3.1 Introduction

In continuation with the end results of the literature review, the present chapter reports the design and development of kernel part of the system. Our design focus is to today’s medical challenges pertaining to personal health monitoring system (PHS) and wearable medical systems (WMD). The first and foremost objective of this work is to design and development of low power battery operated impedance analyzer. In order to accomplish it is imperative to select such a suitable processor for the system i.e. a microcontroller which perfectly fits in the design goal as well as low power requirements of the setup. After a thorough survey and after going through the specifications of the diversified families of the microcontrollers we have zeroed on the Ultra Low Power 16 bit Mixed Signal Processor MSP430 microcontroller. This flash based MCUs run up to 16MIPS with 1.8V to 3.3V operation. It exhibits six different low power modes, from which we can configure the clocks and CPU ON or OFF as per the requirement of system. At idle mode the current consumption of MSP430 is less than 1µA. Many variants of MSP430 are drawn from Texas Instruments specialized with memory type, analog front end solution, inbuilt communication support peripherals and some of for specific application. MSP430Gxxxx is the value line series used in the design which open up with 16 bit performance up to 16 MHz clock operation at low cost range of 8 bit MCU. Subsequently, novel based portable impedance analyzer measurement technique in cost sensitive solution which has been presented in the later part of this chapter.
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3.2 Rationale behind the system design

As per demands of today’s medical technology and by thinking concurrently with the theme of our research design as well, the essential objective is to build such a portable customized instrumentation which gives the low cost, affordable, portable and easy to use solution to patients. The design has been oriented especially in view of the following points:

1. The device must be mini packaged, airiness from low weight and volume parameters.
2. The device should operate at low power and driven by a simple dry cell. The battery must have rechargeable capability and ability to supply stand alone power minimum 1 day without charging.
3. The device should exhibit good accuracy in the external environment also.
4. It must be electrically safety i.e. shockproof and persevere the requirements according to standard protection rating imposed by international medical commission.
5. For wearable and portable application, the device be equipped with suitable solution which further enables us to provide wireless interface.

In view of the above design aspects, we have selected the appropriate electronic components. At the outset, the programmable function generator in the design range of few KHz is required to apply the sine wave regularity through human body to measure the body impedance. Thus to generate the spurious free desired frequency is one of the challenging tasks in the present system. Hither we designate DDS based function generator which is the neoteric technique using digital processing capability to generate a phase tunable frequency by programmable features. High performance with micro hertz resolution, different functionality integrated on a single chip area, comparatively low cost and low power with programmable ability are the assured features which results into the widespread of DDS technology in recent times.
3.3 Selection of appropriate platform for portable impedance analyzing system

Analog Devices is one of the leading company offering many variants of DDS based IC with standard communication interface. While selecting the DDS function IC, we have had gone through the latest generation of SoC based impedance converter and network analyzer AD5933 IC. The said IC embeds several functions concatenating on a single chip. It has on board 27 bits DDS function generator core to generate the frequency up to 100 KHz with a less than 0.1Hz resolution capability to measure complex impedance at a particular frequency. It also consists on board analog solution such as programmable gain amplifier, low pass filter and current to voltage controller along with analog to digital converter. This solution used to sampling the response signal and applying the DFT technique which is processed by an inbuilt DSP engine. Figure 3.1 shows the internal structure of AD5933 IC.

Figure 3.1: Internal structure of functional block diagram of Impedance Network Analyzer IC AD5933
The complete chip is controlled by the programmable setting register by only two wire interface protocol, I^2C protocol. This block forwards and gathers the resulting parameters from different functional blocks and accordingly communicates with the microcontroller over SDA & SCL lines. This IC also has yet another featured i.e.an internal temperature sensor with ±2^oC accuracy, which makes it more useful in many applications. The range of impedance measurement is 1KΩ to 10MΩ. The device application note reveals that it is also capable to measure 100Ω to 1KΩ impedance with the aid of external analog operational amplifier circuitry with accuracy 0.5%. So hereabouts the frequency can be generate up to 100 KHz with high resolution and complex impedance can be measure from 100Ω to 10MΩ. It is perfectly pertinent in requirement range of bio-impedance measurement especially for the present system i.e. for human species wherein the impedance range nearly varies in the range of 300Ω to 800Ω. This on-board technology based solution proposed herein promises features such as: flexible platform, cost-effective solution, energy efficient computation and easy customization and communication. This IC AD5933 package only occupy very small foot print area (16 lead SSOP package) with such excellent performance is enormous relevant with respect to our research aim. To design suitability and easiness the AD5933 based portable impedance analyzer is divided into mainly two parts – Design DDS based portable frequency generator and Implementation of portable single frequency and multi frequency bio-impedance analyzer. The said setup has also many other useful applications such as electrochemical analysis, blood coagulation detection, electro impedance spectroscopy, proximity sensor, portable precise function synthesizer just to name a few.

3.4 Design and development of DDS based portable frequency generator

The function generator is one of the essential test and diagnostics equipment used in the life cycle of the system realization for designing and testing. Modern telecommunication and medical technology have growing number of applications of various kinds which require several types of test signals. In the present application, KHz
range of sine frequencies is required to test the impedance of the body. The basic building block of DDS is shown in Figure 3.2

![Diagram of DDS block](image)

**Figure 3.2: Basic building block of DDS**

The two inputs of the DDS are: sample clock of the system and desired frequency word in N-bit format which is compared in the phase accumulator stage. The Phase accumulator operates on the basis of simple arithmetic to compute the sine look up table addresses for each sample. The sine waveform information is stored in the look up table memory. In the last stage as per the desired input frequency word the above said digital sine wave data is manipulated and converted into analog domain by digital to analog converter. To obtain the pure sine wave, the harmonics of generated sine wave is filtered by low pass filter mechanism. So overall resolution of output waveform depend on the bit resolution of phase accumulator resisters, strength of sine look up table unit and the resolution of DAC unit. Figure 3.2 shows the internal structure of the frequency generator unit and the built-in analog programmable gain circuitry of the transmit stage of AD5933 IC.

### 3.5 Block Diagram of DDS based function generator using AD5933

The block diagram of portable function generator module of AD5933 is depicted in Figure. 3.3.
Figure 3.3: Block Diagram of portable function generator

The system consists of following subparts:

1. IC AD5933 –
IC AD5933 is functions as the impedance converter and network analyzer. For that it generates the sine wave through on chip DDS technique and with its complementary blocks which called as ‘transmit stage’. This DDS core has made up of 27 bit phase accumulator that produces output sine wave signal at given frequency. The transmit stage of AD5933 is shown in Figure 3.4.

Figure 3.4: Transmit stage of AD5933
The corresponding digital count of required frequency is given through the setting registers. This IC is used in the present system for generation of the sine wave between ranges of 0 Hz to 100 KHz with 0.1 Hz resolution. The oscillator clock for DDS is generated through external oscillator clock or by choosing an internal oscillator.

2. Microcontroller MSP430
   The MSP430 microcontroller is the central core of the system that takes care of the overall processing. MSP430G2452 series is equipped with 8 KB flash, 256 byte RAM, Universal Serial Interface (USI) support for interface SPI and I2C peripherals. Here the USI I²C mechanism used to interface with AD5933.

3. Keypad Module and LCD Display
   A keypad with 5 keys is interfaced with the system used for setting the value of desired frequency. MSP430 has inbuilt internal pull up resistor capability which is used for the individual keys. The LCD Display is interfaced with system for interacting with the user and to let them know regarding the frequency set-in.

4. Power Supply Module
   This module provides power to entirely system. It generates 5V and 3V from 12V or 9V battery respectively. IC7805 and UA78M33 have used to regulate voltage which capable to provide output current up to 1mA and 500mA respectively.

3.6 Designing steps of function generator

- The value of frequency is displayed on LCD module; the default value of frequency is 000001 which is minimum set as 1 Hz and can be maximized up to 100 KHz as per the frequency range of AD5933.
- The input desired frequency value is set through the keypad module with the help of five keys; right and left keys are used for shifting the digit, while up and down
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Keys are used to increase and decrease the selected digit count from 0 to 9. The center key is used for freezing the value of frequency.

- After accomplishing the above step, the internal register parameters of AD5933 IC is set as per the required system mode.
- Thereafter the control register is configured with output excitation voltage range as 2.0 V peak to peak typical, PGA gain as multiplied with 5. Here the system clock operates on the internal oscillator 16 KHz.
- Thereafter the frequency register parameters as per the user inserted value of frequency needs to be calculated. The value is converted into the 8 bit formats for different frequency registers and stored in arrays as per the address of frequency registers and affined with its value.
- Master MSP430 microcontroller communicates with the slave AD5933 IC through the I²C communication protocol. At first MSP430 communicates with the device by sending the default serial 7 bit bus address i.e. 0001101 (0x0D).
- To send and receive the appropriate commands subsequently to set the AD5933 at DDS function generator mode.
- The desired sine wave output is obtained on V_{out} pin of IC as per the inserted input frequency value.

The following section covers the requisite details pertaining to configuration of registers parameters and necessary calculations.

### 3.6.1 Configuration of function registers of AD5933 IC

In order to configure the AD5933 IC and set the frequency, there is need to set the control and frequency registers with the appropriate values. Following table lists gives the details of registers and their functions.
Table 3.1: Details of AD5933 Frequency registers map, their address and respective function

<table>
<thead>
<tr>
<th>Name</th>
<th>Register Address</th>
<th>Data length</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Register</td>
<td>0x80, 0x81</td>
<td>16 bit</td>
<td>Set the AD5933 in different modes as per the command</td>
</tr>
<tr>
<td>Start Frequency</td>
<td>0x82 - 0x84</td>
<td>24 bit</td>
<td>Digital code for initiated frequency</td>
</tr>
<tr>
<td>Frequency Increment</td>
<td>0x85 - 0x87</td>
<td>24 bit</td>
<td>Digital code amount for frequency increment between consecutive frequency points</td>
</tr>
<tr>
<td>Number of Increments</td>
<td>0x88 - 0x89</td>
<td>16 bit (accessible only lower 8 bit)</td>
<td>This register determines the frequency sweep range.</td>
</tr>
</tbody>
</table>

To set the desired frequency we have to first set the registers with the digital code. For instance the 50 KHz frequency is used for measurement SFBIA which calculated as per the equations used herein. To step up to the next frequency the increment frequency command has to be used. It also required incremental value calculation which is also exhibited in this section. This feature is very beneficial to
take the multiple stepwise incremental readings for MFBIA. The step up value chosen in our design is 1 KHz. Also this IC provides one another best feature is repeat frequency which can be used to take average successive readings at same frequency.

➤ Calculation of start frequency register

The code to be programmed for start frequency has been calculated as per the following equation.

\[
Start \ Frequency \ Code = \left[ \frac{Desired \ Frequency}{Clock \ Frequency} \right] \times 2^{27} \ \ \ \ \text{Eq. 3.1}
\]

\[
Start \ Frequency \ Code = \left[ \frac{50 \ KHz}{16 \ MHz} \right] \times 2^{27} \ \ \ \ \text{Eq. 3.2}
\]

*Code Value = 0x199999*

As there are three 8 bit frequency registers the values assigned to the register address are: 0x19 to Register Address 0x82, 0x99 to Register Address 0x83 and 0x99 to Register Address 0x84 respectively.

➤ Calculation of frequency increment register

The code to be programmed for increment frequency has been calculated using the following equation,

\[
Increment \ Frequency \ Code = \left[ \frac{Desired \ Increment \ Frequency}{Clock \ Frequency} \right] \times 2^{27} \ \ \ \ \text{Eq. 3.3}
\]

\[
Increment \ Frequency \ Code = \left[ \frac{1 \ KHz}{16 \ MHz} \right] \times 2^{27} \ \ \ \ \text{Eq. 3.4}
\]

*Increment Frequency Code = 0x008312*

Here the programmed value assignments are: 0x00 to Register Address 0x85, 0x83 to Register Address 0x86 and 0x12 to Register Address 0x87 respectively.
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- Calculation of Number of Increments

Although this is the 16 bit register, the user can access D8 to D0 bit and rests all are don’t care bits. So it is possible to increment frequency pints up to maximum 511 times.

These calculated codes of distinct registers are set in concerning register address by programming in sequential manner. Following flowchart shown in Figure 3.5 elaborates the algorithm steps of programming for single 50 KHz frequency sweep.
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START

- Set internal DCO
- Configure port pin 1.6(SDA) & 1.7(SCL) direct as output
- Enable the internal pull up registers of 1.6 & 1.7 pins

Set flag and start communication

Generate start condition & send 0x1A address to AD5933

Receive Acknowledge?

Detect error, Go to run stop condition

A

B

Yes

No
Figure 3.5: Flow Diagram of programming of I2C communication and generating frequency
3.6.2 Embedded C implementation to generate 50 KHz frequency

The following program takes care of master and slave communication between MSP430G2452 and AD5933 and also generation of 50 KHz sine wave.

/******************************
/* Description: I2C Master MSP430G2452 communicates with I2C Slave AD5933 IC using the USI. */
//  ACLK = n/a, MCLK = SMCLK = Calibrated 1MHz
 ******************************/

#include <msp430g2452.h>

unsigned char* MST_Data; // Variable for transmitted data
char SLV_Addr = 0x1a; // Address is 0x0D << 1 bit + 0 for Write
int I2C_State = 0; // State variable
unsigned char SetPointer[] = {0xb0, 0x80, 0xff};
unsigned char BlockWrite[] = {0xa0, 0x0a, 0xb0, 0x00, 0x19, 0x99, 0x99, 0x00, 0x83, 0x12, 0x00, 0x20, 0xff};
unsigned char Init_frequency[] = {0xa0, 0x02, 0x10, 0x00, 0xff};

void main(void)
{
    volatile unsigned int i; // Use volatile to prevent removal
    WDTCTL = WDTPW + WDTHOLD; // Stop watchdog
    if (CALBC1_1MHZ == 0xFF || CALDCO_1MHZ == 0xFF)
    {
        while(1); // If calibration constants erased
    }
    BCSCTL1 = CALBC1_1MHZ; // Set DCO
DCOCTL = CALDCO_1MHZ;

/*-----------------------------------Port Configuration-----------------------------------*/
P1OUT = 0xC0; // P1.6 & P1.7 Pullups, others to 0
P1REN |= 0xC0; // P1.6 & P1.7 Pullups
P1DIR = 0xFF; // Unused pins as outputs
P2OUT = 0;
P2DIR = 0xFF;

/*-----------------------------------USI Setup Configuration-----------------------------------*/
USICTL0 = USIPE6+USIPE7+USIMST+USISWRST;
    // Port & USI mode setup
USICTL1 = USII2C+USIIE; // Enable I2C mode & USI interrupt
USICKCTL = USIDIV_3+USISSEL_2+USICKPL;
    // Setup USI clocks: SCL = SMCLK/8 (~125kHz)
USICNT |= USIIFGCC; // Disable automatic clear control
USICTL0 &= ~USISWRST; // Enable USI
USICTL1 &= ~USIIFG; // Clear pending flag
_EINT();

MST_Data = SetPointer;
USICTL1 |= USIIFG; // Set flag and start communication
LPM0; // CPU off, await USI interrupt
for (i = 0; i < 5000; i++); // Dummy delay between communication cycles

MST_Data = BlockWrite;
USICTL1 |= USIIFG; // Set flag and start communication
LPM0; // Low power mode, CPU off, await USI interrupt
for (i = 0; i < 5000; i++); // delay between communication cycles
MST_Data = SetPointer;
USICTL1 |= USIIFG; // Set flag and start communication
LPM0; // Low power mode, CPU off, await USI interrupt

for (i = 0; i < 5000; i++); // delay between communication cycles
MST_Data = Init;
USICTL1 |= USIIFG; // Set flag and start communication
LPM0; // Low power mode, CPU off, await USI interrupt
for (i = 0; i < 5000; i++); // delay between communication cycles
while(1);

#pragma vector = USI_VECTOR
__interrupt void USI_TXRX (void)
{
    switch(I2C_State)
    {
    case 0: // Generate Start Condition & send address to slave
        P1OUT |= 0x01; // LED on: sequence start
        USISRL = 0x00; // Generate Start Condition...
        USICTL0 |= USIGE+USIOE;
        USICTL0 &= ~USIGE;
        USISRL = SLV_Addr; // ... and transmit address, R/W = 0
        USICNT = (USICNT & 0xE0) + 0x08; // Bit counter = 8, TX Address
        I2C_State = 2; // Go to next state: receive address (N)Ack
        break;
    }
case 2: // Receive Address Ack/Nack bit
    USICTL0 &= ~USIOE;  // SDA = input
    USICNT |= 0x01;     // Bit counter = 1, receive (N)Ack bit
    I2C_State = 4;      // Go to next state: check (N)Ack
break;

case 4: // Process Address Ack/Nack & handle data TX
    USICTL0 |= USIOE;  // SDA = output
    if (USISRL & 0x01)  // If Nack received...
    { // Send stop...
        USISRL = 0x00;
        USICNT |= 0x01; // Bit counter = 1, SCL high, SDA low
        I2C_State = 10; // Go to next state: generate Stop
        P1OUT |= 0x01;  // Turn on LED: error
    }
    else
    { // Ack received, TX data to slave...
        USISRL = *MST_Data; // Load data byte
        USICNT |= 0x08;    // Bit counter = 8, start TX
        I2C_State = 2;     // Go to next state: receive data (N)Ack
        P1OUT &= ~0x01;    // Turn off LED
        MST_Data++;
        if(*MST_Data ==0xff)
        {
            I2C_State = 6;
        }
    }
break;

case 6: // Receive Data Ack/Nack bit
USICTL0 &= ~USIOE;       // SDA = input
USICNT |= 0x01;          // Bit counter = 1, receive (N)Ack bit
I2C_State = 8;           // Go to next state: check (N)Ack
break;

case 8: // Process Data Ack/Nack & send Stop
    USICTL0 |= USIOE;
    if (USISRL & 0x01)       // If Nack received...
        P1OUT |= 0x01;       // Turn on LED: error

    // Send stop...
    USISRL = 0x00;
    USICNT |= 0x01;       // Bit counter = 1, SCL high, SDA low
    I2C_State = 10;       // Go to next state: generate Stop
    break;

case 10:// Generate Stop Condition
    USISRL = 0xFF;          // USISRL = 1 to release SDA
    USICTL0 |= USIGE;       // Transparent latch enabled
    USICTL0 &= ~(USIGE+USIOE);// Latch/SDA output disabled
    I2C_State = 0;          // Reset state machine for next transmission
    LPM0_EXIT;             // Exit active for next transfer
    break;
    }
    USICTL1 &= ~USIIFG;       // Clear pending flag
    }

/**************************************************************************/
3.6.3 Test Setup and Results

As depicted in the earlier section, we have developed system using the MSP-EXP430G launchpad for special for value line series of MSP430 microcontrollers. It provides useful features such as: USB interface, on-board emulation for programming and debugging by simple Spi-Bi-Wire JTAG interface. The code composer studio has been used as IDE for programming and debugging purpose. Figure 3.6 shows the hardware setup of MSP430 Launchpad and AD5933.

![View of actual debugging with embedded hardware and software setup portraying the results on CRO](image)

**Figure 3.6: View of actual debugging with embedded hardware and software setup portraying the results on CRO**

Figure 3.7 shows the hardware setup of MSP430 value line series launchpad with USB debugging and 16 SSOP package of network analyzer AD5933 IC. Figure 3.8 substantiates the result of system tested on CRO which is 50 KHz sine wave with 2.2 V Amplitude as per the design.
Figure 3.7: Hardware setup of AD5933 IC with MSP430 value line LaunchPad

Figure 3.8: Actual testing of the system result using CRO showing a 50 KHz Sine Wave with Amplitude 2.2 V
3.7 Overall System design for portable function generation

The fully portable DDS based function generator has finally assembled by combining and formatting the \( \text{I}^2\text{C} \) communication interface routine, 5 keypad interface routine, 16x2 type LCD displaying routine by 4 bit interfacing method. Following flowchart presents the logic for implementation of function generator shown in figure 3.9.

START

- Define LCD data and control lines as \( \text{P2.0-P2.3 for D4-D7, P2.7 for RS and P2.6 for EN} \)
- Define keypad Right, Left, Increment, Decrement and Enter Key respectively for \( \text{P1.3, P1.4, P2.5, P2.4 and P1.5} \)
- Define SCL and SDA pins as \( \text{P1.6 and P1.7} \)

Configure system software flag register to detect key pressed event, display change event and frequency change event

Initialize structure routine for Frequency Display

A
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- Configure internal DCO
- Configure port pins input or output as per necessity
- Enable internal pull pin for keypad and I²C communication pins
- Enable port interrupt for keypad key detection

- Start LCD initialization with sending first 8 bit command routine
- Appropriate delay routine
- Send command function set (0x28) for LCD Configure as 4 bit data lines
- Delay for 50 usec
- Send command entry mode (0x06) for auto-increment
- Delay for 50 usec
- Send command display on (0x0C)
- Delay for 50 usec
- Send command for clear display (0x01)
- Delay for 4 msec

Display default value 000001 Hz on LCD through data write function

Set Low Power Mode 0 with interrupt enable

Main Loop:

Check System Flag Register to detect event?
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Diagram:

- **E**: Frequency Display Digit No. 9?
  - No: Increase Frequency Digit No. by 1
  - Yes: Set Frequency Display Digit No. 0
  - Set the Display change event bit of System Flag Register
  - Break

- **F**: Frequency Display Digit No. 0?
  - No: Decrease Frequency Digit No. by -1
  - Yes: Set Frequency Display Digit No. 9
  - Set the Display change event bit of System Flag Register
  - Break

- **C**: Frequency Digit 0?
  - No: Decrease Frequency Digit No. by 1
  - Yes: Set Frequency Digit No. 6
  - Set the Display change event bit of System Flag Register
  - Break

- **D**: Frequency Digit 6?
  - No: Increase Frequency Digit No. by 1
  - Yes: Set Frequency Digit No. 0
  - Set the Display change event bit of System Flag Register
  - Break
Interrupt Routine Flow Diagram

Figure 3.9: Flow Diagram of portable function generator system
3.8 Hardware Setup and Test Results

Entire hardware setup of portable function generator and the corresponding results are shown through the snaps. Figure 3.10 shows the complete embedded system of portable function generator with the design result probed on CRO. Figure 3.11 elaborates the structure of hardware design in detail.

Figure 3.10: Portable function generator system with actual testing result carried out by probed on CRO
Figure 3.11: Hardware setup of portable sine wave function generator system

The value of frequency is set through the 5 keys input unit and subsequently the same is displayed on LCD in Hz. As shown in the figure the frequency set herein is 25.0137 KHz; the minimum resolution is 0.1 Hz has offered to the user to set the frequency. The device can set maximum frequency up to 100 KHz.
3.9 Realization of portable single frequency and multi frequency bio-impedance analyzer

Impedance analysis is one of the prevalent, non-destructive measurement techniques that give diagnostic solution by informing traits about broad range of substances, materials of physics or chemistry such as semiconductors, nanomaterials, ferroelectrics, polymers and biomaterials. Since last 100 years, the analytical methods have been developed in order to measure the changes of impedance in biomedical organisms and their component parameters. The diagnosis of the various disease states are determined by changes in impedance with the variations in structure of biochemical components, metabolism and composition.[9] Though there are several instances of such a development in literature, not many research groups are working on the portable aspects. Portability is the main focus of our design as the same is apt in view of today’s wearable personal health care medical devices. As mentioned previously, the impedance measurement instrument is designed and developed based on the novel technology of impedance network analyzer IC AD5933 which gives all in one solution. The internal structure along with the details of frequency generation mechanism has already been dealt in the previous section. In this section we focus on the analog front end of design along with the details of the real and imaginary part of impedance measurement. The system has been designed to measure the bio-impedance in the frequency range of 1 KHz to 100 KHz which covers both measurement at single frequency and multi frequency. Several reading of the order of 100 have been taken for test and analysis at both single frequency and multifrequency bioimpedance analysis. The calculated and resulted data obtained from AD5933 IC has been collected on PC by means of serial communication.

3.10 Block Diagram of portable impedance measurement unit

Figure 3.12 shows the general functional block diagram of portable impedance measurement unit.
Figure 3.12: Block Diagram of Portable Impedance Measurement Unit

System consists of following parts.

1. AD5933 – Impedance Network Analyzer Solution
   On board technology based IC AD5933 has been used for the impedance converter solution. The same is equipped with on board support of DDS technology to produce sine wave frequency. The digital signal processing DFT technique has been used to calculate the real and imaginary magnitude of impedance. It can compute the impedance value with resolution 0.5% with measurement range from 1KΩ to 1MΩ. This is accomplished in the typical measurement range of frequencies from 1KHz to 100KHz. Total functionality of this IC divides in basically four working stages:

   A. Transmit stage: This stage generates the sine wave frequency for transmission purpose so as to calculate the impedance of subject. It is capable to give 0.1 Hz resolution with the built-in 27 bit phase accumulator DDS technology. The programming and more details regarding this have already been covered in the previous section.
B. Receiver Stage: This stage contains current to voltage converter, amplifier, PGA, low pass filter and 12 bit ADC. The signal gained is collected by Current to voltage unit and further fed to ADC unit for DFT calculation.

C. The DSP core processes signal in terms of discrete fourier transform to calculate the real and imaginary magnitude of impedance. The following equation shows the DFT algorithm of AD5933 core.

\[ X(f) = \sum_{n=0}^{1023} \left( x(n)(\cos(n) - jsin(n)) \right) \]

...............Eq. 3.5

Here, x(n) is the ADC output of impedance signal. 
\( \cos(n) \) and \( \sin(n) \) are the vector quantity of frequency point f.

The 1024 samples point DFT multiplication is carried out for every frequency point. It returns a 16 bit real and imaginary magnitude contents which are stored in the respective 16 registers. The said parts are communicated through I2C interface mechanism. In order to gain the final magnitude value, the calibration technique is necessary which is elaborated in the datasheet [4] of this IC. Once the scaling factor for known impedance is calculated it can be used for unknown impedance too. The detail calculation pertaining to this is discussed in the later part of the chapter.

D. I\(^2\)C Interface Control: This stage consists of I\(^2\)C interface core module which controls the chip function by appropriate support circuitry for sending and receiving mechanism. The storing of the calculated parameters is done in the register array.
2. Analog Front End:

As per the datasheet of AD5933 the IC is capable of measuring the impedance range within 1KΩ to 1MΩ. Generally the human body impedance range is around 500Ω which cannot fit in the given range. Therefore an extra analog front end is necessitated for the purpose of signal conditioning. AFE also controls the excited injected current which benefited to maintain the electrical safety standards. The selection and criteria to choose the operational amplifiers, electrical components is of immense importance. Figure 3.13 shows the hardware circuitry details of analog front end.

![Analog Front End Circuitry](image)

**Figure 3.13: Analog Front End Circuitry for measuring small impedance**

The R_{FB} feedback resistor is used at the receiver side amplifier to increase the signal current. At output side the signal current is reduced by attenuating the excitation voltage by selecting the appropriate resistor value of R3 and R4. This reducing signal current minimizes the output series resistance effect of impedance.
calculation. The resistor parameters value has been calculated based on selecting the peak to peak output voltage, internal gain setting resistor, series resistor. The op-amp OPA2737 is chosen by taking into account appropriate the device parameters such as the load current, gain and bandwidth.

3. Microcontroller MSP430G2452:

The MSP430 microcontroller is the central core of the system. The said microcontroller controls the I^2C peripheral interface of AD5933 IC and also does data processing and management functions along with mechanism for sending the data to PC through serial communication. The Universal serial interface (USI) module of MSP430G2452 series supports the synchronous serial communication which has built in hardware to ease the interface of SPI or I^2C protocol devices. The I^2C functionality of the same is used here for communication with AD5933. Out of three timers of microcontroller, Timer A is used to make out the function for serial communication to PC. The final result of impedance value is sent to PC and displayed on hyper terminal window after converting of float type value into integer format.

3.10.1 Impedance and Phase Magnitude Calculations

Before going into the details of the software part, it is imperative to detail out the impedance and phase calculations.. The DFT magnitude is calculated from the obtained value of 8 bit real number (R) and imaginary number (I) stored registers at address respectively 0x94, 0x95, 0x96, 0x97. The DFT magnitude is calculated by following equation 3.6,

\[
\text{Magnitude} = \sqrt{(\text{Real number})^2 + (\text{Imaginary number})^2} \quad \text{............Eq. 3.6}
\]

Assuming, Real number  = 0x0DB9 = 3513
Imaginary number   = 0x0907 = 2311
\[ \text{Magnitude} = \sqrt{3513^2 + 2311^2} = 4204.98 \]

The scaling factor is calculated to convert magnitude obtained into impedance. This factor is calibrated by calculating the gain factor by putting initially known impedance \( (Z_{\text{cal}}) \) between \( V_{\text{out}} \) and \( V_{\text{in}} \) pin. The equation for gain factor calculation is,

\[
\text{Gain Factor} = \frac{\text{Admittance}}{\text{Magnitude}} = \frac{\left( \frac{1}{Z_{\text{cal}}} \right)}{\text{Magnitude}} \quad \text{………………..Eq. 3.7}
\]

To calculate the unknown impedance the derived gain factor is multiplied with respective magnitude of unknown impedance. The equation to accomplish this is

\[
Z_{\text{unknown}} = \frac{1}{\text{Gain Factor} \times \text{Magnitude of unknown impedance}} \quad \text{………………..Eq. 3.8}
\]

Appropriate selection of calibration resistor \( R_{\text{cal}} \) and feedback resistor \( R_{\text{fb}} \) are the parameters to increase the accuracy of bioimpedance measurement. Programming facilitates selection within four range of output voltages. Each range has typical output resistance allies with it. In our design, we have selected peak to peak range of 1.98V as output voltage and typical 200Ω resistance associate with it. This \( R_{\text{out}} \) influences the unknown impedance measurement at from the accuracy view point, especially in the lower range. In view of this during the gain factor calculation the value of \( R_{\text{out}} \) is taken into account. To minimize the effect of the external amplifier attenuating the peak voltage, proper values of R3 and R4 have been selected as shown in figure 3.11. The said resistors reduce the current passing and thus minimize the influence of \( R_{\text{out}} \) in the impedance calculation. The selected parameters of IC have been listed in table 3.2
Table 3.2: Settled parameters value of AD5933

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal crystal frequency (MCLK)</td>
<td>16 MHz</td>
</tr>
<tr>
<td>Programmable Gain Amplifier (PGA)</td>
<td>x 1</td>
</tr>
<tr>
<td>Peak to Peak Output Voltage (V_{p-p})</td>
<td>1.98V</td>
</tr>
<tr>
<td>DC offset Voltage (V_{dcoffset})</td>
<td>1.48V</td>
</tr>
<tr>
<td>Output impedance (R_{out})</td>
<td>200Ω</td>
</tr>
</tbody>
</table>

**Calculation of R_{fb} and R_{cal} parameters:**

The accuracy of unknown impedance of resistor heavily depends on the choice of resistor values mainly the feedback resistor and known impedance for calibration i.e. Rcal resistor. The resistor R_{fb} ascertains the internal reference of the ADC, therefore care has to be taken so as not to over saturate the voltage. The formula to calculate R_{fb} value is given as,

$$
R_{fb} = \frac{(V_{dd} - 0.2) * Z_{min}}{(V_{p-p} + V_{dd} - V_{dcoffset})} * \frac{1}{Gain} 
$$

.......................Eq. 3.9

$$
R_{cal} = (Z_{min} + Z_{max}) * \frac{1}{3} 
$$

.......................Eq. 3.10

V_{dd} is the supply voltage,
Z_{min} is the minimum value of unknown impedance,
Z_{max} is the maximum value of unknown impedance.
The human bio-impedance varies within range of 300Ω to 800Ω over frequencies of the order of 50 KHz. Experimentation is done by passing the frequencies in the range of 1 KHz to 100 KHz to characterize the bio-impedance variations with frequencies. Therefore the $Z_{\text{min}}$ value is chosen to be 300Ω and $Z_{\text{max}}$ value is 1000Ω and the Gain is 1. By putting the parameters value in Eq. 1 & Eq. 2 as,

$$R_{\text{fb}} = \frac{\left( \frac{3.5}{2} - 0.2 \right) \times 300}{(1.98 + \frac{3.5}{2} - 1.48)} \times \frac{1}{1}$$

$$R_{\text{fb}} = 234 \Omega$$

$$R_{\text{cal}} = (300 + 1000) \times \frac{1}{3}$$

$$R_{\text{cal}} = 433 \Omega$$

The approximate values opted for $R_{\text{fb}}$ and $R_{\text{cal}}$ are 220Ω and 430Ω respectively.

The computation part to measure the magnitude value of impedance, phase and gain factor calibration has done by microcontroller with the aid of included math library file.

3.10.2 Design aspects of portable impedance measurement system

This section details out the various design aspects of portable bioimpedance measurement system.

- The Timer A is used to implement UART function at 9600 baud rate. The output and input latch timing are perfectly synchronized with Timer A, The Port Pin P1.1 and P1.2 are configured as TX and RX pin respectively. The UART function is initialized at the outset to send and print data along with the ‘READY’ signal on hyper terminal window before setting the MSP430 USB COM port and other relevance parameters.
- This is followed by resetting the AD5933 and setting appropriate parameters.
The control register is configured for peak to peak output excitation voltage of 2.0 V, unity PGA gain, and the system clock is set to operate on internal oscillator. Up to this instant, the AD5933 is kept in standby mode.

Total 100 reading are taken beginning from frequency range 1 KHz to 100 KHz with incremented sweep frequency by 1 KHz at every point. In accordance with the same the start frequency code, frequency increment code, number of increment register and sufficient settling time cycles are calculated and send to address of concerned register by I2C communication. The details of configuration frequency register parameter name, address and value are given in table 3.3

Table 3.3 Configuration details of frequency register parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Register Address</th>
<th>Calculate Value</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start frequency</td>
<td>0x82, 0x83, 0x84</td>
<td>0x00,0x83,0x12</td>
<td>Set starting frequency with 1 KHz</td>
</tr>
<tr>
<td>Frequency increment</td>
<td>0x85, 0x86, 0x87</td>
<td>0x00,0x83,0x12</td>
<td>Increment and sweep frequency by 1 KHz</td>
</tr>
<tr>
<td>Number of increments</td>
<td>0x88, 0x89</td>
<td>0x00,0x64</td>
<td>Increment frequency at 99 times</td>
</tr>
<tr>
<td>Number of settling time cycles</td>
<td>0x8A, 0x8B</td>
<td>0x00,0xFE</td>
<td>Conversion process timing settle for minimum 1 ms to maximum 10 ms</td>
</tr>
</tbody>
</table>
Other design steps are as follows:

- Running the necessary task to start up with initialize frequency 1 KHz and sweeping the frequency.
- Checking the status register bit to confirm the task has successfully been completed or not. By getting affined signal from the status register bit, the decision has taken to wait or capture the register value.
- Read the Real data and Imaginary data of impedance value. The key is assigned at port P1.4 to put the calculation mode in two modes; one at gain calculation mode and other at unknown impedance value calculation mode. The necessary mathematical function routines are driven based on the above discussed formulae.
- The computed result of impedance value is converted in integer format and send to PC through serial communication.
- This procedure is repeated until the settled sweep frequency is reached up to 100 KHz frequency and respected impedance value is displayed on the PC every time.

3.11 Algorithm

Figure 3.14 delineate the flow diagram of system implementation
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START

- Define variables, functions
- Define constant character arrays of AD5933 register parameters as per the different command

- Configure internal DCO
- Configure port pins input or output as per necessity
- Enable internal pull pin for I²C communication pins SDA, SCL - P1.6, P1.7 and key for P1.3 to change the calculation mode
- Disabled the interrupt pin of port 1.0 and 1.1 pin for UART_TXD and UART_RXD
- Enable appropriate P1 direction register

- Initialize the setup to set USI for I²C peripheral
- Setup SMCLK for USI clock SCL (125 KHz)
- Enable USI and clear the pending flag

- Initialize the setup of Timer A for UART mode
- Set Timer Capture Register bits of TACCTL1 as synchronous capture mode, capture on rising edge, capture mode & interrupt enable
- Set Timer A control register as continuous mode

Send and Display on PC ‘READY’ string
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A

Reset the AD5933

Run function to place the AD5933 at standby mode

Setup the AD5933 register sweep parameters into relevant register

Run function of initialize with start frequency command

Run sweep frequency command

Read and poll the status register to check DFT conversion process complete?

Yes

Read Impedance - Real & Imaginary registers

Concatenate the real and impedance registers & converted in float format

B

No
Figure 3.14 Flow diagram of portable impedance measurement system implementation.
3.12 Integration of the final hardware and Results

Testing of the system is done by initially outputting the value of unknown impedance and subsequently displaying the result on the HyperTerminal. MSP430 launchpad is used herein for USB to serial transmit by setting the appropriate value of baud rate as 9600 and parity bit set as none. Figure 3.15 shows photograph at the time of testing the impedance of bio-organism. Just for the purpose of testing the tomato sample were observed to test their freshness.

Figure 3.15: Portraiture at time of testing the bio-impedance of tomato sample
Figure 3.16 shows the snapshot of actual enumeration carried throughout concerning variations of human body impedance by sweeping the frequency from 1 KHz to 100 KHz through electrodes attached to the skin of both hand. We used here the conventional Ag/AgCl electrodes around the circumference of limb of both the hands. The aqueous gel is applied between the surface of skin and connecting electrodes. Processed magnitudes of impedance values are captured on the HyperTerminal window of PC. Figure 3.17 and Figure 3.18 shows the entire assembly of the system while figure 3.18 delineates more details about the programming workbench.
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Figure 3.17 Assembled of the entire circuitry and another modality

Figure 3.18 Portable hardware of the system with analog front end
3.13 Graphical analysis of changing frequency versus bioelectrical impedance in human body

In order to verify the accuracy of result, the system is tested on the known impedance value and compared it with the obtained value. The output data was analyzed statistically by plotting the graph of frequency passed throughout the subject body versus corresponding obtained bioimpedance value. The designed bio-impedance analyzer was studied on many subjects. Detail analysis of few of them is given below in graphical format, in which 3 are male and 2 are female subjects.
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Figure 3.20: Bio-impedance analysis on subject 1 – male at various frequencies

Figure 3.21: Bio-impedance analysis on subject 2 – female at various frequencies
Figure 3.22: Bio-impedance analysis on subject 3 – female at various frequencies

Figure 3.23: Bio-impedance analysis on subject 4 – male at various frequencies
The entire graph of frequency versus bio-impedance is compared and reaffirmed with the help of medical professional. At low frequency, the passed current is unable to penetrate the cell, and flows through only external region i.e. extracellular fluid. As the passing frequency increases the properties of cell membrane is changed and increases the extent of current penetration region. The graph expressed in detailed pertaining to variations in bio-impedance value with increasing frequency. It is seen that over 40 KHz frequency, the impedance value is becoming steady. The graph also ensured that the bio-impedance value of female subject is higher than the male counterpart. The SFBIA method is used to evaluate on only one frequency especially at 50 KHz frequency and MFBIA method uses many frequencies by taking average of at 1, 5, 30, 50, and 100 KHz. In many times the 200 KHz and 500 KHz frequency also consider within this range. Above 40 KHz frequency the change in impedance gradually becomes small and settles at steady value. In the MFBIA method, the lower frequency value of impedance is makes more impact on the average of impedance reading.
3.14 Conclusion

In this chapter we have gone through the conceptualization of design, development and implementation of portable DDS based function generator and embedded based portable bio-impedance measurement system. The on board solution of AD5933 impedance analyzer IC is best suitable to design the portable application of bio-impedance measurement with providing good accuracy. It produced spurious free sine wave with less than 0.1 Hz resolution by using 27 bit phase accumulator. The on board DSP mechanism processed complex part of the system by discrete Fourier transform method which reduces the design complexity time and promote to focus on the end application. The major advantage of this solution over the traditional is the fully chip function controlled by programming mode like changing the frequency, repeat the reading which enhancing the system proficiency. The added reset and standby mode feature of IC are more favorable to reduce the power dissipation which beneficial for long battery time especially for portable embedded application. The obtained system results portrayed in the presented chapter is adequate to realize the functioning of the system.

The measurement has taken by bipolar electrode configuration method. By analyzing both of the method SFBIA and MFBIA it is obtained that, there are low variations between impedance value at 50 KHz and average readings of multi frequencies (from 40 KHz to 100 KHz). Actual MFBIA uses diverse frequency range of 1 KHz to 500 KHz to estimate ICW, ECW, TBW and FFM. Through literature survey and also from the gist of our experimental observation, it educed that very much lower frequency and upper frequencies are poorly affected on the output reading. As 50 KHz is not determining the differences in intracellular water and extracellular water, however it estimates the Total Body Water (TBW) content and Fat Free Mass (FFM). The researchers also noticed, SFBIA is more accurate and less biased than MF-BIA especially for TBW. Moreover used network analyzer ICAD5933 is only capable to generate the maximum highest frequency with good resolution up to 100 KHz. So to realize the hydration of the body we decided to design final system based on SFBIA method.
References:

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