A MICROCONTROLLER-BASED SYSTEM FOR MONITORING AND CONTROLLING THE OPERATION OF AN UNINTERRUPTIBLE POWER SUPPLY

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Abstract The design of a real time system that measures and monitors fundamental parameters of an Uninterruptible Power Supply (UPS) in which it is incorporated is described. The system is based on a microcontroller (MCS-96 family) with a built-in 10-bit A/D converter. The parameters being measured in real time are the amplitude, the frequency and the distortion of the UPS output ac signal. The charging state of the battery cells, the supply current of the battery and the signal level at specific test points on the UPS circuit board are also measured and monitored. These parameters are used in the real-time calculation of the remaining time before the UPS battery is exhausted and, in case of malfunction, the fault is located and the UPS is safely turned off.

I. INTRODUCTION

The power generated by electric systems, like a UPS or an engine generator, usually provide adequate and reliable supply of electric energy. However, sometimes these systems suffer from voltage or frequency disturbances and other more or less serious malfunctions.

Most of the equipment served by an auxiliary power supply can tolerate short-term voltage variations or harmonic distortion without affecting their operation or lifetime. However, there is growing use of computers, communication systems and process control systems that are very sensitive to electric disturbances. Overvoltage in a UPS output may cause equipment malfunction or even equipment damage. Harmonic distortion may affect the power supply stability, motor speed or produce overheating in power components, such as transformers [1].

This paper describes the development of a low-cost, real-time control system whose basic function is to calculate and verify, whether the UPS ac output signal satisfies the following basic specifications:

i) amplitude: $V_{rms} = 220V \pm 5\%$

ii) frequency: $f = 50Hz \pm 1\%$

iii) harmonic distortion: $THD(\%) < 5\%$

Such a sytem must operate in real time in order to be capable of effectively protecting any devices powered by it (user) from a possible UPS malfunction.

IEEE Catalog Number: 95TH8081

Samples obtained from specific test points on the UPS circuit board are compared with expected values to determine if the system operates properly. In case of malfunction, the location of the error is pointed out and the UPS system is safely turned off.

Communication between a UPS and its user is always a desirable feature, particularly when the UPS is placed far from the user. In this system, a serial RS-232 communication protocol is used.

II. HARDWARE CONFIGURATION

The basic part of this system is Intel's high performance microcontroller 80C196KC. This is a microcontroller with a 16-bit CPU which includes dedicated high speed I/O subsystems, a 64 Kbyte addressable memory space and a 10-bit, 8-channel successive approximation A/D converter [2]. On the main controller board there are also a 4 Kbyte static RAM and a 16 Kbyte EPROM. Serial communication is achieved by the full duplex asynchronous serial port of the 80C196KC and the DS14C88/DS14C89 RS-232 driver and receiver integrated circuits.

The microcontroller circuit operates at a clock frequency of 16MHz resulting in a CPU state time equal to 0.125 microsecond [2].

The reference voltage of the A/D converter is 5.5 V and is obtained by a voltage reference integrated circuit and an LM358 single power supplied operational amplifier.

The A/D converter is specified to have an absolute error less than 3 LSBs in a 10-bit conversion [2].

Analog signals are obtained by the controller through instrumentation amplifiers, one for each channel, implemented by using an IC quad operational amplifier (TL084). The ac output of the UPS is first reduced by a resistive voltage divider and then it is rectified by a full wave rectifier circuit, in order to increase the resolution of the A/D conversion, and is finally applied to the inputs of the instrumentation amplifier. A power supply provides power at three output voltages: ±12V and +5V.

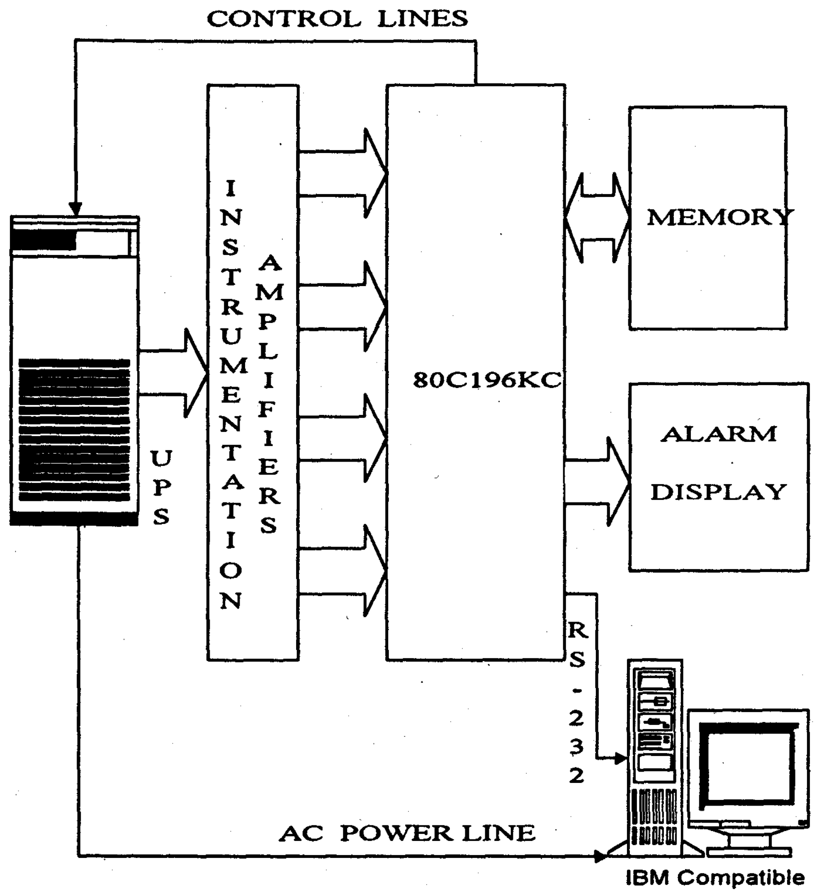

Fig. 1. Block diagram of the control system

III. OPERATIONAL FLOW OF THE SYSTEM

Figure 2 shows the main operational flowchart of the system, where V is the amplitude, f is the frequency, and THD(%) is the percentage Total Harmonic Distortion of the UPS output signal. This operational flowchart was created for a specific on-line UPS developed in the Electronics Laboratory of Technical University of Crete [3], but can be used with other types of UPS with slight modification.

The basic phases of operation of the control system are described bellow.

A. PHASE I

The controller in this phase turns on the UPS and monitors its output signal for at least five periods (0.1sec) in order to detect any malfunctions during the turn-on transition [1]. If a malfunction is found, the controller sends an alarm message and safely turns the UPS off. If the controller is incorporated in an on-line UPS, this phase is executed only once, when the UPS is powered. Otherwise, if UPS is of a standby type, it is executed every time there is an interruption of the AC power network.

B. PHASE II

This phase is executed continuously for five out of every seven periods of the output ac signal and forms the main loop of the system operation. This loop is interrupted only by a UPS fault. If a fault occurs, messages are transmitted to the user and samples are obtained from the circuit board in order to find out the location of the fault. In this phase, the controller verifies that the UPS operates properly and satisfies the basic specifications for amplitude, frequency and harmonic distortion.

C. PHASE III

This phase is executed for the other two out of the seven periods of the UPS ac signal (0.04 sec). In this phase, the load current and the charging state of the battery cells, are monitored and the remaining time before UPS batteries are exhausted is estimated. If the controller detects that the

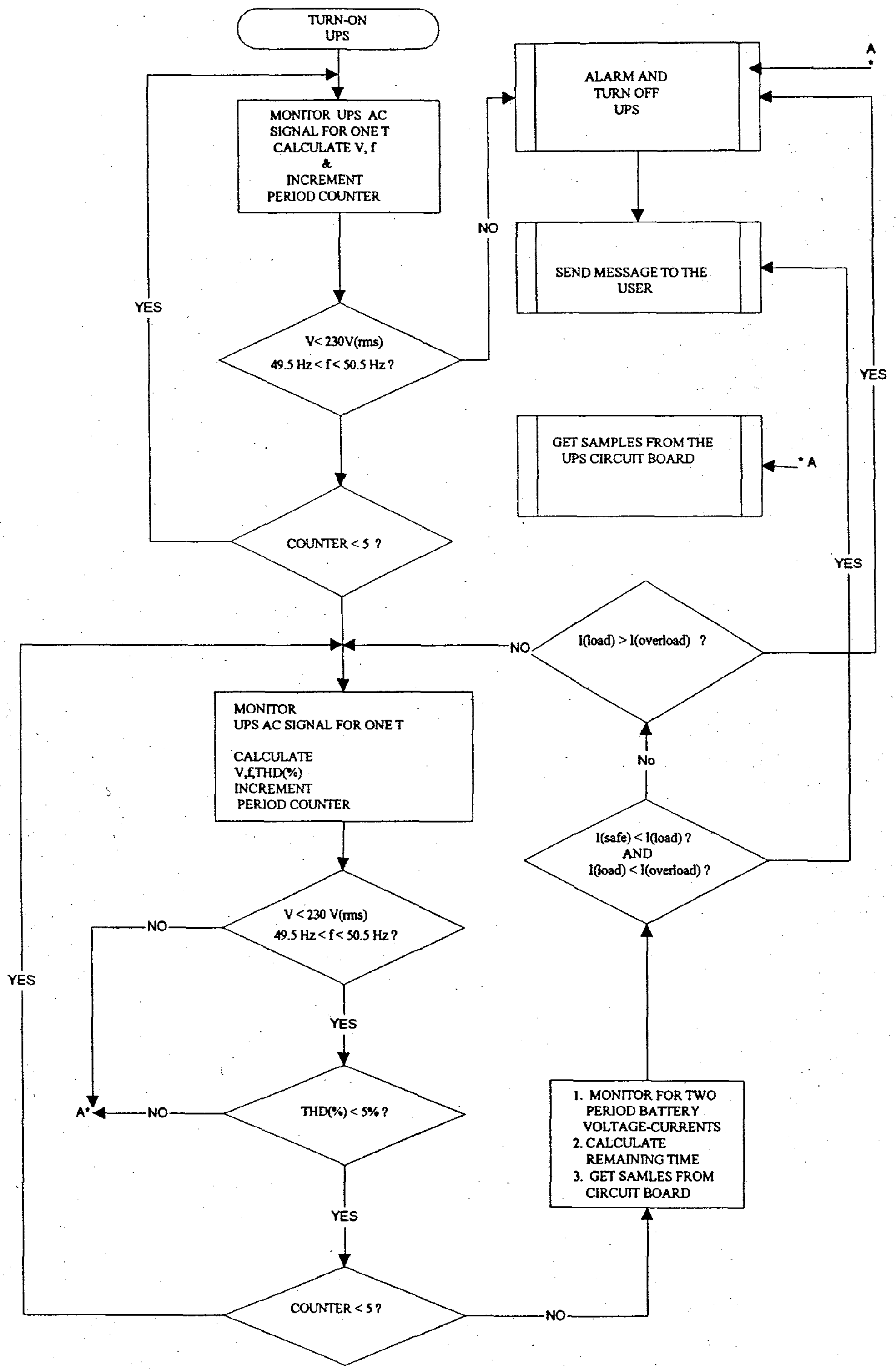

Fig. 2 Operational flowchart for the control system

supply current is more than the maximum allowable current but less than the overload current, it transmits a warning message to the user. Overload protection provided in this phase is complementary to the hardware current protection incorporated in the UPS design. At the end of this phase, the controller obtains samples from the UPS circuit board in order to predict a possible UPS malfunction. In the latter case, it transmits a special warning message to the user.

If this controller system is used with a standby mode UPS, monitoring of the charging state must be continuous, regardless of the UPS being active or inactive, in order to be able to calculate the remaining capacity of the battery cells.

IV. CALCULATING AND CONTROLLING ALGORITHMS

A. AMPLITUDE AND FREQUENCY CALCULATION

The amplitude is calculated by finding the A/D converter's output word with the maximum magnitude. The maximum allowable amplitude of the ac signal is V_{max}=325V(peak) which is made to correspond to a word with a magnitude equal to 605 steps. The minimum amplitude of the ac signal is V_{min}=296V(peak) corresponding to a word with a magnitude equal to 550 steps. The controller compares every sample of the A/D converter output with V_{max} and V_{min} to determine if the UPS output is within its voltage specification.

The frequency is calculated by counting the number of samples obtained by the A/D converter during one period of the ac signal. The controller determines when the input signal has completed a whole period by making a software zero-crossing detection. If the sampling frequency is 20 kHz and the ac signal frequency is between f_{min}=49.5 Hz and f_{max}=50.5 Hz, then the number of samples will be in the range of 404 and 396. If the number of samples is within these two boundaries, then the UPS output signal frequency satisfies its frequency specification.

B. CALCULATION OF THE HARMONIC DISTORTION

The Total Harmonic Distortion (THD) is calculated by using Eq. (1) :

$$\mathrm{THD}(\%) = \frac{\sqrt{H_2^2 + H_3^2 + \ldots + H_k^2}}{H_1} 100\% \qquad (1)$$

where H_i specifies the amplitudes of each harmonic and k is the number of harmonics considered.

The controller calculates the square of THD, in order to avoid the calculation of the square root, so Eq. (1) becomes:

$$[\mathrm{THD}(\%)]^2 = \frac{H_2^2 + H_3^2 + \ldots + H_k^2}{H_1^2} (100\%)^2 \qquad (2)$$

The summation of squares of the harmonics is calculated by Parseval's equation for Fourier series [4]:

$$\frac{2}{T}\int_0^T f^2(t)dt = \sum_{j=1}^{k} (a_j^2 + b_j^2) \qquad (3)$$

where:

$$f(t) = \sum_{j=1}^{k} [a_j \sin(n\omega t) + b_j \cos(n\omega t)] \qquad (4)$$

and in Eq(2)

$$H_j = \sqrt{a_j^2 + b_j^2} \qquad (5)$$

Parseval's equation (3) includes the square of the first harmonic besides higher order harmonics. Therefore Eq. (2) is modified to the following equation :

$$\frac{[\mathrm{THD}(\%)]^2}{(100\%)^2} = \frac{\sum_{j=1}^{k} (a_j^2 + b_j^2)}{(a_1^2 + b_1^2)} - 1 \qquad (6)$$

The amplitude of the fundametal harmonic is calculated by the following equations :

$$a_1 = \frac{2}{T}\int_0^T f(t)\sin(\omega t)dt \qquad (7)$$

$$b_1 = \frac{2}{T}\int_0^T f(t)\cos(\omega t)dt \qquad (8)$$

If the fundametal harmonic has only a sine term (i.e. b_1=0) then the amplitude of the fundametal harmonic is equal to a_1. The function f(t), for the system described in this paper, is the UPS output signal which, after the A/D conversion is in discrete form.

The controller calculates intergral (7) by using Simpson's algorithm for discrete integration:

$$a_1 = \frac{2}{n \cdot \Delta t} \sum_{i=1}^{n} f(i \cdot \Delta t) \cdot \sin\left(\frac{2\pi}{n \cdot \Delta t} i \cdot \Delta t\right) \cdot \Delta t \qquad (9)$$

In Eq.(9) n is the total number of samples, Δt is the time duration between two consecutive conversions, $f(i \cdot \Delta t)$ is the i-th sample and $T = n \cdot \Delta t$ is the period of the UPS output ac signal. The following equation is obtained by applying Simpson's algorithm to Eq. (3) :

$$\sum_{j=1}^{k} (a_j^2 + b_j^2) = \frac{2}{n \cdot \Delta t} \sum_{i=1}^{n} f^2 (i \cdot \Delta t) \cdot \Delta t \qquad (10)$$

In order to evaluate Eq.(9) in real time, the controller EPROM is preloaded the term $\sin(2\pi i/n_o)$ for n_o=400 that is proportional to a 50 Hz ac signal. Equation (9) is modified to Eq. (11) :

$$a_1 = SF \cdot \frac{2}{(n_o \cdot \Delta t)} \sum_{i=1}^{n} f(i \cdot \Delta t) \cdot \sin\left(\frac{2\pi}{n_o} i\right) \cdot \Delta t \qquad (11)$$

where SF in Eq.(11) is a scaling factor that modifies a_1 to the expected value by eliminating the calculation error. This error is produced by a possible difference in the frequency between the UPS ac output and the 50Hz pure sine waveform which is loaded in the controller's EPROM and is computed by :

$$\frac{1}{SF} = \frac{2}{T_o} \int_0^T \sin\left(\frac{2\pi}{T} t\right) \sin\left(\frac{2\pi}{T_o} t\right) dt \qquad (12)$$

$$= -\frac{T T_o}{\pi (T_o^2 - T^2)} \sin\left(2\pi \frac{T}{T_o}\right)$$

Several SF values are given in Table I.

TABLE I
FACTOR SF FOR VARIOUS NUMBERS OF SAMPLES

n	396	397	398	399
SF	1.006	1.004	1.003	1.001

n	401	402	403	404
SF	0.999	0.998	0.997	0.996

Thus, by Eq.(6), (9) and Eq.(10) THD is calculated by the following equation :

$$\frac{[THD(\%)]^2}{[100\%]^2} = \frac{\frac{2}{n} \sum_{i=1}^{n} f^2 (i \cdot \Delta t)}{\left(SF \cdot \frac{2}{n_o} \sum_{i=1}^{n} f(i \cdot \Delta t) \cdot \sin\left(\frac{2\pi}{n_o} i\right) \right)^2} - 1$$

C. ESTIMATION OF THE REMAINING OPERATING TIME

The controller measures the battery voltage and by using Table II estimates its charging state [CS(%)] as a percentage of its initial capacity. Discharge current is measured through a sense resistor in the ground line of the battery.

TABLE II
DEPENDENCE OF THE CELL POTENTIAL ON THE STATE OF CHARGE

V/cell	2.10	2.15	2.20	2.3-2.4	2.50	2.75
CS %	20	40	60	80	100	125

The estimation of the remaining operation time before a lead-acid battery fully discharges is based on the empirical equation formulated by Peukert [5]:

$$C = \frac{K}{I_d^{0.3}} \qquad (14)$$

where C is the capacity of the battery, K is a constant depending on the battery type and I_d is the discharge current. The effective remaining charge is estimated by multiplying C and the percentage charging state (CS%).

The remaining operating time is estimated by dividing the effective remaining charge by the discharging current :

$$t = \frac{CS(\%) \cdot C}{I_d} = CS(\%) \frac{K}{I_d^{1.3}} \qquad (15)$$

Constant K is estimated by Eq. (14) with C equal to the initial rated capacity of the battery (e.g. 100Ah at 20h discharging rate) and with I_d being the ratio of C and the discharging rate i.e.

$$I_d = \frac{100Ah}{20h} = 5A$$

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V CONCLUSION

A low-cost, real-time system has been developed which can monitor and control the operation of an auxiliary power supply, such as a UPS. The parameters monitored are the line voltage, the line frequency and the harmonic distortion. The system has also the capability to safely turn off the UPS, in case of a malfunction. With slight modifications, this system may be used to monitor similar parameters of an electric power system. The design of the system is based on a high-performance microcontroller and includes a number of easily-found ICs. The operation of the control system has been tested with a UPS unit and has been found to work within its specifications.

ACKNOWLEDGEMENT

The assistance offered by Ph. Valianatos, John Hatzakis and Theodore Ioannides is greately appreciated.

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