

David
COMER

Donald
COMER

Advanced
Electronic
Circuit
Design

INTERNATIONAL EDITION

RESTRICTED

Not for sale in North America

CONTENTS

INTRODUCTION AND REVIEW	2
1.1 ADVANCED ELECTRONIC CIRCUITS	2
1.2 TRANSISTORS	2
1.3 THE MOSFET	3
1.3.1 The Triode Region	3
1.3.2 The Active Region	4
1.3.3 The Midband Incremental MOSFET Model	7
1.3.4 High-Frequency Model of the MOSFET	10
1.4 MOSFET IC STAGES	13
1.4.1 Active Load Stage	13
1.4.2 Source Follower with Active Load	19
1.4.3 The Cascode Connection	23
1.5 THE BJT	27
1.5.1 The Hybrid- π Equivalent Circuit	28
1.5.2 Some Important Equations for the BJT	28
1.6 BJT IC STAGES	34
1.6.1 The Current Mirror Load	35
1.6.2 The Emitter Follower	39
1.6.3 The Cascode Amplifier Stage	42
FUNDAMENTAL POWER AMPLIFIER STAGES	58
2.1 CLASSIFICATION OF POWER STAGES	58
2.2 ALLOWABLE DISSIPATION	61
2.2.1 Thermal Resistance	62
2.2.2 Method 1: Specification of $T_{J,max}$ and θ_{JM}	64
2.2.3 Method 2: Graphical Determination of Allowable Dissipation	64
2.2.4 Power Transistors	67
2.2.5 Power Dissipation Review	67
2.3 CLASS-A POWER OUTPUT STAGES	69
2.3.1 Resistive Stages	69
2.3.2 Class-A Transformer-Coupled Stage	74
2.4 CLASS-B POWER OUTPUT STAGES	82
2.4.1 Analysis of Class-B Transformer Stages	83
2.5 CLASS-C POWER OUTPUT STAGES	90
ADVANCED POWER AMPLIFICATION	107
3.1 AMPLIFIER SPECIFICATIONS	107
3.1.1 Power Gain	107
3.1.2 Distortion in Power Stages	109
3.2 TRANSFORMERLESS CLASS-B POWER STAGES	113
3.2.1 Class-B Complementary Emitter Followers	114
3.2.2 The Quasi-Complementary Symmetry Class-B Stage	116
3.2.3 Integrated Amplifier Class-B Stages	116
3.2.4 Additional Class-B Output Configurations	119
3.3 PULSE-WIDTH MODULATED AUDIO POWER AMPLIFIERS	123
3.3.1 The Concept of Pulse-Width Modulation	123
3.3.2 Class-D Output Stages	125
3.3.3 Generating the PWM Drive Signal	130

4 WIDEBAND AMPLIFIERS	138
4.1 WIDEBAND SINGLE STAGES	139
4.1.1 The Op Amp Single-Stage Amplifier	140
4.1.2 Transistors	145
4.2 MULTISTAGE WIDEBAND AMPLIFIERS	154
4.2.1 Multistage Theory	155
5 NARROWBAND AMPLIFIERS	168
5.1 NARROWBAND AMPLIFICATION	168
5.2 INDUCTORS AND RESONANT CIRCUITS	169
5.2.1 Inductor Losses	169
5.2.2 Parallel Resonance	170
5.2.3 Relation of Bandwidth to Q in the Parallel Circuit	173
5.2.4 Review of Simple Tuned Circuit Relationships	176
5.2.5 The Series Resonant Circuit	178
5.3 TAPPED CAPACITOR AND INDUCTOR CIRCUITS	182
5.3.1 Tapped Capacitor Circuits	183
5.3.2 Tapped Inductors and Transformers	187
5.4 STAGGER-TUNED STAGES	189
5.5 TUNED AMPLIFIERS	191
5.5.1 The Transistor Tuned Amplifier at Low Frequencies	192
5.5.2 The Tuned Stage at High Frequencies	194
5.6 TUNED STAGES WITH NONSINUSOIDAL INPUTS	197
5.6.1 Nonsaturating Tuned Stages	198
5.6.2 Saturating Tuned Stages	200
6 SINUSOIDAL OSCILLATORS	208
6.1 DESIGN CONSIDERATIONS	208
6.1.1 General Design Considerations	208
6.1.2 Amplitude Stability	211
6.1.3 Frequency Stability	213
6.2 PRACTICAL OSCILLATOR CONFIGURATIONS	214
6.2.1 The RC Oscillator	214
6.2.2 Active Phase-Shift Oscillator	219
6.2.3 The Tuned-Circuit Oscillator	220
6.2.4 The Wien Bridge Oscillator	222
6.2.5 Hartley and Colpitts Oscillators	224
6.2.6 Crystal-Controlled Oscillators	225
6.2.7 General Comments on Oscillators	228
7 BASIC CONCEPTS IN COMMUNICATIONS	236
7.1 BRIEF HISTORY OF ELECTRONIC COMMUNICATIONS	236
7.1.1 The Vacuum Tube and Radio	236
7.1.2 Television	238
7.1.3 The Telephone	239
7.1.4 Satellite Communications	240
7.2 ELECTRONIC COMMUNICATION SYSTEMS	241
7.2.1 Communication Systems	241
7.2.2 A Communication System Example	242
7.2.3 The Electromagnetic Spectrum	245
7.2.4 Selected FCC Specifications	248
7.3 MULTIPLEXING	249
7.3.1 Frequency-Division Multiplexing	250

7.3.2	Time-Division Multiplexing	250
7.4	AMPLITUDE MODULATION	252
7.4.1	The Amplitude-Modulated Waveform	252
7.4.2	Index of Modulation	253
7.4.3	Mathematical Description of the AM Waveform	254
7.4.4	Power Relations in AM Waveforms	257
7.4.5	Carrier Suppression	258
7.4.6	Single-Sideband Systems	258
7.4.7	Vestigial-Sideband (VSB)	259
7.4.8	On-Off Keying (OOK)	259
7.4.9	Quadrature Amplitude Modulation (QAM)	261
7.4.10	Frequency Requirements for AM Broadcasting	263
7.5	ANGLE MODULATION	264
7.5.1	Phase Modulation	265
7.5.2	Frequency Modulation	267
7.5.3	Phase-Shift Keying (PSK)	269
7.5.4	Frequency-Shift Keying (FSK)	271
AMPLITUDE MODULATION CIRCUITS		277
8.1	PRODUCTION OF AM WAVEFORMS	278
8.1.1	Variable-Gain Modulators	278
8.1.2	Class-C Modulators	285
8.1.3	The Loop-Gain Modulator	294
8.1.4	A Class-D Amplitude Modulator	298
8.2	PRODUCTION OF SUPPRESSED-CARRIER WAVEFORMS	301
8.3	PRODUCTION OF SINGLE-SIDEBAND WAVEFORMS	303
8.3.1	Filtering to Obtain SSB	303
8.3.2	The Phase-Shift Method	303
8.3.3	The Weaver Method	304
8.4	MIXERS	305
8.4.1	Simple Mixers	306
8.4.2	A Perfect Square-Law Multiplier	307
8.4.3	Practical Multipliers	309
8.4.4	Double Conversion	310
8.5	DETECTORS	311
8.5.1	The Nonsynchronous Detector	311
8.5.2	Synchronous Detection	313
8.6	AUTOMATIC GAIN CONTROL	315
ANGLE MODULATION CIRCUITS		325
9.1	PHASE MODULATORS	325
9.1.1	Phase Modulators Based on Amplitude Modulators	325
9.1.2	A Large-Deviation Phase Modulator	328
9.2	FREQUENCY MODULATORS	330
9.2.1	The Indirect Method of Frequency Modulation	330
9.2.2	The Direct Method of FM Generation	334
9.2.3	Pre-Emphasis in FM Transmitters	336
9.3	FM DETECTORS	339
9.3.1	The Foster-Seeley Discriminator	339
9.3.2	The Quadrature Detector	341
9.3.3	The Phase-Locked Loop	343
9.4	FM RECEIVERS	347

9.4.1	A Monaural FM Receiver	348
9.4.2	FM Stereo Transmission	348
10	MIXED-SIGNAL INTERFACING CIRCUITS	356
10.1	INTRODUCTION TO MIXED-SIGNAL SYSTEMS	356
10.2	CONVERTER INTERFACE CIRCUITS	357
10.2.1	Sample-and-Hold Circuit	357
10.2.2	The Comparator Circuit	363
10.2.3	The Analog Switch	368
10.3	THE DIGITAL-TO-ANALOG CONVERTER	373
10.3.1	Performance Parameters of the DAC	375
10.3.2	The Current-Scaling DAC	376
10.3.3	The Voltage-Output DAC	378
10.3.4	Ratiometric Design	379
10.4	THE ANALOG-TO-DIGITAL CONVERTER	381
10.4.1	Types of ADC	381
11	BASIC CONCEPTS IN FILTER DESIGN	391
11.1	ELECTRONIC FILTERS	391
11.1.1	Definition of an Electronic Filter	392
11.1.2	Applications of Filters	392
11.1.3	Other Classifications of Filters	394
11.2	OVERVIEW OF FILTER SYNTHESIS PROCEDURES	396
11.2.1	Specifications	397
11.2.2	The Advantage of Normalization	400
11.2.3	The Approximation Problem	402
11.2.4	Finding the Transfer Function from the Magnitude Function	405
11.2.5	Synthesizing the Network	406
11.3	POLES AND ZEROS OF NETWORK FUNCTIONS	406
11.3.1	Definition of Poles and Zeros	406
11.3.2	Examples of Simple Network Functions	407
11.3.3	Relationship of Pole and Zero Locations to Frequency Response	408
11.3.4	Restrictions on Pole Locations	413
11.4	APPROXIMATING THE IDEAL FILTER RESPONSE	414
11.4.1	The Butterworth (Maximally Flat Magnitude) Response	415
11.4.2	The Chebyshev (Equiripple) Response	420
11.4.3	Comparison of Chebyshev to Butterworth	422
11.4.4	Linear Phase (Bessel) Filters	425
11.4.5	The Transfer Function for the Bessel Filter	428
12	ACTIVE SYNTHESIS	435
12.1	ACTIVE FILTERS	435
12.2	ACTIVE CIRCUIT PRELIMINARIES	437
12.3	ACTIVE SYNTHESIS USING BACH FILTERS	439
12.3.1	Lowpass Transfer Function	439
12.3.2	Highpass Transfer Function	441
12.4	DRIFT IN FILTER RESPONSE	443
12.4.1	Passive Circuit Parameter Variation	443
12.4.2	Active Circuit Parameter Variation	445
12.5	SENSITIVITY CALCULATIONS	447
12.5.1	Useful Sensitivity Relations	447
12.6	COMPONENTS USED IN BIQUAD SYNTHESIS	447
12.6.1	The Op Amp	448

12.6.2	Transconductance Amplifiers	452
12.6.3	Current Conveyors	455
12.7	THE GENERAL BIQUAD FUNCTION	459
12.8	SALLEN-KEY BIQUADS	459
12.8.1	A Lowpass Biquad	460
12.8.2	A Highpass Biquad	462
12.8.3	The Bandpass Biquad	462
12.8.4	A Band-Reject Biquad	465
12.8.5	Problems of Sallen-Key Circuits	466
12.9	TWO-INTEGRATOR ACTIVE BIQUADS	467
12.9.1	Op Amp Two-Integrator Biquads	468
12.9.2	Two-Integrator Integrated Circuits	473
12.10	NARROWBAND FILTERS BASED ON CURRENT CONVEYORS	475
12.10.1	A Narrowband Current Conveyor	475
12.10.2	An Earlier Proposal	475
12.10.3	Synthesis with the Controlled Current Conveyor	477
12.11	NARROWBAND FILTERS BASED ON ALLPASS CIRCUITS	479
12.11.1	The Allpass Biquad	479
13	PRESENT AND FUTURE DIRECTIONS IN ELECTRONICS	490
13.1	PREDICTING THE FUTURE	490
13.2	ELECTRONIC SYSTEMS	490
13.2.1	Discrete Circuits	490
13.2.2	Discrete Element/IC Hybrid Circuits	491
13.2.3	Multiple IC Chips	491
13.2.4	A Single IC Chip	491
13.3	COMPUTER-AIDED DESIGN AND MODELING	492
13.4	FUTURE DIRECTIONS	492
13.4.1	MOSFET Channel Lengths Will Continue to Shrink	493
13.4.2	Higher Performance MOSFET Circuits Will Use Silicon-on-Insulator	493
13.4.3	Usage of Heterojunction and Gallium Arsenide BJT Devices Will Increase	493
13.4.4	Mixed-Signal Systems Will Increase in Importance	493
13.4.5	Rapid Simulation Tool Development Will Continue	494