

The Development of a Programmable Single-Phase AC Power Source with a Linear Power Amplifier

Jeong-Chay Jeon* · Hyun-Jae Jeon · Jae-Geun Yoo · Jae-Hyun Son

Abstract

This paper presents a programmable single-phase ac power source that provides a sinusoidal output voltage with an adjustable output amplitude and frequency over a wide range as well as an arbitrary waveform. The ac power source under consideration have a linear power amplifier. The desired output values can be programmed with a personal computer. The power source operates at 220[V]/60[Hz] mains and the output voltage is isolated from the input circuit. The system consists mainly of a power converter to generate and amplify the waveform signal, a controller to control the desired output signal and measure the output parameters, and a control program to set the desired output and display the values. The prototype ac power source was constructed and tested with the results demonstrating a good performance.

Key Words : Programmable power source, Sinusoidal output, Arbitrary waveform, Power amplifier

1. Introduction

Many standard pieces of experiment or tests of electrical power devices require the use of different ac sources that can provide ac voltage with variable amplitude and frequency over a wide range as well as arbitrary waveform. In order to understand to the effects of harmonic and waveform distortion on the various power devices including protection, control, instrumentation and measurement equipments, in particular, the test and evaluation of the effects of the harmonics may

require sinusoidal waveforms with various voltages and frequencies.

A programmable ac power source can be very useful for testing the effects of harmonics on the various devices. A programmable ac power source provides sinusoidal output voltages whose amplitude and frequency can be programmed independently from each other. The waveform generated is based on the concept of the complex Fourier series [1]. Any periodic waveform can be reproduced by generating and summing together a set of harmonically related sine-waves with the proper magnitude and phase-shift components.

The basic function of an ac power source is to implement power conversion and frequency control, and to generate arbitrary voltages and waveforms. These generated waveforms consist of a sinusoidal function at the fundamental frequency

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with several harmonic components. Most ac power sources available today are types of linear power amplifiers and pulse width modulated inverters. The computer based harmonic generator facilities of [1] explained principal of a harmonic generator and its needs. A single and three-phase AC power source using a sliding mode control was proposed by Low and a predictive control with pulse width modulated inverters was generalized [2, 3].

A power source with a pulse width modulated inverter has the problem that switching losses increase with the elevation of the switching frequency [4, 5]. Also, although a power source with a linear power amplifier is inefficient, is in essence a large heat sink and requires an isolation transformer to increase the size and the weight of the systems, it allows the generation of any waveform and has good input-output features. This paper, therefore, considers the linear power amplifier type of ac power source.

This paper describes the design and implementation of a programmable single-phase ac power source, which is able to synthesize voltage waveforms and amplitude. In this system, harmonics can be added to the fundamental frequency, so that arbitrary waveforms can be generated. Various experiments have been conducted to verify the performance of this system and the results have shown that the developed single-phase ac power source performs well.

2. Description of AC power source

2.1 Description of AC power source

The block diagram of the ac power source under consideration is depicted in Fig. 1. This power source consists mainly of power input, a power

converter (SCR rectifier and power amplifier) to generate and amplify waveform signals, a controller to control the output signal and measure the output parameters, and a control program to program the desired output values and display the output parameters. A personal computer (PC) and control program are used to provide interface with the power source. The PC and control program control the waveform's shape with harmonic order and amplitude, and measure the output parameters including voltages and currents.

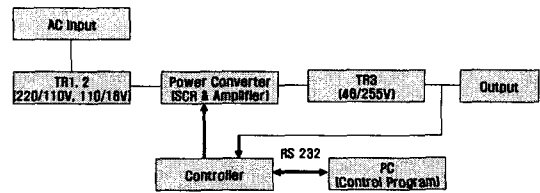


Fig. 1. The block diagram of the system

2.2 Output stage of a class B power amplifier

Amplifiers are classified into different classes such as A, B, C, and F according to their circuit configurations and methods of operation. These classes range from entirely linear with low efficiency to entirely non-linear with high efficiency [6].

The class B amplifier is a two-transistor circuit that is designed to improve on the efficiency characteristics of class A amplifiers. A class B amplifier is shown in Fig. 2. The circuit shown in Fig. 2 is a complementary-symmetry amplifier, or a push-pull emitter follower. The circuit contains one npn transistor (Q_1) and one pnp transistor (Q_2).

The average dc power $P_{(+ve)}$ supplied by a dc source can be expressed as

$$P_{(+ve)} = V_s \overline{I_{c1}} \quad (1)$$

Where V_s is the supply of dc voltage.

The average current \bar{I}_{c1} through each transistor of the amplifier is given by

$$\bar{I}_{c1} = \frac{1}{2\pi} \int_0^{2\pi} I_{c1}(\theta) d\theta = \frac{1}{2\pi} \int_0^{\pi} \frac{A}{R_L} \sin(\theta) d\theta = \frac{A}{\pi R_L} \quad (2)$$

Where R_L is the load, and A is the output ac voltage.

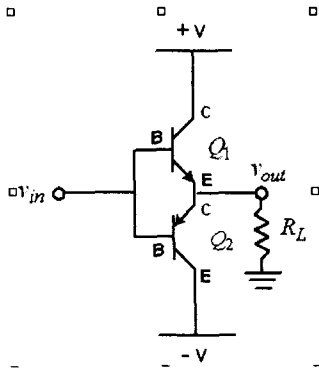


Fig. 2. A class B amplifier

Thus, the average power is calculated by using (2) and (1) as

$$P_{(+ve)} = \frac{V_s A}{\pi R_L} \quad (3)$$

The total average dc power P_s supplied by the two dc sources when the output voltage is at its maximum value is given by

$$P_s = P_{(+ve)} + P_{(-ve)} = 2P_{(+ve)} = \frac{2V_s A}{\pi R_L} \quad (4)$$

Also, the average ac power P_L delivered to the load when the output voltage is at its maximum value can be expressed as

$$P_L = \frac{\overline{v_{out}^2}}{R_L} = \frac{\overline{A^2 \sin^2(\omega t)}}{R_L} = \frac{A^2}{2R_L} \quad (5)$$

The efficiency of an amplifier is the measure of its ability to convert the dc power of the supply into the signal power delivered to the load. The efficiency of the amplifier η can be computed as

$$\eta = \frac{PL}{P_s} = \frac{A^2}{2R_L} \frac{\pi R_L}{2V_s A} = \frac{A\pi}{4V_s} \quad (6)$$

The maximum efficiency can be obtained when $V_s = A$. We can now compute the maximum efficiency of the class-B amplifier as

$$\eta = \frac{\pi}{4} = 78.53\% \quad (7)$$

The transistors used in a power amplifier must have a maximum power dissipation rating that is sufficient to meet the demands of the circuit. The power dissipation P_D can be expressed as

$$P_D = P_s - P_L = \frac{2V_s A}{\pi R_L} - \frac{A^2}{2R_L} \quad (8)$$

The maximum power dissipation can be obtained by $\frac{dP_D}{dA} = 0$. Differentiating equation (8), and equation (9) can be obtained :

$$\frac{2V_s}{\pi R_L} - \frac{A}{R_L} = 0, \quad A = \frac{2V_s}{\pi} \quad (9)$$

Thus, the maximum power dissipation $P_{D(max)}$ can be written as

$$P_{D(max)} = \frac{4V_s^2}{\pi^2 R_L} - \frac{2V_s^2}{\pi^2 R_L} = \frac{2V_s^2}{\pi^2 R_L} \quad (10)$$

In order to design an amplifier that has an output power of 200[W] and drives a load of 25 [Ω], the output voltage is calculated as

$$P_L \leq 200 \rightarrow \frac{A^2}{2R_L} \leq 200 \rightarrow A \leq 35.36 \quad (11)$$

Considering the saturation voltage of transistors, the supply dc voltage V_s of the amplifier should be larger than the maximum output voltage A_{max} . The designed amplifier of Fig. 3 has power transistor 2SA1494(PNP) and 2SC3858(NPN), while the supply dc voltage V_s was chosen as 39.5[V]. Thus, the maximum power dissipation can be calculated as

$$P_{D(max)} = \frac{2V_s^2}{\pi^2 R_L} = 17.15[W] = 28.6[W] \quad (12)$$

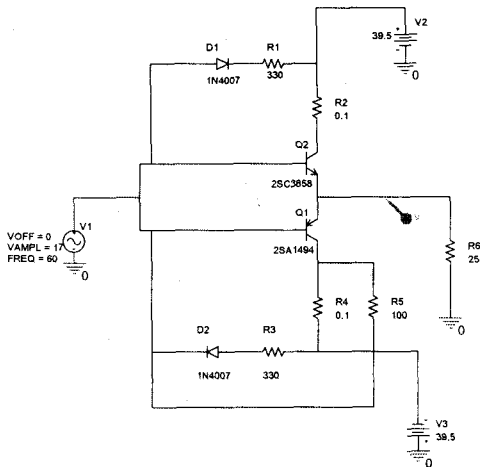


Fig. 3. The basic structure of the designed amplifier

3. Implementation of Hardware

A power level of about 1.5[kW] is necessary in order to be able to supply most single-phase

equipment. The main specification of the ac power source designed is summarized in Table 1.

Table 1. The specification of the ac power source

Output Power	1.5[kW]
Output Type	Single-phase
Output Voltage	max 255[Vrms]
Output Current	max 6[Arms]
Output Frequency	45-999[Hz]
Harmonic Synthesis	1-15th
Waveform	16 waveform library
Interface	RS232C
Operation Method	Set / PC
Display	Voltage (RMS), Current (RMS, peak and crest factor), KVA, KW and power factor (PF)

The output reference signal is first generated in the controller illustrated in Fig. 4 and 5. In spite of the output voltage and waveform control of the ac power source being analogue, the reference signal as well as an on/off signal is generated by the controller in order to allow easy programming of the output voltage and waveform from a PC. An 8-bit microcomputer (PIC18F8720) and digital to analogue (DA) converter (AD 7523) are used to generate the output signal. In order to maintain the independent output function of the DA converter when the microcomputer performs another task, a latch-IC 74F573 between the microcomputer and DA converter is used. To execute the waveform output command from the PC at a high speed, a 4Mbit static random access memory (S-RAM) was used. Also, in order to save the information of the waveform saved inside the controller by modifying and saving the command of the waveform from the PC, a 4Mbit flash read only memory drive (F-ROM) is used.

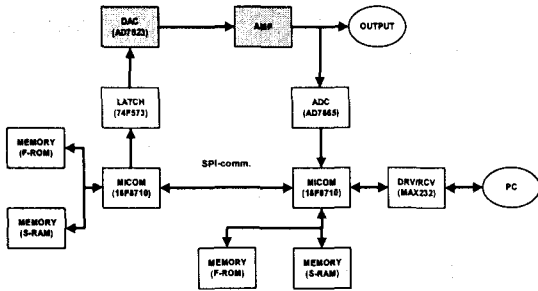


Fig. 4. The block diagram of the controller

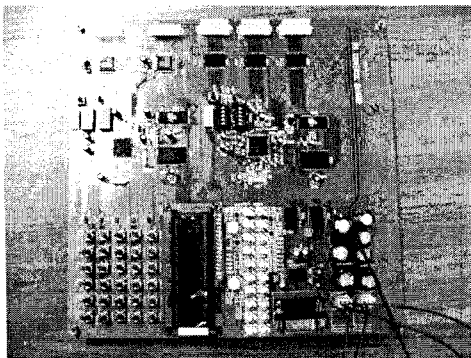


Fig. 5. The controller

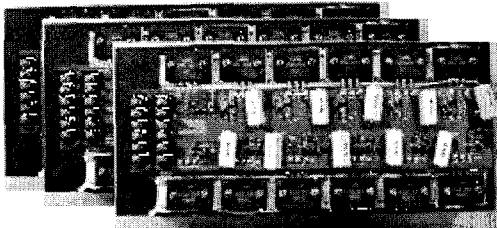


Fig. 6. The power amplifier module

In the ac power source, in order to provide dc power for the digital components and a signal for the power amplifier, a silicon-controlled rectifier (SCR) is used. The signal generated by the controller is then sent to a linear power amplifier module. The power amplifier module consists of power transistor 2SA1494 (PNP) and 2SC3858 (NPN). These linear ac power amplifiers are constructed as shown in Fig. 6. The module has an output capacity of 1.5[kW] and is designed so that its capacity could be enlarged in the future.

Finally, the amplified voltage is sent to the 46/255[V] transformer to amplify the voltage level.

In the ac power source developed herein, the output voltage and current were measured by the voltage transducer LV 25-P and current transducer LTS 25-NP, and the measured data were converted to digital signals via a 14bit analogue to digital AD converter (AD 7865) as shown in Fig. 3. In order to protect the system from surges and over-voltage, a varistor TNR 20D751K and zener diode 1.5KE15 were used, respectively. An 8 bit microcomputer (PIC18F8720) for analogue to digital conversion (ADC) was used to measure and save the output of the ac power source in the memory. It was connected to a microcomputer for digital to analogue conversion (DAC) by using serial peripheral interface (SPI) communication in order to transmit the output command from the PC to the microcomputer for the DAC. A 4Mbit S-RAM for the high-speed saving of the 14 bit data per channel from the AD converter was used. Also, in order to save the transmission command from the PC and ADC data, a 4Mbit F-ROM was used. The prototype ac power source is illustrated in Fig. 7.

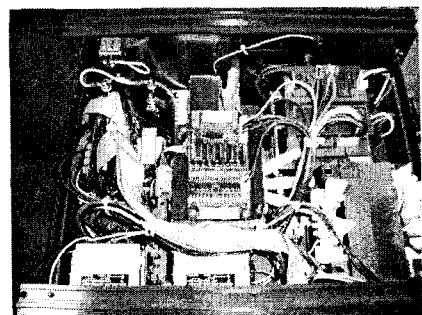


Fig. 7. The developed single-phase ac power source

4. Control program

In order for the user to determine the desired

output voltage amplitude, frequency and waveforms of the ac power source and confirm the output data, a control program using Borland's C++ Builder was developed and an RS-232 serial interface was used. An ac power source that can be operated remotely has a great advantage. As a serial interface is used, distances between user and the ac power source can be managed for safety and convenience.

Fig. 8 demonstrates the main window formation of the control program, by which the user can confirm the operational state of the ac power source, as well as the output data including voltage (RMS), current (RMS, peak and crest factor), KVA, KW and power factor (PF). This allows the output voltage to be checked prior to applying power to the load. The serial interface that is used for communication to the microcomputer can be chosen with the setup menu. The setting and synthesis of the waveform including the harmonic can be performed in the synthesis menu. Each waveform signal can be any of the first 16 waveforms stored in the memory. The first of these 16 waveforms is a sine wave and cannot be altered while the other 15 waveforms can be altered by the user to produce any arbitrary waveforms as shown Fig. 8. These waveform libraries can be saved to and read from files. Fig. 9 indicates the window by which to set and synthesize the desired output waveform including the harmonic order and magnitude.

Finally, the ac power source is operated by the execute menu of Fig. 8 and the operating time of the ac power source is demonstrated by the elapsed time menu. Communication and output status are confirmed by the com port and the output disable menu, and output information is displayed by the measuring menu.

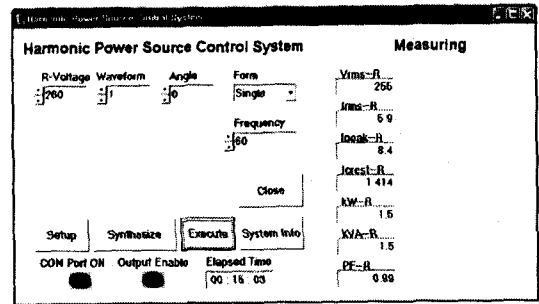


Fig. 8. The main window of the developed control program

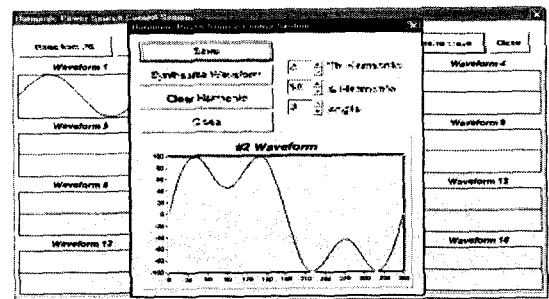


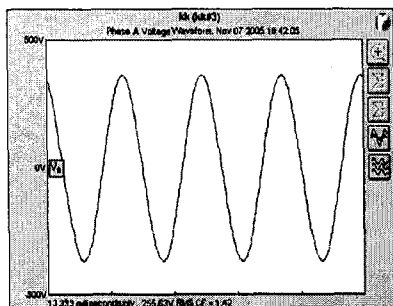
Fig. 9. The window to set the desired output waveform including the harmonic

5. Results

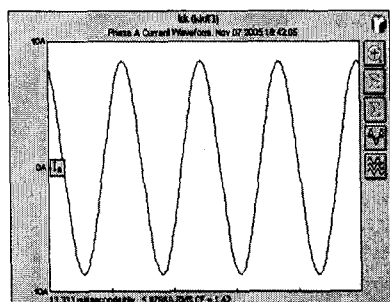
The performance of the ac power source was measured. In order to measure the output voltage, current amplitude and waveform of the ac power source, a power quality analyzer (RPM 1650) was connected to the ac power source.

The maximum output voltage and current of the ac power source were also tested. In this test, the desired output voltage was set at 260[V](rms) and a fixed frequency of 60[Hz]. A constant resistive load was connected to the output such that an output current of 6 A (rms) is drawn. The results measured by RPM 1650 were presented in Fig. 10. As can be seen from the test results, there is no noticeable distortion of the output voltage and current; the output voltage(a) and current(b) yield about 255.63[V](rms) and 5.97[A](rms) with little

error because the maximum output voltage and current are limited to 255[V](rms) and 6[A](rms) respectively.



(a) The output voltage



(b) The output current

Fig. 10. The maximum output voltage and current

In order to demonstrate the ac power source for the generation of arbitrary waveforms, various experiments were performed. In these experiments, the output of the ac power source was connected to a resistive load and RPM 1650 for measuring the output voltage and waveform.

Fig. 11 shows the result in which the output voltage was set as 131[V](rms) at 60[Hz], and 10 [%] third harmonics, 30[%] fifth harmonics, and 50 [%] seventh harmonics were added. It is clear from the test results that the desired waveform is accurately obtained.

Figs. 12 and 13 depict the other waveforms with harmonic content, where the fundamental frequency is 60[Hz]. Test results demonstrate that

the developed programmable ac power source performs well.

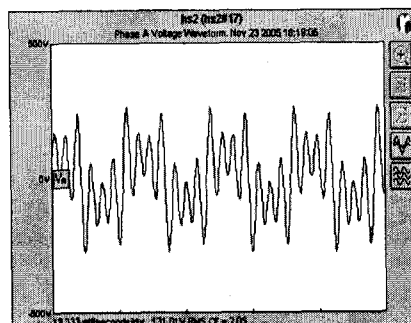


Fig. 11. The output voltage waveform of $131(\sin wt + 0.1\sin 3wt + 0.3\sin 5wt + 0.5\sin 7wt)$

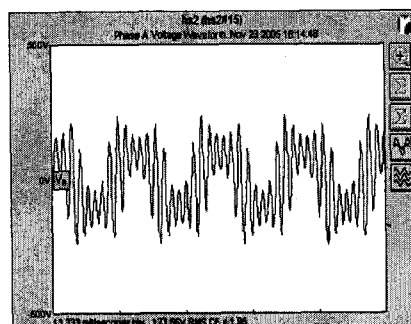


Fig. 12. The output voltage waveform of $123(\sin wt + 0.1\sin 7wt + 0.3\sin 9wt + 0.5\sin 11wt)$

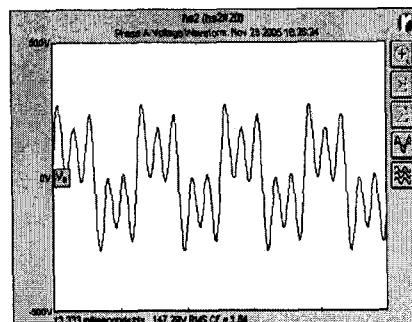


Fig. 13. The output voltage waveform of $147(\sin wt + 0.3\sin 3wt + 0.5\sin 5wt)$

6. Conclusion

A programmable single-phase ac power source

with adjustable output voltage amplitude and frequency has been successfully developed. In this ac power source, in order to control the desired signal and measure the output signal, a controller using two 8 bit microcomputers was developed. Linear power amplifiers to amplify the output signal and a control program to set and display the output of the ac power source were also developed. In order to verify the adequacy of the developed ac power source, various experiments have been conducted. The results have demonstrated that the desired output voltage and waveform of the ac power source can be correctly obtained. Further work to develop a power amplifier with high accuracy and large capacity will be needed.

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References

- [1] Adly A. Girgis, Elham B, Makram and Thomas L. Baldwin, "Computer Based Harmonic generator Facilities to Study Harmonic Related Problems", IEEE Trans. on Power system, Vol. 4, No. 3, pp. 1252-1257, August 1989.
- [2] Kay-Soon Low, "A DSP-Based Variable AC Power Source", IEEE Transaction on Instrumentation and Measurement, Vol. 47, No. 4, pp 992-996, August 1998.
- [3] Kay-Soon Low, "A DSP-Based Single-Phase AC AC Power Source", IEEE Transaction on Industrial Electronics, Vol. 46, No. 5, pp 936-941, October 1999.
- [4] Richer, C. M, Carti, E. G., Pinheiro, H., Hey, H. L., Pinheiro, J. R. and Grundling, H. A., "A Three-Phase AC Power Source using Multi Variable Repetitive Robust Model Reference Adaptive Control", 2003 proceedings of American Control, Vol. 3, pp 2300-2305, June 2003.
- [5] Carati, E. G., Richter. C. M, and Grundling, H. A., "A Three-Phase AC Power Source using Robust Model Reference Adaptive Control", 2000 Proceedings of the 39th IEEE Conference on Design and control , Vol. 4, pp 4078-4083, December 2000.
- [6] Vamsi Paidi, Shouxuan Xie, Robert Coffie, Brendan Moran and Sten Heikman "High Linearity and High Efficiency of Class-B Power Amplifiers in GaN HEMT Technology", IEEE Transaction on Microwave Theory and Techniques, Vol. 51, No. 2, pp 643-652, February 2003.

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