SINGLE-PHASE CURRENT SOURCE INVERTER WITH PULSE AREA MODULATION SCHEME FOR SOLAR POWER CONDITIONER

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ABSTRACT – In general, a single-phase current-fed PWM inverter using IGBTs has some unique advantages for small scale distributed utility-interactive power supply system as compared with voltage-fed PWM inverter. In particular, this is more suitable and acceptable for a non-isolated type utility-interactive power conditioner, which is going to be widely used for residential solar photovoltaic (PV) power generation system in Japan. However, this current-fed PWM inverter has a significant disadvantage. The output current of this inverter includes large harmonic contents when the inductance of smoothing reactor in its DC side is not large enough to eliminate its current ripple components of this inverter. In order to overcome this problem, a new conceptual pulse area modulation scheme for this inverter is introduced in difference with conventional PWM strategy. This paper presents a new effective control implementation of this PV power conditioner which is able to reduce the harmonic component in the output current produced by the single-phase current-fed PWM inverter even when the ripple current in the smoothing DC reactor is relatively large. The operating principle of the proposed control strategy introdued for this inverter system is described, and its simulation results are evaluated and discussed herein.

1. INTRODUCTION

In general, the current source type PWM inverter using power semiconductor switching devices produces high AC voltages and can be used advantageously as high-impedance DC power supplies. This type of inverter provides considerably high resistance for output short-circuited operation. There is a variety of developments on utility-connected interactive inverters in a dispersed power supplies that effectively make use of the DC power from solar photovoltaic panel assembly, storage batteries, battery and electric double layer capacitor band, fuel cell and the other types of new energy sources [2-6]. In recent years, the solar photovoltaic (PV) generating conditioner has rapidly increased year by year in accordance with a highlighted social interest in clean energy utilization. Some voltage-fed PWM inverters using MOS-gate power transistors have attracted special interest as compared with current-fed PWM inverters selected in some rare occasions. However, the current-fed PWM inverter is more suitable from a practical point of view, which includes some unique advantages such as simplified control system configuration, improved efficiency and lowered costs.

It is necessary as utility-interactive distributed PV power conditioner to reduce the harmonics components in the output current within a certain small level. According to Japanese guideline, the design specification of utility-interactive inverter requires the output current THD (Total Harmonic Distortion) less than 5% [7]. For this reason, special feasible implementation to lower the harmonic current components in output current is to be required for the utility-interactive single-phase current-fed PWM inverter. This paper presents a utility-interactive current source-fed sinewave inverter suitable for residential solar photovoltaic generation conditioner, along with a new conceptual modulation control strategy to reduce all the harmonic components in the output current of this inverter without a feedback control scheme sufficiently.

2. INTERACTIVE INVERTER TOPOLOGIES FOR SOLAR POWER CONDITIONER

Of late years, the actual number of Japanese residential houses with small scale solar photovoltaic generation (PVG) systems has more increased rapidly, and there are a variety of researches and developments of utility-interactive inverters acceptable for PVG systems. Conventional utility-interactive inverter with a low-frequency transformer link is capable of insulating solar PV array from the utility-grid bus line, since this type of isolated transformer has actually heavy weight and large volumetric physical size. On the other hand, high-frequency transformer isolated utility-interactive inverters which include DC-DC power converter type and cycloconverter type power converter. At present, the PVG systems have begun to employ the simple and cost effective non-isolated type of inverter that does not include an isolated transformer in order to realize further system reduction in physical size and weight, and to improve cost effectiveness [10].

In Japan, the commercial utility connected power supply using PVG system is generally 100V-linked single-phase three-wire systems. This utility-interfaced inverters are interconnected between the U- and V-phases of 200V AC source. The utility interactive inverter is a single-phase voltage-fed sinewave PWM inverter with a high-frequency carrier, which needs a DC busline voltage higher than the peak value of the AC output voltage. However in practice, raising the output voltage of PV cells involves feasible problem with respect to safety. For this reason, a step-up DC chopper or step-up and down intermediate DC chopper is added to the power stage between the inverter and PV array. This DC chopper can raise the output voltage of PV array up to about 400V cells, whose rated voltage is designed for about 200 V, and supplies this voltage to the inverter. Fig.1 shows a schematic circuit configuration of the non-isolated utility-interactive voltage-fed PWM inverter using IGBTs, which is put into practical use. In this system, because of boost converter performance, a low voltage solar PV array can introduce, but this system configuration becomes a relatively complex.

On the contrary, Fig.2 indicates a system configuration for residential solar PV generating and conditioning in case of employing a single-phase current-fed PWM inverter. Because current-fed PWM inverter can simply step up its output voltage, this system can use the low-voltage solar PV array. As shown in Fig.2, the low quality output power obtained from the solar PV array can be directly supplied to the inverter with simplified total system configuration. Accordingly, the use of current-fed PWM inverter becomes more cost effective for non-isolated interactive PV systems.

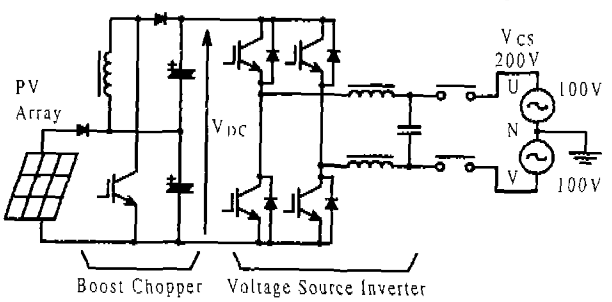


Fig.1 Conventional Non Insulated Interactive Inverter

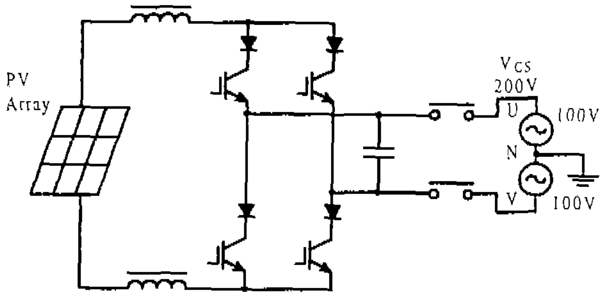


Fig.2 Non Insulated Interactive Inverter with Current Source Topology

3. CONTROL STRATEGIES FOR CURRENT-FED INVERTER

Fig.3 shows a full bridge configuration of utility-interactive single-phase current-fed PWM inverter circuit using IGBTs. Smoothing reactor (DCL) of this inverter can reduce the ripple components of its input current. The filter; (Cf and Lf) can lower high frequency components in the output current of this inverter.

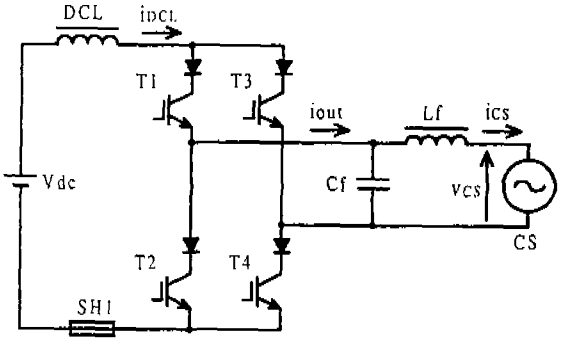


Fig.3 Circuit Configuration of Current Source PWM Inverter

In order to produce a sinewave shaping output current waveform, current-mode control PWM inverter effectively can use a new control method that is based on the comparison between a reference sinewave as signal wave and a high frequency sawtooth waveform as carrier wave to determine the PWM pattern of switching power devices T1-T4. In this method, when the inductance of the DCL is sufficiently large, and then, the ripple component of current "i_{DCL}" can be ignored. It is possible to obtain an output current with a distortion-free sinewave. Because this type of inverter must be made much smaller so as to be more economical. The inductance of DCL must be reduced so as to be a relatively small value. It is necessary to develop the control method to realize the output current distortion factor of this inverter to a small value even when the current ripple of the DCL is relatively large. This is an actual major theme that has to be accomplished in order to introduce single-phase current source utility-interactive PWM inverter. For this purpose, the following methods have been proposed so far.

(a) A method to impose the third harmonics on a reference sinewave. [1]
(b) A method to control the magnitude of the third harmonics with a feedback control scheme. [2]
(c) A method to impose the second harmonics on a reference sinewave. [4]
(d) A method to provide a parallel resonant circuit for the second harmonics in series with the DCL. [5]
(e) A method to put a DC-DC converter in the front power stage of inverter. [6]

However, several conventional methods proposed mentioned above are not sufficiently perfect because they have some problems such as inadequate effectiveness in harmonic current reduction, more complicated circuits in addition to higher costs. The new control strategy for current source PWM inverter can simply realize the suppression of output current harmonics by adopting a new conceptual control method known as a new conceptual pulse area modulation, which has been already proposed for the advanced control strategy of PFC converters [8], [9]. With this method, complete-harmonic suppression of the output current can be achieved on the basis of only a simple control circuit procedure without a feedback control scheme.

4. CONVENTIONAL CONTROL STRATEGY

Control Approach in No Ripple Reactor Current Design

Fig.4 shows typical waveforms to explain the conventional control method used in single-phase current source PWM inverter in Fig.3. T1 and T3 turn on and off at each half cycle of the commercial AC voltage in the utility-grid power source. T2 and T4 turn on and off according to the comparison processing between a high-frequency sawtooth carrier signal and a reference signal obtained by a fullwave rectification of a sinusoidal signal synchronized with the utility-power source voltage. Although an 800Hz-carrier signal is selected as shown in Fig.4 in order to illustrate the modulation mechanism clearly. In this case, the carrier frequency is usually set at several tens of kHz in practice.

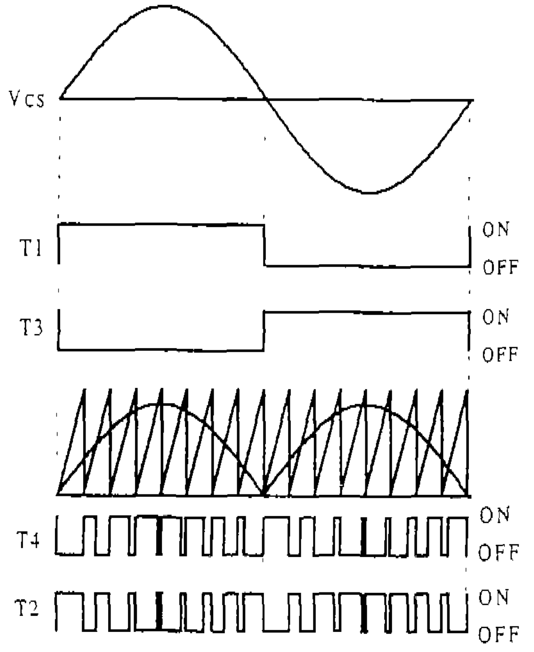


Fig.4 Conventional PWM Control Strategy

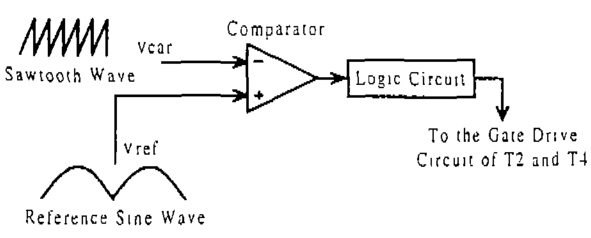
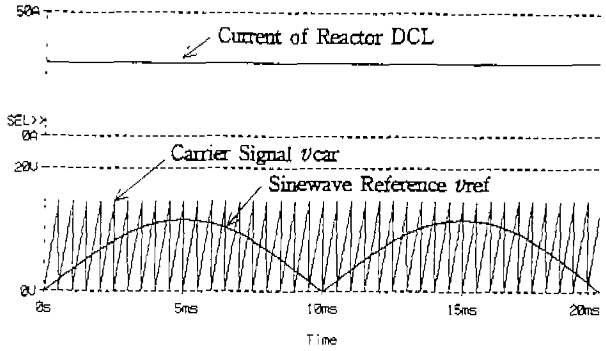


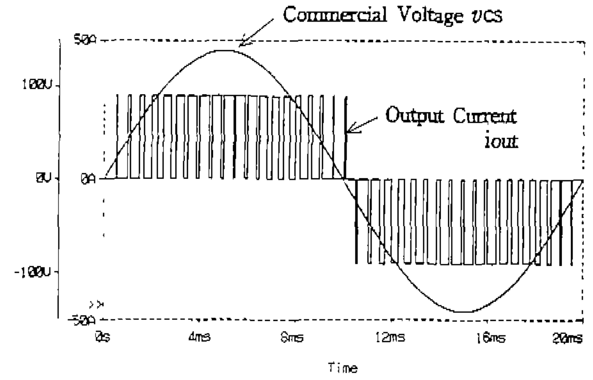
Fig.5 Conventional Control Circuit

Fig.5 indicates a block diagram of the control processin circuit to produce the gate signals as displayed on the lowe side of Fig.4 to the switches T2 and T4 in Fig.3. Assumin that PWM control is introduced in this manner and the curren "i_{DCL}" is ripple-free, the inverter output current delivered int the power source basically becomes a high quality sinusoida waveform.

Fig.6 displays the simulated waveforms of utility-interactiv current-fed inverter as operating at a conventional sinewav PWM control method under a ripple free DC reactor curren



(a) Waveforms of Reactor and Control Circuit



(b) Output Voltage and Current Waveforms of Inverter

Fig.6 Waveforms When Ripple Current of Smoothing Reactor DCL can be Ignored

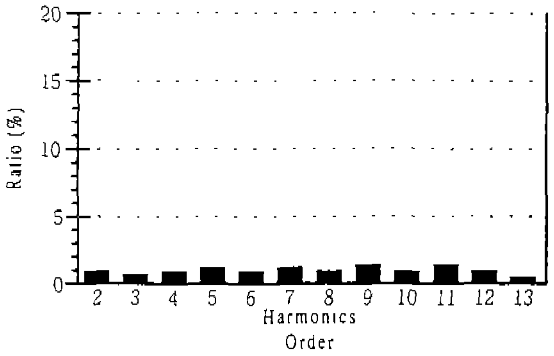


Fig.7 Spectrum Analysis of Output Current iout with no Ripple Current at Smoothing Reactor

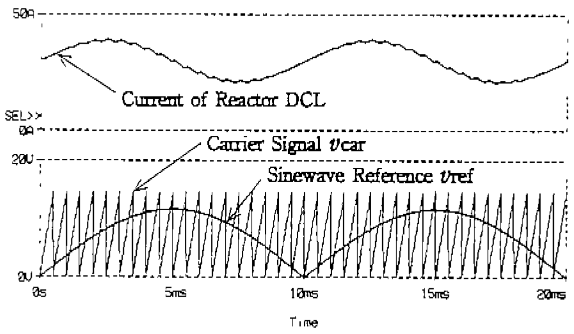
"i_{DCL}". In this case, the DC reactor current is sufficiently smoothed as depicted on the upper side of Fig.6 (a). As a result, the output current i_{out} draws a PWM waveform whose pulse amplitude is exactly flat as shown in Fig.6 (b).

Fig.7 indicates harmonic contents of the simulated output current i_{out}. It is confirmed on the basis of the illustration that the low order harmonics of the output current under this condition are suppressed sufficiently. Since higher order urrent harmonics are filtered by the effectiveness of second order low pass filter which is composed of Cf and Lf shown in Fig.3. This low pass filter is connected between the inverter output and the commercial utility power source grid, a desirable distortion-free current is fed to the AC power source grid interfaced into this inverter which is connected to the solar PV array.

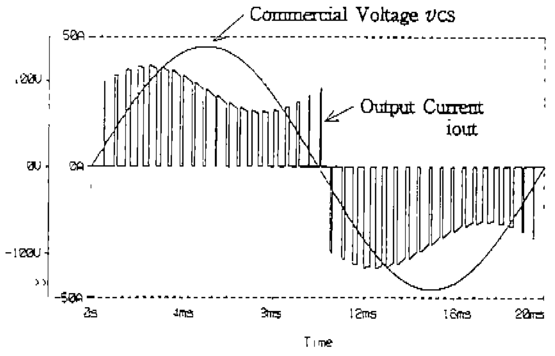
In principle, to make the circuit operation easy to see, the oscillating frequency of carrier wave is set at 2 kHz in this simulation. In a practical current-fed PWM inverter, the carrier frequency is to set at several tens of kHz. The simulation results illustrated in this paper are carried out in the case of the carrier frequency 2kHz.

Control Approach in Ripple Reactor Current Design

As discussed above, the conventional PWM control method may result in a desirable output current waveform if the reactor current of the DCL is sufficiently smoothed by using a DC reactor with a large inductance. However, it is indispensable to make the inverter smaller and more economical in order to reduce the volumetric physical size and weight of the DC smoothing reactor. To achieve these requirements, the inductance of DC reactor must be sufficiently decreased.



(a) Waveforms of Reactor and Control Circuit



(b) Output Voltage and Current Waveforms of Inverter

Fig.8 Waveforms When Ripple Current of Smoothing Reactor DCL can not be Ignored

This results in undesirable distortion of the output current of this inverter. This fact can be explained through some simulation results as below.

Fig.8 provides the simulated waveforms obtained from the current-fed PWM inverter operating at the PWM control scheme in Fig.4. The circuit condition in this simulation is listed in Table 1.

As shown in Table 1, the inductance of the DCL is set at 10 [mH] and is extremely small as compared with that in conventional current-fed inverter. Due to a small inductance value, the current of the DCL includes a large ripple as shown on the top of Fig.8 (a). As a result, the amplitude of output current pulse largely fluctuates as shown in Fig.8 (b). Since this method generates a PWM pattern, which is independent of the fluctuation of the pulse amplitude, the output current produces undesirable distortion. This fact is clearly understood by analyzing harmonics included into the output current, and the spectrum analysis of output current is indicated in Fig.9. As can be seen from this figure, the large ripples of the DC reactor current i_{DCL} result in a large third harmonic content of the output current i_{out} in conventional PWM control method. In this case, the third harmonic component comes to 15% of the fundamental component. Note that the condition would not sufficiently meet the Japanese guideline [7].

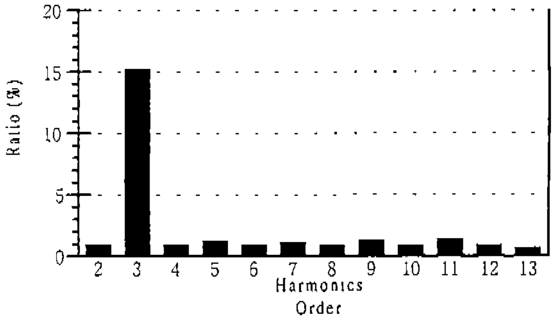


Fig.9 Spectrum Analysis of Output Current iout with Large Ripple Current at Smoothing Reactor

Table 1 Simuration Specification

Input Voltage Vdc	60V
Smoothing Reactor DCL	10mH
Commercial Voltage V_{cs}	100Vrms

5. PULSE AREA MODULATION

Operating Principle

Fig.10 shows the circuit configuration of a new pulse modulation scheme, which is defined as pulse area modulation proposed here. The output current i_{CS} of this inverter is detected at a precise shunt resister SH1 or DCCT-based current sensor, whose voltage v_{SH1} is amplified and fed into the

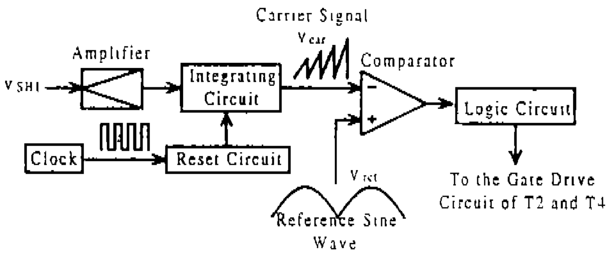


Fig.10 Proposed Control Circuit Configuration

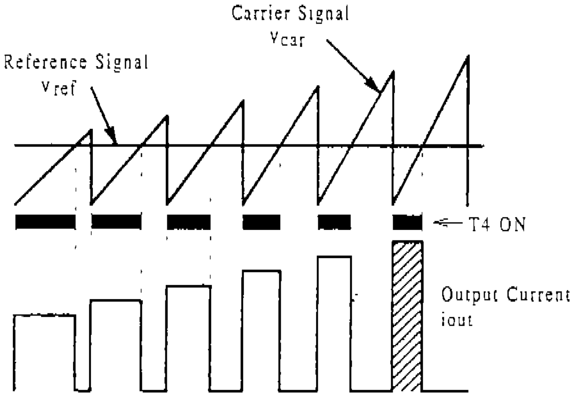


Fig.11 Principle of Pulse Area Modulation

electronically-processed integrating circuit. This integrating circuit is to be reset with a constant sampling interval, and its output voltage becomes the sawtooth wave v_{car}, which has a peak voltage that is proportional to the value of i_{DCL}. This sawtooth wave is compared to the reference sinewave v_{ref}, which is specified by the fullwave rectified voltage v_{CS} synchronized with a utility power source grid voltage. In terms of obtaining the PWM wave, the switching power devices T2 and T4 are driven.

Fig.11 illustrates the basic principle of pulse area modulation, which is implemented in power control circuit for current-fed inverter. In this case, the sawtooth carrier wave v_{car} adopted in this unique modulation is subsequently produced on the basis of integrating the sensing signal of the reactor current i_{DCL} with difference from the conventional carrier wave generation. Its peak voltage varies in proportional to i_{DCL}. For example, considering that reactor current gradually increases for simplicity, the current of the DCL generates a sawtooth wave whose peak voltage increases as shown in Fig.11. Assuming that the reference wave v_{ref} has a constant voltage under a certain portion of sinewave as shown in Fig.11, the duty ratio of T4 gradually decreases on the basis of the comparator processing. Therefore, the output current waveform i_{out} of this inverter becomes a square wave in which peak value gradually increases and the pulse width gradually decrease as illustrated in Fig.11.

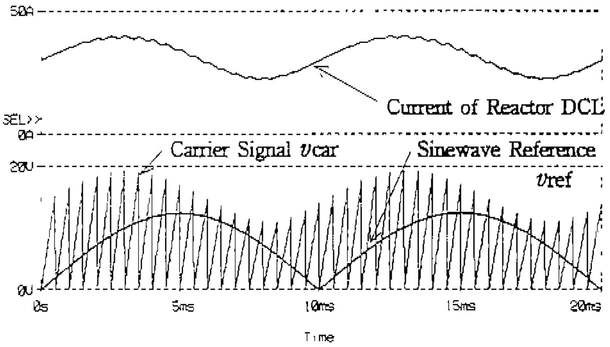
It is noted that pulse portion displayed with a shaded area has twice peak value as the pulse portion shown with a dotted area. On the other hand, the shaded area pulse current has one-half under pulse width principle with an equal area. The case that the reference waveform is constant for simplicity, the area of each pulse train will not change. On the contrary, if the reference waveform increases or decreases, the pulse areas increase or decrease proportionally in accordance with reference signal. And pulse area is equal to the instantaneous value of the output current i_{out}. Thus, the case of that the reference waveform is changed so as to be a sinewave as shown in Fig.10, the output current will vary so as to be a sinewave.

Simulation Results and Their Discussions

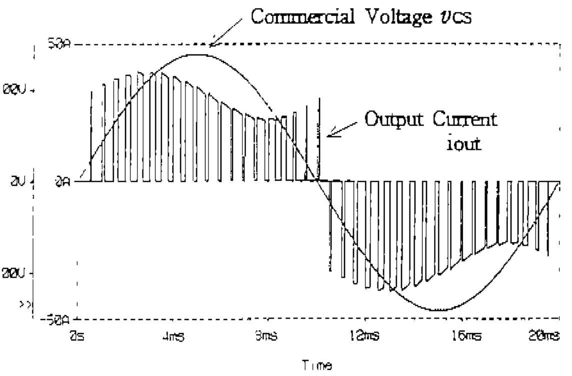
Fig.12 gives the simulated output current waveforms for the current source type inverter operating under the proposed control circuit shown in Fig.10.

The reactor current i_{DCL} has a large ripple (18Ap-p), and the peak value of a sawtooth carrier signal v_{car} varies in proportion to the sensing signal of the reactor current. The output current i_{out} has a pulse width that is greater than that in Fig.8 (b) in the low-peak region. It means that the control method treated here operate exactly.

Fig.13 displays the spectrum analysis for the output current i_{out} illustrated in Fig.12 (b). The third harmonic current component is much smaller than that shown in Fig.9. The effectiveness of this new control strategy-based pulse area modulation is proved for the utility-interactive current-fed inverter used in solar PVG system.



(a) Waveforms of Reactor and Control Circuit



(b) Output Voltage and Current Waveforms of Inverter

Fig.12 Waveforms with Proposed Control Strategy

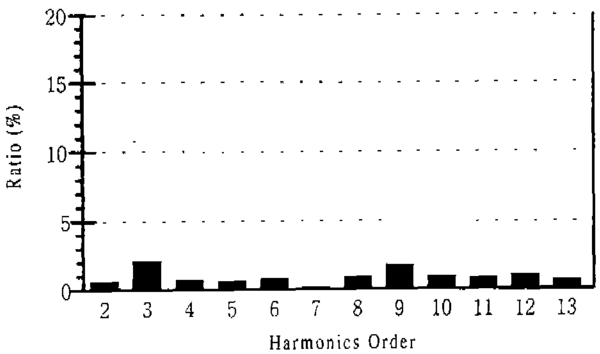


Fig.13 Spectrum Analysis of Output Current iout with Proposed Control Stragegy

6. CONCLUSIONS

A novel sinewave modulated control strategy defined as a new conception pulse area modulation, which has been originally proposed by the authors as the control strategy for high-power factor correction converter has been introduced to a utility-interactive current-fed sinewave inverter for the solar power conditioner. Simulation results were indicated that the harmonic components in the AC output current of the current-fed inverter using pulse area modulated processing was able to eliminated completely on the basis of the proposed control strategy in case of the reduced DC reactor design. Note that the analogue-oriented signal processing circuits implemented for this pulse area modulated control method is composed of only a current sensor device such as a high-precise shunt or DCCT-based current sensor, an integrating circuit and the other simple control circuits. As demonstrated above, this control strategy of this inverter was more cost-effective for improving the steady-state characteristics of single-phase current source sinewave inverter, and was suitable for practical utility-interactive distributed power supply incorporating current source sinewave pulse area modulated inverter applications.

In the future, this new control strategy of current-fed inverter for utility-interactive solar power conditoner should be investigated and evaluated from an experimental point of view, together with an further development of current source type pulse area modulated inverter operating under a principle of zero voltage soft-switching.

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