

APPLICATION OF TUNNEL DIODES
TO POWER SYSTEM PROTECTION

Thesis presented to

INDIAN INSTITUTE OF TECHNOLOGY, DELHI
New Delhi-29

for the degree of

DOCTOR OF PHILOSOPHY

by

Y.G. PAITHANKAR, B.E.(Hons.),M.E.

November 1967

THE AUTHOR

The author completed the post-graduate M.E. degree course in Power Engineering (Electrical) at the Indian Institute of Science, Bangalore in December 1959 and since then he has been in the teaching profession.

After being selected as a Research Scholar, he joined the Indian Institute of Technology, Delhi in November 1965.

INTRODUCTION

Static relays so far reported for application to power system protection employed thermionic valves, rectifier bridges, transducers, transistors, hall crystals and recently zener diodes. These devices with the exception of hall crystals and transducers (excluding the unpublished work on high speed Ramey type of magnetic amplifier) are basically used as switching elements to develop either an amplitude or a phase comparator; the comparator being the basic building block for all protective relays. They all have found wide applications in high speed relaying. The advantages claimed by the pioneers in favour of the static relays over the conventional electro-mechanical relays are now well established and in fact there is no doubt about the tremendous potentiality of realizing new types of high speed protective relays using semi-conductors.

With the development and availability of a comparatively new semiconductor device called the "Tunnel Diode or the Esaki Diode" and its well established application as a switching element in the bistable mode of operation, it was felt that it could well be investigated to develop basic comparators giving, with

respect to the controlling signal derived from the measuring circuit, almost instantaneous saturated output (100 per cent output) suitable for operating the slave relay directly. An attempt to obtain this sort of instantaneous saturated output characteristic was reported using highly feedback Ramey type Magnetic Amplifiers, but proved unsatisfactory for the time delay involved in it.

The tunnel diode having a unique and inherent negative resistance characteristic is essentially a small and very fast two terminal semiconductor device, lending itself to high speed switching applications. When critically biased as a switching element in its bistable mode, it can theoretically give infinite power amplification. This could lead to higher sensitivity of the comparator.

The limit to sensitivity at low operating levels for most of the semiconductor devices is due to the fact that a minimum threshold voltage is required before they start conducting. In case of tunnel diodes the switching action is confined to a voltage less than the so called threshold voltage. Thus, amplification coupled with speed and ability to operate at low operating levels were believed to lend the comparator

the desired sensitivity and speed.

The greatest disadvantage of the tunnel diode is the low output voltage available. The available voltage swing for germanium units is less than 0.5 volts, gallium arsenide units providing less than 1.0 volts. Peak currents, however, range from 10 microampere to more than 200 amperes. Hence the problem of increasing the power output can be solved to some extent by choosing high current tunnel diodes.

The work that is submitted contains the application of this new device to develop the amplitude and the phase comparator operated from either voltage or current and the application of these comparators to distance protection. Besides this, a critical level detector is built up and found useful in designing a high speed over-current relay with adjustable reset ratio and is considered almost free from transients in the operating current.

CONTENTS

Introduction	: x
CHAPTER 1. TRENDS AND DEVELOPMENTS OF STATIC PROTECTION OF POWER SYSTEMS	: 1
1.1 The Trend	: 1
1.2 Developments in Static Technique	: 4
CHAPTER 2. BASIC RELAY FUNCTIONS AND STATIC TECHNIQUES	: 10
2.1 Introduction	: 10
2.2 Basic Relay Functions	: 11
2.2.1 Summation	: 11
2.2.2 Single Input Devices	: 11
2.2.2.1 Noncritical Functions	: 11
2.2.2.2 Critical or Measuring Function	: 12
2.2.2.3 Fixed or Definite Time Function	: 12
2.2.2.4 Function Time Dependent on Input	: 13
2.2.3 Two Input Devices	: 13
2.2.3.1 Amplitude Comparator	: 14
2.2.3.2 Phase Comparator	: 14
2.2.3.3 Relation Between Amplitude and Phase Comparator	: 15
2.2.4 Multi-Input Devices	: 15
2.3 Suitability of Semiconductor Devices to Functional Requirements	: 16
2.4 Two Input Comparator Circuits	: 16
2.4.1 Rectifier Bridge Amplitude Comparator	: 16

2.4.2	Rectifier Bridge Phase Comparator	: 17
2.4.3	Transistor Phase Comparator	: 18
2.4.3.1	The Pulse or Block Spike Principle:	18
2.4.3.2	Direct Phase Comparison Principle :	19
2.4.4	Phase Comparator Using Hall Effect	: 20
2.4.5	Phase Comparator Using Zener Diodes	: 21
2.4.6	Some Other Types	: 22
CHAPTER 3. COMPARATORS AS RELAYS		: 24
3.1	Introduction	: 24
3.2	Generalised Circle Diagrams for Two Input Comparators	: 24
3.2.1	Input Quantities	: 24
3.2.2	Relay Characteristics Employing Amplitude Comparator	: 25
3.2.3	Relay Characteristics Employing Phase Comparator	: 28
3.3	Input Requirements for Common Types of Distance Relays	: 31
3.4	Polar Characteristics Using Multi-Input Comparators	: 31
CHAPTER 4. THE TUNNEL DIODE		: 34
4.1	Introduction	: 34
4.2	General Description	: 35
4.3	Characteristics	: 37
4.3.1	Static Characteristics	: 37
4.3.1.1	The Peak Forward Current I_p	: 37

4.3.1.2	The Valley Point Current I_V	: 38
4.3.1.3	The Peak Voltage V_P and the Valley Voltage V_V	: 38
4.3.1.4	Projected Peak Voltage V_{FP}	: 38
4.3.2	Dynamic Characteristics	: 39
4.3.2.1	Junction Resistance R_J	: 39
4.3.2.2	Series Resistance R_S	: 40
4.3.2.3	Series Inductance L_S	: 40
4.3.2.4	Junction Capacitance C_J	: 40
4.4	Tunnel Diode as a Switching Element	: 40
4.4.1	Bistable Mode : Current Gain and Switching Speed	: 41
4.4.2	Circuits for Increased Sensitivity	: 45
4.4.2.1	Tunnel Diode and Rectifying Diode	: 46
4.4.2.2	Tunnel Diode and Transistor	: 48
CHAPTER 5. THE RAMEY MAGNETIC AMPLIFIER AND THE TUNNEL DIODE IN PHASE SENSITIVE NETWORKS		: 50
5.1	Introduction	: 50
5.2	Ramey's Magnetic Amplifier	: 52
5.2.1	Principle of Operation	: 52
5.2.2	Phase Characteristic	: 54
5.2.3	Voltage Gain Considerations	: 54
5.2.4	Possible Gain Improvement	: 54
5.2.4.1	Reduction in Control Winding Turns:	55
5.2.4.2	Positive Feedback	: 56

5.3	Critical Summary	: 57
5.4	The Tunnel Diode	: 60
5.4.1	The Tunnel Diode Bistable Amplifier Circuit	: 60
5.4.2	Transfer Characteristic	: 61
CHAPTER 6. TUNNEL DIODE PHASE COMPARATOR		: 62
6.1	Basic Comparator Circuit	: 62
6.1.1	Principle of Operation	: 63
6.1.2	Output Voltage versus Phase Displacement Characteristic	: 64
6.1.3	Output Voltage versus Measuring Voltage Characteristic	: 65
6.1.4	Maximum Output Voltage	: 65
6.1.5	Maximum Power Output	: 66
6.1.6	Response Time	: 67
6.1.7	Conclusions	: 67
6.2	Choice of Clipping Circuit	: 68
6.2.1	Transistor Switching Circuit	: 69
6.2.2	Circuit using Zener Diodes	: 69
6.2.3	Conventional p-n Junction Diodes	: 70
6.3	Voltage Operated Phase Comparator using p-n Junction Diode Clipping Circuit	: 71
6.3.1	Choice of Circuit Elements	: 71
6.3.1.1	Tunnel Diodes	: 71
6.3.1.2	Load Resistances	: 76
6.3.1.3	The Clipping Circuit Elements	: 76
6.3.1.4	The Measuring Circuit Elements	: 77

6.3.2	Experimental Verification	: 79
6.3.2.1	Phase Characteristic	: 79
6.3.2.2.	Voltage Characteristic	: 79
6.3.2.3	Measuring Voltage versus Polarising Voltage Characteristic for Constant Output and Fixed θ	: 82
6.3.3	Certain Improvements	: 86
6.3.3.1	Optimum Choice of Auxiliary p.t. Ratio	: 90
6.3.3.2	Experimental Verification	: 91
6.4	Current Operated Comparator	: 92
6.4.1	General	: 92
6.4.2	Circuit Modifications	: 94
6.4.3	Experimental Verification	: 95
6.4.3.1	Phase Characteristic	: 95
6.4.3.2	Output Characteristic	: 96
6.4.3.3	Measuring Current versus Polarising Current for Constant Output and Fixed θ	: 96
6.5	Conclusions	: 96
CHAPTER 7. APPLICATION OF VOLTAGE OPERATED TUNNEL DIODE PHASE COMPARATOR		: 99
7.1	Mho Relay	: 99
7.1.1	General	: 99
7.1.2	Limitations	: 100
7.1.3	Application to 3 Phase System	: 100
7.2	Polarised Mho Relay	: 102
7.2.1	Polarising Voltages	: 102
7.2.2	Choice of Polarising Voltage	: 104

7.2.3	Polarised Mho Relay Characteristics	:	104
7.2.3.1	Phase Fault Relay with Sound Phase Polarising	:	105
7.2.3.1.1	Unbalanced Fault in Forward Direction	:	106
7.2.3.1.2	Unbalanced Fault in Backward Direction	:	107
7.2.3.1.3	Balanced Conditions	:	108
7.2.4	Conclusions	:	109
7.3	Mho Relay Employing Tunnel Diode Phase Comparator	:	109
7.3.1	Transactor	:	110
7.3.2	The Auxiliary p.t.	:	111
7.3.3	Burden Considerations	:	111
7.3.4	Static Tests	:	112
7.3.5	Conclusions	:	112
7.4	Polarised Mho Relay Employing Tunnel Diode Phase Comparator	:	113
7.4.1	Introduction	:	113
7.4.2	Choice of Polarising Voltage for the T.D. Phase Comparator	:	115
7.4.3	Compensation	:	118
7.4.4	Prototype Relay	:	119
7.4.4.1	Measuring Circuit	:	120
7.4.4.1.1	Fault Voltage Trans- former	:	120
7.4.4.1.2	Transactor	:	120
7.4.4.1.3	Compensation for Z_0	:	120
7.4.4.2	Polarising Circuit	:	121
7.4.4.2.1	Polarising Voltage Transformer	:	122
7.4.4.2.2	Phase Shifting Network	:	122

7.4.4.3	Compensating Circuit	:	123	
7.4.4.4	Simulated Slave Relay	:	123	
7.4.5	Performance Tests	:	124	
7.4.5.1	Static Characteristics	:	124	
7.4.5.2	Dynamic Characteristics	:	125	
7.4.5.3	Transient Performance	:	125	
7.4.5.4	VA Consumption	:	126	
7.4.5.5	Error Due to Variation in Polarising Voltage	:	126	
7.4.6	Interpretation of Results and Conclusions	:	127	
7.4.6.1	Transient Performance	:	127	
7.4.6.1.1	Transients in Polarising Voltage	:	127	
7.4.6.1.2	Transient Performance of Transactor	:	127	
7.4.6.1.3	Transients in Fault Voltage	:	128	
7.4.6.1.4	Transients in Measuring Voltage	:	129	
7.4.6.1.5	Conclusions	:	130	
7.4.6.2	Range versus Accuracy	:	131	
7.4.6.3	Response Time	:	132	
7.4.6.4	Impedance Setting	:	132	
CHAPTER 8. TUNNEL DIODE AMPLITUDE COMPARATOR			:	133
8.1	Introduction	:	133	
8.2	Basic Circuit	:	138	
8.3	The Experimental Comparator	:	142	
8.3.1	The Comparator Circuit	:	142	

8.3.2	Choice of Bias Resistance R_b	: 142
8.3.3	Pickup Value of the Slave Relay Element	: 143
8.3.4	Choice of R and X_c in the Phase Splitting Circuit	: 143
8.3.5	Ratio of Coupling Transformer	: 144
8.4	Experimental Verification	: 144
8.4.1	Restraining Volt./Operating Voltage Characteristic Without Compensation	: 144
8.4.2	Restraining Volt/Operating Voltage Characteristic With Compensation	: 145
8.4.3	Operating Speed	: 146
8.5	Conclusions	: 147
8.5.1	General Remarks	: 147
8.5.2	VA Consumption for Given Output	: 147
8.5.3	Operating Range for Given Accuracy	: 148
8.5.4	Operating Speed	: 148
8.5.5	Transient Response	: 148
8.6	Possible Improvements to Increase the Operating Range	: 150
CHAPTER 9. CRITICAL LEVEL DETECTOR AND ITS APPLICATION TO OVER-CURRENT RELAY		: 152
9.1	Critical Level Detector	: 152
9.1.1	Electromechanical Types	: 152
9.1.2	Static Bistable Circuits as Critical Level Detectors	: 153
9.2	Tunnel Diode Critical Level Detector	: 154
9.3	Over-Current Relay Employing the Tunnel Diode Critical Level Detector	: 155
9.3.1	Basic Circuit	: 155

9.3.2	Experimental Verification	: 155
9.3.2.1	Pickup Value, Reset Value and Reset Value	: 155
9.3.2.2	Operating Speed	: 156
9.3.2.3	VA Consumption and the Output	: 156
9.4	Conclusions	: 157
9.4.1	Reset Ratio	: 157
9.4.2	Operating Speed	: 157
9.4.3	Mechanical Stability	: 157
9.4.4	Accuracy of Setting	: 157
9.4.5	Transient Response	: 158
9.4.5.1	Transient Response for Sinusoidal Wave	: 158
9.4.5.2	Transient Response for Fully Offset Cosine Wave	: 159
CHAPTER 10.	GENERAL CONCLUSIONS.	: 161
10.1	Relay Functions Using Tunnel Diodes	: 161
10.2	The Phase Comparator	: 161
10.3	The Amplitude Comparator	: 164
10.4	The Critical Level Detector	: 166
10.5	Outlook	: 167
Appendix		: 170
References		: 173
Acknowledgement		: 180