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Cost Effective Quasi-Resonant Soft Switching PWM High Frequency Inverter With Minimum Circuit Components for Consumer IH Cooker and Steamer

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Abstract - This paper presents a cost effective quasi-resonant soft-switching PWM high frequency inverter with minimum circuit components. This inverter can achieve wider soft commutation, simpler power circuit configuration, smaller volumetric size, lower cost and wider power regulation range, higher-efficiency as compared with single ended quasi-resonant ZVS-PFM inverter and active voltage clamped quasi-resonant ZVS-PWM inverter. The operation principle of the proposed inverter is described on the basis of the simulation and experimental results, together with its operating performances in steady state. The operating performances of this unique proposed high frequency inverter based on ZVS and ZCS arms-related soft commutation principle is evaluated and discussed as compared with the active voltage-clamped ZVS-PWM inverter and a conventional single-ended ZVS-PFM inverter. The practical effectiveness of a novel type quasi-resonant soft-switching PWM high frequency inverter using IGBT is actually proved for consumer induction heated appliances as rice cooker, hot water producer, steamer and super heated steamer. The extended bidirectional circuittopology of quasi-resonant PWM high frequency inverter with minimum circuit components is demonstrated, which operate as the direct frequency changer.

1. Introduce

1.1 Technical Background

In recent years,high frequency electromagnetic induction eddy current based heating (IH) technologies have been introduced so far for consumer specific applications from effective energy utilization point of view [1-2]. Of these, the voltage source type single-ended quasi-resonant ZVS-PFM high frequency (HF) inverter using a single Insulated gate bipolar transistor (IGBT), which is used for the commercial utility AC 100V grid, has been practically developed so far for energy saving consumer power applications [3]. This type of HF inverter circuit has attracted special interest because of its simple configuration, high reliability, low cost, compactness, high efficiencyand low electromagnetic noises. But, it generates beat frequency related audible acoustic noise below 20kHz due to frequency difference in multi burner IH cooking heater composed of two or three single ended ZVS PFM inverter. Its voltage peak stress across the power semiconductor switching device (IGBT) also becomes relatively high. As a result, the saturation voltage of IGBT used for this inverter is actually high and its conduction loss is relatively large.

Besides, the soft-switching operating area in this type of ZVS high frequency inverter is relatively narrow under a pulse frequency modulation strategy. On the other hand, an active subsidiary power switch IGBT connected in series with the capacitor for the voltage clamping of main power IGBT on the basis of conventional single ended ZCS-PFM HF inverter. This inverter is termed as the active voltage clamped ZVS PWM inverter and has been practically developed before by the authors for 200V AC utility interactive consumer high power applications.However, further technological improvement of the active voltage clamped ZVS PWM inverter should be made from viewpoints of a constant frequency ZVS operation, physical size-based compactness in high power appliance, and the power regulation range.

1.2 Research Objective

This paper presents an improved prototype of cost effectivevoltage source type quasi-resonant soft-switching HF inverter with minimum circuit components and devices. The inverter is based upon a constant frequency PWM implementation due to asymmetrical pulse modulation Time Ratio Control or Duty Factor Control / Duty Cycle Control. It is proved that two-switch quasi-resonant ZVS PWM HF inverter treated here can achieve relatively wider soft-switching and power regulation ranges with simpler circuit topology [4-5]. This inverter is superior to a conventional single-ended ZVS-PFM HF inverter with a single power switch. In addition to this, the proposed inverter has advantageous points as lower cost, higher efficiency, and higher power density as compared with the active voltage-clamped ZVS-PWM inverter developed previously by the authors. Its operation principle is actually described for consumer induction heating cooker, including unique salient features. The steady state performances are evaluated and discussed for home and business-use consumer IH appliances on the basis of thecomputer-aided simulation and feasible experimental results [6-7].

2. Quasi-Resonant Soft Switching PWM HF Inverter with Minimum Circuit Components

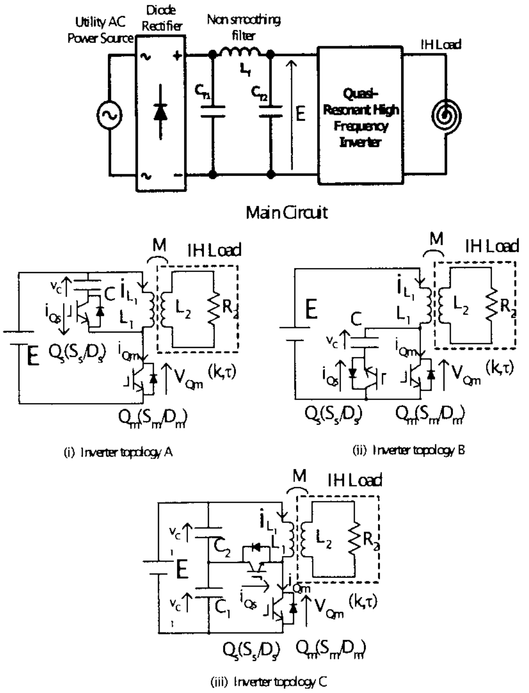
2.1 System Description with Non Smoothing Filter DC Link

The schematic total power processing system configuration of quasi-resonant soft-switching PWM HF inverter proposed newly is shown in Fig. 1 for small scale consumer IH. It is composed of minimum circuit components and two power switching devices.

This HF inverter is based on a constant frequency variable power regulation function scheme for IH loads such as cooker, warmer and super heated steamer. The inverter circuit proposed here can efficiently work under two principles of soft switching schemes based upon both ZCS and ZVS commutation arms.It is noted that the IH appliances driven by this HF inverter havepractical advantages such as low cost, high efficient, miniaturization in physical volumetric size, constant frequency PWM, wide soft-switching and power regulation rangesas compared with the latest consumer IH appliances based on active voltage clamped ZVS-PWM HF inverter. The HF inverter, as shown in Fig. 1 is composed of diodebridge rectifier with non-smoothing filter L_f, C_f (C_{f1},C_{f2}) that convert the single-phase 60Hz-100V AC to non-smoothing DC power sources. The HF inverter with minimum circuit components and IH load are represented by the transformer model. The non-smoothing filter in the input side consists of inductor $L_f$to block higher harmonic current components, and capacitors C_{f1}, C_{f2} to bypass higher harmonics current components. The utility AC power source side harmonic current components can be reduced with a unity power factor.

2.2 Circuit Configuration and Modified Versions

The new quasi-resonant soft-switching PWM HF inverter with reverse-conducting IGBTs does not have any lossless snubber capacitors. It consists of the main switching block $Q_m(SW_m/D_m)$ and subsidiary switching block $Q_S(SW_S/D_S)$ as shown in Fig. 2. This configuration is different from the previously developed for the active voltage-clamped ZVS-PWM inverter. The capacitor C is not a voltage clamping or lossless snubbing capacitor. Fig.2 shows adirect frequency changer or HF cycloconverter composed of the new low cost soft switching PWM inverter using bidirectional power switching devices. This frequency changer is modified on the basis of the minimized circuit component HF PWM inverter as depicted in Fig.1.



(i) Inverter topology A (ii) Inverter topology B

(iii) Inverter topology C

Fig.1 Circuit topology of proposed soft-switching PWM high frequency inverter and its modified version

2.3 Induction Heated Load Model

The HF inverter circuit with IH loads includesnon-magnetic conductive stainless steel plate or vessel via ceramic spacer which is magnetically coupled with a spiral planer, rectangular or cylindrical working coil. The IHload circuit of this quasi-resonant inverter consists of the working coil composed of litz wire and IHmetal-based object (pan or vessel) represented by the transformer equivalent circuit model of the IH load(Load time constant $t=L_2/R_2$ [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], Electro-magnetic coupling coefficient $k=M/\sqrt{L_1\cdot L_2}$ and self-inductance L_1 of the working coil) with loosely-coupled mutual inductance M. The equivalent effective inductance and resistance are derived from the working coil side of a variety of IH load. The current stored in the equivalent inductor component is required to achieve ZCS in the low side main power switch Q_m and ZVS in the high side subsidiary power switch Q_S. The inductor makes resonance in accordance with the resonant capacitor C. The high side power switch Q_S is in series with the series resonant capacitor C that serves to the induction heated load for the quasi-resonance requirement.

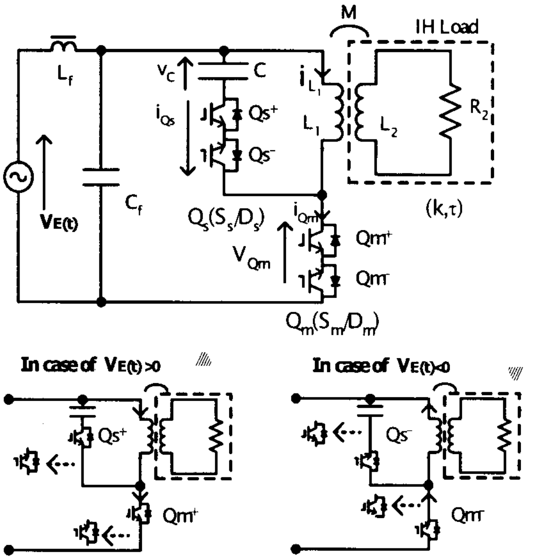


Fig. 2 High frequency cycloconverter with minimum circuit components and bi-directional power switching device

3. Steady State Operation Principle of Proposed Inverter

The soft switching commutations and equivalent circuits in the operating modes of the inverter circuit are shown in Fig.3. The corresponding gate pulse timing sequences and transition modes of the proposed inverter are shown in Fig.4. It is assumed that the input DC power source voltage E is specified around the peak value of the utility AC power source voltage. The operating principle of this basic inverter for induction heater is described as follows;

(i) MODE1 The subsidiary power switch $SW_s$is now conducting under the conduction state and the resonant charging state of the resonant capacitor C that is non voltage clampingcapacitor begins to charge. Then, the reverse conducting diode switch D_m turns on naturally, when the voltage across the resonant capacitor C exceeds the DC power source voltage E. **MODE1** goes to **MODE2**.

(ii) MODE2 This operating state becomes the instantaneous power regeneration mode with the loop through D_m to E. The gate pulse voltage signal of the main switch $SW_m$is applied for its gate ports during this operating period. When the load current commutates to the power switch, this main power switch SW_m turns on naturally, and MODE2 goes to MODE3 (SW_m with ZVS&ZCS).

(iii) MODE3 Inthis operating mode, the DC supply power is injected into the IH load (see Fig.3) from the DC power source voltage E. This operating mode is determined under the operating period due to Duty Factor as a power control variable defined in Fig. 4. The main power switch $SW_m$is turned off in accordance with the constant frequency type Duty Factor or Duty Cycle control strategy.

(iv) MODE4 Discharging the resonant capacitor C in series with the subsidiarypower switch Qs(SWs/Ds) whilethe main power switch SW_m turns off with ZVS. On the other hand, the subsidiary power switch SW_s can turn off with ZCS, when the load current becomes zero.

(v) MODE5 During thisoperation mode, all the currents do not flow through this processing circuit because the gate pulse voltage signals of the power switches of Q_m and Q_s are both off state. The resonant capacitorC, which is completely different from the voltage clamped capacitor begins to charge, when the subsidiary power switch SW_s is turned on. This circuit becomes MODE1.

The current through the subsidiary power switch SW_s of Q_s tends to increase the initial current stored in the equivalent effective load inductor of the working coil. The subsidiary power switch SW_sturns on with ZCS. This inverter circuit operation mentioned above is sequentially repeated in a periodic steady state. The subsidiary power switch SW_s of $Q_s$is turned on during the particular period determined by the switching frequency, as the inverter operating frequency and SW_s of Q_s is turned off during the interval of MODE2 to MODE4. The main power switch SW_m of Q_m is turned on during a diode D_m conduction period, and can adjust the output power by determining the turn-off timing sequences. The Duty Factor defined in Fig. 4 becomes 0.3 as the smallest value for SW_s conduction, so that it may be changed by adjusting the pulse width of the gate voltage signal to the main power switch SW_m of Q_m under a constant pulse width. The power regulation of this quasi-resonant PWM HF inverter can continuously regulate the input power.

4. Experimental Results and Discussion

The feasible experimental setup is built and tested under the design specifications stated below of this HF inverter operating at PWM scheme. Its circuit parameters in addition to the design specifications are indicated in Table 1. In the actual breadboard setup, the non-smoothing filter circuit component in DC side of this HF PWM inverter is employed to cut the high-frequency current components and to improve the utility AC power source side current distortion due to harmonic current components and unity power factor correction in the utility AC power source side.

Accordingly, the output voltage of the non-smoothing filter becomes a full-wave voltage is used for IH load in the consumer power applications. The HF PWM inverter design (see Fig.1) is carried out so as to provide a power rating of 1202 [W]. Observed waveforms and simulating waveforms are respectively depicted in Fig. 5. The operating waveforms around the rectified sine-wave are different from that in case of using the non-smoothing filter. The power semiconductor switching devices used in the experimental setup are the IGBTs (Fuji Electric Co.Ltd. 2MBI50N-120H 1200V-50A), and the iron vessel (k=0.64, t=12.54[msec]).

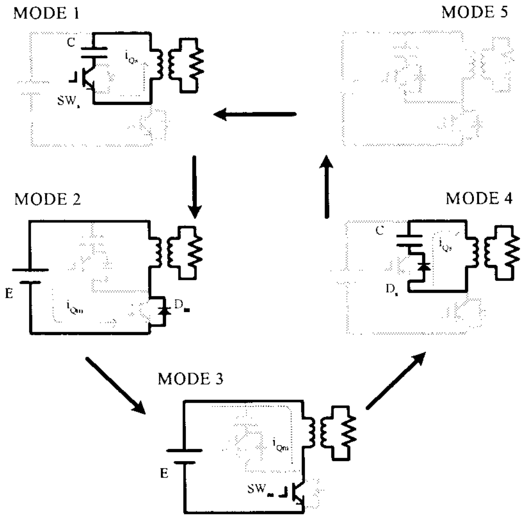


Fig. 3 Operating commutation modes and equivalent

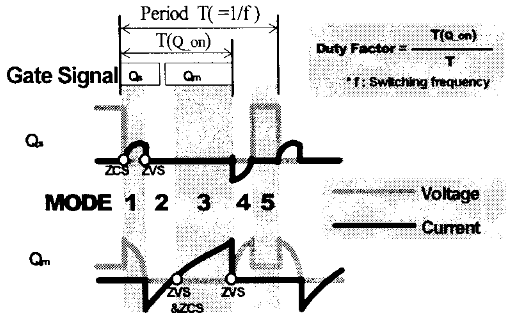


Fig. 4 Voltage and current waveforms in switching mode transitions

Table. 1 Design specifications and circuit parameters

Symbol	Item	Parameter Value
E	DC Source Voltage	141.2 [V]
f	Switching Frequency	20.0 kHz]
L_1	Inductance of Working Coil	65.4 [μH]
C	Resonant Capacitor Capacitance	0.3 [μF]
$K = M/\sqrt{L_1 \cdot L_2}$	Electromagnetic Coupling Coefficient	0.8
$\tau = L_2/R_2$	Load Time Constant	9.0 [μsec]

The proposed PWM HF inverter under the soft commutations isbasically similar to the operating waveforms for the single-ended high frequency ZVS-PFM inverter with a single power switch $Q_m$which is a circuit topology without SW_s of the proposed HF inverter circuit. Measured voltage and current waveforms are represented in Fig. 6. The Duty Factor vs. input power characteristics for this high frequency inverter using IGBTs power modules is illustrated in Fig. 7, and the Duty Factor vs. power conversion efficiency characteristics for this HF inverter is illustrated in Fig. 8.It is clear from Fig. 7 and Fig. 8 that the simulation results agree well with those obtained experimentally. The efficiency of the proposed inverter goes to 95% for wide range of the Duty Factor as shown.

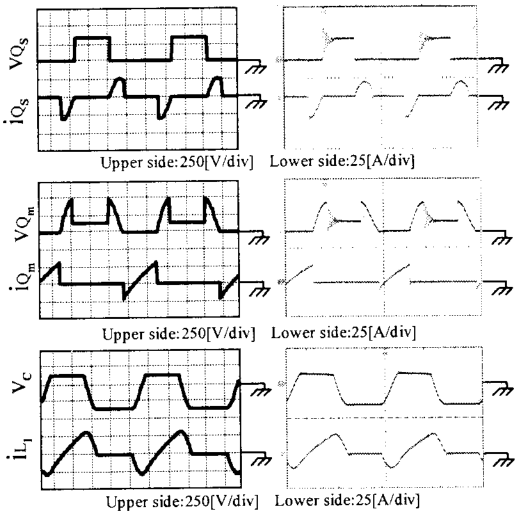
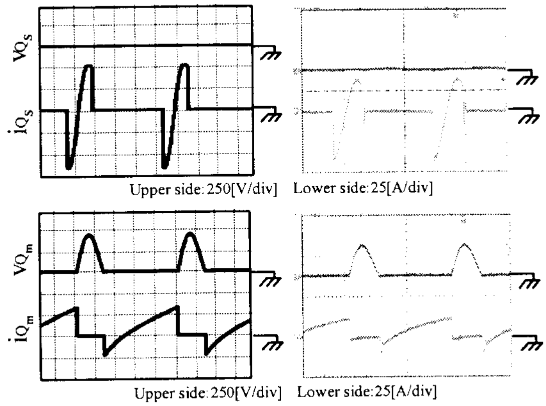


Fig. 5 operation waveforms under the condition of Duty Factor D=0.5, input power 251.2[W]



(a) Simulation (b)Experiment

Fig. 6 Switching operating waveforms under Duty Factor D=0.9 (Input Powern 1202[W]

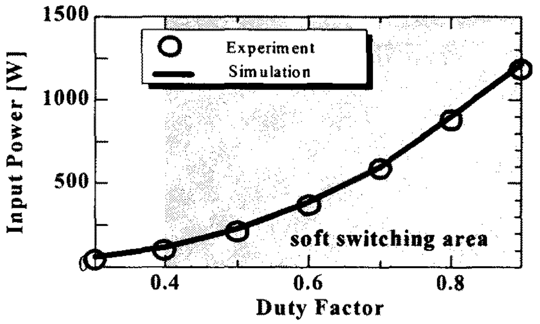


Fig. 7 Duty Factor vs. input power regulation characteristics

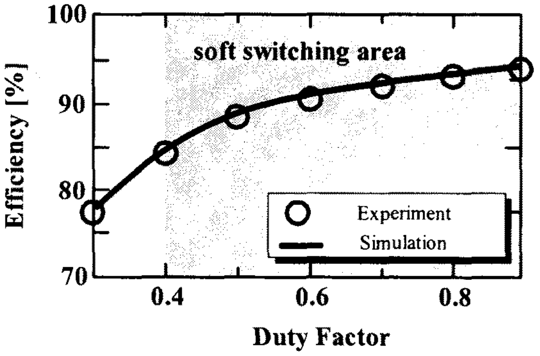


Fig. 8 Duty Factor vs. power conversion efficiency characteristic

5. Comparative Operating Characteristics

The power regulation versus Duty Factor characteristics under the soft-switching commutation area, the peak voltages and currents of the main power switch $Q_m(SW_m/D_m)$are respectively depicted in Fig. 9(a). The input power can be continuously regulated by varying the Duty Factor. The load parameters L_1, k, t are made as particular values for the enameled pot as well as the experimental circuit parameters. The corresponding characteristics for the voltage-clamped quasi-resonant ZVS-PWM inverterand the single-ended PFM inverters are shown in Fig. 9(b) and Fig. 9(c), respectively.

In the proposed inverter circuit, there is no voltage-clamping function because of the resonant components of L_1 and C. The peak voltage across the power switch of the proposed HF inverter becomes high as well as that of the conventional single-ended ZVS-PFM inverter circuit with a single power switch. However, the proposed HF inverter circuit configuration is simple topology, and can achieve soft-switching PWM operation under the constant frequency condition. Observing Fig. 9, the lowest power for the rated output power 5[kW] under soft-switching commutation area is 548[W] for the proposed inverter. On the other hand, the lowest output power is also 965[W] for the voltage-clamped PWM HF inverter becomes sufficiently a little bit wider.

It is worth to mention that the clamped capacitor has capacitance of 3[F] and the switching frequency is 20[kHz] for the voltage clamped inverter, while it is 15-50[kHz] for the single-ended inverter. The other circuit parameters are the same as listed in table 1.

6. Conclusion

In this paper, the cost effective high frequency (HF)quasi-resonant PWM inverter circuit topology is discussed. The proposed HF inverter is operated for PWM related soft-switching commutation under a constant frequency strategy. This HF inverter used for IH loads is evaluated from an experimental point of view. The performance characteristics of the inverter are compared to the voltage-clamped PWM and single-ended PFM HF inverters developed previously by the authors. Finally, it was substantially confirmed that the proposed inverter has simple configuration, low cost, compactness and high efficient HF soft-switching PWM, withminimum circuit components.

In addition to wider and more stable soft-switching commutation operation as compared with the voltage-clamped ZVS PWM and single-ended ZVS PFM quasi-resonant HFinverter circuit so far developed by the authors. This soft-switching PWM HF inverter with minimum circuit components was applied for clean and energy saving consumer high power IH products. These products include cooker, hot water producer steamer and super heated steamer in home and business utilization. The practical effectiveness of the proposed high-frequency inverter operating undersoft commutation was proved on the bases of simulation and experimental results for consumer induction heater.The simulation results are compared favorably to the experimental results for the HF inverter developed for variable Duty Factor.

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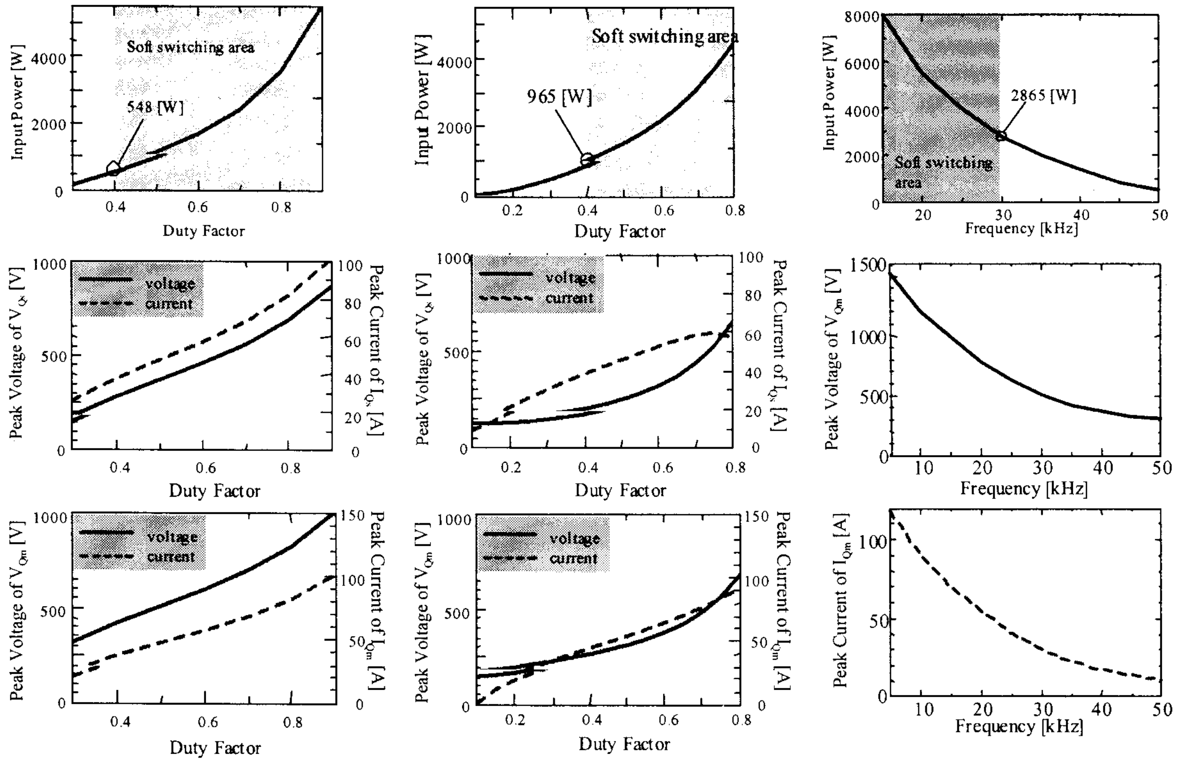

(a) Proposed inverter (b) Active voltage-clamped inverter (c) Single-ended PFM inverter

Fig. 9 Comparative inverter power, voltage and current characteristics for several inverters

[참고문헌]

[1] S. Hishikawa, M. Nakaoka, I. Hirota, H. Omori, H. Terai "High frequency eddy current-based fluid heater using soft-switching inverter" the Institute of Electronics Information Communication Engineers (IEICE)-Japan Technical Research Report on Energy Electronics, Vol.100 No.628, EE2000-64, pp.19-24 February 2001

[2] H. Terai, I. Hirota, T. Miyauchi, H. Omori, K. Ogura, Y. Hirota, M. Nakaoka "Comparative Performance Evaluations of IGBTs and MCT in Single-Ended Quasi-Resonant Zero Voltage Soft-switching Inverter", Proceedings of Power Electronics Specialists Conference (PESC)-Vancouver, pp.2178-2182, June, 2001

[3] H. Tanaka, H. Sadakata, H. Muraoka, A. Okuno, E. Hiraki, M. Nakaoka "Innovative Electromagnetic Induction Eddy Current-based Far Infrared Rays Radiant Heater using Soft-switching PWM Inverter with Duty Factor Control Scheme", Proceedings of the Institute of Electrical Engineers-Korea International Conference of Power Electronics (ICPE), pp. 64-68, October 2001.

[4]S. Muraoka, Y. L. Feng, H. Kunimoto, S. Chandhaket, M. Nakaoka "Zero Voltage Soft-switching PWM High-Frequency Inverter with Active Inductor Snubber for Induction Heated Roller in New Type Copy Machine", Proceedings of the Institute of Electrical Engineers-Korea International Conference of Power Electronics (ICPE), pp. 75-79, October 2001

[5] H. Sadakata, M. Nakaoka "Innovative Development of Electro-magnetic Induction Fluid Heater using Active Clamped ZVS-PWM Inverter", Proceedings of the Korea-Japan Joint symposium on Advanced Industry Applications, pp.31-33.Octorber 2002

[6] T. Nishida, L. Gamage, H. Muraoka, E. Hiraki, M. Nakaoka "Cost Effective Soft-Switching PWM High Frequency Inverter with Minimum Circuit Components for Consumer Induction Heater", Proceedings of Power Electronics Specialists Conference (PESC)-Mexico Vol4, pp.2015-2020, June 2003

[7] T. Nishida, S. Moisseev, E. Hiraki, M. Nakaoka "Duty Cycle Controlled Soft Commutation High Frequency Inverter for Consumer Induction Cooker and Steamer",Proceedings of IEEE, Industrial Electronics Conference (IECON) Vol5, pp.1846-1851, November 2003