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COMPUTER AIDED DESIGN OF THE BIQUADRATIC FILTERS USING MEMRISTORS

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Computer Aided Design Of The Biquadratic Filters Using Memristors

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Sakar JAMEEL

ABSTRACT

COMPUTER AIDED DESIGN OF THE BIQUADRATIC FILTERS USING MEMRISTORS

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This thesis presents new circuit topologies realized by using the fourth passive element memristor. The terminal equations and the properties of memristor are given and its SPICE model is simulated.

Some active circuit applications such as biquadratic active filters, frequency dependent negative resistor realization oscillator design are given employing the memristors instead of capacitors. The fully integrated circuit configurations are derived and their terminal relations are calculated.

The gain curves of the proposed filters, i-v characteristics of the frequency dependent negative resistor, the oscillation wave form of oscillator are plotted using SPICE simulator.

Key words: Memristor, Biquadratic filter, FDNR, Oscillator.

ÖZET

MEMRISTÖR YAPILARI KULLANILARAK BİLGİSAYAR DESTEKLİ İKİNCİ DERECE FİLTER TASARIMI

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Bu tezde 4. temel eleman olan memristör kullanılarak yeni devre yapıları sunulmuştur. Memristörün uç eşitlikleri verilmiş ve memristör SPICE modelinin benzetimi yapılmıştır.

İkinci dereceden aktif süzgeç, frekans bağımlı negatif direnç, osilatör gibi bazı aktif devre uygulamaları kapasitör yerine memristör kullanılarak gerçeklenmiştir. Tamamen tümleşikleştirilmiş devre konfigürasyonları çıkartılmışve terminal ilişkileri hesaplanmıştır. Önerilen süzgeç devrelerinin kazanç eğrileri, negatif direncin frekans bağımlı akım-voltaj karakteristiği, osilatör devresinin salınım eğrisi SPICE kullanılarak çizilmiştir.

Anahtar Kelimeler: memristör, ikinci dereceden filtre, FDNR, osilatör

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LIST OF SYMBOLS

I	current (Am per)
V	voltage (Volts)
R	resistance (Ohm)
C	capacitor (Farad)
L	inductance (Henry)
M	memristor (Ohm)
Φ	flux (Weber)
q	charge (Coulomb)
η	indicate polarity of memristor (unit less)
G	gain (unit less)
Q	quality factor (unit less)
Z	impedance (Ohm)
Y	admittance (Siemens)
D	frequency dependent negative resistance (Farad second)
ω	frequency (Hertz)
ω_o	resonance frequency (Hertz)
ω_c	cutoff frequency (Hertz)
W	size of doped region (meter)
W_o	initial size of doped region (meter)
BW	band width (unit less)
R_o	initial resistance of memristor (Ohm)

R_{on}	resistance of doped region for HP memristor (Ohm)
R_{ofF}	resistance of undoped region for HP memristor (Ohm)
ΔR	difference between doped and undoped resistance (Ohm)
D_o	maximum drift distance of memristor (meter)
Q_o	charge required to pass through memristor (Coulomb)
μ_v	ionic mobility (m^2/s.volts)
δ	impulse voltage (voltage)
V_D	drift velocity (m/s)
V_{in}	input voltage (voltage)
V_{out}	output voltage (voltage)
LP	low pass
HP	high pass
BP	band pass

Abbreviations

FDNR	Frequency Dependent Negative Resistance
KHN	Kerwin- Huelsman – Newcoub
Op-amp	Operational amplifier
CMOS	Complementary Metal–Oxide–Semiconductor
VLSI	Very Large Scale Integration
MIM	Metal Insulator Metal

CHAPTER 1

INTRODUCTION

1.1 Introduction

A filter has property of selecting some harmonics among the complete signal. Each filter should have components which reveal different impedance to different frequencies and, by divider logic, shows different gain and phase for different harmonics. Filters are mostly classified with respect to the operator frequency range and they are named as audio, radio, intermediate frequency filters.

System power supplies often use band-rejection filters to suppress the 60-Hz line frequency and high frequency transients [1]. The memristor makes the filter adaptive. The main characteristics such as frequency, bandwidth, and gain can be altered by means of changing the memristance value, memory resistor is a passive, two-terminal dynamical device which represents some of the properties of resistors and has the same unit of measurement (Ohms).

A memristor first was found by gen Leon Chua in 1971. Memristor is a new electronic circuit which simulates the relation between magnetic flux and charge. The electronic structure for the memristor is generally complex. Their design needs computer simulations, generally made from metal insulator-metal (MIM) sandwich with the insulator usually consisting of a thin film of TiO_2. One of the reasons the memristor remained hidden for so long is the fact that memristive behavior disappears quickly as the thickness of the thin film is increased above the nanometer scale [2]. However, the most significant difference of memristor from the conventional resistors is that they show the memory feature. This property makes them more preferable in circuit design [3]. One of the popular circuits used to realize a second order filter is Kerwin-Huelsman-Newcomb (KHN) filter.

In this study, the new electric circuit known as memristor will be presented and the realization of specific networks including the memristors used in many different areas are given.

Although it was possible to present many different circuits using memristors, we have limited our examples with the biquadratic RC filter and frequency dependent negative resistor.

The second order (biquadratic) basic building blocks are essential and the higher order transfer function can be obtained easily by cascading the biquadratic blocks. To decrease the power consumption and to increase the efficiency, the memristor structures will be defined and used in the realization.

This realization offers low pass, high pass and band pass outputs simultaneously in one design by using the memristor device with this type of filter leads not only to decrease circuit size, but also make it possible to get higher reconfigurable filters.

The main objectives of this study considered new structure which is used for filter realization. Although the proposed filter structures will be second order, the presented building blocks can be combined to obtain any kind of filters. In general there are many software used for filter realization.

In this work, the codes of programs for memristor – resistance filter is given. The use of memristors in the circuit improves the quality of the circuit from adaptability, low power consumption point of view.

In the literature, a few of works focused on the memristors and this work is supposed to fill partly the filter design techniques. This work is directed to write a computer program to obtain the circuit structure to satisfy the given filter characteristics.

1.2 Structure of the Thesis

In Chapter 2, the memristor is introduced as the missing element in the circuit theory. Its characteristic and equivalent structures are given and the terminal equation is derived.

In Chapter 3, typical RC active circuits are introduced to be realized by using memristors. In this study RC active biquadratic network structure and frequency dependent negative resistance circuit are examined.

Chapter 4 gives the SPICE application of the circuits including memristors. Chosen circuits are analyzed using SPICE model.

The proposed structure and the results are discussed in Chapter 5.

CHAPTER II

MEMRISTOR

2.1 Introduction

In this chapter, definition of memristor, the historical background, types of memristor, realization of memristor model, properties, and applications, is presented.

2.2 Historical Background

Prof. Bernard W. [5] in 1960, has discovered a new circuit element. This element is called as memristor. It was found a three-terminal device which is the conductance between two of the terminals was controlled by time integral of the current into the third terminal. F.Argall in 1968 [10] found that switching phenomena in titanium oxide thin films, which shows results similar to that of the memristor model proposed by Stanley Williams and his team [7].

In 1971 Dr. Leon Chua [6] was firstly found the memristor. Based on the symmetry of the equations that govern the resistor, inductor and capacitor, the first found was emphasized that fourth device should exist that holds a relationship between magnetic flux and charge.

Chua’s verified that the abilities of the memristor could not be duplicated by any of the other three passive elements, which is that an active circuit that mimics the utility of the theorized device would require approximately 25 transistors. Meanwhile the memristor was expected to be a device with a dynamic resistance that is determined by the integral of current flowing through it. Since this is an integral relationship, applying zero current would result in a constant charge, thus leaving the resistance constant. It shows that the theorized memristor possesses the ability to retain a resistance value even after the power source is removed from the device. Unlike the inductor and capacitor, that’s mean is not a storage device of energy, so the voltage must equal to zero whenever the current goes to zero. This causes the I-V curve of the device to produce a drawn hysteresis loop, the device has a memory effect linked with it [7].

Last decade, Dr. Chua was specified the existence of the memristor. He and Kang have generalized the concept of a broader class of systems, called memristive systems. Meanwhile all memristive systems should have a zero output whenever the input is zero, that is distinguishes from arbitrary dynamical system. Until 1990, there was a few paper about memristor. S.Thakoor, [14] have demonstrated a tungsten-oxide variable- resistance device that is electrically reprogrammable. Meantime it is not clear if the memistor device described has any relation with Chua‘s memristor [6].

2.3 Definition of a Memristor

Memristor is the contraction of “memory resistor” shown in Fig. (2.1). The memristor is the fourth passive element [4]. It carries memory from its past. When the electric circuit’s voltage is turned off the memristor still remembers the amplitude and the duration of voltage applied on it. The device was physically published in Hewlett Packard Labs in 2008 [5].

It is defined as relationship between two of the four fundamental circuit variables, namely the current i, the voltage v, the charge q and the flux Φ, memristor provides a functional relation between charge and flux as

$$d\Phi = M dq \tag{2.1}$$

It is not storage energy element but the flux between the two terminals is a function of the amount of electric charge that has passed through the device [6].

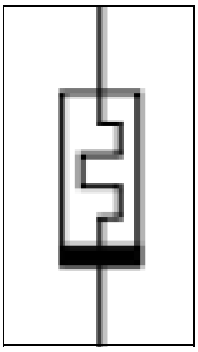

Figure 2.1 Symbol of memristor

2.4 Types of Memristor

There are several types of memristor utilized, titanium dioxide memristor, polymeric memristor, spin memristive systems, magnetite memristive systems and resonant tunneling diode memristor [8].

2.4.1 Titanium Dioxide Memristor

In 2008, R. Stanley Williams of Hewlett Packard was reported an experimental solid state version. [5]. A semi-conductor device was either use magmatic field as flux or keeps charge as capacitor, memristor which has memory feature used chemical mechanism. This type of memristor is constructed by 5 mm thick titanium dioxide film in two conductors. One of the film slide depletion of oxygen atoms. The absence oxygen act as carriers it mean that the depleted layer has lower resistance than the non-depleted layer.

Meanwhile the resistance of the film as all is dependent on how much charge has been passed through it, in a particular direction, which is reversible by changing the direction of current.

2.4.2 Polymeric Memristor

In 2008, V.Erokhin and Marco P.F, in electrochemically controlled polymeric device a memristor.[19]

2.4.3 Spin Memristive Systems

A different system for memristor is discovered by Yuriy V. P and M. Di Ventra in their paper "Spin memristive systems"[9]. It has been shown that some of the semiconductor spin tronic structures belong to a broad class of memristive systems. The mechanism of memristor in this structure is dependent on the electron spin degree of freedom. When an external control parameter is changed, the adjustment of electron spin polarization is delayed.

2.4.4 Manganite Memristive Systems

Manganite memristor system was found by researchers at the University of Houston. Bilayer oxide films are used dependent on manganite for non-volatile memory. More of the figures show tunable resistance dependent on the number of input voltage pulses which was the same of effects of the titanium dioxide memristor as the paper of "The missing memristor found"[4].

2.4.5 Resonant Tunneling Diode Memristor

Resonant Tunneling Diode Memristor was found in 1994, F. A. Buot and A. K. Rajagopal [10]. Naval Research Laboratory demonstrated that a ‘bow-tie’ current-voltage (I-V). Which occurs in AlAs/GaAs/AlAs quantum-well diodes containing special doping design of the spacer layers in the source and drain regions, in agreement with the published experimental results. There are many possible application areas of the memristor such as, Non-volatile nano memory, Crossbar latches as transistor replacement, Analog computing, Programmable logic and signal processing, Model for biological phenomena, Learning circuits, Quantum computing.

2.5 The Properties of Memristor

Memristor is memristive [11]. When the charge flows in one direction of circuit, the resistance of memristor increases, and when it is in the opposite direction resistance of memristor decreases. If the input voltage is turned off position, which is the flow of charge is stopping; the memristor remembers that last resistance it had. When it is starting again, the resistance of the circuit will be known that it was last active.

2.6 Review on the Studies of Memristors

CMOS DDCC based memristor realization and its application to chaotic communication was carried out by S.Yener and H.Kuntman [12]. They have emphasized that design of CMOS based memristor realization using DDCCs which are easy for VLSI implementation. Another paper of them [13] has presented a study on a CMOS memristor implementation and its chaotic applications. They have proposed a new CMOS memristor model. The model was very suitable especially for chaotic communication circuits. Performance of the model is proved via simulation.

Demonstrated a tungsten-oxide variable- resistance device that is electrically reprogrammable carried out by S.Thakoor, et al. [14]. He emphasized that it is not clear if the memristor device described has any relation with Chua‘s memristor .The analysis showed no direct connection to Chua‘s memristor [6].

Buot and Rajgopal have published an article entitled Binary information storage at zero bias in quantum-well diodes [10]. The hysteretic features of these switches are similar to the memristor. Liu, et al., researchers in the Space Vacuum, presented study [15] during a non-volatile memory conference held in San Diego, California, presented the importance of oxide bilayers to achieve high-to-low resistance ratio. Beside the article showed voltage-current characteristics similar to that of the memristor in AlAs/GaAs/AlAs quantum-well diodes.

Beck, et al., described reproducible resistance switching effects in thin oxide films [16]. J. Joshua Yang, Matthew D. Pickett et al. [17] published the memristive switching behavior and mechanism in nano devices.

Identifying a link between the two-terminal resistance switching behaviors found in nanoscale systems and Leon Chua's memristor was presented by Williams and his group in the Information and Quantum Systems (IQS) Lab at HP.

Dmitri Strukov, Gregory Snider, Duncan Stewart, and Stanley Williams, of HP Labs, [18]. Since 2008, Yu V. Pershin, S. La Fontaine, M. Di Ventra presented a paper [19] identifying memristive behavior in amoeba's learning.

Furthermore Sung Hyun Jo and Kuk-Hwan Kim et al. studied on [20] an amorphous-silicon–based memristive material capable of being integrated with CMOS devices. In 2009, scientists at NIST [21] have presented a study that they had fabricated nonvolatile memory using a flexible memristor that is both inexpensive and low-power. Whatever valsa et al. have studied on a memristor mimicking circuits [11].

2.7 Benefits of Memristors

Memristor can be function as synapses which meanwhile lead to simulation of human brain, it withstand up to a million read-write cycles and less power hungry and faster, that make it able to scale faster and farther than flash. The device could lead to the integration of the CPU and memory into one block, and it has great data density. It is used as non volatile memory because does not consume power when it is idle [8].

2.8- Realization of Memristor Model

Classical way to introduce the memristor which is so called axiomatic approach it postulates that the basic circuit parameters such as current, voltage, flux and charge are related to each other by using the well known theorems and laws. They can be combined two at the time in six possible ways [4]. The v-i characteristic of memristor can be described by

$$v(t) = \left(R_{on}\left(\frac{w(t)}{D_o}\right) + R_{off}\left(1 - \frac{w(t)}{D_o}\right)\right) i(t) \qquad (2.2)$$

where w(t) width of dopped region, D_o maximum drift distance, R_{on} resistor of dopped region, R_{off} resistance of undoped region μ_v shows signal of ionic mobility, v_D is the drift velocity under any applied bias voltage and η indicates the polarity of memristor. η is equal to 1 if the voltage is applied to the doped region and equal -1 in reverse case. The structure of the memristor is shown in Fig. (2.2).

The rate of the width of the doped region can be formulated as.

$$\frac{dw}{dt} = v_D + \frac{\eta \mu_v R_{on}}{D_o} i(t) \qquad (2.3)$$

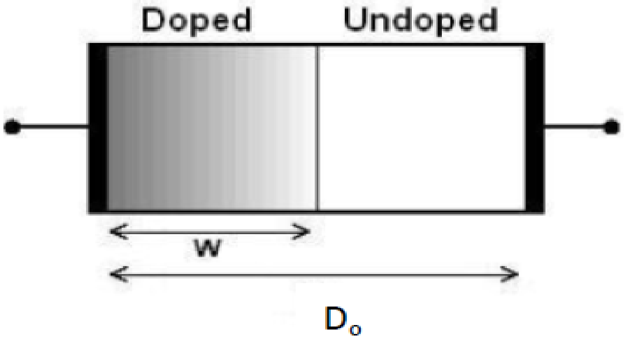

Figure 2.2 The structure of the memristor

Taking the integral of both sides of Eq. (2.3) we obtain w as function of time as

$$w(t) = w_o + \frac{\eta\mu_v R_{on}}{D_o} q(t) \tag{2.4}$$

where w_o is the initial size of the doped region. As it is shown in Eq. (2.4), the width of the doped region w(t) changes linearly with the amount of charge passing through it, Using Ohm's law, Coulomb's law and Faraday's laws the memristor can be defined by

$$M\big(q(t)\big) = \frac{\frac{d\varphi}{dt}}{\frac{dq}{dt}} = \frac{v(t)}{I(t)} = R_o - \frac{\eta\Delta R}{Q_o} q(t) \tag{2.5}$$

The initial resistance of the memristor is

$$R_o = R_{on}\left(\frac{w_o}{D_o}\right) + R_{off}\left(1 - \frac{w_o}{D_o}\right) \tag{2.6}$$

The charge that is required to pass through the memristor for the dopant boundary is given by [22]

$$Q_o = \frac{{D_o}^2}{\mu_v R_{on}} \tag{2.7}$$

The difference between the undoped (off) and doped (on) resistance is

$$\Delta R = R_{off} - R_{on} \tag{2.8}$$

Using Eqs. (2.2), (2.5) and (2.7), charge-voltage relation is written as

$$v(t) = \left[R_o - \frac{\eta\Delta R}{Q_o} q(t)\right] \frac{dq}{dt} \tag{2.9}$$

Since the flux is the integral of $v(t)$ the integral of Eq.(2.9), we obtain

$$\varphi(t) = R_o q(t) - \frac{\eta \Delta R\, q^2(t)}{2Q_o} \tag{2.10}$$

The charge is an invertible function of the magnetic flux, and solving the Eq. (2.10) for positive root, we obrain

$$q(t) = \frac{Q_o R_o}{\Delta R}(1 - \sqrt{1 - \frac{2\eta \Delta R \varphi\,(t)}{Q_o R_o^2})} \tag{2.11}$$

Substituting Eq. (2.11) in to Eq. (2.5), we obtain

$$M(q) = R_o \sqrt{1 - \frac{2\eta \Delta R \varphi\,(t)}{Q_o R_o^2}} \tag{2.12}$$

The current flow through the memristor device can be solved by insert the Ohm's law equation into Eq. (2.9) become

$$i(t) = \frac{v(t)}{R_o \sqrt{1 - \frac{2\eta \Delta R \varphi\,(t)}{Q_o R_o^2}}} \tag{2.13}$$

Eq. (2.13) shows that the terminal equation of the memristor is not constant, but is the function of flux. Since there is time dependence between charge and flux as given in Eq. (2.10) the equivalent impedance of the memristor is also time varying. The non-linear and time invariant characteristics of the memristor make this component usable in the realization of the dynamic linear and non-linear circuits.

In the following chapter, RC active filters will be realized using memristors to show the reliability of the dynamic linear circuits. Frequency dependent negative resistor circuits and oscillator will be realized to show its non-linear use in the circuit design. In both realization, the SPICE model of memristor will be used and the i-v characteristics, independence variations of the circuits will be obtain by using SPICE.

CHAPTER III

ACTIVE FILTERS AND FREQUENCY NEGATIVE RESISTANCE (FDNR)

3.1 Active RC Filter

Filters as name indicate, are used to allow certain range of frequencies to pass and reject the remaining. They are widely used in many analog and digital communication systems not only to eliminate the noise in the information carrying signal but also to select required part of the signal and to enhance the quality of the signal. Filter circuits are used in a wide variety of applications. In the field of telecommunication, band-pass filters are used in the audio frequency range (0 kHz to 20 kHz) for modems and speech processing. High-frequency band-pass filters (several hundred MHz) are used for channel selection in telephone central offices. At high frequencies (> 1 MHz), all of these filters usually consist of passive components such as inductors L, resistors R, and Capacitors C. [1] and [23]. They are then called RLC filters which is simply shown in Fig. 3.1(a).

The value of inductor in this filters highly dependent on the frequency. At relatively lower frequencies inductor value becomes very large and it is not visible to construct high value of inductors with visible dimensions. Therefore inductorless filters gained great importance which are realized using resistors, capacitors and op-amps employed instead of inductors. These filters are active and they can have amplification as shown in Fig. 3.1(b).

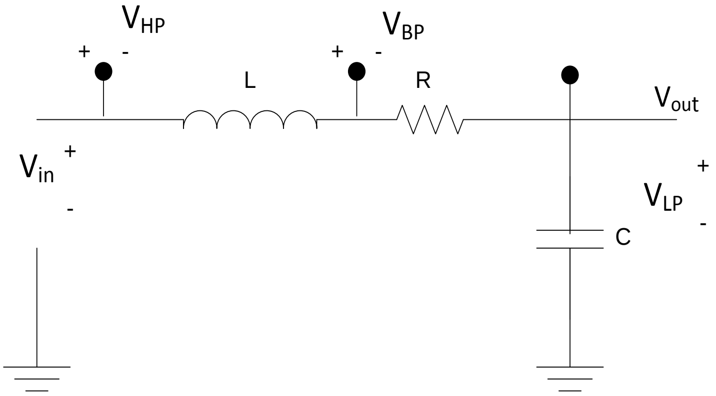

Figure 3.1(a) Second order passive low pass filter

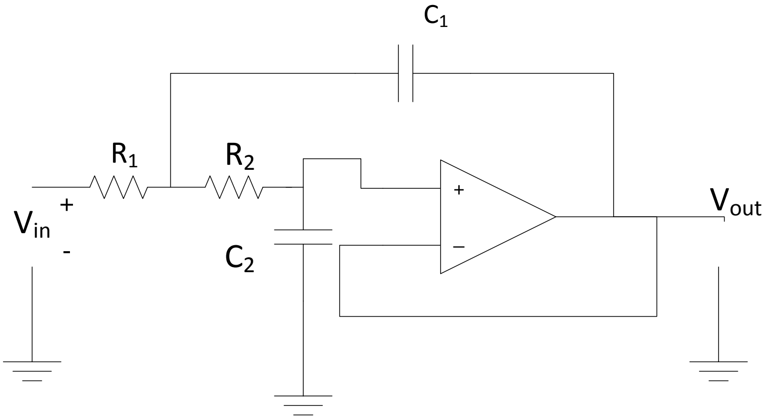

Figure 3.1(b) Second order active low pass filter.

The problem of designing a circuit that will have a specified transfer function is called filter design. Consider the following example

$$v_i(t) = cos\omega_1 t + cos\omega_2 t + cos\omega_3 t \tag{3.1}$$

The input consists of a sum of sinusoids, each at a different frequency. The filter separates the input voltage into parts, using frequency as the basis of separation. Although the input given biquad has purely separated components, since none of the filters are ideal any of this components or blocked by the filter with some noises generated by the neighbor harmonics. The quality of the filter must be high, to reduce the noise effect.

There are typical active RC circuits used for any type of filterzing. Some of them are Single-Op amp Biquad, Sallen and Key Biquadratic cell, Rauch Biquadratic cell, Multi-Op amp Biquad, Kerwin-Huelsman-Newcomb (KHN) Biquadratic, Tow-Thomas Biquadratic cell. Some of them have superiorities against the other. Depending on the application area, the suitable one may be chosen [1].

3.2 Biquadratic Filter (LP, HP, BP)

In many applications we may need higher order active RC filters. But in general, in the design of high order filters, we can cascade many biquadratic filters which may help the simple design procedure. The name derives from the fact that the transfer function is a quadratic (2^{nd} order) function in both the numerator and the denominator. Thus, the transfer function is a biquadratic function.

One of the popular circuits used to realize a second order filter is Kerwin-Huelsman-Newcomb (KHN) filter. This realization offers low pass, high pass and band pass outputs simultaneously in one design [25].

The Biquad topology is derived by generating an analog computer diagram for a biquadratic transfer function, where coefficients of the transfer function are related directly to the passive RC elements which interconnect the operational amplifiers. The application of filters can range from high frequency band pass filters, used in channel selection at the telephone central offices, low pass filters for data acquisition systems, high pass filters for signal separation in the audio amplifier, band reject (notch) filters used for suppression of interfering signals also called as wave traps.

Depending upon technology used a possible classification can be given as follows: (i) Passive filter, (ii) Active filter, (iii) Digital filter and (iv) Mechanical filter.

All filters can be realized by employing active elements and passive components. Radio, television, mobile phones, radar, satellite and biomedical equipments are few typical examples of systems that employ active filters [23].

The general transfer function of biquadratic filter is given as

$$H(s) = \frac{k_1 s^2 + k_2 s + k_3}{s^2 + s\left(\frac{\omega_o}{Q}\right) + \omega_o^2} \tag{3.2}$$

In this equation ω_0 is the resonance frequency of the circuit and Q is a quality factor. This equation may be modified replacing some of the numerator constants k_1, k_2 and k_3 by zero. If $k_1$and k_2 set to zero it becomes

$$H_{LP} = \frac{k_3}{s^2 + s\left(\frac{\omega_o}{Q}\right) + \omega_o^2} \tag{3.3}$$

which yields the LP characteristics. But if k_2 and k_3 set to zero it becomes

$$H_{HP} = \frac{k_1 s^2}{s^2 + s\left(\frac{\omega_o}{Q}\right) + \omega_o^2} \tag{3.4}$$

which is obviously a high pass filter. If k_1 and k_3 are se t to zero it becomes BP filter.

$$H_{BP} = \frac{k_2 s}{s^2 + s\left(\frac{\omega_o}{Q}\right) + \omega_o^2} \tag{3.5}$$

For special application such as notch filters, comb filters, numerator coefficients may be calculated using well-known methods. The general active RC structure realizing Eq. (3.2) is given in Fig. (3.2).

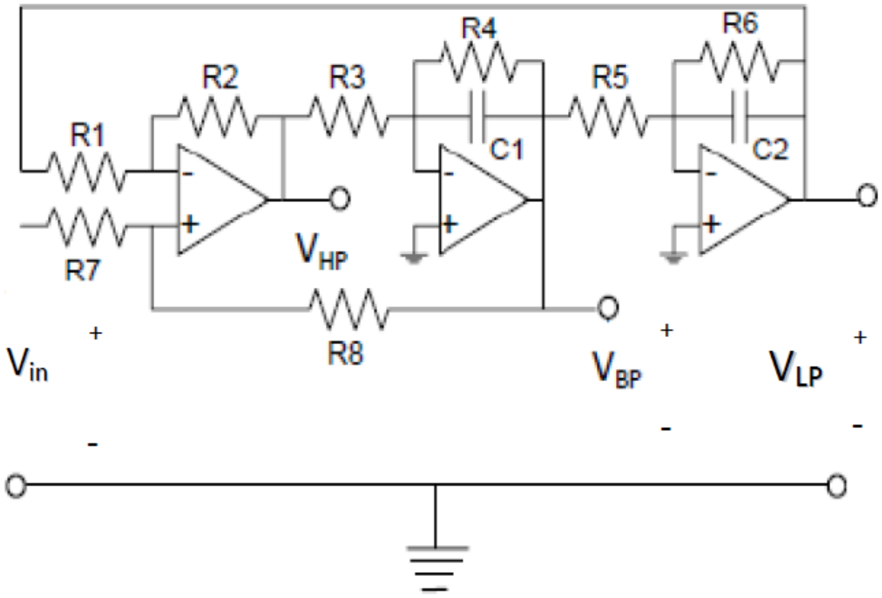

Figure 3.2 Schematic of a Biquad filter

Comparing the circuit parameters given in Eq.(3.2) and the circuit equations obtained from Fig. (3.2) the resonance frequency, quality factor and the gain is found as

$$\omega_0 = \sqrt{\frac{R_2}{R_1}\,\frac{1}{C_2\,C_1}\,\frac{1}{R_3\,R_5}} \tag{3.6}$$

$$Q = \sqrt{\frac{R_2}{R_1}\,\frac{C_1}{C_2}\,\frac{R_3}{R_5}} \times \frac{1}{1+\frac{R_2}{R_1}} \times \left[1 + \frac{R_8}{R_7}\right] \tag{3.7}$$

$$\mathrm{G_o} = \frac{\mathrm{R_8}}{\mathrm{R_7}} \tag{3.8}$$

As obvious from these equations R and C values in the circuit directly affect the parameters. Since there are three equations with eight element, it is possible to choose some of these components arbitrarily which helps the availability of the components. Q which represents the quality factor shows the bandwidth of the filter. In this Band pass application the biqaudratic gain, the bandwidth, resonance frequency ω_o and the critical frequencies ω_{c1} and ω_{c2} are shown in Fig. (3.3).

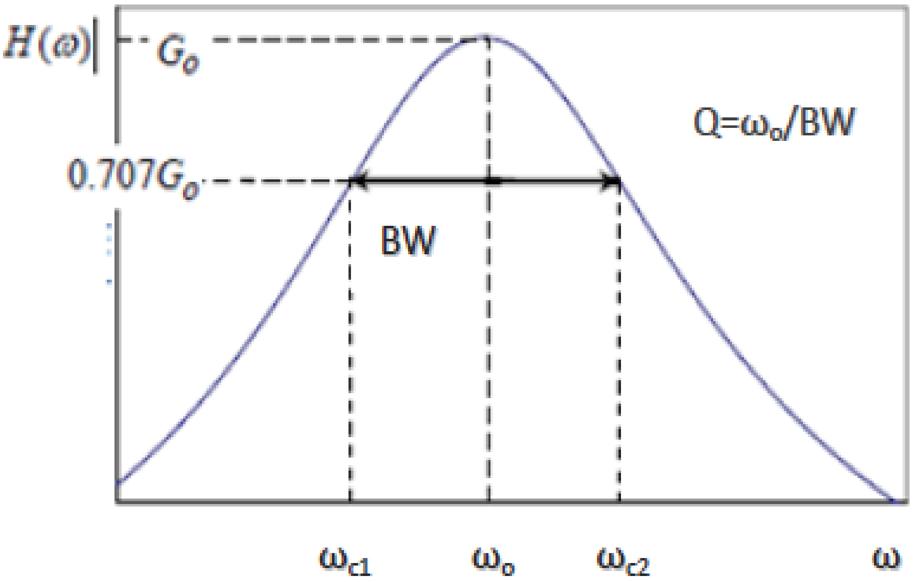

Figure 3.3 The gain curve of the BP filter

As it is seen from the equations, the bandwidth is defined as the difference of the 3dB loss cut of frequencies. Narrower BW results with higher quality. The similar conclusions may be given for LP and HP cases.

3.3 Frequency Dependent Negative Resistance (FDNR)

In some active RC design procedures, the given filter specifications are used to design the corrosponding passive RLC circuit and then the transformation method is used to obtain the equivalent active RC network. Since the division or multiplication of each impedance as in the passive RCL circuit doesn't affect the overall transfer function, inductor L in these circuits may be removed by this way. For example, let us consider the 2nd order RLC passive circuit given in Fig. (3.4).

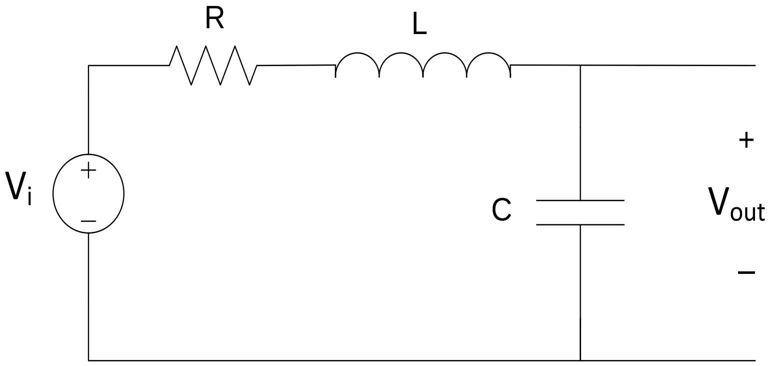

Figure 3.4 RLC passive circuit

It is a low pass filter and its transfer function is

$$H(s) = \frac{\frac{1}{LC}}{s^2+\frac{R}{L}s+\frac{1}{LC}} \tag{3.9}$$

If is replaced L with L/s , R with R/s and C with C/s in this transfer function, it does not change. But the structure of the circuit becomes as shown in Fig. (3.5).

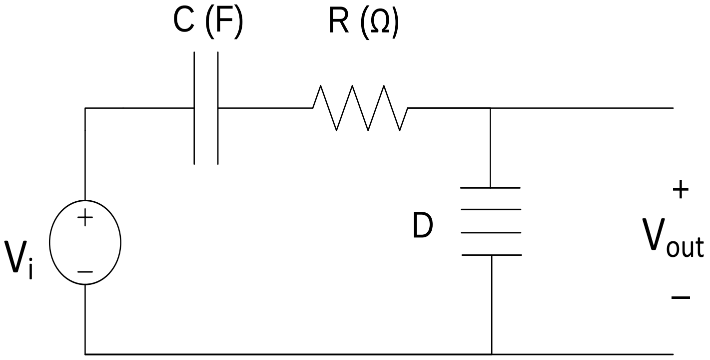

Figure 3.5 RCD passive circuit

In this circuit the symbol D represents frequency dependent negative resistance and the impedance of it becomes

$$Z(s) = \frac{1}{DS^2}\mid_{s=j\omega} = \frac{1}{-\omega^2 D} \tag{3.10}$$

Since FDNR is fictitous element, it may be realized using active RC circuits. One possible circuit which gives the FDNR impedance between the terminals is given in Fig. (3.6).

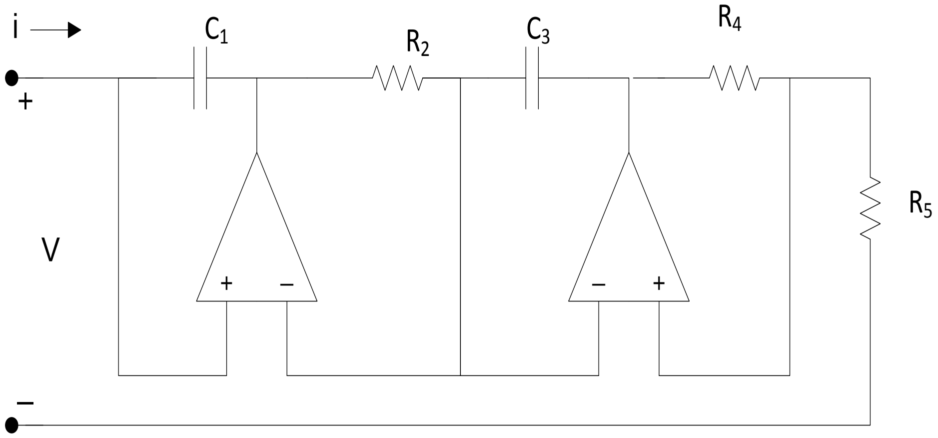

Figure 3.6 System diagram of FDNR

The V/I of this circuit is

$$Z(s) = \frac{R_5\left(\frac{1}{j\,\omega C_1}\right)(\left(\frac{1}{j\,\omega C_3}\right)}{R_2 R_4} \tag{3.11}$$

combining the Eqs. (3.10) and (3.11), it is obtain that

$$D = \frac{R_2 R_4 C_1 C_3}{R_5} \tag{3.12}$$

which means the magnitude of the impedance may be directly set to any value choosing R and C element. Eq. (3.11) is sketched versus frequency in Fig. (3.7).

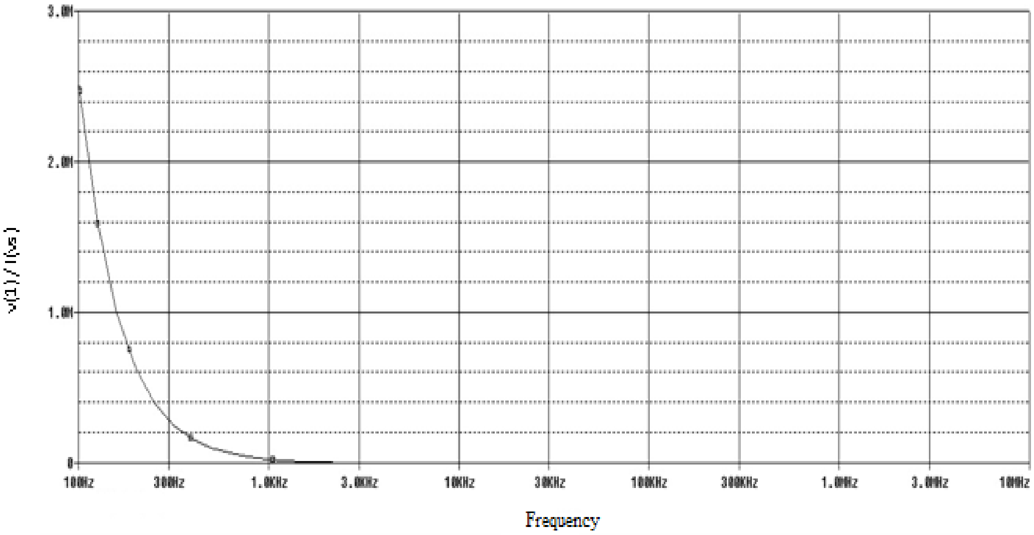

Figure 3.7 Impedance vs frequency of FDNR

The SPICE simulation of FDNR is given in Table 3.1.

Table 3.1 FDNR with RC element

```
* connections:   non-inverting input
*                | inverting input
*                | | positive power supply
*                | | | negative power supply
*                | | | | output
*                | | | | |
.subckt ad741    1 2 3 4 5
c1   11 12 2.645E-12
c2    6  7 30.00E-12
dc    5 53 dy
de   54  5 dy
dlp  90 91 dx
dln  92 90 dx
dp    4  3 dx
egnd 99  0 poly(2),(3,0),(4,0) 0 .5 .5
fb    7 99 poly(5) vb vc ve vlp vln 0 16.32E6 -1E3 1E3 16E6 -16E6
ga    6  0 11 12 188.5E-6
gcm   0  6 10 99 5.961E-9
```

Table 3.1 *Continued*

```
iee  10  4 dc 15.16E-6
hlim 90  0 vlim 1K
q1   11  2 13 qx
q2   12  1 14 qx
r2    6  9 100.0E3
rc1   3 11 5.305E3
rc2   3 12 5.305E3
re1  13 10 1.837E3
re2  14 10 1.837E3
ree  10 99 13.19E6
ro1   8  5 45
ro2   7 99 65
rp    3  4 18.16E3
vb    9  0 dc 0
vc    3 53 dc 1
ve   54  4 dc 1
vlim  7  8 dc 0
vlp  91  0 dc 25
vln   0 92 dc 25
.model dx D(Is=800.0E-18)
.model dy D(Is=800.00E-18 Rs=1m Cjo=10p)
.model qx NPN(Is=800.0E-18 Bf=93.75)
.ends
vs 1 0 AC 1
R2 2 3 10k
R4 4 5 10k
R5 5 0 10k
C1 1 2 10E-9
C3 3 4 10E-9
* nodelist name
x3 1 3 va vb 2 ad741
x4 5 3 va vb 4 ad741
VCC va 0 DC 12
VEE vb 0 DC -12
.AC DEC 10 100Hz 10000kHz
.PROBE
.END
```

The low sensitivity to component tolerance is an important advantage of FDNR. The FDNR filter advantage in more circles is that there are no op-amps in direct signal path, which can add noise and or disfiguration, while it is small to the signal. It is also comparatively insensitive to component variation. These advantages of the FDNR filter come at the expense of increasing in number of components are desired [24] and [25].

3.4 FDNR with RC Element and Oscillator

Oscillators are very important part of many electronic circuits. They are used to produce time varying signals. These circuits are excited by DC signal and they give sinusoidal, square, triangle, and some other wave shapes. Depending on the operation frequency of these devices, the element used in circuit should have special types and values. For example at very high frequencies inductor and capacitor pairs are required but considerably lower frequencies active RC or FDFNR structures may be used. Another important application of the FDNR is oscillator. For example, the circuit given in Fig. (3.8) represents a simple oscillator. If $V_{in}(t)$ is the impulse function as

$$V_{in}(t)=\delta(t) \tag{3.13}$$

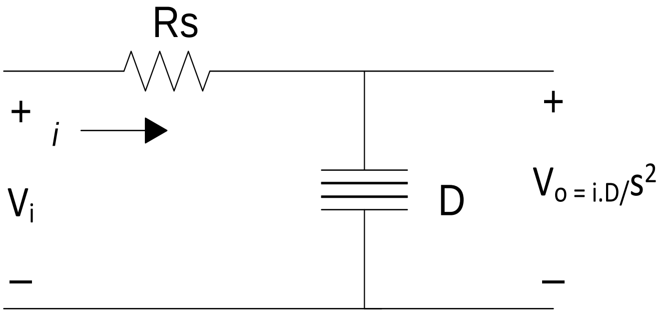

Figure 3.8 FDNR with oscillator

the output voltage in s domain becomes

$$V_o = i.\frac{D}{s^2} = \frac{D}{s^2+D} \tag{3.14}$$

and its inverse Laplace transformation results as

$$V_o(t) = D\, sin \sqrt{D}\, t \tag{3.15}$$

Since D is function of R and C in Fig. (3.6), the resonance frequency and the amplitude of the oscillator may be adjusted easily.

To determine some properties of FDNR real nagative values for s = jω, it is potentially unstable networks. Let us consider the structure of FDNR shown in Fig. (3.9) is driven by the impluse source. The realization of FDNR is written as

Z1(s) =$Z_1(s) = \frac{1}{sC_1}$,$Z_2(s) = R_2$,$Z_3(s) = \frac{1}{sC_3}$,$Z_4(s) = R_4$ and $Z_5(s) = R_5$.

$$Y(s) = \frac{\mathrm{I(s)}}{V(s)} = s^2 D \tag{3.16}$$

$$Y(j\omega) = -\omega^2 D \tag{3.17}$$

$$\omega_o = \sqrt{\frac{R_5}{R_s R_2 R_4 C_1 C_3}} \tag{3.18}$$

$$D = \frac{R_2 R_4 C_1 C_3}{R_5} \tag{3.19}$$

Consider the case where C_1= C_3= 0.01μF and R_2= R_4= R_5 = R_s = 10KΩ. For the values we found D = 10^{-12} Fs and ω_o = 10^4 rad / s.

Active RC FDNR with oscillator circuit and the wave obtained from the circuit are shown in Fig. (3.9), Fig. (3.10) and Fig. (3.11), respectively .

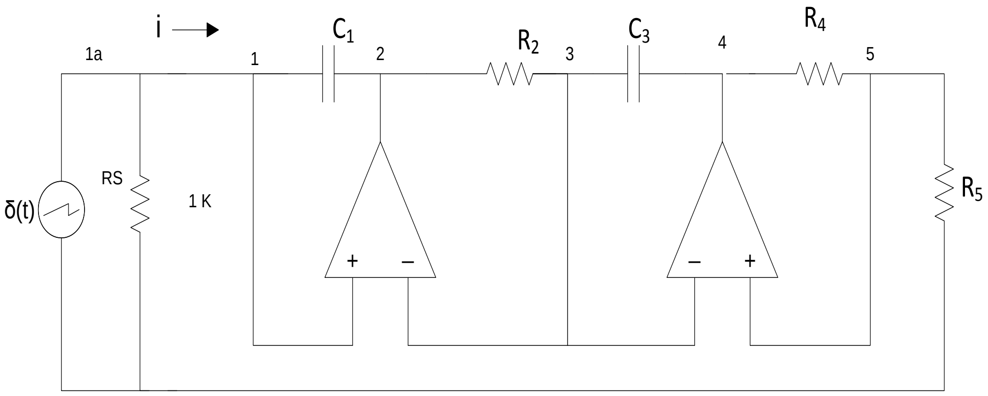

Figure 3.9 The structure of RC FDNR with oscillator

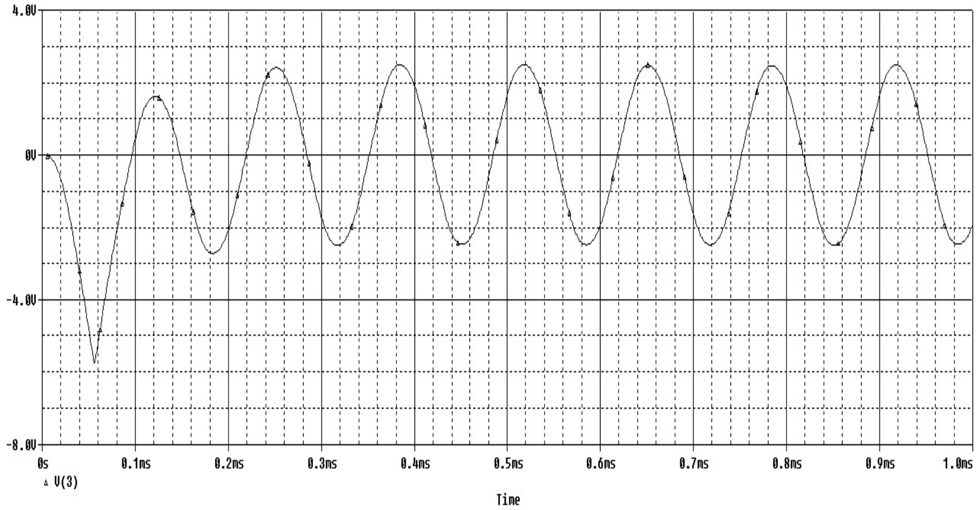

Figure 3.10 The Voltage at node 3

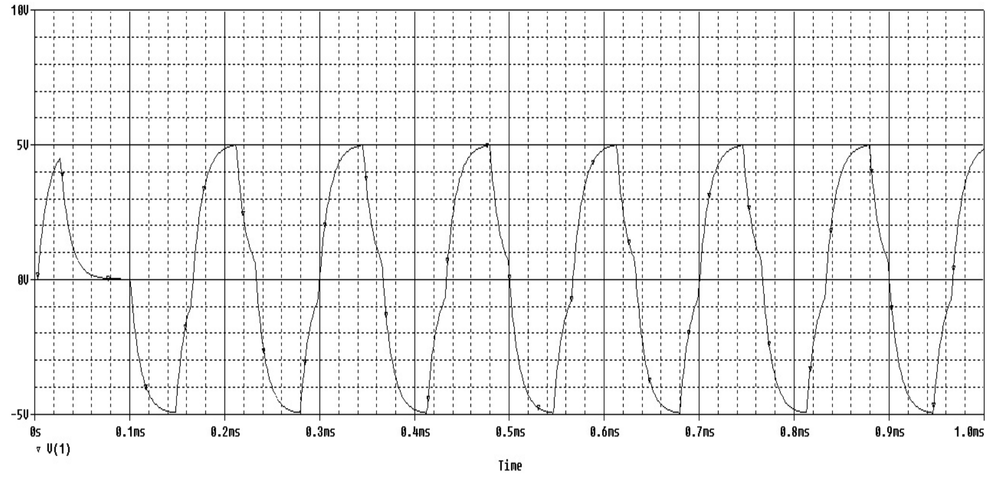

Figure 3.11 Voltage at node 1

The SPICE simulation of Oscillator with FDNR is given in Table 3.2

Table 3.2 Oscillator with FDNR with RC element

```
* connections:   non-inverting input
*               | inverting input
*               | | positive power supply
*               | | | negative power supply
*               | | | | output
*               | | | | |
.subckt ad741    1 2 3 4 5
  c1   11 12 2.645E-12
  c2    6  7 30.00E-12
  dc    5 53 dy
  de   54  5 dy
  dlp  90 91 dx
  dln  92 90 dx
  dp    4  3 dx
  egnd 99  0 poly(2),(3,0),(4,0) 0 .5 .5
  fb    7 99 poly(5) vb vc ve vlp vln 0 16.32E6 -1E3 1E3 16E6 -16E6
  ga    6  0 11 12 188.5E-6
  gcm   0  6 10 99 5.961E-9
  iee  10  4 dc 15.16E-6
  hlim 90  0 vlim 1K
  q1   11  2 13 qx
  q2   12  1 14 qx
  r2    6  9 100.0E3
  rc1   3 11 5.305E3
  rc2   3 12 5.305E3
  re1  13 10 1.837E3
  re2  14 10 1.837E3
  ree  10 99 13.19E6
  ro1   8  5 45
  ro2   7 99 65
  rp    3  4 18.16E3
  vb    9  0 dc 0
  vc    3 53 dc 1
  ve   54  4 dc 1
  vlim  7  8 dc 0
  vlp  91  0 dc 25
  vln   0 92 dc 25
.model dx D(Is=800.0E-18)
.model dy D(Is=800.00E-18 Rs=1m Cjo=10p)
.model qx NPN(Is=800.0E-18 Bf=93.75)
.ends
```

Table 3.2 *Continued*

```
vs 1a 0 pulse(0 0.5m 0 1u 1u 1u)
RS 1 0 1k
R2 2 3 10k
R4 4 5 10k
R5 5 0 10k
C1 1 2 10E-9
C3 3 4 10E-9
* nodelist name
x3 1 3 va vb 2 ad741
x4 5 3 va vb 4 ad741
VCC va 0 DC 12
VEE vb 0 DC -12
.TRAN 1us 1ms 0s 1us
.PROBE
.END
```

In this chapter the active RC filter presented and it is role in analog and digital communication circuit. We also presented the type of RC circuit and it is transfer function with the band width and cut off frequency in the subsequent section. The active RC circuit used for the realization of the FDNR is given which is highly important for the realization of oscillator.

The biquadratic filter presented in this chapter realizes the second order denominator and numerator which show LP, HP and BP gains of three different outputs of operational amplifiers. In both applications, the circuits contain only R and C elements and op.amp as an active component.

In some applications, the stray capacitance of capacitor may be the cause of the generation of the noise. Therefore, it may be better choice to realize the circuit as fully integrated used op-amps and resistance. It can be obtained by changing the capacitors by equivalent semi-conductor structure like memristor. Hence, the value of the capacitance may be controlled by the bias voltage applied to the memristor.

In the next chapter, the identification of the memristor will be presented and it is terminal equations will be given to make the analysis of the active R-memristor active filters and R-memristor FDNR circuits possible.

CHAPTER IV

R-MEMRISTOR (R-M) ACTIVE CIRCUITS

4.1 Introduction

The definition of memristor has been presented in Chapter 2. It is an electronic component to retain its resistance level even after power had been shut down or lets it remember the last resistance it had before being shut off. A memristor device can be used in both analog and digital circuit [8]. Memristor can be programmed or switched to different resistance states based on history of the voltage applied to the memristance material. This phenomena can be understood graphically in the relationship between the current flowing through memristor and voltage applied to it.

In literature, many different circuits are presented for many different purposes. In general the systems used in the communication systems (filters, modulators, etc…) include well-known components such as resistors, capacitors, inductors, transistors.

Since in the last years the fully integration of the circuit is important as well as uniqueness of the component of the circuit, some component such as inductors or resistors are replaced with their equivalent semi-conductors structures. In this chapter we will present the active biquadratic filter using memristor in structure instead of RC elements. The simulation will be programmed by using SPICE model.

The biquadratic RC filter is chosen because of it is flexible modification feature to different problems. It may be used as the building block of the higher order networks. It may also be used as different kinds of filters changing only output terminal.

As the second important application, frequency dependent negative resistance realization is studied. Because of its characteristics which may be changed by the frequency of the signal apuly on it, it may be used as frequency magnitude convertor circuits, as oscillators, as demodulator circuits.

The realization type of the network is important not only because of the availability of the component but also the power consumption of the networks. It has been shown that the memritors are low power consuming semi-conductor structures and replacement of the some resistors with memristors reduces the cost of energy of the system.

4.2 R-M Active Biquadratic Filter

Active filters are implemented by using passive and active (amplifying) components. To set the operation point of the semi-conductors components, dc biasing voltage must be applied and it means for active filters, in addition to information carrying input, it is necessary to use externally connected dc sources. Op-amps are widely used in active filter designs. These can have high quality factor and it can realize resonance without using of inductors. While, their maximum frequency limit is limited by the bandwidth of the amplifiers used.

The all type mentioned filters offer only one filter response while state variable filter (KHN) offers three filter responses simultaneously. However, performance of these filter circuit using active circuit (Op-Amp) is limited due to lower gain-bandwidth product and higher supply voltage.

The memristor makes the filter adaptive, which means the main characteristics such as frequency, bandwidth, and gain can be altered by means of changing the memristance value. By using the memristor device with this type of filter leads not only to decrease circuit size, but also make it possible to get higher reconfigurable filters [26]. One of the popular circuit used to realize a second order filter is Kerwin-Huelsman-Newcomb (KHN) filter as discussed in previous chapter. This realization offers low pass, high pass and band pass outputs simultaneously in one design [27]. The filter realizations may be considered to be novel as the most proposed filters having same Q and ω_0 available from the realization of biquadratic structure.

In this section, properties of memristor based biquadratic filter will be given using op-amp on filter response and to support quicker design cycles. The memristor is coded in SPICE as shown in Table (4.1).

Table 4.1 SPICE sub circuit model for memristor

```
* nodelist name
.SUBCKT MEMRISTOR 1 2 6
Eres 1 9 poly(2) (8,0) (10,0) 1
vsens 9 4 Dc 0v
Fcopy 0 8 vsens 1
Rstep 8 0 1k
Rser 2 4 10
Gmem 6 0 0 8 1
Cmem 6 0 10nf
Ecpx 10 0 6 0 1
Rsp 6 0 10E6
.ENDS
vs 1 0 AC 1
vd 4 0 DC 0.5
R1 2 0 1k
R2 4 6 1G
```

Table 4.1 *Continued*

```
* nodelist name
x 1 2 6 memristor
.AC DEC 20 100Hz 100kHz
.PROBE
.END
```

Hysteresis i–v relation current i, and voltage v, of memristor is plotted parametrically in Fig. (4.1). they also plotted verses time in Fig.(4.2).

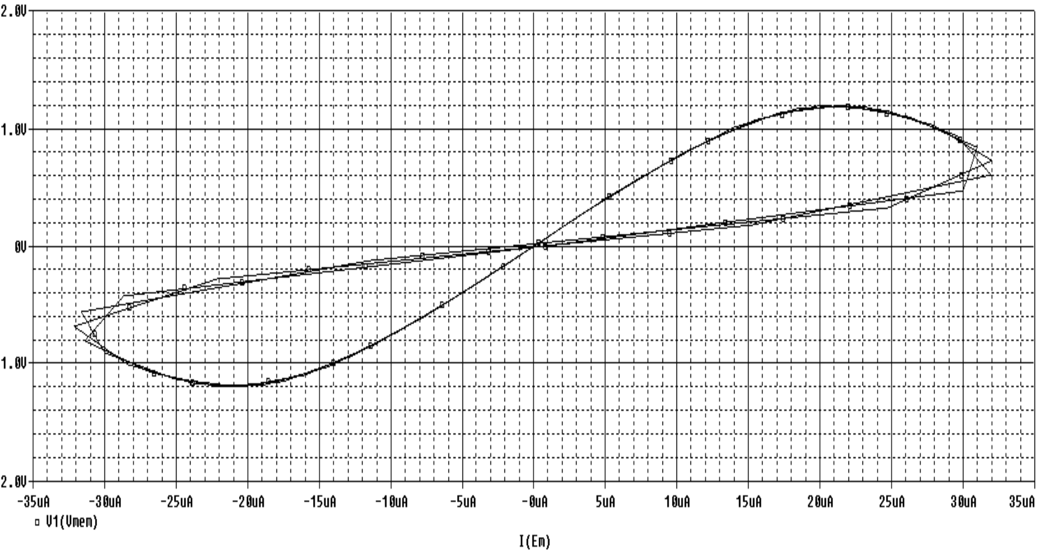

Figure 4.1 i-v curve of memristor

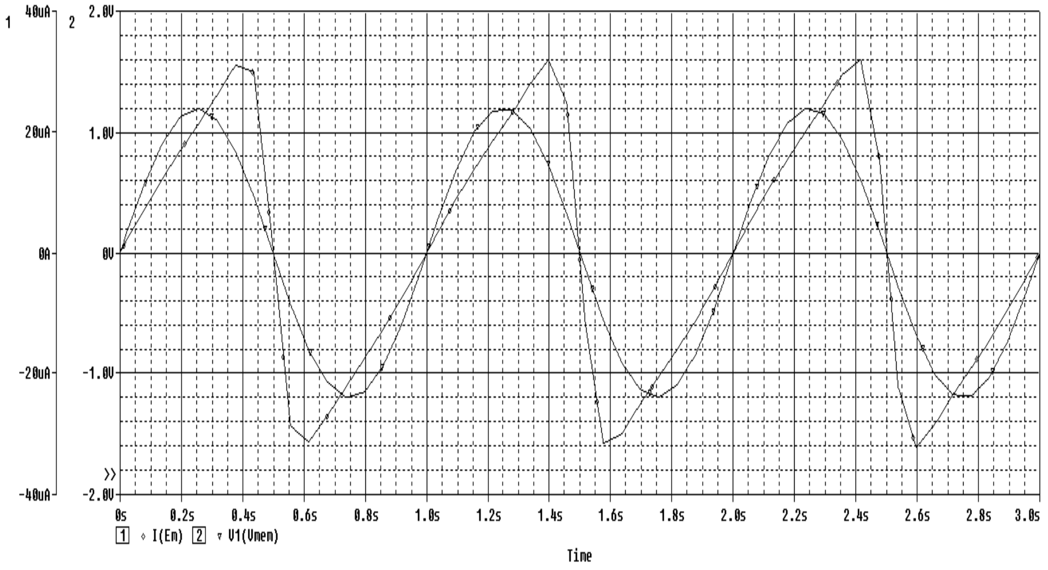

Figure 4.2 Voltage and current variation of memristor

To simulate the biquadratic filter we use the structure of the circuit shows in Fig. (4.3). The structure is divided into three parts as lossy integrator, integrator and inverter. SPICE model of memristor is used to convert RC Op-amp circuit given in Fig. (4.3) into R-M Op-amp circuit which is presented in Fig. (4.4).

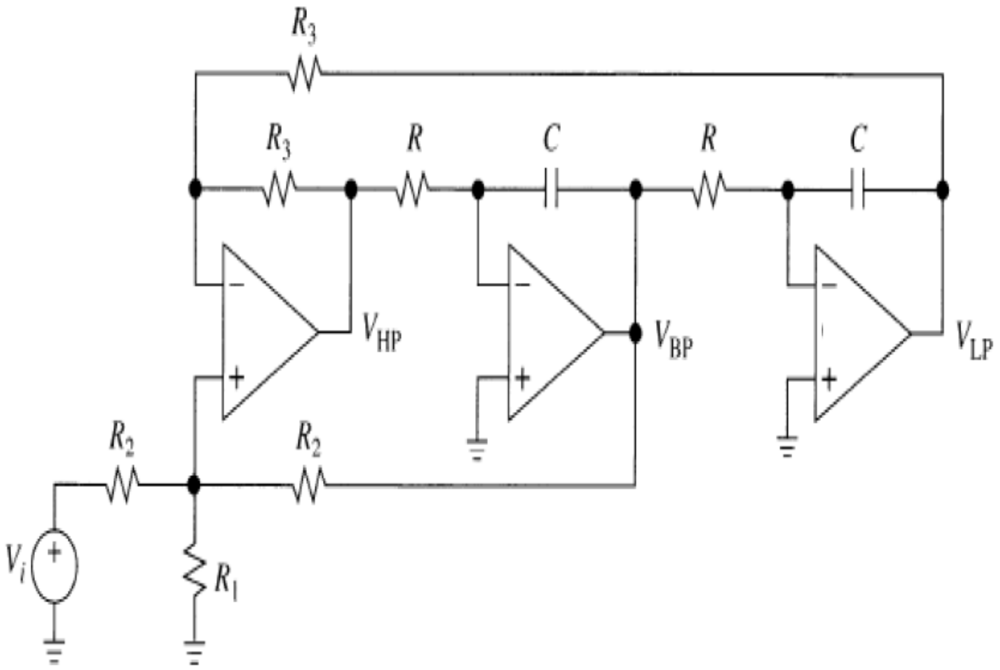

Figure 4.3 The biquadratic filter with RC element

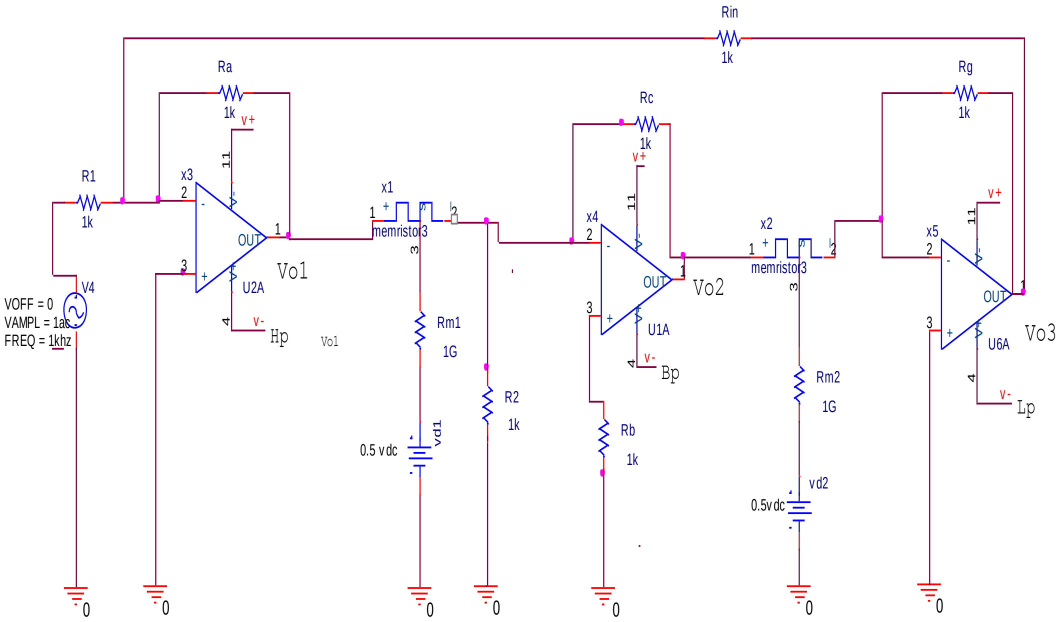

Figure 4.4 Circuit diagram of biquadrate filter based on memristor

Since the current voltage relation of the memristor is non-linear and dynamic, the terminal equations obtained from the circuit given in Fig. (4.4) are derived as follows

$$\frac{Vin}{R_1}+\frac{V_{o1}}{R_a}+\frac{V_{o3}}{R_{in}}=0 \tag{4.1}$$

$$V_{o2}=R_c.f(-V_{o1}) \tag{4.2}$$

$$V_{o3}=R_g.f(-V_{o2}) \tag{4.3}$$

$$V_{o3}=R_g.f[-R_C-f(V_{o1})] \tag{4.4}$$

Then $\frac{\mathrm{V_{o1}}}{\mathrm{V_{in}}}$ is HP case and the transfer function becomes:-

$$\frac{\mathrm{Vin}}{\mathrm{R1}}+\frac{\mathrm{V_{o1}}}{\mathrm{R_a}}+\frac{1}{\mathrm{R_{in}}}[\mathrm{R_g}.\mathrm{f}[-\mathrm{R_c}\mathrm{f}(-\mathrm{V_{o1}})]=0 \tag{4.5}$$

As it is obvious, this circuit contains only op-amps, resistor and memristor. The simulated circuit is forced by sinusoidal input for different frequencies and the gains of three types of filters (LP, HP and BP) are obtained and sketched in Fig. (4.5).

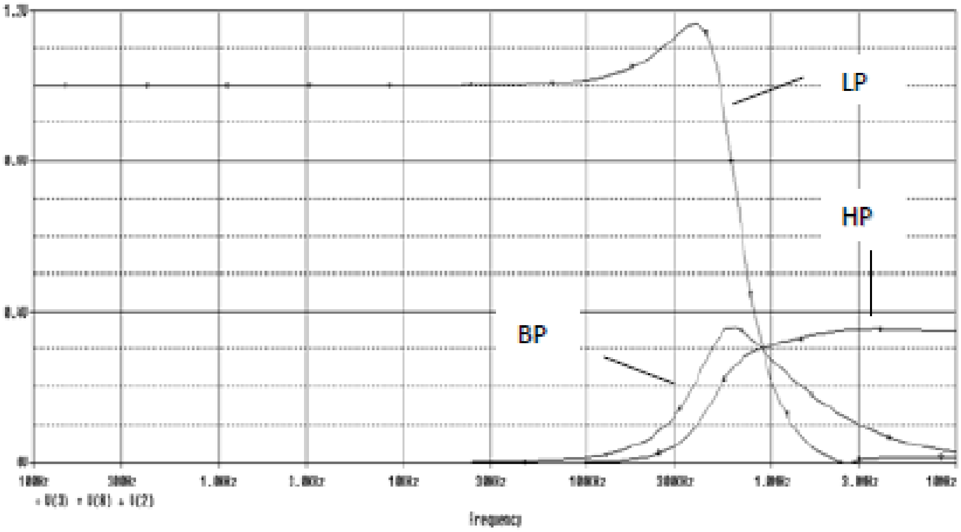

Figure 4.5 The gain of LP, HP and BP for given biquatratic

The characteristics of the gain curves can be adjusted by either changing the resistors or the parameters of the memristors changing the biasing conditions of them. Fig 4.5 is obtained using the given resistance values as in Fig. (4.4), and the spice code of memristor is parameters are given in Table. (4.1).

It can be noted that the 3 dB cut off frequency for LP case is 640 KHz. If the same circuit is used as BP filter taking output from Vo_2, the center frequency of the filter ω_o become 2πx600 rad/sec and quality factor Q become 0.88 KHz, the cutoff frequencies become $\omega_{c1} = 2\pi x425 \text{ rad/sec}$ and $\omega_{c2} = 2\pi x1100 \text{ rad/sec}$, the bandwidth becomes $\omega_{c2} - \omega_{c1} = 2\pi x675 \text{ rad/sec}$ for the given element characteristic .

Table 4.2 SPICE code for R-M active biquadratic filter

```
* name   nodelist
.SUBCKT MEMRISTOR 1 2 6
Eres 1 9 poly(2)(8,0) (10,0) 1
vsens 9 4 Dc 0v
Fcopy 0 8 vsens 1
Rstep 8 0 1k
Rser 2 4 10
Gmem 6 0 0 8 1
Cmem 6 0 10nf
Ecpx 10 0 6 0 1
Rsp 6 0 10E6
 .ENDS
* connections:   non-inverting input
*               | inverting input
*               | | positive power supply
*               | | | negative power supply
*               | | | | output
*               | | | | |
.subckt ad741    1 2 3 4 5
*
  c1   11 12 2.645E-12
  c2    6  7 30.00E-12
```

Table 4.2 *Continued*

```
  dc    5 53 dy
  de   54  5 dy
  dlp  90 91 dx
  dln  92 90 dx
  dp    4  3 dx
  egnd 99  0 poly(2),(3,0),(4,0) 0 .5 .5
  fb    7 99 poly(5) vb vc ve vlp vln 0 16.32E6 -1E3 1E3 16E6 -16E6
  ga    6  0 11 12 188.5E-6
  gcm   0  6 10 99 5.961E-9
  iee  10  4 dc 15.16E-6
  hlim 90  0 vlim 1K
  q1   11  2 13 qx
  q2   12  1 14 qx
  r2    6  9 100.0E3
  rc1   3 11 5.305E3
  rc2   3 12 5.305E3
  re1  13 10 1.837E3
  re2  14 10 1.837E3
  ree  10 99 13.19E6
  ro1   8  5 45
  ro2   7 99 65
  rp    3  4 18.16E3
  vb    9  0 dc 0
  vc    3 53 dc 1
  ve   54  4 dc 1
  vlim  7  8 dc 0
  vlp  91  0 dc 25
  vln   0 92 dc 25
.model dx D(Is=800.0E-18)
.model dy D(Is=800.00E-18 Rs=1m Cjo=10p)
.model qx NPN(Is=800.0E-18 Bf=93.75)
.ends
vs 1 0  AC 1
vd1 4 d1 DC 0.5
vd2 7 d2 DC 0.5
R1 1 2  1k
R2 4 0  1k
Ra 2 3  1k
Rc 4 6  1k
Rb 5 0  1k
Rg 7 8  1k
Rm1 d1 0 1G
Rm2 d2 0 1G
```

Table 4.2 *Continued*

```
Rin 2 8 1k
* nodelist name
x1 3 4 vd1 memristor
x2 6 7 vd2 memristor
x3 0 2 va vb 3 ad741
x4 5 4 va vb 6 ad741
x5 0 7 va vb 8 ad741
VCC va 0 DC 12
VEE vb 0 DC -12
.AC DEC 20 100Hz 10000kHz
.PROBE
.END
```

4.3 R-M Active FDNR

Bruton’s elegant method of inductorless filter design using the concept of FDNR is well known[27] where a time continuous filter is mandatory, various topologies are available, such a Sallen and Key, KHN, Rausch, etc. The transfer function of the circuit including energy storage elements such as inductors and capacitors are in form of ratios of the s-polynomials. The coefficients of the transfer function are the functions of R, L and C values. If all impedances in the circuit are divided by “s”, the transfer function does not change, but the element types change.

After division, resistor becomes capacitor, inductor becomes resistor and capacitor becomes a new component with impedance of 1/s^2, namely FDNR. FDNR is two terminal elements which show voltage- current relation as in Eq. (4.6).

$$v = \frac{D}{(j\omega)^2} i \tag{4.6}$$

The inductorless active networks are also named as RCD structures it is widely used in area of communication systems. In this section we will present R-M active

FDNR by using memristor in the structure instead of C and D in the circuit .In the literature, the realization of FDNR is given by using RCD Op-amp structures. SPICE model replacement of D converts the FDNR circuit into R-memristor Op-amp circuit form and it is shown in Fig. (4.6). The impedance of FDNR verses frequency is given in Fig. (4.7).

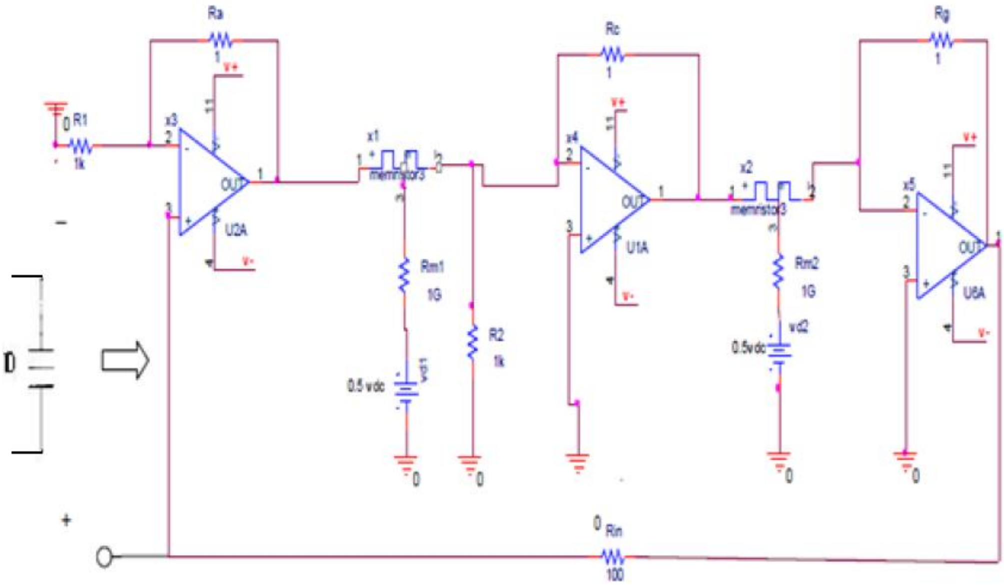

Figure 4.6 FDNR structure using memristor

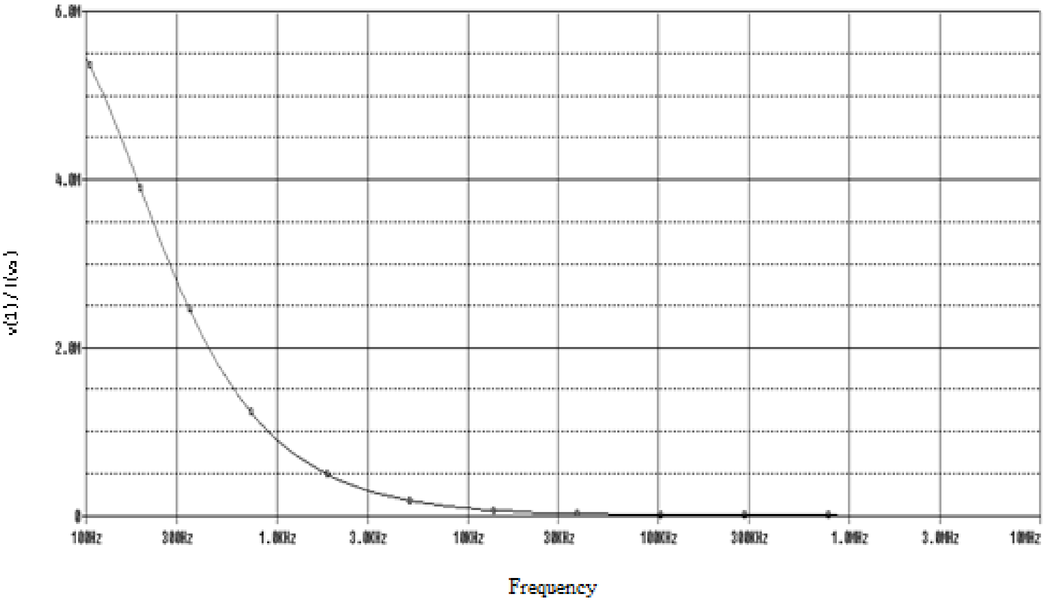

Figure 4.7 The impedance of FDNR using memristor in structure.

Table 4.3 SPICE code for R-M active FDNR

```
* name   nodelist
.SUBCKT MEMRISTOR 1 2 6
Eres 1 9 poly(2)(8,0) (10,0) 1
vsens 9 4 Dc 0v
Fcopy 0 8 vsens 1
Rstep 8 0 1k
Rser 2 4 10
Gmem 6 0 0 8 1
Cmem 6 0 10nf
Ecpx 10 0 6 0 1
Rsp 6 0 10E6
 .ENDS
* connections:   non-inverting input
*                | inverting input
*                | | positive power supply
*                | | | negative power supply
*                | | | | output
*                | | | | |
.subckt ad741    1 2 3 4 5
*
  c1   11 12 2.645E-12
  c2    6  7 30.00E-12
  dc    5 53 dy
  de   54  5 dy
  dlp  90 91 dx
  dln  92 90 dx
  dp    4  3 dx
  egnd 99  0 poly(2),(3,0),(4,0) 0 .5 .5
  fb    7 99 poly(5) vb vc ve vlp vln 0 16.32E6 -1E3 1E3 16E6 -16E6
  ga    6  0 11 12 188.5E-6
  gcm   0  6 10 99 5.961E-9
  iee  10  4 dc 15.16E-6
  hlim 90  0 vlim 1K
  q1   11  2 13 qx
  q2   12  1 14 qx
  r2    6  9 100.0E3
  rc1   3 11 5.305E3
  rc2   3 12 5.305E3
  re1  13 10 1.837E3
  re2  14 10 1.837E3
  ree  10 99 13.19E6
  ro1   8  5 45
  ro2   7 99 65
  rp    3  4 18.16E3
```

Table 4.3 *Continued*

```
  vb    9  0 dc 0
  vc    3 53 dc 1
  ve   54  4 dc 1
  vlim  7  8 dc 0
vlp  91  0 dc 25
  vln   0 92 dc 25
.model dx D(Is=800.0E-18)
.model dy D(Is=800.00E-18 Rs=1m Cjo=10p)
.model qx NPN(Is=800.0E-18 Bf=93.75)
.ends
vs 1 0  AC 1
vd1 4 d1 DC 0.5
vd2 6 d2 DC 0.5
R1 1 2  1
Ra 2 3  1
Rb 4 5  1
Rg 6 7  1
Rm1 d1 0 1G
Rm2 d2 0 1G
Rin 7 8 10
* nodelist name
x1 3 4 vd1 memristor
x2 5 6 vd2 memristor
x3 8 2 va vb 3 ad741
x4 0 4 va vb 5 ad741
x5 0 6 va vb 7 ad741
VCC va 0 DC 12
VEE vb 0 DC -12
.AC DEC 10 100Hz 10000KHz
.PROBE
.END
```

4.4 R-M Active Oscillator

Oscillators are circuits which produce specific, periodic waveforms such as square, sinusoidal, sawtooth, and triangular. They generally use some form of active device, lamp, or crystal, surrounded by passive devices such as resistors, capacitors, and inductors to generate the output.

There are two main classes of oscillators namely relaxation oscillator and sinusoidal oscillator. Relaxation oscillators generate the triangular, saw tooth and other non-sinusoidal waveforms and will not be discussed in this study. Sinusoidal oscillators consist of amplifiers with external components used to generate oscillation, or crystals that internally generate the oscillation [29]. The focus here is on sine wave oscillators created using operational amplifiers resistors and memristors used instead of capacitors.

An oscillator realization using the concept of FDNR was first proposed by Genin [28] and since then the approach has been used many times for the realization/analysis of single resistance-controlled sine wave oscillators [27].

R-memristor sinusoidal oscillators have adjustable oscillation frequencies, or the crystals that have a fixed oscillation frequency.

Op-amp sine-wave oscillators operate without an externally-applied input signal. Instead, some combination of positive and negative feedback is used to drive the Op-amp into an unstable state causing the output to cycle back and forth between the supply rails at a continuous rate.

The frequency and amplitude of oscillation are set by the arrangement of passive and active components around a central Op-amp. Oscillators do not require an externally-applied input signal; instead, they use some fraction of the output signal created by the feedback network as the input signal. The simplest circuit configuration for the oscillators designed using R and FDNR is given in Fig. (4.8).

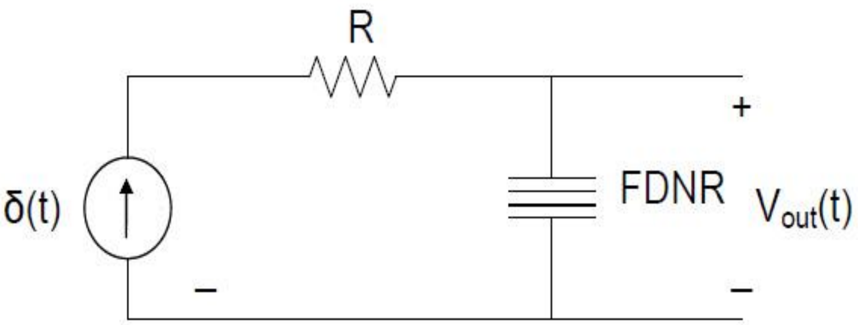

Figure 4.8 FDNR oscillator

The voltage equation for the circuit given in Fig 4.8 is

$$\delta(t) = -i.R - i.\frac{D}{S^2} = 0 \tag{4.8}$$

The solution of Eq. (4.8) is

$$V_o(t) = D \sin \sqrt{D}\, t \tag{4. 9}$$

Since on the realization of FDNR, memristors are used instead of capacitors the overall R-M oscillator circuit is given in Fig. (4.9).

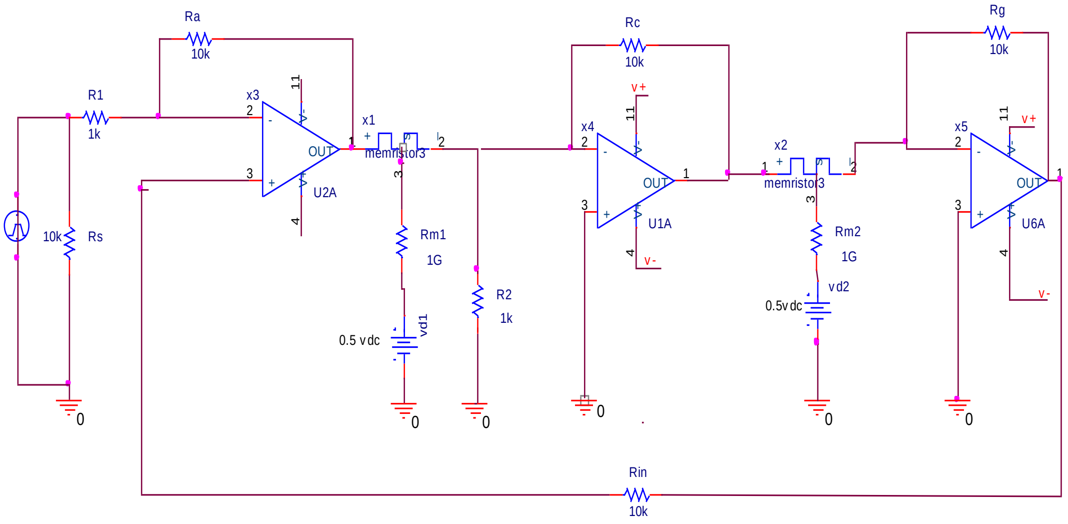

Figure 4.9 R-M active FDNR with Oscillator

Active R-M FDNR with osilator circuit and the wave form obtained from the circuit are shown in Fig. (4.9), Fig. (4.10) and Fig. (4.11), respectively,

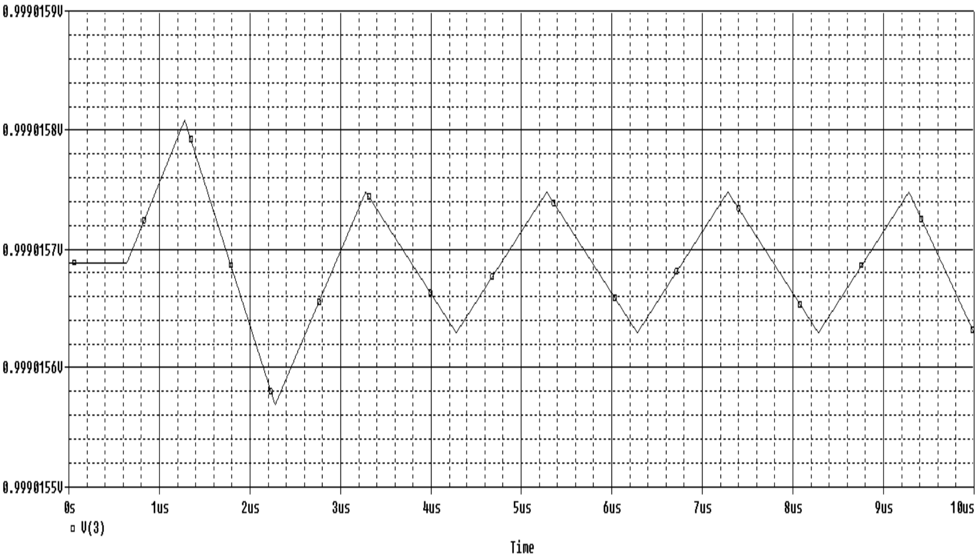

Figure 4.10 Voltage of node 3

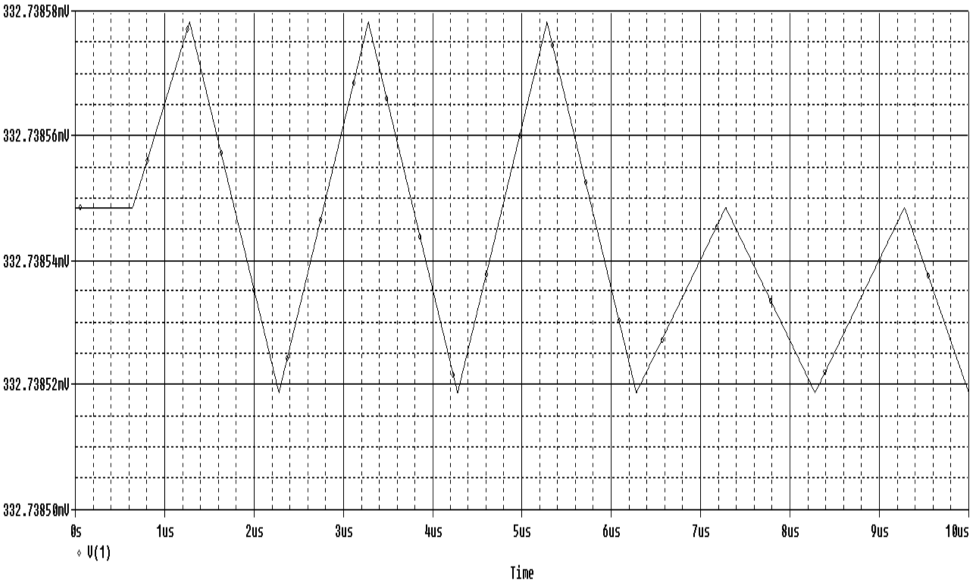

Figure 4.11 Voltage of node 1

Table 4.4 SPICE code for R-M FDNR with Oscillator

```
* name   nodelist
.SUBCKT MEMRISTOR 1 2 6
Eres 1 9 poly(2)(8,0) (10,0) 1
vsens 9 4 Dc 0v
Fcopy 0 8 vsens 1
Rstep 8 0 1k
Rser 2 4 10
Gmem 6 0 0 8 1
Cmem 6 0 10nf
Ecpx 10 0 6 0 1
Rsp 6 0 10E6
 .ENDS
* connections:   non-inverting input
*                | inverting input
*                | | positive power supply
*                | | | negative power supply
*                | | | | output
*                | | | | |
.subckt ad741    1 2 3 4 5
*
  c1   11 12 2.645E-12
  c2    6  7 30.00E-12
  dc    5 53 dy
  de   54  5 dy
  dlp  90 91 dx
  dln  92 90 dx
  dp    4  3 dx
  egnd 99  0 poly(2),(3,0),(4,0) 0 .5 .5
  fb    7 99 poly(5) vb vc ve vlp vln 0 16.32E6 -1E3 1E3 16E6 -16E6
  ga    6  0 11 12 188.5E-6
  gcm   0  6 10 99 5.961E-9
  iee  10  4 dc 15.16E-6
  hlim 90  0 vlim 1K
  q1   11  2 13 qx
  q2   12  1 14 qx
  r2    6  9 100.0E3
  rc1   3 11 5.305E3
  rc2   3 12 5.305E3
  re1  13 10 1.837E3
  re2  14 10 1.837E3
  ree  10 99 13.19E6
  ro1   8  5 45
  ro2   7 99 65
  rp    3  4 18.16E3
```

Table 4.4 *continued*

```
vb    9  0 dc 0
 vc    3 53 dc 1
 ve   54  4 dc 1
 vlim  7  8 dc 0
  vlp  91  0 dc 25
 vln   0 92 dc 25
model dx D(Is=800.0E-18)
.model dy D(Is=800.00E-18 Rs=1m Cjo=10p)
.model qx NPN(Is=800.0E-18 Bf=93.75)
Ends

Vs 1a 0 PULSE(0V 10V 0s 100ms 100ms 900ms 10s)
RS 1 0 10k
vd1 4 d1 DC 0.5
vd2 6 d2 DC 0.5
R1 1 2 10k
Ra 2 3  10k
Rc 4 5  10k
Rg 6 7  10k
Rm1 d1 0 1G
Rm2 d2 0 1G
Rin 7 8 10k
* nodelist name
x1 3 4 vd1 memristor
x2 5 6 vd2 memristor
x3 8 2 va vb 3 ad741
x4 0 4 va vb 5 ad741
x5 0 6 va vb 7 ad741
VCC va 0 DC 12
VEE vb 0 DC -12
.TRAN 1us 0.01ms 0s 1us
.PROBE
.END
```

CHAPTER V

CONCLUSIONS

In the last decade, improvement in the semiconductor technology forced the scientists to realize the circuits without inductors .The basic circuit parameters such as current, voltage, flux and charge are related to each other by using the well known theorems and laws. The dependence of these parameters are formulated as the terminal equations, for example, for electronic applications the Ohm’s law is defined as the linear variation of the voltage and current of the component with tangent R, namely resistance. Gauss law is used to relate the charge and voltage and linear and linear dependence is represented by capacitor.

Nowadays, the parameters relating the flux and charge is defined and their relation as represented by memristor. The terminal equation of memristor shows that the relation is not linear and its hysteresis reveals that this relation has memory property. The employment of the memristor in active circuit design reduces the complexity of the circuit and it has been reported in some paper that they give superior behaviors from power consumption point of view.[9-20]

In this work, the SPICE model of the memristor is given. In the design of more complicated circuits, the SPICE simulation is possible and the proposed memristor model is embedded in to these more complex circuits. To show the validity of the model, memristor simulation is used in design of biquadratic active filters, frequency dependent negative resistors, and oscillators.

The simulation results have shown that the replacement of the capacitors by memristor make the controllability of these circuits easier. We believe that the memristors can be used to design of some non linear communication systems.

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