CHAPTER – 8
CONCLUSION
This thesis presents design and synthesis of signal processing and generating circuits using OTRA, a current mode analog building block of relatively recent origin. In this chapter a summary of the major conclusions of the work reported in various chapters of the thesis are presented.

8.1 SUMMARY OF WORK PRESENTED IN THIS THESIS

The introductory chapter presents a short note on evolution of current mode signal processing, its advantages and a brief review of various current mode analog building blocks that emerged for analog electronic design. A review of earlier work on signal processing and generation circuits using OTRA has also been presented in this chapter.

A detailed study of the OTRA has been presented in chapter 2. The ideal OTRA, its nullor based model, the effect of nonidealities on ideal circuit model and the OTRA realizations available in literature have been reviewed. The CMOS OTRA implementation presented in [30] is discussed and characterized using SPICE to validate its functionality. This OTRA configuration is used to verify the workability of the circuit structures proposed in this study. Few basic circuit applications of the OTRA such as voltage amplifiers, adder, subtractor, and integrator, which can be readily used as plug-in modules wherever needed, are also described. In OTRA based circuits, how passive resistor can be implemented using MOSFETs is discussed in concluding section which not only makes circuits suitable from integration viewpoint but also introduces electronic tunability in the circuit. Chapters 3 to 7 present the research contribution of this study.

In chapter 3 design of lossy and lossless active grounded inductance simulator topologies have been dealt with. A brief review of existing literature in the area has been presented first followed by the design of a lossy inductance topology based on single OTRA, two lossless inductor topologies using two OTRAs and yet another lossless inductor based on a single OTRA. The proposed lossy inductor can realize ± L parallel with R. It uses a single OTRA, two resistors and two virtually grounded capacitors. The two OTRA based topologies presented use five resistors and one capacitor apart from OTRAs and for both the topologies the inductance value can be controlled independent of condition of realization. The next
The design structure discussed is a new grounded simulated inductor topology based on single OTRA, three resistors and two capacitors. It provides non interactive control between inductance value and realizability condition. For the proposed topologies effect of nonidealities associated with OTRA has also been taken into consideration. The workability of all these structures is verified through SPICE simulations. The lossy inductor topology is simulated using CFOA based realization of OTRA whereas the lossless inductor topologies are simulated using the CMOS implementation of the OTRA. To demonstrate the practical use of the proposed topologies few applications have been realized using component replacement technique. The theoretical propositions are also verified through experimental results wherein OTRA is realized using ICs AD844.

Realization of OTRA based biquadratic and higher order filters is presented in chapter 4. A brief record of earlier work dealing with the filter design using OTRA is also presented. The work reported in this chapter has been classified as single and multi amplifier filters. For the applications having power consumption as an important design constraint, single active element based (SAB) filter is a useful choice. In this work, single OTRA based two biquadratic filter topologies are presented which can realize the LP, HP, and BP filter functions by appropriate admittance selection. The first configuration is based on Sallen Key approach whereas the second configuration is based on multiple feedback topology. High $Q_0$ realization with moderate component spread is possible through first topology which also provides independent adjustment of $\omega_0$ and $Q_0$. SABs are less versatile and more sensitive to parameter changes when compared to multi amplifier filters. This led to design of multi amplifier configurations which are further categorised as biquads and higher-order filters. Review of earlier work suggested that no OTRA based structure that provided all five standard responses simultaneously was available. To fill this gap a biquadratic universal filter, with simultaneous five outputs, is developed. It exhibits the feature of orthogonal controllability of $\omega_0$ and $Q_0$. The chapter is concluded with wave method based higher order filter design using OTRA. It uses wave equivalents for different passive elements which can be readily substituted in higher order resistively terminated LC ladder to realize a filter. The proposed universal biquad and wave active filter configurations are made fully integrated by implementing the resistors using matched transistors operating in linear region. The
resistance value may be adjusted by appropriate choice of gate voltages thereby making filter parameters electronically tunable. All proposed structures are validated through SPICE simulations. The simulated results closely follow the theoretical propositions. The filter configurations are also analyzed in the light of nonidealities of OTRA.

Chapter 5 deals with sinusoidal signal generation. General scheme of sinusoidal signal generation is discussed in the chapter followed by design description of proposed sinusoidal oscillators. Design of a single phase, a third order quadrature phase and three multiphase sinusoidal oscillators is presented in this chapter. The proposed single phase sinusoidal oscillator uses two OTRAs three resistors and three capacitors. This oscillator circuit provides independent control on frequency and condition of oscillation which are made electronically tunable through MOS implemented resistors. It also supports equal component usage; a preferred choice from integrated circuit implementation viewpoint. The third order quadrature oscillator is designed using two OTRAs four resistors and three capacitors. Frequency and condition of oscillation can be made orthogonal through iterative control and are electronically tunable. The MSO circuits find wide applications in communication, instrumentation and control. Out of three proposed MSOs the first structure utilizes ‘n’ inverting LPFs to produce ‘n’ odd-phase oscillations which are equally spaced in phase and are of equal amplitude. The second configuration uses ‘n’ noninverting LPFs and an inverting amplifier having \( n \geq 3 \), to produce ‘n’ odd or even phase oscillations equally spaced in phase. The third circuit is based on a concept of using an SRCO followed by a phase shifter network. The phase shifter circuit uses (n-1) OTRA based inverting/noninverting LPF blocks to give a total of ‘n’ oscillations. An Automatic Gain Control circuitry (AGC) has also been implemented which helps in the stabilization of the signal amplitude. To analyze the behaviour of the proposed circuits in presence of the parasitics of the OTRA, nonideality analysis is performed for all the proposed structures. Workability of all oscillator circuits is verified through SPICE simulations. The simulated results closely follow the theoretical propositions. The workability of MSO circuits is established experimentally also.

Chapter 6 deals with instrumentation and control applications of OTRA. OTRA based transimpedance instrumentation amplifier (TIA) is proposed as first application. For amplification of signals from current-source transducers TIA is a preferred choice and due to
its very nature of current input and voltage output OTRA is the most suitable ABB for TIM signal processing wherein the current input can be directly processed without conversion to voltage signal. The proposed TIA shows a high 3 dB bandwith which is independent of gain. Its functionality is verified through SPICE simlations. The simulated 3 dB frequency of the amplifier is 10 MHz and is independent of gain. The proposed TIA exhibits a CMRR magnitude of 64.5dB and bandwidth of 10 KHz, independent of gain. The noise performance analysis of the proposed TIA suggests that it also exhibits a high signal-to-noise ratio. The workability of the proposed TIA is tested experimentally also.

In succession, design of feedback controllers based on proportional-integral-derivative (PID) algorithm is presented. Feedback controllers are most popularly used in the process industries, to control various processes satisfactorily, with proper tuning of controller parameters. The proposed analog controllers namely proportional (P), proportional derivative (PD), proportional integral (PI) and proportional derivative and integral (PID) controllers have orthogonally tunable proportional, integral and derivative constants. Functionality of the proposed circuits is verified through SPICE simulations. The effect of the proposed controllers on step response of a second order system is analyzed and their performance is evaluated on the basis of various process parameters. It is observed that PID controller enhances transient as well as steady state response of the system which is in tune with the well established result of control theory.

The effect of OTRA parasitics, on the performance of all proposed applications in this chapter, is also analyzed. For high-frequency applications, compensation methods are employed, to account for the error introduced due to parasitics. All the applications are made fully integrated by implementing the resistors using MOS transistors operating in non-saturation region. This also facilitated electronic tuning of the circuit parameters.

In Chapter 7 nonlinear applications of OTRA are proposed. Realization a VCM circuit having a wide range of frequency of oscillation which can be controlled through an external voltage is presented first. It can provide adjustable amplitude of the triangular wave signal and also provides adjustable sensitivity (Hz per Volts). This circuit can also be used as a general square/triangular waveform generator by grounding the control voltage terminal and
is capable of operating approximately up to 3MHz. An application of the proposed VCM as a compound pulse frequency and width modulator (CPFWM) is illustrated. It uses compound multiplexing technique for multiplexing two channels, carrying analog and digital information respectively. This can be a suitable choice for moderate distance communication such as in local area networks.

Another modulator circuit using a simple modulation scheme is presented next. This scheme uses minimum number of active and passive components wherein the modulating signal is combined with an exponential carrier waveform and compared with a reference. The exponential carrier wave being a non linear signal yields relatively inaccurate PWM signal at lower carrier frequencies as compared to the triangular/saw tooth wave, however, one can trade off accuracy for simplicity depending upon the application.

A four quadrant analog multiplier which can be used for various analog operations such as true RMS conversion, analog division, square and square root computation, voltage controlled amplification, filtering and oscillation is also presented. It does not require any passive element and is suitable for integration. Its application as a squarer and an amplitude modulator is also discussed.

Various performance parameters for analog multiplier are evaluated through SPICE simulations using 0.5 µm CMOS process parameters from MOSIS (AGILENT) and are found in close agreement to theoretical predictions. Workability of the proposed VCM and PWM applications is verified through SPICE simulations using CFOA based realization of OTRA and experimental results are also included.

**8.2 AUTHOR’S ENDING NOTE**

The current-mode approach represents an efficient way to realize CMOS circuits and has made a great impact on IC design. It claims to provide advantages such as higher BW and slew rates, lower power consumption, improved linearity, and smaller chip area, in contrast to their voltage–mode counterparts. The complexity of a circuit determines its performance. Current-mode circuits are often less complex than the voltage-mode circuits they are compared to [130], thus explaining the performance differences.
It is also worth mentioning, that advantages offered by CM circuits are often achieved at the cost of higher distortion and gain variation [130]. Also, there are applications in which the VM techniques are more appropriate. For example to realize the voltage buffers with rail to rail input and output swing, and to fulfill low input offset current requirement, voltage-mode op-amp is a preferred choice [5]. Thus conglomoration of two domains would be a further step in evolution of analog IC design where, the research findings of CM techniques may give valuable insight to voltage-mode designers and the techniques like Miller feedback, offset compensation used in classical voltage-mode design [130], can also be used in circuits that process current signals.

Emerged as an alternative analog design approach, the current-mode technique has broadened the horizon of analog IC design by giving way to a number of active building blocks for analog signal processing. These blocks may serve one or more of the variety of specific requirements imposed on the analog subsystems working in various operating modes [4]. This study explored circuit applications of one such active element, OTRA, which is most suitable for transimpedance mode applications. It is expected that this study would serve as a ready reckoner of available information on OTRA and circuits built using the block.