A Single-Phase Grid-Connected Inverter by Utilizing Ready-Made PWM Power IC

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Abstract- **For popularization of photovoltaic (PV) systems, it is important not only approach to cost reduction, but also approach to mass production. As one of the approaches, this paper presents the inverter by utilizing ready-made power integrated circuit. The integrated circuit (IC), Audio Power Amplifier, has been developed and mass-produced with the PWM switching technique recently. Most of photovoltaic (PV) inverters are based on the PWM technique. The proposed inverter has possibility of the dramatically cost reduction and mass production. Availability of the application of the IC to the PV inverter is shown by experimental results.**

I. INTRODUCTION

During the last few years, there has been a growing market demand for photovoltaic systems. In Japan, the long-term R&D roadmap titled "PV2030" was set up in May 2004, in which 100 GW of total domestic installation of PV systems are expected. When 20 GW/y PV market is considered to exist in 2030, the level of their need is considered adaptable enough for automated assembly lines and power ICs [1]. On the other hand, power ICs, for example audio power amplifiers, have been developed and mass-produced with PWM techniques often called "class-D audio amplifier." A typical class-D audio amplifier consists of a modulator that converts an analog or digital audio signal into a high-frequency PWM signal, followed by a half bridge or full bridge power switch. The circuit configuration can be found in the main circuit of photovoltaic (PV) inverters. Therefore, if the IC is used in place of the main circuit of the PV inverter, a lot of discrete elements of the inverter can be reduced. That increases productivity of PV inverter.

In this paper, a stereo class-D audio IC was tested with bridge-tide -load (BTL) configuration.

II. READY-MADE PWM ICS FOR AUDIO POWER AMPLIFIER

There are many kinds of class-D audio ICs available. For monaural one, the amplifier consists of an audio input channel,

(a) Half bridge power stage.

(b) Full bridge power stage.

(c) Single ended power stage for stereo and Bridge tide load power stage for monanual.
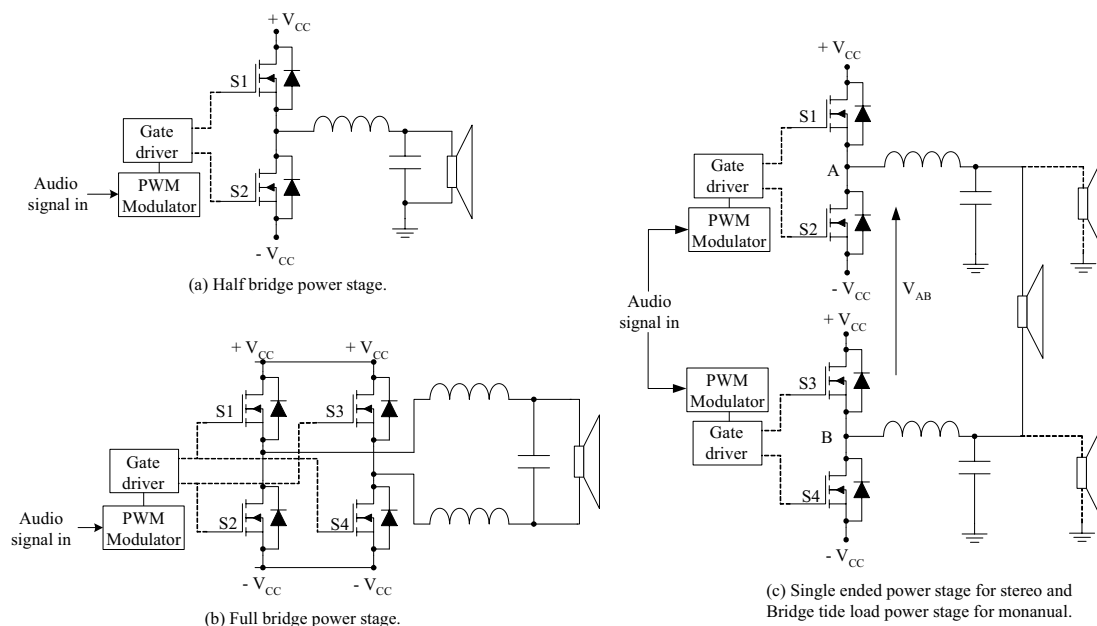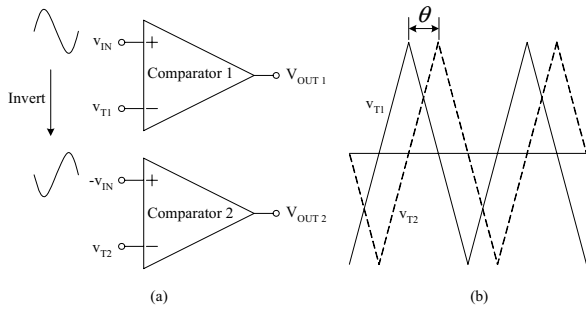
Fig. 1. Power stage of class-D audio amplifier.

Fig. 2. Input stage of BTL configuration (a) and relationship of phase difference between two carrier signals (b).

a PWM modulator, a half bridge power stage as shown in Fig. 1 (a) or a full bridge power stage as shown in Fig. 1 (b). For stereo one, the amplifier consists of two audio input channels, two PWM modulators, two half bridge power stages or two full bridge power stages. In addition, the stereo amplifier makes single-ended (SE) as well as bridge-tied-load (BTL) operation possible as shown in Fig. 1 (c).

In the BTL application, two audio input channels receive an audio signal 'v_{IN}' but the phase of one of the channels should be inverted '$-v_{IN}$' as shown in Fig. 2. In this case an approximately four times higher output power can be obtained with the same loudspeaker impedance. In some of the ICs, the switching patterns for the two channels are not synchronized by the phase difference θ between the two carrier waves.

III. APPLICATION OF GRID-CONNECTED SYSTEM

Fig. 3 shows the circuit model of grid-connected system with a class-D audio IC. The particular parameters for the system are shown in Table I. In this circuit, a stereo class-D audio IC "TDA7490 (STMicroelectronics) [2]" was used as a main
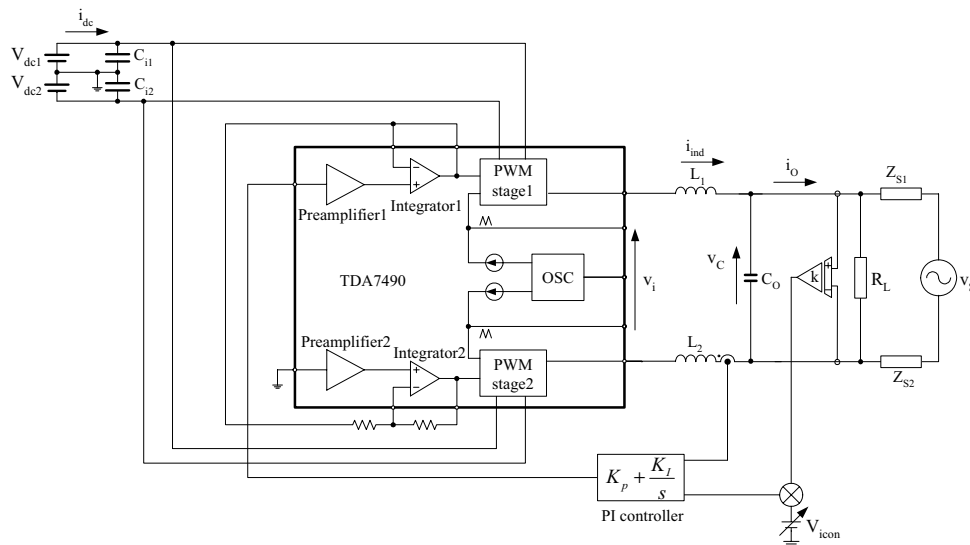
TABLE I
SYSTEM PARAMETERS

Parameter	Value
L_1, L_2	31 μH
C_O	1 μF
R_L	15.6 Ω
v_S	14.26 V
Z_{S1}, Z_{S2}	51 mΩ + 2 μH
V_{dc1}, V_{dc2}	22 V
C_{i1}, C_{i2}	2200 μF

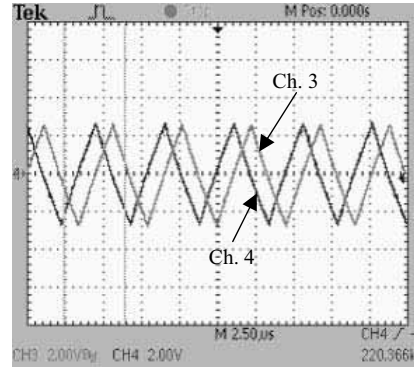
Fig. 4. Carrier waveforms of TDA7490 for PWM stage 1 (Ch. 3), and PWM stage 2 (Ch. 4). Horizontal: 2.5 μs/div., channel 3, 4: 2.0 V/div.

circuit of this system. The TDA7490 consists of two preamplifiers has a constant gain $G = 2.5$, two integrators, two PWM stages containing of a half bridge and a common section which contains an oscillator and some protection circuit. These components are designed optimally in the IC. In this circuit, the two integrators are treated the same as OP amplifier and the integrator 1 operates as a voltage follower, and the integrator 2 operates as an inverting amplifier for the BTL configuration. The two switching carriers have the phase difference about 90
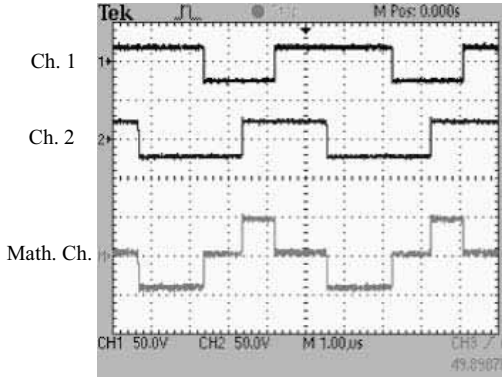

Fig. 3. Circuit configuration

Fig. 5. Output voltage from PWM stage 1 (Ch. 1), PWM stage 2 (Ch. 2) and v_i (Math. ch.). Time base: 1.0 μs/div., channel 1, 2: 50 V/div., math channel: 50 V/div.
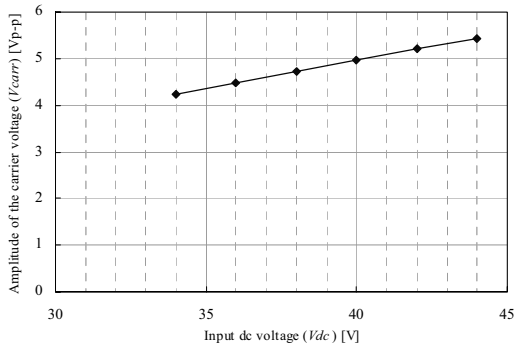

Fig. 6. Relationship between input dc supply voltage (V_{dc}) and carrier voltage (v_{carr}).

degrees at 200 kHz as shown in Fig. 4 and output voltage from PWM stage 1, PWM stage 2 and v_i is shown in Fig. 5. The inverter has constant gain K given by

$$K = \frac{V_{CC}}{v_{carr}} \times 2.5 \cdot \qquad (1)$$

The carrier voltage v_{carr} changes proportionally inside of the IC with dc supply voltage $V_{dc} (= V_{dc1} + V_{dc2})$ as shown in Fig. 6. Therefore the value of the inverter gain K is approximately 40 calculated using (1). In this system, the inverter uses one current sensor to sense inductor current i_{ind} for current control by a PI controller consisted of the analog circuit. The transfer function of the PI controller is given by

$$C(s) = K_P + \frac{K_I}{s} \cdot \qquad (2)$$

The complementary sensitivity function is given by

$$T(s) = \frac{K(sK_P + K_I)}{s^2 L + K(sK_P + K_I)} \cdot \qquad (3)$$

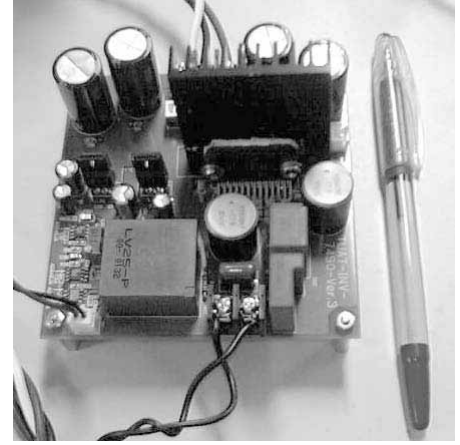The angular frequency ω_O and resonant frequency f_{con} of this controller are:

Fig. 7. Printed circuit board (PCB). Scale: 100 mm × 100 mm

$$\omega_O = \sqrt{\frac{KK_P}{L}}, \qquad (4)$$

$$f_{con} = \frac{\omega_O}{2\pi} \cdot \qquad (5)$$

The value of proportional gain $K_P = 0.47$ VA^{-1} and integral gain $K_I = 1000$ VA^{-1}s^{-1} are selected for the current feedback. From these values, this system is free of the influence of the resonant frequency (f_Z) between inverter filter capacitor (C_O) and grid impedance (Z_{S1} and Z_{S2}) because the resonant frequency of the control f_{con} ($\approx$ 4 kHz) is lower than f_Z ($\approx$ 113 kHz). Therefore, the controller responds quickly to the target frequency of this system (50Hz) with stability.

Synchronization of the inverter output current (i_O) to the capacitor voltage (v_C) is achieved by the analog multiplier implemented for the regulation of the current reference by multiplication of the sensed capacitor voltage ($k_{sense}v_C$) and the regulated dc voltage as the current control level (V_{icon}). The sensor gain (k_{sense}) is adjusted constant gain level about 0.015.

IV. EXPERIMENTAL AND SIMULATION RESULTS

An experimental circuit based on Fig. 3 was designed and built on the 100 mm × 100 mm printed circuit board (PCB) as shown in Fig. 7. A stabilized dc power supply was used as a dc link voltage. Since of class-D audio IC has the limited input dc link voltage within ± 25 V, this system cannot output the grid voltage in fact. For this approach, it's possible to convert the voltage level with a transformer. However, it isn't necessary to use a transformer if an appropriate power IC which withstands the voltage level of the grid voltage. In the experiment, the 4 quadrants bipolar power supply (KIKUSUI: PBX40-10, output impedance $Z_{OUT} \approx 0$ [Ω]) and function generator (KENWOOD: FG273A) was used as the simulated grid voltage to connect the circuit without low frequency (LF) transformer. The voltage of the simulated grid v_S was assumed to be 14.6 V and maintain
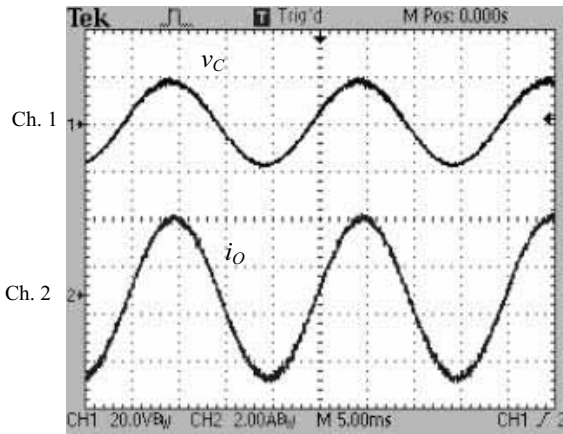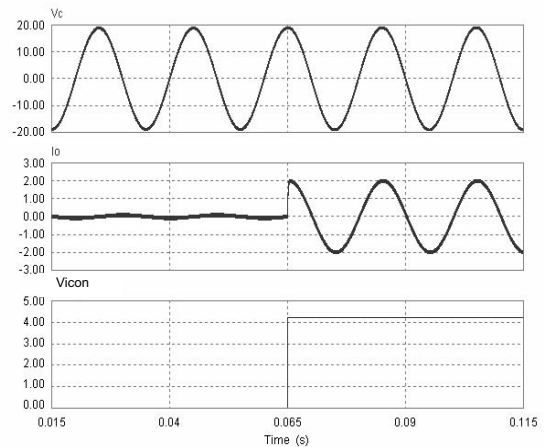
Fig. 8. Capacitor voltage (v_C) and inverter output current (i_O) in steady-state condition. Time base: 5 ms/div., channel 1: capacitor voltage 20 V/div., channel 2: inverter output current 2 A/div.

of the voltage. Although it is likely to connect the class-D audio IC to the real grid with LF transformer, it is enough to check the operation whether the inverter using the IC can be connected to the distribution grid or not with this scale downed system.

Fig. 8 shows the observed waveforms of the capacitor voltage v_C and the inverter output current i_O when the system output power is 28.7 W in steady state. In this condition, the multiplied current control level V_{icon} was constant.

Fig. 9 shows the simulated and measured waveforms of the capacitor voltage and inverter output current before and after a step change of the control level V_{icon}. These waveforms show the consistency between the predicated and the experimental results. From these results, it is clarified that this system operates stably in the gird-connected condition.
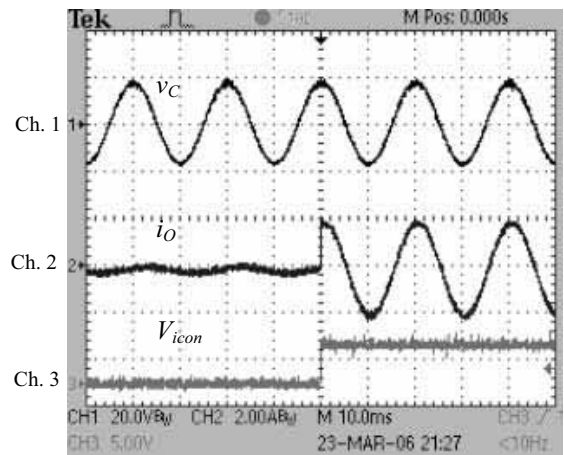
The Fig. 10 shows the measured power conversion efficiencies and power factors of the class-D audio IC in the grid-connected condition. This result was measured with a power analyzer (PZ4000: YOKOGAWA). The efficiency η is calculated within PZ4000 with:

$$\eta = \frac{P_{ac} = \dfrac{1}{T}\displaystyle\int_0^T v_C(t)i_O(t)\,dt}{P_{dc} = \dfrac{1}{T}\displaystyle\int_0^T V_{dc}(t)I_i(t)\,dt}, \qquad (6)$$

and the power factor λ is calculated with:

$$\lambda = \frac{P_{ac} = \dfrac{1}{T}\displaystyle\int_0^T v_C(t)i_O(t)\,dt}{V_{rms}\,I_{rms}}. \qquad (7)$$

The maximum value of the efficiency is 76.6 % and power factor is 0.9828 at 20.1 W, and that of the power factor is 0.9882 and efficiency is 73.9 % at 29.4 W. From the datasheet [2], the power conversion efficiency of the power IC is 89 % at

(a) Simulation results (Time base: 25 ms/div., capacitor voltage (v_C): 10 V/div., inverter output current (i_O) :1A/div., current regulation level (V_{icon}) : 1 V/div.)

(b) Observed waveforms in circuit experiments (Time base: 10 ms/div., channel 1: capacitor voltage (v_C) 20 V/div., channel 2: inverter output current (i_O) 2 A/div., channel 3: current regulation level (V_{icon}) 5 V/div.)

Fig. 9. Comparison of simulated (a) and experimentally obtained (b) capacitor voltage (v_C) and inverter output current (i_O).
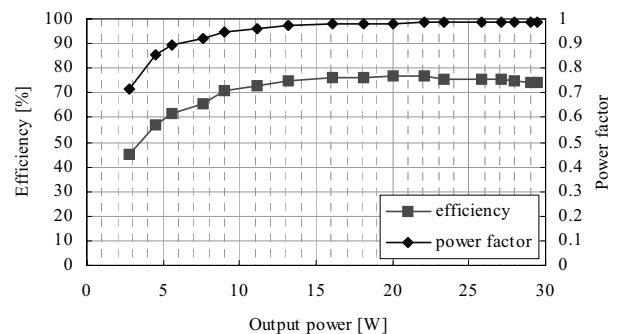

Fig. 10. Measured power factor and power conversion efficiency of the class-D audio IC in the grid-connected condition.

25 W + 25 W output power for each speaker in stereo audio configuration when 1 kHz audio signal is given. These results also cannot be made an easy comparison each other from the standpoint such as difference of the circuit configuration, the load impedance and power factor. However, this system operates in the grid-connoted condition with marinating more than 70 % of the power conversion efficiency in the range of 8.95 W to 29.47 W. Additional selection of the power device may increase the efficiency.

V.   CONCLUSION

This paper has presented a prototype of grid-connected inverter utilizing ready-made ICs for class-D audio power amplifier. Simulation results and hardware measurements have demonstrated the feasibility of the proposed system in scale-downed grid-connected condition. There remains a few challenges, for example withstand voltage. However, the implementation ready-made IC will make a large contribution to the mass-production with the reduction of discrete elements in the system and the simplification of the production process.

REFERENCES

[1] K. Kurokawa, "Mass Production Scale of PV Modules and Components in 2030s and beyond," *in Proc. 15th International Photovoltaic Science & Engineering Conference (PVSEC-15).*, Shanghai, 2005, pp.272-274.
[2] STMicroelectronics. "TDA7490 25W + 25W STEREO CLASS-D AMPLIFIER 50W MONO IN BTL," Product review Dec. 1999.
[3] Marco Berkhout., "An Integrated 200-W Class-D Audio Amplifier," *IEEE Journal of Solid-State Circuits*, vol. 38, No. 7, JULY 2003.
[4] T. Abeyasekera, C. Mark Johnson, D. J. Atkinson, and M. Armstrong, "Suppression of Line Voltage Related Distortion in Current Grid Connected Inverters," *IEEE Trans. Power Electronics*, vol. 20, no. 6, pp. 1393-1401, Nov. 2005.
[5] M. Liserre, R. Teodorescu, F. Blaabjerg, "Stability of Grid-Connected PV Inverters with Large Grid Impedance Variation," in Proc. IEEE Power Electronics Specialist Conference, 2004, pp.4773-4779.