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Research Article

Blood Glucose Measurement Using Bioimpedance Technique

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Bioimpedance measurement is gaining importance in wide field of bioresearch and biomedical systems due to its noninvasive nature. Noninvasive measurement method is very important to decrease infection and physical injuries which result due to invasive measurement. This paper presents basic principle of bioimpedance along with its application for blood glucose analysis and effect of frequency on impedance measurement. Input from bioimpedance sensor is given to amplifier and signal conditioner AD5933. AD5933 is then interfaced with microcontroller LPC1768 using I2C bus for displaying reading on LCD. Results can also be stored in database using UART interface of LPC1768.

1. Introduction

Impedance of any material can be defined as the opposition offered by material to the electric current flowing through it. It can be formulated as the frequency domain ratio of voltage to current. Impedance can also be represented using resistance and reactance. Every material shows property to dissipate energy and to store energy. Reactance (Xc) indicates energy storage in material whereas resistance (R) is indicator of energy dissipation [1].

When electricity is passed through body, two types of resistances that is capacitive R (reactive) and resistive R (resistance) are offered by body, where capacitance arises due to cellular membrane and resistance arises due to body water (intracellular or extracellular water). Cell membrane consists of a layer of nonconductive lipid material sandwiched between two layers of conductive protein molecules. High reactance value indicates good health and cell membrane integrity. Cell membrane structure makes them behave as capacitors when alternating current is applied to it. Hence impedance of tissue varies with frequency. At high frequency, current can flow through both intra- and extracellular water which means that it can penetrate the cellular membrane while at low frequency current cannot penetrate cellular membrane so it flows only through extracellular fluid. As a result, at low frequency, impedance is resistive in nature and at high frequency it has a resistive as well as a reactive component [1] (see Figure 1).

The incidence of diabetes is increasing worldwide every year [2]. Therefore, it is important to control as well as to treat diabetes. There are various invasive and noninvasive methods available for blood glucose measurement. Glucometer which depends on radio wave transmission uses continuously transmitting and receiving antenna. The transmitting antenna sends a signal of frequency in a range from 5 GHz to 12 GHz while receiving antenna monitors signal attenuation to determine the blood sugar level. The main drawback of radio wave transmission is the requirement of high frequencies which helps to minimize influence of the skin and to improve the accuracy of measurement results [3].

Another glucometer based on photoplethysmography method uses principle of infrared absorption measurement. This method uses the concept that the blood with increased sugar level has higher absorption rate of infrared radiation than human skin. Requirement of additional sensor for detecting heart rhythm is the main drawback of such measurement methods [4]. The change in glucose level can be detected using electrode sensor by measuring changes in conductivity and permittivity of measuring component [5]. But the main drawback of this type of measurement

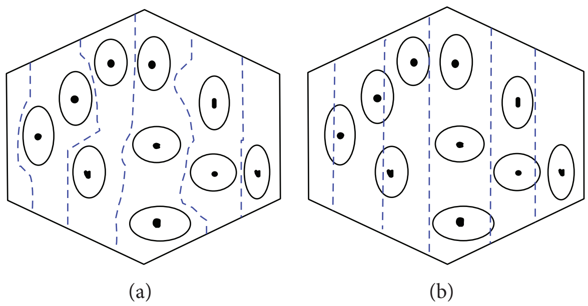

FIGURE 1: Current flow through body: (a) low frequency and (b) high frequency.

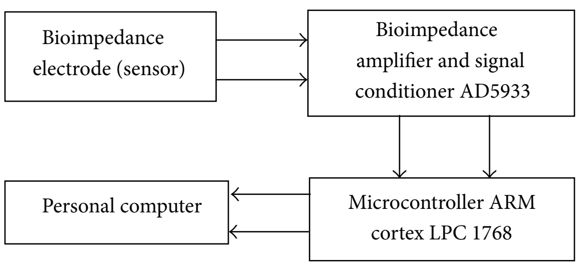

FIGURE 2: Block diagram of system.

system is the design of interdigital electrode sensor which is complicated and very expensive; also the sensor impedance depends on frequency so it is not convenient to use this parameter for blood glucose level estimation. In this paper, we have discussed blood glucose measurement system which is more accurate and less expensive as it is using AgCl electrodes [2].

2. Methodology

The measurement environment for continuous and non-invasive monitoring of the impedance for blood glucose measurement has been developed. The block diagram of the proposed measurement system, shown in Figure 2, consists of the bioimpedance electrodes, integrated circuit AD5933, microcontroller LPC1768, and a personal computer. Each block of system is discussed in detail in the following sections.

The integrated circuit AD5933 is the core of the proposed measurement system (Figure 4). Bioimpedance electrodes are used for measurement of the impedance. Impedance is calculated by the microcontroller LPC1768 through I2C interface. The microcontroller sends this measured data to a personal computer, where we can store data, using a serial interface UART. The microcontroller also provides an initial configuration of the integrated circuit AD5933 which includes mainly setting the frequency and amplitude of the input signal used for measurement of unknown impedance. The ARM Cortex LPC1768 microcontroller also controls time slots during which the measurements are performed. When microcontroller is done with measurement in respective time slot, it reads the data from AD5933 by using I2C interface and sends measured data to PC by using UART interface where data is stored and further processed.

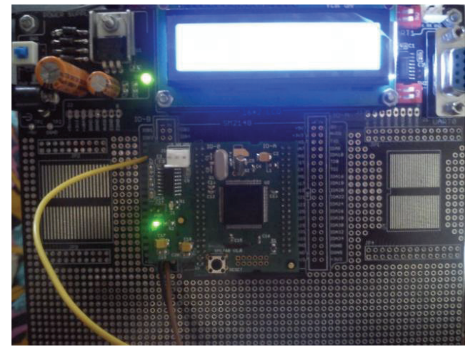

FIGURE 3: LPC1768 ARM Cortex board.

2.1. Microcontroller Cortex LPC1768 M3. The LPC1768 is an ARM Cortex-M3 32 bit microcontroller which is designed for embedded applications which require a high level of integration as well as low power dissipation. Here, UART is used for downloading the program and for PC interface. The communication between AD5933 and controller is through I2C bus. LPC1768 works at a maximum operating frequency of 100 MHz. Figure 3 shows hardware of LPC 1768. The ARM Cortex-M3 CPU has a 3-stage pipeline and uses Harvard architecture with separate local instruction and data buses as well as a third bus for peripherals. The I2C interfaces of LPC1768 I2C are byte oriented and have four operating modes: master transmitter mode, master receiver mode, slave transmitter mode, and slave receiver mode [6].

2.2. Bioimpedance Amplifier. Bioimpedance amplifier is heart of impedance measurement system. Impedance converter and network analyzer AD5933 functions as signal conditioner for bioimpedance signal. Low noise voltage reference IC AD820 and low power amplifier IC ADR 423 act as supporting blocks for signal amplification and noise reduction. Figure 5 shows hardware for bioimpedance amplifier and signal conditioner AD5933. A precision, low power FET input op amp AD 820 which can operate from a single supply of 5 V to 36 V, or dual supplies of ±2.5 V to ±18 V. In the AD820, N-channel JFETs are mainly used for providing a low offset, low noise, high impedance input stage which is required by most of the embedded applications. It also keeps low noise performance to low frequencies. Low noise performance, low input current, and current noise are features of the AD820 which contributes negligible noise for applications [7, 8].

Integrated circuit AD5933 consists of the various blocks such as an input signal generator, a 12-bit A/D converter, a DFT (discrete Fourier transform) circuit, a thermal sensor, and I2C interface. The function of generator is to supply a sine wave input signal of certain frequency and amplitude at the output VOUT. Unknown impedance to be calculated is connected between VOUT and VIN terminals. Therefore, magnitude and phase of the current flowing through a load depend on its impedance. The current is then transformed

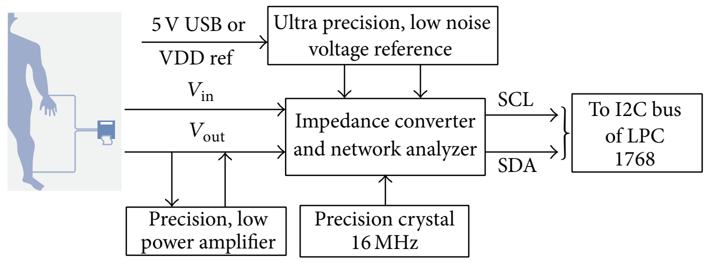

FIGURE 4: Block diagram of bioimpedance amplifier.

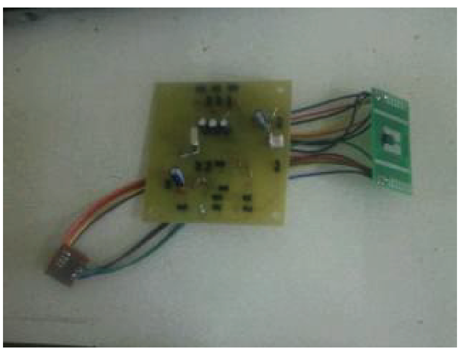

FIGURE 5: PCB of the realized monitoring system bioimpedance amplifier with signal conditioning circuit.

to voltage that is converted into a digital signal by the digital to analog converter. The DFT circuit provides discrete Fourier transform of the converted impedance signal. This will lead to measurement of real and imaginary parts which are measured. Functional block diagram of AD5933 is shown in Figure 6 [9].

The obtained response signal from the impedance is then sampled by the on-board discrete Fourier transform (DFT) and ADC. This operation returns a real (R) and imaginary (I) data-word at each output frequency. Impedance magnitude and phase are then easily calculated using the following equations:

$$\text{Magnitude} = \sqrt{R^2 + I^2} \tag{1}$$

$$\text{Phase} = \tan^{-1}\frac{I}{R}. \tag{2}$$

Once calibration is done, the magnitude of the impedance and relative phase of the impedance at each frequency point along the sweep can be easily calculated. This is done off chip using content of real and imaginary register, which can be read from the serial I2C interface [9].

There are two stages of operation of AD5933, namely, transmit stage and receive stage. The excitation signal required for transmit stage is given by DDS technique. AD5933 has an in built 27-bit accumulator DDS core in the transmit stage. At a particular frequency this DDS core provides on-chip output excitation signal. Input current signal is provided from unknown impedance to receive stage. The current to voltage amplifier, a programmable gain amplifier (PGA), antialiasing filter, and ADC are main constituents of receiving stage of AD5933. This receive stage obtains input current signal from the impedance which is unknown then performs signal processing followed by digitization of the result. An external reference clock or internal oscillator provides clock for DDS [9].

The DFT operation is as follows.

A DFT is estimated for each frequency point in the sweep. The AD5933 DFT algorithm is expressed using following equation:

$$X(f) = \sum_{n=0}^{1023} \left(x(n)\left(\cos(n) - j\sin(n)\right)\right), \tag{3}$$

where $X(f)$ is the power in the signal at the frequency point f. $X(n)$ is the ADC output. $\cos(n)$ and $\sin(n)$ are the sampled test vectors provided by DDS core at the frequency point f [9].

3. Impedance Measurement

The readings for impedance measurement are taken in the measurement frequency range of 10 kHz to 100 kHz. Electrical contact with the body was made using silver electrodes. In order to increase the accuracy and to minimize noise in measurement, high precision impedance converter system, AD5933, is used. Then the body part, which is connected between input and output ports of electrodes, is excited with different frequencies. The current which is the response from the body is then converted into voltage using a transimpedance amplifier. The output voltage of this transimpedance amplifier is then sampled and processed by a DSP engine of AD5933 at each frequency of excitation. Both the real and imaginary components were stored in two 16-bit registers of AD5933. The stored data in each of these registers must be read after each ADC conversion to get impedance reading. These results which contain real and imaginary parts are then read by the microcontroller using I2C and are further processed and displayed on a personal computer [1].

4. Result

Normal glucose level for healthy human being is 4.4 to 6.1 mmol/L. To study low as well as high blood glucose level, graph is plotted in the range of 4 to 6.8 mmol/L. The dependency of impedance on blood glucose level is initially

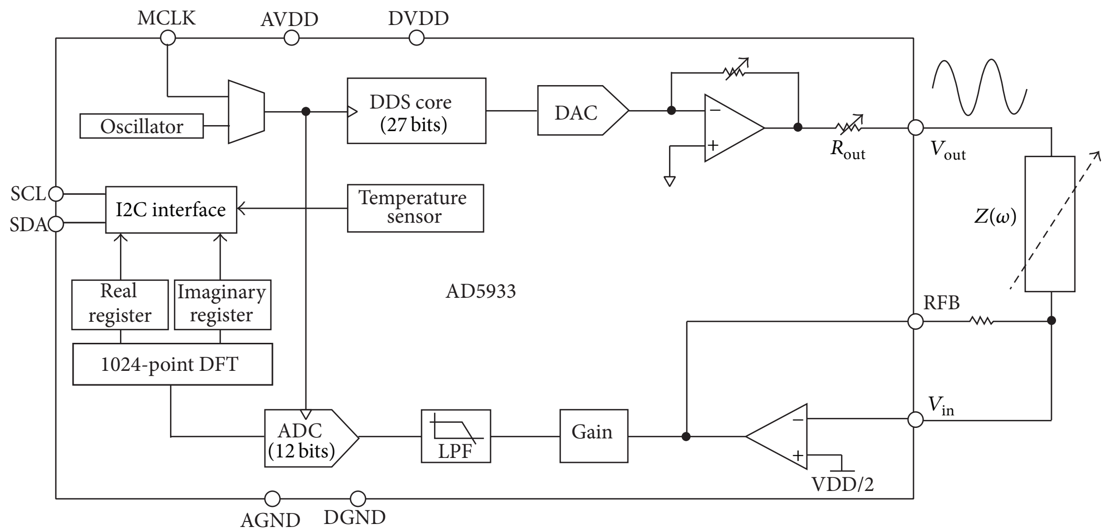

FIGURE 6: Functional block diagram of AD5933.

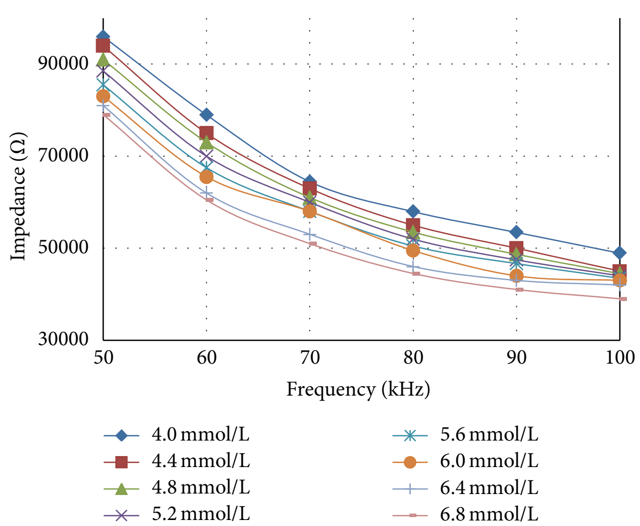

FIGURE 7: Impedance dependence on frequency and blood glucose level in a range from 50 kHz to 100 kHz.

determined using readings obtained from ACCU-CHEK glucometer that is invasive measurement of glucose level. The results obtained from blood glucose measurement system are compared with readings obtained from invasive glucometer measurements. Measurements of blood impedance at various frequencies starting from low frequency to high frequency are carried out. Impedance measurement of several subjects at various frequencies is done to study possibility of change of blood glucose level.

Impedance measurement of eight subjects is carried out at different frequencies. The results of impedance at different blood glucose levels are presented in Figure 7. It can be seen that impedance decreases when blood glucose level increases and impedance module decreases when blood glucose level decreases. Frequency is limited to the range of 10 kHz to 100 because the highest scattering of points of measurement results is observed in this range of frequencies. So frequencies outside this range are not used in further measurement.

5. Conclusion

Study of impedance blood glucose level results and its graphical representation shows that noninvasive method can be used for accurate measurement. For accurate measurement, a system is designed using AD5933. Use of noninvasive method for blood glucose level estimation eliminates continual finger pricking and risk of infection. It is determined from the results that impedance depends on blood glucose level. The achieved results have proven that the accuracy of results, input signal voltage, and frequency ranges are suitable for biomedical monitoring applications.

Additionally, the proposed measurement system is versatile, flexible, and easy to be used for different measurement approaches like heartbeat, ECG, blood pressure, skin impedance for cancer detection, and so forth. This developed measurement system will offer new approaches and opportunities to noninvasive biomedical systems in the field of medicine and other useful areas.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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