IJEE Volume-6 • Number-1 Jan -June 2014 pp. 12-19 (ISSN: 0973-7383)

# Bio-impedance Computation based on Hardware Implementation using FPGA

**D. K. Kamat**
Asst Prof, Dept of E & TC,
Sinhgad Academy of
Engineering, Pune and Research
Scholar, SCOE, Pune, India
dkkamat@gmail.com

**Shreeyog Nimkar**
Dept of E & TC,
RMD Sinhgad Technical Institutes
Campus,
Warje, Pune, India
shreeyog.nimkar@gmail.com

**Dr. P. M. Patil**
Director,
RMD Sinhgad Technical Institutes
Campus,
Warje, Pune, India
patil_pm@rediffmail.com

**ABSTRACT**

Bio-impedance measurement technique is used for body composition analysis. Bio-impedance measurement system working on reconfigurable platform is presented in this paper. Digital synchronous phase detection system is used to compute human body composition parameters at high frequency. The digital synchronous phase detection system is implemented in reconfigurable hardware. The mathematical analysis for calculating complex voltage and current of bio-impedance measurement system is presented. To estimate the human body composition parameters the bio-impedance analyzer tools need to operate at high frequency and the digital synchronous phase detection system is the solution for this requirement. Magnitude and phase detection method is the most common technique to calculate the phase difference between current and voltage of measuring cell and can also be used for magnitude calculation. Current-voltage method based on synchronous phase detection system is used to calculate the phase difference between voltage and current using four electrode configuration. Parallel processing can be used to obtain the complex value of voltage and current of high frequency bio impedance measurement system. The measured value of complex voltage and current is used to calculate bio-impedance of human body.

**Indexing terms/Keywords**

Bio-impedance, synchronous phase detection system, current-voltage method, four electrode measuring configuration, FPGA, Xilinx system generator tool, Direct digital synthesizer

## 1. INTRODUCTION

Electrical bio-impedance monitoring technology assists bio-medical research for analysis of many diseases. This rapidly developing technology forms the basis of many bio-impedance measurement systems that are discovered and implemented on various hardware platforms such as micro-processers, micro-controllers, digital signal processors and reconfigurable hardware like field programmable gate arrays (FPGA). This paper demonstrates use of FPGA for bio-impedance computing. Electrical bio-impedance analysis method is used to estimate human body composition and has potential to measure human body parameters like total body water (TBW), fat free mass (FFM), fluid volume (FV) and body cell mass (BCM). A number of bio-impedance measuring techniques are available in literature. A comparative study of bio-impedance measurement techniques is presented in Table 1 [1, 3, 5, 6].

**Table 1 Comparative study of bio-impedance measurement techniques**

| Technique | Advantage | Disadvantage | Application |
|---|---|---|---|
| Balancing Bridge method | High Measurement Resolution | Time Consuming, work only at Low Frequency | Low frequency Application |
| Classical analog Synchronous demodulation method | Comparatively Cost is less. | Filtering is Necessary, Increasing circuit complexity | Low frequency Application |

| | | | |
|---|---|---|---|
| Digital Synchronous demodulation Method | Sub-Sampling technique used | High cost | Medium Frequency Application |
| Magnitude ratio and phase detection | Cost Effective | Circuit complexity. | Medium and High frequency Application |

The magnitude and phase detection method is the most common technique to calculate the phase difference between current and voltage of measuring cell and can also be used for magnitude calculation. The current-voltage method based on synchronous phase detection system is used to calculate the phase difference between voltage and current from four electrode configuration [1].

**Table 2 Bio-impedance analyzer tools**

| Tools | Frequency | Impedance |
|---|---|---|
| AD5933 | 5Khz-100Khz | Less than 100Ω |
| AD5934 | Max 100Khz | 100 Ω to 10M Ω |
| SFB47 for body composition | 4Khz-1000Khz | 200 Ω-800 Ω |
| Cole-Cole Impedance Meter | 100kHz-1MHz | 100 Ω-1K Ω |

There are many bio-impedance analyzer tools and integrated circuits available in market. The working frequency along with impedance measurement range of these tools is shown in Table 2 [8, 11, 12, 13]. To estimate the human body composition parameters like TBW, FFM, FV, BCM, the bio-impedance analyzer tools need to operate at high frequency. The digital synchronous phase detection system fulfills this requirement and estimates the human body composition parameters at high frequency. In this paper we are presenting digital system to measure these parameters. In digital stage, we have shown digital synchronous phase detection system that is the solution of high frequency bio-impedance parameters for frequency is up to 10 MHz. The proposed design is implemented in reconfigurable hardware.

## 2. BLOCK DIAGRAM OF BIOIMPEDANCE MEASUREMENT SYSTEM

The block diagram of bio-impedance measurement system is shown in Figure 1. The block diagram has two stages namely digital stage and analog stage.

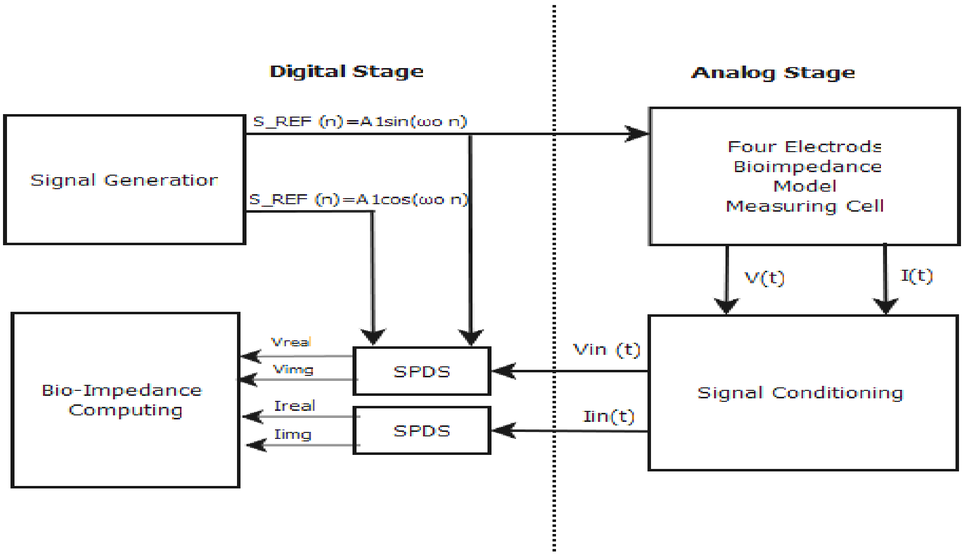


**Fig 1 Block diagram of bio-impedance measurement system**

### 2.1 Digital Stage

The digital stage contains signal generation, synchronous phase detection system and bio-impedance computing block.

#### 2.1.1 Signal Generation

The signal generation block generates three output signals namely the injected current to the tissue and two reference signals. These reference signals are defined by equations (1) and (2).

$$S_{REF}(t) = A_1 \sin(\omega_0 n) \quad \text{... (1)}$$

$$S_{REF}(t) = A_1 \cos(\omega_0 n) \quad \text{... (2)}$$

The direct digital synthesis (DDS) is a method of producing an analog waveform by generating a time varying signal in digital form. The basic principle of DDS is to produce a sine wave based on numerical controlled oscillator (NCO). The frequency, phase and amplitude of this wave is adjustable.

The output frequency of DDS compiler is calculated by using equation (3).

$$f_{out} = \frac{f_{clk}\Delta\theta}{2^{B_{\theta(n)}}} \quad \text{... (3)}$$

In equation (3),

$f_{out}$ is output frequency,
$f_{clk}$ is system clock frequency,
$B_{\theta(n)}$ is number of bits,
$\Delta\theta$ is phase accumulator and phase increment value

The Xilinx DDS Compiler 4.0 is used to generate two reference signals. Block parameter is system clock of 50 MHz with the maximum signal frequency of 10 MHz. Figure 2 shows implementation of Xilinx DDS Compiler 4.0.

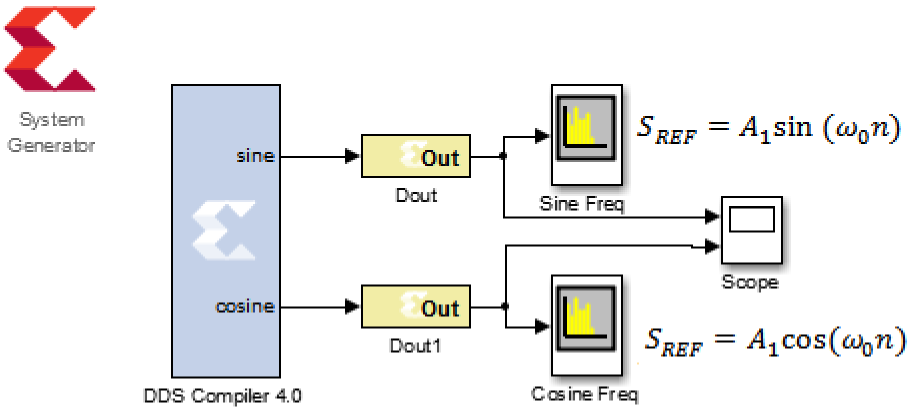


**Fig 2 Xilinx DDS Compiler 4.0 Implementation**

#### 2.1.2 Synchronous Phase Detection System

The synchronous phase detection system is an analog multiplier, generating a DC voltage signal according to phase difference between two input periodic signals. First one is the system generated reference signal $S_{REF}(t)$ generated by Xilinx DDS Compiler 4.0 and the second one, the input signal $V_{IN}(t)$ obtained from measuring cell. The digital synchronous phase detection system consist of Xilinx multiplier which is used for mixing the frequency of the signals $S_{REF}(t)$ and $V_{IN}(t)$ with Xilinx n-tap MAC FIR filter used as a low pass filter. Figure 3 shows implementation of digital synchronous phase detection system.

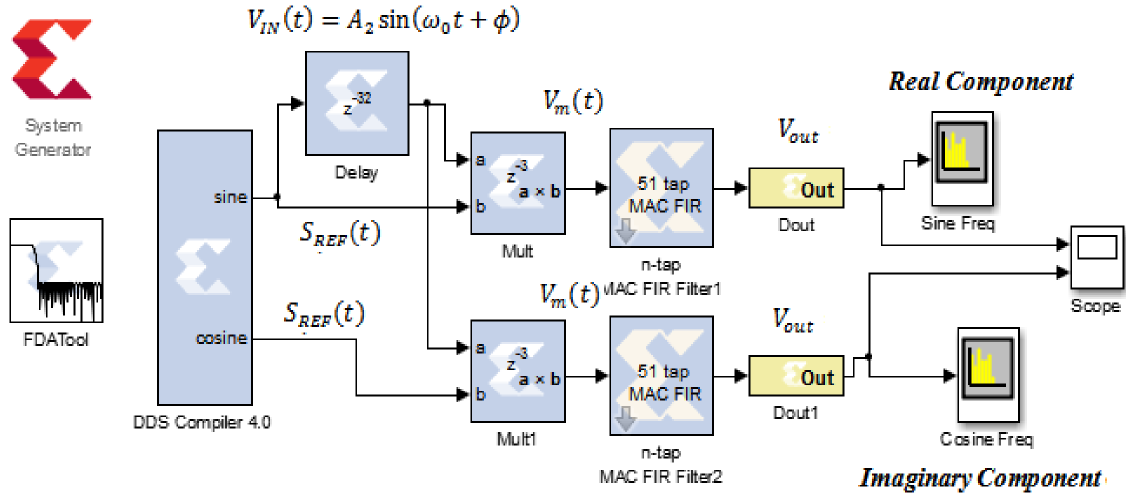


**Fig 3 Implementation of digital synchronous phase detection system**

### 2.1.3 Computation of Complex Voltage and Current

This section describes the mathematical calculations for complex voltage and current for calculation of bio-impedance. The complex voltage is calculated based on the reference signal to the signal generator. For calculating real voltage component of bio-impedance signal, the reference signal from signal generator is defined in equation (4).

$$S_{REF}(t) = A_1 \sin(\omega_0 t) \quad \dots (4)$$

The measured tissue voltage is the input signal defined in equation (5).

$$V_{IN}(t) = A_2 \sin(\omega_0 t + \phi) \ \dots (5)$$

In equation (5), $\phi$ is the delay between the measured voltage and injected current. The output of multiplier block is defined in equation (6).

$$V_m(t) = S_{REF}(t) V_{IN}(t)$$

$$V_m(t) = A_1 \sin(\omega_0 t) A_2 \sin(\omega_0 t + \phi)$$

$$V_m(t) = \mathrm{A_1 A_2} \frac{[\cos(\phi) - \cos(2\omega_0 t + \phi)]}{2}$$

$$V_m(t) = \frac{\mathrm{A_1 A_2}}{2} [\cos(\phi) - \cos(2\omega_0 t + \phi)] \quad \dots (6)$$

The real component of complex voltage is obtained as by using equation (7).

$$V_{out}(t) = \frac{\mathrm{A_1 A_2}}{2} \cos(\phi) \quad \dots (7)$$

The real component of complex voltage is the output of low pas filter.
For calculating the imaginary voltage component of bio-impedance signal, the reference signal from signal generator is defined in equation (8).

$$S_{REF}(t) = A_1 \cos(\omega_0 t) \quad \dots (8)$$

The measured tissue voltage is the input signal defined in equation (9).

$$V_{IN}(t) = A_2 \sin(\omega_0 t + \phi) \quad \dots (9)$$

In equation (9), $\phi$ is the delay between the measured voltage and injected current.

The multiplier block output is defined by equation (10).

$$V_m(t) = S_{REF}(t) V_{IN}(t)$$

$$V_m(t) = A_1 \cos(\omega_0 t)\, A_2 \sin(\omega_0 t + \phi)$$

$$V_m(t) = \mathrm{A_1 A_2} \frac{[\sin(\phi) + \sin(2\omega_0 \mathrm{t} + \phi)]}{2}$$

$$V_m(t) = \frac{\mathrm{A_1 A_2}}{2} [\ \sin(\phi) + \sin(2\omega_0 \mathrm{t} + \phi)\ ] \quad \dots (10)$$

The imaginary component of complex voltage is obtained by using equation (11).

$$V_{out}(t) = \frac{\mathrm{A_1 A_2}}{2} \sin(\phi) \quad \dots (11)$$

The output of low pas filter is the imaginary component of complex voltage.

For calculating real current component of bio-impedance signal, the reference signal from signal generator is defined by equation (12).

$$S_{REF}(t) = A_1 \sin(\omega_0 t) \quad \dots (12)$$

The measured tissue current is the input signal defined in equation (13).

$$I_{IN}(t) = A_2 \sin(\omega_0 t + \phi) \quad \dots (13)$$

In equation (13), $\phi$ is the delay between the measured voltage and injected current. The output of the multiplier block is defined by equation (14).

$$I_m(t) = S_{REF}(t) I_{IN}(t)$$

$$I_m(t) = A_1 \sin(\omega_0 t)\, A_2 \sin(\omega_0 t + \phi)$$

$$I_m(t) = \mathrm{A_1 A_2} \frac{[\cos(\phi) - \cos(2\omega_0 \mathrm{t} + \phi)]}{2}$$

$$I_m(t) = \frac{\mathrm{A_1 A_2}}{2} [\cos(\phi) - \cos(2\omega_0 \mathrm{t} + \phi)] \quad \dots (14)$$

The real component of complex current is obtained by using equation (15).

$$I_{out}(t) = \frac{\mathrm{A_1 A_2}}{2} \cos(\phi) \quad \dots (15)$$

The output of low pass filter is the real component of complex current.

For calculating the imaginary current component of bio-impedance signal, the reference signal from signal generator is defined by equation (16).

$$S_{REF}(t) = A_1 \cos(\omega_0 t) \quad \dots (16)$$

The measured tissue voltage is the input signal defined in equation (17).

$$I_{IN}(t) = A_2 \sin(\omega_0 t + \phi) \quad \dots (17)$$

In equation (17), $\phi$ is the delay between the measured voltage and injected current.
The output of the multiplier block is defined by equation (18).

$$I_m(t) = S_{REF}(t) V_{IN}(t)$$

$$I_m(t) = A_1 \cos(\omega_0 t)\, A_2 \sin(\omega_0 t + \phi)$$

$$I_m(t) = \mathrm{A_1 A_2} \frac{[\sin(\phi) + \sin(2\omega_0 \mathrm{t} + \phi)]}{2}$$

$$I_m(t) = \frac{A_1A_2}{2}[\sin(\phi) + \sin(2\omega_0 t + \phi)] \quad \dots (18)$$

The imaginary component of complex current is obtained by using equation (19).

$$I_{out}(t) = \frac{A_1A_2}{2}\sin(\phi) \quad \dots (19)$$

The output of the low pas filter is the imaginary component of complex current.

### 2.1.4 Computation of bio-impedance

The electrical bio-impedance $Z = R + jX$ is determined by measuring voltage response (*V*) to the excitation current (*I*) flow through the tissue or organ and computed by using equation (20).

$$Z = \frac{V}{I} \quad \dots (20)$$

The complex voltage *(V)* and current *(I)* signal is obtained from synchronous phase detection system block.
Let the complex voltage and current be defined as $V = a + jb$ and $I = c + jd$ then bio-impedance Z can be expressed by using equation (21).

$$Z = \frac{V}{I} = \frac{a + jb}{c + jd} = \frac{ac + bd}{c^2 + d^2} + j\frac{bc - ad}{c^2 + d^2} \quad \dots (21)$$

## 2.2 Analog Stage

The analog stage has four electrode measuring configuration and signal conditioning circuitry.

### 2.2.1 Four Electrode Measuring Configuration

The application decides the types of electrodes to be used. The configuration used in this paper is the four electrode system. It is most common technique for whole body analysis. In this technique, two electrodes are placed on the top of the foot and ankle (lower limb) and other two placed on back of hand and wrist (upper limb). Small electrical current $I_o$ (measuring a few tens or hundreds of microamperes) flow into living tissue through two electrode ($Z_{e1}$ *and* $Z_{e4}$) and the voltage drop $V_o$ between other two electrodes ($Z_{e2}$ *and* $Z_{e3}$) is measured. The four-electrode measuring technique is shown in Figure 4. It reads the voltage and current and has potential to detect the difference (phase angle) between both values. Ohm's law is used to calculate the bio-impedance.

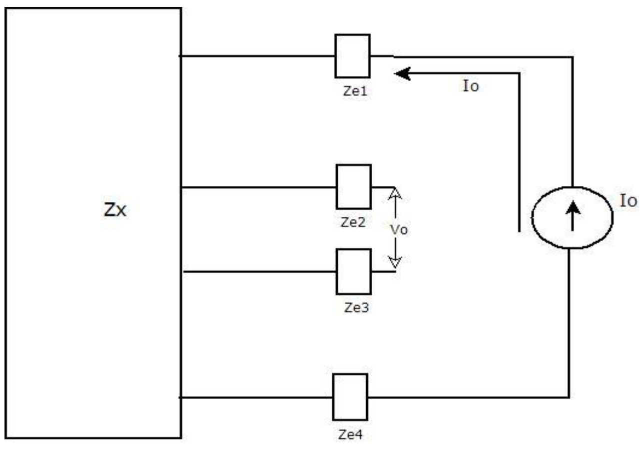


**Fig 4 Four electrode measuring configuration**

### 2.2.2 Signal conditioning

The signal conditioning is used for manipulating the analog signal so that it meets the requirements of the next stage. The bio-impedance measurement system uses analog to digital converter for converting analog bio-impedance signal to digital form and then further feeding to FPGA.

## 3. METHODOLOGY

The system generator design flow is described in this section.
1. Determining the design specification.
2. Design a system in Matlab and Simulink by using system generator design blocks.
3. Simulating the design in Simulink.
4. System generator software to provide VHDL code and test bench.
5. Simulate/Implement VHDL code by using Xilinx software.

The Xilinx system generator program creates project file for ISE 14.2 software. The project created allows the designer to simulate the code and download the code onto FPGA kit [9].

## 4. IMPLEMENTATION

The presented system is implemented on a Xilinx XC3S500 FPGA using a Digilent Spartan 3E development board. The implemented bio-impedance measurement system is shown in Figure 5.

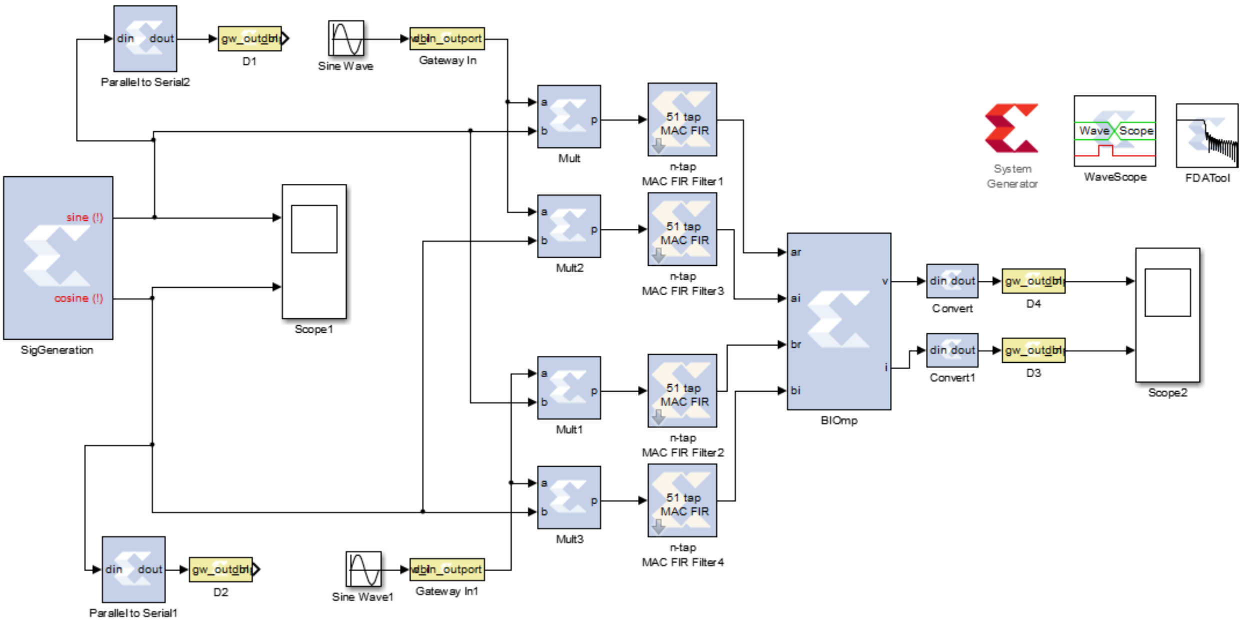


**Fig 5 Implementation of bio-impedance measurement system**

The synchronous phase detection system inputs and reference signals are multiplied using Mult block available in Xilinx system generator tool. The filtering process is implemented with the MAC FIR filter block of Xilinx system generator tool. The signal generation block is based on direct digital synthesis (DDS). This DDS has three output signals namely the injected current to tissue and two reference signals. These signals are generated through the DDS compiler 4.0 block of Xilinx system generator.

## 6. RESULT

The system presented in this paper is implemented on Xilinx XC3S500 FPGA with a Digilent Spartan 3E development board. The resulting output is observed on digital storage oscilloscope and Matlab virtual scope. The Xilinx XC3S500 device utilization summary is as shown in Table 3.

**Table 3 XILINX XC3S500 device utilization summary**

| Logic Utilization | Used | Available | Utilization |
|---|---|---|---|
| **Number of slice Flop Flop** | 690 | 9312 | 7% |
| **Number of 4 input LUTs** | 414 | 9312 | 4% |
| **Number of occupied slices** | 464 | 4656 | 9% |
| **Total Number of 4 input LUTs** | 520 | 9312 | 5% |

| | | | |
|---|---|---|---|
| **Number of bonded IOBs** | 7 | 232 | 3% |
| **Number of RAMB 16s** | 5 | 20 | 25% |
| **Number of BUFGMUXs** | 1 | 24 | 4% |
| **Number of MULT18X18SIOs** | 4 | 20 | 20% |

## 7. CONCLUSION AND DISCUSSION

Bio-impedance measurement technique can be used in body composition analysis for parameters like total body water, fat free mass, fluid volume and body cell mass. The design of digital synchronous phase detection system focused on bio-impedance measurement application is presented in this paper. The digital synchronous phase detection system is implemented on reconfigurable hardware as the digital stage of a bio-impedance measuring system where real and imaginary component of bio-impedance signal are computed. The mathematical analysis for calculating complex voltage and current of bio-impedance measurement system is also presented. To compute human body composition parameters we need bio-impedance analyzer tools that operate at high frequency. From Table 1 and Table 2, we conclude that operating frequency of available bio-impedance analyzer tools is limited to 1 MHz. We have presented a programmable frequency analysis system that measures body composition parameters at higher frequencies for persons suffering from obesity. The presented digital signal generation block and digital synchronous phase detection system is implemented on a Xilinx XC3S500 Spartan 3E development board. The output signal is observed on digital storage oscilloscope.

## ACKNOWLEDGMENTS

The authors are thankful to Sinhgad Technical Education Society for providing facilities of conducting experimental work.

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**AUTHOR BIOGRAPHY**

Durgaprasad K. Kamat received his BE degree in the field of Electronics Engineering in 1994 from Shivaji University, Kolhapur. He has completed ME in Electronics Engineering at SCOE, affiliated to University of Pune in 2008. He is working as Assistant Professor in the Department of E & TC Engineering of Sinhgad Academy of Engineering, Pune, since 2005. His research interests are Signal Processing, Embedded Systems and Biomedical Applications. He has 8 years of teaching experience and 8 years of industry experience. Mr. Kamat is a life member of IETE. He has published four papers in International Journal and seven papers in International and National Conferences

Shreeyog D.Nimkar received his B.E. degree in Electronics & Telecommunication engineering in the year 2012, from P.R.Patil College of Engineering, Amravati University, Amravati. He is pursuing his M.E. in Electronics and Telecommunication with the specialization in VLSI & Embedded systems, since 2012, at RMD Sinhgad Technical Institutes Campus, Warje, Pune, under Pune University. His areas of interest include VLSI Design, Embedded systems, and biomedical applications.

Dr. Pradeep Mitharam Patil received his B. E. (Electronics) degree in 1988 from Amravati University, Amravati, (India) and M. E. (Electronics) degree in 1992 from Marathwada University, Aurangabad, (India). He received his Ph.D. degree in Electronics and Computer Engineering in 2004 at Swami Ramanand Teerth Marathwada University, (India). From 1988 to 2011 he worked as Lecturer and Assistant Professor and Professor in department of Electronics Engineering at various engineering colleges in Pune University, (India). Presently he is working as Dean, RMD Sinhgad School of Engineering and Director of RMD Sinhgad Technical Institutes Campus, Warje, Pune, (India). He is member of various professional bodies like IE, ISTE, IEEE and Fellow of IETE. He has been recognized as a PhD guide by various Universities in the state of Maharashtra (India). His research areas include pattern recognition, neural networks, fuzzy neural networks and power electronics. His work has been published in various international and national journals and conferences including IEEE and Elsevier.