

FEEDFORWARD LINEARIZATION OF COMMUNICATION TRANSMITTERS

by

Petter M. Bakken

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	
PART I. INTRODUCTION	1
REFERENCES PART I	5
PART II. OUTPUT DISTORTION SPECTRUM FOR ALMOST LINEAR COMMUNICATION TRANSMITTERS	
I. Introduction	7
II. Properties of Hermitian polynomials	8
III. Output correlation function	11
IV. Narrow band amplifiers	15
V. Narrow band amplifiers with known envelope characteristics	17
VI. Narrow band amplifiers with amplitude-phase conversion	20
VII. Numerical methods	22
VIII. Example	27
IX. Conclusion	29
PART III. FEEDFORWARD LINEARIZER THEORY	
1.1. Principles of feedforward error correction system ..	30
1.2. Mathematical models of components	31
1.2.1. Amplifiers	31
1.2.2. Directional couplers	32
1.2.3. Hybrid circuit	33
1.3. Block diagram representation of feedforward amplifier	33
1.3.1. Linear operation	35
1.3.2. Almost linear operation	36
2. ANALYSIS OF FEEDFORWARD WITH THIRD ORDER NONLINEARITY	
SINGLE AMPLIFIERS	37
2.1. Broadband amplifier	37
2.1.1. Single tone input signal	38
2.1.2. Gaussian input signal	39
2.2. Narrowband amplifier	42
2.2.1. Single tone input	46
2.2.2. Two tone input	46
2.2.3. Narrow band Gaussian input	47
3. DESIGN OF FEEDFORWARD AMPLIFIERS	49
3.1. Both loops balanced	49
3.1.1. Quality of the single amplifiers	49
3.1.2. Optimum design parameters	50

	Page
3.2. Loops balance sensitivity	53
4. PERFORMANCE OF FEEDFORWARD COMPENSATION	61
4.1. Broadband amplifier	61
4.1.1. Single tone input	61
4.1.2. Gaussian input	62
4.2. Narrow band amplifier	63
4.2.1. Single tone input	63
4.2.2. Two tone input	63
4.2.3. Gaussian input	63
4.3. Performance, summary	64
5. FEEDFORWARD AMPLIFIERS WITH SATURATION	68
5.1. Backoff for the two separate amplifiers	68
5.2. Dummy power dissipation	70
5.3. Maximum saturation power	72
6. SPECIFICATION OF POWER AMPLIFIERS USING FEEDFORWARD COMPENSATION	74
6.1. Single amplifier	74
6.2. Feedforward amplifier with power constrained performance	75
6.3. Example of two-tone test	75
7. MULTI-STAGE FEEDFORWARD AMPLIFIERS	77
7.1. Analysis of three-loop amplifier, configuration A ...	79
7.2. Analysis of three-loops amplifier, configuration B ..	81
7.3. Generalisation of the results	82
7.4. Feedforward amplifier with redundancy	85
7.4.1. Design of redundancy amplifier	86
8. COMPUTERIZED STUDY OF FEEDFORWARD LINEARIZERS	91
8.1. Perfectly balanced feedforward amplifier	91
8.2. Feedforward amplifier with unbalanced loop 1	94
8.3. Feedforward amplifier with unbalanced loop 2	95
8.4. Output distortion spectrum for feedforward amplifiers	97
8.5. Class B or C amplifiers used as main amplifier	98
CONCLUSIONS	104
REFERENCES, PART III	105

PART IV FEEDFORWARD LINEARIZED TV TRANSPONDER OUTPUT STAGES

1.	INTRODUCTION	106
2.	LINEARITY TEST METHODS FOR TRANSPONDER OUTPUT STAGES ..	107
2.1.	Three-tone linearity test	107
2.2.	Cross compression linearity test	109
3.	PERFORMANCE ANALYSIS	110
3.1.	Three tone test performance	110
3.1.1.	Feedforward amplifier	111
3.1.2.	Single amplifier	114
3.2.	Cross compression test performance	114
3.2.1.	Feedforward amplifier	114
3.2.2.	Single amplifier	115
3.3.	Improvement in RF-DC efficiency	116
4.	EXPERIMENTAL CIRCUIT	119
4.1.	Main amplifier	121
4.2.	Subsidiary amplifier	123
4.3.	Input sampling coupler	125
4.4.	Output sampling coupler	125
4.5.	Error injection coupler	126
4.6.	Error definition RF-hybrid	126
4.7.	Main amplifier compensation delay line	126
4.8.	Subsidiary amplifier compensation delay line ...	127
4.9.	Adjustable attenuators, D_1 and D_2	127
4.10.	Adjustable coaxial delay lines	127
4.11.	Adjustments of balance	128
5.	LINEARITY PERFORMANCE OF FEEDFORWARD AMPLIFIER	131
5.1.	Three-tone linearity test	131
5.2.	Cross compression test	134
5.3.	Single carrier measurements	134
5.4.	Two-tone linearity test	137
6.	CONCLUSIONS	140
Appendix 1 TEST METHODS		
AI-1	Linearity tests	141
AI-2	Single carrier measurements	143
REFERENCES, PART IV		144

PART V FEEDFORWARD LINEARIZED SATELLITE TRANSPONDER

	Page
1. INTRODUCTION	145
2. ANALYSIS OF TWT FEEDFORWARD LINEARIZED AMPLIFIER	146
2.1. Feedforward TWT amplifier circuit	146
2.2. Distortion sensitivity to balance parameters	151
2.3. Stability against oscillations	160
2.4. Small signal response errors	163
2.4.1. Improvement of single tube small signal response	163
2.4.2. Response errors introduced by the second loop	163
2.4.3. Response errors introduced by echo distortion in the delay lines	166
2.4.4. Linearity sensitivity to power division ratio	167
3. FEEDFORWARD LINEARIZER EXPERIMENT	169
3.1. Linearizer circuit	169
3.2. Traveling wave tubes	169
3.3. Passive microwave components	176
3.3.1. Variable attenuators	176
3.3.2. Variable phase shifters	177
3.3.3. Ferrite isolators	177
3.3.4. Directive couplers	180
3.3.5. Coaxial delay lines	184
3.4. Adjustments of feedforward amplifier	185
3.4.1. Initial set-up of first loop	185
3.4.2. Initial set-up of second loop balance	186
3.4.3. Adjustment of loop balance parameters	189
4. EVALUATION OF EXPERIMENTAL CIRCUIT	191
4.1. Single carrier output saturated power	191
4.2. Measurement of DC-input to TWT	192
4.3. Output power versus C/I requirement	195
4.4. Gain, gain slope and phase slope measurements	201
4.5. Input and output port reflections	206
5. EXPERIMENTAL INVESTIGATION OF THE FEEDFORWARD LINEARIZER	209
5.1. Linearizer sensitivity to loop balance of first loop	209
5.1.1. First loop amplitude unbalance	209
5.1.2. First loop phase unbalance	211
5.1.3. Combined effects of first loop amplitude and phase unbalance	212

	Page
5.2. Linearity sensitivity to TWT supply voltages	214
5.3. Single carrier nonlinear transfer characteristic ..	217
5.3.1. Input - output single carrier nonlinear transfer characteristic	217
5.3.2. Power dissipation in C_3 termination	218
5.3.3. RF loading of the two separate TWTS	219
5.4. Power transfer characteristics with Gaussian input signal	221
5.4.1. Output and C_3 termination power level	221
5.4.2. Loading of the two separate TWTS	222
5.5. Loop balances at lower frequencies	224
5.6. Two carrier linearity tests	226
5.7. Feedforward amplifier with two equal TWTS	230
6. ANALYSIS OF LONG TERM PERFORMANCE	232
6.1. Sensitivity to RF balance parameters	232
6.2. Aging of TWTS	238
6.3. Temperature effects	239
6.3.1. Temperature dependence of TWT parameters ..	239
6.3.2. Temperature dependence of delay line parameters	239
6.3.3. Temperature dependence of other microwave passive components	242
6.4. TWT power supply requirements	242
6.4.1. Helix cathode voltage required stability ..	242
6.4.2. Helix cathode voltage reported stability ..	243
7. CONCLUSIONS	244
7.1. Feedforward linearization for TWT satellite transponders	244
7.2. The ELAB experiment	247
7.3. Flight model feedforward linearizers	247
7.4. Final remarks	248
REFERENCES	249
APPENDIX I MEASUREMENTS SET-UPS USED DURING EXPERIMENTS	AI-I
APPENDIX II PERFORMANCE TEST	AII-I
APPENDIX III TEST PROCEDURE, ACCURACY	AIII-I
PART VI CONCLUDING REMARKS	252