $\phi = 90^\circ$ or less. In this case, it is noted that the soft switching PWM inverter operation in Fig.5 could be in principle completed on the power switch *SW1* (*SW2*) for all the difference angle control ranges. The proposed high-frequency inverter circuit to solve this problem is taken up in the next chapter.

4. Phase Shifted ZVS-PWM High-Frequency Series Load Resonant Inverter with A Single AC Load Side Active Auxiliary Edge Resonant Snubber

Generally, the active auxiliary snubber circuits of the high-frequency PWM inverters are classified into 4 types; auxiliary resonant AC link snubber type (Fig.12), auxiliary resonant DC link edge-commutation snubber type (Fig.13), auxiliary resonant commutation bridge leg link snubber type (Fig.14)(a)(b), the bridge arm link snubber type (Fig.15). In this paper, the auxiliary resonant AC link soft commutation snubber circuit which is suitable and acceptable for high-frequency series load resonant inverter is effectively used for a variety of induction heating applications. With a great advance of reverse blocking IGBT, the bi-directional power switch could be realized recently. The auxiliary resonant AC link snubber using anti-parallel reverse blocking IGBT will be effectively introduced for the voltage source bridge type series load resonant inverter in order to expand the soft switching operation area from full load to no load.

4.1 Improved Inverter with Soft Switching Commutation

The control phase related power switch *SW3* or *SW4* in the voltage source full bridge type load resonant high frequency inverter in Fig.5 becomes the hard switching PWM operation in case of approximately phase difference angle $\phi = 90^\circ$, for the voltage source full bridge type phase-shifted ZVS-PWM inverter with bridge arm linked

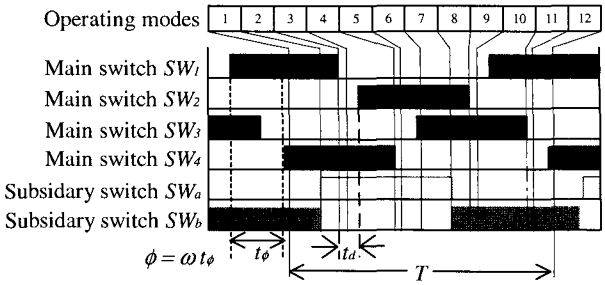


Fig. 16. Gate voltage pulse signal sequences and operating modes

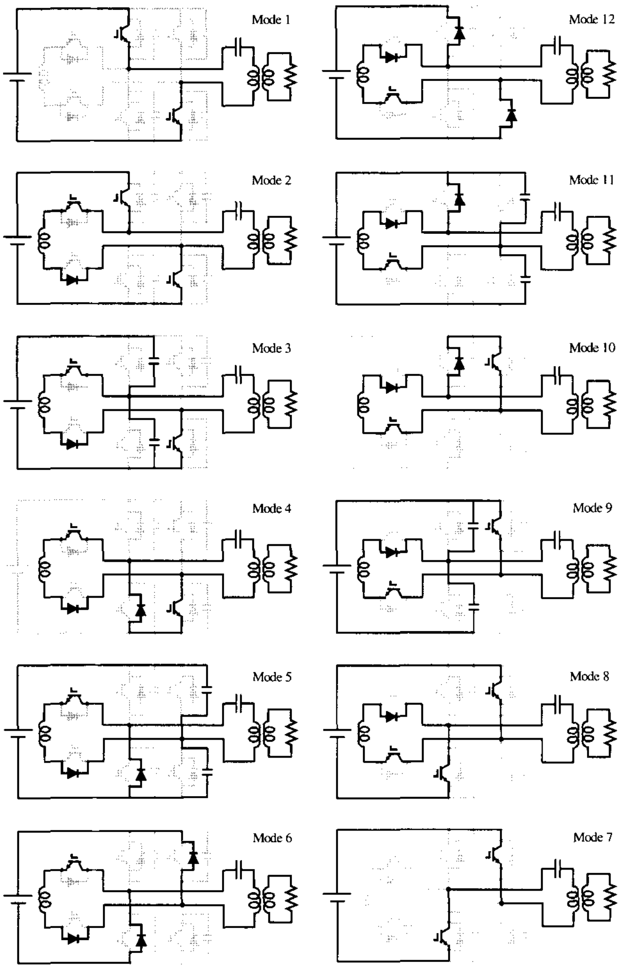


Fig. 17. Mode transitions and equivalent circuits of phase-shifted PWM series resonant soft switching inverter with auxiliary resonant AC link snubber

lossless capacitive snubbers as shown in Fig.5. The high-frequency soft switching PWM inverter circuit with the bi-directional switch composed of the reverse blocking IGBTs in parallel with high-frequency AC load side shown in Fig.12 is proposed for solving aforementioned problems described in chapter III. In short, the bridge arm linked lossless snubber capacitor in parallel with the active power switches by driving the bi-directional switch in order to inject a certain value of initial edge resonant inductor current is needed to discharge and charge the bridge leg lossless capacitors with the aid of the auxiliary edge resonant inductor, together with bridge arm link lossless capacitor snubbers. As a result, the complete zero voltage soft switching commutation operation of *SW3* (*SW4*) can be achieved completely. The circuit design specifications and circuit parameters are indicated in Table 2.

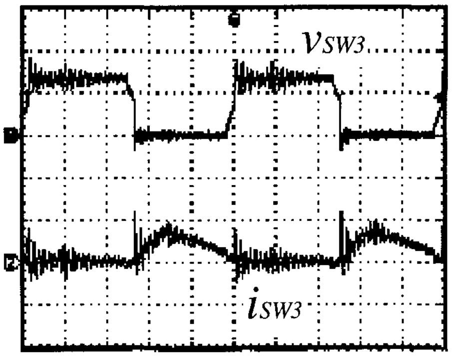
4.2 Gate Pulse Control Implementation

The gate pulse timing sequences of the edge resonant AC link inductor snubber and lossless capacitive snubber-assisted series load resonant high-frequency inverter circuit in Fig.12 are given in Fig.16. The auxiliary back to back reverse blocking IGBTs type bi-directional switch in parallel with the series compensated capacitor connected to the induction heating load is directly coupled to the actual induction heated inductive load circuit (*Rl*,

Table 2. Design specifications and circuit parameters

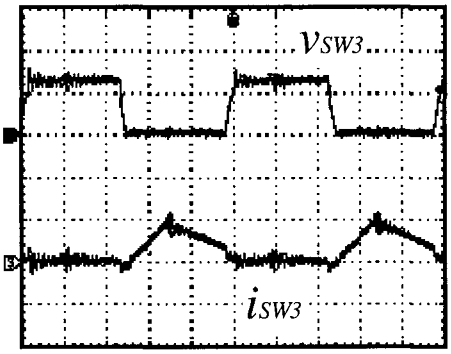
Item	Symbol	Parameter constant
DC Source Voltage	E	140 V
Switching Frequency (Inverter Operating Frequency)	f	20 kHz
Capacitance of Power Factor Compensated Series Resonant Capacitor	C	2.9 μF
Inductance of Working Coil composed of Lits Wire	L_l	31.0 μH
Coupling Coefficient between L_1 and L_2	k	0.632
Load Time Constant	τ	8.1μs
Capacitance of Lossless Snubber Capacitor	C_s	0.1μF
Inductance of Auxiliary Resonant Inductor	L_a	22 μH
Resistance of Auxiliary Resonant Inductor	R_a	0Ω
Effective Resistance at Working Coil Side	R_l	0.78Ω
Effective Inductance at Working Coil Side	L_l	24.7μH

Remarks:
R_l; Resistance component of working coil, $R_1 \cong 0$
$k = M/\sqrt{L_l L_2}$
M; Mutual inductance between L_l and L_2
L_2; Secondary-side self inductance
$\tau = L_2/R_2$
R_2; Skin effect related resistance which varies in accordance with the inverter operating frequency



(10μs/div, 100V/div, 50A/div)

Fig. 18. For ϕ=120° phase difference, hard switching voltage and current



(10μs/div, 100V/div, 50A/div)

Fig. 19. For ϕ=120° phase difference, soft switching voltage and current waveforms of SW_3 in the control phase of bridge leg.

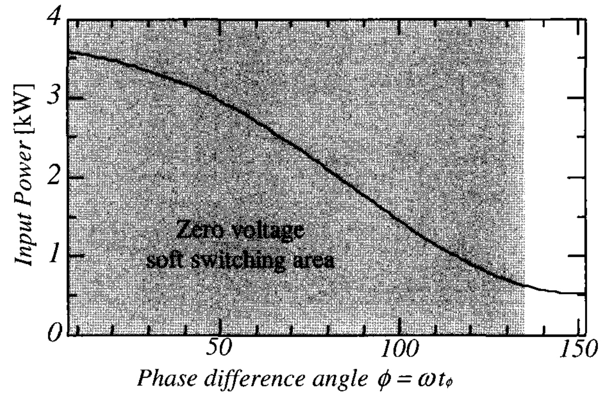


Fig. 20. Input power vs. phase difference angle characteristics.

Ll) without the high frequency matching transformer. By turning on the active auxiliary bi-directional switch in the auxiliary inductive snubber during the initial switching period, the auxiliary inductor current is sufficiently stored into the edge resonant inductor. This initial mode is to be utilized to discharge and charge for the lossless snubber capacitors for complete soft commutation.

4.3 Operation Modes of Improved Inverter

The equivalent circuits for mode transitions of the phase-shifted ZVS-PWM high-frequency series load resonant inverter (see Fig.12) with auxiliary edge resonant snubber circuit are respectively shown in Fig.17. The phase-shifting PWM controlled high-frequency soft switching commutation series load resonant inverter circuit with the auxiliary resonant AC link inductor snubber includes 12 operating modes during this complete one output period when a single active auxiliary edge resonant AC link snubber circuit is operated in order to achieve the soft commutation. This auxiliary resonant AC link snubber is designed so as to operate in order to achieve soft commutation in the operating range less than the phase shift angle $\phi \cong 90°$.

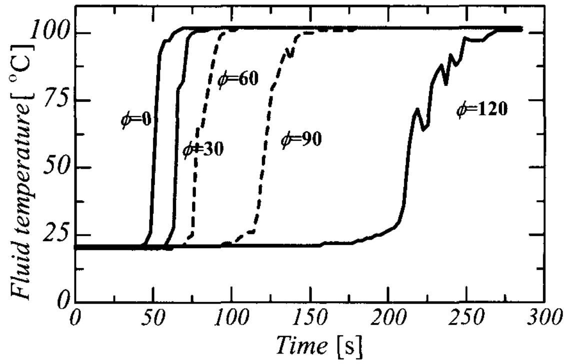


Fig. 21. Dynamic temperature responses for different phase angle setting points.

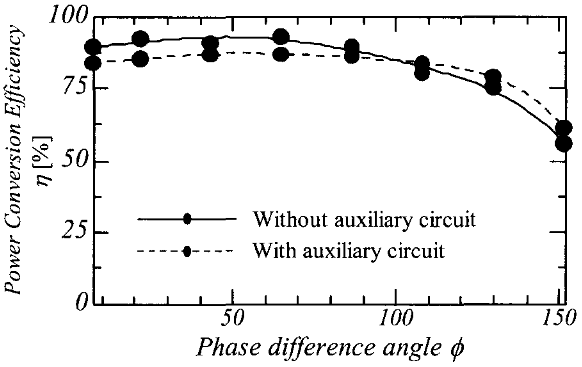


Fig. 22. Power conversion efficiency characteristics for different phase angle setting points. ($\phi = \omega t_\phi, \omega = 2\pi/T = 2\pi f$)

5. Experimental Results and Discussions

5.1 Comparative Operating Waveforms

The measured operation waveforms of this improved high-frequency soft switching PWM inverter using IGBT power modules are shown in Fig.18 and Fig.19, respectively. These can extend the soft switching commutation operation range even under the low power setting conditions in case of phase difference angle $\phi = 120°$. Figure 18 represents the voltage and current waveforms in case of a non-auxiliary resonant AC link snubber circuit. In this case, it is noted that the hard switching operation for *SW3* appears. The waveforms in Fig.19 are depicted in case of using the AC load side active auxiliary edge resonant snubber circuit (see Fig.12). In comparison with these figures, it is proven that this improved high frequency inverter circuit with a single auxiliary resonant snubber treated here is more cost effective as its soft switching commutation can completely achieve even in large phase shifted PWM control ranges or low output power setting ranges.

5.2 Power Regulation Characteristics

The output effective power regulation vs. the phase-shifted angle ϕ performance of this high-frequency series load resonant PWM inverter is depicted in Fig.20. The rated effective output power is designed for about 4kW. The soft switching commutation range based on the dual mode phase-shifted PWM high frequency inverter (see Fig.12) becomes larger than that of the previously developed high-frequency inverter circuit (see Fig.5).

5.3 Temperature Characteristics of Induction Heating Dual Packs Heater

Figure 21 illustrates the temperature characteristics of the induction heated hot water producer and steamer based on the induction heating dual pack fluid heater using the improved high-frequency inverter breadboard setup. It is noted in the experiment that the compact and cost effective induction heated hot water producer and super heated steamer using new conceptual electromagnetic induction eddy current based dual pack fluid heater (see Fig.3 (b-1)) can provide rapid temperature transient responses in the outlet of the non-metal vessel for various temperature setting values corresponding to the effective output power. Therefore, the wide and quick response temperature control scheme can be actually accomplished for dual mode phase-shifted high-frequency soft switching inverter which includes the bridge arm linked passive resonant capacitive snubbers and a single active auxiliary edge resonant AC load side link inductive snubber.

5.4 Power Conversion Efficiency Characteristics

Figure 22 illustrates the power conversion efficiency characteristics of the dual mode phase-shifted ZVS-PWM high-frequency series load resonant inverter with auxiliary edge resonant snubber circuit and non-auxiliary snubber circuit. In Fig. 22, the efficiency proposed inverter circuit with auxiliary resonant AC link snubber is higher than the previously developed inverter circuit without auxiliary resonant AC link snubber in case of phase difference angle $\phi = 90^{\circ}$ or more. However, the efficiency of the developed inverter circuit is relatively low due to the additional power loss of the auxiliary resonant AC link in cases of phase difference angle $\phi = 90^{\circ}$ or less. Therefore, the dual mode inverter circuit is more effective when in a high power setting condition. This inverter can not operate the auxiliary resonant AC link snubber circuit, and in low power setting condition this inverter can operate the auxiliary resonant AC link snubber circuit.

6. Conclusions

In this paper, the dual mode phase-shifted PWM full bridge series load resonant soft switching high-frequency inverter with bridge arm linked passive capacitor snubbers and/or edge resonant AC load side link inductive snubbers was originally developed by the authors for high efficiency induction heating (IH) type dual pack fluid heater (DPH) as the IH boiler to work steamer and super heated steamer. This high-frequency inverter with phase shifted PWM or asymmetrical PWM can operate under a principle of soft switching commutation with the aid of auxiliary passive capacitive lossless snubbers in the bridge arms and active auxiliary edge resonant AC link snubber in parallel with the high-frequency AC induction heating load. Next, the voltage source type phase-shifted PWM high-frequency series load resonant inverter which adds the AC load side active auxiliary inductor snubber and bridge arm linked auxiliary lossless capacitor snubber circuits were pointed out in order to realize the stable and wide soft switching commutation operated range not only under diversely specified high power setting ranges but also under lower power setting ranges. Its operating voltage/power regulation characteristics were illustrated and discussed herein. In comparison with the passive snubbing capacitor-assisted full bridge phase shifted PWM soft switching inverter developed previously, it was clarified that passive capacitive and active inductive snubber-assisted dual mode soft switching commutation high frequency inverter circuit operating under the condition of the specific phase shifted PWM strategy can expand the soft switching commutation range over high-power to the low power control ranges.

This experimentally produced high-frequency series load resonant inverter setup controlled by the phase shifted PWM scheme for passive capacitive and/or active resonant snubbers was implemented by the open-loop control system for the induction heated steamer and super heated steamer. Moreover, the verification of the dual mode phase shifted PWM controlled high-frequency soft switching inverter equipment was confirmed and practical effectiveness of the edge resonant PWM high-frequency inverter-fed induction heating dual pack fluid heater used in a variety of new type boiler was considered and evaluated from a practical point of view.

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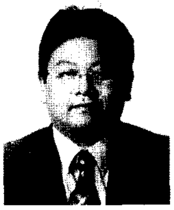
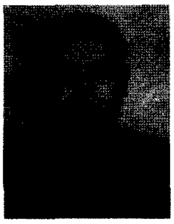
Hisayuki Sugimura was born in Kyoto Prefecture, Japan in 1977. He received the Bachelor of Science Degree in Electrical and Electronics Engineering from Yamaguchi University, Japan, in 2003. He joined the Power Electronics System Engineering Laboratory, a Division of the Electrical and Electronics Engineering Graduate School of Science and Engineering at Yamaguchi University, Yamaguchi, Japan. His research is concerned with high frequency soft switching inverters and soft switching DC-DC converters. He is a member of IEEJ and IEEE.



Hidekazu Muraoka was born in 1974. He received the Master of Science Degree from the Division of Ocean Electro-Mechanical Engineering, the Graduate School of Maritime Science and Technology, Kobe University of Mercantile Marine, Kobe, Japan in 2000. He became an Assistant at Maritime Technology Department, Hiroshima National College of Maritime Technology, in Hiroshima, Japan. He joined Power Electronics System Engineering Laboratory, Division of Electrical and Electronics Engineering, the Graduate School of Science and Engineering, Yamaguchi University, Yamaguchi, Japan. His interest research is concerned with high frequency soft switching inverters and soft switching DC-DC converters. He is a member of IEEJ, JIME, JIPE and IEEE.



Tarek Ahmed received his M.Sc. Degree in Electrical Engineering from the Electrical Engineering Department, Faculty of Engineering, Assiut University, Egypt in 1998. He is working as an assistant lecturer in the Electrical Engineering Department, Faculty of Engineering, Assiut University, Assiut, Egypt. He is currently a Ph. D. candidate student with the Power Electronic System and Control Engineering Laboratory, the Division of Electrical and Electronic Systems Engineering, The Graduate School of Science and Engineering, Yamaguchi University, Yamaguchi, Japan. He has received the Paper Award from the Institute of Electrical Engineers (IEE) of Japan in 2003. His research interests are in the new applications of the advanced high frequency resonant circuits and systems with the renewable energy related soft switching PWM rectifier and sinewave PWM inverter power conditioner. He is a student-member of IEEE-USA, the Institute of Electrical Engineering and Installation of Engineers (IEIE-Japan), the Institute of Electrical Engineers (IEE-Japan) and Japan Institute of Power Electronics (JIPE).

Srawouth Chandhaket was born in Surin, Thailand. He received his B. Eng. degree in Electronics from Kobe University, Hyogo, Japan in 1995 and 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.

Eiji Hiraki received his doctoral degree from Osaka University, Japan, 2004. He joined the Technological Research Institute of Mazda, co. Ltd. He is currently with the Power Electronic and Control System Engineering Laboratory (Nakaoka Lab.) at the Department of Electrical and Electronics Engineering, Yamaguchi University, Yamaguchi, Japan, as a research associate since 1995. His research interest includes soft-switching control techniques for high frequency switching power conversion and energy systems and generic power electronic simulator developments. He is a member of the Institute of Electrical Engineers of Japan, the Japan Society of Power Electronics, the Institute of Electronics, Information and Communication Engineers of Japan and the IEEE-USA.

Mutsuo Nakaoka received his doctoral 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 of Department of Electrical and Electronics Engineering, the Graduate School of Engineering, Kobe University, Kobe, Japan. Since 1995, he has been a professor of the Electrical and Electronics Engineering Department, the Graduate School of Science and Engineering, Yamaguchi University, Yamaguchi, 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, the 2003 IEEE-IAS James Melcher Prize Paper award, among others. He is now a chairman of IEEE Industrial Electronics Society Japan Chapter. Prof. Dr. Eng. Nakaoka is a member of the Institute of Electrical Engineering Engineers of Japan, the Institute of Electronics, Information and Communication Engineers of Japan, the Institute of Illumination Engineering of Japan, European Power Electronics Association, Japan Institute of Power Electronics, Japan Society of the Solar Energy, Korean Institute of Power Electronics, IEE-Korea and IEEE.

Hyun-Woo Lee received the B.E. degree in electrical engineering from Dong-A University, Pusan, Korea, in 1979 and received the M.S. degree in electrical engineering from Yuing-Nam University, Kyungbook, Korea, in 1984 and a Ph.D. degree in electrical engineering from Dong-A University, Pusan, Korea, in 1992. Since 1985 he has been with the Division of Electrical Electronics Engineering, Kyungnam University, Masan, Korea, where he is a Professor. He is interested in the areas of Power electronics and new power generation systems. He is a member of the KIEE, and IEEE.