University of South Wales
2064748

Bound by
Abbey Bookbinding Co.,
Cardiff
Tel: (0222) 395882
Fax: (0222) 223345

# COMPUTER AIDED DESIGN OF PROTECTION SYSTEMS FOR ELECTRICAL DRIVES

by

**Ian Dunn, B.A., M.IEE., C.Eng.**

A dissertation submitted to the University of Glamorgan in support of an application for the Degree of Doctor of Philosophy in Electrical Engineering.

This research project was carried out on a part time basis at the University of Glamorgan and in collaboration with British Steel plc, January, 1994.

This thesis is dedicated to the memory
of my late mother, whose unfaltering
support was the principal factor which
enabled me to complete this work.

# ABSTRACT

The contents of this thesis describe the results of an investigation into the means by which computer aided design (CAD) may be applied to the protection systems of electrical drives, removing much of the repetitive procedures presently used in determining relay settings. To further this aim, a series of algorithms have been devised which allow exploitation of the concept. The areas chosen for demonstration are, direct-on-line started induction motors and transformer fed variable speed drives. In both cases 'standard settings' cannot be implemented as the field of application varies enormously.

The text discusses an algorithm which utilises several databases containing motor, fuse and cable parameters. Chapter three uses a program derived from this algorithm which allows data to be extracted from the databases and manipulated in order to determine the optimum circuit components.

Subsequent chapters examine the implementation of two types of motor protection relay and discusses the algorithms used in modelling them. The text is supported by applications which demonstrate the effectiveness of the derived programs.

Chapter six discusses in depth the application of overcurrent relays for the protection of transformers used on variable speed drive installations. The possibility of using overcurrent elements in two or three phases is examined together with the attendant difficulties which may arise. The algorithms are further expanded to incorporate applications which involve the protection of multi-transformer installations supplied from a common point.

# Declaration

I declare that this thesis has not been, nor is currently being, submitted for the award of any other degree or similar qualification.

Signed: Ian Dunn

Ian Dunn

## Acknowledgements

I would like to express my thanks and appreciation to my mentor, Dr. M.G. Jayne whose valued guidance and encouragement has greatly contributed to the completion of this work. In addition I would like to express my gratitude to Mr. Denis Pope of British Steel plc, for providing technical support and also to all those individuals at GEC-Alsthom and P&B Golds Ltd who provided assistance and permission to reproduce photographs of their devices.

Finally I would like to thank Mr. Terrence Craven who assisted me with the diagrams, tables and flowcharts and Mrs. Susan Thomas who typed the contents of this thesis under difficult circumstances.

CONTENTS


| | | Page |
|---|---|---|
| 1. | INTRODUCTION | 1 |
| 1.1 | Project Implementation | 2 |
| 2. | DEFINING THE PROJECT BOUNDARIES | |
| 2.1 | Selecting protection for direct-on-line started induction motors | 6 |
| 2.1.1 | Historical developments | 6 |
| 2.1.2 | The current approach | 7 |
| 2.1.3 | Fundamental motor information | 8 |
| 2.2 | Variable speed drives | 14 |
| | List of References | |
| 3. | ASSOCIATED COMPONENTS IN THE MOTOR CIRCUIT | |
| 3.1 | Introduction | 17 |
| 3.2 | Switching device considerations | 17 |
| 3.3 | Specifying the circuit components | 19 |
| 3.3.1 | Overcurrent protection | 38 |
| 3.3.2 | Voltage drop considerations | 39 |
| 3.4 | Program description | 44 |
| 3.5 | Interim conclusion | 63 |
| | List of References | 64 |
| 4. | APPLYING THE CTM(F) RELAY | |
| 4.1 | General description | 65 |
| 4.1.1 | Thermal overload protection | 67 |
| 4.1.2 | Unbalanced conditions | 76 |
| 4.1.3. | High-set overcurrent | 88 |
| 4.1.3.1 | NPS High Set Overcurrent | 91 |
| 4.1.3.2 | Fuse/relay coordination | 91 |
| 4.1.3.3 | The Problem | 96 |
| 4.1.4 | Earth fault | 98 |
| 4.2 | The CTM(F) program | 103 |
| 4.3 | Program description | 116 |
| 4.4 | Interim conclusion | 126 |

5. APPLYING THE P&B GOLDS TYPE PBSJ 3E5 N11 RELAY

| | | |
|---|---|---|
| 5.1 | General description | 128 |
| 5.1.1 | Thermal Overload Protection | 128 |
| 5.1.2 | The $t_{6x}$ control | 133 |
| 5.1.3 | Locked rotor and stall protection | 133 |
| 5.1.4 | High Set overcurrent trip | 136 |
| 5.1.5 | Earth fault protection | 137 |
| 5.1.6 | Phase unbalance protection | 138 |
| 5.1.7 | Undercurrent protection | 139 |
| 5.1.8 | Switchgroup SG1 | 139 |
| 5.2 | Method employed | 140 |
| 5.2.1 | Maxcurve | 142 |
| 5.2.2 | Maxcurve with 75% stall setting | 149 |
| 5.2.3 | Maxcurve with 50% stall setting | 156 |
| 5.2.4 | Mincurve | 158 |
| 5.2.5 | Mincurve with 75% stall setting | 162 |
| 5.2.6 | Mincurve with 50% stall setting | 165 |
| 5.3 | Potentiometer 3 - High set overcurrent setting | 172 |
| 5.4 | Potentiometer 4 - Earth fault setting | 173 |
| 5.5 | Display of settings | 175 |
| 5.6 | Program description | 175 |
| 5.6.1 | P&B | 175 |
| 5.6.2 | P&B10 | 175 |
| 5.6.3 | P&B30 | 178 |
| 5.6.4 | P&B301 | 178 |
| 5.6.5 | P&B3011 | 181 |
| 5.6.6 | P&B302 | 183 |
| 5.6.7 | P&B303 | 183 |
| 5.6.8 | P&B304 | 183 |
| 5.6.9 | User choice option | 184 |
| 5.6.10 | P&B40 | 184 |
| 5.7 | Interim Conclusion | 184 |

6. THE PROTECTION OF VARIABLE SPEED DRIVE TRANSFORMERS

| | | |
|---|---|---|
| 6.1 | Introduction | 186 |
| 6.1.1 | The problems | 186 |
| 6.2 | Case Study 1 - The variable speed fan | 188 |
| 6.2.1 | The transformer with 7.5° overall phase shift | 193 |
| 6.2.2 | The transformer with 37.5° overall phase shift | 196 |
| 6.3 | Case Study 2 - The application to a multi-transformer circuit | 206 |
| 6.3.1 | The Temper Mill application | 206 |
| 6.3.2 | Determining the thermal withstand of circuit components | 210 |
| 6.4 | Determining the relay current and time setting multipliers | 221 |
| 6.4.1 | The IDMTL overcurrent strategy | 221 |
| 6.4.2 | The definite time overcurrent strategy | 230 |

6.5 Instantaneous overcurrent elements 233
6.5.1 IDMTL - Standard inverse characterstic 233
6.5.2 Instantaneous overcurrent setting associated with the DTL strategy 234
6.6 Earth fault 235
6.6.1 The IDMTL strategy 236
6.6.2 The DTL strategy 238
6.7 Program description for transformer protection on variable speed drive installations 239
6.7.1 Protsel - Project Control Routine 242
6.7.2 TX - Program Control routine 242
6.7.3 TX10 Voltage Selection menu 242
6.7.4 TX20 Transformer data displays 245
6.7.5 TX30 Circuit constraints 245
6.7.6 TX40 System definition 250
6.7.7 TX50 Switching device and clearing time routine 250
6.7.8 TX60 Current transformer selection 252
6.7.9 TX70 Displays fuse catalogue 255
6.7.10 TX80 Displays fuse data 255
6.7.11 TX90 Displays cable catalogue 257
6.7.12 TX100 Cable rating calculations 260
6.7.13 TX110 Displays cable data 261
6.7.14 TX120 Fault current calculations 261
6.7.15 TRIG Calculates sine and Cosine of angles 263
6.7.16 TX1201 Fault current calculation data input 263
6.7.17 TX1202 Transformer winding fault current distribution 263
6.7.18 TX130 Assigns constants to selected relay characteristics 264
6.7.19 Inverse time characteristics 264
6.7.20 Definite time lag characteristics 268
6.7.21 TX150-152 User option settling data input 268
6.7.22 TX160-162 Circuit withstand and constraints IDMTL calculation 272
6.7.23 TX170-172 Circuit withstand and constraints DTL calculation 272
6.7.24 TX180 and TX190 DTL and IDMTL calculation routines 273
6.7.25 TX210 Settings display 273
6.7.26 TX310 Fault current withstand and constraints menu 273
6.7.27 TX320 and TX330 Fault current listings 276
6.7.28 TX340 Withstand/relay operating times - min source impedance 276
6.7.29 TX350 Withstand/relay operating times - max source impedance 276
6.7.30 TX360 Constraints/Relay operating times 281
6.8 Interim Conclusion 281

7. CONCLUSION 284

7.1 Future Enhancements 285

**Bibliography** 287

**Appendices**

Appendix 1 Determining the motor withstand characteristics 288
Appendix 2 Prediction of motor acceleration times for directly coupled motor/drive units 292
Appendix 3 Harmonics in the supply voltage 300
Appendix 4 Effects of unbalanced supply voltage 304
Appendix 5 Determination of terminal fault currents for typical transformer sizes 317
Appendix 6 Determination of zero sequence impedance of a cable 345
Appendix 7 Typical electric motor information 352
Appendix 8 Typical fuse characteristics 358
Appendix 9 Motor protection relay thermal characteristics 361
Appendix 10 Current transformers 370

## List of Illustrations


| | | |
|---|---|---|
| Fig. 1.1 | Main selection menu | 4 |
| Fig. 1.2 | 'Protsel' program flowchart | 5 |
| Fig. 3.1 | Main selection menu | 20 |
| Fig. 3.2 | Motor type display listing | 22 |
| Fig. 3.3 | 415V 4 pole Motor rating display | 23 |
| Fig. 3.4 | 75kW Motor data display | 24 |
| Fig. 3.5 | Typical systems condition display for 1500kVA transformer | 26 |
| Fig. 3.6 | Fuse type listing | 29 |
| Fig. 3.7 | Fuse rating listing | 30 |
| Fig. 3.8 | Cable type listing | 31 |
| Fig. 3.9 | Cable limitation display for 75kW Motor fed from an 800kVA transformer | 42 |
| Fig. 3.10 | Cable limitation display for 75kW Motor fed from an 1500kVA transformer | 43 |
| Fig. 3.11 | Circuit voltage conditions and acceleration time display | 45 |
| Fig. 3.12 | Protection relay menu | 46 |
| Fig. 3.13 | Motor protection relay selection - flowchart | 48 |
| Fig. 3.14 | Display motor types - flowchart | 49 |
| Fig. 3.15 | Display motor ratings - flowchart | 50 |
| Fig. 3.16 | Display motor data - flowchart | 52 |
| Fig. 3.17 | Routine for entering unclassified motor data - flowchart | 53 |
| Fig. 3.18 | Determine system conditions - flowchart | 54 |
| Fig. 3.19 | Selects routine according to voltage - flowchart | 56 |
| Fig. 3.20 | Display fuse ratings - flowchart | 58 |
| Fig. 3.21 | Displays listing of all cable types for selection - flowchart | 59 |
| Fig. 3.22 | Calculates cable parameters from selected cable CSA's and length - flowchart | 61 |
| Table 3.1 | Fuse rating/5 second disconnecting current | 28 |
| Table 3.2 | Minimum CSA of protective conductors/5 sec disconnecting current | 35 |
| Fig. 4.1 | Comparison between actual and desired characteristic | 68 |
| Fig. 4.2(a) | Block diagram of CTM relay components | 77 |
| Fig. 4.2(b) | Block diagram of CTMF relay components | 77 |
| Fig. 4.3(a) | Single-phase circuit for three-phase star-connected motor | 86 |
| Fig. 4.3(b) | Equivalent circuit for loss of phase on a three phase star connected motor | 86 |
| Fig. 4.4(a) | Single phase circuit for three phase delta-connected motor | 86 |
| Fig. 4.4(b) | Equivalent circuit for loss of one supply phase on a three-phase delta-connected motor | 86 |
| Fig. 4.5 | Fuse/Thermal/Motor/Acceleration time coordination graph | |
| Fig. 4.6(a) | Wiring connections for relay with internal star connection | 101 |
| Fig. 4.6(b) | Wiring connections for relay with external star connection | 101 |
| Fig. 4.7 | Relay type option menu - display | 104 |
| Fig. 4.8 | Current transformer data requirement - display | 106 |
| Fig. 4.9 | Thermal strategy option menu - display | 107 |

| | | |
|---|---|---|
| Fig. 4.10 | Operating times and margins for CTM4-02 relay - display | 108 |
| Fig. 4.11 | Thermal/Motor/Acceleration time coordination graph for CTM4-06 | 110 |
| Fig. 4.12 | Operating times and margins for CTM4-31 relay - display | 111 |
| Fig. 4.13 | Thermal/Motor/Acceleration time coordination graph for CTM4-31 | 112 |
| Fig. 4.14 | Operating times and margins for CTM4-06 relay - display | 113 |
| Fig. 4.15 | Thermal/Motor/Acceleration time coordination graph for CTM4-06 | 114 |
| Fig. 4.16 | User selected characteristic menu - display | 115 |
| Fig. 4.17 | Relay settings - display | 117 |
| Fig. 4.18 | CTM (F) Solution flowchart | 118 |
| Fig. 4.19 | CTM (F) Control routine - flowchart | 120 |
| Fig. 4.20 | CTM60, User characteristic menu - flowchart | 122 |
| Fig. 4.21 | CTM70, Inequality tests - flowchart | 124 |
| Fig. 4.22 | CTM80, Relay operating time margins - flowchart | 125 |
| Table 4.1 | Typical correlation of relay and motor types | 66 |
| Table 4.2 | Time inequality checks | 89 |
| Fig. 5.1 | The P&B Microgolds relay | 129 |
| Fig. 5.2 | Key to P&B Microgolds relay controls | 131 |
| Fig. 5.3 | Typical Hot and Cold thermal characteristics including 75% and 50% stall functions | 134 |
| Fig. 5.4 | Typical relay faceplate 'set up' arrangement | 141 |
| Fig. 5.5 | Thermal strategy option menu | 143 |
| Fig. 5.6 | Operating times and margins for 'MAXCURVE' with full thermal characteristic and a $t_{6x}$ setting of 17 seconds | 148 |
| Fig. 5.7 | Operating times and margins for 'MAXCURVE' with 75% step in the thermal characteristic and a $t_{6x}$ setting of 17 seconds | 150 |
| Fig. 5.8 | Operating times and margins for 'MAXCURVE' with 50% step in the thermal characteristic and a $t_{6x}$ setting of 17 seconds | 151 |
| Fig. 5.9 | Motor withstand and relay thermal characteristic with a $t_{6x}$ setting of 17 seconds. Graph includes 75% and 50% steps in the relay characteristic. | 152 |
| Fig. 5.10 | Operating times and margins for 'MAXCURVE' with 75% step in the thermal characteristic and a $t_{6x}$ setting of 22.5 seconds | 154 |
| Fig. 5.11 | Operating times and margins for 'MAXCURVE' with 50% step in the thermal characteristic and a $t_{6x}$ setting of 22.5 seconds | 155 |
| Fig. 5.12 | Motor withstand and relay thermal characteristic with a $t_{6x}$ setting of 22.5 seconds. Graph shows 75% and 50% steps in the relay characteristic. | 157 |
| Fig. 5.13 | Operating times and margins for 'MAXCURVE' with 50% step in the thermal characteristic and a $t_{6x}$ setting of 34 seconds. | 159 |
| Fig. 5.14 | Motor withstand and relay thermal characteristic with a $t_{6x}$ setting of 34 seconds. Graph shows 50% step in the relay characteristic. | 160 |

Fig. 5.15 Operating times and margins for 'MINCURVE' with full thermal characteristic and a $t_{6x}$ setting of 7 seconds. 163
Fig. 5.16 Motor withstand and relay thermal characteristic with a $t_{6x}$ setting of 7 seconds. Graph shows the full characteristic. 164
Fig. 5.17 Operating times and margins for 'MINCURVE' with a 75% step in the thermal characteristic and a $t_{6x}$ setting of 9.5 seconds. 166
Fig. 5.18 Motor withstand and relay thermal characteristic with a $t_{6x}$ setting of 9.5 seconds and a 75% step in the relay characteristic. 167
Fig. 5.19 Operating times and margins for 'MINCURVE' with a 50% step in the thermal characteristic and a $t_{6x}$ setting of 14 seconds. 168
Fig. 5.20 Motor withstand and relay thermal characteristic with a $t_{6x}$ setting of 14 seconds and a 50% step in the relay characteristic. 169
Fig. 5.21 Typical relay setting display. 176
Fig. 5.22 P&B Control routine - flowchart. 177
Fig. 5.23 Calculate time settings - flowchart. 179
Fig. 5.24 Calculate $t_{6x}$ for 'MAXCURVE' - flowchart. 180
Fig. 5.25 Calculate and display operating times - flowchart. 182

Fig. 6.1 General arrangement of synchronous motor powered variable speed fan. 189
Fig. 6.2 Current distribution in transformer windings for phase-phase fault on secondary terminals - delta/delta winding arrangement. 197
Fig. 6.3 Current distribution in transformer windings for phase-phase fault on secondary terminals - delta/star winding arrangement. 197
Fig. 6.4 Coil temper mill transformer supplies diagram. 207
Fig. 6.5 Current distribution in transformer windings for 3-phase and phase-phase faults - delta/delta winding arrangement. 214
Fig. 6.6 Current distribution in transformer windings for 3-phase and phase-phase faults - delta/star winding arrangement. 215
Fig. 6.7 Fault currents observed at the relays for phase-phase and 3-phase fault conditions on each transformer. 216
Fig. 6.8 Protsel - Main system program. 243
Fig. 6.9 Variable speed drive transformer protection. 244
Fig. 6.10 Voltage selection menu - display. 246
Fig. 6.11 Voltage selection menu - flowchart. 247
Fig. 6.12 TX20 - Record transformer data. 248
Fig. 6.13 Transformer data input display. 249
Fig. 6.14 System source conditions. 251
Fig. 6.15 Switching device and protection operating times. 253
Fig. 6.16 Current transformer data. 254
Fig. 6.17 Fuse catalogue. 256
Fig. 6.18 Fuse rating summary. 258
Fig. 6.19 Cable catalogue. 259
Fig. 6.20 Cable limitation display for a typical installation. 262
Fig. 6.21 Relay characteristic and element selection display. 265
Fig. 6.22 Definite time lag strategy flowchart. 269
Fig. 6.23 'User Choice' flowchart 270
Fig. 6.24 Typical settings display. 274
Fig. 6.25 'User Choice'menu. 275

Fig. 6.26 TX310 - 'User Option' results display flowchart. 277
Fig. 6.27 Fault condition summary. 278
Fig. 6.28 Transformer withstand times/protection clearing times supplied from a minimum source impedance. 279
Fig. 6.29 Transformer withstand times/protection clearing times supplied from a maximum source impedance. 280
Fig. 6.30 Circuit constaints/protection clearing times for the transformer with a Phase shift of +7.5°. 282

Table 6.1(a) Current distribution for a 3-phase fault on the LV windings - 93 MVA Source 198
Table 6.1(b) Current distribution for a phase-phase fault on the LV windings - 93 MVA Source 198
Table 6.1(c) Current distribution for a 3-phase fault on the LV windings - 25kA Source 198
Table 6.1(d) Current distribution for a phase-phase fault on the LV windings - 25 kA Source 199
Table 6.1(e) Current distribution for a 3-phase fault on the LV windings - Infinite Source 199
Table 6.1(f) Current distribution for a phase-phase fault on the LV windings - Infinite Source 199
Table 6.2(a) Winding withstand times for a 3-phase fault on the LV windings - 93 MVA Source 200
Table 6.2(b) Winding withstand times for a phase-phase fault on the LV windings - 93 MVA Source 200
Table 6.2(c) Winding withstand times for a 3-phase fault on the LV windings - 25kA Source 200
Table 6.2(d) Winding withstand times for a phase-phase fault on the LV windings - 25kA Source 201
Table 6.2(e) Winding withstand times for a 3-phase fault on the LV windings - Infinite Source 201
Table 6.2(f) Winding withstand times for a phase-phase fault on the LV windings - Infinite Source 201

For the transformer with Phase Shift of +37.5°

Table 6.3(a) Current distribution for a 3-phase fault on the LV windings - 93 MVA Source 202
Table 6.3(b) Current distribution for a phase-phase fault on the LV windings - 93 MVA Source 202
Table 6.3(c) Current distribution for a 3-phase fault on the LV windings - 25kA Source 202

Table 6.3(d) Current distribution for a phase-phase fault on the LV windings - 25 kA Source 203
Table 6.3(e) Current distribution for a 3-phase fault on the LV windings - Infinite Source 203
Table 6.3(f) Current distribution for a phase-phase fault on the LV windings - Infinite Source 203

| | | |
|---|---|---|
| Table 6.4(a) | Winding withstand times for a 3-phase fault on the LV windings - 93 MVA Source | 204 |
| Table 6.4(b) | Winding withstand times for a phase-phase fault on the LV windings - 93 MVA Source | 204 |
| Table 6.4(c) | Winding withstand times for a 3-phase fault on the LV windings - 25kA Source | 204 |
| Table 6.4(d) | Winding withstand times for a phase-phase fault on the LV windings - 25kA Source | 205 |
| Table 6.4(e) | Winding withstand times for a 3-phase fault on the LV windings - Infinite Source | 205 |
| Table 6.4(f) | Winding withstand times for a phase-phase fault on the LV windings - Infinite Source | 205 |
| Table 6.5 | Fault Currents and Thermal withstand times for phase-phase and 3-phase LV faults when supplied from a 5kA fault level source. | 223 |
| Table 6.6 | Fault Currents and Thermal withstand times for phase-phase and 3-phase LV faults when supplied from a 25 kA fault level source. | 224 |
| Table 6.7 | Calculated maximum time multipliers with a csm setting of 0.40 under listed conditions using three overcurrent elements for transformers 1-6. | 227 |
| Table 6.8 | Summary of fault currents, relay operating times and cable withstand times. | 237 |
| Fig. A2.1 | Manufacturers typical motor test record | 294 |
| Fig. A2.2 | Torque/Speed characteristic | 295 |
| Table A2.1 | Motor and Fan Torque/Speed relationship | 297 |
| Table A2.2 | Motor/drive acceleration time at 100% line volts | 298 |
| Table A2.3 | Motor/drive acceleration time at 90% line volts | 298 |
| Fig. A3.1 | Diagram of fundamental and second harmonic | 303 |
| Fig. A3.2 | Diagram of fundamental and third harmonic | 303 |
| Fig. A4.1 | Induction motor equivalent circuit diagram | 305 |
| Fig. A4.2 | Simplified induction motor equivalent circuit diagram | 305 |
| Fig. A4.3 | Simplified induction motor NPS equivalent circuit | 305 |
| Fig. A5.1 | 400 kVA transformer test certificate | 318 |
| Fig. A5.2 | 800 kVA transformer test certificate | 322 |
| Fig. A5.3 | 1.5 MVA transformer equivalent circuit | 333 |
| Fig. A5.4 | 2.0 MVA transformer equivalent circuit | 333 |
| Fig. A5.5 | 3.5 MVA transformer test certificate | 337 |
| Fig. A5.6 | 4.0 MVA transformer transfer equipment certificate | 342 |
| Table A6.1 | Zero sequence cable resistance calculation | 350 |
| Table A6.2 | Zero sequence cable reactance calculation | 351 |
| Fig. A7.1 | Motor withstand calculation | 354 |
| Fig. A7.2 | Torque/speed characteristic | 355 |

| | | |
|---|---|---|
| Fig. A7.3 | Equivalent circuit phase values | 356 |
| Fig. A7.4 | Manufacturers typical motor test record | 357 |
| Table A7.1 | Information requirements for electric motors | 353 |
| Fig. A8.1 | Typical Fuse Time/Current characteristics | 359 |
| Fig. A8.2 | Typical Fuse Cut-off current characteristics | 360 |
| Table A8.1 | Typical Fuse $I^2t$ characteristics | 360 |
| Fig. A10.1 | Current transformer equivalent current | 373 |
| Fig. A10.2 | Current transformer vector diagram | 373 |

## List of Abbreviations

| | | |
|---|---|---|
| ALF | - | Accuracy Limit Factor |
| BSS | - | British Standard Specification |
| CBCT | - | Core Balance Current Transformer |
| CSM | - | Current Setting Multiplier |
| CT | - | Current Transformer |
| D/O/L | - | Direct on Line |
| DTL | - | Definite Time Lag |
| EI | - | Extremely Inverse |
| FLC | - | Full Load Current |
| HV | - | High Voltage |
| IDMTL | - | Inverse Definite Minimum Time Lag |
| LV | - | Low Voltage |
| MPR | - | Motor Protection Relays |
| MSD | - | Motor Switching Device |
| NPS | - | Negative Phase Sequence |
| PPC | - | Point of Common Coupling |
| PPS | - | Positive Phase Sequence |
| SI | - | Standard Inverse |
| TMS | - | Time Multiplier Setting |
| VI | - | Very Inverse |
| ZPS | - | Zero Phase Sequence |

## CHAPTER 1

## 1. INTRODUCTION

The core of this project originated in the design philosophy of the first generation of electronic motor protection relays (MPR). Advances in the design of these devices have resulted from the introduction of digital electronic techniques which enable the relays to provide previously unheard of applications. The selection is usually carried out by means of miniature slide switches which select the desired functions and characteristic from a library of inbuilt features that the devices now possess. On some of the latest devices, multifunction selection is achieved by sequential operation of push buttons mounted on the relay faceplate. Such is the complexity of the available options that in the opinion of the author a need exists for a document which sets out a practical approach to the application of protection relays for direct-on-line (D/O/L) started induction motors in a general industrial environment. To achieve this objective in full would indeed be extremely difficult and would require a vast expenditure in man-hours to complete the task. The difficulty lies in the potential field to be explored which is extensive and increasing rapidly with the advent of modern microprocessor based relaying equipment. Hence, to provide 'proof of concept' the field has been limited to achievable proportions, these limits being set out in Chapter 2.

A further problem which can prove extremely time consuming arises from the protection requirements associated with equipment supplying large variable speed motors. A typical arrangement for this type of equipment comprises a main step-down transformer with two secondary windings phase displaced to provide twelve pulse convertor operation. The difficulties encountered with this type of installation can be readily appreciated as the motors are often not operated at their continuous rating but are driven into the overload state as part of their designed operating mode. By careful consideration of the operating parameters, it may be possible to select protection relay characteristics and settings which will bring about substantial cost savings by minimising the switchgear and cabling requirements. A method is suggested which demonstrates the potential of this approach.

For both D/O/L started and variable speed motors, problems will inevitably arise if an attempt is made to incorporate late design changes into the project. In the case of D/O/L started drives the change may involve a larger motor coupled with different acceleration parameters. The general dearth of information available coupled with a reluctance by manufacturers to provide customers with the required machine specifications can make the life of the protection engineer very difficult. Similar problems may be encountered with variable speed machines where the ratings, vector grouping and impedance of the transformers are not generally known until late in the project and even then are likely to further change. Theoretically a "design freeze" should eliminate the problem but countless projects have proved the contrary to be the case. To this end the work undertaken in the research project reported may point the way ahead because the effect of any changes can be rapidly incorporated and assessed thus enabling the earliest possible placement of orders to proceed. As a guide typical delivery times range from twelve weeks for relaying equipment to twenty four weeks for switchgear.

## 1.1 Project Implementation

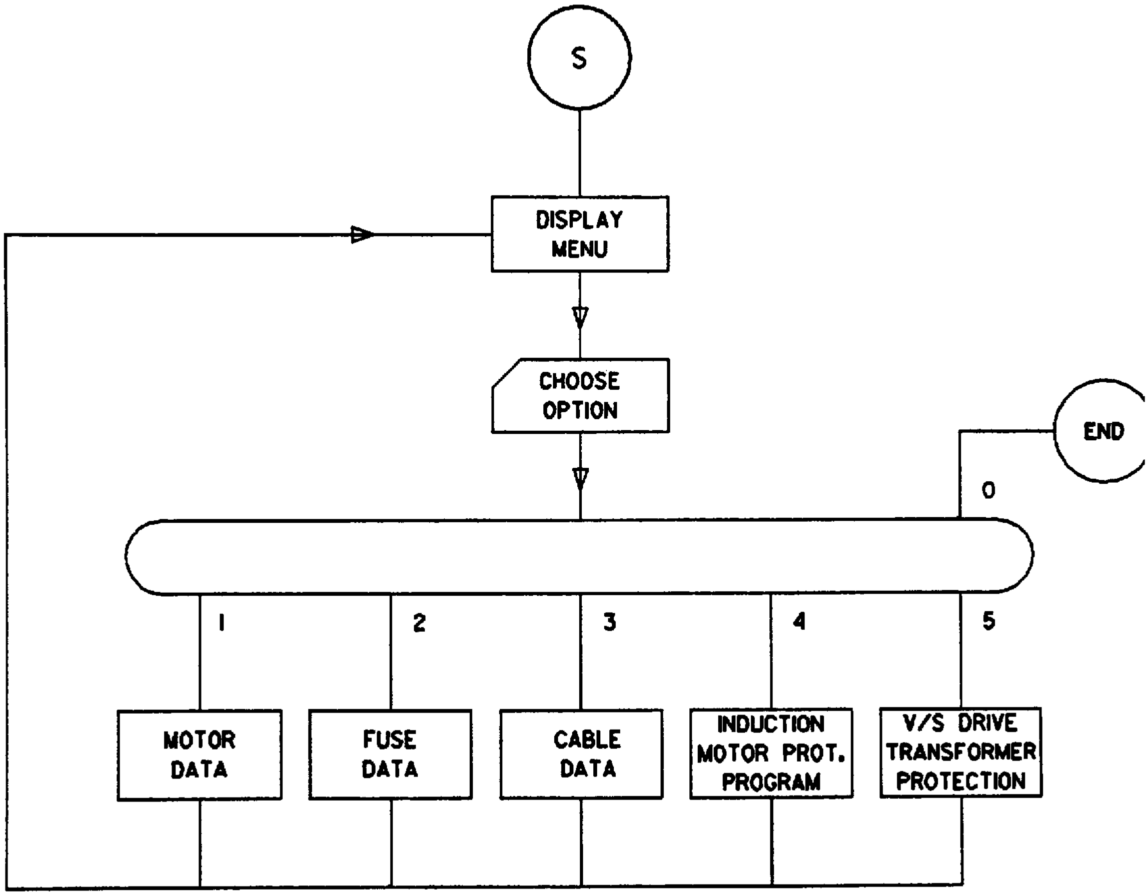
The research project undertaken may sensibly be separated into two parts. The first part is mainly concerned with the application of motor protection relays to direct-on-line started induction motors, whilst the latter part deals with the protection requirements applicable to transformer fed variable speed drives. Both parts of the project utilise a computer based solution based on a suite of novel algorithms developed in a modular format. The resulting programs are presented sequentially taking the user through a series of logical steps until a suitable solution is arrived at. To implement the solutions to the problems outlined in the project and detailed later, a database of subject matter has been established using standard DBASE III + software running on a personal computer. The benefits of using this software accrue from the inbuilt programming language which enables specific programs to be written to manipulate the stored data. Each section of the work contains general details of the individual programs which are used to determine the appropriate solution. The entire suite of programs is controlled by a master program called 'PROTSEL' from which the user is able to select five distinct options from a menu. A copy of the menu display is shown in Fig. 1.1. It can be seen that options 1-3 allow the user to access the motor, fuse and cable databases whilst options 4 and 5 involve the heart of this project. A flowchart of the 'PROTSEL' program is shown in Fig. 1.2.

```
THE DISTRIBUTION ENGINEERS ASSISTANT
MAIN SELECTION MENU

1.      FUSE  DATA
2.      CABLE DATA
3.      MOTOR DATA
4.      PROTECTION - MOTORS
5       PROTECTION - TCD TRANSFORMERS

Q.      QUIT

SELECT OPTION
```

*Fig 1.1 Main selection menu.*

ROUTINE : PROTSEL

TITLE : MAIN SYSTEM PROGRAM




1. MODATA - DATABASE OF MOTOR DATA INFORMATION
2. FUSEDATA - DATABASE OF FUSE DATA INFORMATION
3. CABDATA - DATABASE OF CABLE DATA INFORMATION
4. MPROT - D/O/L INDUCTION MOTOR PROTECTION PROGRAM
5. TX - VARIABLE SPEED DRIVE TRANSFORMER PROTECTION

Fig 1.2

## CHAPTER 2

# 2. DEFINING THE PROJECT BOUNDARIES

## 2.1 Selecting Protection for Direct-on-Line Started Induction Motors

Many papers[1,2,3] have been produced on this subject, generally by manufacturers or those parties who have a vested interest in extolling the virtues of a particular product, with the specific intention of increasing sales. Any inherent deficiencies which the device may exhibit are of course suppressed. It is with this background in mind that an attempt has been made to research, analyse and document both relay information and application techniques from a variety of sources and opinions which are relevant to a large cross section of the protection devices available today. Using the knowledge acquired from this research it has been found feasible to produce a novel algorithm which when applied to the problem, will produce the satisfactory selection of relay characteristics when required, together with the appropriate settings. The algorithm has been enhanced such that the system studied comprises cable, motor and where applicable, fusegear.

### 2.1.1 Historical Developments

Prior to the introduction of the electronic MPR, the protection function was carried out using electro-mechanical relays equipped with a thermal element. The thermal element comprised a small heating element supplied with a replica current proportional to the current taken by the motor. The heating element was located adjacent to a bimetallic coil. The coil was rigidly attached at the outside point to the relay case whilst it's centre was connected to a rotating shaft on which a moving contact was mounted. Excessive current drawn by the motor resulted in the shaft being rotated sufficiently to allow the moving contact to complete a trip circuit and disconnect the machine. The heating elements were usually applied to all three phases and mechanically coupled to a common shaft. The use of three phases allowed the variation in heat output to be used as a measure of phase current unbalance. The resultant movement of the bi-metallic coil caused by this differential heating effect being conveyed via mechanical linkages to effect tripping. The design was usually complemented with an additional unheated bimetallic coil whose function was to compensate for the ambient air temperature within the case. This was the general arrangement followed by MPR manufacturers for decades, the main variation being found in the quality of the mechanical implementation.

### 2.1.2 The Current Approach

With current technology it is possible to provide a high degree of protection for virtually any motor performing any duty under any particular set of conditions, provided the conditions and constraints are accurately specified and that sufficient funds are available to provide devices capable of sensing the imposed limitations. Clearly there is an economic constraint which suggests that the fitting of a sophisticated protection relay to a small low voltage machine would appear to be unrealistic although undoubtedly beneficial to the life expectancy of the motor. The essence of the problem is one of insurance, the engineer may choose cheap protection providing minimal coverage or alternatively more expensive protection for greater security. The solution may well result from a combination of both. There are also circumstances where minimal protection may be deemed desirable, such as the case where an unplanned shutdown of a motor for any reason other than a short circuit may have catastrophic results on the industrial process, certainly far in excess of the price of a new motor. For some situations, the sacrifice of a motor and the resulting loss of production may be tolerable, but for others, the solution may require built in redundancy in the form of duplicate or triplicate motors performing the vital function in order that the failure of one machine would not adversely affect the process. Such is the nature of the exercise that these often intangible factors must all be considered when assessing the protection requirements for any particular installation.

### 2.1.3 Fundamental Motor Information

As a precursor to writing a motor protection relay program it is sensible to consider some of the more fundamental aspects of the nature of the machines which are to be protected. The "Specification of General Requirements for Rotating Electrical Machines" is defined in British Standard (B.S.) 4999[4] and provides a wealth of information for consideration. Part 30 of this document relates to the "Duty and Rating" of machines. Clearly if a machine is used intermittently or for short periods of time, it may be run at a higher power output level than a motor which has a continuous running duty, provided adequate cooling periods follow the running mode. BS 4999 Part 30 lists and defines eight independent duty types which are designated from S1 to S8 inclusive. It is the S1 or continuous running duty which this project considers, as it is the most common type found in industrial applications. A further essential requirement is to consider the temperature excursions to which the machine may be subjected. BS 4999 Part 32 defines the limits of temperature rise for all insulation classes in order to prevent premature failure of the windings. The document also includes methods of temperature measurement and extrapolation techniques for predicting final machine temperatures. Both Parts 30 and 32 of BS 4999 are considered as essential reading.

If a load increase is envisaged for a particular machine it is sensible to perform a few preliminary calculations to predict the final winding temperature increase caused by a step change. A reasonable guide is provided by the following relationship.[5]

$$Temperature\,Rise\,(^{\circ}C) = T1 + (T2 - T1)\left(\frac{P}{Pn}\right)^2 \quad (2.1)$$

$T_1$ = Iron Loss temp rise °C (No Load)

$T_2$ = Temperature rise °C on Load at power output $P_n$ kW

$P_n$ = Nominal power output

P = New power output

Application of the above relationship to a typical example is described as follows: A motor submitted to Iron and Copper loss tests is rated at 150kW. With iron losses only the temperature rise is 20°C whilst at full load the temperature rise is 49°C (value obtained from test sheet). Predict the temperature rise for (a) 180kW (b) 217kW outputs respectively.

(a) For 180kW Output, $P = 180, P_n = 150, T_1 = 20, T_2 = 49$

Substituting the values in eq (2.1) gives:

$$Temperature\,Rise = 20 + (49 - 20)\left(\frac{180}{150}\right)^2 = 61.76^{\circ}C$$

Similarly

(b) For 217kW Output, $P = 217, P_n = 150, T_1 = 20, T_2 = 49$

Again substituting the values in equation (2.1) gives:

$$Temperature\,Rise = 20 + (49 - 20)\left(\frac{217}{150}\right)^2 = 80.69^{\circ}C$$

These temperature rise predictions compare favourably with the manufacturers declared temperature rise of 60°C and 80°C for the 180kW and 217kW rating respectively.

If such output increases were to be contemplated it should be noted that the 'hot' thermal withstand characteristic of the motor, which is the curve relating the sustained motor overload current to its allowable duration, would be reduced. This reduced withstand time must be reflected in the 'hot' thermal withstand characteristic of the protection relay if protection is to be maintained. The 'cold' or starting characteristic would of course remain unchanged for both motor and relay.

Improvements in motor insulating materials have resulted in the widespread adoption of class F insulation to supersede the older class B insulated machines. This change of insulation class allows a typical increase of 20°C on the previous maximum running temperature, enabling induction motors of a given frame size and configuration to produce increased output at the shaft. Utilisation of this temperature increase results in the motor exhibiting the reduced thermal withstand ability referred to above, particularly under locked rotor conditions. Hence a more discerning analysis of both machine and protective device would be deemed appropriate.

Exceeding the maximum specified temperature rise of an induction motor is to be avoided. As a general guide, the machine life is halved for each 10°C increase over rated temperature or expressed as an equation

$$Relative\,Insulation\,Life = 0.5^{\frac{x}{10}} \bullet 100\% \qquad (2.2)$$

where x is the temperature increase (°C) over rated temperature

Alternatively if the working temperature of the machine is reduced then an increase in life span may be expected, albeit at the expense of a lower operating efficiency.

The thermal withstand capabilities of a machine may be represented by means of a single time constant exponential curve, which models the hot and cold characteristics of the insulation. Appendix 1 contains a derivation of these characteristics which can be used to provide suitable thermal modelling of a motor.

The method of protection adopted by the relay manufacturer is intended to provide a device with operating characteristics which comply with the desired withstand characteristics laid down in BS 142[6]. Two models are referred to in this document. The first, a general curve, models both hot and cold characteristics using a single time - constant exponential curve; whilst the second suggested arrangement uses an adiabatic relationship. It is the characteristic defined in the former case which is utilised by the two relays examined in this investigation. The link between motor and device model can clearly be seen.

Some machine manufacturers provide customers with composite withstand characteristics. These characteristics provide a more accurate assessment of the thermal withstand capability of the machine by using the exponential approach in the overload region (1 - 2½ x flc) whilst an adiabatic arrangement is used to represent the high current, low speed/locked rotor zone. Clearly this is a more realistic representation for machines which are fitted with internal cooling fans driven from the shaft. In such cases satisfying the locked rotor condition will usually result in a generous protective margin in the overload region. It is however, essential to check and confirm that such margins exist.

Before considering the type of protection to be employed, the engineer must determine whether sufficient supply capacity is available to allow the machine to start in the first place. Indeed, regulation in the motor supply may reduce the starting torque to a level insufficient for the machine to break away. Bearing in mind that torque is proportional to Applied Voltage$^2$, then 80% applied voltage results in 64% starting torque. The magnitude of the supply "voltage dip" may well cause distress to other circuits supplied from the same busbar, and will probably prove to be the limiting factor especially in the case of 415V machines, where the busbar will usually supply lighting and voltage sensitive solid state/computer type loads. To quantify a potential problem it is expedient to carry out a few simple checks. Consider the following 415V Induction Motor.

Output 150kW; FLC 245 amp; Starting current 670% FLC

Supply arrangement

1. An 11/0.431kV, 800kVA transformer of 6.3% Impedance
2. An 11/0.431kV 1500kVA transformer of 7.75% Impedance

   11kV Source MVA = 150

(Q) What is the busbar voltage at the instant of starting?

(A) Let base MVA = 5

Then impedance of 11kV source expressed at base MVA

$$= 100 \bullet \frac{5}{150} = 3.33\%$$

Similarly for transformers

$$1. \quad 800kVA\ unit \quad \frac{5}{0.8} \bullet 6.3 = 39.38\%$$

$$2. \quad 1500kVA\ unit \quad \frac{5}{1.5} \bullet 7.75 = 25.83\%$$

$$Motor\ locked\ rotor\ impedance = \frac{100}{6.7} = 14.93\%$$

$$and\ referred\ to\ base\ MVA = \frac{5}{0.15} \bullet 14.93 = 497.51\%$$

Assuming % motor reactance = % motor impedance at start due to low starting power factor it follows that:

Motor Terminal Voltage = Busbar Voltage

$$\simeq \frac{Motor\,\%Z}{Motor\,\%Z + Transformer\,\%Z + Source\,\%Z}$$

$$For\ the\ 800kVA\ unit\ Busbar\ Voltage \simeq \frac{497.51}{497.51 + 39.38 + 3.33} \bullet 100\% = 92.09\%$$

$$For\ the\ 1500kVA\ unit\ Busbar\ Voltage \simeq \frac{497.51}{497.51 + 25.83 + 3.33} \bullet 100\% = 94.46\%$$

For large machines where the voltage dips produced may be troublesome, a more rigorous approach using resistance and reactance values should be employed, and should include cable impedance values and some method of modelling the standing load.

On 11kV supply systems the more rigorous approach is essential, where standard 'tools' in the form of 'load flow' programs are readily available. In systems where synchronous machines are present and where the possibility of loss of synchronism during the starting period may exist, then "Transient System' studies for the investigation of the stability of the system must be made. It is not the intention to discuss 'Power System Analysis' by mathematical modelling, but to draw the readers attention to the importance of thorough pre-installation examination of the system to which the machine is to be connected, and the consequential effect of 'getting it wrong'.

Having established that the system in question can sustain the increased load and is able to accommodate the initial voltage dip, the engineer should calculate the effects of the reduced voltage on the time taken for the motor to accelerate the load up to full speed. The usual approach is to calculate the acceleration time assuming that the reduced voltage remains constant throughout the acceleration period, then to recalculate the acceleration time assuming the presence of 100% voltage at all times. A further calculation for the overvoltage condition should also be carried out if possible. The three values thus calculated represent the maximum, minimum and nominal values of acceleration time and are used as constraints when determining the upper and lower limits of the protection relay thermal withstand characteristic. A method suitable for determining the acceleration times is described in Appendix 2.

## 2.2 Variable Speed Drives

The use of solid state devices and drives in industrial installations is becoming increasingly prevalent. One of the many applications to be found is in the role of starting and speed control of induction motors. The control being achieved by either varying the output voltage magnitude, the frequency or both. The former case is generally used in 'Soft Start' units where an increasing voltage ramp is applied to the motor to accelerate it up to speed. The unit usually incorporates a current limiting feature and some form of motor protection. Where speed control of the machine is considered, a far more sophisticated arrangement is required which will produce the required output voltage and frequency. The topology of the convertor equipment varies considerably but will ultimately be dictated by the economics of producing adequate supplies at the correct voltage level, ac or dc, to satisfy the load requirements. Most modern variable speed drives are invariably supplied from ac sources. Here again some form of motor protection is a built in feature of the equipment.

The vast majority of such devices are to be found on 415V systems where solid state control devices capable of handling such voltage levels are readily available. Where larger drives are required they may be supplied from more substantial sources at higher voltage levels, step down transformers being utilised to reduce the supply voltage to the required working voltage level. Whilst this is the arrangement usually encountered, variable frequency equipment at both 3.3kV and 11kV does exist and may prove useful where variable speed modifications are envisaged on an existing machine. The by product of using such devices may be observed by monitoring the busbar voltage which can be seen to contain an increased harmonic content. Guidance for the maximum permissible distortion values may be gleaned from 'The Electricity Council Engineering Recommendation G5/3 - Limits for Harmonics in the United Kingdom Electricity Supply System'.[7]

A direct effect of harmonic content in the supply voltage waveform may be seen in Appendix 3 which discusses the implications of waveforms containing harmonics.

Similar detrimental effects to the life span of a machine are caused by the application of unbalanced voltages to three phase induction motors. Such effects may be caused by motors being supplied from busbars containing heavy single phase loads, transformer tap changer damage, or in an extreme case, open-circuits in a supply phase. Appendix 4 examines some of the undesirable effects and why they should be avoided.

## References

1. Advanced Motor Protection using microcomputers by Joe Brandolino, Multilin Inc, Markham, Ontario, Canada.

2. Guide for the choice of protective relays - CEE.

3. Protective relays application guide published by GEC Measurements.

4. BS 4999 - The Specification of General Requirements for Rotating Electrical Machines.

5. Electro-Magnetic Machines by Langlois Berthelot.

6. BS 142 Electrical Protective Relays.

7. The Electricity Council Engineering Recommendation G5/3 - Limits for Harmonics in the United Kingdom Electricity Supply System.

# CHAPTER 3

## 3. ASSOCIATED COMPONENTS IN THE MOTOR CIRCUIT

### 3.1 Introduction

When considering the application of protection systems to induction motors it should be emphasised that the relaying equipment must protect the entire circuit comprising of the motor, associated mains cabling, terminal boxes, isolators, switchgear and any other component which may be subjected to the through fault current. In the case where a motor is supplied via a circuit breaker then all components must be fully rated to withstand the forces and heating effects which are imposed by the fault current during the fault detection period and the subsequent opening time of the device.

### 3.2 Switching Device Considerations

When the switching device used is a contactor the stresses imposed during fault conditions are far in excess of the switching capabilities of the device. The solution is of course found in the use of fuses which contain no moving parts and are thus capable of extremely fast operation at high fault levels, such that the magnitude of the potential fault current is limited and the associated energy dissipated at the fault location, is restricted to a low level. The benefit of using such devices results in cable and associated components of much reduced current rating because they are only required to withstand the thermal effects associated with the normal current demanded by the motor and the maximum 'let thro' energy of the fuse. In such cases the motor, cabling, isolator and switching device is protected against overloads by the thermal protection relay, whilst the fuses provide the short circuit protection. When considering protection of 415V motors, the resulting installation is required to conform with the 16th edition of the IEE Wiring Regulations[1]. This requires particular note to be taken of Regulation 435-01-01 which states:

"The characteristics of each device for overload current protection and for fault current protection shall be co-ordinated so that the energy let through by the fault current device, does not exceed that which can be withstood without damage by the overload protective device".

Note: For circuits incorporating motor starters, Regulation 435-01-01 does not preclude the type of coordination described in BS 4941.

Unfortunately BS 4941 allows 3 types of co-ordination: "a", "b" and "c" of which only type "c" ensures that the overload relay is not damaged by short circuit current. The relevance of the above quotation emphasises that in circuits where potentially high fault currents are available, the short circuit fuse protection must be capable of providing type 'c' protection. Standards however are subject to change, the frequency of change now being greater than that experienced previously as authorities strive to produce harmonised documents which will be valid throughout the EEC. A new International Standard IEC 947-4[2] was published in 1990 to replace IEC 158[3] and IEC 292-1[4] (equivalent to BS 4941)[5]. As the document will no doubt become a British Standard (BSS) eventually, due note should be taken of the revised categories which are now reduced to two, types 1 and 2. The type 1 category allows damage to the starter whilst the type 2 does not. This latter category is far more onerous as it is essential for manufacturers to subject the various combinations of equipment to type tests at official testing stations (ASTA[6], KEMA[7], etc). The object of the tests being to establish that cut-off current and 'let thro' energy are below the limits that the thermal overload device and contactor can withstand without damage.

Great care should be taken in HV installations where it is intended that the short-circuit duty is to be controlled by the rupturing of a fuse element. It is imperative to ensure that the switching device remains closed for currents in excess of its switching capability until sufficient time has elapsed to allow the fault current to be removed. The potential danger of this problem is highlighted in an example cited in Chapter 4, section 4.1.3.3.

Where circuits are controlled by fully rated circuit breakers, due attention must be paid to the rated burden of the current transformers (CT) in order to prevent the short time withstand capabilities of the protective relay being exceeded. This is particularly important when considering HV motors where CT ratios are relatively low and potential fault current is high. Additional short time limitations may also be imposed on the CT's themselves in cases where wound primary windings are being used to overcome low CT ratios. It is in this area of high powered machines utilising motor protection relays, whose measuring current is derived from current transformers, that this project is directed. The remainder of this chapter will discuss the steps in the design of typical direct on line started motor installations and attempt to reduce the process to a series of linked steps which may be coded in a program and presented in modular form as an aid to circuit design. The major design stages dealt with are motor, cable and where appropriate fuse selection. A typical example is used in the next section to illustrate the procedure adopted.

## 3.3 Specifying the Circuit Components

The program for the selection of motor protection relays is chosen by selecting option 4 from the main system menu. A copy of the menu display is illustrated in Fig. 3.1. On selection the screen is cleared and replaced by a list of available motor types indexed in an ascending voltage order with the least number of poles

```
THE DISTRIBUTION ENGINEERS ASSISTANT
MAIN SELECTION MENU

1.      FUSE  DATA
2.      CABLE DATA
3.      MOTOR DATA
4.      PROTECTION - MOTORS
5       PROTECTION - TCD TRANSFORMERS

Q.      QUIT

SELECT OPTION
```

*Fig 3.1* *Main selection menu.*

listed first. A typical display is shown in Fig. 3.2. The listing is of course subject to change as additional ranges of motors are added to the database. The user is required to make a selection from the range of motor types offered or alternatively an option is available to enter data for individual motors not listed in the main database.

As an example let the range chosen be:

415V, 4 pole, BCPM 'ARGUS' 55, TEFC with class F insulation

That is to say: option 2. Selecting this option internally determines that the voltage level used in the program is 415V. The screen is then cleared and replaced by a full listing of the motor output powers for the range selected. A typical display is shown in Fig. 3.3. A further selection is now necessary to determine the required motor rating. Provided a valid selection is made, that is, the rating is listed, the appropriate location in the database is accessed and all available data displayed on the screen. The user being invited to supply any missing information. A typical display is shown in Fig. 3.4.

Consider the chosen motor to have an output rating of 75kW with a predicted acceleration time of less than 10 seconds. The following information may be extracted from the database:

| | |
|---|---|
| Full load current | 132 Amp at 0.86 lag |
| Starting current | 858 Amp at 0.25 lag |

MOTOR PROTECTION
MANUFACTURERS AND TYPES

| | | | | |
|---|---|---|---|---|
| 1 | 415 V | 2 pole | BCPM ARGUS 55 TEFC | Cl.F 80C |
| 2 | 415 V | 4 pole | BCPM ARGUS 55 TEFC | Cl.F 80C |
| 3 | 415 V | 6 pole | BCPM ARGUS 55 TEFC | Cl.F 80C |
| 4 | 415 V | 8 pole | BCPM ARGUS 55 TEFC | Cl.F 80C |
| 5 | 3300 V | 2 pole | GEC IMPAK IP44,W44 & W45S:IC0161,0661 | Cl.F 80C |
| 6 | 3300 V | 4 pole | GEC IMPAK IP44,W44 & W45S:IC0161,0661 | Cl.F 80C |
| 7 | 3300 V | 6 pole | GEC IMPAK IP44,W44 & W45S:IC0161,0661 | Cl.F 80C |
| 8 | 3300 V | 8 pole | GEC IMPAK IP44,W44 & W45S:IC0161,0661 | Cl.F 80C |
| 9 | 3300 V | 10 pole | GEC IMPAK IP44,W44 & W45S:IC0161,0661 | Cl.F 80C |
| 10 | 3300 V | 12 pole | GEC IMPAK IP44,W44 & W45S:IC0161,0661 | Cl.F 80C |

Select option ... 2

<Q>uit
<U>nclassified

*Fig 3.2 Motor catalogue.*

MOTOR PROTECTION
415V 4 pole BCPM ARGUS 55 TEFC

Ratings in kW

| | | |
|---|---|---|
| 0.55 | 15 | 132 |
| 0.75 | 18.5 | 150 |
| 1.1 | 22 | 185 |
| 1.5 | 30 | 200 |
| 2.2 | 37 | 225 |
| 3 | 45 | 250 |
| 4 | 55 | 280 |
| 5.5 | 75 | 315 |
| 7.5 | 90 | 355 |
| 11 | 110 | |

Select rating 75

<Q>uit
<P>age back

*Fig 3.3 415V, 4 pole, motor rating list.*

```
                    415V  4 pole  BCPM ARGUS 55 TEFC
                                  75kW

Current :
  at Full Load                     132  Amps      at Start   858  Amps

3 ph Withstand :
  at 2x F/L Current      - Cold  775   Secs         - Hot  588    Secs
  at Locked Rotor        - Cold   12   Secs         - Hot    9    Secs

1 ph Withstand :
  at F/L Output          - Cold   545  Secs         - Hot   475   Secs
  at Locked Rotor        - Cold   11   Secs         - Hot   7     Secs

Starting Seconds         -Cold     20  Secs         - Hot    15   Secs

<A>ccept / <R>eject A                                     <Q>uit
                                                          <P>age back
```

*Fig 3.4     415V, 4 pole, 75kW, motor data display.*

Representing these two conditions by single phase equivalent impedances gives:

1. for running condition

$$Z = \frac{V}{I} = \frac{415}{\sqrt{3}} \bullet \frac{1}{132 \quad Cos^{-1} 0.86} = 1.5610 + j0.9263\Omega$$

2. for starting condition

$$Z = \frac{V}{I} = \frac{415}{\sqrt{3}} \bullet \frac{1}{858 \quad Cos^{-1} 0.25} = 0.0698 + j0.2704\Omega$$

The values determined above are of course calculated within the program but are included to illustrate the strategy employed within the overall algorithm.

Having determined the equivalent impedance of the motor it is now appropriate to define the power system source impedance at the point of common coupling (PCC). The user is invited to enter maximum and minimum fault currents and associated X/R ratios at the PCC as an alternative to a number of typical values which may be selected from the program. The derivation of the typical values used from the data provided by transformer manufacturers is included in Appendix 5. Fig. 3.5 illustrates typical entry screen details for a 1500 kVA transformer source.

At this juncture it is necessary to establish if the motor is to be switched via a circuit breaker or a fused contactor as this factor has a significant bearing on the cable size. Initially, assume that the supply incorporates a fused contactor, the effect of the fuse being to limit the 'let-thro' energy $I^2t$ ($A^2$ sec) fed to the fault thus minimising the large forces generated and the rapid heating effects $I^2R$ (watts) produced by the fault current within the cable and circuit components.

```
                    415V   4 pole   BCPM ARGUS 55 TEFC
                             SYSTEM CONDITIONS

  Circuit controlled by circuit breaker   ..........      N
  Select typical value option number      ..........      4

                                                        Amps   | X/R
  Minimum 3ph fault current at source     ..........    23730  | 5.522
  Maximum 3ph fault current at source     ..........    47460  | 5.522

  Minimum Earth fault current at source   ..........    30531  | 3.291
  Maximum Earth fault current at source   ..........    61062  | 3.291

------------------------------ TYPICAL VALUES ----------------------------
<1>  3.3/ 0.431 kV  YYOD1   400 kVA     <4> 11.0/ 0.431 kV  YYOD1  1500 kVA
<2>  3.3/ 0.431 kV  YYOD1   800 kVA     <5> 11.0/ 0.431 kV  YYOD1  2000 kVA
<3> 11.0/ 0.431 kV  YYOD1   800 kVA

  <A>ccept / <R>eject A                                      <Q>uit
                                                             <P>age back
```

*Fig 3.5    Switching device and source data display for 1500kVA transformer.*

If the fuse links used are GEC TYPE 'T' HRC type then reference to the manufacturers data indicates that the optimum size fuselink for this duty is 250A. For this fuselink the total let thro energy is 550 x $10^3$ $A^2$ sec and, by inspection of table 3.1, the minimum fault disconnecting current required to ensure fuse operation in less than 5 seconds is found to be 1496A.

Typical displays of fuse selection information presented by the program are shown in Figs. 3.6 and 3.7. It can be seen that all unsuitable fuse ratings are marked with an asterisk. The option thus being to select any fuse equal to or larger than 250A. As an example, consider the fuse rating chosen to be 250A.

In this example the cable selection procedure is accomplished by choosing a cable type from a displayed list, a typical display is as shown in Fig. 3.8. The cable selected is option 1. The cable defined by this option is:

600/1000V grade, 3 core, PVC insulated, extruded bedding, single wire armour and an oversheath of PVC. The conductor being of stranded copper construction and generally complying with BS 6346[8].

The user is required to enter the route length of the cable run and the cable derating factor in order to select cables of adequate current rating for examination.

For example consider the cable length selected to be 100 metres with a derating factor of 0.85.

To ensure the satisfactory operation in service and protection of the cable the following series of checks are necessary.

| FUSE RATING (AMPS) | DISCONNECTING CURRENT * (AMPS) |
|---|---|
| 6 | 18 |
| 10 | 31 |
| 16 | 55 |
| 20 | 79 |
| 25 | 100 |
| 32 | 125 |
| 40 | 170 |
| 50 | 220 |
| 63 | 280 |
| 80 | 400 |
| 100 | 550 |
| 125 | 690 |
| 160 | 900 |
| 200 | 1200 |
| 250 | 1496 |
| 315 | 2184 |
| 400 | 2499 |
| 500 | 2699 |
| 630 | 4447 |
| 800 | 7064 |

* The disconnecting current is the current required to ensure fuse operation in 5 seconds.
Values of disconnecting current comply with the 16th Edition I.E.E. Wiring Regulations for fuse ratings of 200A and less.

Relationship between BS88 fuse ratings and current required for operation in less than 5 seconds.

TABLE 3.1

```
                     415V  4 pole  BCPM ARGUS 55 TEFC
                              FUSE CATALOGUE

1    415      GEC  TYPE 'T' HRC FUSELINKS               BSS 88    1988
2    550      GEC  TYPE 'T' HRC FUSELINKS               BSS 88    1988
3    660      GEC  TYPE 'T' HRC FUSELINKS               BSS 88    1988
4   3300      B&S  3.6kV MOFSB,MRFSA    RUT <  6s       BS 2692   1975
5   3300      B&S  3.6kV MOFSB,MRFSA    RUT < 15s       BS 2692   1975
6   3300      B&S  3.6kV MOFSB,MRFSA    RUT < 60s       BS 2692   1975
7   3300      GEC  3.6kV K81PEX FUSES   RUT <  6s       BS 2692   1975
8   3300      GEC  3.6kV K81PEX FUSES   RUT < 15s       BS 2692   1975
9   3300      GEC  3.6kV K81PEX FUSES   RUT < 60s       BS 2692   1975

Select option   1                                          <Q>uit
                                                           <C>ontinue
```

*Fig 3.6    Fuse catalogue.*

415V 4 pole BCPM ARGUS 55 TEFC
415V GEC TYPE 'T' HRC FUSELINKS

75 kW - F/Load 132 Amps
- Start 858 Amps

BS88: Part 1:1975
ASTA 20 Certified

| | RATING | R/U/T | | RATING | R/U/T | | RATING | R/U/T |
|---|---|---|---|---|---|---|---|---|
| * | 2 | 5 | * | 63 | 10 | + + | 500 | 0 |
| * | 4 | 5 | * | 80 | 10 | | 560 | 15 |
| * | 6 | 5 | * | 100 | 10 | | 630 | 15 |
| * | 10 | 10 | * | 125 | 10 | + | 670 | 0 |
| * | 16 | 10 | * | 160 | 10 | + | 710 | 0 |
| * | 20 | 10 | * | 200 | 10 | + | 750 | 0 |
| * | 25 | 10 | | 250 | 15 | + | 800 | 0 |
| * | 32 | 10 | | 315 | 15 | + | 1000 | 0 |
| * | 35 | 10 | | 355 | 15 | + | 1250 | 0 |
| + | 40 | 0+ | + | 400 | 0 | | | |
| * | 50 | 10 | | 450 | 15 | | | |

* Unsuitable - less than flc.
\+ Unsuitable - no start data

Select rating 250

<P>ageback
<Q>uit

*Fig 3.7 Typical fuse rating list.*

```
              415V  4 pole  BCPM ARGUS 55 TEFC
                    CABLE CATALOGUE

 1  600/1000    3c   Str Cu   PVC/EXTR/SWA/PVC         BSS 6346 1969   M
 2  600/1000    1c   Str Cu   XLPE/PVC                 BSS 5467 1977   M
 3  3800/6600   3c   Str Al   XLPE/SCR/SWA/PVC         IEC 502  1983   M
 4  6350/11000  3c   Str Al   XLPE/SCR/SWA/PVC         IEC 502  1983   M

 Select option    1    Cable length 100 mtrs       <C>ontinue  <Q>uit
 Derating factor 0.85  <A>ccept / <R>eject A                   <P>ageback
```

*Fig 3.8* *Cable catalogue.*

To comply with IEE Regulation 433 - 02 - 01 which states:

$I_B \leq \quad I_n \leq I_z$

where $I_B$ = Design current of the circuit, that is a Motor full load current of 132A

$I_n$ = The nominal current setting of the protective device which in this case is a 250 Amp fuselink.

$I_z$ = The current carrying capacity of the conductors.

It should be noted that where the fuse is not the only protective device in the circuit, that is to say: it is augmented by a motor protection relay; then Iz need only be greater than or equal to the relay setting.

Referring to Fig. 3.9 it can be seen that:

(a) Provided the cable is buried a cross-sectional area (CSA) of 35mm$^2$ provides an adequate current rating.

(b) Where the cable route is partly buried and partly in air, a CSA of 50mm$^2$ is satisfactory.

(c) A cable with a CSA of 70mm$^2$ provides an adequate current rating for routes comprising of portions laid in the ground, air and in duct.

Hence, provided the conductor current carrying capacity, Iz, satisfies the appropriate condition a, b or c and is greater than or equal to the motor flc, then the conductor current rating will be adequate providing the proposed relay overload operating point does not exceed 1.45 x Iz. The factor, 1.45, is included because the current causing effective operation of the protective device should not exceed 1.45 x Iz to comply with regulation 433-02-01. This condition is satisfied when BS 88 or BS 1361 fuses are used.

Compliance with IEE Regulation 434-03-03 which states:

Where a protective device is provided for fault current protection only, the clearance time of the device under both short-circuit and earth fault conditions shall not result in the admissible limiting temperature of any live conductor being exceeded.

The time t, in which a given fault current will raise the live conductors from the highest permissible temperature in normal duty to the limiting temperature, can, as an approximation be calculated from the formula stated in
Regulation 434-03-03 as:

$$t = \frac{k^2 S^2}{I^2} \qquad (3.1)$$

| | | | |
|---|---|---|---|
| where: | t | = | duration in seconds |
| | S | = | nominal CSA of the conductor in mm2 |
| | I | = | Short circuit current in amps |
| | k | = | 115 for copper conductors insulated with PVC |

When applying fuse links to protect a 415V motor, one should be aware of the limitations imposed by the earth fault loop impedance for compliance with regulation 543-01-03 which states:

The CSA, where calculated, shall not be less than the value determined by the following formula or shall be obtained by reference to BS 7454.

$$S = \frac{\sqrt{(I^2 t)}}{k} \ mm^2 \qquad (3.2)$$

where: S is the nominal CSA of the conductor in mm2

I is the value in amperes of the fault current for a fault of negligible impedance which can flow through the associated protective device, where due account is taken of the current limiting effect of the circuit impedances and the limiting capability ($I^2t$) of that protective device.

t is the operating time of the disconnecting device in seconds corresponding to the fault current I amperes.

k is the factor taking account of resistivity, temperature coefficient and heat capacity of the conductor material, and the appropriate initial and final temperatures.

Additionaly it should be noted that the maximum disconnecting time for TN-S systems is stated as 5 seconds in regulation 413-02-13.

It can be seen that caution must be exercised particularly when considering large 415V motors supplied via long cable lengths which rely on fuselinks for disconnection of earth fault conditions.

The minimum fault current required to rupture any fuse link complying with BS 88: Part 2 may be determined by reference to table 3.2 which specifies the minimum CSA of protective conductor which satisfies Regulation 543-01-03 assuming a maximum disconnection time of 5 seconds.

Consider a 250A fuselink used in conjunction with a PVC/SWA/PVC cable, the appropriate k factor for steel wire being 51. Referring table 3.2 it can be seen that at the intersection of the row containing the k factor of 51 and the 250A fuse link column lies a value of 66 which represents the minimum size of protective conductor ($mm^2$) satisfying Regulation 543-01-03.

| Fuses to BS88 Part 2 | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| K | 6A | 10A | 16A | 20A | 25A | 32A | 40A | 50A | 63A | 80A | 100A | 125A | 160A | 200A | 250A | 315A | 400A | 500A | 630A | 800A |
| 22 | 1.83 | 3.15 | 5.59 | 8.03 | 10.2 | 12.7 | 17.3 | 22.4 | 28.5 | 40.7 | 32.5 | 70.1 | 91.5 | 122 | 152 | 222 | 254 | 376 | 452 | 718 |
| 23 | 1.75 | 3.01 | 5.35 | 7.68 | 9.72 | 12.2 | 16.5 | 21.4 | 27.2 | 38.9 | 31.1 | 67.1 | 87.5 | 117 | 145 | 212 | 243 | 360 | 432 | 687 |
| 24 | 1.68 | 2.89 | 5.12 | 7.36 | 9.32 | 11.6 | 15.8 | 20.5 | 26.1 | 37.3 | 29.8 | 64.3 | 83.9 | 112 | 139 | 203 | 233 | 345 | 414 | 658 |
| 26 | 1.55 | 2.67 | 4.73 | 6.79 | 8.60 | 10.8 | 14.6 | 18.9 | 24.1 | 34.4 | 27.5 | 59.3 | 77.4 | 103 | 129 | 188 | 215 | 318 | 382 | 608 |
| 27 | 1.49 | 2.57 | 4.55 | 6.54 | 8.28 | 10.4 | 14.1 | 18.2 | 23.2 | 33.1 | 26.5 | 57.1 | 74.5 | 99 | 124 | 181 | 207 | 306 | 368 | 585 |
| 44 | 0.91 | 1.58 | 2.80 | 4.01 | 5.08 | 6.4 | 8.6 | 11.2 | 14.2 | 20.3 | 16.3 | 35.1 | 45.7 | 61 | 76 | 111 | 127 | 188 | 226 | 359 |
| 46 | 0.87 | 1.51 | 2.67 | 3.84 | 4.86 | 6.1 | 8.3 | 10.7 | 13.6 | 19.4 | 15.6 | 33.5 | 43.7 | 58 | 73 | 106 | 121 | 180 | 216 | 343 |
| 48 | 0.84 | 1.44 | 2.56 | 3.68 | 4.66 | 5.8 | 7.9 | 10.2 | 13.0 | 18.6 | 14.9 | 32.1 | 41.9 | 56 | 70 | 102 | 116 | 172 | 207 | 329 |
| 51 | 0.79 | 1.36 | 2.41 | 3.46 | 4.38 | 5.5 | 7.5 | 9.6 | 12.3 | 17.5 | 14.0 | 30.3 | 39.5 | 53 | 66 | 96 | 110 | 162 | 195 | 310 |
| 52 | 0.77 | 1.33 | 2.37 | 3.40 | 4.30 | 5.4 | 7.3 | 9.5 | 12.0 | 17.2 | 13.8 | 29.7 | 38.7 | 52 | 64 | 94 | 107 | 159 | 191 | 304 |
| 54 | 0.75 | 1.28 | 2.28 | 3.27 | 4.14 | 5.2 | 7.0 | 9.1 | 11.6 | 16.6 | 13.3 | 28.6 | 37.3 | 50 | 62 | 90 | 103 | 153 | 184 | 293 |
| 60 | 0.67 | 1.16 | 2.05 | 2.94 | 3.73 | 4.7 | 6.3 | 8.2 | 10.4 | 14.9 | 11.9 | 25.7 | 33.5 | 45 | 56 | 81 | 93 | 138 | 166 | 263 |
| 64 | 0.63 | 1.08 | 1.92 | 2.76 | 3.49 | 4.4 | 5.9 | 7.7 | 9.8 | 14.0 | 11.2 | 24.1 | 31.4 | 42 | 52 | 76 | 87 | 129 | 155 | 247 |
| 76 | 0.53 | 0.91 | 1.62 | 2.32 | 2.94 | 3.7 | 5.0 | 6.5 | 8.2 | 11.8 | 9.4 | 20.3 | 26.5 | 35 | 44 | 64 | 74 | 109 | 131 | 208 |
| 81 | 0.50 | 0.86 | 1.52 | 2.18 | 2.76 | 3.5 | 4.7 | 6.1 | 7.7 | 11.0 | 8.8 | 19.0 | 24.8 | 33 | 41 | 60 | 69 | 102 | 123 | 195 |
| 85 | 0.47 | 0.82 | 1.45 | 2.08 | 2.63 | 3.3 | 4.5 | 5.8 | 7.4 | 10.5 | 8.4 | 18.2 | 23.7 | 32 | 39 | 57 | 66 | 97 | 117 | 186 |
| 87 | 0.46 | 0.80 | 1.41 | 2.03 | 2.57 | 3.2 | 4.4 | 5.7 | 7.2 | 10.3 | 8.2 | 17.7 | 23.1 | 31 | 38 | 56 | 64 | 95 | 114 | 182 |
| 89 | 0.45 | 0.78 | 1.38 | 1.98 | 2.51 | 3.1 | 4.3 | 5.5 | 7.0 | 10.0 | 8.0 | 17.3 | 22.6 | 30 | 38 | 55 | 63 | 93 | 112 | 177 |
| 93 | 0.43 | 0.75 | 1.32 | 1.90 | 2.40 | 3.0 | 4.1 | 5.3 | 6.7 | 9.6 | 7.7 | 16.6 | 21.6 | 29 | 36 | 53 | 60 | 89 | 107 | 170 |
| 94 | 0.43 | 0.74 | 1.31 | 1.88 | 2.38 | 3.0 | 4.0 | 5.2 | 6.7 | 9.5 | 7.6 | 16.4 | 21.4 | 29 | 36 | 52 | 59 | 88 | 106 | 168 |
| 95 | 0.42 | 0.73 | 1.29 | 1.86 | 2.35 | 2.9 | 4.0 | 5.2 | 6.6 | 9.4 | 7.5 | 16.2 | 21.2 | 28 | 35 | 51 | 59 | 87 | 105 | 166 |
| 98 | 0.41 | 0.71 | 1.25 | 1.80 | 2.28 | 2.9 | 3.9 | 5.0 | 6.4 | 9.1 | 7.3 | 15.7 | 20.5 | 27 | 34 | 50 | 57 | 84 | 101 | 161 |
| 110 | 0.37 | 0.63 | 1.12 | 1.61 | 2.03 | 2.5 | 3.5 | 4.5 | 5.7 | 8.1 | 6.5 | 14.0 | 18.3 | 24 | 30 | 44 | 51 | 75 | 90 | 144 |
| 115 | 0.35 | 0.60 | 1.07 | 1.54 | 1.94 | 2.4 | 3.3 | 4.3 | 5.4 | 7.8 | 6.2 | 13.4 | 17.5 | 23 | 29 | 42 | 49 | 72 | 86 | 137 |
| 116 | 0.35 | 0.60 | 1.06 | 1.52 | 1.93 | 2.4 | 3.3 | 4.2 | 5.4 | 7.7 | 6.2 | 13.3 | 17.3 | 23 | 29 | 42 | 48 | 71 | 86 | 136 |
| 134 | 0.30 | 0.52 | 0.92 | 1.32 | 1.67 | 2.1 | 2.8 | 3.7 | 4.7 | 6.7 | 5.3 | 11.5 | 15.0 | 20 | 25 | 36 | 42 | 62 | 74 | 118 |
| 143 | 0.28 | 0.48 | 0.86 | 1.24 | 1.56 | 2.0 | 2.7 | 3.4 | 4.4 | 6.3 | 5.0 | 10.8 | 14.1 | 19 | 23 | 34 | 39 | 58 | 70 | 110 |
| 166 | 0.24 | 0.42 | 0.74 | 1.06 | 1.35 | 1.7 | 2.3 | 3.0 | 3.8 | 5.4 | 4.3 | 9.3 | 12.1 | 16 | 20 | 29 | 34 | 50 | 60 | 95 |
| 176 | 0.23 | 0.39 | 0.70 | 1.00 | 1.27 | 1.6 | 2.2 | 2.8 | 3.6 | 5.1 | 4.1 | 8.8 | 11.4 | 15 | 19 | 28 | 32 | 47 | 56 | 90 |

Minimum cross-sectional area (in sq mm) of protective conductors for compliance with Regulation 543-01-03 assuming actual disconnection time is 5 secs

TABLE 3.2

Transposing the formula above gives:

$$I = \frac{Sk}{\sqrt{t}}$$

and substituting values for S, k and t gives

$$I = \frac{66 \bullet 51}{\sqrt{5}} = 1505\,Amp$$

Reference to Fig. 3.9 provides confirmation of this value of current.

A full listing of the 5 second disconnecting currents for all BS 88: Part 2 fuses are included in Table 3.1.

Using the disconnecting current of 1505A determined above and examining the smallest of the 3 cable CSA's previously considered in item 1, that is to say CSA's of 35mm2, 50mm2 and 70mm2 where k = 115 we see that by using the equation given in eq (3.1).

$$\textit{Transposing the formula gives} \quad t = \left(\frac{Sk}{I}\right)^2$$

$$t = \frac{k^2S^2}{I^2}$$

$$\textit{and by substitution of values } t = \left(\frac{35 \bullet 115}{1505}\right) = 7.15\ secs$$

From which it can be seen that the main conductors satisfy the 5 second fuse disconnection criteria. Whilst this is true for PVC cables used in conjunction with fuses complying with BS 88 Part 2, caution should be exercised when using a cable with a k factor less than that used in this example.

Consider the CSA of the armouring for the same cable. Reference to manufacturers data shows that the allowable armour fault current to earth for a duration of 1 second is 3300A.

$$\text{Substituting in } I = \left(\frac{Sk}{\sqrt{t}}\right) \text{ gives:}$$

$$3300 = \frac{S.51}{\sqrt{1}}$$

$$\text{from which CSA } S = \frac{3300}{51} = 64.7mm^2$$

Using this calculated armour CSA value for an earth fault of 5 seconds duration shows that the armour rating is marginal for use with this fuse size.

$$\text{By substituting in } I = \frac{Sk}{\sqrt{t}} \text{ it can be seen that:}$$

$$I = \frac{64.7 \bullet 51}{\sqrt{5}} = 1475\ Amp$$

In addition it should be noted that manufacturers data has been used in this calculation which will generally have a larger CSA than that called for in BS 6346.

Clearly for circuits which cannot satisfy the 5 second disconnecting time, reliance must be placed on an earth fault detecting device to provide disconnecting times of shorter duration.

### 3.3.1 Overcurrent Protection

Compliance with IEE Regulation 552-01-02 which states:
'Every electric motor greater than 0.37kW shall be provided with control equipment incorporating a means of protection against an overload of the motor'.

This regulation is usually satisfied by incorporating a fuselink as previously discussed in conjunction with contactor controlled circuits or alternatively an overcurrent protective relay element where circuit breakers are used.

Compliance with IEE Regulation 434-03-03 which states:
'Where a protective device is provided for fault current protection only, the clearance time of the device under both short-circuit and earth fault conditions shall not result in the admissable limiting temperature of any line conductor being exceeded.

In this case consideration should be given to the case where an excess of current causes the fuse link to rupture in a very short time of less than 10 msecs. Under these conditions manufacturers data indicates the maximum energy let thro $I^2t$ value is 550 x $10^3$ $A^2s$ which must be compared with the cable withstand value. Transposing the formula in Regulation 434-03-03 shows that;

$$CSA \;\; S = \sqrt{\frac{I^2 t}{k^2}} \;\; mm^2$$

from which the minimum CSA for PVC insulated cables with copper conductors is:

$$\sqrt{\frac{550 \bullet 10^3}{115^2}} = 6.45 mm^2$$

This confirms that the cable CSA's previously considered on current ratings are adequately protected under short-circuit conditions by the 250 Amp fuselink.

### 3.3.2 Voltage Drop Considerations

Compliance with IEE regulation 525-01-02 which states that:

The requirements of regulation 525-01-02 are deemed to be satisfied for a supply given in accordance with the Electricity Supply Regulations 1988 (as amended) if the voltage drop between the origin of the installation (usually the supply terminals) and the fixed current - using equipment does not exceed 4% of the nominal voltage of the supply.

Referring to the 415V, 4 pole, 75kW motor previously discussed, we will examine the voltage drop in the 70mm$^2$ cable for the run condition to determine compliance with regulation 525-01-02.

| | | |
|---|---|---|
| Total Impedance | = | Z cable + Z motor run |
| | = | (0.0321 + j 0.00079)* + (1.561 + j 0.9263) |
| | = | 1.5931 + j 0.9342 |
| | = | 1.8468 $\angle$ 30.4° Ω |

*manufacturers data

$$Current = \frac{V}{Z} = \frac{415 \angle 0^\circ}{\sqrt{3} \bullet 1.8468 \angle 30.4^\circ} \quad A$$

$$= 129.74 \quad \angle \quad -30.4^\circ \quad A$$

Voltage drop in cable $= IZ = 129.74 \angle -30.4^\circ \bullet [0.0321 + j\,0.0079]$

$$= 4.29 \angle -16.56^\circ \quad V$$

$$\% \, Voltage\, drop = \frac{\sqrt{3} \bullet 4.29 \angle -16.56}{415 \angle 0^\circ} \bullet 100$$

$$= 1.79\% \quad \text{which is satisfactory}$$

Similar calculations carried out on the 50mm$^2$ cable indicate a voltage drop of 2.53% whilst for the 35mm$^2$ cable it is 3.37% which may be marginal.

In this case the 70mm$^2$ cable is selected as it satisfies Regulation 522-01-02 and all previously considered regulations.

If it is assumed that the circuit is supplied from an 800kVA transformer source, then referring to Appendix 5 suggests a typical source impedance for a single transformer would be:

$$0.003161 + j\,0.0132189\,\Omega$$

Hence the reference voltage of a fictitious generator of equivalent source impedance would be:

$$I \times Z\,\text{source} + (415/\sqrt{3} + j0)$$
$$= 129.74 \angle -30.4^\circ \bullet Z\,\text{source} + (415/\sqrt{3} + j\,0)$$
$$= 1.76 \angle 46.16^\circ + (415/\sqrt{3} + j\,0)$$
$$= 1.2213 + j1.2719 + 415/\sqrt{3} + j\,0$$
$$= 240.8216 + j1.2719$$

Now consider the circuit under starting conditions where:

Total Impedance: = Source impedance + cable impedance + motor start impedance

Source $= 0.003161 + j\,0.0132189\,\Omega$

| | | | |
|---|---|---|---|
| Cable | = 0.0321 | + j 0.0079 Ω | |
| Motor (start) | = 0.0698 | + j 0.2704 Ω | |

then total impedance = 0.10506 + j 0.29152 Ω

The resulting starting current would be given by:

$$Starting\ Current = \frac{240.8216 + j1.2719}{0.10506 + j0.29152}$$

$$= \frac{240.825\ \angle\ 0.303^\circ}{0.30987\ \angle\ 70.18^\circ}$$

$$= 777.2\ \angle\ -69.88^\circ\ A$$

Similarly, the voltage at the terminal box of the motor would be given by:

Voltage at motor = IZ

$= 777.2\ \angle\ -69.88^\circ \bullet (0.0698 +\ \ 0.2704)$

= 217.04 Volts

$$Hence\ \%\ motor\ volts\ at\ start = \frac{\sqrt{3} \bullet 217}{415} \bullet 100 = 90.58\%$$

The MPROT program is arranged so that checks are conducted in a logical sequence. Those cables which fail to satisfy the various regulations are 'flagged' accordingly, whilst the motor terminal voltage values for both the 'Run' and 'Start' conditions are displayed.

Fig. 3.9 displays the predicted start and run motor terminal voltages for each cable CSA in the range when attempting to supply the 75kW motor from an 800kVA source. Similarly Fig. 3.10 displays the predicted values when supplied from a 1500kVA source.

```
                          415V  4 pole  BCPM ARGUS 55 TEFC
  600/1000 V                3c STR CU  PVC/EXTR/SWA/PVC       BSS 6346 1969

  75 kW - 132/  858  A    Fuse rating -  250 A    Cable length - 100  mtrs

 CSA   GND  DCT  AIR                      CSA   GND  DCT  AIR
SQ MM  AMP  AMP  AMP                     SQ MM  AMP  AMP  AMP
  1.5  23*  19*  17*  **.* 95.7 abcde     70    198* 162* 174*  98.3 90.4     e
  2.5  30*  25*  22*  **.* 95.7 ab de     95    237* 194* 214*  98.7 91.3
  4    40*  32*  31*  **.* 95.7 ab de    120    269  221* 247*  98.9 91.8
  6    50*  41*  38*  **.* 95.7 ab de    150    302  248* 284   99.1 92.1
 10    66*  54*  53*  **.* 95.7  b de    185    341  281  326   99.2 92.3
 16    86*  71*  70*  93.6 77.7  b de    240    393  325  383   99.3 92.6
 25   112*  91*  93*  95.8 84.2  b de    300    439  364  437   99.4 92.8
 35   135* 110* 113*  96.9 87.1    de    400    493  416  501   99.5 92.9
 50   160* 130* 138*  97.6 88.9     e
  '*' cable rating  < fuse rating            'c' armour w'stand  < fuse letthro
  'a' cable w'stand < fuse letthro'          'd' armour w'stand  < 5 secs
  'b' cable w'stand < 5 secs                 'e' e/f current <  disconnect amps

 Select CSA     70                                                <Q>uit
                                                                  <P>age back
```

*Fig 3.9* *Cable limitation display for 75kW motor supplied from an 800kVA transformer.*

600/1000 V

415V 4 pole BCPM ARGUS 55 TEFC
3c STR CU PVC/EXTR/SWA/PVC BSS 6346 1969

75 kW - 132/ 858 A Fuse rating - 250 A Cable length - 100 mtrs

| CSA SQ MM | GND AMP | DCT AMP | AIR AMP | | | |
|---|---|---|---|---|---|---|
| 1.5 | 23* | 19* | 17* | **.* | 96.9 | abcde |
| 2.5 | 30* | 25* | 22* | **.* | 96.9 | ab de |
| 4 | 40* | 32* | 31* | **.* | 96.9 | ab de |
| 6 | 50* | 41* | 38* | **.* | 96.9 | ab de |
| 10 | 66* | 54* | 53* | **.* | 96.9 | b de |
| 16 | 86* | 71* | 70* | 93.6 | 78.5 | b de |
| 25 | 112* | 91* | 93* | 95.8 | 85.1 | b de |
| 35 | 135* | 110* | 113* | 96.9 | 88.1 | de |
| 50 | 160* | 130* | 138* | 97.6 | 89.9 | e |

| CSA SQ MM | GND AMP | DCT AMP | AIR AMP | | | |
|---|---|---|---|---|---|---|
| 70 | 198* | 162* | 174* | 98.3 | 91.5 | e |
| 95 | 237* | 194* | 214* | 98.7 | 92.4 | |
| 120 | 269 | 221* | 247* | 98.9 | 92.9 | |
| 150 | 302 | 248* | 284 | 99.1 | 93.2 | |
| 185 | 341 | 281 | 326 | 99.2 | 93.5 | |
| 240 | 393 | 325 | 383 | 99.3 | 93.7 | |
| 300 | 439 | 364 | 437 | 99.4 | 93.9 | |
| 400 | 493 | 416 | 501 | 99.5 | 94.0 | |

'*' cable rating < fuse rating
'a' cable w'stand < fuse letthro'
'b' cable w'stand < 5 secs
'c' armour w'stand < fuse letthro
'd' armour w'stand < 5 secs
'e' e/f current < disconnect amps

Select CSA

<Q>uit
<P>age back

*Fig 3.10 Cable limitation display for 75kW motor supplied from a 1500kVA transformer.*

Although all the relevant circuit parameters have now been specified, there still remains the final requirement of acceleration or run-up-time of the installation. The user is presented with a screen displaying the calculated minimum percentage voltage of 90.6%V at the motor terminal for which the appropriate acceleration time must be supplied. Similar inputs are required for terminal voltages of 100% and 105%v or whatever overvoltage may be envisaged. A suitable method of calculating acceleration times is contained in Appendix 2. A typical screen display of this section of the program is shown in Fig. 3.11.

Fig. 3.12 depicts the subsequent screen display which follows and allows the user to select the motor protection relay of choice.

## 3.4 Program Description

The purpose of this program is to examine a series of data libraries from which a motor, cable, and if required a fuse of adequate rating may be selected.

This objective is achieved by executing a series of linked modules each of which has a unique function. The first modules access a database from which a motor of desired rating is selected. Subsequent modules enable the selection of the most suitable fuse size to be determined. Further modules provide a choice of cable type and predict the most appropriate conductor CSA. All data determined and collated in the program is used by the protection relay programs detailed in later chapters.

A detailed description of the function of individual modules follows:

```
                    415V  4 pole  BCPM ARGUS 55 TEFC
                            CIRCUIT CONDITIONS

Minimum circuit voltage  .........                      91       %V
Maximum circuit voltage  .........                     105       %V

Run-up time at  91 %V    .........                      4.3      Secs
Run-up time at 100% V    .........                      3.8      Secs
Run-up time at 105% V    .........                      3.5      Secs

<A>ccept / <R>eject A                                           <Q>uit
                                                                <P>age back
```

*Fig 3.11 Circuit voltage conditions and acceleration time display.*

```
                    MOTOR PROTECTION
                        RELAYS

     * 1.       GEC   GEMSTART 2      C.C.U
       2.       GEC   CTM(F)
       3.       P & B GOLDS   PBSJ 3E5 N11

       Q.       QUIT

* not implemented

SELECT OPTION 2
```

*Fig 3.12 Protection relay menu.*

MPROT

The operation of this module may best be understood by examining the flowchart shown in Fig. 3.13. As can be seen 'MPROT' is in itself a control program which functions by selecting a series of modules sequentially. The selection sequence may be reversed thus providing a 'pageback' feature or alternatively a quit command may be invoked which returns the user to the main menu contained in the 'PROTSEL' routine.

MPROT 10

This module is the first routine called by the control program 'MPROT'. On selection, a database containing details of motor voltages and type descriptions is accessed and data extracted. The data is then formatted and displayed sequentially together with an identifying index number beginning with 2 pole 415V motors and proceeding to multi-pole 3300V motors. Selection of motor voltage and the motor type is made by entering the index number displayed alongside the description at the appropriate point. The option is checked and if valid the program returns to the calling 'MPROT'. A flowchart depicting the general arrangement of the module is shown in Fig. 3.14.

MPROT 20

This routine is next selected and it utilises information acquired from 'MPROT 10' to gain access to the motor file containing machines of the required voltage and type. The records representing the entire range are read and displayed on the screen in 3 columns from which a single machine rating must be selected. Error trapping is incorporated to allow the selection of listed machines only, the exceptions being 'escape' and 'pageback' functions. A flowchart depicting the routine is shown in Fig. 3.15.

ROUTINE : MPROT

TITLE : MOTOR PROTECTION RELAY SELECTION

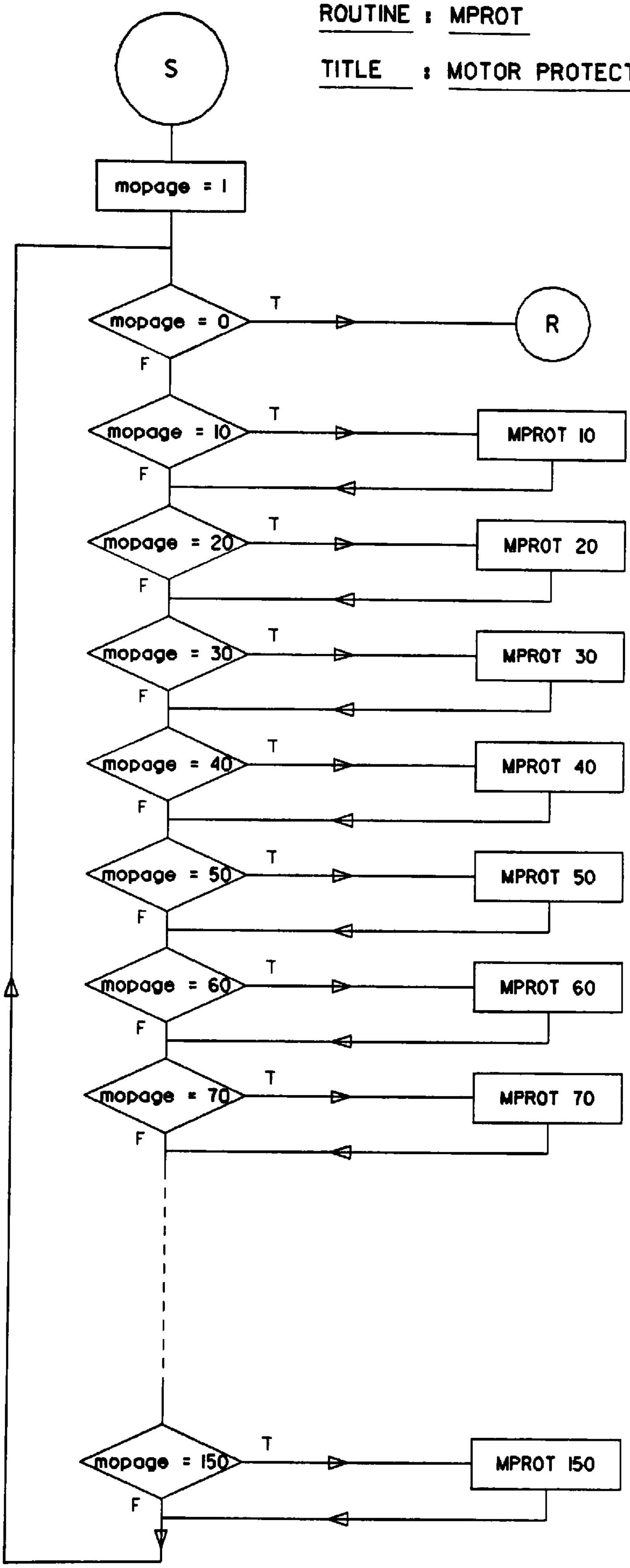



Fig 3.13

ROUTINE : MPROT 10

TITLE : DISPLAY OF MOTOR TYPES

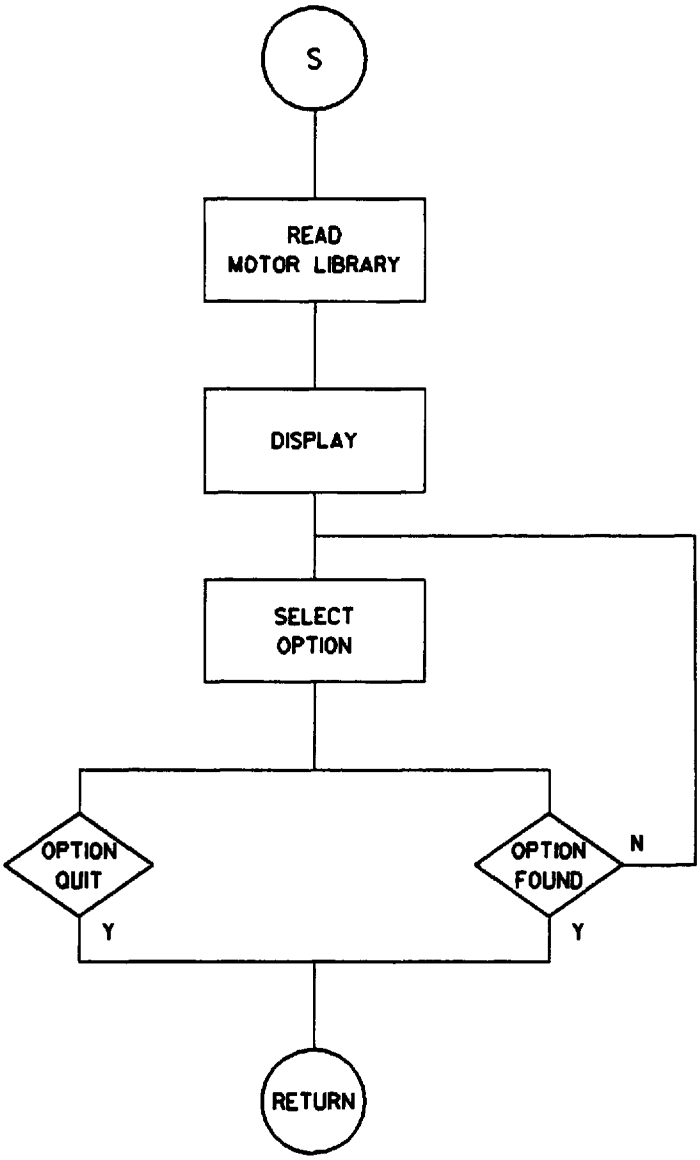



Fig 3.14

ROUTINE : MPROT 20

TITLE : DISPLAY MOTOR RATINGS

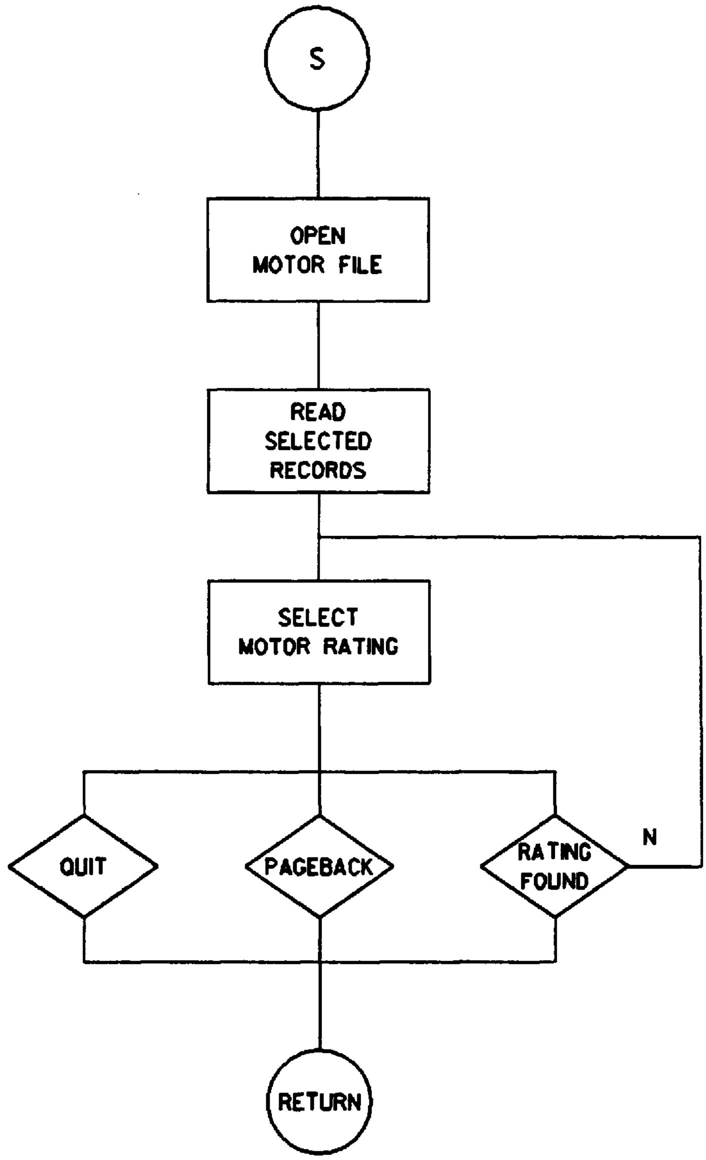



Fig 3.15

MPROT 30

The function of this module is to open the motor database file and conduct an automatic search through the contents until the required motor rating is located. Once found the information is extracted from the file and displayed, a typical display is shown in Fig. 3.4. At this point attention is drawn to any missing data which the user is invited to insert. A simplified flowchart of the module is shown in Fig. 3.16.

MPROT 40

This routine is used where an unclassified machine is to be protected. The term 'unclassified' implies that the motor is a non-standard machine with no information held in the database. However, any machine may be treated as unclassified such that on selecting the option a page is displayed containing a series of requests for motor characteristics which the user is required to furnish. The display presented is identical with Fig. 3.4 except that initially no data is present. The flowchart for the module is contained in Fig. 3.17.

MPROT 50: Determine System Conditions

This routine is used to define the source impedance value of the systems under discussion. The module which is called by the control program 'MPROT', functions as shown in the flowchart labelled Fig. 3.18. The initial requirement of the module is to confirm whether the intended circuit is controlled via a circuit breaker or a fused contactor. Whilst this is not significant in determining the source impedance, the impedance value resulting from the subsequent calculation is extremely relevant to the type of switching device used.

ROUTINE : MPROT 30

TITLE : DISPLAY MOTOR DATA

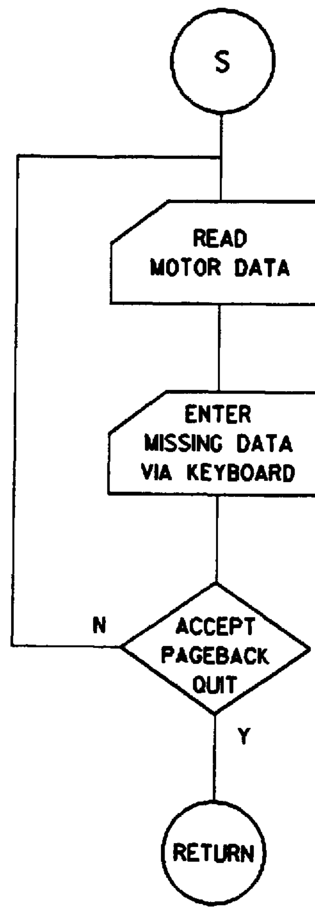



Fig 3.16

ROUTINE : MPROT 40

TITLE : DATA INPUT FOR "UNCLASSIFIED" MOTORS

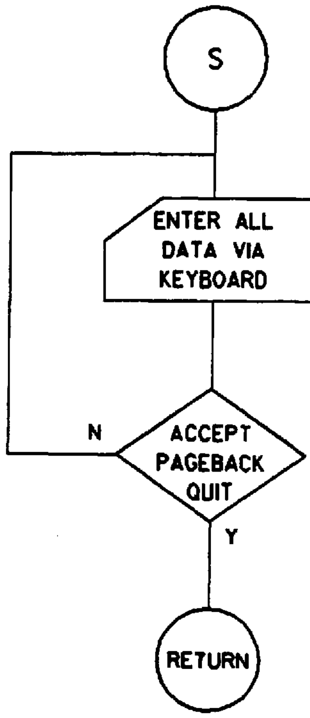



Fig 3.17

ROUTINE : MPROT 50

TITLE : DETERMINE SYSTEMS CONDITIONS

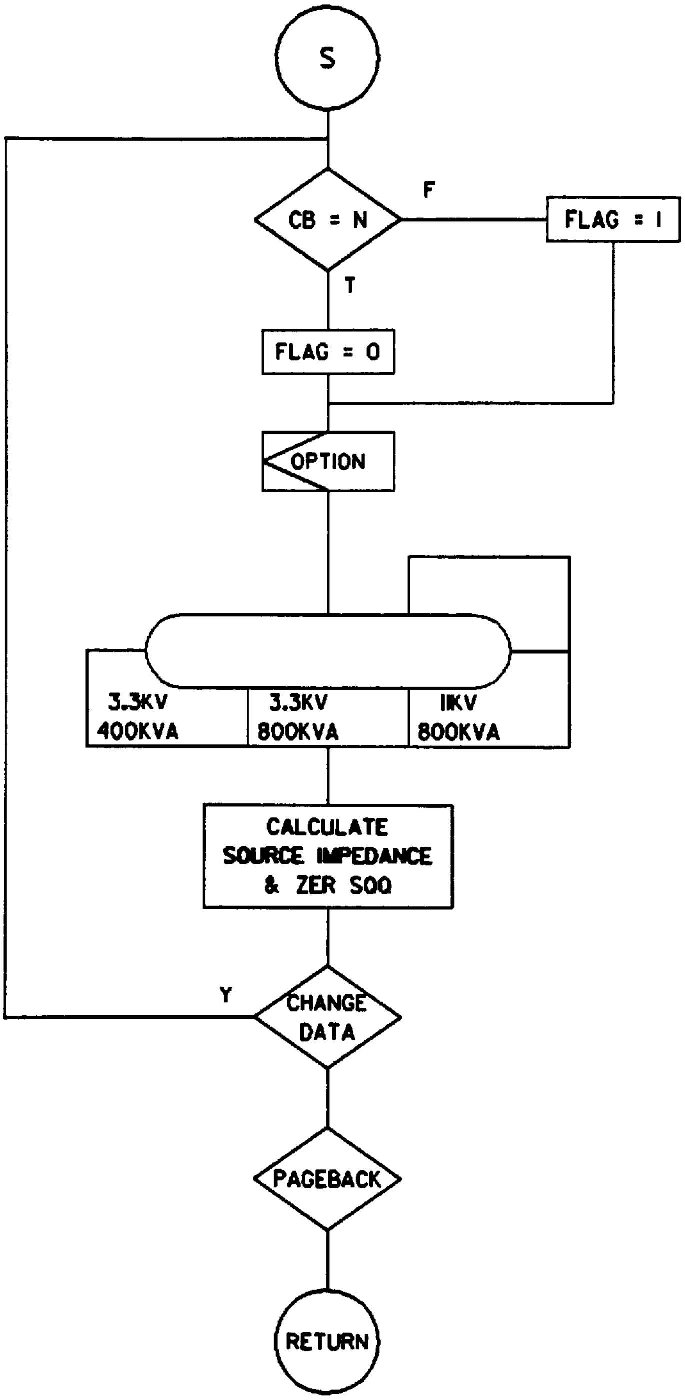



Fig 3.18

In order to determine the source impedance value the approach adopted is to calculate the resistance and reactance values from typical source fault levels and known X/R ratios which may be selected by using the index number placed alongside the appropriate source configuration. The user is given the option to replace any of the displayed values if required. To assist in providing typical data, the program contains 16 values of source fault levels and X/R ratios which are of significance to the investigation reported.

MPROT 60: Selection Routine

This routine is purely a decision making routine with no screen or information output. On selection, the routine assesses the circuit voltage level and determines if the circuit is protected by a fuse link. Using this information the appropriate handling routine for the circuit configuration may then be determined. The flowchart associated with MPROT 60 is shown in Fig. 3.19.

MPROT 70: Fuse Type Catalogue

If the information presented to the MPROT 60 routine indicates the presence of a fuse then the appropriate fuse routine will be selected. This routine is essentially similar to the routine used for cable selection and in operation displays a list of available fuselink types together with associated voltage levels. The user is required to enter an index number to select an option which subsequently allows access to the appropriate set of individual fuselink records provided the voltage level is correct.

MPROT 80: Displays LV Fuse Ratings in 3 Columns

If a fuse type is chosen at a voltage level of 415V the routine 'Fuse' will be selected. This displays the current ratings of all fuses for the entire range. An asterisk may be set against some of the fuse ratings which is intended to signify unsuitability of that particular fuse when used in conjunction with the motor selected.

ROUTINE : MPROT 60

TITLE : SELECTS ROUTINE ACCORDING TO VOLTAGE

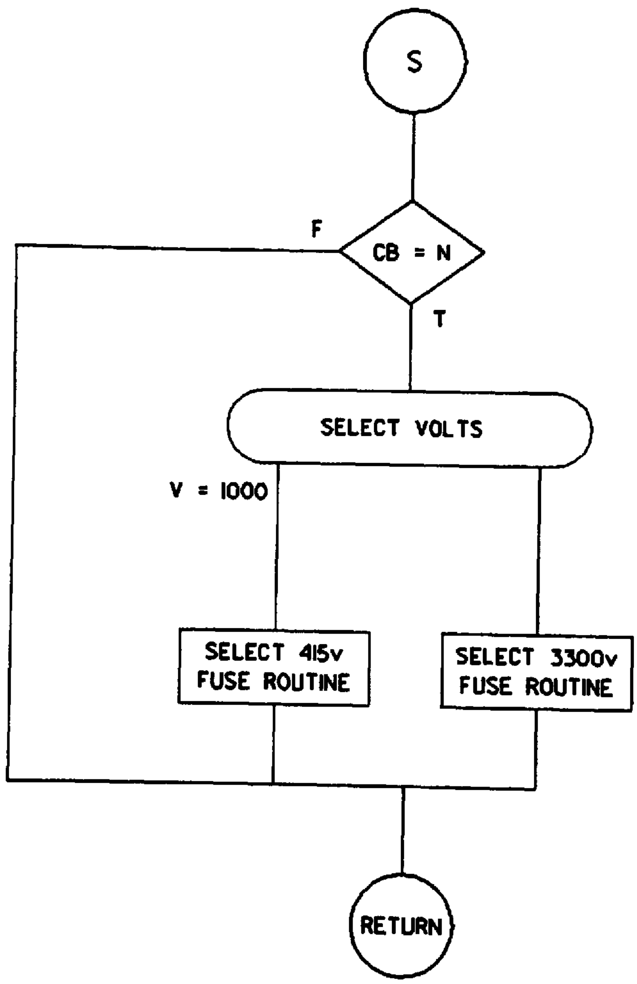



Fig 3.19

Hence: Motor Starting Current > fuse pulse rating for starting duration of 'T' secs.

The flowchart associated with this module is shown in Fig. 3.20

MPROT 90 - displays HV fuse ratings in 1 column

MPROT100 - displays HV fuse ratings in 2 columns

MPROT 110: Displays Cable Catalogue

This module is selected by one of two proceeding modules either MPROT 60 or MPROT 80,90,100 depending on whether the switching device is a fused contactor or a fully rated circuit breaker.

The operation of this module is as shown in the flowchart depicted in Fig. 3.21. The routine uses the same technique as was used in previous data extraction routines. A file containing records of cable types is opened and from each record data is extracted from selected fields, some of which is displayed on the screen together with an identifying index number. The cable type is selected by entering the index number displayed alongside the desired option.

This action isolates the required record and enables further data to be extracted from the individual cable records held in the CA1 database. To complete the cable specification it is necessary to provide details of the installed cable length together with an appropriate thermal derating factor for the intended installation environment.

The module incorporates various checks, one of which ensures that the cable option selected has the correct voltage rating. The usual 'pageback' and 'quit' options are also included.

ROUTINE : MPROT 80,90,100.

TITLE : DISPLAY FUSE RATINGS

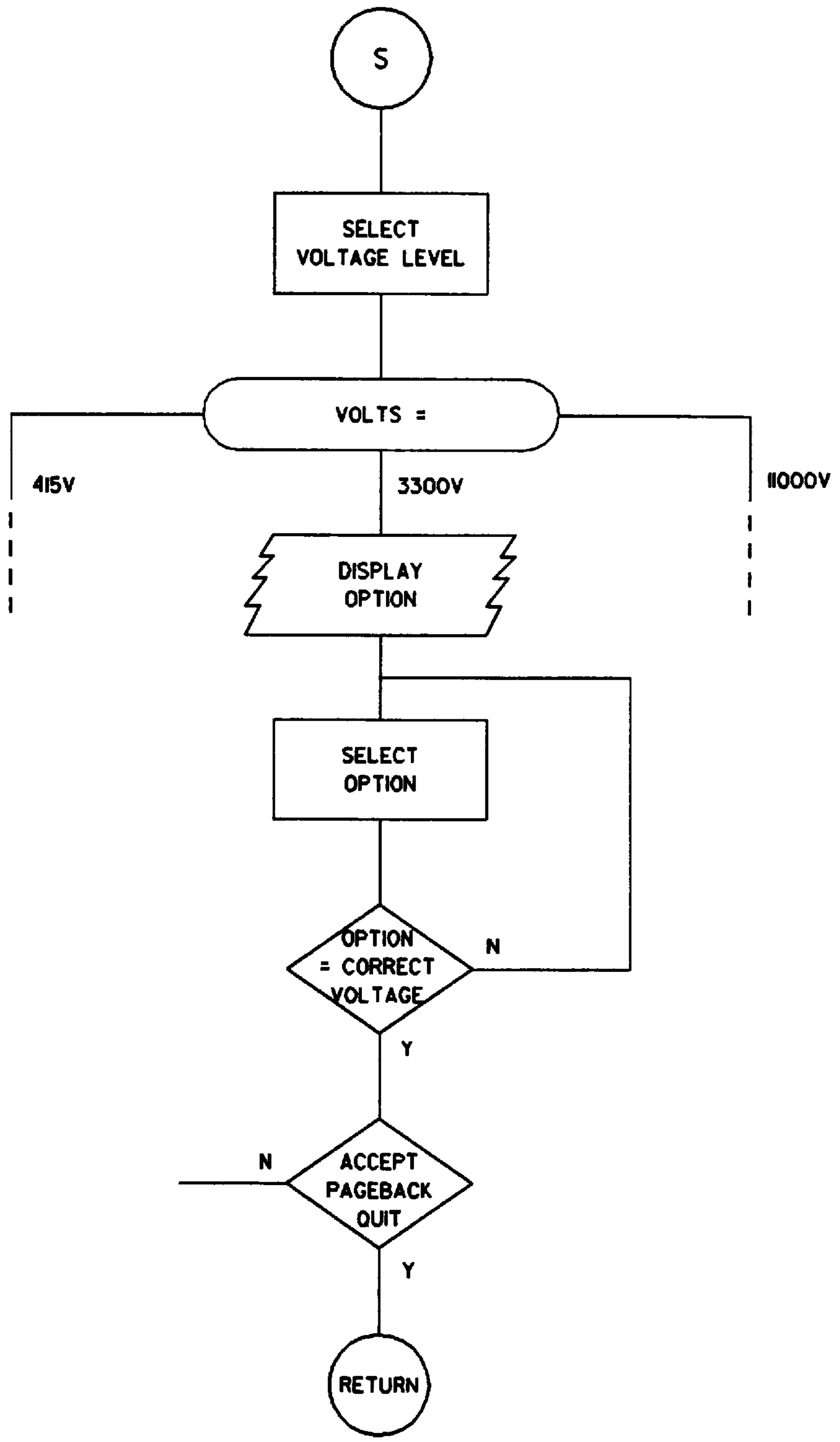



Fig 3.20

ROUTINE : MPROT 110

TITLE : DISPLAYS LISTING OF ALL CABLE TYPES FOR SELECTION

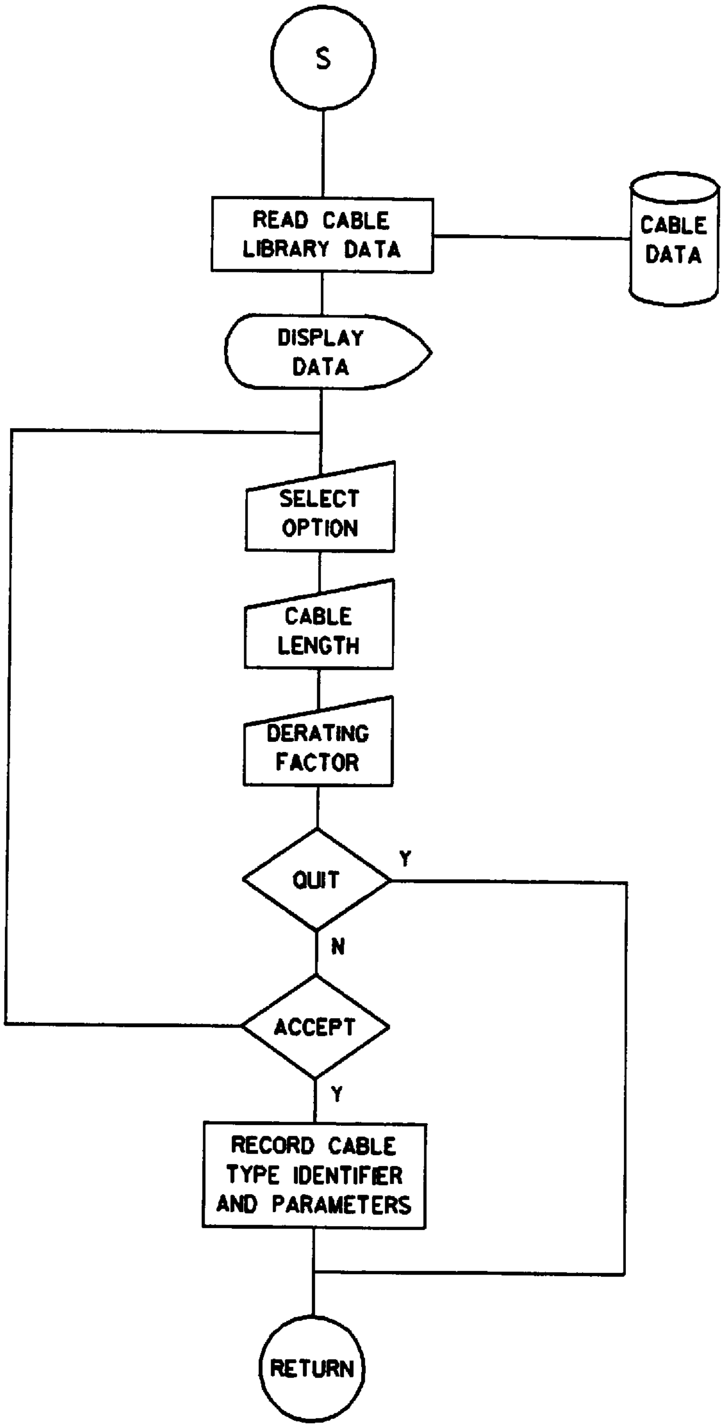



Fig 3.21

MPROT 120: Calculates Currents and Conditions

In this routine much of the data acquired in previous modules is used in computations. The routine begins by opening and clearing the workfile prior to accepting fresh data. A second file containing the required cable data records is opened and the first record extracted. The standard current ratings are modified by the derating factor ready for storage in the workfile. Additionally the cable positive and zero sequence impedance values for the specified length are calculated and used in conjunction with the maximum source impedance value to determine the following computations.

1. Percentage voltage drop in the cable at the motor FLC.
2. The fictitious generator voltage for supplying power through the source impedance to the circuit busbar which is held at nominal voltage when the motor is drawing FLC.
3. The voltage at the motor terminals when drawing starting current.

When fuselinks are used additional checks are conducted to determine if:

4. The derated cable rating $\geq$ fuselink rating.

A flowchart indicating the general arrangement is shown in Fig. 3.22

ROUTINE : MPROT 120

TITLE : CALCULATES CABLE PARAMETERS FROM SELECTED CABLE CSA & LENGTH.

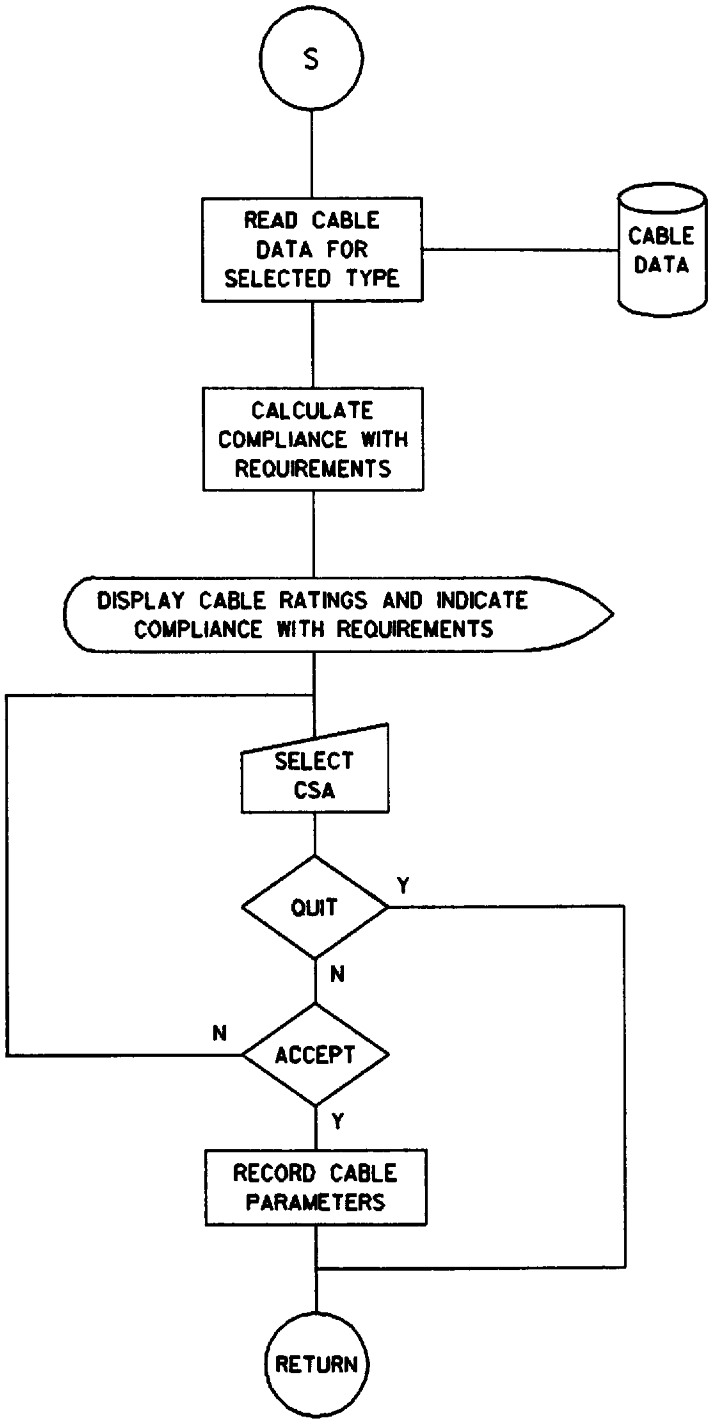



Fig 3.22

MPROT 130:Displays Cable Ratings

The function of this routine is to display a complete cable listing for all CSA's together with their current ratings for operation in Air, Ground and Duct environments. The ratings are all modified in accordance with the declared derating factor. A series of symbols are assigned to each conductor CSA to draw attention to any limitations.

The limitations listed are as follows:

For Fused Circuits

| | | | |
|---|---|---|---|
| * | Cable rating | < | Fuse rating |
| a | Cable withstand energy | < | Fuse 'let thro' energy |
| b | Cable withstand time | > | Fuse disconnecting time |
| c | Armour withstand energy | < | Fuse 'let thro' energy |
| d | Armour withstand time | > | Fuse disconnecting time |
| e | Earth fault current | < | Disconnecting current |

For Unfused Circuits

| | | | |
|---|---|---|---|
| * | Cable rating | < | Full load current |
| a | Cable withstand current | < | Fault current (200mSec) |
| b | Armour withstand current | < | Fault current (200mSec) |

The routine is purely for display and uses data previously calculated in the MPROT 120 routine.

In the case of HV contactors, it is important to check that at the maximum breaking current of the device;

Cable withstand time > Fuse disconnecting time

MPROT 140

The function of this routine is to obtain data for use in later modules. This routine requests the user to enter the run-up time of the motor-drive unit when supplied at:

(a) Minimum circuit voltage
(b) Nominal circuit voltage
(c) Maximum circuit voltage

The minimum circuit voltage is calculated in previous routines but alternative values may be substituted if required.

MPROT 150

This routine displays a menu which lists the protection relay options available for application in the circuit now specified. the routine offers the usual alternative functions which allow the user to 'Quit' or 'Pageback' if required.

## 3.5 Interim Conclusion

In this section of the work, the readers attention is drawn to the need for providing coordination between the circuit components. Whilst the limits of the project ensure that coordination can be achieved downstream of the switching device, it is essential to ensure that where fusegear is used, coordination between the fuses and the switching device is also maintained.

Section 3.3 highlights the requirement to provide databases containing information on cables, motors and fuses. Close scrutiny is required, however, as the quantity of potential information that is available would provide a basis for several projects. It should be noted at this juncture, that whilst the subject area may be vast, the acquisition of some data, particularly for motors, may prove difficult. This is due to a reluctance by certain manufacturers to release actual data without monetary recompense. Hence, to provide 'Proof of Concept', the range of information contained in the database has been deliberately curtailed.

List of References


1. IEE Wiring Regulations - 16th Edition.
2. IEC 947 - Low voltage switchgear and control gear. Part 4: Contactors and motor starters. Section 1: Electromechanical contactors and motor starters.
3. IEC 158 - Low voltage controlgear.
4. IEC 292 - Low voltage motor starters
5. BS 4941 - Specification for motor starters for voltages up to and including 1000V ac. and 1200V dc.
6. ASTA - Formerly 'Association of Short-Circuit Testing Authorities' now 'ASTA Certification Services'.
7. KEMA - N.V. tot Keuring van Elektrotechanische Materialen, Arnhem.
8. BS6346 - Specification for PVC-insulated cables for electricity supply.
9. BS 88 - Cartridge fuses for voltages up to and including 1000V ac. and 1500V dc.

# CHAPTER 4

## Applying the GEC-ALSTHOM TYPE CTM MOTOR PROTECTION RELAY

### 4.1 General Description

The motor protection relay under consideration in this chapter is the type CTM/CTMF produced by GEC-ALSTHOM Ltd. The relay which is electronic in nature uses analogue techniques in its operation. The use of the relay is now in decline as more modern equipment offering improved features and flexibility are readily available. Although dated it is well established in service and still currently available from the manufacturer.

The relay may be mounted on the switchgear or alternatively on a relay panel at a remote location. In operation, it is required to model temperature excursions of the motor under overload and if required, under phase unbalance conditions using current supplied from current transformers, CT's, of suitable ratio. The CT output, which is proportional to the motor supply current and hence to its heating, is processed into its symmetrical component form and used to determine the necessary action to be taken. In addition, where currents of short-circuit magnitude are detected, the relay may be required to initiate immediate isolation, if appropriate.

The CTM/CTMF relay is offered in six distinct forms comprising various combinations of Thermal, Phase Unbalance, Instantaneous Overcurrent and Earth Fault functions, some of the instantaneous elements being available with definite time delays. The definite time delay functions are used in conjunction with switching devices which are not fully fault rated and require the use of series power fuses. Table 4.1 gives the standard range of available options together with a selection of typical applications. For certain applications, it was found that none of the available thermal characteristics offered were able to satisfy the circuit

| APPLICATION CONSIDERATIONS | | TYPICAL CORRELATION OF RELAY AND MOTOR TYPES | | | | | |
|---|---|---|---|---|---|---|---|
| Protection Provided | Motor Controlled by | Submersible Pump Motors | C.M.R. Motors | Standard Industrial Motors | | Special Motors For High Inertia Drives | |
| i) Thermal (Th) | Circuit Breaker | CTM11 | CTM12 | CTM13 | CTM14 | CTM15 | CTM16 |
| i) Thermal (Th)<br>ii) Instantaneous earth fault ($I_0$) | Circuit Breaker | CTM21 | CTM22 | CTM23 | CTM24 | CTM25 | CTM26 |
| i) Thermal (Th)<br>ii) Time delayed, unbalance & single phasing ($I_2$) | Fused Contactor | CTMF21 | CTMF22 | CTMF23 | CTMF24 | CTMF25 | CTMF26 |
| i) Thermal (Th)<br>ii) Instantaneous three phase overcurrent ($I_1$)<br>iii) Instantaneous unbalance & single phasing ($I_2$) | Circuit Breaker | CTM31 | CTM32 | CTM33 | CTM34 | CTM35 | CTM36 |
| i) Thermal (Th)<br>ii) Time delayed, unbalance & single phasing ($I_2$)<br>iii) Time delayed earth fault ($I_0$) | Fused Contactor | CTMF31 | CTMF32 | CTMF33 | CTMF34 | CTMF35 | CTMF36 |
| i) Thermal (Th)<br>ii) Instantaneous three phase overcurrent ($I_1$)<br>iii) Instantaneous unbalance & single phasing ($I_2$)<br>iv) Instantaneous earth fault ($I_0$) | Circuit Breaker | CTM41 | CTM42 | CTM43 | CTM44 | CTM45 | CTM46 |
| Relay Thermal Operation Characteristic: Curve Number | CTM & CTMF | 1 | 2 | 3 | 4 | 5 | 6 |
| Relay Thermal Operation Characteristic: Nominal Operation Time (s) at 5 x Setting Current ('Cold' curves) | | 4 | 8 | 16 | 32 | 64 | 128 |

Table 4.1

design requirements, thereby limiting its potential use. Early recognition of this problem resulted in the production of a series of supplementary characteristics which were sufficiently numerous to provide an adequate solution.

Considering each of the relay functions in turn, it can be seen that the following observations apply:

### 4.1.1 Thermal Overload Protection

The thermal element operates with an inverse time/current characteristic generally in accordance with the published characteristics. The published characteristics however, deviate slightly at both extremities from the 'idealised' type A.1 characteristic as defined in BS 142. The difference between the actual and theoretical characteristic are shown in Fig. 4.1. The equation which satisfies the theoretical characteristic may be represented by:

$$t = \tau \log e \frac{Ieq^2}{Ieq^2 - Is^2} \tag{4.1}$$

| | | | |
|---|---|---|---|
| where | $t$ | = | operating time in secs |
| | $Ieq^2$ | = | $I_1^2 + 6I_2^2$ |
| | $I_1$ | = | Positive phase sequence (PPS) component of the supply current |
| | $I_2$ | = | Negative phase sequence, (NPS) component of the supply current |
| | $Is$ | = | Current setting = 1.05 (Relay begins to operate at 1.05 x relay current setting) |

$\tau$ Curve 1 Cold = 88.7

Hot = 29.6 (88.7/3)

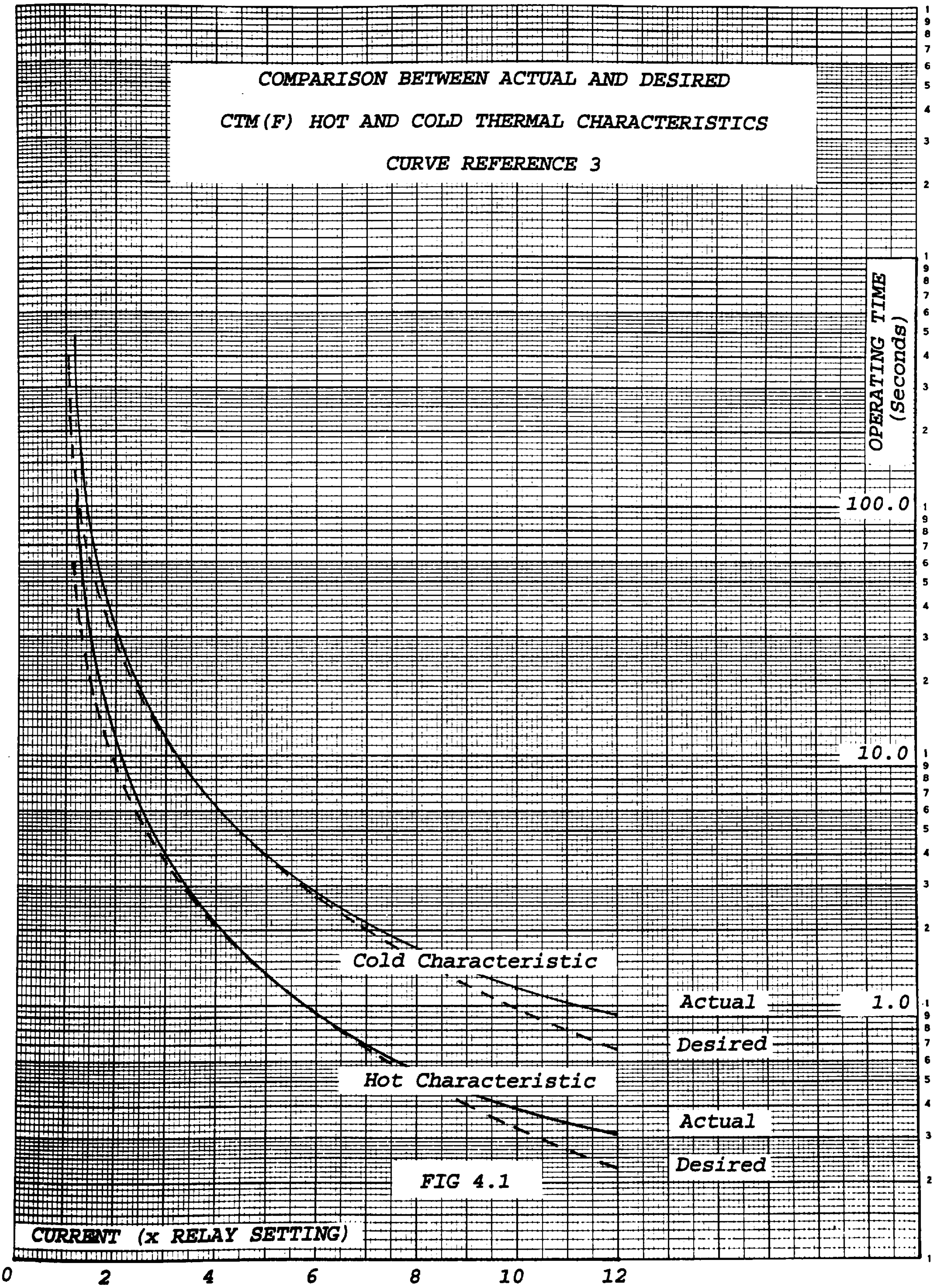

COMPARISON BETWEEN ACTUAL AND DESIRED
CTM(F) HOT AND COLD THERMAL CHARACTERISTICS
CURVE REFERENCE 3
OPERATING TIME (Seconds)
100.0
10.0
1.0
Cold Characteristic
Actual
Desired
Hot Characteristic
Actual
Desired
CURRENT (x RELAY SETTING)
0
2
4
6
8
10
12

FIG 4.1

The NPS multiplying factor of 6 provides a weighted allowance for the heating effect of this current. An earlier electro-mechanical relay, the type CMM offered by the same manufacturer incorporated a multiplying factor of 3. More recently, the latest model, the type MCHN, provides a range of selectable factors from 3 to 10.

Inspection of the standard characteristics associated with Table 4.1 indicates that for a given multiple of current (x relay setting) the thermal trip time varies in the ratio 2:1 between each set of characteristics.

That is to say, at 5 x current (x relay setting) for characteristic 6, the thermal tripping time from the cold state is 128 secs. For characteristic 5 it is 64 secs, characteristic 4, 32 secs and so on to characteristic 1.

Associated with each cold characteristic is a hot characteristic whose purpose is to thermally protect the motor when it has reached its running temperature. The ratio of the tripping times on the cold characteristic to the tripping times on the hot characteristic for any multiple of current ( x relay setting) are constant and in the proportion 3:1.

In addition to the six standard characteristics, five further supplementary characteristics are available. These characteristics are arranged to fit midway between each of the six standard characteristics thus making a total of eleven thermal characteristics with cold:hot tripping times in the proportion 3:1. The supplementary curves may be identified by a 2 digit reference number the first number being 0, that is 00,01,02,03 and 04.

To increase the versatility of the relay a further set of eleven characteristics are available with identical cold characteristics but with cold:hot tripping times modified to the proportion 1.5:1. These prove particularly suitable for modern machines where the user has, in the interest of longevity, declined to fully utilise the maximum operating temperature offered by the use of improved insulating materials. Thus the total choice of thermal characteristics amounts to twenty two fixed sets of curves.

The standard relay characteristic is arranged to operate for overloads in excess of 105% of the setting. The setting of the thermal element is achieved by rotating the two potentiometers mounted on the relay faceplate to the required position. Two separate potentiometers are used to overcome the difficulty encountered in getting the two units to accurately track together.

Hence for operation at 105% of setting

$$Setting = \frac{Ieq}{100 \bullet 1.05}$$

$$where\ Ieq = 105\% - the\ required\ trip\ level$$

If a 5A relay is used the setting potentiometer is modified as follows:

$$Setting = \frac{Ieq \bullet Ir}{100 \bullet 1.05}$$

$$where\ Ir = 5A - the\ relay\ rating$$

and allowing for the discrepancy between motor flc and the CT ratio results in the general expression:

$$Setting = \frac{Ieq \bullet Ir \bullet I}{100 \bullet 1.05 \bullet Ip} \qquad (4.2)$$

| | | | |
|---|---|---|---|
| where | I | = | motor full load current |
| | Ip/Ir | = | current transformer primary ratio |

By substituting in equation 4.2 the setting required to satisfy the following data is determined.

We have:

| | | | | |
|---|---|---|---|---|
| Ieq | = | 105% | | |
| I | = | 40A | : | Using data from Appendix 7 |
| Ip/Ir | = | 50/1 | | |

from which:

$$Setting = \frac{105 \bullet 40 \bullet 1}{100 \bullet 1.05 \bullet 50} = 0.8$$

The action of the thermal element may be better understood by considering the heating and cooling cycles separately. In the former case if the applied current is less than the trip setting, the trip response is exponential whilst for input currents greater than the trip setting the trip response is linear.

Similarly during the cooling cycle there are two cases to be considered. The simpler of the two cases occurs when the motor is shut down whilst the second case considers the response of the thermal element to a motor which having been accelerated up to speed is followed by a current reduction to a value dictated by the load.

Both the cases highlighted are important when cyclic loading is to be considered because to neglect to examine the relationship could result in unnecessary tripping of the motor, or alternatively, the relay may allow the motor to execute an excessive number of starts and overheat.

Consider the following 3.3kV motor

Motor rating 180kW; FLC 40A; Start Amps 230A

Minimum starting voltage 85% of nominal line volts.

For a trip level of 110% FLC the required setting would be:

$$\frac{110 \bullet 40 \bullet 1}{100 \bullet 1.05 \bullet 50} = 0.84$$

For a FLC of 40A, the trip level for:

5% overload is 42A

and for 10% overload is 44A

Now the relay operates at 5% overload and the relay characteristic does not change. Hence for a trip level of 110% FLC the motor FLC appears to the relay as:

$$\frac{44}{1.05} = 41.9A$$

So when the motor is run at its true FLC of 40A, it appears to the relay as a load of

$$\frac{40}{41.9} \bullet 100 = 95.45\% flc$$

which will be the value displayed on the load indicator mounted on the faceplate of the relay.

At 2 x motor FLC, that is 2 x 40 = 80A which when expressed in terms of multiples of FLC as seen by the relay is 80/41.9 = 1.91A.

If an allowance of 20% is made for timing errors in the thermal element at 2 x FLC then for stable operation the following inequalities must be satisfied.

1.2 x Relay Thermal Curve (Cold) at 1.91 FLC $<$ MotorWithstand (Cold) at 2 x FLC (that is $<$ 770 secs)

and

1.2 x Relay Thermal Curve (Hot) at 1.91 FLC $<$ Motor Withstand (Hot) at 2 x FLC (that is $<$ 600 secs)

For the starting condition three cases should be considered

1. Starting with full line voltage available
2. Starting with reduced line voltage typically 85% x nominal voltage
3. Starting with raised line voltage typically 105% nominal voltage

The starting current at full line voltage stated in terms of multiples of relay FLC is:

$$\frac{230}{41.9} = 5.49A$$

The manufacturers state that the maximum error of the thermal element at 5 x FLC is ± 10% hence this value will be included in the following inequalities which are to be satisfied.

1.1 x Relay Thermal Curve (Cold) at 5.49 x FLC $<$ Motor Withstand (Cold) when stalled (that is $<$ 23 secs)

and

1.1 x Relay Thermal Curve (Hot) at 5.49 x FLC $<$ Motor Withstand (Hot) when stalled (that is $<$ 15 secs)

Similarly when starting with a line voltage reduced to 85% the starting current stated in terms of multiples of relay FLC will be reduced to:

$$\frac{0.85 \bullet 230}{41.9} = 4.67A$$

Due to the lower stall current the withstand time for the motor is increased. The increase is considered to be adiabatic resulting in the following revised withstand times at this reduced current level.

$$I_1^2 \bullet R \bullet T_1 = I_2^2 \bullet R \bullet T_2 \qquad (4.3)$$

where

$I_1$ = Stall current with 100% line voltage applied

$T_1$ = Motor Withstand time with 100% line voltage applied

$I_2$ = Stall current with 85% line voltage applied

$T_2$ = Motor Withstand time with 85% line voltage applied

R = Motor equivalent resistance at standstill

By substituting the respective values in equation (4.3), the following is obtained.

1. Revised cold withstand time with 85% line voltage applied

$$40^2 \bullet R \bullet 23 = (0.85 \bullet 40)^2 \bullet R \bullet T_2$$

$$\text{from which } T_2 = \frac{23}{0.85 \bullet 0.85} = 31.83 \text{ secs}$$

2. Revised hot withstand time with 85% line voltage applied

$$40^2 \bullet R \bullet 15 = (0.85 \bullet 40)^2 \bullet R \bullet T_2$$

$$\text{from which } T_2 = \frac{15}{0.85 \bullet 0.85} = 20.76 \text{ secs}$$

The inequalities to be satisfied then become:

1.1 x Relay Thermal Curve (Cold) at 4.67 FLC < Motor Withstand (Cold) when stalled (that is < 31.83 secs)

1.1 x Relay Thermal Curve (Hot) at 4.67 x FLC < Motor Withstand (Hot) when stalled (that is < 20.76 secs)

A similar exercise is conducted for the case where excess voltage is applied to the machine. This case would arise if the machine was the first to be started after a shutdown or maintenance period when busbar volts tend to be higher than nominal.

From the information calculated so far it is possible to determine a thermal curve which will satisfy the set of inequalities. Such a characteristic is given by the curve shown in reference 3, which yields the following results:

1.2 x Relay Thermal Curve (Cold) at 1.91 x FLC < Motor Withstand (Cold) at 2 x FLC 184.6 secs < 770 secs

1.2 x Relay Thermal Curve (Hot) at 1.91 x FLC < Motor Withstand (Hot) at 2 x FLC 61 secs < 600 secs

1.1 x Relay Thermal curve (Cold) at 5.49 x FLC < Motor Withstand (Cold) when stalled 14.2 secs < 23 secs

1.1 x Relay Thermal Curve (Hot) at 5.49 x FLC < Motor Withstand (Hot) when stalled 4.7 secs < 15 secs

1.1 x Relay Thermal Curve (Cold) at 4.67 x FLC < Motor Withstand (Cold) when stalled at 85% Volt 19.9 secs < 31.8 secs

1.1 x Relay Thermal Curve (Hot) at 4.67 x FLC < Motor Withstand (Hot) when stalled at 85% Volt 6.6 secs < 20.8 secs

1.1 x Relay Thermal Curve (Cold) at 5.76 x flc < Motor Withstand (Cold) when stalled at 110% Volt 19.0 secs

1.1 x Relay Thermal curve (Hot) at 5.76 x flc < Motor Withstand (Hot) when stalled at 110% Volt < 12.4 secs

These inequalities, when satisfied, provide thermal protection of the motor for all balanced overloads up to and including the locked rotor or stall condition. However, when other constraints such as negative phase sequence components and run-up time considerations are examined the characteristic may prove unsuitable as can be seen by exploring further considerations in the next section.

### 4.1.2 Unbalanced Conditions

When unbalanced supply voltages are presented to the motor, the effects are generally as described in Appendix 3. The cause of the unbalance may be external in the form of unbalanced phase voltages and supply harmonics or alternatively the motor itself may be the source of the problem. During unbalanced conditions the magnitude of the negative phase sequence component, NPS, of the current assumes great importance as at running speed the frequency of the NPS current in the rotor is almost twice the supply frequency. At this frequency the ratio of the rotor ac resistance to the virtual dc resistance presented to the positive phase sequence, PPS, currents is in the range 3-8 times from which it can be readily understood that the $I^2R$ heating effects will limit the power that can be extracted from the rotor if temperature limits are not to be exceeded.

In order to provide adequate thermal protection it is necessary for the relay to detect and quantify the magnitude of the NPS current supplied to the motor, and if appropriate, produce a tripping signal or alternatively accelerate the tripping time if a preset threshold level is exceeded. The operation of the NPS element may be seen by examining Figs. 4.2a and 4.2b. Fig. 4.2a depicts a block diagram of

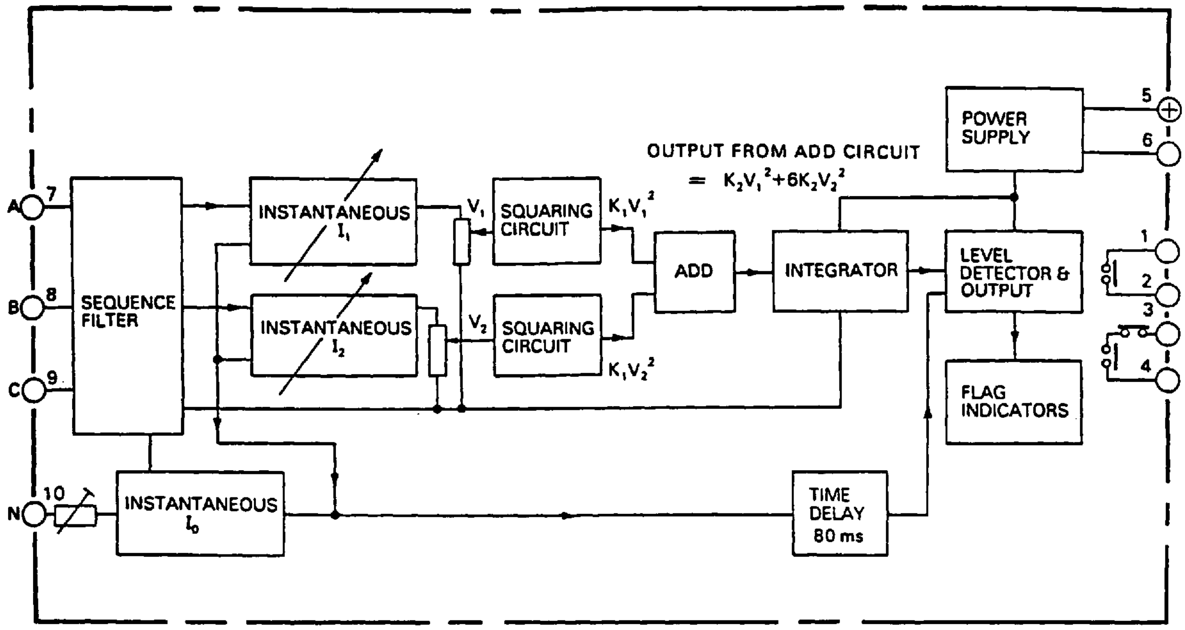



*Fig 4.2a Block schematic diagram of CTM relay.*

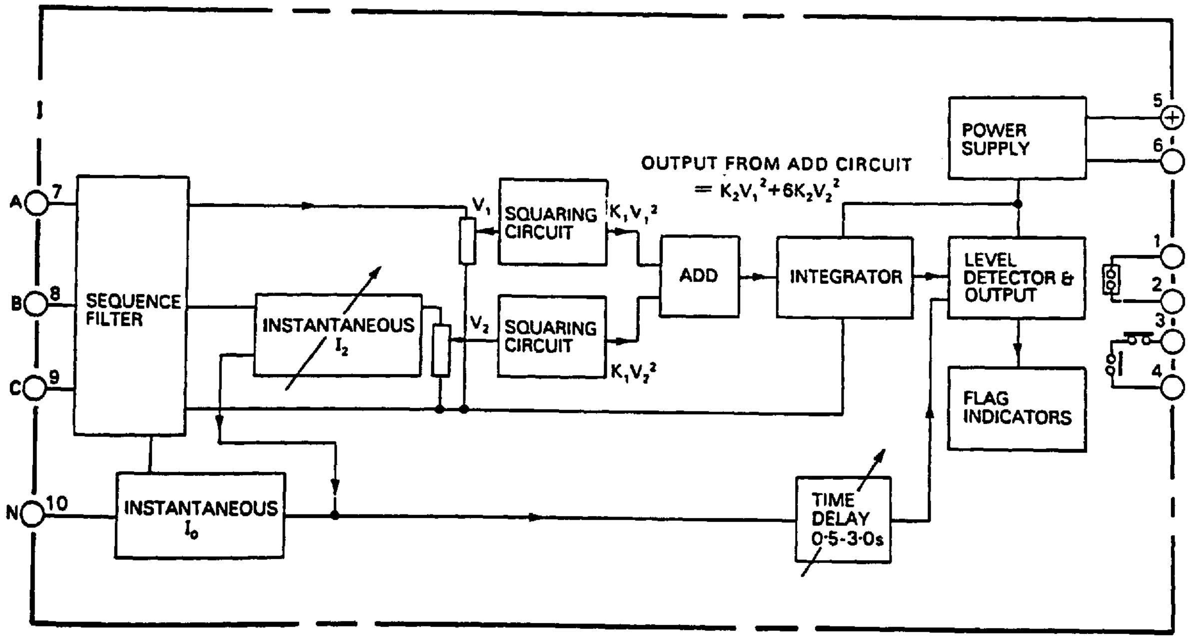



*Fig 4.2b Block schematic diagram of CTMF relay.*

the internal functions of the CTM relay. The relay is used in circuits supplied through circuit breakers.

Fig. 4.2b shows similar information for the CTMF relay. This relay is suitable for duty with motors supplied via fused contactors.

An examination of Fig. 4.2a shows that the three phase currents supplied to the relay from the current transformers are initially presented to a sequence filter which resolves the input currents into their positive, negative and zero sequence components. In the case where unbalanced phase currents are presented to the filter, an NPS current output will be produced. This NPS current is passed to an instantaneous element which will operate if its threshold is exceeded. In the case of the CTM relay, operation of the NPS instantaneous element results in a direct tripping signal to the circuit breaker, whilst, in the case of the CTMF relay, the trip signal is passed through a delay circuit whose function is to defer instantaneous tripping to allow discrimination with the power fuse protection. If the overall current is insufficient to operate the primary fuse protection then the contactor will be tripped after the delay period has elapsed. The procedure for determining the delay setting is discussed later in this section.

If the magnitude of the NPS current is insufficient to operate the instantaneous element it is further presented to the outer limbs of a potentiometer arrangement from which a representative voltage, $V_2$, is derived at the tapping. The voltage, $V_2$, provides the input to a squaring circuit whose output is defined as:

$$NPS\ Potentiometer\ output = K_1 \bullet V_2^2 \qquad (4.4)$$

where $K_1$ is a constant

Similar processing is applied to the positive phase sequence (PPS) component of current from which a representative output voltage is obtained. The value of which is defined by:

$$PPS\ Potentiometer\ output = K_1 \bullet V_1^2 \tag{4.5}$$

where K1 is a constant

Both values are presented to an adder circuit which applies selective amplification to the value representing the NPS component, such that the output of the adder circuit is represented by:

$$Composite\ output\ voltage = K_1 \bullet V_1^2 + 6K_1 \bullet V_2^2 \tag{4.6}$$

This composite voltage is applied to an integrator circuit which produces an output voltage which rises exponentially from zero to 105% of the relay setting current and linearly for multiples of current above this value.

As stated previously, the relay is designed to operate when the applied current Ieq exceeds 105% of the setting value. Ieq is defined as:

$$Ieq = \sqrt{(I_1^2 + kI_2^2)} \tag{4.7}$$

where I1 = Positive-phase-sequence component of the current

I2 = Negative-phase-sequence component of the current

k = 6, a weighting factor applied to the negative-phase-sequence component.

It follows that for a motor running at full load with a protective overload relay setting of 105%, the relay will tolerate without operating an NPS current up to a level determined as follows:

Operating Level 105%, that is 1.05 x FLC

$I_1 = FLC = 1$

Then substituting in equation (4.7) gives:

$$1.05 = \sqrt{(1 + 6I_2^2)}$$

$$1.1025 = 1 + 6I_2^2$$

$$I_2 = \frac{\sqrt{(1.1025 - 1)}}{6} = 0.1307$$

That is, there will be no trip operation at full load output with less than a 13.07% negative phase sequence current component (excluding relay tolerances).

The potential user of this relay should be aware that if the relay is set to operate at a value greater than 5% overload then the NPS current tolerated, will also increase.

Consider the following example:

Desired operating level is 110% - to achieve this the setting must be raised to 110/105 = 1.048, so that to the relay, the motor appears to be running at 1/1.048 = 0.954 of the relay setting.

That is a 110% overload produces tripping at 0.954 x 1.1 = 1.05 FLC

Substituting $I_1$ = 0.945 in the equation (4.7) gives:

$$1.05 = \sqrt{( 0.954^2 + 6I_2^2 )}$$

$$1.1025 = 0.911 + 6I_2^2$$

$$I_2 = \frac{\sqrt{(1.1025 - 0.911)}}{6} = 0.1786$$

This means no operation at full load output will occur with less than a 17.86% negative phase sequence current component (excluding relay tolerances).

Consider two extreme cases of loss of a supply phase to a 3.3kV, 3ph, 180kW motor (similar to that detailed in Appendix 7).

Case (1) At full load output

Case (2) At standstill

In the case of a star connected motor, Fig. 4.3a and Fig. 4.3b show that the loss of a phase results in two windings being connected in series across the remaining two supply phases. The star arrangement is the connection generally found on HV motors for which this application is intended.

Case (1)

Under normal conditions

$$Output\,power/phase = \frac{180}{3} = 60\,kW$$

$$and\,voltage/phase \quad \frac{3300}{\sqrt{3}} = 1905V$$

To maintain output with the loss of one phase.

$$The\,output/phase\,must\,rise\,to\,\frac{180}{2}\,kW = 90kW$$

$$= \frac{3}{2} \bullet Normal\,condition$$

The new value of current will therefore be equal to 3/2 x Original value of current. (In practice both power factor and rotational speed will change).

Additionally, with the single phase configuration, the phase voltage reduces to 3300/2 = 1650 volts which implies a further increase in current to sustain constant output

$$Therefore\ new\ value\ of\ current = \frac{2}{\sqrt{3}} \bullet (\frac{3}{2} \bullet Original\ Current) = \sqrt{3} \bullet Original\ Current$$

Resolving the unbalanced current into its symmetrical components gives

$$\begin{aligned} Ia1 &= \tfrac{1}{3}\,(Ia + hIb + h^2Ic) \\ Ia2 &= \tfrac{1}{3}\,(Ia + h^2Ib + h\,Ic) \\ Iao &= \tfrac{1}{3}\,(Ia + Ib + Ic) \end{aligned} \qquad (4.8)$$

where $Ia = \sqrt{3}.I_{flc}$; $Ib = -\sqrt{3}.I_{flc}$; $Ic = 0$

Substituting for Ia, Ib and Ic in equation (4.8) gives:

$$\begin{aligned} Ia1 &= \tfrac{1}{3}(\sqrt{3}\,I_{flc} + h(-\sqrt{3}\,I_{flc}) + 0) \\ Ia2 &= \tfrac{1}{3}(\sqrt{3}\,I_{flc} + h^2(-\sqrt{3}\,I_{flc}) + 0) \\ Iao &= \tfrac{1}{3}(\sqrt{3}\,I_{flc} + (-\sqrt{3}\,I_{flc}) + 0) \end{aligned} \qquad (4.9)$$

From the above set of equations it can be seen that Iao = 0. This means no zero sequence components of current are present.

Simplifying equation (4.9) for Ia1, gives:

$$Ia1 = \tfrac{1}{3}(\sqrt{3}\,I_{flc} + (1 \angle 120° \bullet (-\sqrt{3}\,I_{flc})))$$

$$Ia1 = \tfrac{1}{3}(\sqrt{3}\,I_{flc} + (-\frac{1}{2} + j\frac{\sqrt{3}}{2})(-\sqrt{3}\,I_{flc}))$$

$$I_{a1} = \tfrac{1}{3}(\sqrt{3}\, I_{flc} + \frac{\sqrt{3}}{2} I_{flc} - j\frac{3}{2} I_{flc})$$

$$I_{a1} = \tfrac{1}{3}(\frac{3\sqrt{3}}{2} I_{flc} - j\frac{3}{2})_{flc}$$

$$I_{a1} = \frac{\sqrt{3}}{2} I_{flc} - j\frac{1}{2} I_{flc}$$

From which it can be seen that the magnitude of Ia1 = Iflc

Similarly it can be shown that the magnitude of Ia2 = Iflc

Hence for this condition the operating time may be determined by calculating Ieq using equation (4.7) and applying either value to the relay characteristic

$$I_{eq} = \sqrt{(I_1^2 + 6I_2^2)}$$

$$I_{eq} = \sqrt{(I_1{}^2{}_{flc} + 6I_2{}^2{}_{flc})}$$

$$I_{eq} = \sqrt{(7I^2_{flc})}$$

$$I_{eq} = \sqrt{7} \bullet I_{flc} \quad \textit{for 105\% trip level}$$

For 110% trip level Ieq is modified as follows:

$$I_{eq} = \sqrt{((\frac{105^2}{110^2})I_1^2 + 6(\frac{105^2}{110^2})I_2^2)}$$

$$I_{eq} = \sqrt{7} \bullet \frac{105}{110} \bullet I_{flc}$$

Considering the second case where the motor is supplied from only two phases whilst in the standstill or locked rotor condition:

Then for normal 3 phase operation

kVA supplied in standstill condition $= \sqrt{3} \bullet V_L \bullet I_{LR}$

Equivalent phase impedance for this condition $= Zph = V_L/(\sqrt{3} \bullet I_{LR})$ Ω

Under single phase conditions the arrangement reduces to two windings in series supplied with line volts, hence single phase locked rotor current reduces to:

$$V_L/(2V_L/(\sqrt{3} \bullet I_{LR})) = \sqrt{3} \bullet I_{LR}/2 \text{ Amps}$$

Resolving this single phase value of current into its symmetrical phase sequence components gives:

$$Ia1 = \tfrac{1}{3}\left(\frac{\sqrt{3} \bullet Ilr}{2} + \left(-\frac{1}{2} + j\frac{\sqrt{3}}{2}\right) - \frac{\sqrt{3} \bullet Ilr}{2} + 0\right)$$

$$Ia2 = \tfrac{1}{3}\left(\frac{\sqrt{3} \bullet Ilr}{2} + \left(-\frac{1}{2} - j\frac{\sqrt{3}}{2}\right)\left(-\frac{\sqrt{3} \bullet Ilr}{2}\right)\right)$$

$$Iao = \tfrac{1}{3}\left(\frac{\sqrt{3} \bullet Ilr}{2} + \left(-\frac{\sqrt{3} \bullet Ilr}{2}\right) + 0\right) \qquad 4.10$$

$$\text{where} \quad Ia = \sqrt{3} \bullet \frac{I_{LR}}{2}; \quad Ib = \sqrt{3} \bullet \frac{I_{LR}}{2}; \quad Ic = 0$$

Simplifying for Ia1, gives:

$$Ia1 = \tfrac{1}{3}\left(\frac{\sqrt{3} \bullet Ilr}{2} + \frac{\sqrt{3} \bullet Ilr}{4} - j\frac{3 \bullet Ilr}{4}\right)$$

$$Ia1 = \tfrac{1}{3}\left(\frac{3\sqrt{3} \bullet Ilr}{4} - j\frac{3 \bullet Ilr}{4}\right)$$

$$Ia1 = \frac{\sqrt{3} \bullet Ilr}{4} - j\frac{Ilr}{4}$$

$$Ia1 = \frac{Ilr}{2} \tan^{-1}\frac{1}{\sqrt{3}} \quad Amps$$

*Similarly it can be shown that the magnitude of Ia2 is* $\frac{Ilr}{2}$ *Amps*

Substituting these values in the characteristic equation gives

$$Ieq = \sqrt{(I_1^2 + 6I_2^2)}$$

$$= \sqrt{((\frac{Ilr}{2})^2 + 6(\frac{Ilr}{2})^2)} = \frac{\sqrt{7} \bullet Ilr}{2}$$

$$For\ 110\%\ trip\ level\ Ieq = \frac{105}{110} \bullet \frac{\sqrt{7} \bullet Ilr}{2}$$

The derived values of symmetrical phase sequence current components are lower than would be experienced in practice. Under no-load conditions a three-phase motor when subjected to a loss of a phase would experience a current increase of $\sqrt{3}$ times the no load current. In the practical case, where the motor would be loaded prior to the single phase fault occurring, the expected current increase to sustain the load under single phase conditions would be in excess of $\sqrt{3}$ times the loaded current value. Under full load conditions the anticipated single phase current increase would be of the order of 2-2½ times flc providing sufficient torque is available to sustain the load[(1)]. The logic used in this analysis requires the motor manufacturer to provide maximum withstand times for the single phase condition occurring during the fully loaded run condition and also for the stalled condition which may arise due to a locked rotor. In both run cases the analysis assumes a current increase of $\sqrt{3}$ times flc whilst the latter case assumes a value of $\sqrt{3}/2$ times locked rotor current. Both cases when satisfied will provide an effective margin of safety.

In the case of a delta wound machine running under normal healthy conditions the phase current is given by:

$$\text{phase current} = \text{line current} / \sqrt{3}$$

Referring to Figs. 4.4a and 4.4b it can be seen that with the loss of one supply phase the circuit effectively consists of a single winding in parallel with the other

Single phase circuit for 3 - phase star connected motor

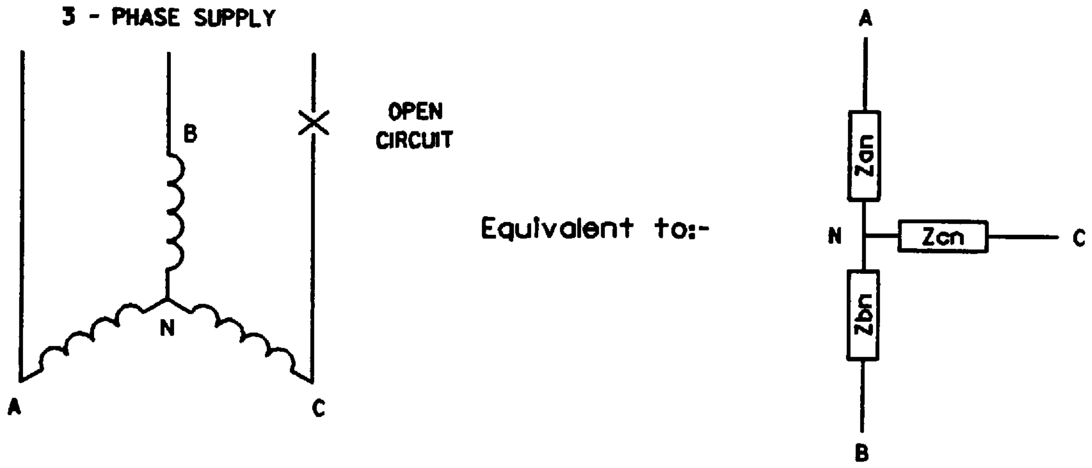



Fig 4.3A

Fig 4.3B

Single phase circuit for 3 - phase delta connected motor

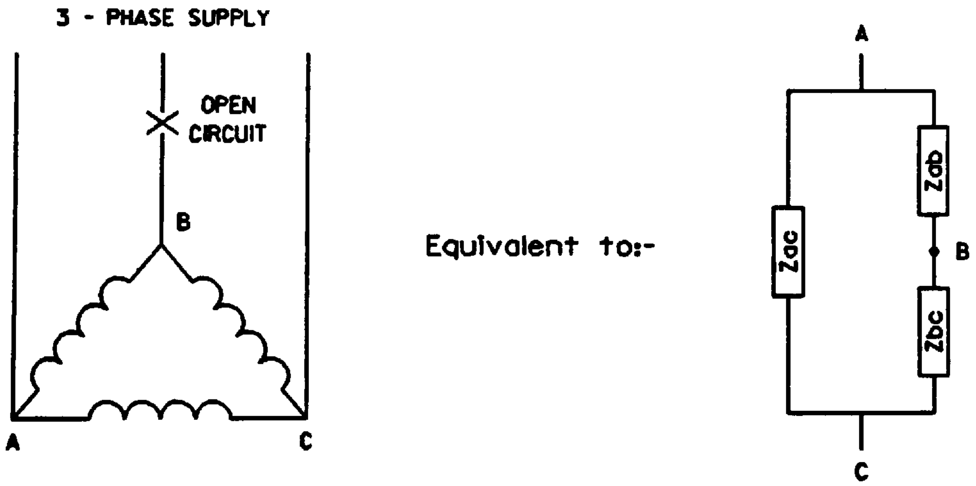



Fig 4.4A

Fig 4.4B

two windings arranged in series. To maintain full load output the line current in the two sound phases must rise by a factor of $\sqrt{3}$. Under this arrangement the single winding across the supply will dissipate four times more power than that dissipated in the other two windings. The heating effect will be substantial as 2/3 of the overall current will be passed through the single winding. The value of this current will be:

$$> \frac{2}{3} \bullet \sqrt{3} \bullet flc \quad \geq \quad 1.15\, flc$$

This phase current value of 1.15 flc is twice the phase current experienced under normal healthy three-phase supply operation. It can be resolved into symmetrical components of positive and negative phase sequence component currents of magnitude:

$$\frac{1}{\sqrt{3}} \bullet \sqrt{3} \bullet \frac{2}{3} \bullet flc = 0.667\, flc$$

Both these values are 115% greater than the phase current experienced under healthy three phase operation and will lead to rapid heating of the windings. Similarly in the case of a single phase locked rotor condition, the current measured by the protective device, the line current, will be identical to the line current for a star connected machine under single phase conditions. The internal current distribution however again will allow two thirds of the line current to pass through one of the windings which in the case of a delta wound machine is identical to the current observed under 3-phase locked rotor conditions. This condition is of course remedied by detecting and magnifying the negative phase sequence component of the line current in order to accelerate tripping in accordance with the chosen thermal characteristic.

From the above discussion it is therefore evident that it is now possible to provide additional inequalities such that when satisfied they provide thermal protection against the unbalanced condition. The conditions may be described as follows.

Minimum NPS current content determined from the trip setting < Maximum continuous NPS current content allowable for the motor

As it is difficult to obtain a continuous thermal withstand characteristic containing a declared NPS content for any motor, it is prudent to examine and check the constraints at the two locations already considered, that is single phase at full load and single phase for the stall condition. A summary of the checks carried out are listed in table 4.2.

### 4.1.3 <u>High Set Overcurrents</u>

Reference to Fig. 4.2A shows that the CTM relay can be fitted with two instantaneous elements, one which is sensitive to positive-phase-sequence overcurrents, the other, to negative-phase-sequence overcurrents. The usual approach adopted when setting the PPS element is to aim for an operating threshold at:

$$1.25 \times \text{CT Secondary steady state current} \qquad (4.11)$$

The setting arrived at should be sufficient to ensure that mal-operation due to assymetry on starting does not occur. Assymetry on starting will of course occur, due to the three phase motor being energised by simultaneous closure of contacts in each phase. The closure of each phase taking place at a different point on the voltage waveform. The effect of this assymetry will produce unequal currents of large magnitude in each phase of the motor supply. The magnitude of these

## TIME INEQUALITY CHECKS

| | | | |
|---|---|---|---|
| 1) | 1.1 x RELAY CURVE (COLD) @ STALL (100%V) | < | MOTOR STALL (COLD) @ 100%V |
| 2) | 1.1 x RELAY CURVE (COLD) @ STALL (100- %V) | < | MOTOR STALL (COLD) @ 100- %V |
| 3) | 1.1 x RELAY CURVE (COLD) @ STALL (100+ %V) | < | MOTOR STALL (COLD) @ 100+ %V |
| 4) | 1.2 x RELAY CURVE (COLD) @ 2 X FLC | < | MOTOR WITHSTAND (COLD) @ 2 X FLC |
| 5) | 1.1 x RELAY CURVE (HOT) @ STALL (100%V) | < | MOTOR STALL (HOT) @ 100%V |
| 6) | 1.1 x RELAY CURVE (HOT) @ STALL (100- %V) | < | MOTOR STALL (HOT) @ 100- %V |
| 7) | 1.1 x RELAY CURVE (HOT) @ STALL (100+ %V) | < | MOTOR STALL (HOT) @ 100+ %V |
| 8) | 1.2 x RELAY CURVE (HOT) @ 2 X FLC | < | MOTOR WITHSTAND (HOT) @ 2 X FLC |
| 9) | 0.9 x RELAY CURVE (HOT) @ START (100%V) | > | 1.02 X RUN-UP-TIME @ 100%V |
| 10) | 0.9 x RELAY CURVE (HOT) @ START (100- %V) | > | 1.02 X RUN-UP-TIME @ 100- %V |
| 11) | 0.9 x RELAY CURVE (HOT) @ START (100+ %V) | > | 1.02 X RUN-UP-TIME @ 100+ %V |

## FOR RELAYS WITH UNBALANCE CHARACTERISTICS - TYPES 3-6 INCL.

| | | | |
|---|---|---|---|
| 12) | 1.1 x RELAY CURVE (COLD) IPH @ STALL | < | MOTOR IPH STALL (COLD) |
| 13) | 1.1 x RELAY CURVE (COLD) IPH @ RATED OUTPUT | < | MOTOR IPH WITHSTAND (COLD) @ RATED OUTPUT |
| 14) | 1.1 x RELAY CURVE (HOT) IPH @ STALL | < | MOTOR IPH STALL (HOT) |
| 15) | 1.1 x RELAY CURVE (HOT) IPH @ RATED OUTPUT | < | MOTOR IPH WITHSTAND (HOT) @ RATED OUTPUT |

TABLE 4.2

currents being determined by the point of closure on the waveform and the transient reactance of the machine.

Early electro-mechanical type relays utilised instantaneous attracted armature elements for detecting overcurrents. These elements produced perfectly satisfactory results when used with 'old' style induction motors which contained large amounts of iron in the frame but resulted in mal-operation when used with modern small frame machines. Tests conducted on a modern small frame induction motor using a high speed recorder showed the problem to be caused by peak currents with a magnitude approaching twenty times full load current. The small time constant associated with these currents resulted in their rapid decay. The solution adopted by certain manufacturers was to 'slug' the operation of the instantaneous overcurrent element for the first few cycles of operation. This was usually achieved by attaching a sealed dashpot containing silicon fluid or liquid of a similar viscosity arranged to delay closure of the element armature. Modern relays including the CTM incorporate a built in delay of 80 msecs to overcome the problem. It should be noted that the CTM relay is used in conjunction with fully rated circuit breakers and that fault clearance time is additive to the 80 msecs relay operating time. In the case of a modern vacuum circuit breaker the clearing time will be less than 50 msecs whereas clearing time in an old oil-circuit breaker may stretch to 150 msec or greater. This may be of critical importance when contemplating the installation of minimum size cabling.

It can be seen that the PPS overcurrent element offers no protection for any motor overloads up to and including the stall condition. Its sole response is to detect abnormal conditions outside the envelope encountered during the starting and acceleration states.

#### 4.1.3.1 NPS High Set Overcurrent

The negative phase sequence element also incorporates a time delay such that the nominal operating time of 80 msecs is sufficient to overcome most assymetry encountered on starting.

The recommended setting for the element is:

$$<0.4 \times \text{Positive phase sequence element setting} \qquad (4.12)$$

This value is one half of the 3 phase steady state starting current and is equal to the maximum NPS current found in the single phase stall condition. The lowest setting possible should be used consistent with stable operation of the element. Caution should be exercised as if the setting chosen is too low, mal-operation of the element may occur resulting in unecessary tripping of the motor. The cause of such tripping may not be immediately obvious and could result in unnecessary delay before resetting takes place.

#### 4.1.3.2 Fuse/Relay Co-ordination

Fig. 4.2B, the block schematic diagram for the CTMF relay shows that there is no PPS high set overcurrent element installed in this unit. Instead, the fault current detection and isolation function is carried out by inline power fuses. The inline power fuses are mandatory due to the inability of the motor switching device, MSD, to interrupt the high levels of current found under fault conditions. It is of course essential to establish that the clearing time of the fuse is substantially less than the opening time of the MSD, otherwise the MSD will attempt to break the fault current. Most manufacturers of power fuses for motor applications provide information to deduce optimum fuse size for given values of motor starting current, duration and starting frequency. In practice, however, the usual approach is to establish the largest size fuse that offers complete protection for the MSD and equip all circuits alike. On the debit side this action may result in using minimum sized cables which are larger than required but is offset by requiring only one size of fuse to be retained for emergencies.

It can be seen that the CTMF relay is equipped with a high set NPS element which trips the MSD following a time lag which is adjustable between 0.5 - 3.0 secs. The adjustment being to allow discrimination between the MSD and the inline power fuses. The usual procedure adopted to determine the delay setting may be observed in the following example.

Consider a circuit with the following specification

| | | |
|---|---|---|
| Relay | - | GEC type CTMF Motor Protection Relay equipped with thermal characteristic reference 3 with a thermal setting of 105%. The relay is supplied from 40/1 ratio current transformers. |
| Power Fuse | - | GEC 3.3kV, type K81 PE |
| Rating | - | 250 Amp |
| Max' pre arc $I^2t$ | - | 235 x $10^3$ $Amp^2$ secs |
| Max' Total $I^2t$ | - | 1400 x $10^3$ $Amp^2$ secs |
| Motor switching device | - | Allen West type CV432H-GAT, 3.3kV Vacuum Contactor |
| Current rating | - | 350 Amp |
| Max' interrupting capacity | - | 4400 Amp |
| Short time rating | - | 20kA for 0.1 sec |
| Opening time | - | 90-120m sec |

| | |
|---|---|
| Motor | GEC 180kW, 3.3kV, 50Hz 'Impak' type CACA induction motor as specified in appendix 7 driving a pump with a 2 sec acceleration time. |

It can be seen from Fig. 4.5 that for potential fault currents in excess of 6kA, the pre-arcing time of the 250A fuse is of the order of 10-20 msecs. It is at this point that the peak value of current is experienced before the onset of the arcing period and subsequent current decay.

In this particular case, assuming a potential fault current of 10kA, the fuse cut-off current is limited to 15kA peak (see Appendix 8).

Using the fuse data specified and the knowledge that the motor full load current is 40A, the minimum sized cable may be determined as follows:

Cable type: PVC insulated, steel wire armoured, pvc oversheath with stranded copper conductors.

Minimum size on current consideration alone 16mm$^2$ (Generally the minimum size available in the cable manufacturers industrial range - current rating 79 - 94A).

Maximum current withstand for 1 sec = 1732A (assuming fully loaded at start).

Maximum $I^2t$ withstand = 3 x 10$^6$ Amp$^2$ secs which is greater than the maximum let thro', $I^2t$, value for the fuse of 1.4 x 10$^6$ Amp$^2$ secs. Provided the cable length is not excessive and voltage drop is within prescribed limits then this cable will be satisfactory. Caution must be exercised when dealing with paper insulated cables as it is important to calculate the peak current withstand capability of the cable from the manufacturers supplied data. Failure to do so may cause peak fuse let thro' current to exceed the capabilities of the paper insulation resulting in possible damage by "tearing" or "bursting" of the papers. Referring to the contactor specification, the shortest opening time is quoted as 90 msecs.

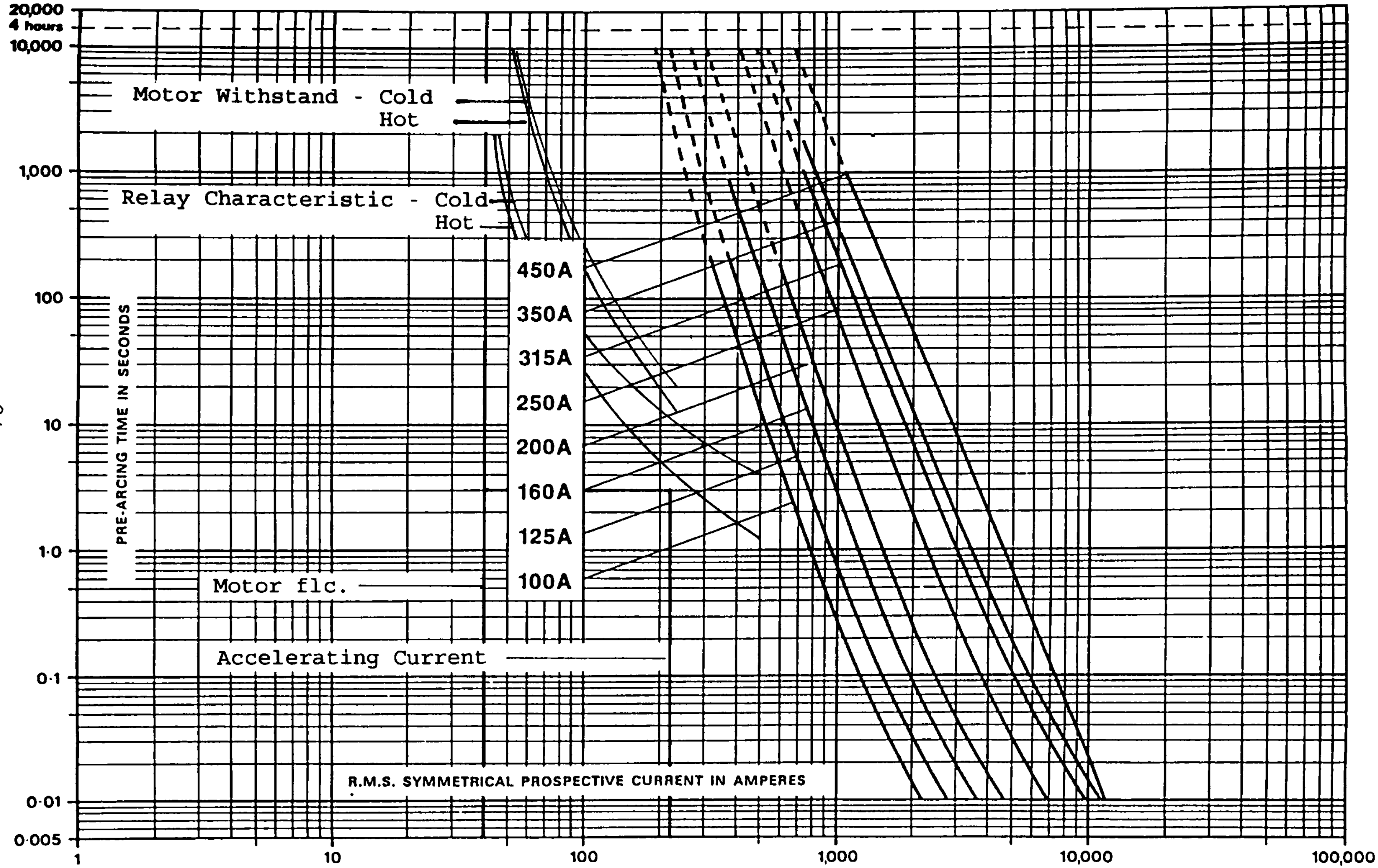



*Fig 4.5 Fuse/Thermal/Motor/Acceleration time co-ordination graph*

Allowing a 20% margin indicates that for an operating time of 90/1.2 = 75 msecs, the prospective RMS symmetrical current is 4kA which is less than the contactor breaking capability of 4.4kA. Where larger prospective fault currents are available the fuse clearance time becomes shorter thus ensuring a larger discrimination time with the contactor.

Extending the logic to larger fuse sizes suggests that the 315A fuse should not be used as it does not provide complete discrimination with the contactor. More modern contactors exhibit much improved capabilities and may be obtained with maximum interrupting capabilities extending to 12kA. Typical general purpose contactors of around 6-8kA interrupting capacity are readily available.

All fuse sizes greater than 250A can be used with the contactor under discussion but a zone of uncertainty now appears to exist where pre-arcing time exceeds contactor opening time. It should be noted however that the opening time quoted only occurs after trip initiation. This may result from:

1. Operation of the main fuses removing power from the control transformer from which the contactor holding coil supplies may be derived. The fault may however be an earth fault affecting only one phase which could leave the control transformer output unaffected.
2. If the control transformer remains energised then the striker pins contained within the body of the main fuses will on operation activate micro switches via a common tripping bar and remove power from the contactor holding coil.
3. Operation of the high set $I_2$ NPS element or the $I_o$, ZPS element.

Examination of case (1) indicates an inconsistent method of tripping. The resulting trip time being a function of the type of fault.

In case (2) the action of ejecting a striker pin through the end cap to operate micro-switches via a mechanical linkage takes a finite time. This time is of course additive to the contactor opening time but may be modified by the action of case (1).

Case (3) refers to the NPS and ZPS sensing elements which could operate providing the current values presented exceed the operating threshold of the elements. It should be noted that both of these elements operate into a delay circuit prior to tripping, the minimum delay being 500 msecs. Hence tripping from these elements will only take place at low fault current levels where the fusing time exceeds the operating time of these elements.

The recommended approach to setting the $I_2/I_o$ time delay is to establish the clearance time of the fuse at the maximum breaking capacity of the contactor. The $I_2/I_o$ time delay is then set to 120% of this value which is adequate to cover fuse operating time tolerances as it is in addition to the contactor opening time. The total clearance time of the fuse is difficult to predict as the arcing period during the fusing cycle will vary with circuit power factor, voltage level, fault level, electrical angle at which arcing commences and several other less important factors. However, provided voltage levels are within limits, the arcing time only becomes a significant proportion of the total time at high fault currents where the pre-arc times are very short. Using this technique the entire range of fuses up to the maximum available size of 450A may be accommodated provided the thermal rating of the contactor is not exceeded during the duration of the fault.

#### 4.1.3.3 The Problem

Herein lies the problem as seen by the author of this thesis. There can be no guarantee that the contactor will remain closed during the period when fault current is present when used in conjunction with fuses which have a rating greater than 250A. As previously stated the supply for the contactor holding coil is derived from a control transformer whose primary is connected to the circuit side of the main fuses and as such may be subject to severe voltage depressions prior to fuse clearance. It should be noted that contactors are required to remain closed during voltage depressions down to 70% of nominal voltage levels. Examination of test reports indicate that many will remain closed down to 40% of this value, but this figure may prove optimistic as there will be a force present tending to open the contactor when heavy fault currents are flowing. The contactor holding coil is usually controlled by a pilot relay which also has the function of removing the holding coil supply for voltage excursions to less than 70% of nominal voltage. Such is the sensitivity and response of these relays to short duration voltage dips that they may cause the contactor to open prematurely whilst carrying current in excess of its rated breaking capacity. This is a potential hazard which could conceivably arise when large fuse sizes are utilised.

One solution to the problem would be to supply all contactor holding coils and pilot relays from a source not affected by the fault such as a dc battery system. This solution whilst feasible calls for a battery installation which is capable of sustaining a large standing load - clearly not a cost effective option. A more realistic approach would be to utilise latched contactors. Whilst a battery supply is still necessary it is now only required to provide a short impulse to close the contactor until the mechanism latches and retains it. Similarly a short low power impulse is required to trip it. Both these requirements can easily be met from the closing/tripping battery which is necessary to operate the circuit breakers which provide the incoming supply to the switchboard. Many other solutions exist but the cost will depend on whether the closing/tripping supplies provided for the incoming circuit breakers can be utilised.

Technology will solve the problem in due course as earlier comments imply. The interrupting capacity of the contactors are constantly being improved allowing discrimination to be obtained with maximum sized fuses. Extreme caution should be exercised as a large variation in interrupting capabilities for both new and previously installed equipment does exist.

### 4.1.4 Earth Fault

There are two earth fault options catered for in the CTM relay series. The first as fitted to the CTM relay, utilises a type CAG 11 instantaneous attracted armature measuring element set to operate after a delay of 80 msecs when its value exceeds a nominal operating threshold of either 10% or 20% of relay rating as specified by the purchaser. This element is supplied with zero sequence current derived from the input sequence filter as shown in Fig. 4.2a. The unit fitted to the CTMF relay is identical in all respects save the inclusion of a variable time delay feature which inhibits the output of the element until the delay has elapsed. This relay is illustrated in Fig. 4.2b.

The second option as fitted to the CTMC variant utilises a core balance current transformer (CBCT) in addition to the line current transformers (CT). This configuration is well suited to systems where available earth fault current is low. Due to only one CBCT being required the operating threshold may be set low as 'spill' current is not a problem as is the case with three residually connected CT's. In addition the accuracy of the operating setting is good, as magnetising current is only required for one CT. Despite the stated attraction the relay is seldom encountered and will not be further considered.

The normal residually connected earth fault arrangement requires the addition of a stabilising resistor in series with the zero-sequence sensing element. The purpose of the resistor is to allow the element to remain stable during the starting period when heavy current is drawn. Assymetry during this period may cause saturation or partial saturation of a CT resulting in an imbalance or 'spill' current to flow in the CT neutral conductor.

The usual method of calculating the value of the stabilising resistor is to assume the worst case where one CT is completely saturated whilst the other two transform perfectly.

Consider an example using the previously mentioned 3.3kV 180kW motor with the following basic characteristics:

| | |
|---|---|
| Full Load Current | 40A |
| Starting Current | 230A |
| Current Transformer Ratio | 40/1A |
| Then CT output at start | 230/40 = 5.75A |

The CT output from each phase is supplied initially to a sequence filter mounted in the relay. The general arrangement of the connections is shown in Fig. 4.2a and 4.2b. Under normal conditions of transformation only 'spill' current passes through the neutral conductor to the instantaneous Io element and stabilising resistor RV6. However when considering the unbalanced case of one CT being saturated, the current supplied to it is the vector sum of the output from the two sound phase CT's. Hence the voltage generated across the phase containing the saturated CT may be determined as follows.

$$V = IS\,(R_{CT} + NR_L + 0.6/I_n^2) \qquad (4.13)$$

| | | | | | |
|---|---|---|---|---|---|
| where | $R_{CT}$ | = | Resistance of saturated CT | = | 2Ω |
| | $R_L$ | = | Resistance of Lead | = | 0.1 Ω |
| | In | = | Relay Rating | = | 1A |
| | IS | = | Starting Current (CT Output | = | 5.75A |
| | 0.6 | = | Relay Burden/Phase | = | 0.6 VA |
| | N | = | 1 For 4 wire CT connection (star point formed at CT's) | | |
| | N | = | 2 For 6 wire CT connection (star point formed at relay panel) | | |
| | let | | N = 1 | | |

At this point it should be noted that the relay may be supplied with either internal or external star point phase connections. Figs. 4.6a and 4.6b are included to illustrate the difference.

Substituting these values in equation (4.13) gives:

$$V = 5.75\,(2 + 0.1 + 0.6/1) = 15.53V$$

which is the voltage impressed across the Io element and the stabilising resistor. The instantaneous Io element used is a type CAG 11 attracted armature unit designed to operate at 0.2 x In. Test results(2) obtained from the manufacturer show that for a 1A rated relay with the armature open the following characteristics apply.

| | | | |
|---|---|---|---|
| a.c. Resistance of CAG 11 element | = | 5.8 Ω | = $R_{ZS}$ |
| Inductive Reactance of CAG 11 element | = | 13.4 Ω | = $X_{ZS}$ |

and for a 5A rated relay

| | | | |
|---|---|---|---|
| a.c. Resistance of CAG 11 element | = | 0.8 Ω | = $R_{ZS}$ |
| Inductive reactance of CAG 11 element | = | 0.8 Ω | = $X_{ZS}$ |

EXTERNAL CONNECTIONS CTM21 TO 26, CTM41 TO 46 AND CTM31 TO 36
with internal star connection.

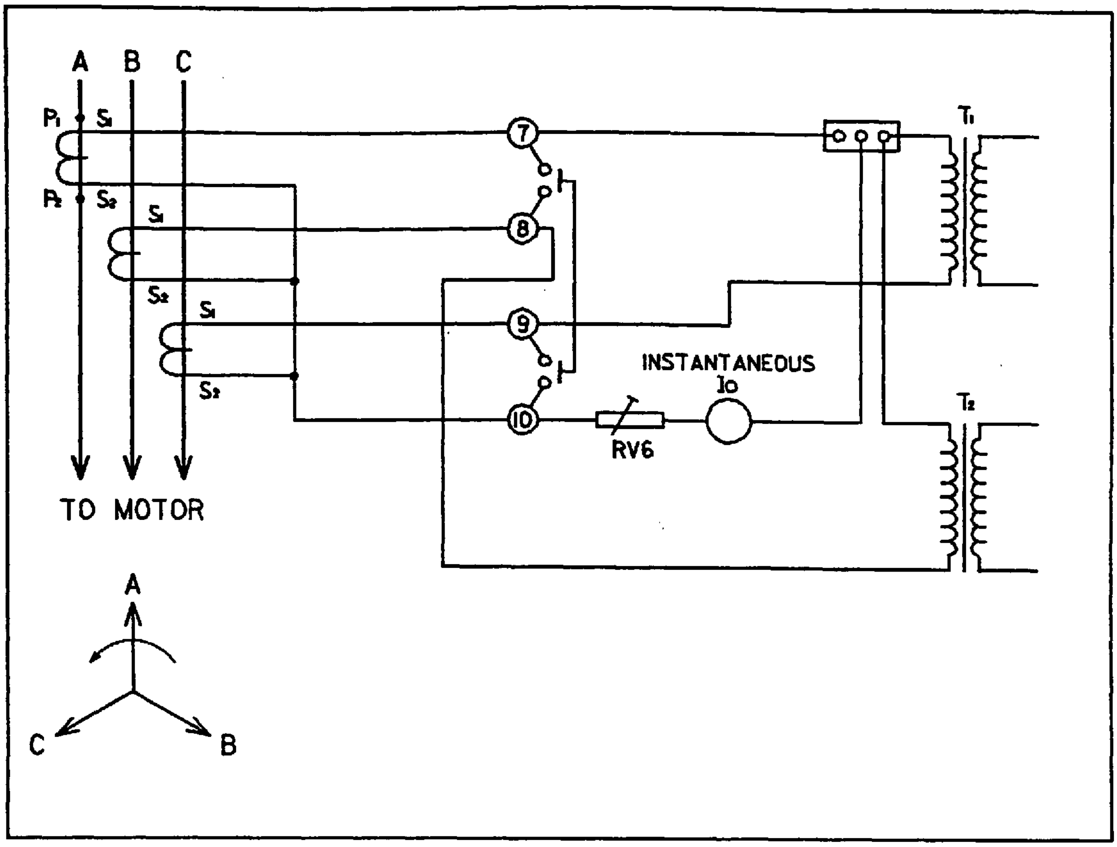



Fig. 4.6a

EXTERNAL CONNECTIONS CTM21 TO 26, CTM41 TO 46 AND CTM31 TO 36
with external star connection.

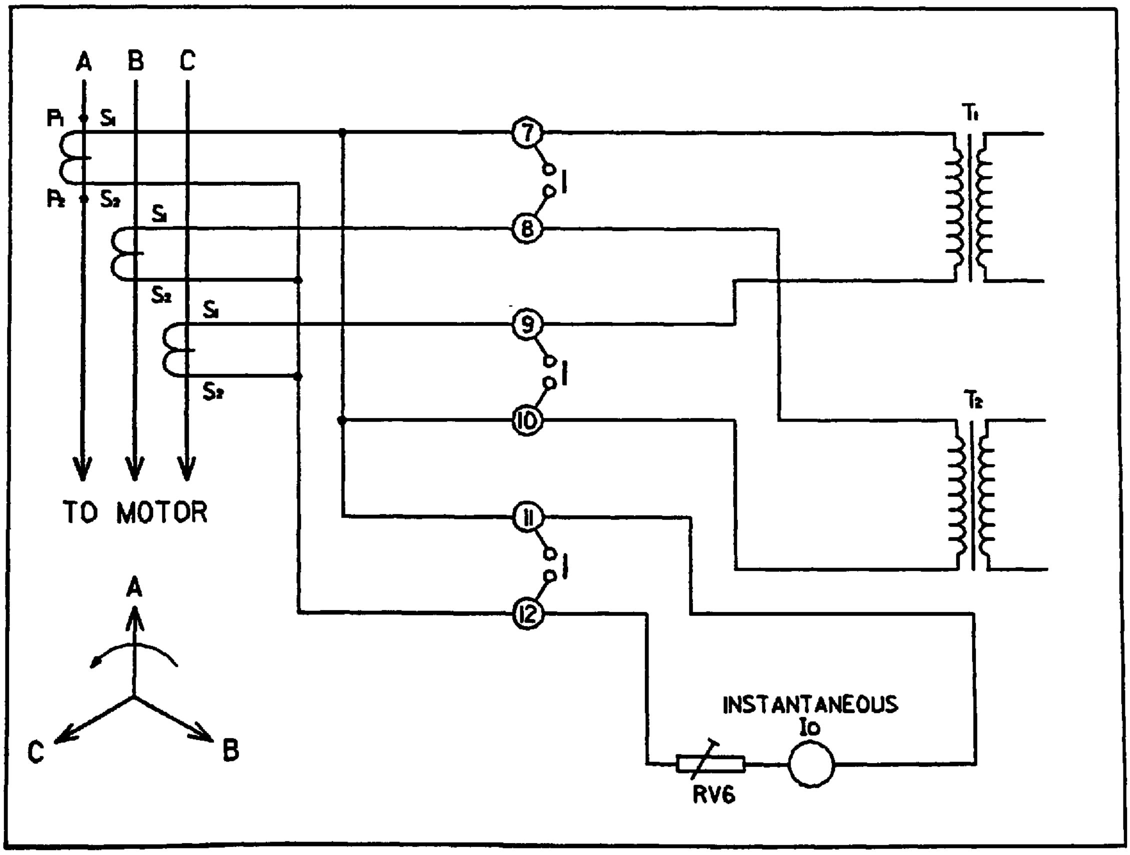



Fig. 4.6b

It is necessary to consider both resistance and reactance of the CAG 11 element as the voltage generated across the Io measuring circuit is low due to the light VA burden of 0.6VA (resistive) imposed by the CTM relay.

Interpolation of manufacturers graphical data suggest the following resistive and reactive values for modelling other available ratings.

CAG 11 element for 1A Relay with 10% setting

ac. resistance of CAG 11 element $\simeq$ 14 $\Omega$

Inductive reactance of CAG 11 element $\simeq$ 57.35 $\Omega$

CAG 11 element for 5A Relay with 10% Setting

ac. resistance of CAG 11 element $\simeq$ 1.1$\Omega$

Inductive reactance of CAG 11 element $\simeq$ 2.074$\Omega$

Now for stability purposes the impedance of the zero sequence element and stabilising resistor must be equal to or greater than 15.53/0.2 = 77.65 $\Omega$

From which the required value of the stabilising resistor may be deduced by subtracting the impedance of the Io element. Hence the complete formula used by the manufacturer for calculating the stabilising resistance may be written as:

$$R_{STAB} = \sqrt{\left(\left(\frac{Is(Rct+N.Rl+0.6/In^2)}{0.9\,Io}\right)^2 - X^2_{zs}\right)} - Rzs \qquad (4.14)$$

where

$I_S$, $R_{CT}$, N, $R_L$, 0.6, $I_n$ are as previously defined

and $R_{ZS}$ - ac. resistance of CAG 11 element

$X_{ZS}$ - Inductive reactance of CAG11 element

Io - CAG11 current setting i.e. 10% or 20% x In

0.9 - Safety factor to allow for variation in pick-up

Substituting the derived values in equation (4.14) gives

$$R_{STAB} = \sqrt{\left(\left(\frac{5.75\,(2 + 0.1 + 0.6)}{0.9 \bullet 0.2}\right)^2 - 13.4^2\right)} - 5.8$$

$$= \sqrt{(86.25^2 - 13.4^2)} - 5.8$$

$$= 79.4\ \Omega$$

## 4.2 The CTM(F) Program

The logic previously discussed has been incorporated in a computer program, a description of which is included in the next section.

Consider a 180kW, 3.3kV motor for which details are included in Appendix 7. Assume that the motor requires 5 seconds to accelerate at 85% line voltage, 4 seconds at 100% line voltage and 3 seconds at 110% line voltage.

On running the program a menu is displayed as shown in Fig. 4.7. If it is assumed that the selection chosen is option 4 as this option selects a CTM relay configured to include the following functions, Thermal, NPS, Earth fault, Instantaneous PPS and NPS high set overcurrent elements. At this stage it is necessary to specify the ratio of the CT's which are to be used. To assist in this operation both motor rating and associated full load current are clearly displayed. The ratio chosen is 40/1. Two further items require specification, the trip level for which a setting of 110% is used and an earth fault setting for which a 20% fixed setting is chosen (standard fixed element setting). As the relay option chosen contains an instantaneous

```
                    GEC   - CTM(F)
                  STANDARD  OPTIONS

        1.     THERMAL ONLY
        2.     THERMAL + I0             (Inst.)
        3.     THERMAL + I1 + I2        (Inst.)
        4.     THERMAL + I1 + I2 + I0   (Inst.)
        5.     THERMAL + I2          (Delayed.)
        6.     THERMAL + I2 +I0      (Delayed.)

   Select option :           ..............        4

   Motor rating              ..............      180  kW
   Full load current         ..............       40  Amps
   CT Ratio                  ..............      40 /1
   Thermal trip level        ..............      110  %
   Earth fault setting       .( 10%,20% )..       20  %

 <A>ccept / <R>eject      A                          <Q>uit
```

*Fig 4.7  Relay type option menu.*

earth fault element it is necessary to provide further information to enable the program to determine the value of the appropriate stabilising resistance. Fig. 4.8 displays the information required. On satisfying the requirements a further menu is displayed which lists the available characteristic solution strategies. This menu is shown in Fig. 4.9, the options available are discussed below.

Option 1 'MAXCURVE' 3/1 Cold/Hot ratio using standard characteristic.
The 'Maxcurve' option selects the relay characteristic which is closest to the motor thermal withstand characteristic. As all the constraints previously listed in the text cannot be satisfied, the option fails.

Option 2 'MAXCURVE' 3/1 Cold/Hot ratio using non-standard characteristic.
This option is similar to option 1 except that all constraints to be satisfied are now applied to the range of optional non-standard relay thermal characteristics, these are 00,01,02,03 and 04 which can be seen in appendix 7. In this case the option enables all conditions to be satisfied by characteristic 02. A table of relay operating times compared against motor withstand times under defined conditions is then displayed on the screen to allow the user to assess the protective margin available. A copy of the screen display is shown in Fig. 4.10 and is followed by Fig. 4.11 which shows a graphical representation of relay characteristic and the constraints which are accommodated.

Option 3 'MAXCURVE' 1.5/1 Cold/Hot Ratio using non-standard characteristic.
This option again uses the same technique as in the two previous cases except that the set of constraints are now applied to the series of supplementary characteristics defined as 11, 05, 21, 06, 31, 07, 41, 08, 51, 09 and 61. In this case the conditions are all satisfied by curve 31, the calculated values being shown in Fig. 4.12 whilst Fig. 4.13 provides a graphical representation.

```
                    GEC   - CTM(F)
              CURRENT TRANSFORMER DATA

  CURRENT TRANSFORMER RATIO                   ..........     40/1

  CURRENT TRANSFORMER RESISTANCE (dc)         ..........    2.000 Ohms
  CORE RESISTANCE CT. TO RELAY                ..........    0.100 Ohms
* 4 / 6 WIRE CONNECTION CONFIGURATION         ..........    4

* 4-Wire connection (Star point formed at current transformers)
* 6-Wire connection (Star point formed at relay panel          )

<A>ccept / <R>eject A                                      <Q>uit
                                                           <P>ageback
```

*Fig 4.8  Current transformer data requirements.*

```
                    GEC  - CTM(F)
                  STANDARD  OPTIONS

   1.     MAXCURVE    3/1 CURVE RATIO        ST'D
   2.     MAXCURVE    3/1 CURVE RATIO    NON-ST'D
   3.     MAXCURVE  1.5/1 CURVE RATIO    NON-ST'D

   4.     MINCURVE    3/1 CURVE RATIO        ST'D
   5.     MINCURVE    3/1 CURVE RATIO    NON-ST'D
   6.     MINCURVE  1.5/1 CURVE RATIO    NON-ST'D

   7.     USER CHOICE

   Q.     QUIT

Select option :     1
```

*Fig 4.9 Thermal strategy option menu.*

GEC - CTM 402

OPERATING TIMES AND MARGINS

| 3 ph Conditions | Relay Cold | Motor Cold | Margin %age | Relay Hot | Motor Hot | Margin %age |
|---|---|---|---|---|---|---|
| RATINGS at 2x FLC | 230.6 | 770.0 | +233 | 76.8 | 600.0 | +680 |
| RATINGS at LRC - 85% V | 27.1 | 31.8 | + 17 | 9.0 | 20.7 | +129 |
| RATINGS at LRC - 100% V | 19.4 | 23.0 | + 18 | 6.4 | 15.0 | +131 |
| RATINGS at LRC - 105% V | 17.6 | 20.8 | + 18 | 5.8 | 13.6 | +130 |
| 1 Ph Conditions | | | | | | |
| RATINGS at F/L Output | 109.6 | 720.0 | +556 | 36.5 | 600.0 | +*** |
| RATINGS at LRC - 100%V | 11.7 | 14.0 | + 19 | 3.9 | 8.0 | +104 |
| RUN-UP-TIME at - 85% V | 27.1 | 5.0 | +442 | 9.0 | 5.0 | + 80 |
| RUN-UP-TIME at - 100% V | 19.4 | 4.0 | +385 | 6.4 | 4.0 | + 61 |
| RUN-UP-TIME at - 105% V | 17.6 | 3.0 | +489 | 5.8 | 3.0 | + 96 |

All times in seconds

SELECT OPTION S PASS <P>ageback

<S>ettings,<M>enu <Q>uit

*Fig 4.10 Operating times and margins for CTM 4.02 relay.*

Option 4 'MINCURVE'

3/1 Cold/Hot Ratio using standard characteristics.

The 'Mincurve' option selects the relay characteristic which is furthest from the motor thermal withstand characteristic yet allows sufficient time to enable the motor to accelerate up to running speed. As in option 1 the strategy fails as none of the standard characteristics satisfy the imposed constraints.

Option 5 'MINCURVE'

3/1 Cold/Hot Ratio using non-standard characteristic

This option uses the same approach as in option 4 albeit applied to the range of characteristics listed in option 2. In this case the fastest operating characteristic to satisfy the imposed conditions is found to be 02. This is of course identical with the result obtained in option 2 which indicates that the only characteristic with a 3/1 Cold/Hot Ratio which can satisfy the constraints is curve 02 - see Figs 4.10 and 4.11.

Option 6 'MINCURVE'

1.5/1 Cold/Hot Ratio using non standard characteristic.

The method used to locate the solution is identical with that used in options 4 and 5 except that it is applied to the set of characteristics listed in option 3. Curve 06 provides a solution by satisfying all the constraints. The associated data and graphical representation is shown in Figs. 4.14 and 4.15.

Option 7 'User Option'

Presents the user with a list of all available relay thermal characteristics from which one can be selected. The screen display listing these characteristics is shown in Fig. 4.16. The characteristic which is chosen is then subjected to a series of constraint tests followed by a display of the calculated values. In the case where

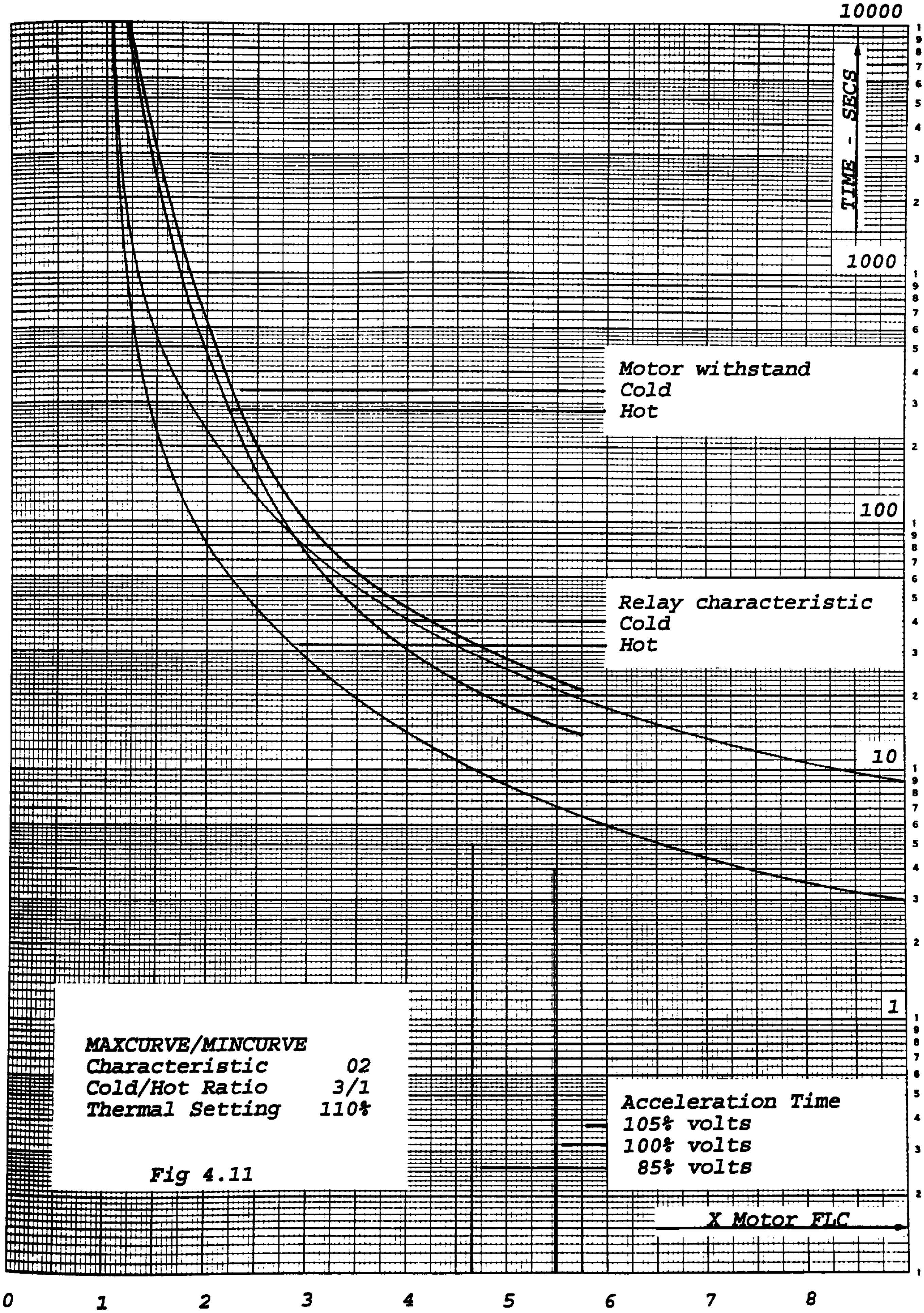

10000
TIME - SECS
1000
100
10
1
Motor withstand
Cold
Hot
Relay characteristic
Cold
Hot
MAXCURVE/MINCURVE
Characteristic 02
Cold/Hot Ratio 3/1
Thermal Setting 110%
Acceleration Time
105% volts
100% volts
85% volts
X Motor FLC
0
1
2
3
4
5
6
7
8

Fig 4.11

GEC - CTM 431
OPERATING TIMES AND MARGINS

| 3 ph Conditions | Relay Cold | Motor Cold | Margin %age | Relay Hot | Motor Hot | Margin %age |
|---|---|---|---|---|---|---|
| RATINGS at 2x FLC | 153.7 | 770.0 | +400 | 102.5 | 600.0 | +485 |
| RATINGS at LRC - 85% V | 18.0 | 31.8 | + 76 | 12.0 | 20.7 | + 72 |
| RATINGS at LRC - 100% V | 12.9 | 23.0 | + 77 | 8.6 | 15.0 | + 73 |
| RATINGS at LRC - 105% V | 11.7 | 20.8 | + 77 | 7.8 | 13.6 | + 73 |
| 1 Ph Conditions | | | | | | |
| RATINGS at F/L Output | 73.1 | 720.0 | +884 | 48.7 | 600.0 | +*** |
| RATINGS at LRC - 100%V | 7.8 | 14.0 | + 78 | 5.2 | 8.0 | + 53 |
| RUN-UP-TIME at - 85% V | 18.0 | 5.0 | +261 | 12.0 | 5.0 | +140 |
| RUN-UP-TIME at - 100% V | 12.9 | 4.0 | +223 | 8.6 | 4.0 | +115 |
| RUN-UP-TIME at - 105% V | 11.7 | 3.0 | +292 | 7.8 | 3.0 | +161 |

All times in seconds

SELECT OPTION S PASS <P>ageback
<S>ettings,<M>enu <Q>uit

*Fig 4.12 Operating times and margins for CTM 4.31 relay.*

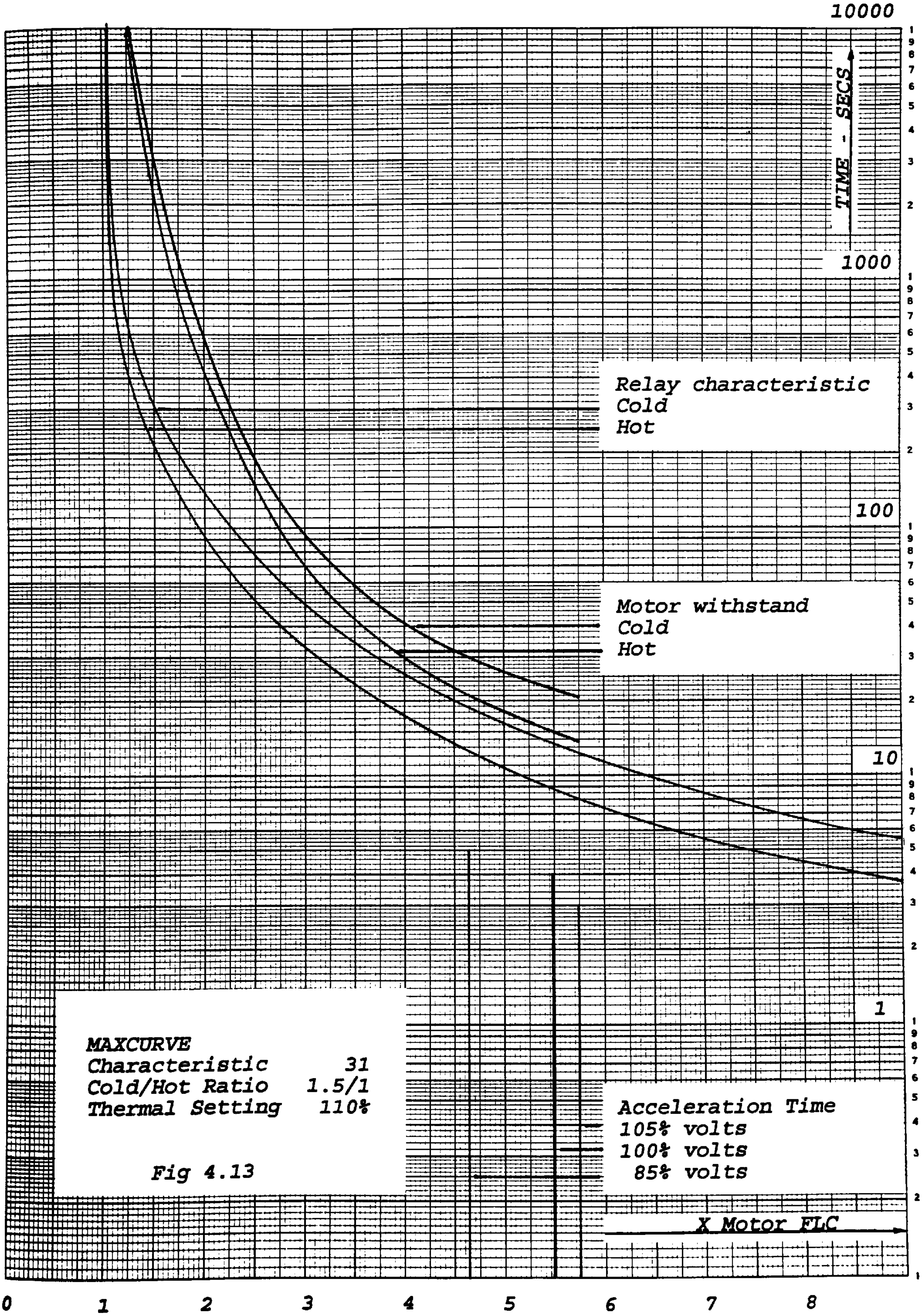

10000
1000
100
10
1
TIME - SECS
Relay characteristic
Cold
Hot
Motor withstand
Cold
Hot
MAXCURVE
Characteristic 31
Cold/Hot Ratio 1.5/1
Thermal Setting 110%
Acceleration Time
105% volts
100% volts
85% volts
X Motor FLC
0
1
2
3
4
5
6
7
8

Fig 4.13

GEC - CTM 406

OPERATING TIMES AND MARGINS

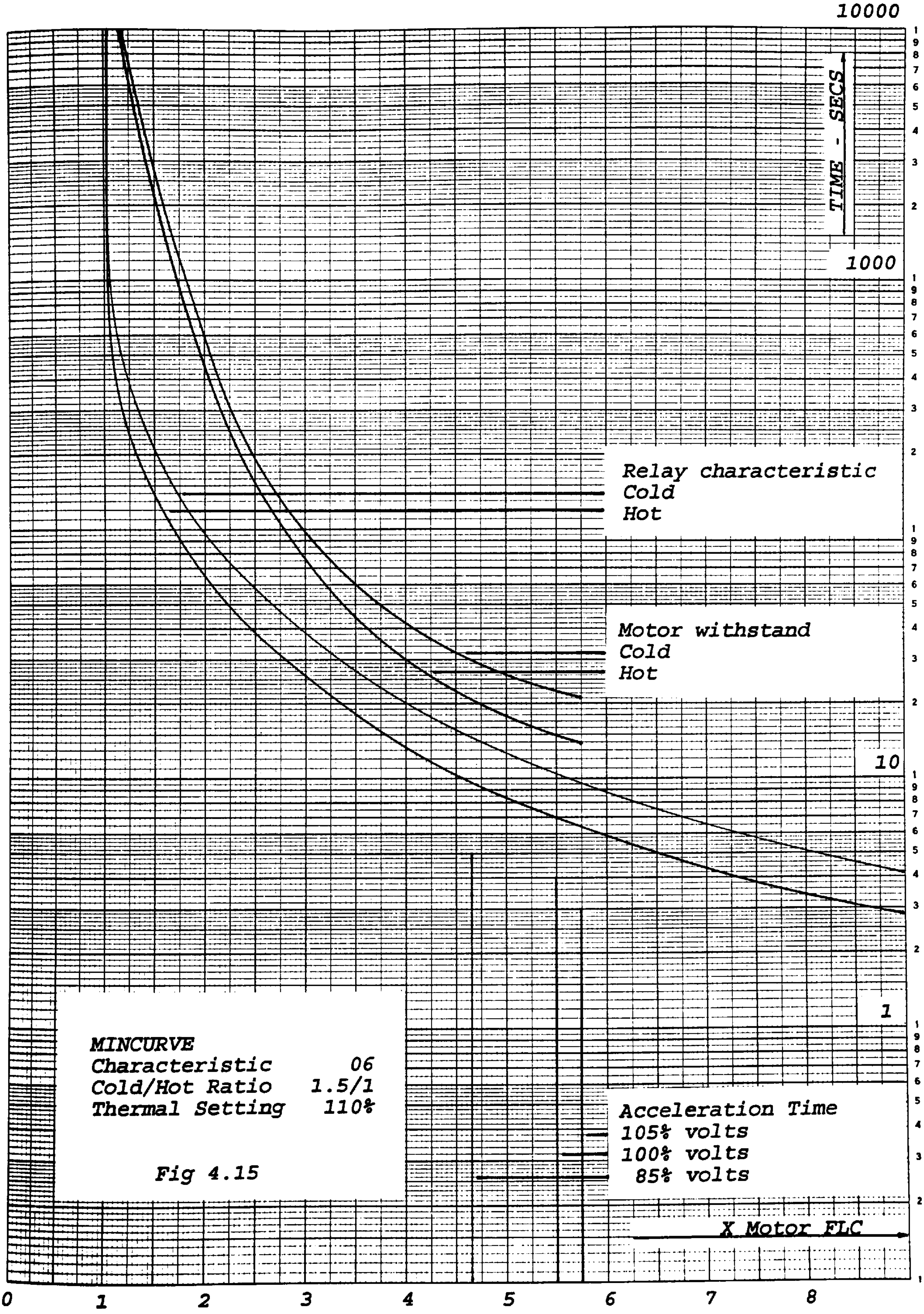
| 3 ph Conditions | Relay Cold | Motor Cold | Margin %age | Relay Hot | Motor Hot | Margin %age |
|---|---|---|---|---|---|---|
| RATINGS at 2x FLC | 115.3 | 770.0 | +567 | 76.8 | 600.0 | +680 |
| RATINGS at LRC - 85% V | 13.5 | 31.8 | +134 | 9.0 | 20.7 | +129 |
| RATINGS at LRC - 100% V | 9.7 | 23.0 | +137 | 6.4 | 15.0 | +131 |
| RATINGS at LRC - 105% V | 8.8 | 20.8 | +136 | 5.8 | 13.6 | +130 |
| 1 Ph Conditions | | | | | | |
| RATINGS at F/L Output | 54.8 | 720.0 | +*** | 36.5 | 600.0 | +*** |
| RATINGS at LRC - 100%V | 5.8 | 14.0 | +138 | 3.9 | 8.0 | +104 |
| RUN-UP-TIME at - 85% V | 13.5 | 5.0 | +171 | 9.0 | 5.0 | + 80 |
| RUN-UP-TIME at - 100% V | 9.7 | 4.0 | +142 | 6.4 | 4.0 | + 61 |
| RUN-UP-TIME at - 105% V | 8.8 | 3.0 | +194 | 5.8 | 3.0 | + 96 |

All times in seconds

SELECT OPTION S PASS <P>ageback

<S>ettings, <M>enu <Q>uit

*Fig 4.14 Operating times and margins for CTM 4.06 relay.*


10000
TIME - SECS
1000
10
1
Relay characteristic
Cold
Hot
Motor withstand
Cold
Hot
MINCURVE
Characteristic 06
Cold/Hot Ratio 1.5/1
Thermal Setting 110%
Acceleration Time
105% volts
100% volts
85% volts
X Motor FLC
0
1
2
3
4
5
6
7
8
Fig 4.15

GEC - CTM(F)
CHARACTERISTIC OPTIONS

| | | | |
|---|---|---|---|
| 1 | 1 | 12 | 11 |
| 2 | 00 | 13 | 05 |
| 3 | 2 | 14 | 21 |
| 4 | 01 | 15 | 06 |
| 5 | 3 | 16 | 31 |
| 6 | 02 | 17 | 07 |
| 7 | 4 | 18 | 41 |
| 8 | 03 | 19 | 08 |
| 9 | 5 | 20 | 51 |
| 10 | 04 | 21 | 09 |
| 11 | 6 | 22 | 61 |

Select option 16

<P>ageback
<Q>uit

*Fig 4.16 User selected characteristic menu.*

an inequality is not satisfied the value displayed is supplemented by a symbol and a legend indicating the failure condition.

Option 8 'QUIT'
returns the program to an earlier stage where an alternative relay type may be chosen.

Following the successful selection of a thermal characteristic and the subsequent examination of displayed operating times, the user may return to the strategy option menu shown in Fig. 4.7 to examine further possibilities by depressing the 'M' key. This selection also enables the CT ratio and thermal setting to be altered if required. Alternatively the required relay settings may be displayed by selecting the 'S' key. The 'S' key initially displays a table which contains the required settings and where applicable ohmic values for the stabilising resistor. Fig. 4.17 is a replica of the screen display produced. As in option 8, operation of the 'Q' key returns the program to an earlier stage which allows the selection of an alternative relay.

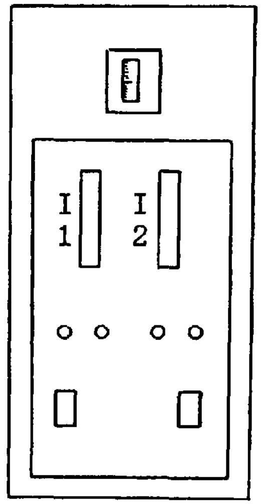
## 4.3 The CTM(F) Program Description

The program is again constructed in a modular form, each module being selected sequentially using an address supplied by the routine currently in use. A flowchart outlining the logic of the program is shown in Fig. 4.18.

On selecting the CTM/CTMF option from the relay menu the program is directed to the CTM routine, a description of which follows:

GEC - CTM 431
SETTINGS

| | | | |
|---|---|---|---|
| Relay type | .............. | CTM 431 | |
| Relay rating | .............. | 1 | Amp |
| CT. Ratio | .............. | 40/1 | Amp |
| Thermal | .............. | 1.04 | Amp |
| Negative Phase Sequence | I2 | 2.2 | Amp |
| Instantaneous Overcurrent | I1 | 6.8 | Amp |
| Earth fault | .......... I0 | 20 | % |
| Stabilising resistance | ..... | 83.7 | Ohm |
| Min I2 for op' at F/L | ..... | 17.85 | % |
| Max no of starts | .......... | 3 | |




Load Indicator

Instantaneous I1 & I2

Operation Indicators

Thermal Th1 & Th2

Select option M
<M>enu

<P>ageback
<Q>uit

*Fig 4.17 Typical 'Settings' display.*

TITLE : GEC ALTHSOM CTM(F)
SOLUTION FLOWCHART

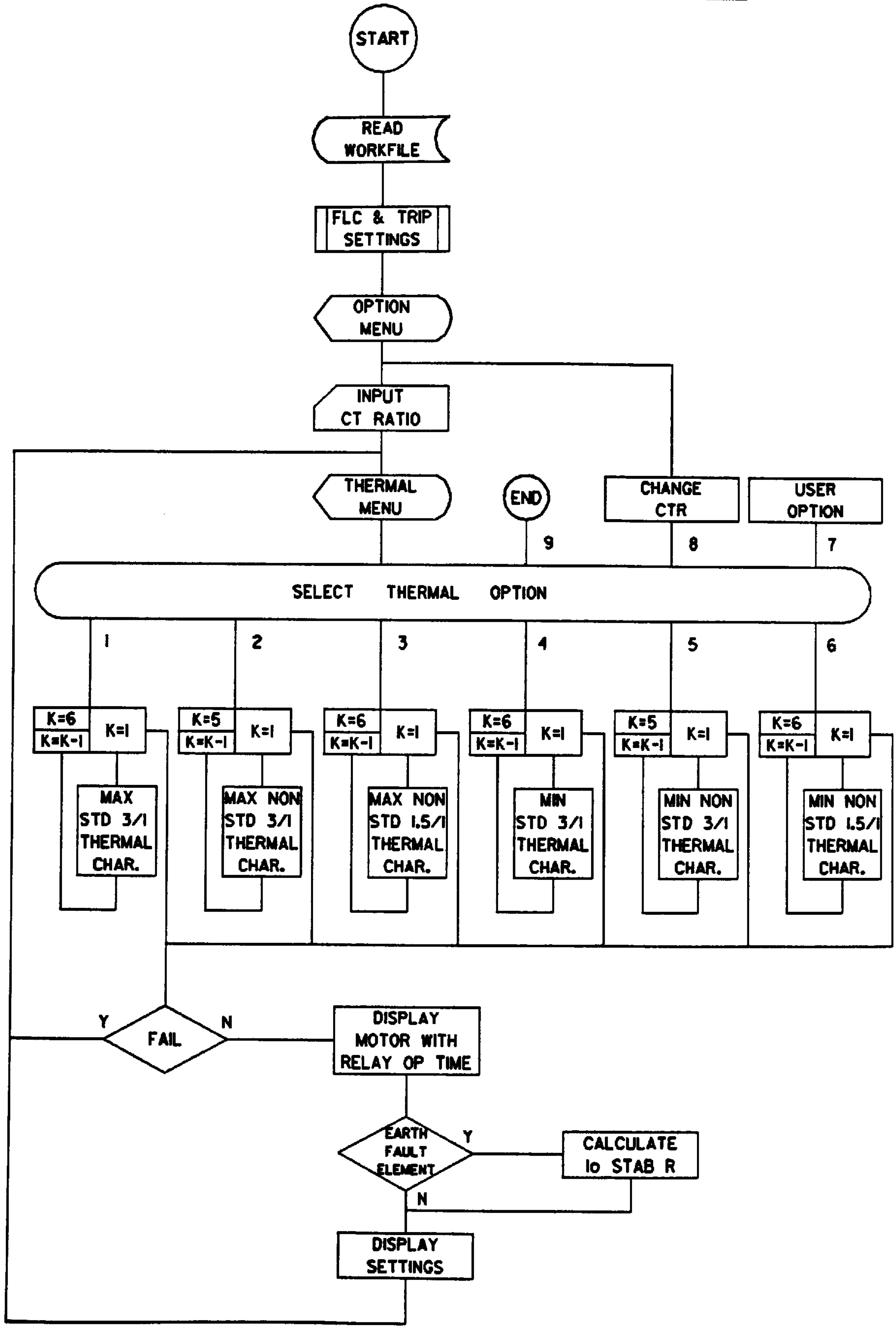



Fig 4.18

CTM

This routine is the control module for the CTM relay selection program and is the module which allows the individual sections of the program to be sequentially accessed. Selecting this option directs the flow of all data previously established in the MPROT routines through the following appropriate CTM modules. A generalised flowchart of the CTM module is shown in Fig. 4.19. The first module selected by this routine is CTM10.

CTM10

The function of the routine is to display the initial program menu from which one of six options may be chosen. The options presented enable the type, function and number of relay elements to be selected. The menu display is shown in Fig. 4.7.

CTM30

A further menu containing 8 options is presented in this routine. The options displayed allow the user to specify the approach used by the program in the selection of the thermal characteristics required. The menu display is shown in Fig. 4.9.

CTM40

In this routine data is assigned to variables based on the selections made in earlier routines. The data is used in subsequent routines to identify the characteristic previously chosen.

CTM50

In this module the characteristic is identified and labelled accordingly based on the previously supplied information. The routine calls a subroutine labelled CTM501 whose function is to select the characteristic type previously determined and to apply a series of inequality tests which compare motor withstand times

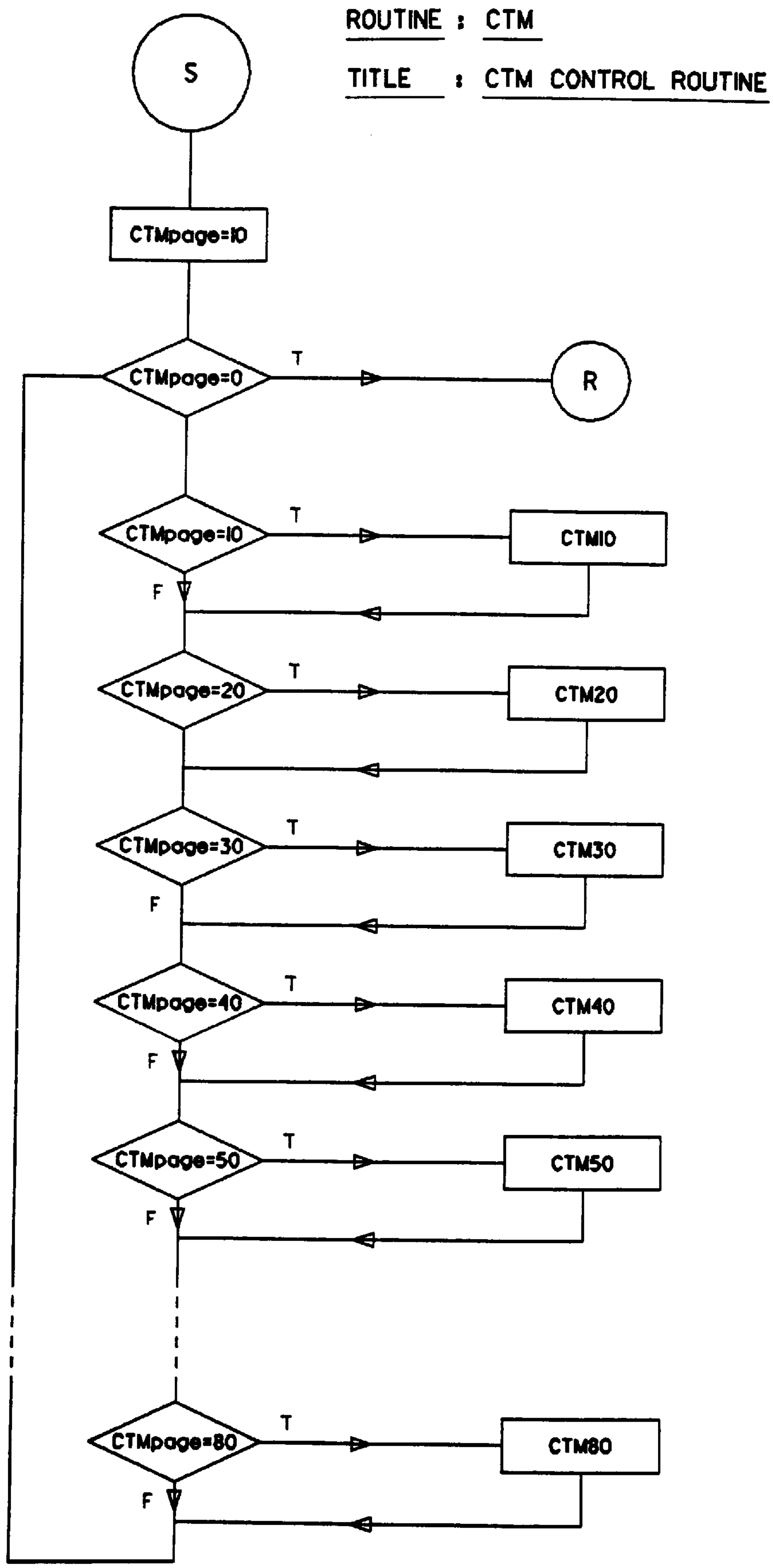

ROUTINE : CTM
TITLE : CTM CONTROL ROUTINE
S
CTMpage=10
CTMpage=0
T
R
CTMpage=10
T
CTM10
F
CTMpage=20
T
CTM20
CTMpage=30
T
CTM30
F
CTMpage=40
T
CTM40
F
CTMpage=50
T
CTM50
F
CTMpage=80
T
CTM80
F

Fig 4.19

with predicted relay operating times. The operating time of the relay for each particular current condition being determined in a routine labelled CTM5011. In general a set of characteristics comprise either 5 or 6 individual characteristics each of which must be tested until a satisfactory match is found. The characteristics may be checked by examining the lowest characteristic first and incrementing the curves or alternatively commencing with the maximum operating characteristic and decrementing the curves until a satisfactory solution is encountered. The result may either:

1. Fail to satisfy the set of inequalities
2. Detect a maximum characteristic which satisfies the set of inequalities
3. Detect a minimum characteristic which satisfies the set of inequalities

CTM5011

This module uses the Neville-Aitken interpolation method to model the relay thermal operating characteristics such that for any given current input value the routine provides an operating time as output.

CTM60

This routine is used to display the 'User Characteristic' menu. A small database file CTM1 is opened from which a series of characteristic multipliers and associated reference names are extracted and displayed in sequential form. The user is required to select the appropriate curve for comparison against the motor and associated circuit constraints. A flowchart of the routine is shown in Fig. 4.20.

CTM70

This routine is used to evaluate the operating times for the series of conditions detailed in table 4.2 when applied to the characteristics selected in the previous routine. The routine records the conditions where the relay operating time

ROUTINE : CTM60

TITLE : MAIN USER CHARACTERISTIC MENU

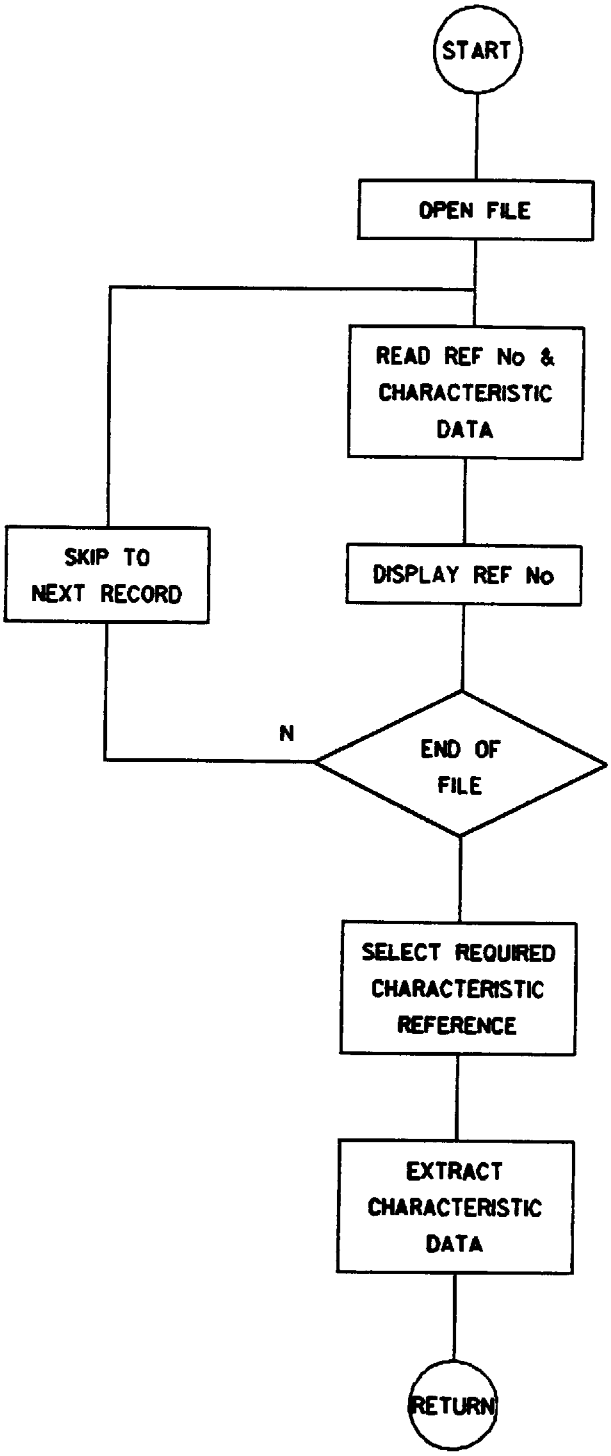



Fig 4.20

exceeds the withstand time of the motor or circuit components. The comparison includes the maximum possible error margin for the condition under review. A flowchart of the general arrangement is shown in Fig. 4.21.

CTM80

In this routine, the withstand times of the motor and circuit components together with the nominal relay operating times for each condition are sequentially applied to a subroutine called CTM801. The subroutine which is short, processes the input values and produces an output which quantifies the margin of discrimination between the relay operating time and the motor withstand time. The calculated values for each of the conditions analysed are stored for subsequent display in CTM90 and other modules. The simplified flowchart is shown in Fig. 4.22.

CTM90

The function of this module is purely that of displaying data calculated in previous routines. The conditions investigated are tabulated together with the motor withstand times, the corresponding relay operating times and the percentage discrimination margin between them. Both positive and negative margins are accommodated.

CTM100

This module is used to display the relay settings for types which do not contain an earth fault element. The setting displayed will be in full accordance with the conditions satisfied in the CTM90 routine. The module also records current transformer ratio information.

ROUTINE : CTM70

TITLE : INEQUALITY TESTS

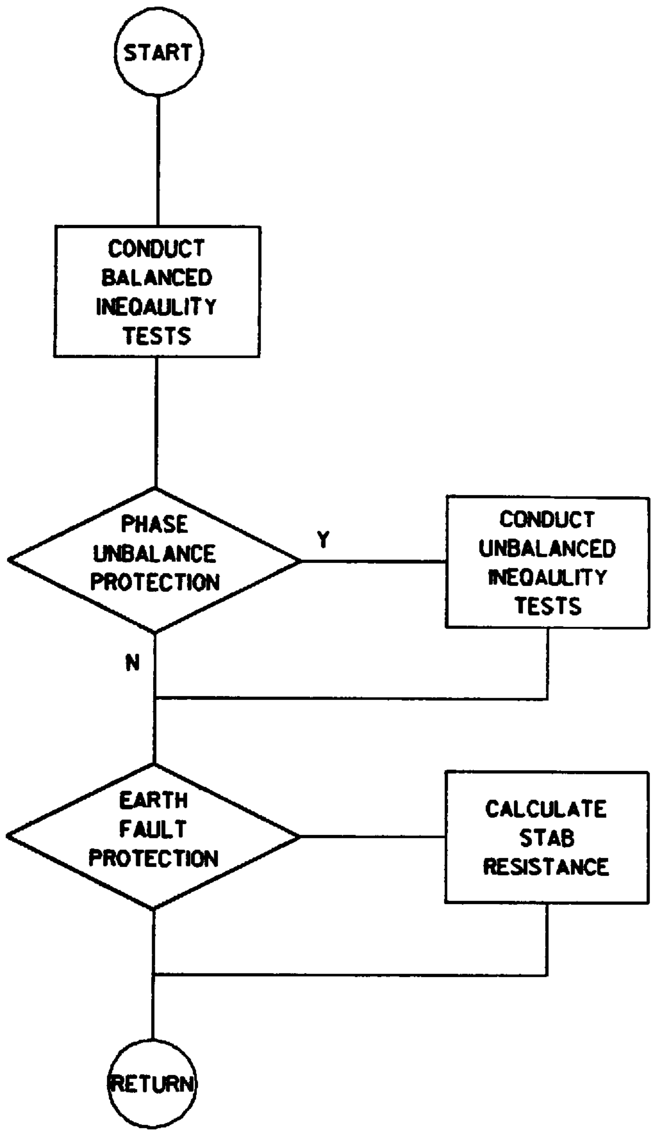



Fig 4.21

ROUTINE : CTM80

TITLE : RELAY OPERATING TIME MARGINS

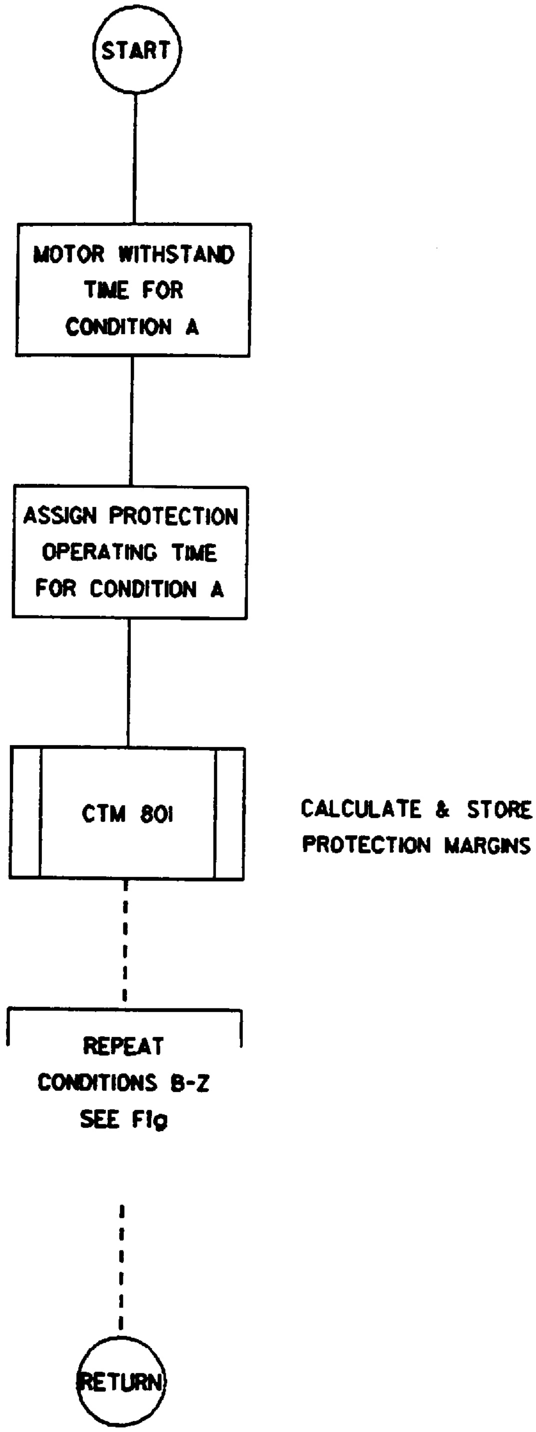



Fig 4.22

CTM110

This routine is called when earth fault protection is required. To function the algorithm requires further specific circuit parameters to complete the calculation. The additional parameters required are:

1. Current transformer dc resistance
2. Lead resistance
3. Location of star point
4. Operating level of element (10% or 20%)

Utilising the additional data, the routine calculates the value of the series stabilising resistor using the method outlined in the text. A screen display for the example discussed is shown in Fig. 4.5. It should be noted that the increased stabilising resistor value is due to the program taking account of the line voltage supplying the motor being 110% greater than nominal.2B

CTM120

The routine is used purely for the display of final settings for relays which include the earth fault element and associated stabilising resistor. The routine is very similar to CTM100.

## 4.4 Interim Conclusion

The contents of Chapter 4 discuss the major elements which must be considered by the protection engineer when applying a CTM(F) protection relay to a motor circuit. The novel approach using standard desktop PC programs, ensures that the relay operating times are accurately quantified to ensure maximum utilisation of the relay. The resultant settings when determined take full account of the declared maximum and minimum tolerances.

The most obvious benefit which arises from using the program is the ease with which a suitable thermal characteristic or range of characteristics can be selected, thus enabling the optimum relay to be requisitioned. Further benefits accrue from the comprehensive set of checks which are applied each time the program is run. This factor ensures consistency and eliminates the possibility of error or the taking of short cuts, thus providing a sound engineering basis for the resulting characteristic choice and applied settings.

## References


1. Correspondence with J. Middlemiss, Peebles Electric Ltd
2. Correspondence with A. Marshall, GEC Alsthom

GEC Alsthom Publication No. R-5171

GEC Alsthom Publication No. R-5738

Protection of Industrial Power Systems by T. Davies

Power System protection Volume 3 - Electricity Council

Protective Relay Application Guide - GEC Measurements

# CHAPTER 5

# APPLYING THE P&B GOLDS TYPE PBSJ 3E5 N11 MOTOR PROTECTION RELAY

## 5.1 INTRODUCTION

The purpose of this section is to introduce a more modern motor protection relay, (MPR), and to highlight its increased versatility resulting from enhanced features. The MPR referred to is the P&B Golds type PBSJ 3E5 N11 which is illustrated in Fig. 5.1. It is a medium priced digital electronic device which is capable of operating from current transformers producing either a 1A or 5A secondary output at their nominal ratio. An auxiliary voltage supply of 80-265V ac or dc is necessary to power the device.

The main functions offered by the relay are:

1. Thermal overload protection
2. Locked Rotor and stall protection
3. Earth fault protection
4. Phase unbalance protection
5. Undercurrent protection

These functions will be discussed in the following sections

### 5.1.1 Thermal Overload Protection

The thermal element settings are applied to the relay by operation of the selection button R1 on the relay faceplate. The locations of the selection button R1 together

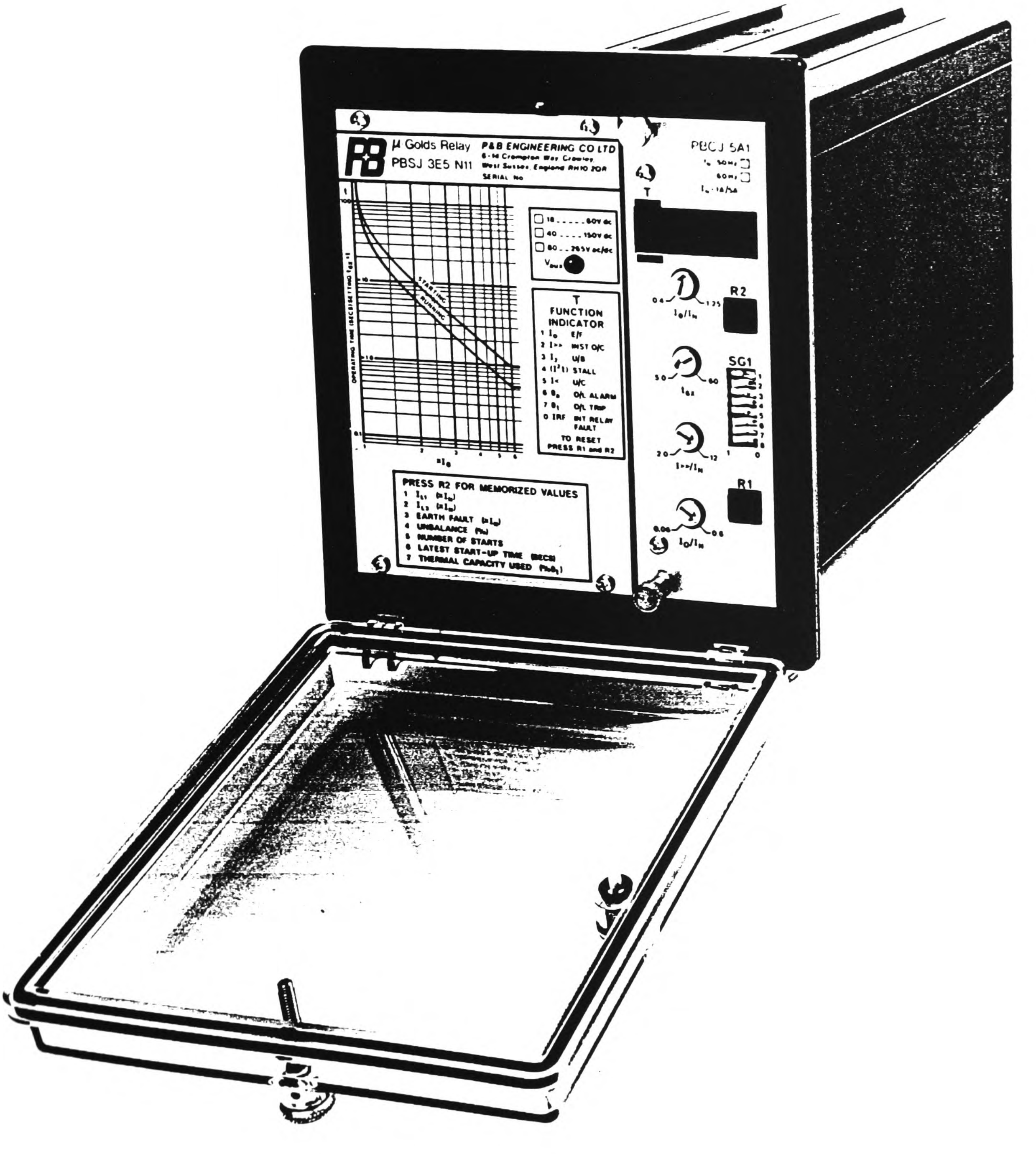



*Fig 5.1* *The P & B Microgolds relay*

with other relevant features are shown in Fig. 5.2. Pressing the R1 button enables the Iq/In, thermal setting potentiometer, to be adjusted to the desired value anywhere in the range 0.40 to 1.25 of the relay rated current, In. The Iq/In potentiometer control matches the relay to the motor flc by considering the CT ratio as follows:

CT Ratio: 50/1 or 50/5 as required

Motor flc: 40A

$$Thermal\,setting = flc \bullet \frac{CT\,secondary\,rating}{CT\,primary\,rating} \bullet \frac{1}{Relay\,rating\,(In)} \tag{5.1}$$

$$= 40 \bullet \frac{1\,(or\,5)}{50} \bullet \frac{1}{1\,(or\,5)}$$

$$= 0.8\,In$$

With the above setting the relay will begin to operate at 5% overload, that is 42A (1.05 • 40A).

If overload settings other than 105% are required, the desired setting may be determined as follows.

Assume an overload setting of 110% is required then:

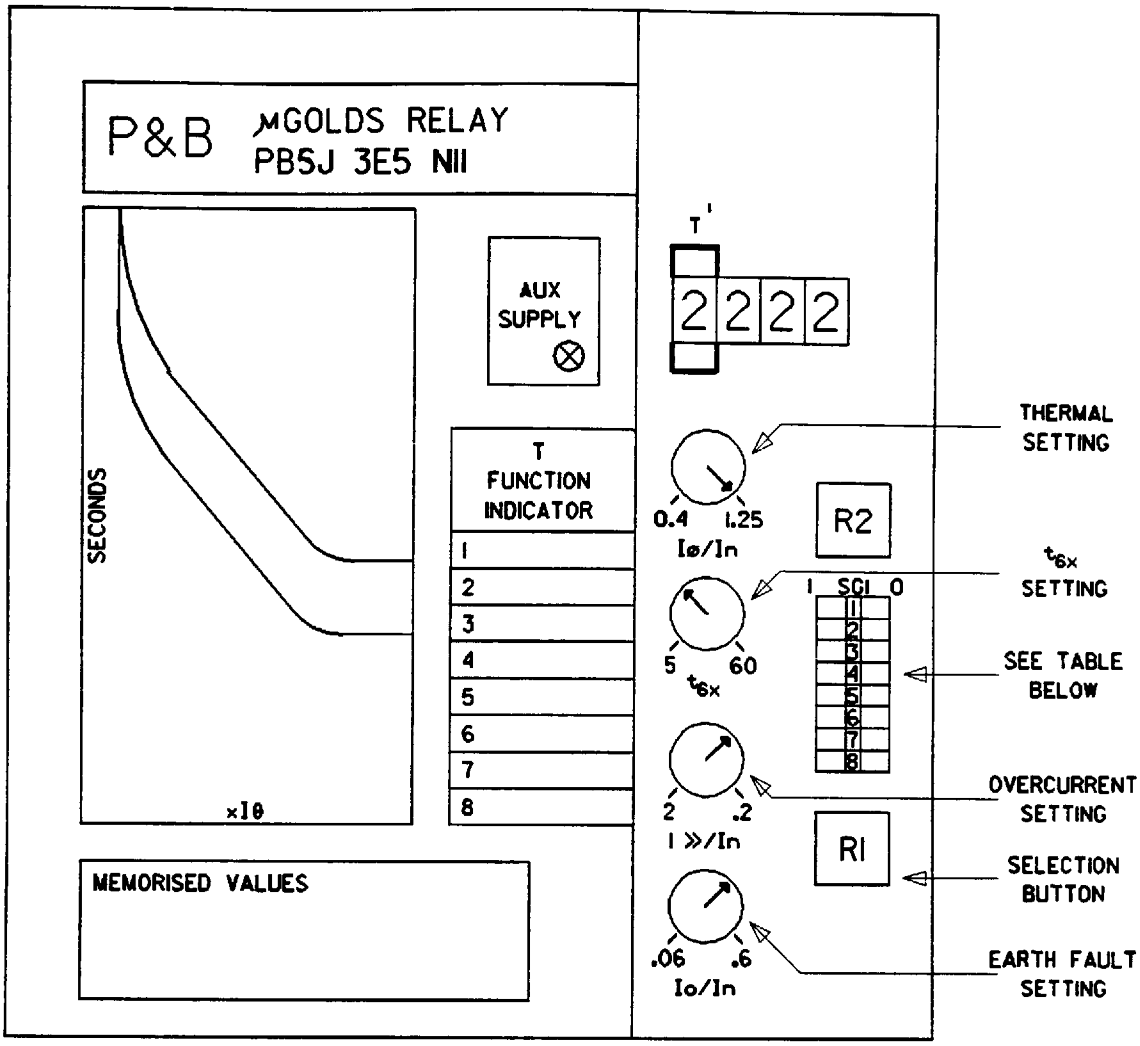
$$Thermal\,setting = flc \bullet \frac{CT\,secondary\,rating}{CT\,primary\,rating} \bullet \frac{1}{Relay\,rating\,(in)} \bullet \frac{Desired\,setting}{105} \tag{5.2}$$

$$= 40 \bullet \frac{1\,(or\,5)}{50} \bullet \frac{1}{1\,(or\,5)} \bullet \frac{110}{105}$$

$$= 0.84\,In$$

This revised setting has the effect of raising the motor flc from a true 40A to an apparent value of:

$$40 \bullet \frac{110}{105} = 41.9\,Amp$$




KEY TO SWITCHGROUP SGI SETTINGS

| SWITCH | I | O | DESCRIPTION |
|---|---|---|---|
| SI | CONT | CB | CONTACTOR / CIRCUIT BREAKER CONTROL |
| S2 | 50ms | ISEC | OPERATING TIME OF EARTH FAULT UNIT |
| S3 | MAN | AUTO | MANUAL / AUTO RESET OF TRIPPING RELAY |
| S4 | 50% | 75% | STALL PROTECTION TIME COMPARED TO FULL CHARACTERISTIC |
| S5 | ON | OFF | NEGATIVE PHASE SEQUENCE CURRENT PROTECTION |
| S6 | ON | OFF | PRIOR ALARM (95% OF θt) |
| S7 | ON | OFF | UNDERCURRENT PROTECTION |
| S8 | TEST | NORM | HARDWARE TEST / NORMAL OPERATION |

Fig 5.2 KEY TO P & B MICROGOLDS RELAY CONTROLS

A further 5% increase on this load causes the thermal unit to become active and if sustained eventually to cause tripping.

By accommodating differing values of overload setting, it can be observed that adjustment of the thermal setting controls the pick up point on the horizontal current axis. (Fig. 5.3). This factor should be borne in mind when adjusting the other controls.

It should be noted that if the setting arrived at lies between 0.9 - 1.1 • relay rating then the operating setting will have an accuracy within ± 1% of the calculated characteristic. Outside these limits setting errors may be up to ± 5% of the calculated values.

The characteristic of the thermal unit fully accords with the characteristics detailed in B.S. 142: Section 2.3, Appendices A and B. The operating time of the element, subject to setting errors, may be accurately determined by the equation.

$$t_{cold} = 32.a.\log_e\left(\frac{p^2}{p^2 - s^2}\right) \text{ secs} - \textit{for the starting or cold condition} \quad (5.3)$$

$$\text{and} \quad t_{hot} = 32.a.\log_e\left(\frac{p^2 - 0.5(IL)^2}{p^2 - s^2}\right) \text{ secs} - \textit{for the running or hot condition} \quad (5.4)$$

where:

| | | |
|---|---|---|
| p | is a multiple of motor flc | (p.u. value) |
| s | is the desired overload setting | (p.u. value) |
| a | is the setting of the $t_{6x}$ control | (referred to later) |

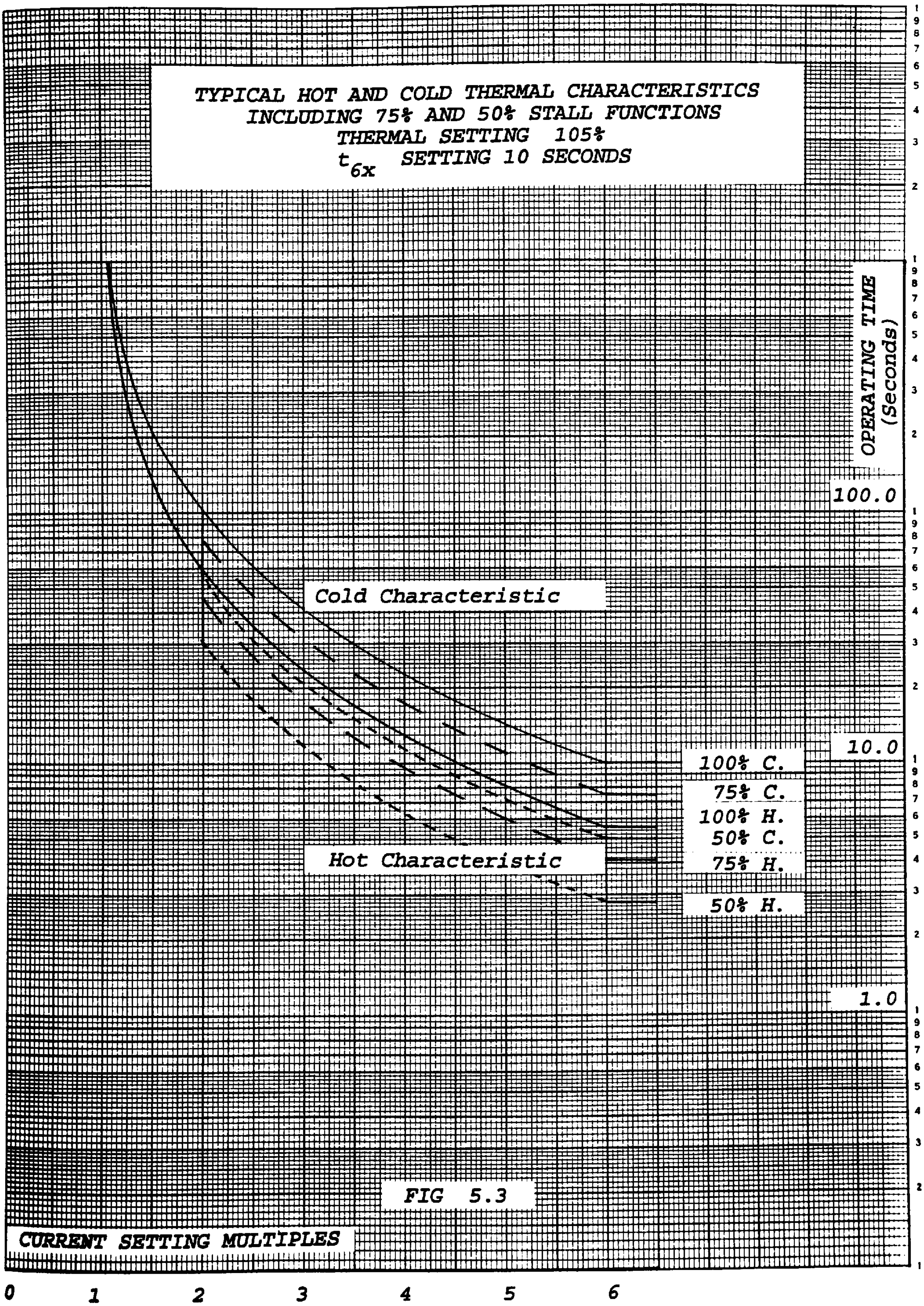
A derivation of the above characteristics is included in Appendix 9.

### 5.1.2 The $t_{6x}$ Control

A typical thermal characteristic is shown in Fig. 5.3. The characteristic may be adjusted vertically in order to increase or decrease its operating time for any given multiple of relay rated current. The adjustment is affected by using the $t_{6x}$ control potentiometer, the location of which is shown in Fig. 5.2. The $t_{6x}$ setting is the elapsed time required to trip the relay from the cold state at 6 times motor flc and may be adjusted within the range 5-60 seconds in 0.5 second increments. It is important to note that the $t_{6x}$ setting always refers to the operating time at six times flc which implies that the motor withstand time for start or stall current for other conditions must be modified to take this into account. The setting so determined must also take into account the relay errors, relay overshoot time, switchgear clearance time, consider the effects of starting at other than nominal voltage and any other relevant ordinates on the operating characteristic. The adjustment is made by again pressing the selection button R1 on the relay faceplate to select the second option. The exact setting is determined by observing the value on the digital display as the $t_{6x}$ potentiometer is adjusted. Thus, it can be seen that the $t_{6x}$ potentiometer effectively controls movement of the vertical or time axis by moving both the Cold and Hot characteristics up or down as dictated by the setting.

### 5.1.3 Locked Rotor and Stall Protection

The relay operating time may be modified by introducing a step in the characteristic at the twice times flc ordinate. The effect of the modification is to reduce the operating time of the thermal element by a selectable factor of 0.75 or 0.5 for all values of current in excess of twice times flc. The chosen factor is selected by means of a miniature rocker switch located in the switchgroup SG1 on the faceplate of the relay. The location of the switchgroup is shown in Fig. 5.2.


TYPICAL HOT AND COLD THERMAL CHARACTERISTICS
INCLUDING 75% AND 50% STALL FUNCTIONS
THERMAL SETTING 105%
$t_{6x}$ SETTING 10 SECONDS
OPERATING TIME (Seconds)
100.0
10.0
1.0
Cold Characteristic
Hot Characteristic
100% C.
75% C.
100% H.
50% C.
75% H.
50% H.
CURRENT SETTING MULTIPLES
0
1
2
3
4
5
6
FIG 5.3

This inbuilt thermal characteristic modification, the stall function, is activated by supplying auxiliary power to a pair of designated terminals on the rear of the relay.

Activation of the stall function allows an increased $t_{6x}$ value to be selected whilst still permitting full thermal protection of the motor to be achieved. As a direct consequence of raising the $t_{6x}$ setting, the relay operating times for motor overloads of magnitude less than twice times flc will be increased. This increased operating time can prove beneficial by allowing greater use to be made of the thermal withstand of the motor in this region. Such a condition could arise in the case of a stone crusher or similar machine where frequent overload excursions are experienced when particularly hard stone is encountered. This method of solution is discussed in Section 5.2.1.

Alternatively, where the accelerating time of the motor is short in relation to the maximum allowable acceleration period, the stepped characteristic may be adjusted to satisfy the motor acceleration period yet will still enable greater use to be made of the overload capability of the motor up to twice times flc. This technique is further discussed in Section 5.2.4.

Where acceleration periods in excess of locked rotor withstand time are encountered, it may be possible to arrange for the stepless characteristic to satisfy the motor overload requirements up to twice times flc whilst still allowing sufficient time to accelerate the motor. On completion of the acceleration period the stall function may be activated to allow total thermal protection of the motor to be maintained. The signal required to introduce the step in the characterteristic may be produced by various sources such as timers, current sensing elements, or external devices such as speed sensing switches on the motor itself.

It can be readily understood that this protective approach must be supplemented by additional protective relays to ensure prompt disconnection should the motor fail to rotate.

### 5.1.4 High-Set Overcurrent Trip

The relay incorporates an instantaneous high-set overcurrent feature which may be enabled or disabled as required. If the motor is supplied through a fully rated circuit breaker and cabling, the element should be set to the active mode to detect and initate the clearance of a short-circuit as quickly as possible. Alternatively if the circuit is supplied by fused contactor, the element should be disabled to allow the fuses to clear the fault whilst the contactor remains closed. The contactor may, of course, fail to stay closed for reasons discussed in 4.1.3.2.

In order to enable or disable the element, a rocker switch in the faceplate mounted switchgroup SG1 must be moved to the required position. The location of the switch is shown in Fig. 5.2. If the active mode is selected a setting must be applied to the element within the range 2.0-12.0 • In. In order to apply a setting to the element, the function selection button R1 is operated until the appropriate selection is made. Selection is signified by the function identifier '3' being displayed on the faceplate panel. The actual setting is applied by adjusting the faceplate mounted overcurrent setting potentiometer and observing the setting on the faceplate digital display. As a general rule and to avoid mal-operation, a high set instantaneous overcurrent element must be set at a value which exceeds the starting current and any assymetry in the current wave form likely to be encountered immediately after switch closure. This relay, however, incorporates a novel form of overcurrent element which doubles its setting during the starting period. In addition to detecting short-circuits, at all times this useful feature can also be used to detect a locked rotor condition occurring during the running mode.

This high-set overcurrent function is of course, not available when contactor control is utilised.

### 5.1.5 Earth Fault Protection

The relay incorporates an element whose function is to detect the presence of earth fault currents in the motor circuit. The earth fault current may be detected using either a core balance CT or alternatively, a residually connected CT arrangement. The operating setting of the element is not fixed but may be adjusted within the range 0.06-0.6 • In. To assign an E/F setting to the relay the procedure requires the function selection button R1 to be pressed until the function identifier '4' is displayed on the faceplate panel. This allows the earth fault setting potentiometer to be rotated to the desired setting. The setting point may be accurately determined by observing the setting value on the faceplate digital display. The earth fault element is not instantaneous but incorporates a fixed time delay prior to operating. Two time delays are possible, a 50 millisecond delay and a 1 second delay. The 50 millisecond delay is used when the circuit is supplied via a fully rated circuit breaker. This delay is of sufficient duration to prevent maloperation caused by assymetry on starting or operation by system borne transients. The one second delay time is selected for contactor circuit duty and is used to delay the tripping signal thereby allowing heavy current faults to be cleared by the main power fuses. The chosen time delay is selected by means of the S2 rocker switch in the switchgroup SG1 on the faceplate of the relay. It should be noted that if the MSD is a fused contactor the S1 rocker switch in the switchgroup SG1 would be set for contactor control. This action blocks the operation of the instantaneous overcurrent elements and additionally inhibits the operation of the earth fault element for fault currents in excess of four times flc.

### 5.1.6 Phase Unbalance Protection

The relay is equipped with a network which extracts the negative phase sequence component from an unbalanced 3 phase supply. The magnitude of the current is used to initiate disconnection in accordance with an inverse characteristic satisfying the equation

$$t_{nps} = \frac{3910}{(I\%)^{1.95} - 1} \; secs \qquad of\,the\,form \; \frac{A}{B^{c} - 1} \tag{5.5}$$

where I% is the NPS current expressed as a percentage of the maximum phase current being monitored. Hence in the case of a total loss of one phase of the supply to a motor, the current will rise to a value greater than $\sqrt{3}$ times its former value to sustain output power (refer to section 4.1.2). Resolving the assymetrical phase currents into their symmetrical phase components shows that the maximum magnitude of NPS current is $1/\sqrt{3}$ times the current in the sound phase (equation 4.9).

$$Hence\;maximum\;NPS\;component\;of\;current = \frac{1}{\sqrt{3}} \bullet 100 \;= 57.74\%\;of\;sound\;phase\;current$$

Substituting the max value in equation 5.1 gives

$$t_{nps} = \frac{3910}{(57.74)^{1.95} - 1} = 1.44\;secs$$

Thus rapid isolation of the machine is guaranteed for this condition at all values of current in excess of 0.25 • flc.

The phase unbalance function, may be set to the active mode or inhibited as required. To ensure the function is active, the rocker switch S5 in the switchgroup SG1 shown in Fig. 5.2 must be set to the 'ON' position.

### 5.1.7 Undercurrent Protection

An interesting feature contained within the relay is an ability to detect loss of load such as a broken coupling or failure of a pump impeller. The condition is detected by setting a current threshold below that observed in normal service. If the threshold is breached by the motor current falling below 40% flc for a period of 10 seconds, circuit tripping is initiated. The 10 second delay overcomes any transient load losses that may occur. To prevent the unit sensing a trip condition when stationary this function is inhibited for motor currents which are less than 12% flc.

As in the previous case the function may be selected or inhibited as required. The rocker switch S7 in the switchgroup SG1 shown in Fig. 5.2 is used for this purpose.

### 5.1.8 Switchgroup SG1

The switchgroup SG1 referred to previously in this section comprises eight minature rocker switches which have a direct affect on several of the protection features previously discussed. The function of each rocker switch is listed below and the location of the switchgroup SG1 is shown in Fig. 5.2.

| SG1 | 1 | O | |
|---|---|---|---|
| S1 | Cont | C.B. | Contactor/Circuit Breaker Control |
| S2 | 50 mS | 1 sec | Operating time of Earth Fault Unit |
| S3 | Man | Auto | Auto/manual resetting of output relay |
| S4 | 50% | 75% | Stall protection times |
| S5 | On | Off | Negative Phase Sequence Current Protection |
| S6 | On | Off | Thermal pre-overload alarm |
| S7 | On | Off | Undercurrent protection |
| S8 | Test | Norm | Normal operation/Hardware test |

## 5.2 Method Employed

In general only larger induction motors supplied at 3.3kV and above warrant the expense of a relay of this type. Such a relay can provide reassurance in the case where the total loss of a machine could result in irreversible consequences.

The thermal characteristic selection procedure used in this section differs from the approach adopted in chapter 4 for determining the desired CTM characteristic. One of the fundamental differences between the two relays is the mobility of the P&B relay's characteristic, which, by incrementing the $t_{6x}$ control in 0.5 second steps enables a family of 111 closely spaced thermal characteristics to be produced from the single relay.

A program has been written to aid selection of the appropriate thermal characteristic and associated functions. The program which subjects the motor and operational data previously compiled in the MPROT routine to a series of checks from which a group of characteristics capable of satisfying the checks can be extracted. Before the selection procedure can commence further information is required which must be furnished by the user. The initial requirement is to specify the ratio of the current transformers which are intended to be used. This factor together with the required trip level information enables the calculation of the thermal setting to be achieved. Options exist which allow the modification of both CT ratio and trip level if so required.

The user is next presented with a series of statements requiring a simple 'Y' or 'N' response. Each of the statements has a default answer which may be accepted by pressing the return key or alternatively may be changed by pressing the appropriate Y or N key. The response to the statements provides the final position of the slideswitches in the SG1 switchgroup. A typical display is shown in Fig. 5.4.

```
                    P & B GOLDS - PBSJ 3E5 N11
                         FACEPLATE SETUP

     Motor rating                  ..............       180      kW
     Full load current             ..............        40      Amps
     CT. Ratio                     ..............       50 /1
     Thermal trip level            ..............       110      %
     Thermal setting               ..............         0.84
     Setting accuracy              ..............         5      %

     Change CT Ratio / Setting     .... (Y/N) ...         N

     NPS Protection  ............... (Y/N) ...            Y
     Undercurrent trip  ............ (Y/N) ...            N
     Trip Auto Reset    ............ (Y/N) ...            N
     Pre-Trip thermal alarm    ..... (Y/N) ...            N

 <A>ccept / <R>eject       A                                   <Q>uit
```

*Fig 5.4 Typical relay faceplate 'setup' arrangement*

Following the satisfactory input of data, the screen display is replaced by the option menu shown in Fig. 5.5. The menu provides seven options for determining the $t_{6x}$ thermal setting assigned to potentiometer 2. The application method employed to find a suitable setting may be divided into two broad strategies namely 'MAXCURVE' and 'MINCURVE'. To illustrate the approach a typical 180kW induction motor supplied from a 3300V, 3ph, 50Hz unearthed supply will be considered, details of which are contained in Appendix 7.

### 5.2.1 Maxcurve

The object of the 'MAXCURVE' technique, initially without the stall feature connected, is to raise the relay thermal characteristics as close as possible to the motor Hot and Cold withstand characteristics taking due account of the setting tolerances. The $t_{6x}$ control always refers to the relay setting at 6 x flc which means that the actual stall current value and its associated Hot and Cold withstand times must be referred to this datum.

As stated earlier, potentiometer 1 must be set to accommodate the full load current of the motor, the current transformers selected and the trip level required.

Using the motor data recorded in Appendix 7 it can be seen that the full load and starting currents are 40 Amp and 230 Amp. The maximum stalling times for the machine being 15 and 23 seconds measured from the hot and cold state respectively. As the stall withstand time of the motor is short and the heat radiating area small, the heating of the winding is considered an adiabatic process with the value $I^2t$ a constant.

```
                    P & B GOLDS - PBSJ 3E5 N11
                           MAIN MENU

        1.    'MAXCURVE' with 100% Stall feature
        2.    'MAXCURVE' with  75% Stall feature
        3.    'MAXCURVE' with  50% Stall feature

        4.    'MINCURVE' with 100% Stall feature
        5.    'MINCURVE' with  75% Stall feature
        6.    'MINCURVE' with  50% Stall feature

        7.    'USER CHOICE'

        Q.     QUIT

Select option :     1
```

*Fig 5.5 Thermal strategy option menu*

If the required trip level is 110% flc the equivalent motor current is 40 x 1.1 = 44 Amps. Hence, as the relay is designed to operate at 105% of setting, the pseudo flc to achieve tripping of the machine will be 44/1.05 = 41.905 Amp. This pseudo flc will require a potentiometer setting of:

$$\frac{41.905}{CT\,Ratio} = \frac{41.905}{50} = 0.8381 \bullet In \quad Amp \tag{5.6}$$

The nearest setting value being 0.84 which will operate at a nominal trip level of

$$\frac{50 \bullet 0.84}{40} \bullet 105\% = 110.25\% flc \;\; or \;\; 44.1 \quad Amp \tag{5.7}$$

Effectively this raises the motor flc to a revised flc value of 44.1/1.05 = 42 Amp. The setting 0.84 • In, being less than 0.9 • In, is subject to a ± 5% setting tolerance of 0.798 - 0.882 • In, Substituting these thermal bounds into equation 5.2 we have:

$$Thermal\ Setting\ \frac{Iq}{In} = 0.798 = \frac{flc \bullet Relay\ rating}{CT\,Ratio} \bullet \frac{Desired\ trip\ level}{105} \tag{5.8}$$

$$From\ which\ potential\ trip\ level\ for\ true\ flc \quad = \quad \frac{0.798 \bullet 50 \bullet 105}{40} = 104.7\%$$

$$Similarly\ for\ upper\ bound \qquad \frac{0.882 \bullet 50 \bullet 105}{40} = 115.5\%$$

Using equation 5.3, the operating time of the relay from the cold state is given by:

$$tc = 32 \bullet t_{6x} \bullet \log_e \left( \frac{(Start\ current / flc)^2}{(Start\ current / flc)^2 - (Actual\ trip\ level)^2} \right) \tag{5.9}$$

Now for relay operation, actual trip level is 105% • relay setting subject to setting errors.

Hence for revised flc of 42 Amp

lower tripping bound = 99.75%

upper tripping bound = 110.25%

Substituting values in equation 5.9 gives:

$$23 = 32 \bullet t_{6x} \bullet \log_e\left(\frac{(230/42.0)^2}{(230/42.0)^2 - 1.1025^2}\right)$$

and re-arranging

$$t_{6x} = \frac{23}{32 \bullet \log_e(5.48^2/(5.48^2 - 1.1025^2))} = 17.37\ Secs \qquad (5.10)$$

As the $t_{6x}$ setting is subject to increments of ± 0.5 second the value above must be reduced accordingly. Hence $t_{6x}$ setting becomes 17.0 secs.

The minimum starting voltage must also be considered as during this mode the motor draws a reduced starting current because I is proportional to V. In the example considered the minimum voltage is declared as 85% of nominal line volts, consequently the starting current will be reduced proportionately to 0.85 • 230 = 195.5 Amp. At this reduced current value, the associated motor withstand time increases adiabatically to $23/0.85^2$ = 31.83 seconds.

Hence $t_{6x}$ setting calculated for the reduced voltage condition becomes:

$$t_{6x} = \frac{23/0.85^2}{32 \bullet \log_e((195.5/42.0)^2/((195.5/42.0)^2 - 1.1025^2))} = 17.23\ Secs$$

Similarly for the overvoltage condition where the current rises to 1.05 • 230 = 241.5 Amps. In this case the starting/run current ratio becomes 241.5/42.0 =

5.75. If this ratio exceeds a multiple of 6, the inverse thermal characteristic of the relay changes to that of a constant time characteristic.

For the overvoltage condition the $t_{6x}$ setting becomes

$$t_{6x} = \frac{23/1.05^2}{32 \bullet \log_e (5.75^2/(5.75^2 - 1.1025^2))} = 17.40\ Secs$$

Clearly the lowest value of the $t_{6x}$ must be used to cover the declared voltage depression on starting. Hence $t_{6x}$ setting is 17.0 seconds.

Similarly motor operation from the hot state must be considered together with the attendant reduction in withstand times. To accommodate these reduced values, the relay cold characteristic is modified and represented in accordance with equation 5.4.

$$t_h = 32 \bullet t_{6x} \bullet \log_e \left( \frac{(Start\ current/flc)^2 - 0.5(load\ current/flc)^2}{(Start\ current/flc)^2 - (Actual\ trip\ level)^2} \right) \qquad (5.11)$$

Substituting gives:

$$15 = 32 \bullet t_{6x} \bullet \log_e \left( \frac{(230/42.0)^2 - 0.5(40/42.0)^2}{(230/42.0)^2 - (1.1025)^2} \right)$$

and rearranging

$$t_{6x} = \frac{15}{32 \bullet \log_e ((5.48^2 - 0.5\,(0.952)^2)/(5.48^2 - 1.1025)^2} = 17.93\ secs$$

Similarly for the reduced starting voltage condition

$$t_{6x} = \frac{15/0.85^2}{32 \bullet \log_e ((230 \bullet 0.85/42.0)^2 - 0.5\,(40/42.0)^2)/((230 \bullet 0.85/42.0)^2 - 1.1025^2)} = 17.74\ secs$$

and the overvoltage condition

$$t_{6x} = \frac{15/1.05^2}{32 \bullet \log_e (((230 \bullet 1.05/42.0)^2 - 0.5\,(40/42.0)^2)/((230 \bullet 1.05/42.0)^2 - 1.1025^2))} = 17.98\ secs$$

Similar checks at 2 • flc produce $t_{6x}$ values of 59.0 seconds and 68.3 seconds for cold and hot conditions respectively.

It can be seen that for the conditions tested, the lowest value determined requires a $t_{6x}$ setting of 17.0 seconds. The conditions tested are identical with those listed in table 4.2 where it can be seen that checks are also conducted to satisfy the acceleration time under nominal voltage, reduced voltage, and overvoltage conditions. Consider starting the motor from the hot shutdown condition at nominal voltage.

Then $t_{6x}$ value must allow a sufficient acceleration time of 4 seconds at Nominal voltage.

$$4 = 32 \bullet t_{6x} \bullet \log e\left(\frac{(230/42.0)^2 - 0.5(40/42.0)^2}{(230/42.0)^2 - 0.9975^2)}\right) \quad \textbf{(5.12)}$$

$$t_{6x} = \frac{4}{32 \bullet \log_e(((230/42.0)^2 - 0.5\,(40/42.0^2)/((230/42.0)^2 - 0.9975^2))} = 6.75\ secs \quad \textbf{(5.13)}$$

Similarly for the reduced starting voltage condition **(5.14)**

$$t_{6x} = \frac{5}{32 \bullet \log_e(((230 \bullet 0.85/42.0)^2 - 0.5\,(40/42.0^2)/((230 \bullet 0.85/42.0)^2 - 0.9975^2))} = 6.04\ secs$$

and the overvoltage condition **(5.15)**

$$t_{6x} = \frac{3}{32 \bullet \log_e(((230 \bullet 1.05/42.0)^2) - 0.5\,(40/42.0)^2/(230 \bullet 1.05/42.0)^2 - 0.9975^2))} = 5.6\ secs$$

from which it can be seen that a $t_{6x}$ setting of 17.0 seconds will satisfy the conditions listed in table 4.2. Fig. 5.6 shows the associated screen display for this condition.

In the case where the plant item is a crusher, for example, or similar drive which requires a fairly short acceleration period, but may be subject to situations which

P & B GOLDS - PBSJ 3E5 N11

RELAY & MOTOR WITHSTAND RATINGS 17.0

| 3 ph Conditions | Relay Cold | Motor Cold | Margin %age | Relay Hot | Motor Hot | Margin %age |
|---|---|---|---|---|---|---|
| RATINGS at 2x FLC | 197.0 | 770.0 | +290 | 124.4 | 600.0 | +382 |
| RATINGS at LRC - 85% V | 28.4 | 31.8 | + 12 | 16.9 | 20.7 | + 22 |
| RATINGS at LRC - 100% V | 20.3 | 23.0 | + 12 | 12.0 | 15.0 | + 24 |
| RATINGS at LRC - 105% V | 18.4 | 20.8 | + 13 | 10.9 | 13.6 | + 24 |
| 1 Ph Conditions | | | | | | |
| RATINGS at F/L Output | 1.5 | 720.0 | +*** | 1.5 | 600.0 | +*** |
| RATINGS at LRC - 100%V | 1.5 | 14.0 | +833 | 1.5 | 8.0 | +433 |
| RUN-UP-TIME at - 85% V | 28.4 | 5.0 | +468 | 16.9 | 5.0 | +238 |
| RUN-UP-TIME at - 100% V | 20.3 | 4.0 | +409 | 12.0 | 4.0 | +202 |
| RUN-UP-TIME at - 105% V | 18.4 | 3.0 | +514 | 10.9 | 3.0 | +264 |

All times in seconds

Press any key to continue
<S>ettings,<M>enu

MAXCURVE - 100% Stall

*Fig 5.6* *Operating times and margins for 'MAXCURVE' with full thermal characteristic and a* $t_{6x}$ *setting of 17 seconds* will stall the drive and produce locked rotor conditions, then it is sensible to trip the motor as quickly as possible to avoid unnecessary overheating.

If the motor switching device (MSD) controlling the circuit is a fused contactor, the protection characteristic may be improved by invoking the inbuilt stall feature of the relay. The feature, when activated, introduces a step in the chosen characteristic for all multiples of motor flc greater than 2. The step displaces the characteristic such that the operating time is reduced to 75% or 50% of the original characteristic. The portion of the characteristic up to twice times flc remains unaffected and is available to accommodate modest overloads of medium duration such as may be produced by large stones in a crusher which do not result in jamming the machine. Fig. 5.7 and 5.8 depicts the screen display associated with a $t_{6x}$ value of 17.0 seconds with the 75% and 50% step functions active. Fig. 5.9 clearly shows the protective envelope of the full characteristic and the improvement effected by using the stall feature.

Where the circuit is supplied through a fully rated circuit breaker, the relay will have the instantaneous overcurrent device set to the active state. This feature may be used to further supplement the stall characteristic of the thermal element.

### 5.2.2 Maxcurve with 75% Stall Setting

In section 5.2.1, reference is made to the case of a stone crushing machine which is subject to occasional locked rotor conditions. In the normal overload range where magnitudes of current up to twice times flc are experienced but are of a duration which exceeds the thermal characteristic tripping time then the previous strategy will fail. It is usually found possible to further increase the $t_{6x}$ setting by taking advantage of the 75% stall function. Using this feature the $t_{6x}$ setting can be used

P & B GOLDS - PBSJ 3E5 N11
RELAY & MOTOR WITHSTAND RATINGS 17.0

| 3 ph Conditions | Relay Cold | Motor Cold | Margin %age | Relay Hot | Motor Hot | Margin %age |
|---|---|---|---|---|---|---|
| RATINGS at 2x FLC | 197.0 | 770.0 | +290 | 124.4 | 600.0 | +382 |
| RATINGS at LRC - 85% V | 21.3 | 31.8 | + 49 | 12.6 | 20.7 | + 63 |
| RATINGS at LRC - 100% V | 15.2 | 23.0 | + 50 | 9.0 | 15.0 | + 65 |
| RATINGS at LRC - 105% V | 13.8 | 20.8 | + 50 | 8.2 | 13.6 | + 65 |
| 1 Ph Conditions | | | | | | |
| RATINGS at F/L Output | 1.5 | 720.0 | +*** | 1.5 | 600.0 | +*** |
| RATINGS at LRC - 100%V | 1.5 | 14.0 | +833 | 1.5 | 8.0 | +433 |
| RUN-UP-TIME at - 85% V | 21.3 | 5.0 | +326 | 12.6 | 5.0 | +153 |
| RUN-UP-TIME at - 100% V | 15.2 | 4.0 | +282 | 9.0 | 4.0 | +126 |
| RUN-UP-TIME at - 105% V | 13.8 | 3.0 | +361 | 8.2 | 3.0 | +173 |

All times in seconds

Press any key to continue
<S>ettings,<M>enu

75% Step

*Fig 5.7 Operating times and margins for 'MAXCURVE' with 75% step in the thermal characteristic and a $t_{6x}$ setting of 17.0 seconds*

P & B GOLDS - PBSJ 3E5 N11

RELAY & MOTOR WITHSTAND RATINGS 17.0

| 3 ph Conditions | Relay Cold | Motor Cold | Margin %age | Relay Hot | Motor Hot | Margin %age |
|---|---|---|---|---|---|---|
| RATINGS at 2x FLC | 197.0 | 770.0 | +290 | 124.4 | 600.0 | +382 |
| RATINGS at LRC - 85% V | 14.2 | 31.8 | +124 | 8.4 | 20.7 | +145 |
| RATINGS at LRC - 100% V | 10.1 | 23.0 | +125 | 6.0 | 15.0 | +148 |
| RATINGS at LRC - 105% V | 9.2 | 20.8 | +126 | 5.4 | 13.6 | +148 |
| 1 Ph Conditions | | | | | | |
| RATINGS at F/L Output | 1.5 | 720.0 | +*** | 1.5 | 600.0 | +*** |
| RATINGS at LRC - 100%V | 1.5 | 14.0 | +833 | 1.5 | 8.0 | +433 |
| RUN-UP-TIME at - 85% V | 14.2 | 5.0 | +184 | 8.4 | 5.0 | + 69 |
| RUN-UP-TIME at - 100% V | 10.1 | 4.0 | +154 | 6.0 | 4.0 | + 51 |
| RUN-UP-TIME at - 105% V | 9.2 | 3.0 | +207 | 5.4 | 3.0 | + 82 |

All times in seconds

Press any key to continue
<S>ettings, <M>enu

50% Step

*Fig 5.8* *Operating times and margins for 'MAXCURVE' with 50% step in the thermal characteristic and a $t_{6x}$ setting of 17.0 seconds*

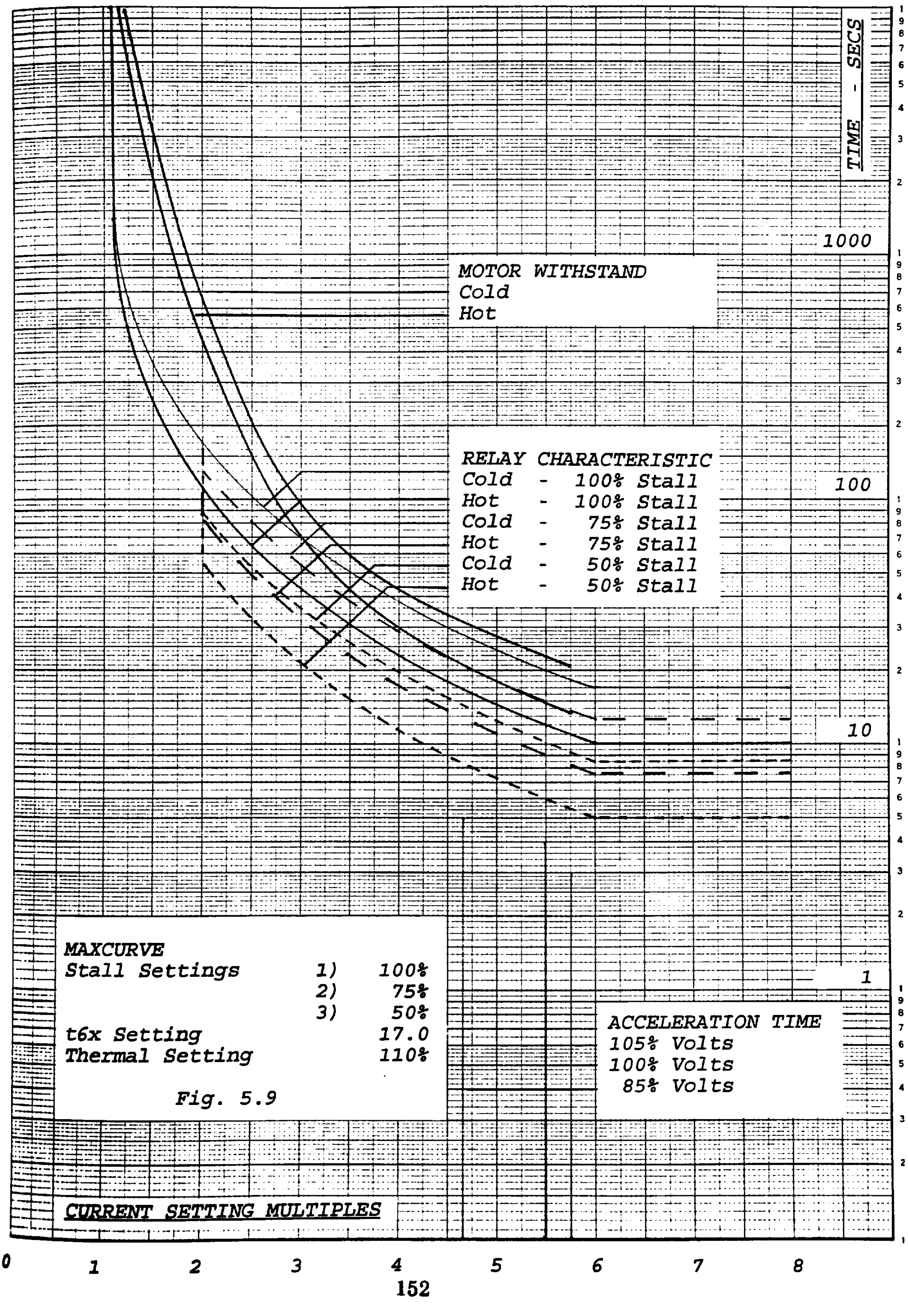

TIME - SECS
1000
100
10
1
MOTOR WITHSTAND
Cold
Hot
RELAY CHARACTERISTIC
Cold - 100% Stall
Hot - 100% Stall
Cold - 75% Stall
Hot - 75% Stall
Cold - 50% Stall
Hot - 50% Stall
MAXCURVE
Stall Settings 1) 100%
2) 75%
3) 50%
t6x Setting 17.0
Thermal Setting 110%
ACCELERATION TIME
105% Volts
100% Volts
85% Volts
CURRENT SETTING MULTIPLES
0
1
2
3
4
5
6
7
8

Fig. 5.9

to raise the stepped characteristic whilst still satisfying the previously discussed constraints.

The approach adopted is identical to that previously discussed except that the characteristic equation is modified for current ordinates greater than 2 • flc. This allows a series of checks to be carried out from which a new $t_{6x}$ setting is determined.

<u>Calculation of $t_{6x}$ at 75% stall setting</u>

Thermal setting = 0.84 as described in Section 5.2.1 producing potential trip levels of 104.7% - 115.5% of flc.

Using the $t_{6x}$ cold value of 17.37 seconds previously calculated at 100% supply volts in equation 5.10, it can be seen that a stall setting 0.75 allows the $t_{6x}$ value to be increased to:

$$t_{6x} = 17.37/0.75 = 23.16 \text{ secs}$$

for which the nearest setting is 23.0 seconds

Similarly

| | | | | |
|---|---|---|---|---|
| $t_{6x}$ hot | - | at full volts and under stall conditions | = | 23.91 secs |
| $t_{6x}$ cold | - | at reduced volts and under stall conditions | = | 22.97 secs |
| $t_{6x}$ hot | - | at reduced volts and under stall conditions | = | 23.65 secs |
| $t_{6x}$ cold | - | at excess volts and under stall conditions | = | 23.21 secs |
| $t_{6x}$ hot | - | at excess volts and under stall conditions | = | 23.98 secs |
| $t_{6x}$ cold | - | at 2 x flc and under stall conditions | = | 59.0 secs |
| $t_{6x}$ hot | - | at 2 x flc and under stall conditions | = | 68.3 secs |

The maximum setting for the $t_{6x}$ control is 22.5 seconds to satisfy all conditions. The associated screen display is shown in Fig. 5.10. Fig. 5.11 shows the effect of

P & B GOLDS - PBSJ 3E5 N11
RELAY & MOTOR WITHSTAND RATINGS 22.5

| 3 ph Conditions | Relay Cold | Motor Cold | Margin %age | Relay Hot | Motor Hot | Margin %age |
|---|---|---|---|---|---|---|
| RATINGS at 2x FLC | 260.8 | 770.0 | +195 | 164.6 | 600.0 | +264 |
| RATINGS at LRC - 85% V | 28.2 | 31.8 | + 12 | 16.7 | 20.7 | + 23 |
| RATINGS at LRC - 100% V | 20.2 | 23.0 | + 13 | 11.9 | 15.0 | + 25 |
| RATINGS at LRC - 105% V | 18.3 | 20.8 | + 13 | 10.8 | 13.6 | + 25 |
| 1 Ph Conditions | | | | | | |
| RATINGS at F/L Output | 1.5 | 720.0 | +*** | 1.5 | 600.0 | +*** |
| RATINGS at LRC - 100%V | 1.5 | 14.0 | +833 | 1.5 | 8.0 | +433 |
| RUN-UP-TIME at - 85% V | 28.2 | 5.0 | +464 | 16.7 | 5.0 | +235 |
| RUN-UP-TIME at - 100% V | 20.2 | 4.0 | +405 | 11.9 | 4.0 | +199 |
| RUN-UP-TIME at - 105% V | 18.3 | 3.0 | +510 | 10.8 | 3.0 | +261 |

All times in seconds

Press any key to continue
<S>ettings,<M>enu

MAXCURVE - 75% Stall

*Fig 5.10 Operating times and margins for 'MAXCURVE' with 75% step in the thermal characteristic and a $t_{6x}$ setting of 22.5 seconds*

P & B GOLDS - PBSJ 3E5 N11

RELAY & MOTOR WITHSTAND RATINGS 22.5

| 3 ph Conditions | Relay Cold | Motor Cold | Margin %age | Relay Hot | Motor Hot | Margin %age |
|---|---|---|---|---|---|---|
| RATINGS at 2x FLC | 260.8 | 770.0 | +195 | 164.6 | 600.0 | +264 |
| RATINGS at LRC - 85% V | 18.8 | 31.8 | + 69 | 11.1 | 20.7 | + 85 |
| RATINGS at LRC - 100% V | 13.4 | 23.0 | + 70 | 7.9 | 15.0 | + 87 |
| RATINGS at LRC - 105% V | 12.2 | 20.8 | + 70 | 7.2 | 13.6 | + 87 |
| 1 Ph Conditions | | | | | | |
| RATINGS at F/L Output | 1.5 | 720.0 | +*** | 1.5 | 600.0 | +*** |
| RATINGS at LRC - 100%V | 1.5 | 14.0 | +833 | 1.5 | 8.0 | +433 |
| RUN-UP-TIME at - 85% V | 18.8 | 5.0 | +276 | 11.1 | 5.0 | +123 |
| RUN-UP-TIME at - 100% V | 13.4 | 4.0 | +237 | 7.9 | 4.0 | + 99 |
| RUN-UP-TIME at - 105% V | 12.2 | 3.0 | +306 | 7.2 | 3.0 | +141 |

All times in seconds

Press any key to continue <S>ettings, <M>enu 50% Step

*Fig 5.11 Operating times and margins for 'MAXCURVE' with 50% step in the thermal characteristic and a* $t_{6x}$ *setting of 22,5 seconds* selecting the 50% stall feature at this $t_{6x}$ setting. Both conditions are shown graphically in Fig. 5.12.

### 5.2.3 Maxcurve with 50% Stall Setting

As in the previous case the $t_{6x}$ setting may be calculated at the 50% stall setting by increasing the motor withstand times by the factor 1/0.5 of their former values for all currents greater than 2 • flc.

This allows the $t_{6x}$ control to be increased still further than was possible in the previous case.

Calculation of $t_{6x}$ at 50% Stall Setting

Thermal setting = 0.84 as previous producing trip levels of 104.7% - 115.5% of flc. The $t_{6x}$ value, starting from cold condition at 100% supply volts may be determined by modifying equation 5.3.

$$t_{cold}/0.5 = 32 \bullet a \bullet \log_e\left(\frac{p}{p^2 - s^2}\right)$$

re-arranging for a, where a is $t_{6x}$ control setting

•

$$a = \frac{tcold/0.5}{32 \bullet \log_e(p^2/(p^2 - s^2))}$$

and substituting values

$$t6x = \frac{23/0.5}{32 \bullet \log_e((230/42)^2/((230/42)^2 - 1.1025^2))} = 37.74\ secs$$

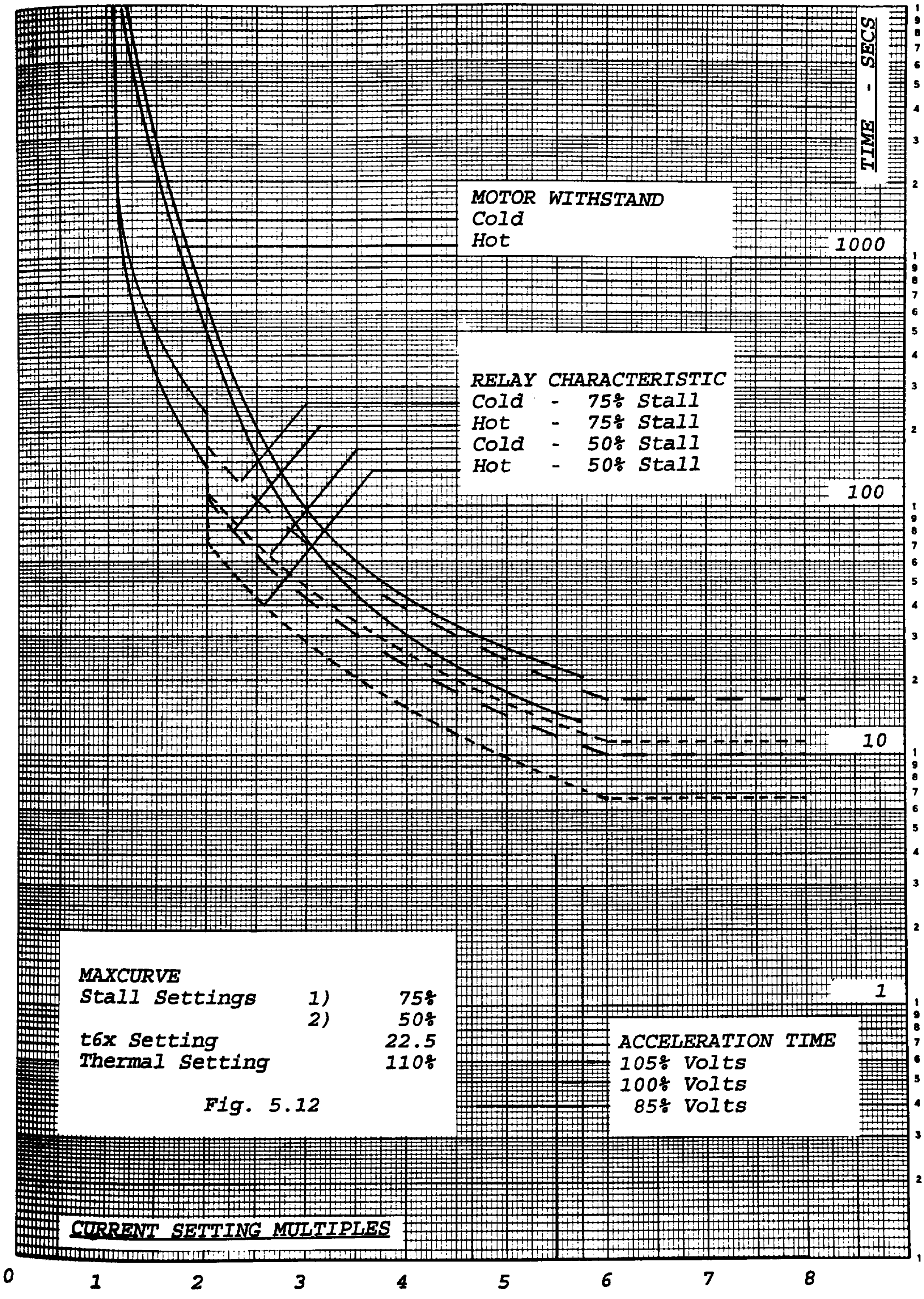

TIME - SECS
MOTOR WITHSTAND
Cold
Hot
1000
RELAY CHARACTERISTIC
Cold - 75% Stall
Hot - 75% Stall
Cold - 50% Stall
Hot - 50% Stall
100
10
1
MAXCURVE
Stall Settings 1) 75%
2) 50%
t6x Setting 22.5
Thermal Setting 110%
ACCELERATION TIME
105% Volts
100% Volts
85% Volts
CURRENT SETTING MULTIPLES
0 1 2 3 4 5 6 7 8

Fig. 5.12

Alternatively, using the $t_{6x}$ cold value of 17.37 seconds previously calculated for the cold condition in equation 5.10 gives

$$t_{6x} = 17.37/0.5 = 34.74 \text{ secs}$$

Selecting the closest setting the value reduces to 34.5 sec

Similarly

| | | | | |
|---|---|---|---|---|
| $t_{6x}$ hot | - | at full volts and under stall conditions | = | 35.86 secs |
| $t_{6x}$ cold | - | at reduced volts and under stall conditions | = | 34.46 secs |
| $t_{6x}$ hot | - | at reduced volts and under stall conditions | = | 35.47 secs |
| $t_{6x}$ cold | - | at excess volts and under stall conditions | = | 34.81 secs |
| $t_{6x}$ hot | - | at excess volts and under stall conditions | = | 35.96 secs |
| $t_{6x}$ cold | - | at 2 x flc under stall conditions | = | 59.0 secs |
| $t_{6x}$ hot | - | at 2 x flc under stall conditions | = | 35.96 secs |

from which the maximum setting for the $t_{6x}$ control is 34.0 sec to cover all conditions.

As in the previous case the $t_{6x}$ setting value is used to calculate the relay operating times which are displayed together with the associated motor withstand times and error margins. Figs. 5.13 and 5.14 depict the display and graphical representation for this condition.

### 5.2.4 Mincurve

When using the 'MINCURVE' technique (initially without the stall feature) the procedure adopted is to reduce the $t_{6x}$ setting until the relay hot characteristic approaches the limits set by the acceleration times of the motor under nominal,

P & B GOLDS - PBSJ 3E5 N11

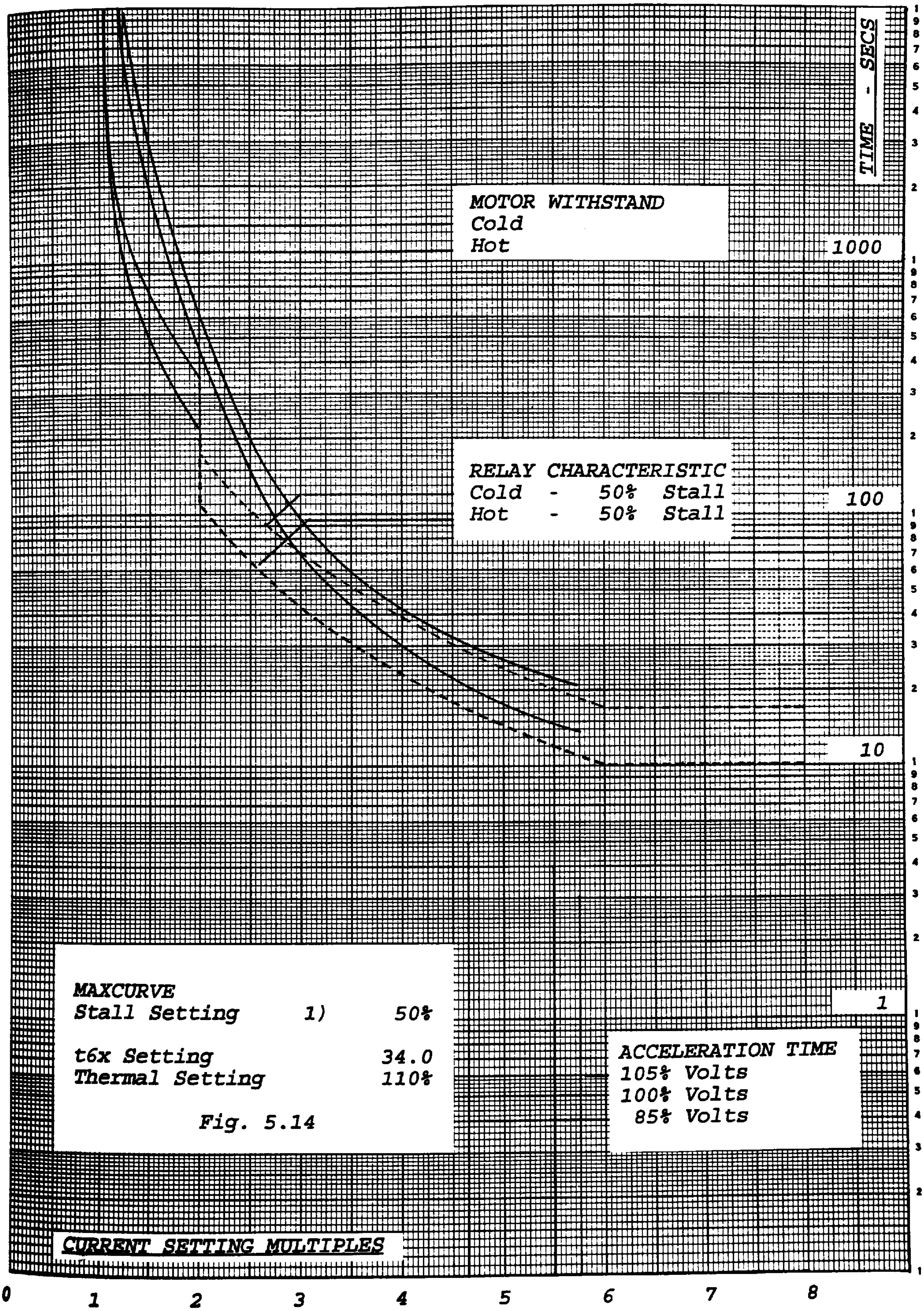
RELAY & MOTOR WITHSTAND RATINGS 34.0

| 3 ph Conditions | Relay Cold | Motor Cold | Margin %age | Relay Hot | Motor Hot | Margin %age |
|---|---|---|---|---|---|---|
| RATINGS at 2x FLC | 394.1 | 770.0 | + 95 | 248.8 | 600.0 | +141 |
| RATINGS at LRC - 85% V | 28.4 | 31.8 | + 12 | 16.9 | 20.7 | + 22 |
| RATINGS at LRC - 100% V | 20.3 | 23.0 | + 12 | 12.0 | 15.0 | + 24 |
| RATINGS at LRC - 105% V | 18.4 | 20.8 | + 13 | 10.9 | 13.6 | + 24 |
| 1 Ph Conditions | | | | | | |
| RATINGS at F/L Output | 1.5 | 720.0 | +*** | 1.5 | 600.0 | +*** |
| RATINGS at LRC - 100%V | 1.5 | 14.0 | +833 | 1.5 | 8.0 | +433 |
| RUN-UP-TIME at - 85% V | 28.4 | 5.0 | +468 | 16.9 | 5.0 | +238 |
| RUN-UP-TIME at - 100% V | 20.3 | 4.0 | +409 | 12.0 | 4.0 | +202 |
| RUN-UP-TIME at - 105% V | 18.4 | 3.0 | +514 | 10.9 | 3.0 | +264 |

All times in seconds

Press any key to continue MAXCURVE - 50% Stall
<S>ettings,<M>enu

*Fig 5.13 Operating times and margins for 'MAXCURVE' with 50% step in the thermal characteristic and a* $t_{6x}$ *setting of 34.0 seconds*



TIME - SECS
MOTOR WITHSTAND
Cold
Hot
1000
RELAY CHARACTERISTIC
Cold - 50% Stall
Hot - 50% Stall
100
10
1
MAXCURVE
Stall Setting 1) 50%
t6x Setting 34.0
Thermal Setting 110%
ACCELERATION TIME
105% Volts
100% Volts
85% Volts
CURRENT SETTING MULTIPLES
0
1
2
3
4
5
6
7
8

Fig. 5.14

excess and reduced voltage conditions. As with the 'MAXCURVE' approach, due cognisance of the inbuilt accuracy of the relay settings must be taken into account.

The 'MINCURVE' approach is essentially a variation of the method previously used with emphasis given to locating a minimum value of $t_{6x}$ setting which provides a thermal envelope that fully accommodates the acceleration period of the machine. The derived $t_{6x}$ value must of course be less than that required to fully protect the machine thermally under all operating conditions. Consider the case of acceleration with nominal voltage applied

Relay operating time

$$32 \bullet t_{6x} \bullet \log_e\left(\frac{(Start\ current/revised\ flc)^2 - 0.5\ (Load\ current/revised\ flc)^2}{(Start\ current/revised\ flc)^2 - (Actual\ trip\ level)^2}\right)$$

where:

| | | |
|---|---|---|
| Start current | = 230A | |
| Revised flc | = 42A | |
| Load current | = nominal flc = 40A | |
| Actual trip level | = minimum trip level | = 0.9975A |

Let acceleration time at nominal voltage be 4 seconds, then substituting these values in the above equation and rearranging to calculate $t_{6x}$ gives:

$t_{6x}$ for nominal voltage condition = 6.75 seconds (see equation (5.13))

Similarly

$t_{6x}$ for reduced voltage condition (85% Nominal Voltage) = 6.04 seconds (see equation (5.14))

$t_{6x}$ for excess voltage condition (105% Nominal Voltage) = 5.60 seconds (see equation (5.15))

From which it can be seen that a $t_{6x}$ setting of 7 seconds will satisfy acceleration requirements at all levels of applied terminal voltage. Further checks indicate that this setting will provide the largest possible margin of thermal safety for the motor although the short time overload capability will be severly reduced by this low $t_{6x}$ setting.

A display of the calculated values are as shown in Fig. 5.15 followed by the graphical representation in Fig. 5.16.

### 5.2.5 Mincurve with 75% Stall Setting

The operating characteristic may be modified by initiating the 75% stall setting. The procedure adopted is identical to that used when determining the $t_{6x}$ value for 'MINCURVE' except that in this case the acceleration times are increased by a factor of 1/0.75. The setting is then calculated as discussed previously. When the 75% stall feature is initiated the relay operating time characteristic is reduced by a factor of 0.75 for all current multiples greater than 2. Discrimination with the actual drive acceleration times is however maintained.

The calculation of $t_{6x}$ at 75% stall setting is as follows:

Thermal setting = 0.84 as previous, producing actual trip levels of 104% - 115.5% of flc.

$t_{6x}$ setting when starting from the 'hot' state with 100% supply volts

$$t_{6x} = \frac{4/0.75}{32\, log_e (5.48^2 - 0.5(0.9524)^2)/5.48^2 - 0.9975^2)} = 9.007\ secs$$

Similarly when starting from the hot state with reduced starting volts

$$t_{6x} = \frac{5/0.75}{32\, log_e ((5.48 \bullet 0.85)^2 - 0.5(0.9524)^2)/ 5.48 \bullet 0.85)^2 - 0.9975^2} = 8.057\ secs$$

and again when starting from the hot state with excess starting volts

P & B GOLDS - PBSJ 3E5 N11
RELAY & MOTOR WITHSTAND RATINGS 7.0

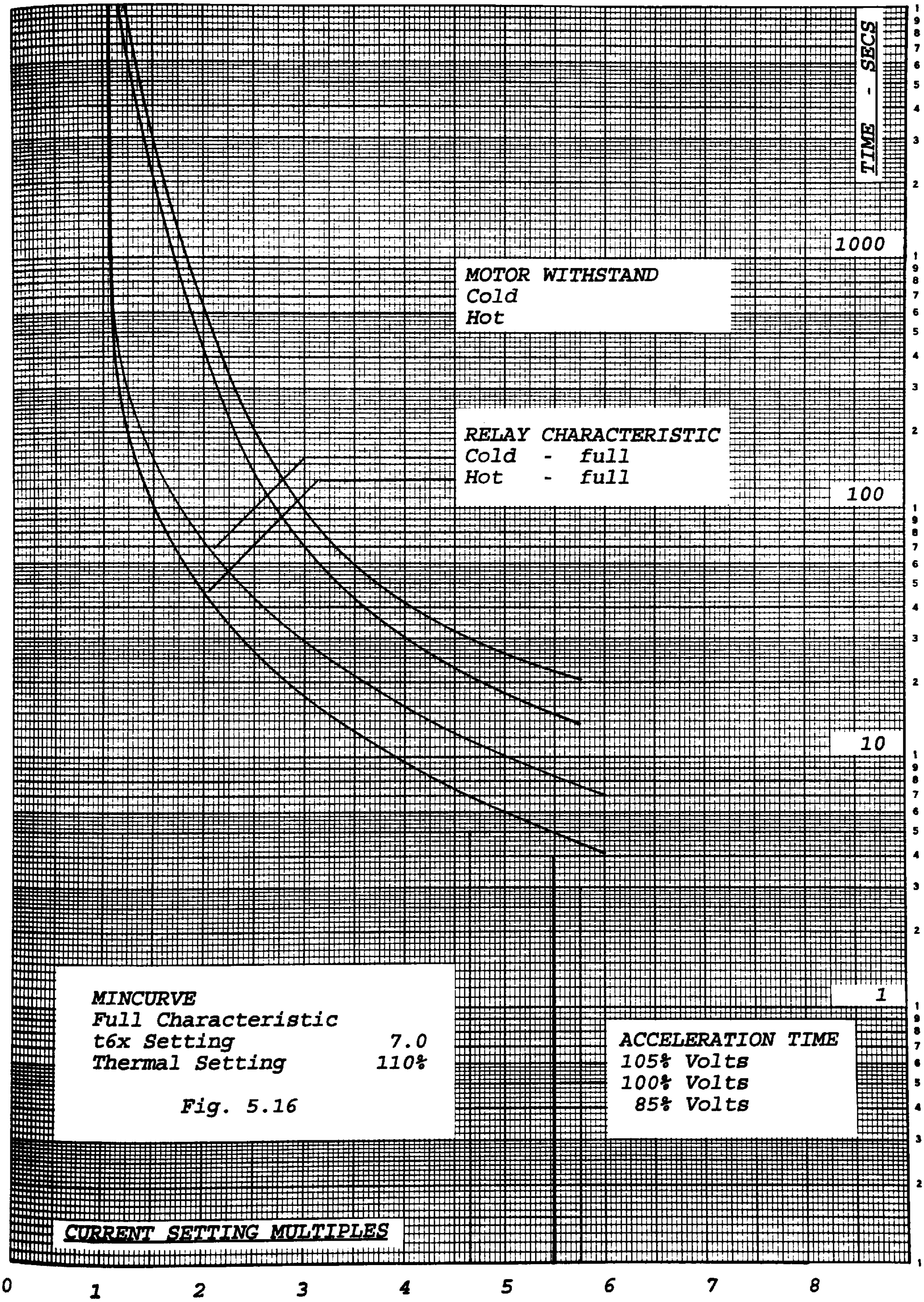
| 3 ph Conditions | Relay Cold | Motor Cold | Margin %age | Relay Hot | Motor Hot | Margin %age |
|---|---|---|---|---|---|---|
| RATINGS at 2x FLC | 81.1 | 770.0 | +848 | 51.2 | 600.0 | +*** |
| RATINGS at LRC - 85% V | 11.6 | 31.8 | +172 | 6.9 | 20.7 | +198 |
| RATINGS at LRC - 100% V | 8.3 | 23.0 | +174 | 4.9 | 15.0 | +201 |
| RATINGS at LRC - 105% V | 7.5 | 20.8 | +174 | 4.5 | 13.6 | +202 |
| 1 Ph Conditions | | | | | | |
| RATINGS at F/L Output | 1.5 | 720.0 | +*** | 1.5 | 600.0 | +*** |
| RATINGS at LRC - 100%V | 1.5 | 14.0 | +833 | 1.5 | 8.0 | +433 |
| RUN-UP-TIME at - 85% V | 11.6 | 5.0 | +133 | 6.9 | 5.0 | + 39 |
| RUN-UP-TIME at - 100% V | 8.3 | 4.0 | +109 | 4.9 | 4.0 | + 24 |
| RUN-UP-TIME at - 105% V | 7.5 | 3.0 | +153 | 4.5 | 3.0 | + 50 |

All times in seconds

Press any key to continue
<S>ettings,<M>enu

MINCURVE - 100% Stall

*Fig 5.15 Operating times and margins for 'MINCURVE' with full thermal characteristic and $t_{6x}$ setting of 7.0 seconds*



TIME - SECS
1000
100
10
1
MOTOR WITHSTAND
Cold
Hot
RELAY CHARACTERISTIC
Cold - full
Hot - full
MINCURVE
Full Characteristic
t6x Setting 7.0
Thermal Setting 110%
ACCELERATION TIME
105% Volts
100% Volts
85% Volts
CURRENT SETTING MULTIPLES
0
1
2
3
4
5
6
7
8


Fig. 5.16

$$t_{6x} = \frac{3/0.75}{32\,log_e(5.48 \bullet 1.05)^2 - 0.5(0.9524)^2)/(5.48 \bullet 1.05)^2 - 0.9975^2} = 7.46\ secs$$

From which it can be seen that a $t_{6x}$ setting of 9.5 seconds will satisfy all the above conditions. The associated screen display is shown in Fig. 5.17 whilst Fig. 5.18 depicts the graphical representation of the arrangement.

### 5.2.6 Mincurve with 50% Stall Setting

The $t_{6x}$ setting may be calculated for the 50% stall setting using the same principle as that used when determining the 75% stall setting. The approach is modified slightly by increasing the acceleration times by a factor of 1/0.5 then proceeding as previous. The resulting $t_{6x}$ setting will be greater than either of the previous two mincurve cases thus allowing a longer delay before tripping occurs for overload values less than twice flc. For overload values greater than twice flc the operating characteristic is the minimum possible to allow discrimination with the acceleration times.

Therefore, calculation of $t_{6x}$ of 50% stall setting is as follows:
Thermal setting = 0.84 as previous producing trip levels of 104.7% - 115.5% of flc.

$t_{6x}$ setting when starting from the 'hot' state with 100% supply volts

$$t_{6x} = \frac{4/0.5}{32\,log_e(5.48^2 - 0.05\,(0.9524)^2)/(5.48^2 - 0.9975^2)} = 13.511\ secs$$

again when starting with reduced volts we have

$$t_{6x} = \frac{5/0.5}{32\,log_e((5.48^2 \bullet 0.85)^2 - 0.5(0.9524)^2)/((5.48 \bullet 0.85)^2 - 0.9975^2)} = 12.0855\ secs$$

and when starting with excess voltage

$$t_{6x} = \frac{5/0.5}{32\,log_e((5.48^2 \bullet 1.05)^2 - 0.5(0.9524)^2)/((5.48 \bullet 1.05)^2 - 0.9975^2)} = 11.197\ secs$$

The final $t_{6x}$ setting is 14.0 seconds which satisfies all the above conditions. The associated displays are shown in Figs. 5.19 and 5.20.

P & B GOLDS - PBSJ 3E5 N11
RELAY & MOTOR WITHSTAND RATINGS 9.5

| 3 ph Conditions | Relay Cold | Motor Cold | Margin %age | Relay Hot | Motor Hot | Margin %age |
|---|---|---|---|---|---|---|
| RATINGS at 2x FLC | 110.1 | 770.0 | +599 | 69.5 | 600.0 | +763 |
| RATINGS at LRC - 85% V | 11.9 | 31.8 | +167 | 7.0 | 20.7 | +193 |
| RATINGS at LRC - 100% V | 8.5 | 23.0 | +169 | 5.0 | 15.0 | +196 |
| RATINGS at LRC - 105% V | 7.7 | 20.8 | +169 | 4.5 | 13.6 | +196 |
| 1 Ph Conditions | | | | | | |
| RATINGS at F/L Output | 1.5 | 720.0 | +*** | 1.5 | 600.0 | +*** |
| RATINGS at LRC - 100%V | 1.5 | 14.0 | +833 | 1.5 | 8.0 | +433 |
| RUN-UP-TIME at - 85% V | 11.9 | 5.0 | +138 | 7.0 | 5.0 | + 41 |
| RUN-UP-TIME at - 100% V | 8.5 | 4.0 | +113 | 5.0 | 4.0 | + 26 |
| RUN-UP-TIME at - 105% V | 7.7 | 3.0 | +157 | 4.5 | 3.0 | + 52 |

All times in seconds

Press any key to continue
<S>ettings,<M>enu

MINCURVE - 75% Stall

*Fig 5.17 Operating times and margins for 'MINCURVE' with 75% step in the thermal characteristic and a $t_{6x}$ setting of 9.5 seconds*

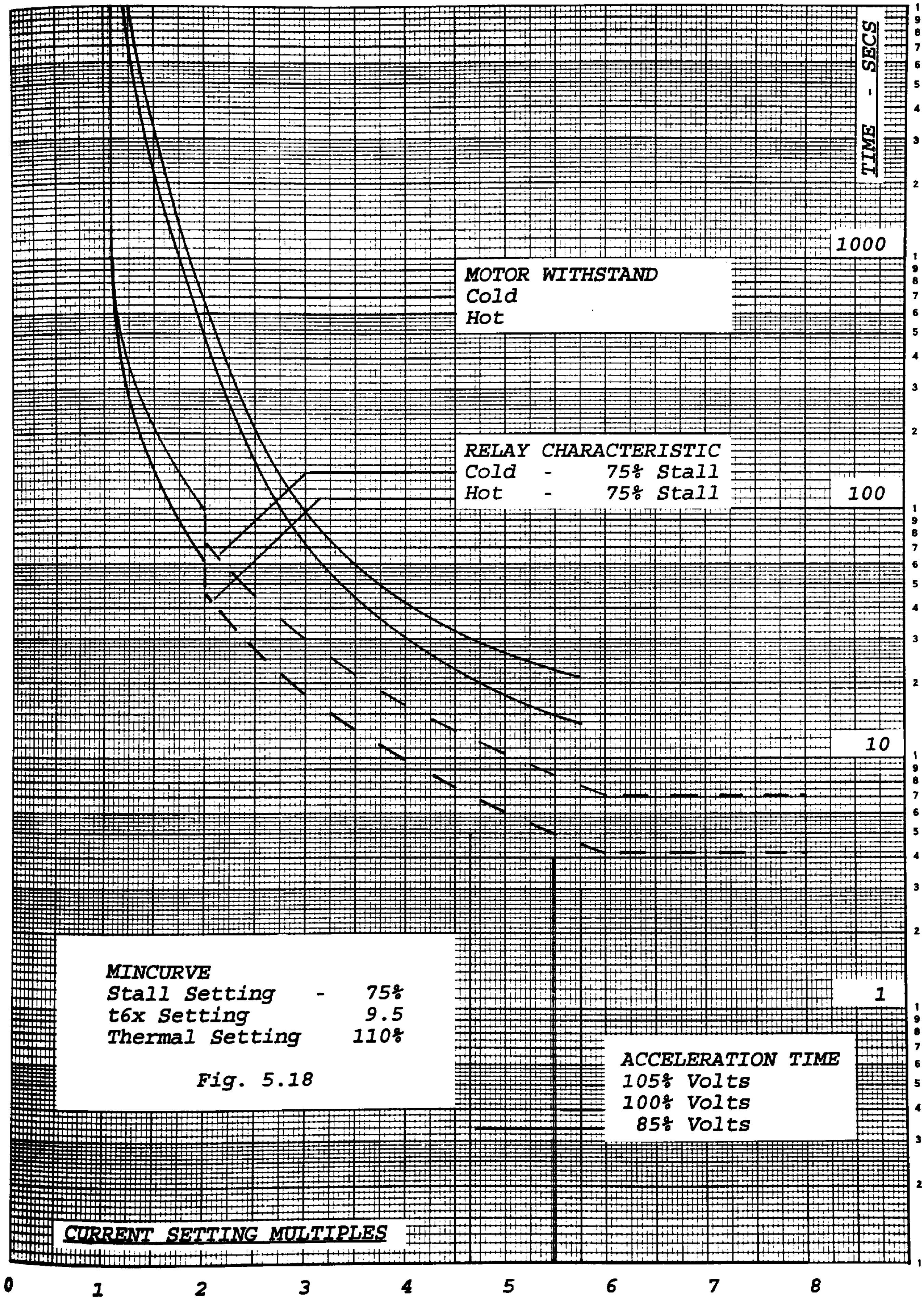

TIME - SECS
1000
100
10
1
MOTOR WITHSTAND
Cold
Hot
RELAY CHARACTERISTIC
Cold - 75% Stall
Hot - 75% Stall
MINCURVE
Stall Setting - 75%
t6x Setting 9.5
Thermal Setting 110%
ACCELERATION TIME
105% Volts
100% Volts
85% Volts
CURRENT SETTING MULTIPLES
0
1
2
3
4
5
6
7
8

Fig. 5.18

P & B GOLDS - PBSJ 3E5 N11
RELAY & MOTOR WITHSTAND RATINGS 14.0

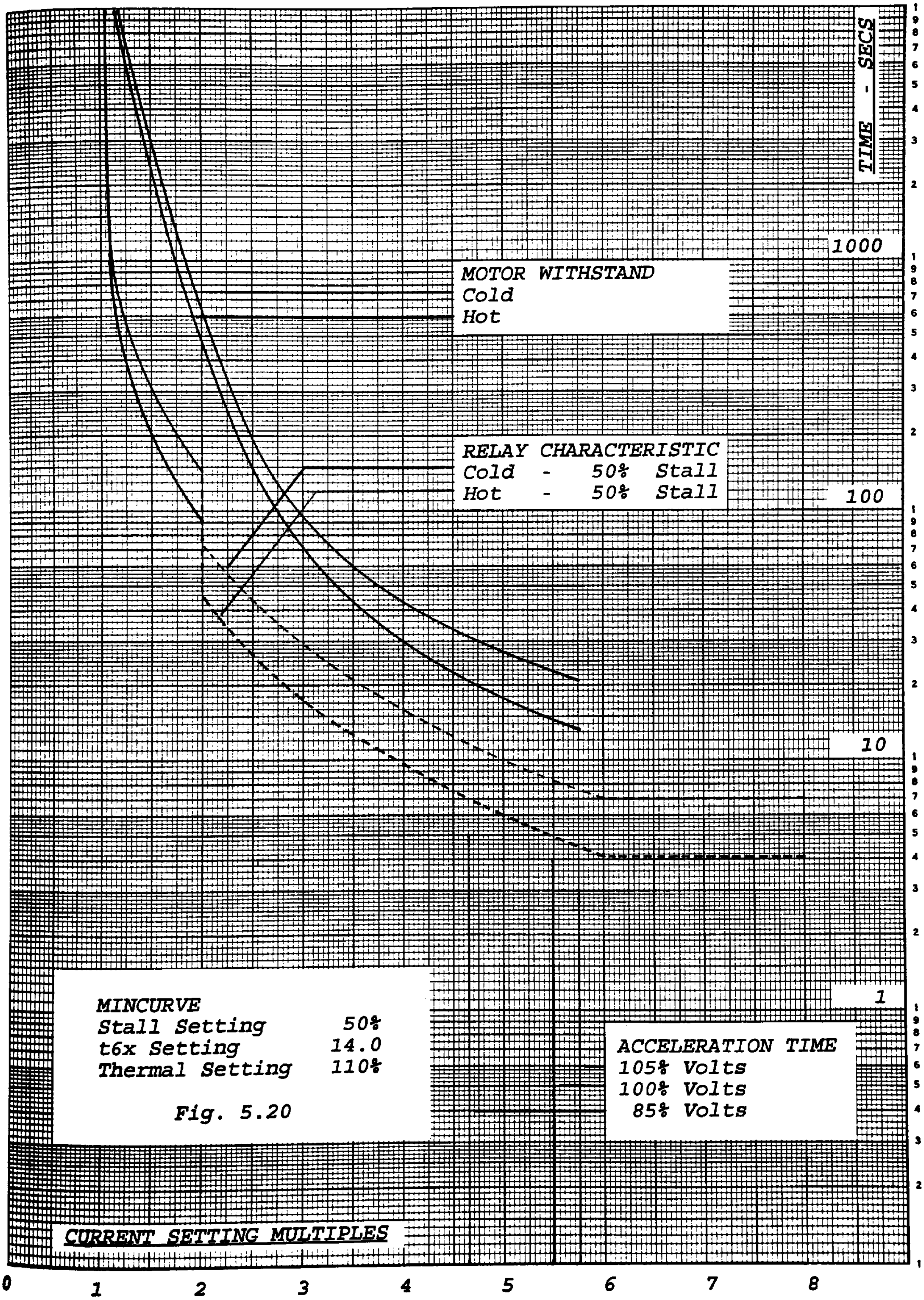
| 3 ph Conditions | Relay Cold | Motor Cold | Margin %age | Relay Hot | Motor Hot | Margin %age |
|---|---|---|---|---|---|---|
| RATINGS at 2x FLC | 162.2 | 770.0 | +374 | 102.4 | 600.0 | +485 |
| RATINGS at LRC - 85% V | 11.6 | 31.8 | +172 | 6.9 | 20.7 | +198 |
| RATINGS at LRC - 100% V | 8.3 | 23.0 | +174 | 4.9 | 15.0 | +201 |
| RATINGS at LRC - 105% V | 7.5 | 20.8 | +174 | 4.5 | 13.6 | +202 |
| 1 Ph Conditions | | | | | | |
| RATINGS at F/L Output | 1.5 | 720.0 | +*** | 1.5 | 600.0 | +*** |
| RATINGS at LRC - 100%V | 1.5 | 14.0 | +833 | 1.5 | 8.0 | +433 |
| RUN-UP-TIME at - 85% V | 11.6 | 5.0 | +133 | 6.9 | 5.0 | + 39 |
| RUN-UP-TIME at - 100% V | 8.3 | 4.0 | +109 | 4.9 | 4.0 | + 24 |
| RUN-UP-TIME at - 105% V | 7.5 | 3.0 | +153 | 4.5 | 3.0 | + 50 |

All times in seconds

Press any key to continue
<S>ettings,<M>enu

MINCURVE - 50% Stall

*Fig 5.19 Operating times and margins for 'MINICURVE' with 50% step in the thermal characteristic and $t_{6x}$ setting of 14 seconds.*



TIME - SECS
1000
100
10
1
MOTOR WITHSTAND
Cold
Hot
RELAY CHARACTERISTIC
Cold - 50% Stall
Hot - 50% Stall
MINCURVE
Stall Setting 50%
t6x Setting 14.0
Thermal Setting 110%
ACCELERATION TIME
105% Volts
100% Volts
85% Volts
CURRENT SETTING MULTIPLES
0
1
2
3
4
5
6
7
8


Fig. 5.20

In the six cases discussed, the $t_{6x}$ setting was determined by considering the starting current/flc ratio. In all cases this ratio was found to be less than 6. For ratios greater than 6, the relay thermal characteristic is modified to that of a constant time characteristic.

Consider the following case which has implications for the $t_{6x}$ setting.

$$Assume \qquad \frac{Motor\,Starting\,Current}{Full\,Load\,Current} = \frac{240A}{40A} = 6$$

The associated thermal withstand time for locked rotor condition is 23 secs

Thermal trip level is 105%

Then in the case of a 5% overvoltage condition, the starting current would rise to 240 • 1.05 = 252 Amp. Hence starting current rises to 6.3 • flc. Similarly the locked rotor thermal withstand capability will decrease to $23/1.05^2 = 20.86$ secs. As the transition between the inverse and constant time characteristics occurs at 6 • flc, the $t_{6x}$ value must be reduced to satisfy the condition when using the 'MAXCURVE' approach. Alternatively when using the 'MINCURVE' approach the acceleration times of the machine are generally shortened when overvoltage is applied. Hence satisfying the 6 • flc will provide the minimum $t_{6x}$ solution. Where the nominal starting currents are greater than 6 • flc and are coupled with extended acceleration times, the change to a constant time characteristic can prove beneficial and will result in a lower $t_{6x}$ setting than would have been produced if the original logarithmic characteristic was continued.

For 3.3kV or higher voltage motors in general, the starting currents do not generally exceed 6•flc thus tripping operations are usually confined to the logarithmic portion of the characteristic. In the case of 415V motors the starting currents are generally higher in the order of 7• flc or greater, consequently locked rotor disconnection will be determined by the constant time characteristic.

In the case where the acceleration time exceeds the maximum thermal withstand time of the machine, tripping during the acceleration period would inevitably occur if a correctly determined characteristic was used.

A solution may be arrived at by setting the acceleration times to a low value then using the 'MAXCURVE' approach to determine the $t_{6x}$ setting with the 50% and 75% stall features selected.

If the true acceleration times are restored, the 'USER CHOICE' option can be invoked to produce a table of results from which it can be clearly seen if either of the two $t_{6x}$ values (previously obtained with 50% and 75% stall feature selected) when used with the full 100% stepless characteristic can accommodate the extended acceleration period. If either setting proves suitable the relay can be arranged so that starting occurs with a stepless characteristic using the selected $t_{6x}$ setting. An external speed switch or similar device is used to switch and seal the selected step in the characteristic by detecting the end of the acceleration period.

The danger associated with this technique arises if the motor fails to rotate at all, as under this circumstance thermal protection of the machine will not be provided. The time to trip will be a function of the full 100% stepless characteristic at the chosen $t_{6x}$ setting which will be in excess of the locked rotor thermal withstand capability of the machine.

The technique has not been specifically incorporated into the program as the approach is essentially flawed. It has however, been included in the text as it could well prove useful when supplemented by additional protective relays.

### 5.3 Potentiometer 3 - High Set Overcurrent Setting

By examining the data read from the workfile the program is able to determine the generic type of motor switching device used for controlling the circuit. Either it is a fully rated circuit breaker or alternatively a fuse protected contactor. In the latter case the fuse must provide short circuit protection for the contactor, cable, motor terminal box and motor by high speed operation on heavy short circuit overcurrents and earth faults. In order to avoid possible damage to the contactor it is essential that switch S1 in the SG1 switchgroup is set for contactor operation. In this mode the instantaneous overcurrent element is inhibited so preventing the contactor opening for current values in excess of its designed interupting limit. When the circuit is switched by a fully rated circuit breaker the switch S1 in the SG1 switchgroup is set for circuit breaker operation. In this mode, settings in the range 2.0-12.0 • In may be assigned. It should be noted that during the starting phase the setting value is doubled. This useful feature enables a setting value lower than flc to be used. Hence this element can be used to detect and disconnect the supply for overcurrents between the setting and the equivalent motor flc. Such an overcurrent may result from a motor in a locked rotor condition.

For the case under consideration the operating level of the element in the run state, should in order to provide an instantaneous stall feature, be set to operate at:

$$< \frac{Starting\ current\ at\ 85\%V \bullet accuracy\ factor}{C.T.\ Ratio}$$

which is the CT secondary current observed with 85% line voltage applied to the motor.

$$= \frac{0.85 \bullet 230 \bullet 0.95}{50} = 3.71\ Amp$$

and in order to avoid nuisance tripping on starting must be:

$$> \frac{\textit{Starting current at } 105\%V \bullet \textit{overreach factor} \bullet \textit{accuracy factor}}{C.T.\ Ratio}$$

$$= \frac{1.05 \bullet 230 \bullet 1.05 \bullet 1.05}{50} = 5.33\ Amp$$

Under starting conditions the instantaneous overcurrent element is doubled, hence to satisfy the overvoltage condition, the setting must be:

$$> \frac{5.33}{2} = 2.7\ Amp$$

and $<$ 3.7 Amp to ensure operation of the instantaneous element under locked rotor conditions in the run mode.

## 5.4 Potentiometer 4 - Earth Fault Setting

The function of this element is to detect the presence of an earth fault on the motor circuit. To obtain operation, the magnitude of the earth fault current must be greater than the operating threshold of the element as determined by the earth fault setting potentiometer.

The setting should satisfy the following conditions.

1. There must be sufficient current to operate the element at the setting applied.
2. The operating setting must discriminate with any upstream protection.

3. For fully rated circuit breaker operation, the 50 millisecond time setting should be used to isolate the faulted circuit as quickly as possible.

4. The faulted circuit must be isolated before thermal damage can occur in potential earth fault paths such as cable armouring.

5. For contactor operation the function of the earth fault element may be inhibited at all settings if the magnitude of the earth fault current is in excess of four times flc. This implies that clearance must result from fault recognition by other means. These are:

   1. Upstream protection
   2. Main power fuses
   3. Thermal protection
   4. NPS/Phase unbalance protection

It can be seen that items 3 & 4 will be used to clear faults of medium magnitude whilst item 2, the main power fuse will remove heavy earth fault currents. If the power fuse is large, discrimination may be lost causing the upstream protection to operate.

Where the earth fault current is of low magnitude and above the operating threshold of the earth fault setting, the operating time of the element introduces either a 50 millisecond or a 1 second delay prior to operating. Where the potential earth fault current approaches the capability of the switching device, it is essential to select the 1 second delay to prevent the contactor opening on receipt of a trip signal from the relay. The trip signal may conceivably be initiated by a high resistance earth fault which subsequently develops into an earth fault of greater magnitude than the clearing capability of the switching device. Any attempt to clear the fault by means of the switching device may result in severe damage. In such circumstances, it is prudent to ensure that the fuse selected is capable of disrupting the fault current in less than 1 second.

To ensure decisive operation, it is essential to ensure that the earth fault setting, typically 20% flc, is from a source which will provide a minimum of twice times the current required to operate the element.

## 5.5 Display of Settings

A screen display is available following a MAXCURVE or MINCURVE calculation which when selected, summarises the potentiometer setting values and SG1 switchgroup positions for the relay faceplate. A typical display is shown in Fig. 5.21.

## 5.6 Program Description

### 5.6.1 P&B

This routine is the main control element of the P&B relay setting program. The start of the program is used as a set-up routine where all variables used throughout the program are declared and assigned initial values.

The main body of the routine is in the form of a loop which is directed to the first module P&B10. Subsequent routines P&B20, P&B30 are called in sequence until the final routine P&B40 is accessed. On completion of this routine the program is rerouted to P&B20 from which it is possible to exit the program. A flowchart for this routine is shown in Fig 5.22.

### 5.6.2 P&B10

The P&B10 module comprises two parts. The first part produces a display of questions which are relevant to the setting of the relay faceplate switches and

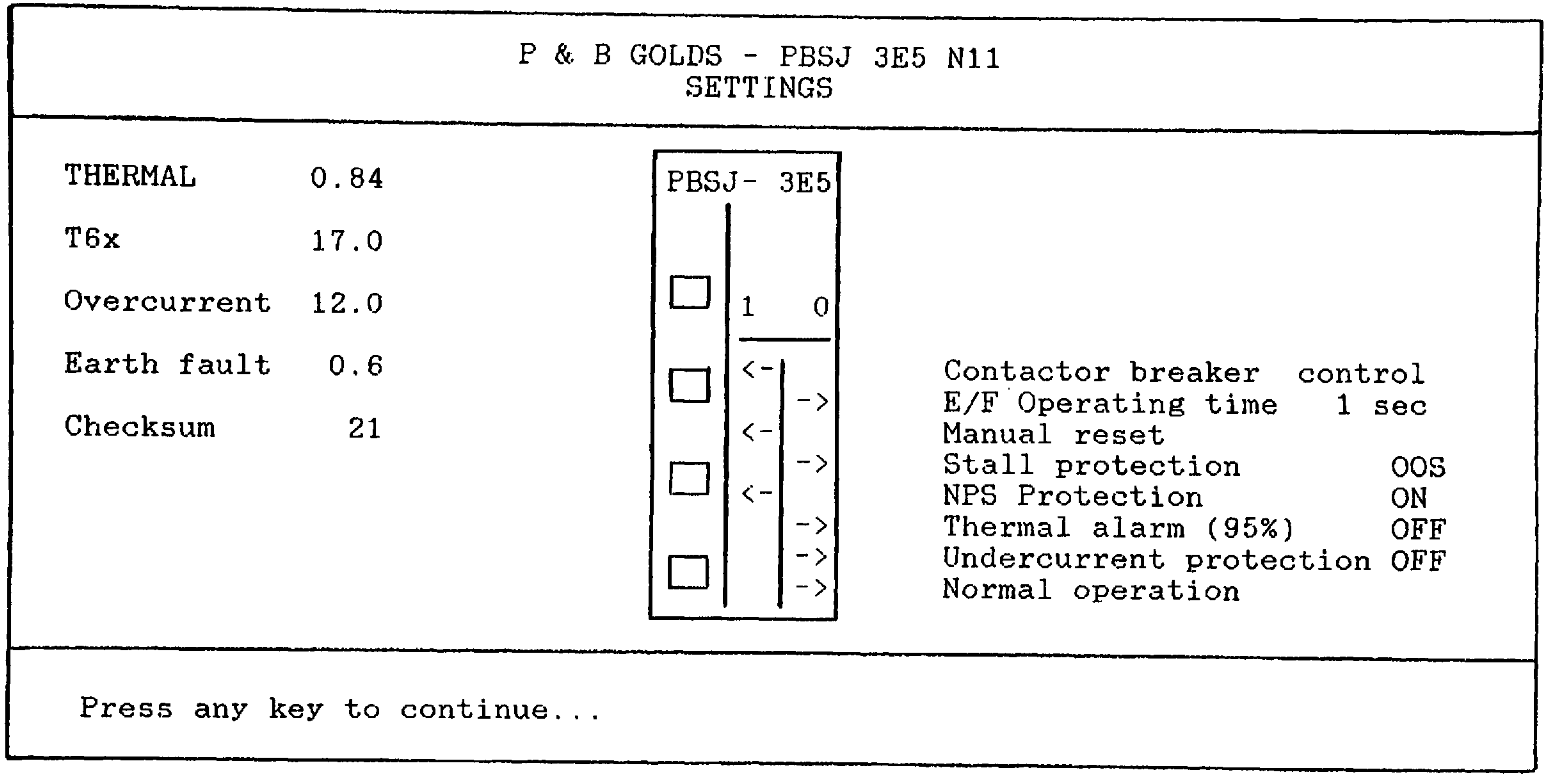



*Fig 5.21 Typical relay setting display*

ROUTINE : P & B

TITLE : P & B CONTROL ROUTINE

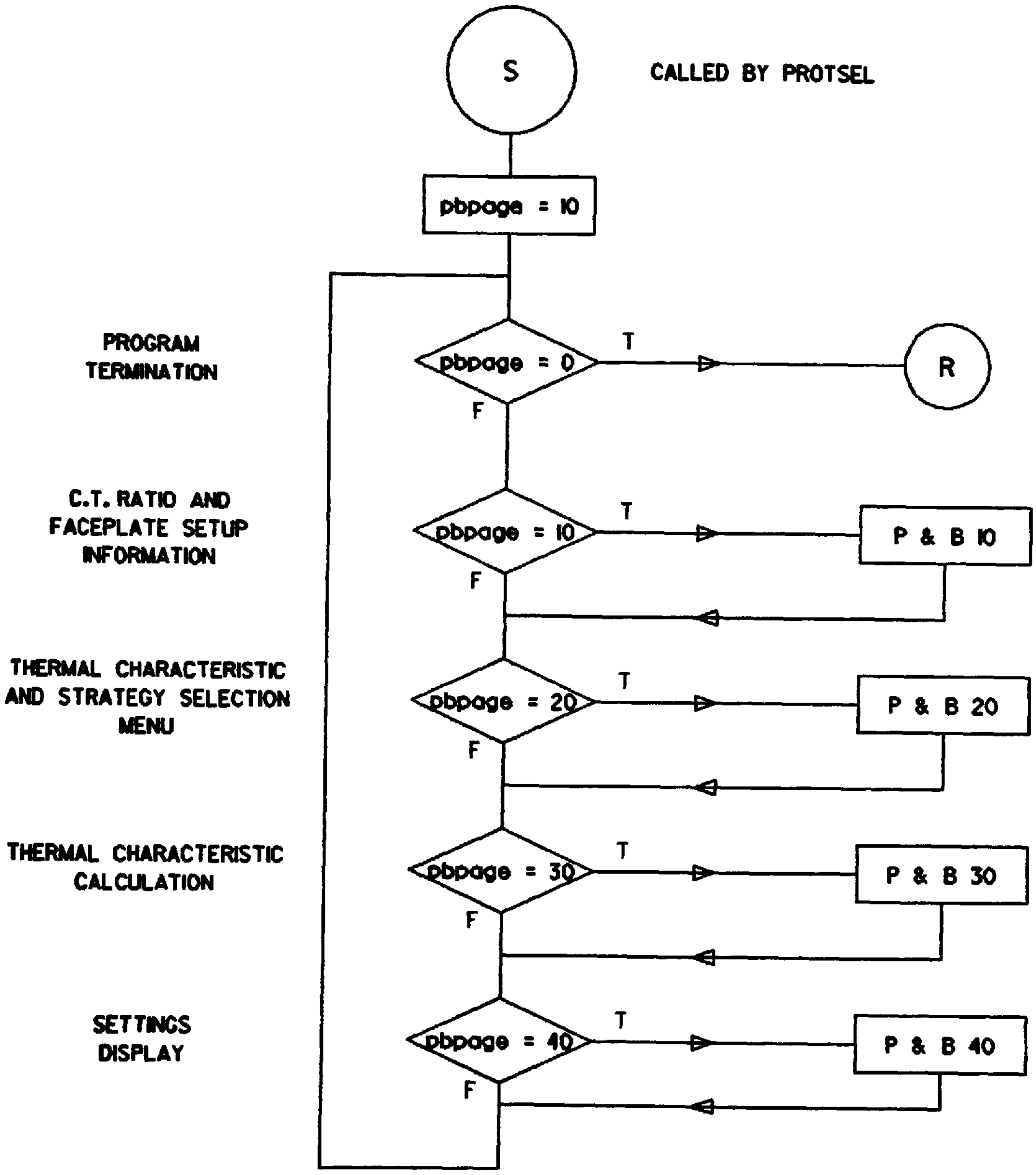



Fig 5.22

potentiometers. The latter part of the routine which forms the major portion is used to acquire and process the data for use in subsequent modules. Beside faceplate setup data the routine produces a setting for potentiometer 1 based on the desired trip level.

### 5.6.3 P&B30

This module forms a major routine in the program. It is used to determine the $t_{6x}$ setting for potentiometer 2 in accordance with the option chosen in P&B20. The flowchart for this module is shown in Fig. 5.23. It can be seen that when accessed the routine calculates the $t_{6x}$ value which will satisfy the 2 • flc condition for both hot and cold characteristics. The remaining $t_{6x}$ calculations which determine the $t_{6x}$ setting are performed in a series of subroutines which are controlled by the P&B30 routine. The subroutine selected is determined by the option chosen in P&B20. Hence the function of the module is mainly that of control rather than calculation.

### 5.6.4 P&B301

If option 1 - 'MAXCURVE' with full characteristic, is selected from the menu displayed by the P&B20 module, the information passed to the P&B30 module enables the selection of subroutine P&B301 to be executed. A flowchart of the P&B301 routine is shown in Fig. 5.24.

In this routine values are assigned to selected variables which represent current values indicative of the condition under examination. The variables are directed to a subroutine, $t_6$max, which processes the information and returns the maximum $t_{6x}$ value which will satisfy the condition whilst taking full account of the various tolerances. Further sets of data are processed in the same way, an

ROUTINE : P & B 30

TITLE : CALCULATE RELAY SETTINGS

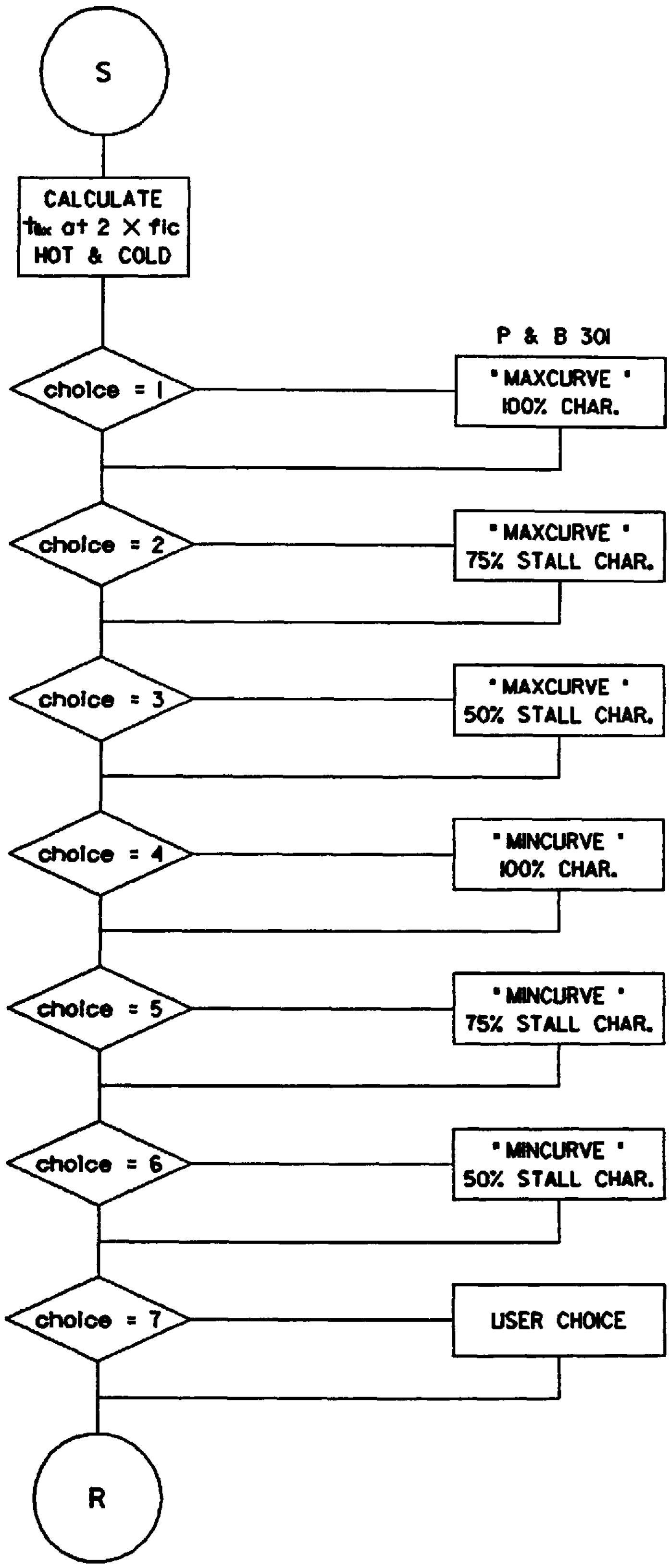



Fig 5.23

ROUTINE : P & B 301

TITLE : CALCULATE $t_{6x}$ FOR MAXCURVE

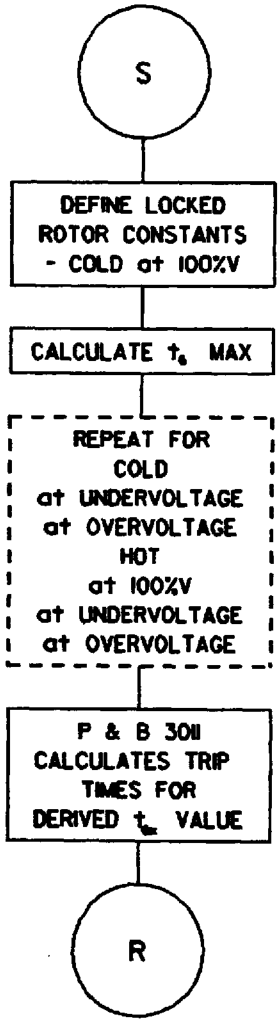



Fig 5.24

overall check being maintained on the returned $t_{6x}$ value. The final $t_{6x}$ value returned is that which satisfied all conditions which have been examined. At this juncture a further subroutine, P&B3011, is accessed and processed before returning to the calling routine P&B30. The P&B3011 routine is also used by other modules.

### 5.6.5 P&B3011

In this routine, the $t_{6x}$ value determined in the calling routine is used in conjunction with values assigned to variables representing the conditions being examined. The values are passed to a subroutine, OPTIME, whose function is to return the nominal tripping time of the thermal element for the conditions presented. This exercise is repeated for all conditions presented, the result being stored for subsequent display together with modified values for both 75% and 50% stall conditions. The stored information is used in a further subroutine, CALCTIME, which compares each derived nominal tripping time with the motor withstand time for the condition under examination. The times are used to produce a percentage value indicative of the margin between them. This procedure is repeated for all values under consideration. A further routine, DISPTIME, is then accessed which displays all values calculated. The option now available is either to return to the main menu for a further choice or alternatively to examine the effect of a 75% time step in the characteristic at the same $t_{6x}$ setting. If the latter option is chosen a further subroutine, STALL1, is invoked. The function of the STALL1 routine is to modify the operating times of the chosen $t_{6x}$ characteristic. The CALCTIME routine is again accessed and the percentage margins recalculated. The revised results are then displayed by again accessing the DISPTIME routine. A further option which uses the same approach is now made available to examine the effects of a 50% time step in the characteristic. A flowchart of the P&B3011 routine and its subroutine calls is shown in Fig. 5.25.

ROUTINE : P & B 3011

TITLE : CALCULATE & DISPLAY OPERATING TIMES

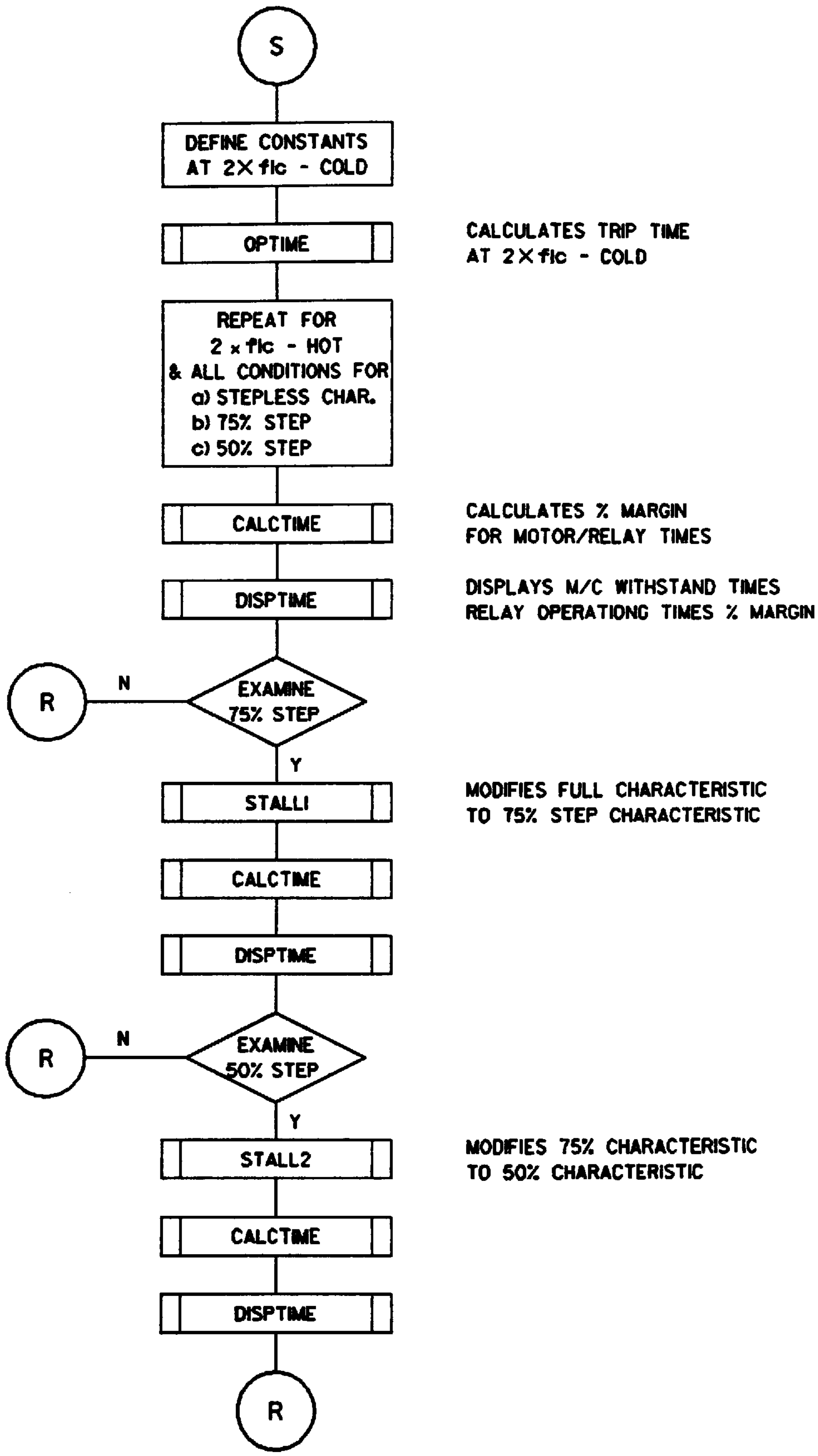



Fig 5.25

### 5.6.6 P&B302

If option 2, 'MAXCURVE' with 75% stall feature, is selected in the P&B20 module, the information when passed to the P&B30 module enables the selection of the subroutine, P&B302, to be carried out.

The P&B302 subroutine follows the same format as found in the P&B301 subroutine except that the initial $t_{6x}$ value is determined with the 75% time step in the characteristic selected. Calculations and display are again carried out by calls to the CALCTIME and DISPTIME routines. The routine also makes provision for the calculated $t_{6x}$ characteristic to be displayed for examination with the 50% stall feature selected.

### 5.6.7 P&B303

This routine is called from the P&B30 module when option 3, 'MAXCURVE' with 50% stall feature, is selected in the P&B20 module.

The routine determines the maximum $t_{6x}$ value that can be accommodated using a 50% time step in the characteristic. The value is processed and displayed using the CALCTIME and DISPTIME routines in the same manner as found in the P&B302 routine.

### 5.6.8 P&B304

This routine is accessed from P&B30 when any of the 'MINCURVE' options are selected in the P&B20 module. In the P&B304 routine precedence is given to determining a $t_{6x}$ value which will allow the drive to accelerate up to speed without encroaching on the tripping envelope. The routine incorporates features which take due account of all possible time steps in the characteristic when processing the conditions presented. The resulting $t_{6x}$ value is the minimum value that satisfies all conditions and is used in the CALCTIME and DISPTIME routines to quantify and display the calculated values.

### 5.6.9 User Choice Option

If option 7, 'USER CHOICE', is selected in module P&B20, the user is invited to supply a $t_{6x}$ value in the range 5-60 seconds. The option number chosen is used in module P&B30 to redirect the $t_{6x}$ value to the P&B3011 routine. The reader is referred to the P&B3011 routine discussed earlier.

### 5.6.10 P&B40

This module when selected displays the relay setting appropriate to the display shown by the calling routine. The display also includes a mimic of the relay faceplate with the SG1 switchgroup shown in its selected form. A typical display is shown in Fig. 5.21.

## 5.7 Interim Conclusion

Chapter 5 introduces a more modern, microprocessor based relay containing inbuilt features which allow the entire range of thermal characteristics incorporated within the relay to be selected by means of a faceplate mounted potentiometer. As discussed in the text, further exploitation of the device is possible by introducing a step in the thermal characteristic. A comparison with the relay described in the previous chapter clearly shows the advancement that has taken place in relay development in a relatively short period of time.

The input signals to this relay are sampled using Analogue to Digital (A/D) convertors before being subjected to measurement. These A/D convertors introduce quantitisation errors into the measured values thus setting a limit on the accuracy obtainable. The overall accuracy of the relay is incorporated into the method used to determine the most appropriate range of characteristics for the application being considered. The solution adopted is discussed at length in the text and can be seen to clearly satisfy the objective of the program.

# CHAPTER 6

# THE PROTECTION OF VARIABLE SPEED DRIVE TRANSFORMERS

## 6.1 Introduction

The usual distribution approach to the protection of transformer fed variable speed drive circuits (VSD) is to provide adequate protection for the transformer and associated HV cabling only, the motor protection and LV cabling being handled by the drive control package.

### 6.1.1 The Problems

Typical VSD circuits are supplied from substations at voltages ranging from 3.3 - 11kV. The remotely sited transformers and drive packages are located as near as possible to the motor to limit voltage drop in the LV cabling system. Such installations vary in size, the most common encountered utilise step down transformers under 3150 kVA. In the case of low rated units it may be difficult to justify the cost of a 630A 3.3kV or 11kV circuit breaker for the primary switching duty. Similar problems can arise when space on a switchboard is at a premium. In such cases where multiple transformers are envisaged, a solution may be found by 'daisy chaining' the transformers together and feeding them from a common circuit breaker. Caution should be exercised, however, as it should be noted that the working current of the arrangement will now be increased necessitating higher overload settings whilst the current passed by the smallest transformer during fault conditions remains unchanged. Hence, the arrangement must be carefully examined to ensure that the maximum protection is afforded to all components when subjected to any combination of fault conditions. To achieve this result manually can be a very time consuming and tedious exercise, so to alleviate this problem and yet still satisfy the requirements, a program has been devised and written which limits the time and effort expended by the engineer to a minimum. Setting aside the standard transformer protection devices such as Bucholtz, Over Temperature, Qualitrol, etc, we are left with the problem of satisfying the circuit overcurrent and earth fault requirements by the application of 2 or 3 phase overcurrent and earth fault detection devices arranged to operate in accordance with a specific time lag characteristic and/or instantaneous operation of the said devices. The method of solution is best explained by examining two actual cases which are shown schematically in Figs. 6.1 and 6.4.

The first case shown in Fig. 6.1 is intended to illustrate the method applied in determining the fault current distribution in the transformer windings. The transformer considered incorporates a winding arrangement which results in an uncommon vector group. The effect of such a vector group on the current distribution in the transformer windings when a phase-phase fault occurs on the secondary side of the transformer is difficult to predict. To overcome this difficulty and effect a generalised approach requires a more rigorous analysis of the problem to be undertaken. By adopting an algorithmic approach, the problem may be reduced to a series of defined steps which result in the determination of anticipated fault currents for all limbs in both primary and secondary windings of the transformer due to 3-Phase and Phase-Phase faults on the transformer secondary side. It is essential to calculate the current in each winding in order to determine the heaviest loaded winding which will provide the limiting factor from which the maximum withstand time is deduced. To achieve this objective the program calculates the current distribution in all windings of the transformer and assigns a corresponding withstand time to each. The method used is discussed in the text. To utilise the program the user is required to enter a series of relevant circuit details in response to screen requests. Using the information the program will select the appropriate main cables and calculate the currents and associated withstand times for all windings taking due account of the additional circuit impedances imposed by the HV cable and source.

## 6.2. Case Study 1 - The Variable Speed Fan

Consider the installation of a variable speed fan powered by a synchronous motor. The 665 volt 3 phase supply to the synchronous motor is derived from a 12 pulse, transformer fed, convertor system. The transformer primaries being supplied at 11000V.

The transformer and supply details are as follows

3 Phase fault level at source: 93 MVA

System X/R ratio: 8

Supply cable: 320 metres, 6.35/11kV, 3 core, 240 $mm^2$, XLPE insulated, single wire armoured, pvc oversheathed with stranded aluminium conductors.

The transformer comprises two, two winding transformers enclosed in a single oil filled tank with both primary windings brought out to common HV terminals. The rating of each individual two winding transformer is 1530 kVA.

The primary winding in both cases comprises a delta with extended star windings

Secondary 1 is delta with a phase shift of +7.5°

Secondary 2 is star with a phase shift of +37.5°

Percentage impedance is 6.5% on rating

The general arrangement described is shown in Fig. 6.1.

Using the data listed above the source impedance may be calculated as follows.

Fault level of source = 93MVA

$$= \sqrt{3} \bullet V_L \bullet I_L \qquad (6.1)$$

## GENERAL ARRANGEMENT OF SYNCHRONOUS MOTOR POWERED VARIABLE SPEED FAN

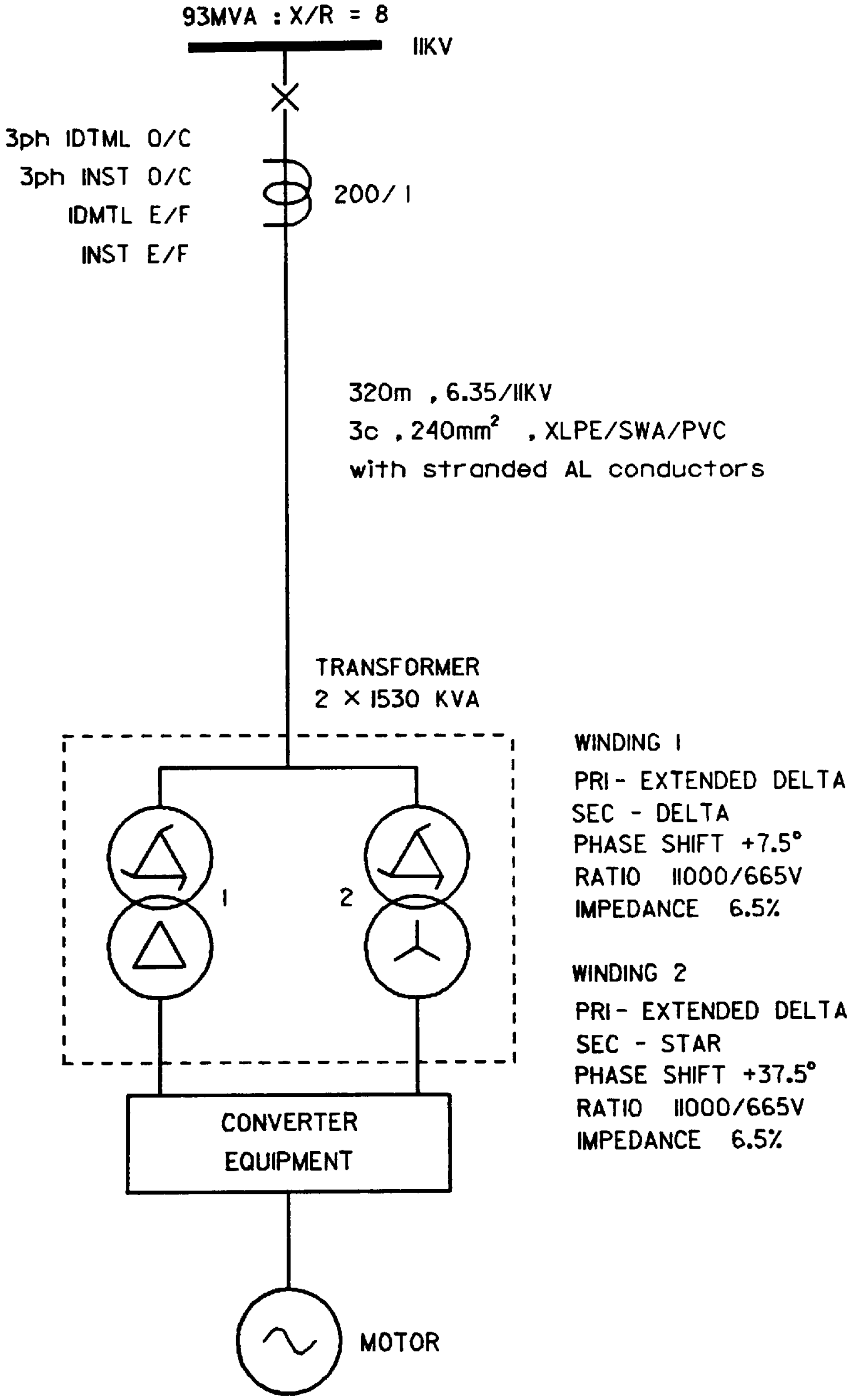



Fig 6.1

where $V_L$ = Line volts

$I_L$ = Fault current

$$\text{Rearranging and substituting for } I_L \text{ gives: } I_L = \frac{93 \bullet 10^6}{\sqrt{3} \bullet 11 \bullet 10^3} = 4881 \ Amp$$

For an X/R ratio of 8,

$$Source\ impedance = \frac{Vph}{I_L} \quad ohm \tag{6.2}$$

$$Source\ impedance = \frac{11000/\sqrt{3}}{4881 \angle tan^{-1} 8} \ ohm$$

$$= \frac{6350.85 \angle 0^\circ}{4881 \angle -82.87^\circ} \ ohm$$

$$= \ 0.1614 + j1.2911 \ ohm$$

The cable which supplies the transformer must of course be chosen on the basis of providing an adequate current and short circuit rating using the same approach as that discussed in Chapter Three.

The impedance of the cable chosen is:

| | | | |
|---|---|---|---|
| | 0.1620 | + | j0.0882 ohm/km |
| From which 320 metre is: | 0.05184 | + | j0.02822 ohm |

For this exercise the transformer impedance will be assumed to be a pure reactance. Then max fault level for 3 phase short-circuit on the secondary side of either transformer will be:

$$\frac{100}{\%\ Reactance} \bullet Transformer\ rating\ (MVA) \tag{6.3}$$

$$\frac{100}{6.5} \bullet 1.53 = 23.54 \ MVA$$

$$Equivalent\ impedance\ referred\ to\ primary = \frac{(Primary\ kV)^2}{Short\ circuit\ MVA} \qquad (6.4)$$

$$= \frac{11^2}{23.54} \quad ohms$$

$$= 5.1405 \quad ohms$$

Hence total circuit impedance = Z source + Z cable + Z transformer

= (0.1614 + j1.2911) + (0.05184 + j0.02822) + j5.1405

= 0.21324 + j 6.45982

= $6.46334\angle 88.109^\circ$ lag

From which the primary current for a three-phase short-circuit condition on the secondary side may be determined as follows:

$$Primary\ Isc = \frac{Vph}{Zph} = \frac{6350.98\ \angle 0^\circ}{6.46\angle\ 88.1^\circ} \quad Amp \qquad (6.5)$$

$$= 32.42 - j982.06$$

$$= 982.6\ \angle -88.1\ Amp$$

$$Equivalent\ secondary\ current = \frac{Vpri}{Vsec} \bullet 982.6 \quad Amp \qquad (6.6)$$

$$= \frac{11000}{665} \bullet 982.6$$

$$= 16253.46 \quad Amp$$

For a phase-phase short circuit on the secondary side of one transformer the fault current would be reduced by a factor of ($\sqrt{3}$)/2.

Hence LV. fault current for a phase-phase fault would be

$$= \frac{\sqrt{3}}{2} \bullet 16253.46 \quad Amps$$

$$= 14075.9 \qquad Amps$$

The concept of symmetrical components must be used to refer this fault current to the primary windings.

Resolving the secondary fault current into its symmetrical components where the initial conditions are:

$$V_b = V_c$$

$$I_c = -I_b$$

$$I_a = 0$$

Now

$$V_b = h^2 \bullet V_1 + h \bullet V_2 + V_o$$

$$V_c = h \bullet V_1 + h^2 \bullet V_2 + V_o$$

From initial conditions $V_b = V_c$

Then $$h^2 \bullet V_1 + h \bullet V_2 + V_o = h \bullet V_1 + h^2 \bullet V_2 + V_o \qquad (6.7)$$

$$V_1(h^2 - h) + V_2(h - h^2) = 0$$

$$-j\sqrt{3} \bullet V_1 + j\sqrt{3} \bullet V_2 = 0$$

from which $V_1 = V_2$

Now

$$I_a = I_{a1} + I_{a2} + I_{ao} = 0$$

$$I_{a1} = -I_{a2}$$

Since $I_{ao} = 0$ (No earth-fault current is present)

It therefore follows that:

$V_1 = E - I_{a1} \bullet Z_1$ where $Z_1$ = +ve phase sequence impedance and $V_2 = -I_{a2} \cdot Z_2$ $\quad Z_2$ = -ve phase sequence impedance

So $E - I_{a1} \cdot Z_1 = -I_{a2} \cdot Z_2$ $\quad E$ = driving voltage

$E = I_{a1} \cdot Z_1 - I_{a2} \cdot Z_2$

$E = I_{a1}(Z_1 + Z_2)$ $\quad$ because $I_{a1} = I_{a2}$

$$\text{From which} \quad I_{a1} = \frac{E}{Z_1 + Z_2} \tag{6.8}$$

similarly

$$I_{a2} = \frac{-E}{Z_1 + Z_2} \tag{6.9}$$

Now $I_b = h^2 \cdot I_{a1} + h \cdot I_{a2} + I_{ao}$ (6.10)

$= h^2 \cdot I_{a1} + h \cdot I_{a2}$ $\quad$ because $I_{ao} = 0$

$= I_{a1}(h^2 - h)$ $\quad$ because $I_{a1} = -I_{a2}$

$= \sqrt{3}|I_{a1}| = 14075.9$ Amp

In the case considered $Z_1 = Z_2$ as all components are static

Then $|I_{a1}| = |I_{a2}| = 14075.9/\sqrt{3} = 8126.7$ Amp

To refer the secondary positive and negative phase sequence currents to the primary we need to consider two cases:-

1. Primary: Extended Delta;Secondary Delta connected; phase shift + 7.5°
2. Primary: Extended Delta;Secondary Star connected; phase shift + 37.5°

### 6.2.1 The Transformer with 7.5° Overall Phase Shift

The phase sequence components observed on the Primary side

= Transformation ratio • Secondary side phase sequence components

Thus

$$I_{A1} = \frac{665}{11000} \cdot I_{a1} \tag{6.11}$$

$$I_{A1} = \frac{665}{11000} \bullet 8126.7\angle 0^\circ$$

As we are calculating current magnitudes only, 0° has been used for convenience

$$I_{A1} = 491.3\ \angle 0^\circ Amp$$

$$and\ \ I_{A2} = 491.3\angle 180^\circ\ Amp \qquad because\ I_{A2} = -I_{A1}$$

Recombination taking account of transformer phase shift gives: (6.12)

$$I_A = 491.3\angle 0^\circ \bullet 1\angle 7.5^\circ + 491.3\angle 180^\circ \bullet 1\angle -7.5^\circ + I_o$$

$$I_B = h^2 \bullet 491.3\angle 0^\circ \bullet 1\angle 7.5^\circ + h \bullet 491.3\angle 180^\circ \bullet 1\angle -7.5^\circ + I_o$$

$$I_C = h \bullet 491.3\angle 0^\circ \bullet 1\angle 7.5^\circ + h^2 \bullet 491.3\angle 180^\circ \bullet 1\angle -7.5^\circ + I_o$$

where $h = 1\angle 120^\circ$, $h^2 = 1\angle 240^\circ$ and $I_o = 0$

Simplifying gives

$$I_A = 491.3\angle 7.5^\circ + 491.3\angle 172.5^\circ$$

$$I_B = 491.3\angle 247.5^\circ + 491.3\angle 292.5^\circ$$

$$I_C = 491.3\angle 127.5^\circ + 491.3\angle 52.5^\circ$$

from which:

$$I_A = 128.26\angle 90^\circ\ \ Amp$$

$$I_B = 907.80\angle -90^\circ\ \ Amp$$

$$I_C = 779.55\angle 90^\circ\ \ Amp$$

which are the line currents and the currents in the extended delta winding on the primary side of the transformer.

Referring to Fig. 6.2, it can be seen that the phase currents in the delta winding satisfy the following equations:-

$$I_{AA'} = I_{A'B'} + I_{C'A'} = 128.26\angle 90° \quad (6.13)$$
$$I_{BB'} = I_{A'B'} - I_{B'C'} = -907.80\angle -90°$$
$$I_{CC'} = - I_{B'C'} + I_{C'A'} = 779.55\angle 90°$$

Solving the equation by means of the Generalised Matrix Inverse method produces currents of magnitude

$$I_{A'B'} = +345.4 \text{ Amp}$$
$$I_{B'C'} = -562.4 \text{ Amp}$$
$$I_{C'A'} = +217.2 \text{ Amp}$$

Current distribution in the secondary delta winding is straightforward and does not need to be calculated.

Referring to Fig. 6.2 it can be seen that for a delta secondary winding the current distribution will be in the ratio $\frac{2}{3}:\frac{1}{3}:\frac{1}{3}$

Hence for a phase-phase fault of magnitude 14075.9A
The currents through the limbs will be,

$$\tfrac{2}{3} \bullet 14075.9 = 9383 \text{ Amp} \quad (6.14)$$
$$\tfrac{1}{3} \bullet 14075.9 = 4691.97 \text{ Amp}$$
$$\tfrac{1}{3} \bullet 14075.9 = 4691.97 \text{ Amp}$$

The above exercise should be repeated, this time using the maximum source fault level likely to be encountered. The currents thus calculated represent the maximum possible currents to which the circuit may be subjected.

A third set of currents are determined based on the transformer alone being supplied from an infinite source. The currents calculated by this means are limited solely by the transformer impedance and are used as a control value from which the withstand time for identical faults of different current magnitude may be determined. The withstand time relationship is assumed to be adiabatic.

Table 6.1 lists all the currents calculated in the three conditions discussed above. Table 6.2 lists the withstand times for the current distributions listed in table 6.1.

### 6.2.2 The Transformer with 37.5° Overall Phase Shift

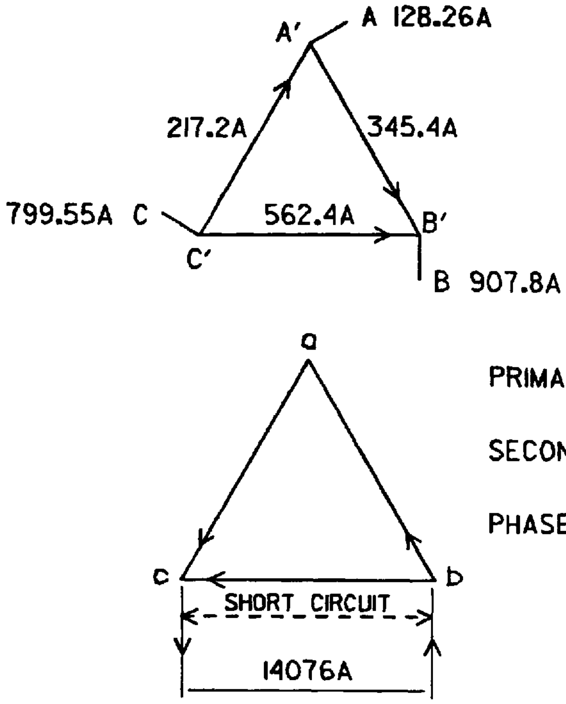
Primary Extended delta; Secondary Star connected; phase shift + 37.5°

The procedure adopted is essentially similar to that conducted in Case 1. The magnitude of the phase sequence components will be identical. The Primary winding positive and negative phase sequence components again being separated by 180° from each other in the case of a phase-phase fault on the secondary star winding.

In the case of a phase-phase fault on the secondary winding it can be seen that two limbs on the secondary winding carry the full fault current whilst the third limb carries no current. The LV current distribution is therefore 1:1:0.

It is not proposed to repeat the calculation for this winding but the exercise has been carried out and the values determined for the standard case are shown in Fig. 6.3. The complete listing of currents calculated for the standard case, the maximum and the infinite source fault level are listed in Table 6.3. The associated withstand times are shown in Table 6.4.

CURRENT DISTRIBUTION IN TRANSFORMER WINDINGS
FOR PHASE - PHASE FAULT ON SECONDARY TERMINALS

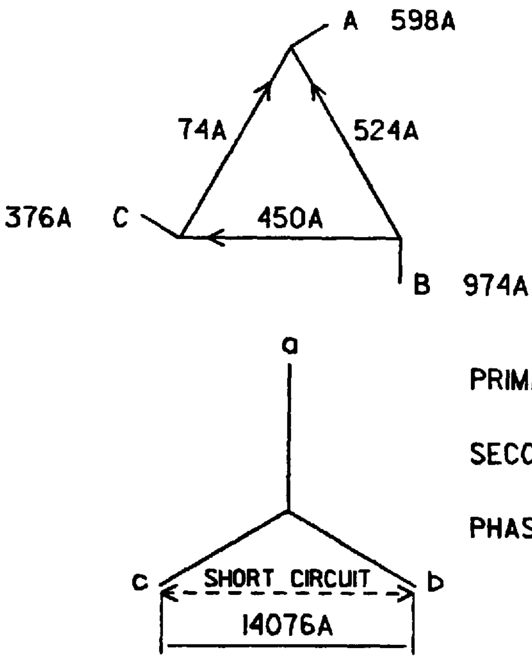



PRIMARY : EXTENDED DELTA

SECONDARY : DELTA

PHASE SHIFT : 7.5°

Fig 6.2




PRIMARY : EXTENDED DELTA

SECONDARY : STAR

PHASE SHIFT : 37.5°

Fig 6.3

**Current Distribution for 3-Phase and Phase-Phase Faults on the LV side of the Transformer with an Extended Star, Delta/Delta winding arrangement and Overall Phase Shift of +7.5°**

**TABLE 6.1(a)** **3-Phase Fault** **93 MVA Source**

| Fault Currents | HV Line Amps | LV Line Amps | HV Star Amps | HV Delta | | LV Delta | |
|---|---|---|---|---|---|---|---|
| | | | | Windings | Amp | Windings | Amp |
| A - Phase | 982 | 16253 | 982 | A'-B' | 567 | a-b | 9384 |
| B-Phase | 982 | 16253 | 982 | B'-C' | 567 | b-c | 9384 |
| C-Phase | 982 | 16253 | 982 | C'-A' | 567 | c-a | 9384 |

**TABLE 6.1(b)** **Phase-Phase Fault** **93 MVA Source**

| Fault Currents | HV Line Amps | LV Line Amps | HV Star Amps | HV Delta | | LV Delta | |
|---|---|---|---|---|---|---|---|
| | | | | Windings | Amp | Windings | Amp |
| A - Phase | 128 | 0 | 128 | A'-B' | 345 | a-b | 4692 |
| B-Phase | 908 | 14076 | 908 | B'-C' | 563 | b-c | 9384 |
| C-Phase | 779 | 14076 | 779 | C'-A' | 217 | c-a | 4692 |

**TABLE 6.1(c)** **3-Phase Fault** **25 kA Source**

| Fault Currents | HV Line Amps | LV Line Amps | HV Star Amps | HV Delta | | LV Delta | |
|---|---|---|---|---|---|---|---|
| | | | | Windings | Amp | Windings | Amp |
| A - Phase | 1171 | 19382 | 1171 | A'-B' | 676 | a-b | 11190 |
| B-Phase | 1171 | 19382 | 1171 | B'-C' | 676 | b-c | 11190 |
| C-Phase | 1171 | 19382 | 1171 | C'-A' | 676 | c-a | 11190 |

TABLE 6.1(d) Phase-Phase Fault 25 kA Source

| Fault Currents | HV Line Amps | LV Line Amps | HV Star Amps | HV Delta | | LV Delta | |
|---|---|---|---|---|---|---|---|
| | | | | Windings | Amp | Windings | Amp |
| A - Phase | 153 | 0 | 153 | A'-B' | 411 | a-b | 5595 |
| B-Phase | 1082 | 16786 | 1082 | B'-C' | 671 | b-c | 11190 |
| C-Phase | 929 | 16786 | 929 | C'-A' | 259 | c-a | 5595 |

TABLE 6.1(e) 3-Phase Fault Infinite Source

| Fault Currents | HV Line Amps | LV Line Amps | HV Star Amps | HV Delta | | LV Delta | |
|---|---|---|---|---|---|---|---|
| | | | | Windings | Amp | Windings | Amp |
| A - Phase | 1235 | 20442 | 1235 | A'-B' | 713 | a-b | 11801 |
| B-Phase | 1235 | 20442 | 1235 | B'-C' | 713 | b-c | 11801 |
| C-Phase | 1235 | 20442 | 1235 | C'-A' | 713 | c-a | 11801 |

TABLE 6.1(f) Phase-Phase Fault Infinite Source

| Fault Currents | HV Line Amps | LV Line Amps | HV Star Amps | HV Delta | | LV Delta | |
|---|---|---|---|---|---|---|---|
| | | | | Windings | Amp | Windings | Amp |
| A - Phase | 161 | 0 | 161 | A'-B' | 434 | a-b | 5901 |
| B-Phase | 1142 | 17703 | 1142 | B'-C' | 708 | b-c | 11801 |
| C-Phase | 979 | 17703 | 979 | C'-A' | 273 | c-a | 5901 |

**Winding Withstand Times for 3 Phase and Phase-Phase Faults on the LV side of the Transformer with an Extended Star, Delta/Delta winding arrangement and Overall Phase Shift of +7.5°**

**TABLE 6.2(a) 3-Phase Fault 93 MVA Source**

| HV Star | | HV Delta | | LV Delta | |
|---|---|---|---|---|---|
| Windings | Secs | Windings | Secs | Windings | Secs |
| A'-A' | 3.16 | A'-B' | 3.16 | a-n | 3.16 |
| B'-B' | 3.16 | B'-C' | 3.16 | b-n | 3.16 |
| C'-C' | 3.16 | C'-A' | 3.16 | c-n | 3.16 |

**TABLE 6.2(b) Phase-Phase Fault 93 MVA Source**

| HV Star | | HV Delta | | LV Delta | |
|---|---|---|---|---|---|
| Windings | Secs | Windings | Secs | Windings | Secs |
| A'-A' | 186.18 | A'-B' | 8.54 | a-n | 12.65 |
| B'-B' | 3.70 | B'-C' | 3.21 | b-n | 3.16 |
| C'-C' | 5.03 | C'-A' | 21.59 | c-n | 12.65 |

**TABLE 6.2(c) 3-Phase Fault 25 kA Source**

| HV Star | | HV Delta | | LV Delta | |
|---|---|---|---|---|---|
| Windings | Secs | Windings | Secs | Windings | Secs |
| A'-A' | 2.22 | A'-B' | 2.22 | a-n | 2.22 |
| B'-B' | 2.22 | B'-C' | 2.22 | b-n | 2.22 |
| C'-C' | 2.22 | C'-A' | 2.22 | c-n | 2.22 |

**TABLE 6.2(d) Phase-Phase Fault 25kA Source**

| HV Star | | HV Delta | | LV Delta | |
|---|---|---|---|---|---|
| Windings | Secs | Windings | Secs | Windings | Secs |
| A'-A' | 130.31 | A'-B' | 6.02 | a-n | 8.90 |
| B'-B' | 2.61 | B'-C' | 2.26 | b-n | 2.22 |
| C'-C' | 3.53 | C'-A' | 15.16 | c-n | 8.90 |

**TABLE 6.2(e) 3-Phase Fault Infinite Source**

| HV Star | | HV Delta | | LV Delta | |
|---|---|---|---|---|---|
| Windings | Secs | Windings | Secs | Windings | Secs |
| A'-A' | 2.00 | A'-B' | 2.00 | a-n | 2.00 |
| B'-B' | 2.00 | B'-C' | 2.00 | b-n | 2.00 |
| C'-C' | 2.00 | C'-A' | 2.00 | c-n | 2.00 |

**TABLE 6.2(f) Phase-Phase Fault Infinite Source**

| HV Star | | HV Delta | | LV Delta | |
|---|---|---|---|---|---|
| Windings | Secs | Windings | Secs | Windings | Secs |
| A'-A' | 117.68 | A'-B' | 5.40 | a-n | 8.00 |
| B'-B' | 2.34 | B'-C' | 2.03 | b-n | 2.00 |
| C'-C' | 3.18 | C'-A' | 13.64 | c-n | 8.00 |

**Current Distribution for 3-Phase and Phase-Phase Faults on the LV side of the Transformer with an Extended Star, Delta/Star, winding arrangement and Overall Phase Shift of +37.5°**

**TABLE 6.3(a)** **3-Phase Fault** **93 MVA Source**

| Fault Currents | HV Line Amps | LV Line Amps | HV Star Amps | HV Delta | | LV Star | |
|---|---|---|---|---|---|---|---|
| | | | | Windings | Amp | Windings | Amp |
| A - Phase | 982 | 16253 | 982 | A'-B' | 567 | a-n | 16253 |
| B-Phase | 982 | 16253 | 982 | B'-C' | 567 | b-n | 16253 |
| C-Phase | 982 | 16253 | 982 | C'-A' | 567 | c-n | 16253 |

**TABLE 6.3(b)** **Phase-Phase Fault** **93 MVA Source**

| Fault Currents | HV Line Amps | LV Line Amps | HV Star Amps | HV Delta | | LV Star | |
|---|---|---|---|---|---|---|---|
| | | | | Windings | Amp | Windings | Amp |
| A - Phase | 598 | 0 | 598 | A'-B' | 524 | a-n | 0 |
| B-Phase | 974 | 14076 | 974 | B'-C' | 450 | b-n | 14076 |
| C-Phase | 376 | 14076 | 376 | C'-A' | 74 | c-n | 14076 |

**TABLE 6.3(c)** **3-Phase Fault** **25 kA Source**

| Fault Currents | HV Line Amps | LV Line Amps | HV Star Amps | HV Delta | | LV Star | |
|---|---|---|---|---|---|---|---|
| | | | | Windings | Amp | Windings | Amp |
| A - Phase | 1171 | 19382 | 1171 | A'-B' | 676 | a-n | 19382 |
| B-Phase | 1171 | 19382 | 1171 | B'-C' | 676 | b-n | 19382 |
| C-Phase | 1171 | 19382 | 1171 | C'-A' | 676 | c-n | 19382 |

**TABLE 6.3(d) Phase-Phase Fault 25 kA Source**

| Fault Currents | HV Line Amps | LV Line Amps | HV Star Amps | HV Delta | | LV Star | |
|---|---|---|---|---|---|---|---|
| | | | | Windings | Amp | Windings | Amp |
| A - Phase | 713 | 0 | 713 | A'-B' | 625 | a-n | 0 |
| B-Phase | 1161 | 16786 | 1161 | B'-C' | 537 | b-n | 16786 |
| C-Phase | 448 | 16786 | 448 | C'-A' | 88 | c-n | 16786 |

**TABLE 6.3(e) 3-Phase Fault Infinite Source**

| Fault Currents | HV Line Amps | LV Line Amps | HV Star Amps | HV Delta | | LV Star | |
|---|---|---|---|---|---|---|---|
| | | | | Windings | Amp | Windings | Amp |
| A - Phase | 1235 | 20442 | 1235 | A'-B' | 713 | a-n | 20442 |
| B-Phase | 1235 | 20442 | 1235 | B'-C' | 713 | b-n | 20442 |
| C-Phase | 1235 | 20442 | 1235 | C'-A' | 713 | c-n | 20442 |

**TABLE 6.3(f) Phase-Phase Faults Infinite Source**

| Fault Currents | HV Line Amps | LV Line Amps | HV Star Amps | HV Delta | | LV Star | |
|---|---|---|---|---|---|---|---|
| | | | | Windings | Amp | Windings | Amp |
| A - Phase | 758 | 0 | 758 | A'-B' | 659 | a-n | 0 |
| B-Phase | 1225 | 17703 | 1225 | B'-C' | 566 | b-n | 17703 |
| C-Phase | 473 | 17703 | 473 | C'-A' | 93 | c-n | 17703 |

**Winding Withstand Times for 3 Phase and Phase-Phase Faults on the LV side of the Transformer with an Extended Star, Delta/Star winding arrangement and Overall Phase Shift of +37.5°**

**TABLE 6.4(a)** **3-Phase Fault** **93 MVA Source**

| HV Star | | HV Delta | | LV Star | |
|---|---|---|---|---|---|
| Windings | Secs | Windings | Secs | Windings | Secs |
| A'-A' | 3.16 | A'-B' | 3.16 | a-n | 3.16 |
| B'-B' | 3.16 | B'-C' | 3.16 | b-n | 3.16 |
| C'-C' | 3.16 | C'-A' | 3.16 | c-n | 3.16 |

**TABLE 6.4(b)** **Phase-Phase Fault** **93 MVA Source**

| HV Star | | HV Delta | | LV Star | |
|---|---|---|---|---|---|
| Windings | Secs | Windings | Secs | Windings | Secs |
| A'-A' | 8.53 | A'-B' | 3.70 | a-n | Inf. |
| B'-B' | 3.22 | B'-C' | 5.02 | b-n | 4.22 |
| C'-C' | 21.58 | C'-A' | 185.67 | c-n | 4.22 |

**TABLE 6.4(c)** **3-Phase Fault** **25 kA Source**

| HV Star | | HV Delta | | LV Star | |
|---|---|---|---|---|---|
| Windings | Secs | Windings | Secs | Windings | Secs |
| A'-A' | 2.22 | A'-B' | 2.22 | a-n | 2.22 |
| B'-B' | 2.22 | B'-C' | 2.22 | b-n | 2.22 |
| C'-C' | 2.22 | C'-A' | 2.22 | c-n | 2.22 |

**TABLE 6.4(d)** **Phase-Phase Fault** **25 kA Source**

| HV Star | | HV Delta | | LV Star | |
|---|---|---|---|---|---|
| Windings | Secs | Windings | Secs | Windings | Secs |
| A'-A' | 6.00 | A'-B' | 2.60 | a-n | Inf. |
| B'-B' | 2.26 | B'-C' | 3.53 | b-n | 2.97 |
| C'-C' | 15.20 | C'-A' | 131.29 | c-n | 2.97 |

**TABLE 6.4(e)** **3-Phase Fault** **Infinite Source**

| HV Star | | HV Delta | | LV Star | |
|---|---|---|---|---|---|
| Windings | Secs | Windings | Secs | Windings | Secs |
| A'-A' | 2.00 | A'-B' | 2.00 | a-n | 2.00 |
| B'-B' | 2.00 | B'-C' | 2.00 | b-n | 2.00 |
| C'-C' | 2.00 | C'-A' | 2.00 | c-n | 2.00 |

**TABLE 6.4(f)** **Phase-Phase Fault** **Infinite Source**

| HV Star | | HV Delta | | LV Star | |
|---|---|---|---|---|---|
| Windings | Secs | Windings | Secs | Windings | Secs |
| A'-A' | 5.31 | A'-B' | 2.34 | a-n | Inf. |
| B'-B' | 2.03 | B'-C' | 3.17 | b-n | 2.67 |
| C'-C' | 13.63 | C'-A' | 117.56 | c-n | 2.67 |

## 6.3 Case Study 2 - The Algorithmic Approach Applied to a Multi Transformer Circuit

The second case discussed is shown in Fig. 6.4. The text is intended to illustrate the method applied to three transformers supplied through a single circuit breaker and cable. The final settings applied to the overcurrent and earth fault time lag and instantaneous elements are required to provide common protection for all circuit components under both phase-phase and three phase fault conditions. The transformers used are of either delta-star or delta-delta winding configurations for which winding fault current distribution can be readily predicted. However, as the transformer current distribution analysis section of the program is of a generalised nature, the procedure adopted is as previously discussed in Case Study 1. The complete program which includes the calculation of settings for the overcurrent and earth fault elements is included in this section of the work.

Options are provided for circuit protection using either two or three time delayed and instantaneous overcurrent elements. The program allows the setting for the selected elements to be calculated using any one of seven different time characteristics. An identical set of options is available for determining the limiting values of earth fault setting.

### 6.3.1 The Temper Mill Application

Consider the supply requirements of a three unit coil temper mill comprising an Uncoiler, Mill and Recoiler section each driven by a dc. motor supplied via thyristor convertors. Each convertor arrangement is supplied at 660V from two, 11000/660V three-phase transformers mounted in a common oil tank and configured as shown in Fig. 6.4. In the case considered it is intended to supply all three transformers from one 11kV circuit breaker. The maximum source

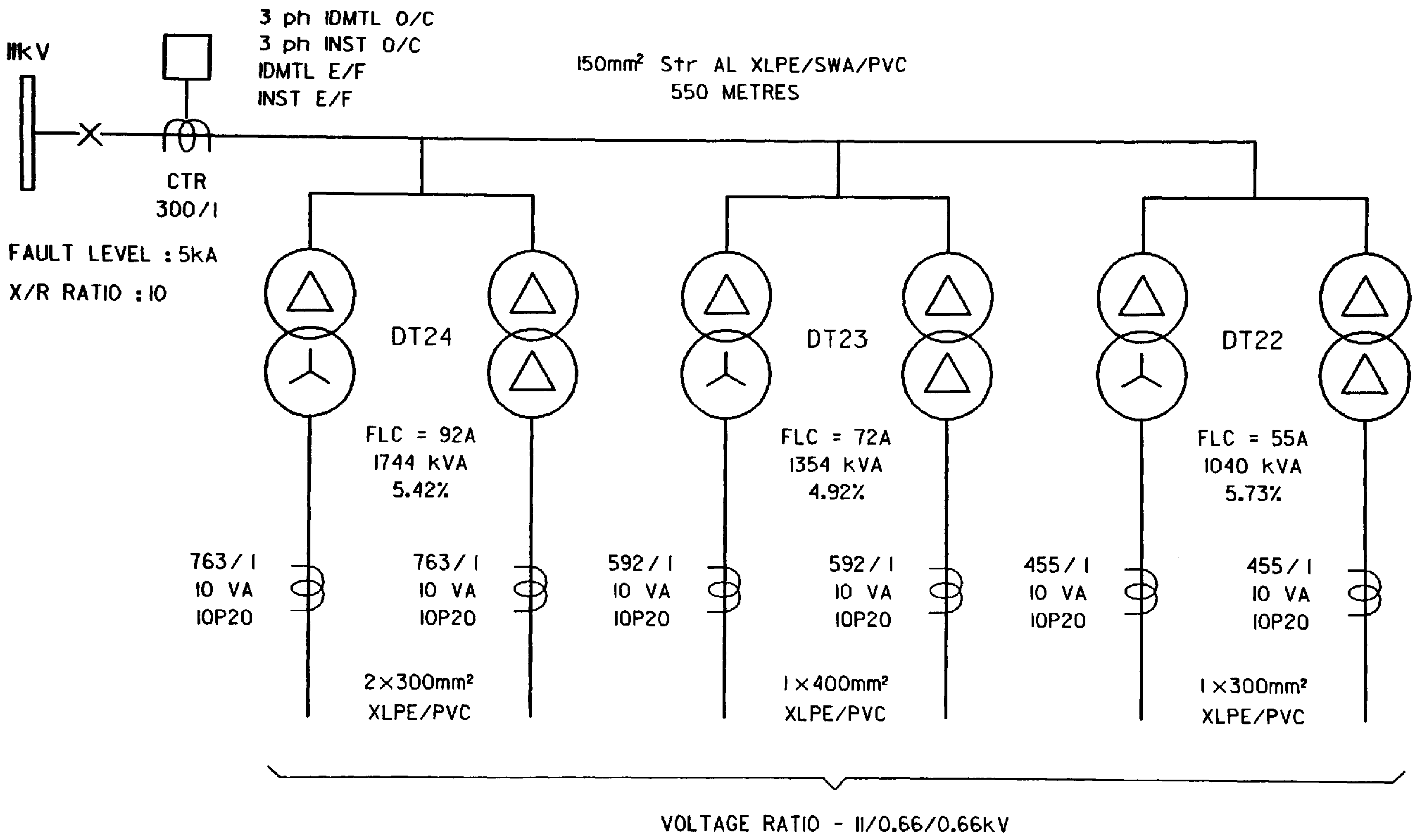



Fig 6.4 COIL TEMPER MILL TRANSFORMER SUPPLIES

impedance of the supply being sufficient to provide a fault level of 5kA with an X/R ratio of 10. Clearly the source impedance will vary with switching conditions and may well reduce in the future with the addition of new supply sources. Under such circumstances prudence suggests that the exercise is also conducted at the maximum rating of the switchgear which in this case is 25 kA. Under normal running conditions the full load current of the mill is 110A which is less than the sum of the full load currents of the individual transformers. Prior to selecting the 11kV supply cable, it is necessary to specify the type of circuit breaking device which is intended to be used. The two options considered are a fully rated circuit breaker or, alternatively, a fused contactor. In this case study the preferred choice is the circuit breaker. As a consequence, the cable used must be capable of carrying the full fault current without damage for the period required to detect and clear the fault. This time will of course be measured in milliseconds as the protection will be provided by an instantaneous type element. The protection relay used in this instance is supplied by GEC ALSTHOM and is electronic in nature. The type MCGG relay is offered in a variety of element combinations, the model selected for this exercise being the MCGG82. This relay offers three-phase IDMTL/DTL overcurrent, instantaneous overcurrent, IDMTL/DTL earth-fault and instantaneous earth-fault protection. This comprehensive selection of elements offers considerable application flexibility as a variety of IDMTL/DTL characteristics may be selected by means of slide switches mounted on the faceplate. The characteristics offered are in accordance with those specified in BS142 and are as follows:-

The four IDMTL (Inverse Definite Minimum time lag) characteristics are

(a) Standard Inverse

(b) Very Inverse

(c) Extremely Inverse

(d) Long time Inverse

Whereas the three DTL (Definite time lag) characteristics are:

(a) 2 sec

(b) 4 sec

(c) 8 sec

As stated earlier it is necessary to select an 11kV supply cable which satisfies the conditions generally outlined. The type of cable favoured by the writer and used in this text is of three core construction, utilising stranded aluminium conductors. The insulation media being XLPE with single wire armouring contained within a pvc oversheath. Aluminium conductors have been specified in preference to copper on the basis that it effectively eliminates cable thefts. In the selection program the entire range of cable CSA's (cross-sectional area) are displayed together with symbols which are indicative of their suitability. The checks carried out are:

| | | |
|---|---|---|
| 1. | Circuit full load current | < cable rating (a) air (b) duct (c) ground |
| 2. | Fault current rating (200m sec) | > cable short circuit withstand |
| 3. | Earth fault current rating (200m sec) | > cable armour fault withstand |
| 4. | Percentage volt drop | < 2½% |

From the displayed list a cable of $150mm^2$ is chosen as it is the smallest size which satisfies the above criteria. The program accesses the datafile from which values of R (Resistance) and $X_L$ (Inductive reactance) are obtained for the required length of 550 metres.

The values are:

$$R_{CABLE} = 0.145\ \Omega$$

$$X_{CABLE} = 0.053\ \Omega$$

### 6.3.2 Determining the Thermal Withstand of Circuit Components

If we consider a three-phase fault on one of the secondary windings of the 1040 kVA transformer (2 • 520 kVA) then:

Circuit Impedance = Source Z + HV cable Z + Transformer Z

Now minimum source fault level is 5kA with an X/R ratio of 10 from which:

$$Source\,Impedance\,Z = \frac{Vph}{Iph} = \frac{11000}{\sqrt{3} \bullet 5000} = 1.2702\,\Omega \qquad (6.15)$$

$$R\,source = \sqrt{\left(\frac{Z^2}{1+(\frac{X}{R})^2}\right)} = \sqrt{\left(\frac{1.2702^2}{1+10^2}\right)} = 0.12639\,\Omega \qquad (6.16)$$

and

$$X\,source = \sqrt{\left(\frac{Z^2}{1+(\frac{R}{X})^2}\right)} = \sqrt{\left(\frac{1.2702^2}{1+(0.1)^2}\right)} = 1.26387\,\Omega \qquad (6.17)$$

The equivalent HV impedance of the transformer (considered as a reactance only in this case) may be determined from

$$X\,transformer = \frac{V^2 \bullet \%X}{10^5 \bullet kVA} = \frac{(11000)^2 \bullet 5.73}{10^5 \bullet 520} = 13.33327\,\Omega \qquad (6.18)$$

$$X = j\,13.33327\,\Omega$$

| | | | |
|---|---|---|---|
| Hence total circuit | Resistance | = | 0.12639 + 0.145 Ω |
| and | Reactance | = | 1.26387 + 0.053 + 13.33327 Ω |
| | Impedance | = | 0.27139 + 14.65014 Ω |
| | | = | 14.65265∠ 88.9° Ω |

from which HV short circuit current Isc may be determined

$$Isc = \frac{Vph}{Zph} = \frac{11000}{\sqrt{3} \bullet 14.65265} = 433.4\,Amp \quad \textbf{(6.19)}$$

or referred to the LV side

$$433 \bullet \frac{11000}{660} = 7223.78\,Amp \quad \textbf{(6.20)}$$

Consider a phase-phase short-circuit on the LV side then

*Referring the circuit impedance to the LV side* (660 V)

$$Z = 14.65265 \bullet \left(\frac{660}{11000}\right)^2 = 0.05275\,\Omega \quad \textbf{(6.21)}$$

$$Isc = \frac{V}{Z} = \frac{660}{2 \bullet 0.05275} = 6256\,Amp$$

$$= \frac{\sqrt{3}}{2} \bullet \textit{Symmetrical three phase condition}\ (7223A)$$

Consider the delta/delta winding of the transformer (0° Phase shift).

Because all components are static and the transformer phase shift is 0°

The PPS impedance is equal to NPS impedance

Similarly

The magnitude of PPS current ($I_1$) is equal to the magnitude of NPS current ($I_2$)

$$|I1| = |I2| = \frac{6256}{\sqrt{3}} = 3612\ Amp \quad \textbf{(6.23)}$$

As current only is being monitored

Let $Ia_1$ = $3612 \angle 0°$ Amp

and $Ia_2$ = $3612 \angle 180°$ Amp

Hence currents observed on HV side = Transformation ratio • LV currents

$$I_{A1} = \frac{660}{11000} \bullet 3612\angle 0° = 217\angle 0°\ Amp \qquad (6.24)$$

$$I_{A2} = \frac{660}{11000} \bullet 3612\angle 180° = 217\angle 180°\ Amp \qquad (6.25)$$

Recombining gives

$$\begin{aligned} I_A &= 217\angle 0° + 217\angle 180° + I_o \qquad (6.26) \\ I_B &= h^2(217\angle 0°) + h(217\angle 180°) + I_o \\ I_C &= h(217\angle 0°) + h^2(217\angle 180°) + I_o \end{aligned}$$

from which

$$\begin{aligned} I_A &= 0 \qquad (6.27) \\ I_B &= (h^2 - h)\,217\angle 0° \qquad \text{Since } I_1 = -I_2 \\ &= \sqrt{3} \bullet 217\ \angle -90° \qquad \text{Amp} \\ I_C &= (h - h^2)\,217\angle 0° \\ &= \sqrt{3} \bullet 217\ \angle +90° \qquad \text{Amp} \\ I_A &= 0\ \ |I_B| = |I_C| = 376 \qquad \text{Amp} \end{aligned}$$

Next consider the Delta/Star winding of the transformer which has a +30° Phase Shift

Currents observed on HT side

= Transformation Ratio • LV Currents • Phase Shift

$$I_{A1} = \frac{660}{11000} \bullet 3612\angle 0° \bullet 1\angle 30° = 217\angle 30°\ Amp \qquad (6.28)$$

$$I_{A2} = \frac{660}{11000} \bullet 3612\angle 180° \bullet 1\angle -30° = 217\angle 150°\ Amp \qquad (6.29)$$

Recombining gives

$$I_A = 217\angle 30^\circ + 217\angle 150^\circ + I_o \qquad (6.30)$$

$$I_B = h^2(217\angle 30^\circ) + h(217\angle 150^\circ) + I_o$$

$$I_C = h(217\angle 30^\circ) + h^2(217\angle 150^\circ) + I_o$$

from which

$$I_A = 217\angle 30^\circ + 217\angle 150^\circ = 217\angle 90^\circ \text{ Amp} \qquad (6.31)$$

$$I_B = 217\angle 270^\circ + 217\angle 270^\circ = 434\angle 270^\circ \text{ Amp}$$

$$I_C = 217\angle 150^\circ + 217\angle 30^\circ = 217\angle 90^\circ \text{ Amp}$$

That is: $I_A = I_C = 217$ Amp; $I_B = 434$ Amp

The current distribution within the primary and secondary windings of both delta/delta and delta/star wound transformers are summarised in Figs. 6.5 and 6.6.

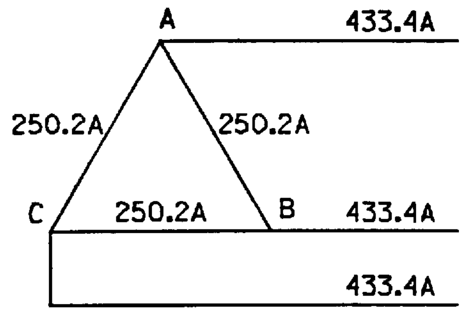
The primary line currents are of course, identical with those calculated in the program and are listed as the fault currents for transformers TX1 and TX2 under the minimum source fault current conditions.

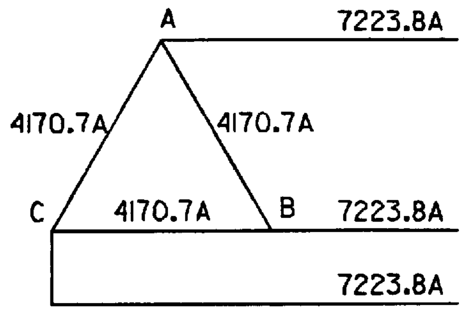
Similar calculations conducted for the other transformers in the system produce the results which are summarised in the display shown in Fig. 6.7. The procedure is again repeated for the condition where maximum source fault current exists, the results obtained from this exercise are also included in the display.

Under three-phase short-circuit conditions, the withstand time of the transformers are considered to be two seconds in accordance with the category 2 rating detailed in BS171, 1970. For phase-phase faults on a transformer of vector group DDO, the LV line fault current is lower than the three phase fault current

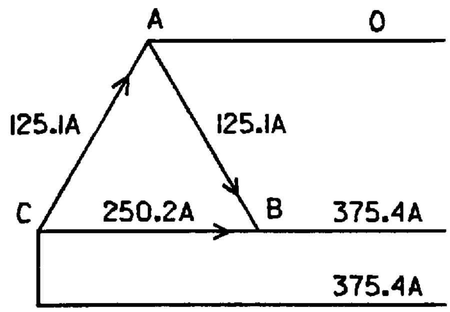
## CURRENT DISTRIBUTION IN TRANSFORMER WINDINGS

### (I) FOR 3 - PHASE FAULT ON SECONDARY TERMINALS




### (II) FOR PHASE - PHASE FAULT ON SECONDARY TERMINALS



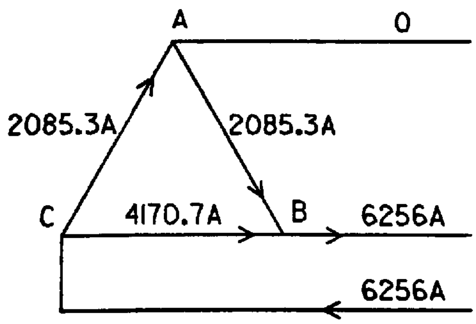
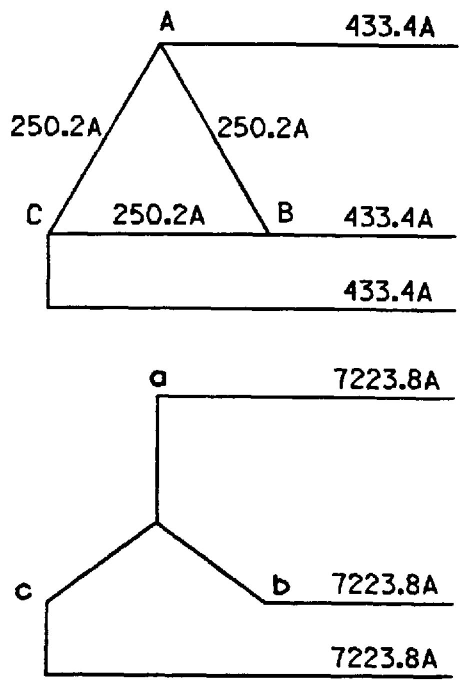




Fig 6.5

# CURRENT DISTRIBUTION IN TRANSFORMER WINDINGS

## (I) FOR 3 - PHASE FAULT ON SECONDARY TERMINALS




## (II) FOR PHASE - PHASE FAULT ON SECONDARY TERMINALS

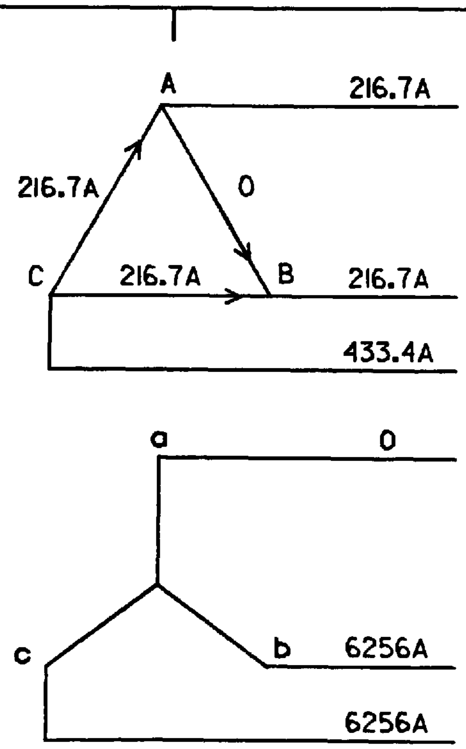



Fig 6.6

| VARIABLE SPEED DRIVE TRANSFORMER PROTECTION FAULT CONDITIONS | | | | | | |
|---|---|---|---|---|---|---|
| FAULT LOCATION | MINIMUM | | | MAXIMUM | | |
| | PH-E | PH-PH | 3-PH | PH-E | PH-PH | 3-PH |
| Source | 1000 | 4330 | 5000 | 5000 | 21650 | 25000 |
| Transformer HV Term' HV Amps | 984 | 4135 | 4775 | 4630 | 17066 | 19707 |
| | PH-PH | | | PH-PH | | |
| TX1 P/SHFT + 0.0 LV Term' HV Amps | 375 | 375 | 433 | 403 | 403 | 465 |
| TX2 P/SHFT +30.0 LV Term' HV Amps | 433 | 216 | 433 | 465 | 232 | 465 |
| TX3 P/SHFT + 0.0 LV Term' HV Amps | 544 | 544 | 628 | 604 | 604 | 698 |
| TX4 P/SHFT +30.0 LV Term' HV Amps | 628 | 314 | 628 | 698 | 349 | 698 |
| TX5 P/SHFT + 0.0 LV Term' HV Amps | 622 | 622 | 718 | 703 | 703 | 811 |
| TX6 P/SHFT +30.0 LV Term' HV Amps | 718 | 359 | 718 | 811 | 405 | 811 |
| Select option P | | | | <P>ageback<br><Q>uit | | |

*Fig 6.7 Fault currents observed at the relays for phase - phase and 3 - phase fault conditions on each transformer.*

by a factor of $\sqrt{3}/2$ but does not permit the withstand time to be extended on adiabatic basis. Additional extensions to withstand time result from the reduction in fault current due to source and cable impedance.

As the transformers are of different kVA and impedance ratings, it is necessary to examine each unit individually as the current attenuation provided by the cable and source impedance vary in each case.

In the case of the 1040 kVA transformer previously referred to, the transformer comprises two, 520 kVA, two winding transformers with secondary windings phase displaced by 30°.

In both cases the maximum potential three-phase short circuit kVA and current when supplied from an infinite source is identical. It may be calculated as follows:

$$\text{three phase short-circuit } kVA = \frac{100}{\%Z} \bullet kVA\ Rating \tag{6.32}$$

$$= \frac{100}{5.73} \bullet 520$$

$$= 9075\ kVA$$

which expressed in terms of primary line current

$$= \frac{9075 \bullet 10^3}{\sqrt{3} \bullet 11 \bullet 10^3} \tag{6.33}$$

$$= 476.32\ Amp$$

and secondary line current

$$= 476.32 \bullet \frac{11000}{660} \tag{6.34}$$

$$= 7938.67\ Amp$$

Consider the delta/delta transformer

| | | | | |
|---|---|---|---|---|
| Primary phase current | = | Line current $/\sqrt{3}$ | | (6.35) |
| | = | $476.32 / \sqrt{3}$ | Amp | |
| | = | 275 | Amp | |
| | | | | |
| From which primary withstand per phase | = | $I \bullet I \bullet t$ | | (6.36) |
| | = | 275.275.2 | | |
| | = | 151253 $A^2$ secs | | |
| Similarly secondary withstand per phase | = | $(7938 / \sqrt{3})^2 \bullet 2$ | | |
| | = | 42014988 $A^2$ secs | | |

Referring to Fig. 6.5 it can be seen that for the 5kA source condition

(i) 3-phase withstand for the primary side

= $151253 / (250.2)^2$

= 2.42 secs

(ii) 3-phase withstand for the secondary side

= $42014988 / (4170.7)^2$

= 2.42 secs (included for completeness)

(iii) Primary side withstand for LV phase-phase fault

= $151253 / (250.2)^2$ (Phases B-C carry 250.2 Amp)

= 2.42 secs

(iv) Secondary side withstand for LV phase-phase fault

= $42014988 / (4170.7)^2$ (Phases b-c carry 4170.7 Amp)

= 2.42 secs

Hence both phase-phase and 3-phase faults must be detected and cleared in less than 2.42 seconds to prevent damage by local overheating.

Consider the delta/star transformer

| | | |
|---|---|---|
| Primary phase current | = 275 Amp | (identical to delta/delta case) |
| Primary withstand per phase | = 151253 $A^2$ secs | (identical to delta/delta case) |
| Secondary phase current | = Secondary line current | |
| | = 7938 Amp | |

Hence secondary withstand per phase = $(7938)^2 \bullet 2$

= 126044963 $A^2$ secs

Referring to Fig. 6.6 it can be seen that for the 5kA source condition

(i) 3-phase withstand for the Primary Side

= 2.42 secs

(ii) 3-phase withstand for the Secondary Side

= 126044963 / $(7223.8)^2$

= 2.42 secs

(iii) Primary side withstand for LV phase-phase fault

= 151253 / $(216.7)^2$

= 3.22 secs

(iv) Secondary side withstand for LV phase-phase fault

= 126044963 / $(6256)^2$

= 3.22 secs

Hence to prevent the possibility of overheating either transformer under fault conditions the relay must be able to detect a primary line current of 375.4 Amp and disconnect the circuit in less than 2.42 secs.

Where only two overcurrent relays are utilised the requirement is more onerous as it is necessary to ensure the relay setting will detect primary currents of 216.7 Amps yet still provide disconnection in 2.42 seconds. All six transformers must be examined of course and their individual withstand times must be determined.

It is not proposed to repeat the calculations for the remaining two pairs of transformers because they have identical vector group arrangements to the two units already discussed and are treated in a similar fashion. Table 6.5 lists the calculated fault currents when supplied from a source of maximum impedance (5kA-Fault level) and is accompanied by the thermal withstand time for each condition and transformer. Table 6.6 provides a further set of values for the arrangement when supplied from a source at minimum impedance (25kA - Fault level).

Having determined the transformer withstand times for each case, it is necessary to ensure that the HV cable is also adequately rated for the longer withstand period at these reduced current ratings in order to ensure that protection can be afforded by the proposed overcurrent relays. In the interests of economy it is sometimes possible to use overcurrent relays which monitor two out of three phases only at the HV switchgear. This approach which was referred to earlier in the text is ideal for all three-phase faults and phase-phase faults on transformers with 0° phase shift. However, caution must be exercised when considering the DY1 unit referred to above where the transformer withstand has been determined on the basis of maximum three-phase short-circuit current being carried in one phase only whilst the two overcurrent elements may be monitoring the other two phases which will carry only 50% of this value. It may of course be possible to accommodate this problem by means of reduced settings which will result in accelerated tripping times for all other fault conditions and a reduction in available time for overload constraints. A practical example is discussed later in the text. A total of seven overcurrent characteristics may be selected for the relay which make the unit extremely flexible and versatile but at the same time producing much work if the full potential of the device is to be explored.

## 6.4 Determining the Relay Current and Time Multiplier Setting

### 6.4.1 IDMTL Overcurrent Strategy

The approach used to overcome the problem is to begin by setting the current setting multiplier (CSM) to the minimum value greater than full load current. In this case the full load current is 110A and the CT ratio 300/1 hence an initial CSM starting value of 110/300 = 0.367 is suggested, the nearest value of 0.40 being applied. The strategy adopted to determine the time multiplier setting (TMS) is to examine the fault currents associated with each set of windings for the three transformers under both minimum and maximum source impedance conditions. For each IDMTL case considered the operating time of the element is calculated using the equation

$$t = \frac{A}{\left(\frac{fault\ current}{CSM \bullet CT\ ratio}\right)^{B} - 1}\ Secs\ (subject\ to\ tolerances) \qquad (6.37)$$

The resulting TMS being determined by:

$$TMS = \frac{Withstand\ time\ of\ transformer\ for\ the\ condition\ considered - e1}{Operating\ time\ of\ the\ overcurrent\ element \bullet e2} \qquad (6.38)$$

where

e1 = Relay overshoot time + CB clearance time + MTR operating time

| | | |
|---|---|---|
| Typical maximum values of which are | Overshoot time | 30m secs |
| | CB clearance time (vacuum) | 48m secs |
| | MTR operating time | 10m secs |

e2 = Relay characteristic timing errors

| | |
|---|---|
| which are for Standard Inverse | ± 5% |
| Very Inverse | ± 5% |
| Extremely Inverse | ± 7½% |
| Long Time Inverse | ± 5% |

The resulting TMS value being rounded down to the nearest discrete setting.

Consider the 1040kVA Transformer.

The transformer comprises two, 520 kVA transformers which are identified as TX1 and TX2 in Tables 6.5 and 6.6. The tables summarise the calculated fault current and associated thermal withstand times for phase-phase and three-phase faults on the transformer LV terminals for both maximum and minimum source impedance conditions.

Using Table 6.5, it can be seen that for transformer TX1, the current detected by the overcurrent element is 433 Amps for the three-phase LV fault condition. The associated thermal withstand time is recorded as 2.42 seconds.

Consider the standard inverse overcurrent element.

Operating time of the element is of the form stated in equation (6.37)

| | | | |
|---|---|---|---|
| where | A | = | 0.14 |
| | B | = | 0.02 |
| | CSM | = | 0.40 |
| | CT Ratio | = | 300 / (1) |

| Fault Location | | Maximum Source Impedance | | | | |
|---|---|---|---|---|---|---|
| | | Phase-Phase Amps (1) | Phase-Phase Amps (2) | Withstand Secs | Three-phase Amps | Withstand Secs |
| TX1 PHASE-SHIFT + 0.0 LV Terminals | HV Amps | 375 | 375 | 2.42 | 433 | 2.42 |
| TX2 PHASE-SHIFT + 30.0 LV Terminals | HV Amps | 433 | 216 | 3.22 | 433 | 2.42 |
| TX3 PHASE-SHIFT + 0.0 LV Terminals | HV Amps | 476 | 476 | 3.46 | 549 | 3.46 |
| TX4 PHASE-SHIFT + 30.0 LV Terminals | HV Amps | 549 | 274 | 4.61 | 549 | 3.46 |
| TX5 PHASE-SHIFT + 0.0 LV Terminals | HV Amps | 622 | 622 | 2.77 | 718 | 2.77 |
| TX6 PHASE-SHIFT + 30.0 LV Terminals | HV Amps | 718 | 359 | 3.69 | 718 | 2.77 |

1. Definite over current observed when three overcurrent elements are used
2. Possible over current observed when two overcurrent elements are used

**FAULT CURRENTS AND THERMAL WITHSTAND TIMES FOR PHASE-PHASE AND THREE-PHASE LV FAULTS WHEN SUPPLIED FROM A 5kA FAULT LEVEL SOURCE**

**TABLE 6.5**

| Fault Location | | Minimum Source Impedance | | | | |
|---|---|---|---|---|---|---|
| | | Phase-Phase Amps (1) | Phase-Phase Amps (2) | Withstand Secs | Three-phase Amps | Withstand Secs |
| TX1 PHASE-SHIFT + 0.0 LV Terminals | HV Amps | 403 | 403 | 2.10 | 465 | 2.10 |
| TX2 PHASE-SHIFT + 30.0 LV Terminals | HV Amps | 465 | 232 | 2.80 | 465 | 2.10 |
| TX3 PHASE-SHIFT + 0.0 LV Terminals | HV Amps | 521 | 521 | 2.88 | 602 | 2.88 |
| TX4 PHASE-SHIFT + 30.0 LV Terminals | HV Amps | 602 | 301 | 3.84 | 602 | 2.88 |
| TX5 PHASE-SHIFT + 0.0 LV Terminals | HV Amps | 703 | 703 | 2.17 | 811 | 2.17 |
| TX6 PHASE-SHIFT + 30.0 LV Terminals | HV Amps | 811 | 405 | 2.89 | 811 | 2.17 |

1. Definite over current observed when three overcurrent elements are used
2. Possible over current observed when two overcurrent elements are used

**FAULT CURRENTS AND THERMAL WITHSTAND TIMES FOR PHASE-PHASE AND THREE-PHASE LV FAULTS WHEN SUPPLIED FROM A 25kA FAULT LEVEL SOURCE**

**TABLE 6.6**

Substituting in equation (6.37) for a TMS value of 1.0, the operating time of the element may be calculated as:

$$t = \frac{0.14}{\left(\frac{433}{0.40 \bullet 300}\right)^{0.02} - 1} \quad secs$$

$$= 5.385 \text{ secs}$$

Then for a CSM setting of 0.40, the maximum possible TMS setting for the condition may be determined by substitution in equation (6.38).

| | | |
|---|---|---|
| where: | Transformer thermal withstand time | 2.420 secs |
| | Circuit breaker clearing time | 0.048 secs |
| | Master tripping relay operating time | 0.010 secs |
| | Relay overshoot time | 0.030 secs |
| | Overcurrent relay timing error | ± 5% |

$$Then\ TMS = \frac{2.420 - 0.048 - 0.010 - 0.030}{5.385 \bullet 1.05}$$

$$= 0.4125$$

For which the nearest selectable value is 0.400.

Referring again to Table 6.5 it can be seen that for an LV phase-phase fault, the current detected by the primary side overcurrent elements is 375 Amp. The transformer withstand time is however, still 2.42 seconds as the winding current distribution will be as shown in Fig. 6.4. Hence the TMS setting must be further reduced.

Substituting in equation (6.37) to determine the operating time at a TMS setting of 1.0 gives:

$$t = \frac{0.14}{\left(\frac{375}{0.40 \bullet 300}\right)^{0.02} - 1}$$

$$= 6.074 \text{ secs}$$

Then using equation (6.38) required TMS setting is:

$$TMS = \frac{2.420 - 0.048 - 0.010 - 0.030}{6.074 \bullet 1.05}$$

$$= 0.366 \text{ secs}$$

for which the nearest setting is 0.350

Referring to transformer TX2, it can be seen from Table 6.5 that the conditions presented to the relay for a three-phase transformer LV fault are identical to that previously calculated for TX1. Hence the condition is satisfied by the TMS value previously determined.

In the case of a phase-phase fault on the LV terminals, when the transformer is supplied from a maximum source impedance, the maximum fault current observed by a primary side overcurrent element is again 433 Amps coupled with a less onerous withstand value of 3.22 seconds. Hence the condition is adequately protected. As previously stated, it is not unusual to install only two primary side overcurrent elements. Under these circumstances it can be seen that there can be no guarantee that a phase-phase fault at the LV terminals will produce 433 Amp in a monitored primary side phase. The possibility therefore exists, for this transformer, that the monitored HV fault current may be only 50% of this value. Substituting this reduced fault current value in equation (6.37) produces the following operating time

$$t = \frac{0.14}{\left(\frac{216.5}{0.40 \bullet 300}\right)^{0.02} - 1}$$

$$= 11.794 \text{ secs}$$

Then required TMS will be:

$$TMS = \frac{3.22 - 0.048 - 0.010 - 0.050}{11.794 \bullet 1.05}$$

$$= 0.253$$

For which the nearest setting is 0.250.

This setting whilst being perfectly adequate will produce severe limitations for any overload constraints that can be accommodated.

Each transformer winding is examined in turn until a sufficiently low TSM value is found which satisfies the withstand times of all units for both phase-phase and three-phase faults. A complete list of the TMS values determined using the method outlined is contained in Table 6.7.

**Table 6.7**
**Calculated Maximum Time Multipliers with a csm setting of 0.40 under listed conditions using 3 overcurrent elements for transformers 1-6**

| Condition | TX1 | TX2 | TX3 | TX4 | TX5 | TX6 |
|---|---|---|---|---|---|---|
| Min 1 | 0.366 | 0.551 | 0.530 | 0.783 | 0.604 | 0.886 |
| Min 2 | 0.4125 | 0.4125 | 0.581 | 0.581 | 0.658 | 0.658 |
| Max 1 | 0.331 | 0.501 | 0.455 | 0.670 | 0.504 | 0.658 |
| Max 2 | 0.371 | 0.371 | 0.496 | 0.496 | 0.545 | 0.545 |

Where :

Min 1 : Minimum Source Impedance - LV phase-phase fault

Min 2 : Minimum Source Impedance - LV 3-phase fault

Max 1 : Maximum Source Impedance - LV phase-phase fault

Max 2 : Maximum Source Impedance - LV 3-phase fault

TX1-6 : Transformers 1 to 6

At this juncture with the CSM and TMS settings for the transformers now established, it is necessary to consider any constraints which may apply. The relay operating time may now be determined by modifying equation (6.37).

Hence operating time

$$t = \frac{A \bullet TMS}{\left( \frac{fault\, current}{CSM \bullet CT\, Ratio} \right)^{B} - 1} \tag{6.39}$$

In practice, the circuit is driven into the overload state for short periods by design. It is therefore necessary to ensure that the duration of the overload excursions can be accommodated by the final settings applied to the relay. Three overload constraints are considered for this circuit.

1. An overload of 175A sustained for 14 secs.
2. An overload of 200A sustained for 9 secs.
3. An overload of 373A sustained for 2 secs.

Substituting the stated values in equation (6.39) produces the following operating times for the relay.

(1) $$\frac{0.14 \bullet 0.325}{\left( \frac{175}{0.4 \bullet 300} \right)^{0.02} - 1} \simeq 6 * secs$$

(2) $$\frac{0.14 \bullet 0.325}{\left(\frac{200}{0.4 \bullet 300}\right)^{0.02} - 1} \simeq 4.43 * secs$$

(3) $$\frac{0.14 \bullet 0.325}{\left(\frac{373}{0.4 \bullet 300}\right)^{0.02} - 1} \simeq 1.98 * secs$$

* neglecting relay timing errors, circuit breaker clearing time, MTR operating time and relay overshoot time.

From which it can be seen that the overload constraints cannot be satisfied with the previously deduced settings. It can be seen that the TMS setting required for the constraint condition is greater than the maximum TMS determined for transformer withstand conditions at a CSM setting of 0.4. Because both conditions cannot be accommodated, the CSM is incremented and the calculation repeated, the procedure being continued until both conditions are satisfied. If it is found not possible to satisfy the conditions, the strategy fails and an alternative characteristic should be substituted. In this particular exercise it was found that the 'Very Inverse' and 'Extremely Inverse' characteristics both satisfy the transformer withstand requirements and overload constraints. A successful outcome is also obtained if the tests are conducted using a Standard Inverse characteristic with a CSM setting of 0.65 and TMS set at 0.175. The following figures illustrate this result later in the text:

Fig. 6.29 Relay operating times/Transformer withstand times (Maximum Source Impedance Only)

Fig. 6.30 Relay operating times/Overload constraint times

### 6.4.2 Definite Time Overcurrent Strategy

This alternative approach allows any one of three definite time lag characteristics to be used for overcurrent protection, the selection being made by means of slide switches mounted on the faceplate.

The strategy adopted in this case is to examine the phase-phase and three-phase short-circuit currents and associated transformer withstand times for each unit in turn. From the data presented, the value of the minimum fault current condition when supplied via the maximum source impedance value is recorded. Similarly the minimum transformer withstand time associated with the maximum fault current condition when supplied via the minimum source impedance condition is also noted. Each set of results being updated as required for each transformer until the two extreme conditions for the system are known. In the case considered, Fig. 6.7 shows that the minimum detectable current condition is 216 Amp when two elements are installed and 375 Amp when three are in use. The minimum transformer withstand time being 2.10 secs as shown in Table 6.6 Clearly if the relay setting is sensitive enough to detect the minimum fault current condition then all other fault conditions are equally protected.

Similarly if the operating time is lower than the lowest transformer withstand value then all conditions are satisfied.

To achieve fault detection of 375 Amp with the three-element arrangement it is necessary to set the CSM to:

$$CSM = \frac{375}{1.1 \bullet 300} = 1.136$$

where 375A is the fault current to be detected

1.1 is a factor representing pick-up errors

300 is the CT ratio

As a current setting of this value does not exist the value must be rounded down to the nearest setting of 1.10 which in primary current terms is nominally 1.10 x 300 = 330 Amp. This is the maximum setting that can be used which will detect all fault conditions.

Next consider the time multiplier setting (TMS) whose setting is a function of the timing range chosen, the selectable ranges offered being 2, 4 or 8 secs with an operating time accuracy of ± 3%.

Hence maximum allowable time multiplier settings for the 3 ranges are calculated in accordance with equation (6.38).

1. Two Second range

$$TMS = \frac{2.10 - 0.088}{1.03 \bullet 2} = 0.977 \quad \textit{Nearest Setting } 0.975$$

2. Four Second range

$$TMS = \frac{2.10 - 0.088}{1.03 \bullet 4} = 0.488 \quad \textit{Nearest Setting } 0.475$$

3. Eight Second range

$$TMS = \frac{2.10 - 0.088}{1.03 \bullet 8} = 0.244 \quad \textit{Nearest Setting } 0.225$$

The above settings when taking maximum tolerances into account result in an operating time range of ± 3% of the chosen setting.

It can be seen that if an operational overload constraint exceeds the primary current pick-up value of 330 Amp its duration cannot exceed 1.892 seconds without the possibility of a trip occurring. Should the overload constraint be less than the pick-up value then its duration may be infinite. Clearly not an ideal solution but the strategy does provide complete protection for all short circuit conditions possible on the secondary sides of the transformers. For low value overload conditions the CSM may be reduced thus offering a range of possible settings. In the case under investigation the strategy is marginal, because the relay is in the energised state due to the overload current of 373 Amp whose duration of two seconds may exceed the relay definite time setting of two seconds (1.892 / 2.009) seconds if negative timing tolerances are present.

## 6.5 Instantaneous Overcurrent Elements

The function of the instantaneous elements are to protect the HV cable and transformer windings under primary short circuit conditions. This is achieved by setting the relay at a higher level than the maximum fault current available at the transformer LV terminals. A minimum allowance of 10% should be included to allow for transient overreach. The maximum setting is determined by the minimum short circuit current which occurs for phase-phase faults at the transformer HV terminals when the system is supplied via the maximum source impedance. Providing the instantaneous overcurrent elements satisfy these conditions then all other HV fault conditions will be equally satisfied. In the case under consideration the calculated minimum phase-phase current for HV short circuits is 4135A (see Fig. 6.7). The usual procedure adopted being to limit the maximum setting to half this value to provide decisive operation, i.e. 2068A. The settings of the instantaneous elements are arranged in multiples of the associated IDMTL/DTL element settings. As both types have been previously discussed the setting ranges for the two approaches will be addressed below:-

### 6.5.1 IDMTL - Standard Inverse Characteristic
- Settings CSM 0.65: TMS 0.175

Maximum HV fault current available under LV fault conditions = 811A

Allowing 10% for relay overreach 811 • 1.1 = 892A

Hence minimum setting > 892A

$$Minimum\ setting = \frac{LV\ Fault\ Current}{CT\ Ratio \bullet CSM} = \frac{892}{300 \bullet 0.65} = 4.57$$

For which the nearest setting is 5

As the instantaneous settings can only be in multiples of the IDMTL CSM setting the value is rounded up to 5 times the time-lag setting. That is a minimum operating level of $5 \bullet 0.65 \bullet 300 = 975A$.

$$Maximum\ setting = \frac{HV\ Fault\ Current}{CT\ Ratio \bullet CSM} = \frac{2068}{300 \bullet 0.65} = 10.61$$

which is rounded down to 10 times the time-lag setting.

That is, a maximum operating threshold of $10 \bullet 0.65 \bullet 300 = 1950A$.

This setting ensures that the lowest current produced by a short-circuit on the HV side of the transformer provides at least twice the required operating current for the element. Sensibly, a setting which is closer to the lower bound should be chosen as this affords greater fault coverage of the transformer primary windings.

### 6.5.2 Instantaneous Overcurrent Setting associated with DTL strategy

As stated previously the strategy fails as it is unable to satisfy both overload constraints and transformer withstand conditions. If the overload constraints were to be relaxed then the CSM setting of 1.1 previously determined could be implemented. Under such conditions the minimum and maximum setting would be calculated as follows:-

$$Minimum\ setting = \frac{Maximum\ LV\ Fault\ Current\ referred\ to\ Primary \bullet Relay\ Overeach}{CT\ Ratio \bullet CSM}$$

which is rounded up to 3 times the time-lag setting

$$= \frac{892}{300 \bullet 1.1} = 2.70 \quad Nearest\ setting\ 3$$

$$Maximum\ setting = \frac{Minimum\ HV\ Fault\ Current}{CT\ Ratio \bullet CSM}$$

$$= \frac{2068}{300 \bullet 1.1} = 6.27 \quad Nearest\ setting\ 6$$

## 6.6 Earth Fault

The earth fault detecting element installed at the point of common coupling (PCC) with the supply will detect the presence of zero sequence current in the main cable and transformer(s) primary circuit only. Any earth faults occurring on the LV side of the transformers must be dealt with separately. As a result there is a requirement for instantaneous earth-fault protection only to be installed. The relay discussed, however, contains both time-lag and instantaneous elements. The instantaneous element setting being a multiple of the time-lag CSM setting. Because the time-lag elements are an integral part of the relay construction, it is proposed to calculate time-lag settings which will provide back-up protection for the instantaneous elements. The two principal methods of detecting zero sequence current flow are by means of a core balance current transformer (CBCT) in which the out of balance current of the three phase conductors which pass through it provide the measurement or, alternatively, by using residually connected current transformers. The latter approach is used in this exercise as three single phase current transformers are used to supply the overcurrent relays, the earth fault element being connected at the star point where it will measure residual current, that is 3.IO.

As the earth fault element passes no current under normal balanced conditions the current setting multiplier (CSM) can be initially set to the minimum value of 0.05 which is 0.05 • 300 or 15 Amp in terms of primary current. The operating time of the element must of course ensure that the conductor and armour withstand times are not exceeded and this can be achieved by means of the time multiplier setting (TMS). Referring to Fig. 6.7 where:

| | | |
|---|---|---|
| Maximum earth fault current | = | 5000 Amp |
| Withstand time of conductor | = | 13.5 kA/sec |

Withstand time of armour = 3.3 kA/sec

from which it can be seen that the limitation is provided by the armour.

Extrapolating adiabatically for 5 kA, gives

$I^2t$ = constant = $3.3^2$ = 10.89 $kA^2$ secs

Hence maximum withstand time at 5kA = $10.89/5^2$

= 0.4356 sec

Four single phase conditions are examined.

They are

1. At the PCC with minimum source impedance (5000A)
2. At the PCC with maximum source impedance (1000A)
3. Transformer HV terminals with minimum source impedance (4630A)
4. Transformer HV terminals with maximum source impedance (984A)

The calculated armour withstand values at these currents are:

| Current (Amp) | Armour Withstand (Secs) |
|---|---|
| 5000 | 0.4356 |
| 1000 | 10.890 |
| 4630 | 0.508 |
| 984 | 11.247 |

Two strategies are available, they utilise (i) The IDMTL characteristics and

(ii) The DTL characteristics.

### 6.6.1 <u>The IDMTL Strategy</u>

Consider the IDMTL (i) strategy using SI, VI and EI characteristics with the CSM set at 0.05 (15A) and the TMS set at 1.000.

Then summarising

**Table 6.8**

| Primary Current | Secondary Current | SI Sec | VI Sec | EI Sec | Cable Withstand Sec |
|---|---|---|---|---|---|
| 5000 | 16.67 | 2 | 0.45 | 0.2 | 0.4356 |
| 4630 | 15.43 | 2 | 0.45 | 0.2 | 0.508 |
| 1000 | 3.33 | 2 | 0.45 | 0.2 | 10.890 |
| 984 | 3.28 | 2 | 0.45 | 0.2 | 11.247 |

Hence it can be seen that if the following TMS values are applied the protection for all conditions will probably be satisfied. All conditions are evaluated, however, before deducing the final TMS setting.

$$SI = \frac{0.4356}{2 \bullet 1.05^*} = 0.207 \quad \textit{nearest setting } 0.200$$

$$VI = \frac{0.4356}{0.45 \bullet 1.05^*} = 0.922 \quad \textit{nearest setting } 0.900$$

$$EI = \frac{0.4356}{0.2 \bullet 1.075} = 1.000 \; max$$

* maximum error allowance

**NB:** These values exclude additional allowances required for MTR, CB and relay overshoot times. It should be noted that the IDMTL characteristics are modified to DTL at high multiples of setting. The limiting time values are shown in Table 6.8.

Generally the SI or VI characteristics are used as they allow the relay operating time to match more closely the cable withstand time throughout the current range, particularly under light earth fault conditions.

### 6.6.2 The DTL Strategy

A similar approach may be adopted using a definite time lag (DTL) element. A minimum CSM setting of 0.05 may be chosen and the time lag TMS set to accommodate the minimum withstand time.

$$\textit{That is} \quad \frac{0.4356}{2 \bullet 1.03^{*}} = 0.211 \qquad \textit{Nearest setting}\ 0.200$$

* maximum error allowance

This of course excludes allowances which must be incorporated for MTR, CB and relay overshoot delays.

The two strategies discussed provide only a back-up function, a precautionary measure as the true HV earth fault protection is instantaneous, the settings being multiples of the IDMTL/DTL earth fault CSM setting where 0.05 Amp is equal to 15 Amp primary current. As stated previously, to ensure definite operation, the relay element should receive a minimum of twice the operating current, hence in this case the maximum setting should not exceed

$$\frac{\textit{Minimum Fault Current}}{2} \bullet \frac{1}{\textit{CT Ratio} \bullet \textit{CSM}}$$

$$= \frac{984}{2} \bullet \frac{1}{300 \bullet 0.05} = 32.80$$

As the maximum setting is 31, the entire range is available for use. In practice however, a limiting value must be selected such that it allows effective discrimination with earth fault relays on the supply system whilst at the same time not being too sensitive as to suffer maloperation.

**Note** The TMS calculated in all IDMTL/DTL functions should of course take account of other factors referred to in the text. Such factors are:

1. Operating time of the Master Trip Relay MTR 10 mSecs
2. Clearing time of the Circuit Breaker 48 mSecs
3. Overshoot time of the Relay 30 mSecs

which if applied to the last calculation would result in a revised TMS of:

$$\frac{0.4356 - 0.01 - 0.048 - 0.03}{2 \bullet 1.03} = 0.1687 \quad \textit{Nearest Setting } 0.150$$

The above factors are incorporated into the program but are deliberately omitted in the text in the interest of clarity. A further fixed time reduction to represent CT errors should be included but is not quantified in the above list.

## 6.7 Program Description for Transformer Protection on Variable Speed Drive Installations

The program is again constructed in a modular format such that sections of the program can be created and tested individually prior to becoming part of the overall structure. The modules used in the construction of this section of program are listed below, the description and function of the main components being included in the text.

They are as follows:

A. **DATABASES which are accessed by the modules**

| | | |
|---|---|---|
| 1. | TX.DBF | Records all transfomer and interim calculated data |
| 2. | TXCON.DBF | Records circuit overcurrent constraints |
| 3. | FUSEDATA.DBF | Contains a catalogue of fuse voltage ratings and types |
| 4. | FU1.DBF | Contains data on individual fuses |
| 5. | CABDATA.DBF | Contains a catalogue of cable voltage ratings and types |
| 6. | CTEMP.DBF | Holds temp cable records |
| 7. | CA1.DBF | Holds individual cable records |
| 8. | CABNDX.NDX | Index for CABDATA |
| 12. | PSHIFT.DBF | Holds interim results for transformer phase shift calculations |
| 13. | H-RHS.DBF | Contains calculation matrix for winding current distribution |
| 14. | Y-MAT.DBF | Contains calculation matrix for winding current distribution |

B. **Program modules**

| | | |
|---|---|---|
| 15. | PROTSEL.PRG | Project Control routine |
| 16. | MENU1.PRG | Program selection menu |
| 17. | TX.PRG | Program control routine |
| 18. | TX10.PRG | Voltage selection menu |
| 19. | TX20.PRG | Transformer data-display |
| 20. | TX21.PRG | Transformer data-acquisition |
| 21. | TX30.PRG | Circuit constraints |
| 22. | TX40.PRG | System definition |
| 23. | TX50.PRG | Switching device and relay clearing times |

| | | |
|---|---|---|
| 24. | TX60.PRG | Current transformer selection |
| 25. | TX70.PRG | Displays fuse catalogue |
| 26. | TX80.PRG | Displays fuse data |
| 27. | TX90.PRG | Display cable catalogue |
| 28. | TX100.PRG | Cable rating calculations |
| 29. | TX110.PRG | Displays cable data |
| 30. | TX120.PRG | Fault current calculations |
| 31. | TRIG.PRG | Calculates Sine and Cosine of angles |
| 32. | TX1201.PRG | Fault current calculation data input |
| 33. | TX1202.PRG | Transformer winding fault current distribution |
| 34. | WINDING.PRG | TX1202 subroutine |
| 35. | TX130.PRG | Assigns constants to selected relay characteristics |
| 36. | TX1301.PRG | Displays relay characteristic menu |
| 37. | TX1302.PRG | Part 1 Overcurrent setting calculation |
| 38. | TX1303.PRG | Part 2 Overcurrent setting calculation |
| 39. | IDMTLOC1.PRG | TX1303 subroutine |
| 40. | DTLOC.PRG | Definite time-lag calculation |
| 41. | TX140.PRG | Earth-fault setting routine |
| 42. | TX1401.PRG | Displays earth-fault option menu |
| 43. | IDMTLEF.PRG | TX140 subroutine |
| 44. | TX150.PRG | User option menu |
| 45. | TX151.PRG | User option o/c data entry |
| 46. | TX152.PRG | User option e/f data entry |
| 47. | TX160.PRG | Calculate cable withstand |
| 48. | TX161.PRG | Calculate transformer withstand |
| 49. | TX162.PRG | Check circuit constraints |
| 50. | TX170.PRG | DTL calculation routine |
| 51. | TX171.PRG | DTL option and flags |
| 52. | TX172.PRG | DTL constraints |

| | | |
|---|---|---|
| 53. | TX210.PRG | Settings display |
| 54. | TX310.PRG | Menu - f/currents, withstand, constraints |
| 55. | TX320.PRG | Lists fault currents for 6 TX's |
| 56. | TX330.PRG | Lists fault currents for 6 + TX's |
| 57. | TX340.PRG | Withstand/prot clearing times - minsource Z |
| 58. | TX350.PRG | Withstand/prot clearing times - maxsource Z |
| 59. | TX360.PRG | Display constraint/relay times |

### 6.7.1 PROTSEL

Fig. 6.8 displays the protsel module which is the overriding program controlling the suite of sub programs. Choosing option 5 selects the TX module which controls the sub-program relevant to this section.

### 6.7.2 TX

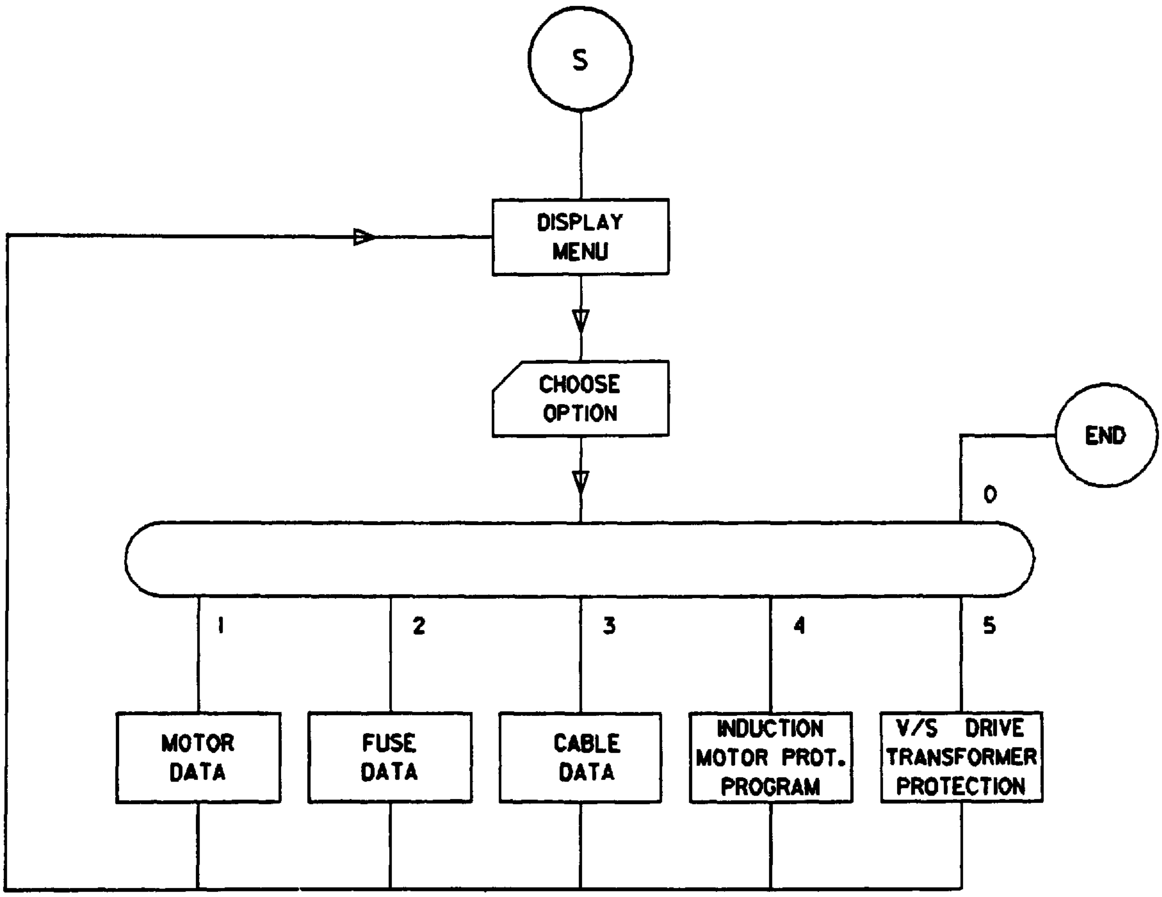
As previously stated the module controls the entire sequence of events in this 'PROTSEL' sub-program. The program again uses the established format from which the individual modules controlling various parts of the overall structure of the program are accessed sequentially. Fig. 6.9 is a flowchart which clearly shows this function. Each module which requests data via the screen/keyboard interface incorporates a feature which allows the user to page back to the previous workpage, and a quit feature which returns the user to the main selection menu.

### 6.7.3 TX10

TX10 is the first module selected by the TX control program. The function of this menu driven module is to determine the voltage level of the system under review. The menu is at present limited to three voltage levels which are of interest to this

ROUTINE : PROTSEL

TITLE : MAIN SYSTEM PROGRAM




1. MDATA - DATABASE OF MOTOR DATA INFORMATION
2. FDATA - DATABASE OF FUSE DATA INFORMATION
3. CABDATA - DATABASE OF CABLE DATA INFORMATION
4. MPROT - D/O/L INDUCTION MOTOR PROTECTION PROGRAM
5. TX - VARIABLE SPEED DRIVE TRANSFORMER PROTECTION

Fig 6.8

ROUTINE : TX

TITLE : VARIABLE SPEED DRIVE TRANSFORMER PROTECTION

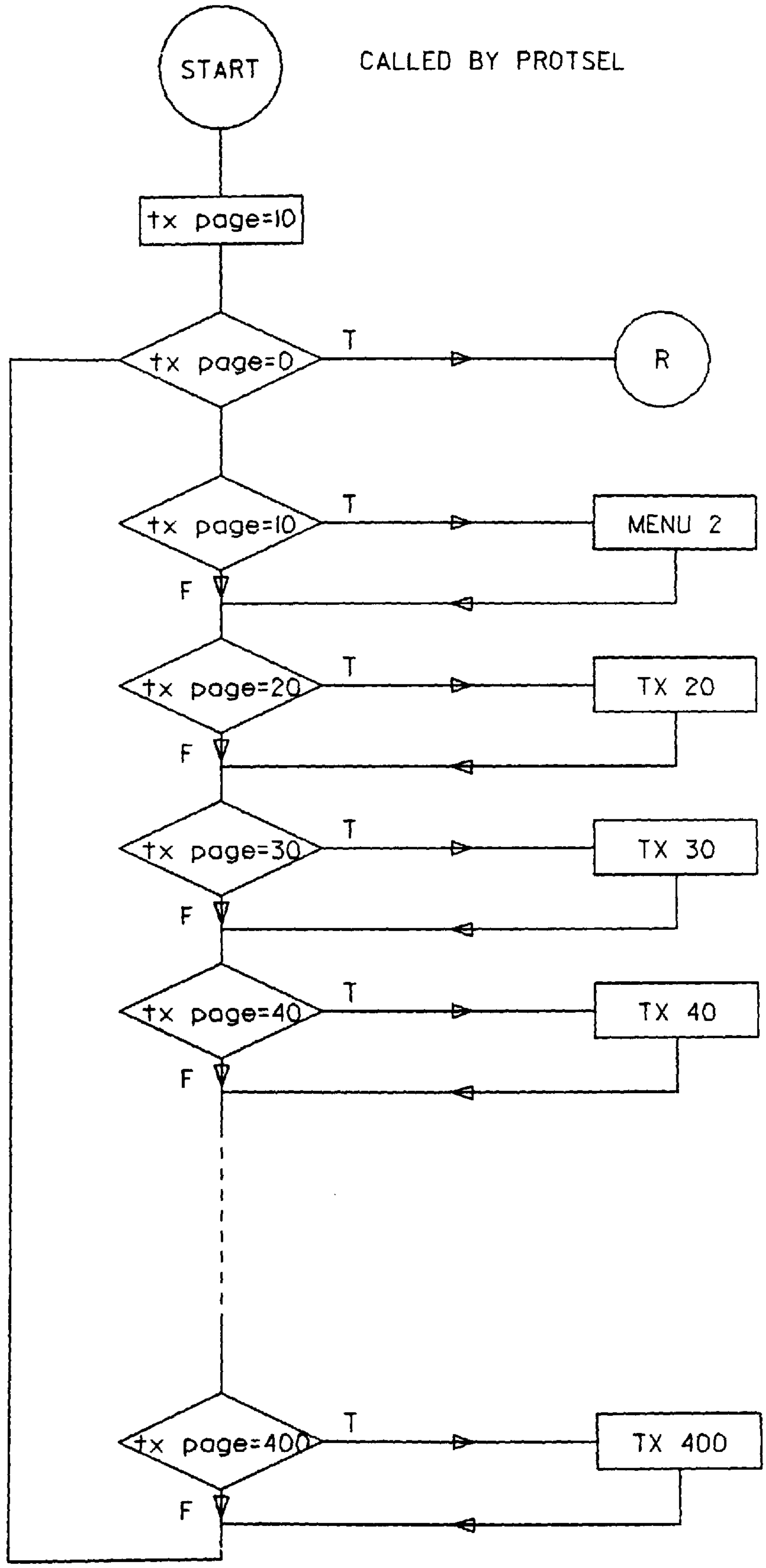



Fig 6.9

project. A screen display of the menu is shown in Fig. 6.10 accompanied by a flowchart of the module in Fig. 6.11

### 6.7.4 TX20

This module is used to acquire and store the transformer data relevant to the circuit under investigation. The routine is shown in the flowchart Fig. 6.12 and requires the following input of information for each individual transformer.

1. Rating (kVA)
2. Vector Group of Windings
3. Percentage Resistance based on Rating
4. Percentage Reactance based on Rating
5. Phase Shift of Secondary Winding
6. Secondary Voltage
7. Secondary CT Ratio, if fitted.
8. Setting of LV instantaneous overcurrent relays

Using the above listed data, the routine counts the number of shunt connected transformers and calculates the overall full load current. The acquired data is, of course, stored for use in later modules. The screen presentation of the data used in the Temper Mill case study discussed in section 6.3 is shown in Fig. 6.13.

### 6.7.5 TX30

This module is used to collate the constraints applied to the circuit. The logic used for data collection is essentially the same as that found in the TX20 routine except that the input data is required to define the magnitude and duration of the overloads that the circuit is routinely subjected to during the duty cycle.

```
VARIABLE SPEED DRIVE TRANSFORMER PROTECTION
SUPPLY SYSTEM VOLTAGE SELECTION

1.     240/  415 V
2.    3300/ 3300 V
3.    6350/11000 V

Q.          QUIT

Select option
```

*Fig 6.10 Voltage selection menu.*

ROUTINE : TXIO

TITLE : VOLTAGE SELECTION MENU

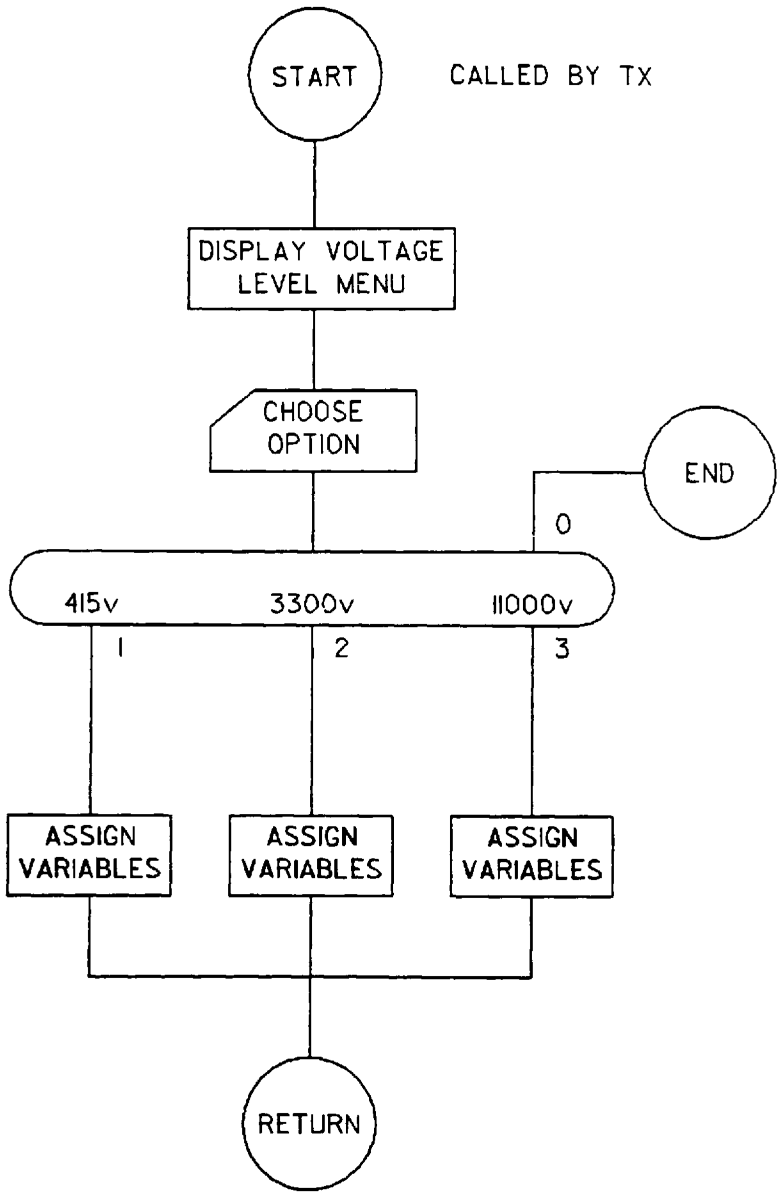



Fig 6.11

ROUTINE : TX20

TITLE : RECORD TRANSFORMER DATA

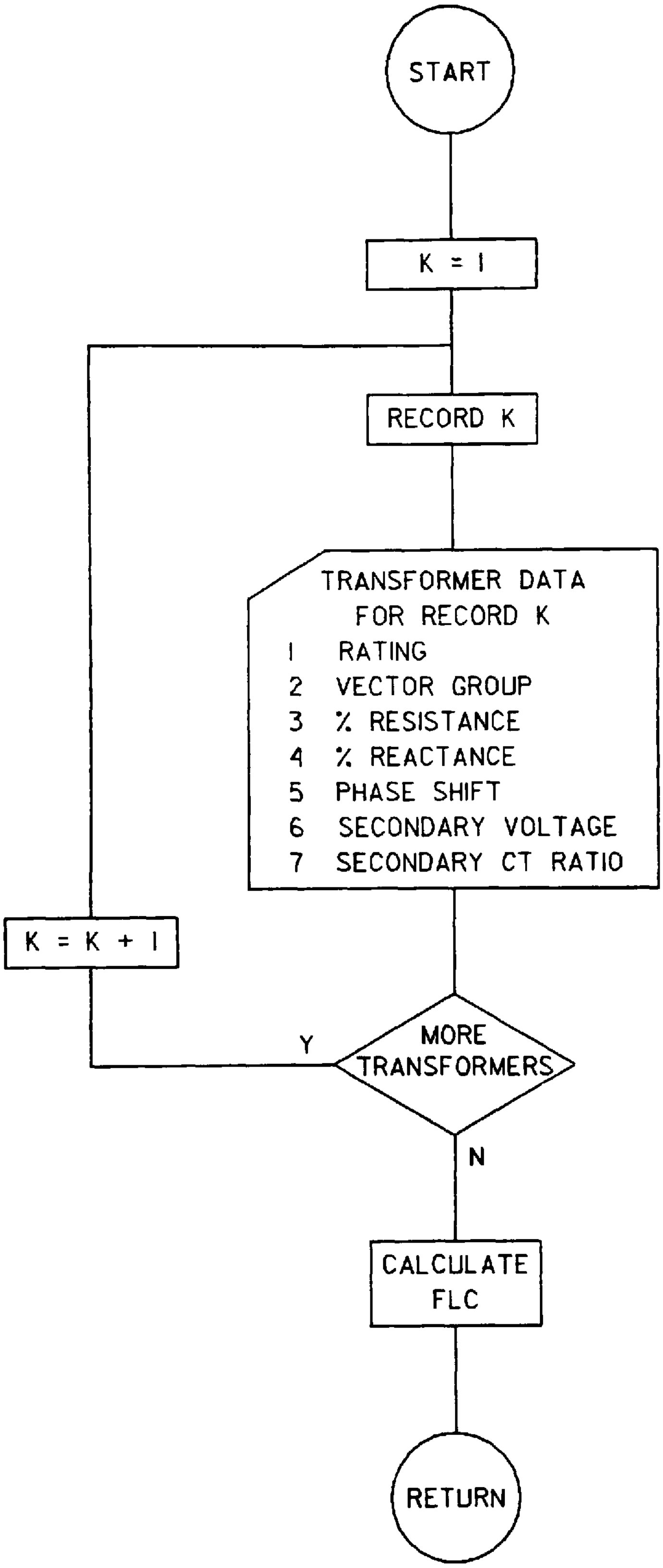



Fig 6.12

VARIABLE SPEED DRIVE TRANSFORMER PROTECTION
CIRCUIT DEFINITION

```
Supply Volts .......................................... 6350/11000
Type  <1 & 1E>  Transformer windings  :  Pri (DELTA) : Sec (DELTA)
      <2 & 2E>  Transformer windings  :  Pri (DELTA) : Sec (STAR )
      <3>       Transformer windings  :  Pri (STAR ) : Sec (DELTA)
      <4>       Transformer windings  :  Pri (STAR ) : Sec (STAR )
```

| WNDG No | RATING kVA | WNDG type | IMPEDANCE %R | %X | PHASE +/- | SHIFT deg' | LINE VOLTAGE Secondary | SECONDARY CTR |
|---|---|---|---|---|---|---|---|---|
| TX1 | 520 | 1 | 0.00 | 5.73 | + | 0.0 | 660 | 455 /1 |
| TX2 | 520 | 2 | 0.00 | 5.73 | + | 30.0 | 660 | 455 /1 |
| TX3 | 677 | 1 | 0.00 | 4.92 | + | 0.0 | 660 | 592 /1 |
| TX4 | 677 | 2 | 0.00 | 4.92 | + | 30.0 | 660 | 592 /1 |
| TX5 | 872 | 1 | 0.00 | 5.42 | + | 0.0 | 660 | 763 /1 |
| TX6 | 872 | 2 | 0.00 | 5.42 | + | 30.0 | 660 | 763 /1 |

```
<M>ore data  ......  A                               <P>ageback
<A>ccept / <R>eject                                  <Q>uit
```

*Fig 6.13 Transformer data input display.*

### 6.7.6 TX40

In this module the user is required to specify the system conditions to which the apparatus will be connected, the data being used to calculate the phase sequence impedance components of the source.

The data required is as follows:

Maximum and minimum three-phase fault current at source
X/R ratio for above conditions from which the positive and negative phase sequence impedance components are calculated.

Maximum and minimum earth fault current at source.
X/R ratio for above condition which are in conjunction with the above allows the zero phase sequence impedance components to be determined.

A screen display with typical values is shown in Fig. 6.14.

### 6.7.7 TX50

As stated in the text, it is of paramount importance to establish the type of switching device to be used, as the use of either circuit breaker or fused contactor imposes its own additional constraints on the circuit data already acquired. If a fully rated circuit breaker is chosen then the final protection should include an instantaneous overcurrent protective device, whereas, in the case of the alternative fused contactor approach, the short circuit protection function is provided by the inline fuse. The contactor approach as discussed earlier does have additional benefits by allowing the installation of a cable which is based on load requirements rather than potential fault current magnitudes. The module

```
VARIABLE SPEED DRIVE TRANSFORMER PROTECTION
SYSTEM CONDITIONS

Maximum 3ph fault current at source     ...........    25000    Amps
Source  3ph X/R Ratio                   ...........     10.0
Minimum 3ph fault current at source     ...........     5000    Amps

Maximum Earth fault current at source   ...........     5000    Amps
Source 1ph X/R Ratio                    ...........      0.5
Minimum Earth fault current at source   ...........     1000    Amps

<A>ccept / <R>eject  A                                 <P>ageback
                                                       <Q>uit
```

*Fig 6.14 System source conditions.*

includes a check to establish that the switching device is adequately rated for the duty intended. The remainder of the module is used to determine the total operating times of the switching device which includes 'master tripping relay' (MTR), relay overshoot time and the number of overcurrent elements used to monitor circuit conditions. A typical screen presentation is shown in Fig. 6.15.

### 6.7.8 TX60

This module is used to specify the CT requirements of the relay for the circuit given the full load current of the connected load. The user is required to enter the following details of the proposed current transformers.

1. Current transformer ratio
2. VA, Class and Overcurrent factor (OCF)
3. Resistance of CT secondary winding
4. Resistance of CT lead to relay
5. 4/6 wire CT leads

Recommended values for item 2 are included in the program. These values may be rejected and replaced by alternatives if required.

Using this data it can be readily established if the proposed CT's have sufficient capacity to satisfy the circuit burden yet still provide adequate output to operate the instantaneous overcurrent settings which will be established in later modules. A method for estimating the current transformer knee point voltage and accuracy limit factor is contained in Appendix 10 Part 2.

A typical screen display is shown in Fig. 6.16.

```
                VARIABLE SPEED DRIVE TRANSFORMER PROTECTION
                              SWITCHING DEVICE

Circuit controlled by Circuit Breaker      ....(Y/N)..        Y
Maximum Interupting current                ...........    25000      Amps
Maximum operating time from trip receipt   ...........       48      mSecs

MCGG relay - 2 or 3 ph o/c                 ...........        3
Maximum operating time of MTR              ...........       10      mSecs


Note 1  - CB Operating times            Note 2 - MTR Operating times
  GEC MX         -  48 mSecs              GEC VAJ          - 10 mSecs
  W&B CV         -  52 mSecs              ASEA RXMVS 4     - 25 mSecs
  REYROLLE C5T   - 100 mSecs              REYROLLE    F    - 10 mSecs
  GEC 1172       - 120 mSecs              REYROLLE   RL    - 40 mSecs

<A>ccept / <R>eject  A                                    <P>ageback
                                                          <Q>uit
```

*Fig 6.15  Switching device and protection operating times.*

```
              VARIABLE SPEED DRIVE TRANSFORMER PROTECTION
                        CURRENT TRANSFORMERS

 Sum of transformer full load currents   ...........        217  Amps
 Primary circuit full load current       ...........        110  Amps

 Current transformer ratio               ...........      300/1
 Current transformer VA.                 ...........        2.5  VA.
 Current transformer CLASS and OCF                        10P20
 Resistance of CT Secondary winding      ...........        ***  Ohms
 Resistance of CT lead                   ...........        ***  Ohms
 4 or 6 wire CT leads                    ...........        ***

 <A>ccept / <R>eject  A                                     <P>ageback
                                                            <Q>uit
```

*Fig 6.16 Current transformer data.*

### 6.7.9 TX70

This routine is selected by the previous module if the declared switching device contains inline fuse protection. The database 'FUSEDATA' is accessed and the contents sequentially extracted. The acquired data is processed and displayed in a catalogue format to enable further selection to take place. The data obtained from each 'FUSEDATA' record is contained in five fields, they are:

1. Declared fuse operating voltage
2. Fuse manufacturer
3. Specification identifier
4. Year of specification issue
5. A code linking the record to all fuse ratings within the manufactured range and contained in the database 'FU1'

The fuse range option is chosen by selecting a reference number which enables the specified range of records to be accessed. Data fields 1-4 are assembled to form a screen title whilst data field 5 is assigned to a variable and passed to the TX80 module. A typical display is shown in Fig. 6.17.

### 6.7.10 TX80

The routine begins by opening the 'FU1' database which contains data relevant to all fuse types and ratings contained within the program. Using the data previously obtained from Field 5 in the TX 70 module enables the routine to locate and extract all relevant data for fuse ratings contained within the specified range. The ratings are displayed in three columns from which the user is required to select the appropriate rating. This allows the individual record to be accessed and enables data, which includes the maximum 'let-through'. $I^2t$ energy value, to be

```
                              FUSE CATALOGUE

1    415      GEC  TYPE 'T' HRC FUSELINKS                  BSS 88    1988
2    550      GEC  TYPE 'T' HRC FUSELINKS                  BSS 88    1988
3    660      GEC  TYPE 'T' HRC FUSELINKS                  BSS 88    1988
4   3300      B&S  3.6kV MOFSB,MRFSA    RUT <  6s          BS 2692   1975
5   3300      B&S  3.6kV MOFSB,MRFSA    RUT < 15s          BS 2692   1975
6   3300      B&S  3.6kV MOFSB,MRFSA    RUT < 60s          BS 2692   1975
7   3300      GEC  3.6kV K81PEX FUSES   RUT <  6s          BS 2692   1975
8   3300      GEC  3.6kV K81PEX FUSES   RUT < 15s          BS 2692   1975
9   3300      GEC  3.6kV K81PEX FUSES   RUT < 60s          BS 2692   1975

Select option                                  <C>ontinue
```

*Fig 6.17 Fuse catalogue.*

recovered. This particular value is used in later cable selection modules. A typical display is shown in Fig. 6.18.

### 6.7.11 TX90

This module is similar in construction to the TX70 module except that the database which is accessed contains general data associated with cable types. The database which is called 'CABDATA' contains sixteen fields, some of which are relevant only to other calling routines.

The more significant fields associated with the TX90 module are:

1. Working voltage
2. Cable type
3. Type of construction
4. Insulation media
5. Type of armouring employed
6. Type of oversheath
7. Number of cores
8. Aluminium (Al) or Copper (Cu) conductors
9. Stranded or solid conductors
10. A code which uniquely defines the construction.

A typical display is shown in Fig. 6.19 from which it can be seen that the required cable is selected using the reference number specified alongside each option.

3300V B&S 3.6kV MOFSB,MRFSA    RUT < 15s

Circuit flc -    69 Amps

| | | | | | |
|---|---|---|---|---|---|
| * | 63 | 3 | 160 | 3 | 500 |
| | 80 | 3 | 200 | 3 | 630 |
| | 100 | 3 | 250 | 3 | 710 |
| | 125 | 3 | 315 | 3 | |
| | 140 | 3 | 355 | 3 | |

* Unsuitable

Select option

*Fig 6.18 Fuse rating summary.*

```
                    THE DISTRIBUTION ENGINEERS ASSISTANT
                              CABLE CATALOGUE

 1  600/1000    3c  Str Cu  PVC/EXTR/SWA/PVC         BSS 6346 1969   M
 2  600/1000    1c  Str Cu  XLPE/PVC                 BSS 5467 1977   M
 3  3800/6600   3c  Str Al  XLPE/SCR/SWA/PVC         IEC 502  1983   M
 4  6350/11000  3c  Str Al  XLPE/SCR/SWA/PVC         IEC 502  1983   M


 Select option    4    Cable length 550 mtrs       <C>ontinue  <Q>uit
 Derating factor 1.00  <A>ccept / <R>eject A                   <P>ageback
```

*Fig 6.19 Cable catalogue.*

### 6.7.12 TX100

The function of this module is to sequentially extract from a database all relevant data contained within the cable files selected in the TX90 module. The following data is extracted for each CSA value of the selected cable type.

1. Cable rating in air, ground and duct.
2. Fault rating of cable conductors and armouring.
3. Positive and zero phase sequence impedance values.

The cable rating values referred to in (1) are each derated in accordance with the derating factor specified in the TX90 module prior to storage. If the switching device is a fully rated circuit breaker then, the fault rating data of both conductor and armouring recorded in (2) are examined in conjunction with the fault currents specified earlier in the TX40 module to determine if the ratings are adequate. A symbol is assigned to signify the result. The cable impedance values referred to in (3) are used in the routine together with the specified cable length to determine voltage drop in the transformer supply cables. The calculated impedance values are also stored for use in later modules to calculate transformer fault current magnitudes. Where the switching device is fuse protected the routine produces additional symbols which indicate

1. The fuse rating > cable rating
2. The fuse 'let thro' energy > Cable conductor/armour withstand capability

Each CSA value is processed in the same manner prior to storing the results in a temporary database.

### 6.7.13 TX110

The function of this module is to provide the maximum information to aid in the selection of the most appropriate and economical cable rating which satisfies the circuit conditions. The routine displays the cable CSA values and revised current ratings in two columns. The data is supplemented by symbols which are indicative of boundary excursions in excess of the conditions stated in 6.7.12. A typical screen display is shown in Fig. 6.20.

### 6.7.14 TX120

In this module no user supplied information is required. The routine performs a series of calculations utilising data previously collated in earlier routines. The calculations carried out establish:

1. Maximum three-phase fault current at source
2. Maximum phase-phase fault current at source
3. Maximum phase-earth fault current at source
4. Maximum three-phase fault current at transformer HV windings
5. Maximum phase-phase fault current at transformer HV windings
6. Maximum phase-earth fault current at transformer HV windings
7. Maximum fault current reflected to primary for three-phase fault on transformer LV terminals
8. Maximum fault current reflected to primary for phase-phase fault on transformer LV terminals
9. As 7 and 8 except fault currents calculated at the remote end of the LV cabling when the circuit is supplied via a maximum source impedance (not implemented).
10. As above except maximum source impedance is used.

```
                    THE DISTRIBUTION ENGINEERS ASSISTANT                  11
   6350/11000V           3c STR AL  XLPE/SCR/SWA/PVC        IEC 502 1983

 Circuit flc - 110 A                                Cable length - 550  mtrs

 CSA    GND   DCT   AIR        %V          CSA    GND   DCT   AIR        %V
SQ MM   AMP   AMP   AMP       @ Tx        SQ MM   AMP   AMP   AMP       @ Tx
  25    115    95*  115       98.5   a     150    300   255   330       99.7
  35    135   115   140       98.9   a     185    335   290   385       99.8
  50    160   135   170       99.2   a     240    380   335   450       99.8
  70    195   165   210       99.4   a     300    435   375   510       99.9
  95    230   200   250       99.6   a     400    490   430   590       99.9
 120    265   225   295       99.7   a

  '*' cable rating  < flc        'a' cable  w'stand < fault current (200 msec)
                                 'b' armour w'stand < fault current (200 msec)

  Select CSA     150            Show  Y                 <C>ontinue  <Q>uit
  Derating factor 1.00  <A>ccept / <R>eject A                        <P>ageback
```

*Fig 6.20  Cable limitation display for a typical installation.*

### 6.7.15 <u>TRIG</u>

The function of this subroutine is to accept a transformer phase shift value in degrees and return the corresponding sine and cosine value to the TX120 calling routine. The values are obtained by converting the angle to radian measure and substituting it in the appropriate Maclaurin's series. It is necessary to provide this routine because DBASE 3+ does not contain these trigometric functions. This subroutine is called from the TX120 module each time a transformer calculation is required which for Case Study 2 requires six calls.

### 6.7.16 <u>TX1201</u>

This subroutine is called by the TX120 module. It is used to calculate the primary and secondary line currents which appear on the occurrence of a phase-phase short circuit fault on the secondary terminals of a transformer. The method used is identical to that described in the text. A feature is included in the routine which allows the calculated values to be displayed for inspection. The routine which calculates the line currents for both maximum and minimum source impedance conditions is called twice for each transformer processed. A total of twelve calls are made for Case Study 2.

### 6.7.17 <u>TX1202</u>

This subroutine is called directly after the previous subroutine. Its function is to calculate the current distribution in each transformer which incorporates delta windings. The solution is deduced using the Generalised Matrix inversion approach. As in the previous case, a routine is included which displays the current distribution if required. With the current distribution now known in all windings, a revised withstand time is allocated to each winding based on an adiabatic comparison with the known maximum current rating of each winding.

### 6.7.18 TX130

This sub section of the program deals with the fitting of the relay characteristics to the overall circuit constraints. Each of the relay characteristics is derived from an internal lock-up table and complies with BS 142. The characteristics used are defined by the manufacturer and detailed earlier in this thesis. Initially the module calls a subroutine whose function is to present the user with a complete menu of the characteristics available on the GEC ALSTHOM type MCGG electronic relay. In addition the user is able to specify the number of current measuring elements used and to verify the effects of any user supplied settings. A further option displays a summary all the phase-phase and three-phase fault currents previously calculated. The menu display is shown in Fig. 6.21. Dependent on the option chosen, constants A and B are selected and substituted in the characteristic equation which for IDMTL relays is of the form:

$$t = \frac{A}{I^B - 1} \; secs$$

where I is the applied current and A and B are constants

### 6.7.19 Inverse Time Characteristics

Consider Option 1 - Standard Inverse IDMTL characteristic

A calculation is first carried out to determine the current setting multiplier (CSM) value. The minimum value being considered as the lowest stable setting in excess

```
                                                                        3
            GEC 'MCGG' OVERCURRENT CHARACTERISTIC MENU                 ELE

                  1.        STANDARD  INVERSE
                  2.        VERY INVERSE
                  3.        EXTREMELY INVERSE
                  4.        LONG TIME INVERSE
                  5.        DEFINITE TIME DELAY  - 2 SECS
                  6.        DEFINITE TIME DELAY  - 4 SECS
                  7.        DEFINITE TIME DELAY  - 8 SECS
                  8.        USER CHOICE

               *  9.        CHANGE OVERLOAD CONSTRAINTS
                 10.        CHANGE NUMBER OF O/L ELEMENTS
                 11.        DISPLAY FAULT CURRENTS

  * Not implemented

  Select option  ........                                   <P>ageback
 <S>ettings  <E>arth fault                                  <Q>uit
```

*Fig 6.21  Relay characteristic and element selection display.*

of the circuit FLC. The program then calls a subroutine which is dedicated to dealing with the circuit overload contraints. This subroutine accesses a database file containing the magnitude and duration of all known overload constraints applied to the circuit, each constraint being accessed in turn. The overload values extracted from the file are substituted in the characteristic equation thus enable the relay operating time to be determined. The operating time is then adjusted by means of the time multiplier setting control (TMS) to equate the relay operating time to the duration of the overload condition. In each case an allowance is made of the following delays.

1. Relay error
2. Relay overshoot
3. Master trip relay (MTR)
4. Circuit breaker (CB)

If the duration of the overload exceeds the operating time for the relay then the PSM setting must be increased and the exercise repeated. Similarly any overloads in excess of thirty seconds are treated as a continuous condition with the CSM set greater than the overload magnitude. If each overload constraint is satisfactorily processed in the above manner then the resulting TMS used is the highest TMS satisfying the constraints. The upper bound checks are carried out by initially setting the TMS to 1.0. The program on returning from the constraint subroutine sequentially examines the fault current at each transformer node. An operating time is calculated for each node using the CSM value previously determined and compared with the transformer and cable withstand time. As withstand checks on the transformer and cables have previously been determined for all potential fault conditions, the TMS, is decremented accordingly to satisfy the circuit withstand requirements. Provided the TMS setting arrived at is greater than the previously obtained value then all conditions examined have been satisfied. The conditions imposed are summarised in Table 6.9.

The same strategy is used for menu items 2, 3 and 4 which invoke constants which when substituted in the characteristic equation produce VI, EI and LTI operating characteristics.

Table 6.9

1. Select curve type SI, VI, EI or LTI.
2. Select CSM based on the circuit full load current (FLC) or long time overload.
3. Obtain TMS for overload constraint conditions - record TMS.
4. Set TMS to 1.0.

   Revise TMS setting for two overcurrent sensing elements only

   (a) Phase-phase fault on transformer LV winding with the circuit supplied from a source at minimum fault level - record HV current distribution in all phases.

   (b) Ditto when circuit supplied from source of maximum fault level.

   or Revise TMS setting for three overcurrent sensing elements only

   (c) As (a) and (b) except record highest HV phase current only.

   plus (d) 3-phase fault on transformer LV terminals fed from both maximum and minimum source fault levels - record HV phase current

5. Carry out checks on item 4 for other transformers.
6. Determine current values of phase-phase fault on HV cable at transformer fed from both minimum and maximum source fault levels.
7. Carry out checks in item 6 for 3 phase fault condition.

### 6.7.20 Definite Time Lag Characteristics

Menu options 5, 6 and 7 select the Definite Time Lag characteristics. Three time lags are available 2, 4 or 8 seconds which may be reduced by use of the TMS control.

The strategy adopted following selection of these options may be best understood by study of the flow chart shown in Fig. 6.22. The strategy is flawed and should not be used unless the IDMTL approach fails. Referring to Fig. 6.22 it can be seen that the minimum CSM setting may be dictated by the magnitude and duration of the overload constraints. Where the duration of the constraint exceeds the definite time selected, the CSM is raised thereby ignoring that constraint and any other of equivalent magnitude but lesser duration. If the circuit withstand times and overload constraint considerations cannot be satisfied the strategy fails and an alternative approach should be pursued.

Option 8 of this routine, the 'User Choice' option executes a call to a module located at TX150.

### 6.7.21 TX150-152

This module is arranged as a group of three interconnected routines. They form a part of the 'User Choice' suite of programs which are depicted on the flowchart shown in Fig. 6.23. The module TX150 displays an entry form on which the user is invited to specify the following information.

ROUTINE : DEFINITE TIME LAG OVERCURRENT

TITLE : DEFINITE TIME ROUTINE

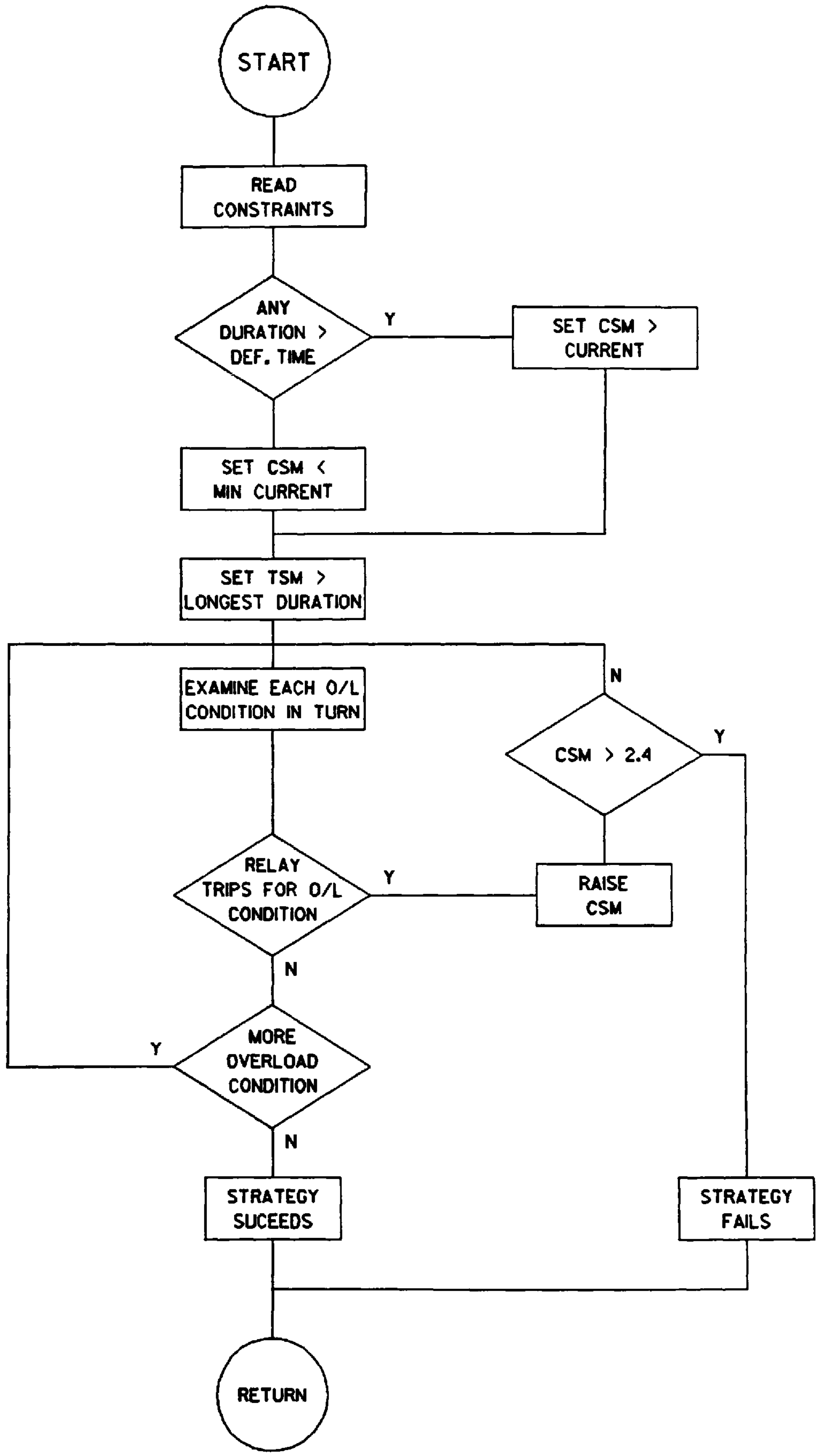



Fig 6.22

ROUTINE : TX150-152

TITLE : USER CHOICE ROUTINES

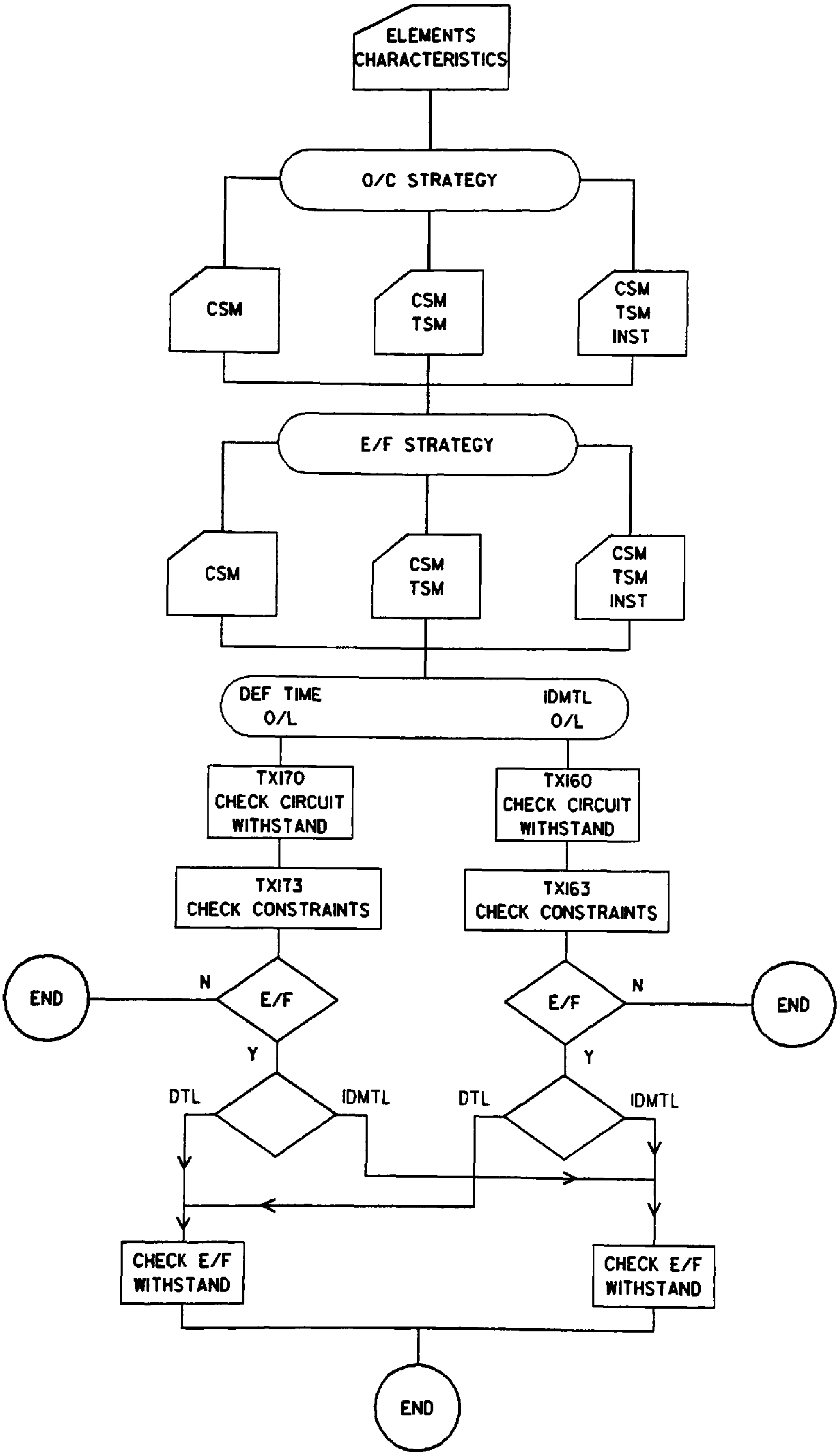



Fig 6.23

(a) Overcurrent strategies 10, 11 and 12 where:

10. User specifies CSM

11. User specifies CSM and TMS

12. User specifies CSM, TMS and Instantaneous element setting

(b) The type of characteristic

| | | |
|---|---|---|
| 1. | SI | Standard Inverse |
| 2. | VI | Very Inverse |
| 3. | EI | Extremely Inverse |
| 4. | LTI | Long Time Inverse |
| 5. | DTL2 | 2 Sec Definite Time Lag |
| 6. | DTL4 | 4 Sec Definite Time Lag |
| 7. | DTL8 | 8 Sec Definite Time Lag |

(c) The Instantaneous element setting

(d) Choice of 2 or 3-phase overcurrent elements

And for the Earth fault element(s)

(e) Choice of strategies as in (a)

(f) Choice of characteristics as in (b)

(g) Choice of instantaneous setting as in (c)

Each of the options are used to select variables and direct the program towards the appropriate IDMTL or DTL routine in the sequence. The program flow is initially directed to the TX160 routine.

#### 6.7.22 TX160-162

This module calculates the cable and transformer withstand times and compares them with the predicted IDMTL relay operating times for the user selected overcurrent settings and characteristic. The routine examines all possible overcurrent locations and where the circuit breaker clearing time is seen to exceed the withstand time of the cable or transformer assigns a flag to draw attention to the problem locations. All transformer checking routines are carried out in the TX161 module. Similar flags are assigned following examination of the overload constraints contained in the TX162 module, where each overload is checked in turn to determine if the relay is stable or its operating time is in excess of the potential overload duration. The routine takes full account of maximum relay timing errors, relay overshoot and circuit breaker clearing times in the calculations. The exercise is conducted for both maximum and minimum current source conditions. On completion the program is directed towards either the IDMTL or DTL Earth fault routine in accordance with the option specified in the TX152 module.

#### 6.7.23 TX170-172

The function of this set of routines is identical with that contained in the TX160-162 modules except that all calculations and predictions are carried out on the basis of user supplied DTL settings. As in the previous case, the program is directed to either an IDMTL or DTL earth fault routine as specified in the TX152 module.

### 6.7.24 TX180 and TX190

If the TX162 or TX172 routines detect the requirement for an earth fault relay, the program flow is directed towards either the TX180 or TX190 routines. In the former case the protective characteristics used are IDMTL whilst the latter uses the DTL approach, both have instantaneous elements. The potential primary earth fault current is evaluated at the source and point of connection to the transformers for both minimum and maximum source impedance conditions, the values obtained being used to determine the withstand times of the supply cable and the operating times of the relay. Both are compared and flags assigned accordingly where the relay operating times exceed the transformer withstand values after taking full account of relay timing errors, circuit breaker clearing times and master tripping relay operating times. The routine also calculates the clearing times of associated instantaneous elements which represent the primary earth fault protection. As before due account is taken of errors and delays in the circuit components.

### 6.7.25 TX210

This routine is used to display the overcurrent and earth fault settings calculated in earlier routines is also used to display other relevant data. A typical display can be seen in Fig. 6.24.

### 6.7.26 TX310

This module is called when the 'User Option' choice is selected from the characteristic menu. All computation work is carried out prior to calling this routine. The function of the routine is to display a menu from which a number of options may be selected. The options available are shown in Fig. 6.25, the menu

```
          VARIABLE SPEED DRIVE TRANSFORMER PROTECTION
                        RELAY SETTINGS

  Circuit supply voltage      ..................   6350 /11000 V
  Circuit full load current   ..................          110 A

  Relay : GEC 'MIDOS'. type MCGG 82                  Min /  Max
  Overcurrent using SI characteristic
               Current  setting multiplier   :     0.65
               Time     setting multiplier   :     0.175/ 0.175
               Instantaneous element         :     5  x / 10  x

  EARTH FAULT using SI characteristic
                Current setting multiplier   :     0.05 / 2.40
                Time    setting multiplier   :     0.050/ 1.000
                Instantaneous element        :     1  x /   31x

 Select option   ....                                  <P>ageback
<C>haracteristic menu                                  <Q>uit
```

*Fig 6.24 Typical Settings Display*

```
FLC          VARIABLE SPEED DRIVE TRANSFORMER PROTECTION          CT.R
110                       USER CHOICE MENU                        300/1

              1.    FAULT CURRENTS
              2.    WITHSTAND    / RELAY TIME - MIN SOURCE Z
              3.    WITHSTAND    / RELAY TIME - MAX SOURCE Z
              4.    CONSTRAINTS / RELAY TIME
              5.    CHARACTERISTIC MENU

              Q.    QUIT

 Select option                                               <P>ageback
                                                             <Q>uit
```

*Fig 6.25 `User choice' menu.*

display. The flowchart, Fig. 6.26 shows how the routine interfaces with the listed options.

### 6.7.27 TX320 and TX330

Where calculations for four transformers or less are carried out, the TX320 routine is called. For more than four transformers the TX330 is used. Both routines are essentially similar, their function being to display phase-earth, phase-phase and three-phase fault currents in various parts of the circuit. Both routines display prospective fault currents at selected node locations when supplied via both minimum and maximum source impedances. Figs. 6.27 shows a typical screen display for a six transformer scheme.

### 6.7.28 TX340

The module is selected in the TX310 routine and is used to display the transformer withstand time for the prospective current at various nodes when the transformers are supplied via a minimum source impedance. The relay operating times of the same set of conditions are also displayed together with a symbol indicative of whether the circuit withstand time is exceeded. A typical display is shown in Fig. 6.28.

### 6.7.29 TX350

This routine is identical in most respects to TX340 except that the program addresses the case where the transformer system is supplied via the maximum source impedance. Fig. 6.29. shows a typical display.

ROUTINE : TX310

TITLE : USER OPTION RESULTS DISPLAY

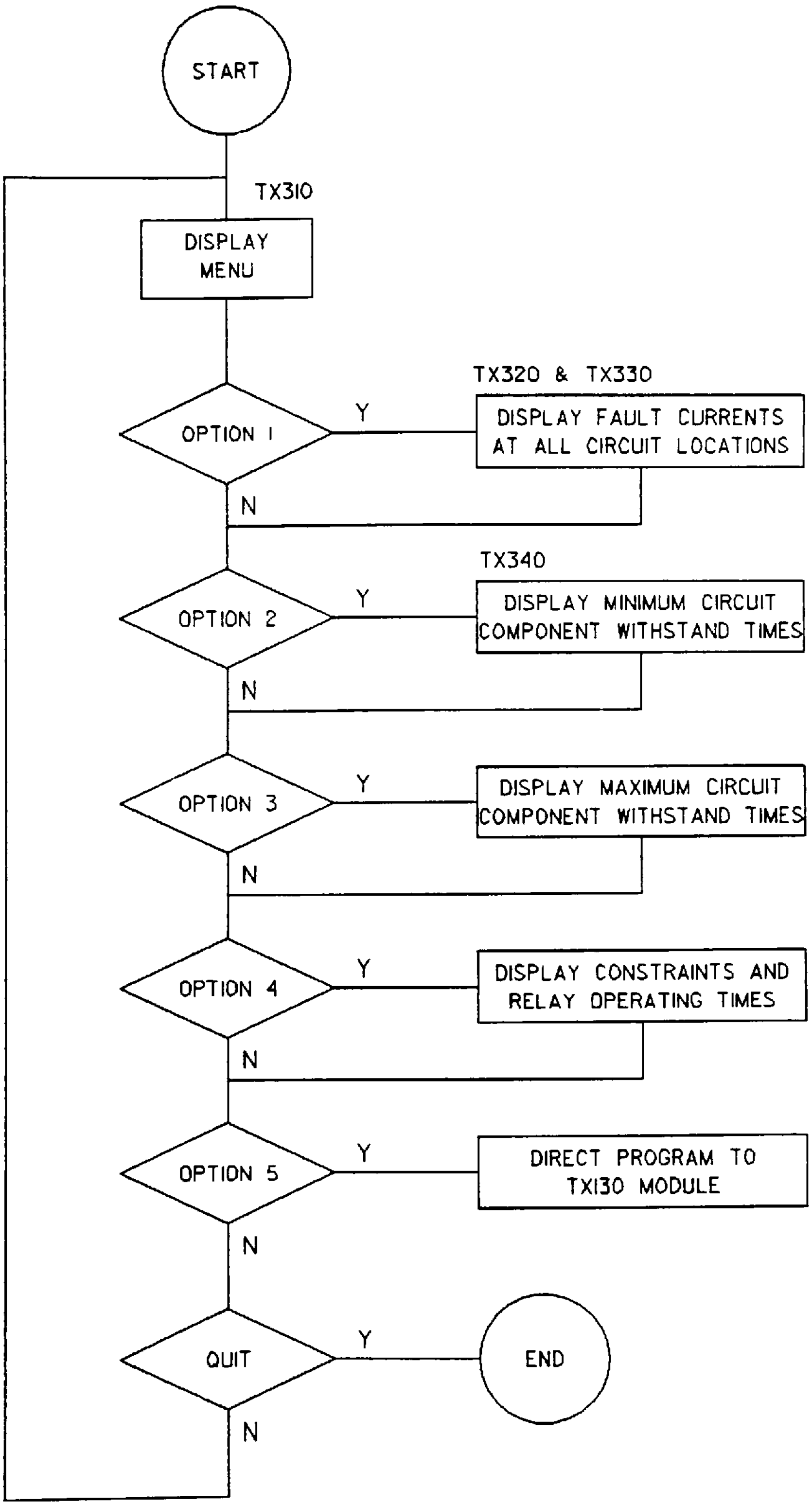



Fig 6.26

| VARIABLE SPEED DRIVE TRANSFORMER PROTECTION FAULT CONDITIONS | | | | | | |
|---|---|---|---|---|---|---|
| FAULT LOCATION | MINIMUM | | | MAXIMUM | | |
| | PH-E | PH-PH | 3-PH | PH-E | PH-PH | 3-PH |
| Source | 1000 | 4330 | 5000 | 5000 | 21650 | 25000 |
| Transformer HV Term' HV Amps | 976 | 4093 | 4726 | 4460 | 15743 | 18178 |
| | PH-PH | | | PH-PH | | |
| TX1 P/SHFT + 0.0 LV Term' HV Amps | 375 | 375 | 433 | 403 | 403 | 465 |
| TX2 P/SHFT +30.0 LV Term' HV Amps | 433 | 216 | 433 | 465 | 232 | 465 |
| TX3 P/SHFT + 0.0 LV Term' HV Amps | 543 | 543 | 628 | 604 | 604 | 697 |
| TX4 P/SHFT +30.0 LV Term' HV Amps | 628 | 314 | 628 | 697 | 349 | 697 |
| TX5 P/SHFT + 0.0 LV Term' HV Amps | 622 | 622 | 718 | 702 | 702 | 811 |
| TX6 P/SHFT +30.0 LV Term' HV Amps | 718 | 359 | 718 | 811 | 405 | 811 |
| Select option | | | | <P>ageback<br><Q>uit | | |

*Fig 6.27 Fault condition summary.*

| FLC 110 | | | VARIABLE SPEED DRIVE TRANSFORMER PROTECTION WITHSTAND TIMES / PROTECTION CLEARING TIMES | | | | | CT.R 300/1 |
|---|---|---|---|---|---|---|---|---|
| | | | MINIMUM SOURCE IMPEDANCE | | | | | |
| FAULT | | | PH-E | | PH-PH | | 3-PH | |
| Source | PCC | Secs | 7.240 | 0.519 | 0.393 | 0.248 | 0.290 | 0.240 F |
| Trafo | HV Term' | Secs | 9.093 | 0.532 | 0.743 | 0.266 | 0.557 | 0.258 |
| | | | PH-PH | | PH-PH | | 3-PH | |
| TX1 + 0 | LV Term' | Secs | 2.092 | 1.673 | 2.092 | 1.673 | 2.092 | 1.395 |
| TX2 +30 | LV Term' | Secs | 2.789 | 1.395 | 2.789 | 1.395 | 2.092 | 1.395 |
| TX3 + 0 | LV Term' | Secs | 2.141 | 1.070 | 2.141 | 1.070 | 2.141 | 0.948 |
| TX4 +30 | LV Term' | Secs | 2.854 | 0.948 | 2.854 | 0.948 | 2.141 | 0.948 |
| TX5 + 0 | LV Term' | Secs | 2.165 | 0.943 | 2.165 | 0.943 | 2.165 | 0.847 |
| TX6 +30 | LV Term' | Secs | 2.887 | 0.847 | 2.887 | 0.847 | 2.165 | 0.847 |
| Select option | | | O/C 0.65 | /0.175 | | | <P>ageback | |
| <C>haracteristic menu | | | E/F 0.10 | /0.400 | | | <Q>uit | |

*Fig 6.28 Transformer withstand times/protection clearing times supplied from a minimum source impedance*

VARIABLE SPEED DRIVE TRANSFORMER PROTECTION
WITHSTAND TIMES / PROTECTION CLEARING TIMES

MAXIMUM SOURCE IMPEDANCE

| FAULT | | | PH-E | | PH-PH | | 3-PH | |
|---|---|---|---|---|---|---|---|---|
| Source | PCC | Secs | **.*** | 0.770 | 9.829 | 0.382 | 7.370 | 0.365 |
| Trafo | HV Term' | Secs | **.*** | 0.776 | *.*** | 0.390 | 8.249 | 0.372 |
| | | | PH-PH | | PH-PH | | 3-PH | |
| TX1 | + 0.0 LV Term' | Secs | 2.414 | 1.858 | 2.414 | 1.858 | 2.414 | 1.521 |
| TX2 | +30.0 LV Term' | Secs | 3.219 | 1.521 | 3.219 | 1.521 | 2.414 | 1.521 |
| TX3 | + 0.0 LV Term' | Secs | 2.644 | 1.182 | 2.644 | 1.182 | 2.644 | 1.035 |
| TX4 | +30.0 LV Term' | Secs | 3.526 | 1.035 | 3.526 | 1.035 | 2.644 | 1.035 |
| TX5 | + 0.0 LV Term' | Secs | 2.762 | 1.043 | 2.762 | 1.043 | 2.762 | 0.927 |
| TX6 | +30.0 LV Term' | Secs | 3.683 | 0.927 | 3.683 | 0.927 | 2.762 | 0.927 |

Select option — O/C 0.65 /0.175 — <P>ageback
<C>haracteristic menu — E/F 0.10 /0.400 — <Q>uit

*Fig 6.29 Transformer withstand times/protection clearing times supplied from a maximum source impedance*

### 6.7.30 TX360

The function of this routine is to display the circuit overload constraints and list alongside each the operating time of the relay together with a label which indicates if the relay setting is sufficient to allow the overload to occur. Fig. 6.30 depicts a typical screen display.

## 6.8 Interim Conclusion

The work detailed in this chapter can effect considerable savings in research, equipment and engineering time. This is particularly evident in the case of transformers wound with unusual vector group configurations as sited in Case 1 or, alternatively, multiple transformer circuits as discussed in Case 2. The financial saving can be substantial.

The work succeeds in providing an algorithmic approach for the selection of protection equipment, relay characteristics and associated settings when applied to drive transformer installations. A full account is taken of all manufacturers declared operating tolerances together with additional allowances which are made for switchgear clearing times. The algorithm developed effects further savings by including source impedance details from which the minimum cable size applicable to the installation may be determined.

The algorithm can be extended to achieve further substantial savings by considering the cabling on the low voltage (LV) side of the transformers. This LV cabling is of large cross-sectional area, often using two or three conductors per phase to satisfy the heavy current requirements. The potential savings that can be achieved are obtained by the installation of instantaneous overcurrent protection on the secondary side of the transformers. The protection inequalities

VARIABLE SPEED DRIVE TRANSFORMER PROTECTION
CIRCUIT CONSTRAINTS / PROTECTION CLEARING TIMES

Supply voltage .... 6350/11000 Full load current ...... 110
Overload Constraints ....... 3 CT.Ratio .... 300/1

| CONSTRAINT No | CURRENT Amps | DURATION Secs | RLY TIME Secs | REMARKS |
|---|---|---|---|---|
| £1 | 175 | 14.0 | **.*** | STABLE |
| £2 | 200 | 9.0 | **.*** | STABLE |
| £3 | 337 | 2.0 | 2.227 | PASS |

Select option O/C 0.65 /0.175 <P>ageback
<Q>uit

*Fig 6.30 Circuit constraints/protection clearing times*

in the algorithm could then be extended so that the HV IDMTL overcurrent relay is required to protect the LV cabling up to the operating setting of the LV instantaneous relay only.

This work has not been carried out because it is usual for the LV cabling to be supplied and protected by the drive equipment supplier, it can however be incorporated if so desired. The concept of adaptive relaying may be fully exploited in this application as relays are now available with settings which can be changed from a remote location. Such relays can be incorporated in many innovative schemes whereby protection settings may be optimised to suit circuit conditions then subsequently changed to satisfy other product mixes. A further option which is worthy of further exploration is to subdivide the outgoing plant cables into groups and provide separate protection to each subgroup based on the principles previously discussed. All subgroups could be supplied from a common circuit breaker. The range of circuit permutations available is quite large but close study will result in substantial savings and provide a sound engineering solution.

# CHAPTER 7

## Conclusion

The scope of this thesis as detailed in Chapter 2, has been effectively fulfilled in the preceding text. The text describes the considerable benefits that may be realised by industry following a rigorous analysis of the intended application.

The problems analysed and solutions suggested may be divided into two parts. The first part deals with the protection application requirements for direct-on-line started motors which are of fundamental importance in heavy industry. The benefits which can be accrued by using this novel approach to exploit the repetitive nature of the task, will effect substantial savings in engineering time, switchgear and cabling costs.

The work detailed in the text will remove much of the repetition work as applied to conventional drive installations, thus allowing engineering time to be used more effectively on installations requiring closer scrutiny. The novel algorithms developed can be easily expanded to incorporate any additional requirements that were suggested as the work proceeded. This tendency has been restrained to some extent to restrict the work within defined limits but they will no doubt be incorporated in due course.

The section of the work concerned with the protection of transformer fed variable speed drives is the area where the greatest single economic benefit can be obtained. The case studies discussed demonstrate the practicalities of the techniques which are used, whilst the enhancements suggested will enable maximum utilisation of the equipment to be obtained.

## 7.1 Future Enhancements

In order to further improve the overall performance of the combined programs, the following areas should be addressed to provide the greatest benefit.

1. More detailed determination of fuse characteristics would be desirable together with an expanded database of contactor equipment characteristics from which fuses and contactor characteristics could be coordinated.

2. More advanced motor protection relays are now available which overcome some of the deficiencies listed in the text. Typical features now incorporated allow the adjustment of the 'hot' operating characteristic independently to that of the cold operating characteristic. Some relays also allow the immediate resetting of the 'hot' characteristic to the 'cold' curve following receipt of an external command. Algorithms using an expanded set of comparisons could be devised to gain maximum utilisation from these improved devices.

3. A further desirable feature would be the addition of a simple impedance measuring device. Such a device could monitor changes in power factor and provide immediate indication of a locked rotor condition during the acceleration period.

4. During the 'run' mode, most machines would benefit from the use of a more inverse characteristic to effectively accelerate tripping for abnormal conditions. Instantaneous or definite time tripping could also be incorporated for activation or blocking above certain user defined overload levels.

5. In the case of transformer fed variable speed drive installations, the use of 'adaptive relaying' techniques either by operator control or by automatic means will considerably enhance the opportunity for closer protection and for major economies to be made. Maximum benefit could be obtained in some cases by dividing the outgoing circuits into separately protected subgroups.

## Bibliography

BS142 - Electrical protective relays

GEC Alsthom Publication No. R-5171

GEC Alsthom Publication No. R-5738

Protection of Industrial Power Systems by T. Davies

Power System protection Volumes 1,2 & 3 - Electricity Council

Protective Relay Application Guide - GEC Measurements

Advanced Motor Protection using microcomputers - J. Brandolino, Multilin

Short circuit currents in three-phase networks - Siemens

Micro-Golds relay instruction manual - P&B Golds

Computer Relaying for Power Systems - A.G. Phadke, J.S. Thorp

## APPENDIX 1

### Determining the Motor Withstand Characteristics

Consider the thermal withstand capability of the motor to be represented in the overload region by a single time constant exponential characteristic, then:

Actual temperature = Final rated temperature - Temperature difference • $e^{-t/\tau}$

$$\theta = \theta m2 - (\theta m2 - \theta r)e^{-t/\tau} \qquad \textbf{(A1.1)}$$

where:

| | | |
|---|---|---|
| θm2 | = | Final rated temperature |
| θr | = | Starting temperature (typical maximum value 40°C) |
| t | = | Elapsed time |
| τ | = | Motor heating time constant |

Subtracting θr from both sides of the equation gives

$$\theta - \theta r = \theta m2 - \theta r - (\theta m2 - \theta r)e^{-t/\tau} \qquad \textbf{(A1.2)}$$

Let θm1 be the maximum allowable temperature at which disconnection must take place (typically 135°C - This gives a 20°C margin for class F insulated machines).

Then θm1 = θ

Substituting in equation A1.2

$$\theta m1 - \theta r = \theta m2 - \theta r - (\theta m2 - \theta r)e^{-t/\tau}$$

$$\theta m1 - \theta r = (1 - e^{-t/\tau})(\theta m2 - \theta r)$$

$$\frac{\theta m1 - \theta r}{\theta m2 - \theta r} = 1 - e^{-t/\tau}$$

$$e^{-t/\tau} = 1 - \frac{\theta m1 - \theta r}{\theta m2 - \theta r}$$

$$e^{-t/\tau} = \frac{\theta m2 - \theta r - (\theta m1 - \theta r)}{\theta m2 - \theta r}$$

$$e^{-t/\tau} = \frac{\theta m2 - \theta m1}{\theta m2 - \theta r}$$

$$e^{t/\tau} = \frac{\theta m2 - \theta r}{\theta m2 - \theta m1}$$

$$t = \tau \log_e \left( \frac{\theta m2 - \theta r}{\theta m2 - \theta m1} \right)$$

rearranging gives

$$t = \tau \log_e \left( \frac{\theta m2 - \theta r}{(\theta m2) - (\theta m1)} \right) \tag{A1.3}$$

$$= \tau \log_e \left( \frac{\theta m2 - \theta r}{(\theta m2 - \theta r) - (\theta m1 - \theta r)} \right) \tag{A1.4}$$

Let temperature rise to final rated temp = $\theta m2 - \theta r$ = $\Delta\theta m2$

Let temperature rise to disconnection temp = $\theta m1 - \theta r$ = $\Delta\theta m1$

Substituting in equation A1.3

$$t = \tau \log_e \left( \frac{\Delta\theta m2}{\Delta\theta m2 - \Delta\theta m1} \right)$$

| | | | |
|---|---|---|---|
| For typical values of | ambient temperature (40°C) | - | θr |
| | disconnection temperature (135°C) | - | θm1 |
| | running temperature (120°C) | - | θm2 |

The continuous overload capability

$$Ipu = \sqrt{\frac{\Delta\theta m1}{\Delta\theta m2}}$$

$$Ipu = \sqrt{\left( \frac{\theta m1 - \theta r}{\theta m2 - \theta r} \right)} = \sqrt{\left( \frac{135-40}{120-40} \right)} = 1.09$$

= 9% Continuous overload capability.

Using equation A1.3

$$t = \tau \log_e \left( \frac{\theta m2 - \theta r}{\theta m2 - \theta m1} \right)$$

It can be seen that the numerator contains θr which is the starting temperature of the machine. When the machine is started from cold, θr = ambient temperature.

| | | |
|---|---|---|
| Now | θm2 ∝ multiple of motor current | $P^2$ |
| | θr ∝ motor load current | $I_L^2$ |

So θm2 - θr ∝ $P^2 - I_L^2$

Substituting in equation A1.3

$$t = \tau \log_e \left( \frac{P^2 - I_L^2}{P^2 - \theta m1} \right)$$

Consider the cold withstand characteristic where $I_L = 0$

then

$$t = \tau \log_e \left( \frac{P^2}{P^2 - \theta m1} \right) \quad \text{(A1.5)}$$

Now θm1, the disconnection temperature ∝ $I^2$, the current required to achieve the disconnection temperature.

Expressing I as a multiple of the relay basic current $I_B$

$$I = k \bullet I_B$$

Substituting in equation A1.5

$$t = \tau \log_e \left( \frac{P^2}{P^2 - (k \bullet I_B)^2} \right)$$

which is generally in accordance with the A.1 characteristic referred to in Appendix A of BS 142 Section 2.3.

Consider the hot withstand chararacteristic with an initial temperature of θr where θr ∝ $I_L^2$

then

$$t = \tau \log_e \left( \frac{P^2 - I_L^2}{P^2 - (k \bullet I_B)^2} \right)$$

which is of the general form B.1 referred to in Appendix B of BS 142 Section 2.3.

# APPENDIX 2

## Prediction of motor acceleration times for directly coupled motor/drive units

A common method which uses the principle of numerical integration to predict accelerating times of a motor/drive unit is described below. Greater accuracy can be obtained by increasing the number of ordinates used. This increased accuracy is however, seldom required.

Let torque available to accelerate the motor and drive unit =
Torque produced by motor - Torque required by drive

For circular motion

Torque = Moment of Inertia • Angular acceleration

Substituting T = Torque

I = Moment of Inertia

ω = Angular velocity

$$So \quad \frac{d\omega}{dt} = Angular\ acceleration$$

We have

$$T = I \bullet \frac{d\omega}{dt}$$

$$\frac{d\omega}{dt} = \frac{T}{I}$$

$$\frac{dt}{d\omega} = I \bullet \frac{1}{T}$$

$$t = I \int \frac{1}{T}\, d\omega \qquad (2.1)$$

$$Now\ \omega\ rads/sec = \frac{2 \bullet \pi \bullet N}{60} \quad where\ N\ is\ RPM$$

Substituting in equation 2.1

$$t = \frac{2 \bullet \pi \bullet I}{60} \int_{o}^{N'} \frac{1}{T}\, dN \quad where\ N'\ is\ full\ load\ RPM \qquad (2.2)$$

The value of equation 2.2 may be calculated by drawing the curve and using numerical integration to calculate the area bounded by the curve.

The programs discussed in Chapters 4 and 5 utilize a conceptual acceleration time based on a constant voltage being available at the motor terminals during the acceleration period. Three voltage level conditions are examined in the motor protection relay programs. The first case examined requires the acceleration time for the motor supplied at 100% line volts, the other two cases require the same data for user defined over and undervoltage conditions.

To illustrate a method used to determine acceleration time, a typical motor/fan installation is discussed. Details of the motor used are contained in the test certificate shown in Fig. A2.1 whilst Fig. A2.2 shows its torque/speed characteristic. To avoid repetition only two conditions are considered, the nominal voltage condition and the undervoltage condition which in this case is 90% of nominal voltage. The reduced terminal voltage is reflected in a reduction in output torque to $0.9^2$pu of the nominal value at any given RPM. The consequential acceleration period being a function of the excess torque produced by the motor over that demanded by the plant.

**OFFICIAL TEST RECORD OF** T/Encl. CACA Squirrel Cage **A.C. INDUCTION MOTOR No** ____________

**CUSTOMER** ______________________ **SIZE** D355-8B

**OUTPUT :** 120 **KW** 3300 **VOLTS** 29.0 **AMPS** 740 **R.P.M.** 50 **CYCLES** 3 **PHASE**

| NO LOAD READINGS | | | |
|---|---|---|---|
| | Phase 1 | Phase 2 | Phase 3 |
| Volts | 3300 | | 3300 |
| Amps | 12.45 | | 12.45 |
| R.P.M. | | 750 | |
| Cycles | | 50 | |
| (Watts x 225) | 103 | | -80 |

| STARTING TORQUE | | | | | |
|---|---|---|---|---|---|
| Volts | Amps | Nm | %F.L.T. | %F.L.C. | Conn. |
| 3300 | 118.0 | 1396 | 122 | 407 | Y |
| | | | | | |
| SHORT CIRCUIT READING | | | | | |
| Volts | Amps | W1(x 225) | W2 | | |
| 847.5 | 28.8 | 80 | -25 | | |

No load loss = Total loss - $I^2R$ = 4741

| Time | Volts | Stator Amps | Cycles | R.P.M. | | KW | KVA | PF | | KW Output | Eff % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 7.00 | 3300 | 28.875 | 50 | 745 | | | | | | | |
| 7.30 | " | " | " | | | | | | | | |
| 8.00 | " | " | " | | | | | | | | |
| 8.30 | " | " | " | 743 | | | | | | | |
| 9.00 | " | " | " | | | | | | | | |
| 9.30 | " | " | " | | | | | | | | |
| 10.00 | " | " | " | 742 | | | | | | | |
| 10.30 | " | " | " | | | | | | | | |
| 11.00 | " | " | " | | | | | | | | |
| 11.30 | 3300 | 28.875 | 50 | 742 | | 129.15 | 165.04 | .783 | | 120.17 | 93.0 |
| Stator winding temperature rise by resistance = 49°c | | | | | | | | | | | |
| | | | | | | | | | | | |
| 3/4 | 3300 | 21.75 | 50 | 744 | | 86.625 | 124.31 | .697 | | 79.58 | 91.9 |
| 1/2 | " | 14.475 | " | 746 | | 33.75 | 82.73 | .408 | | 28.41 | 84.2 |
| O/Load | " | 43.5 | " | 736 | | 197.1 | 248.63 | .793 | | 182.2 | 92.4 |
| | | | | | | | | | | | |
| Calculated Pull-out Torque = 2.03 FLT | | | | | | | | | | | |
| | | | | | | | | | | | |
| Heater - 292 Watts at 110 volts | | | | | | | | | | | |

| RESISTANCE (OHMS) ACROSS TERMINALS | | |
|---|---|---|
| | COLD 20°c | HOT 21°c |
| Stator | 1.53 | 1.83 |
| Conn. | 1.53 | 1.83 |
| Y | 1.53 | 1.83 |
| Rotor | | |
| Conn. | | |
| | | |

**HIGH PRESSURE INSULATION TEST**

**Stator flashed to earth for 1min. at 7600 V.A.C. Insulation Resistance 350 M**

**Heater flashed to earth for 1min. at 1200 V.A.C. Insulation Resistance 100 M**

Fig A2.1 MANUFACTURERS TYPICAL MOTOR TEST RECORD

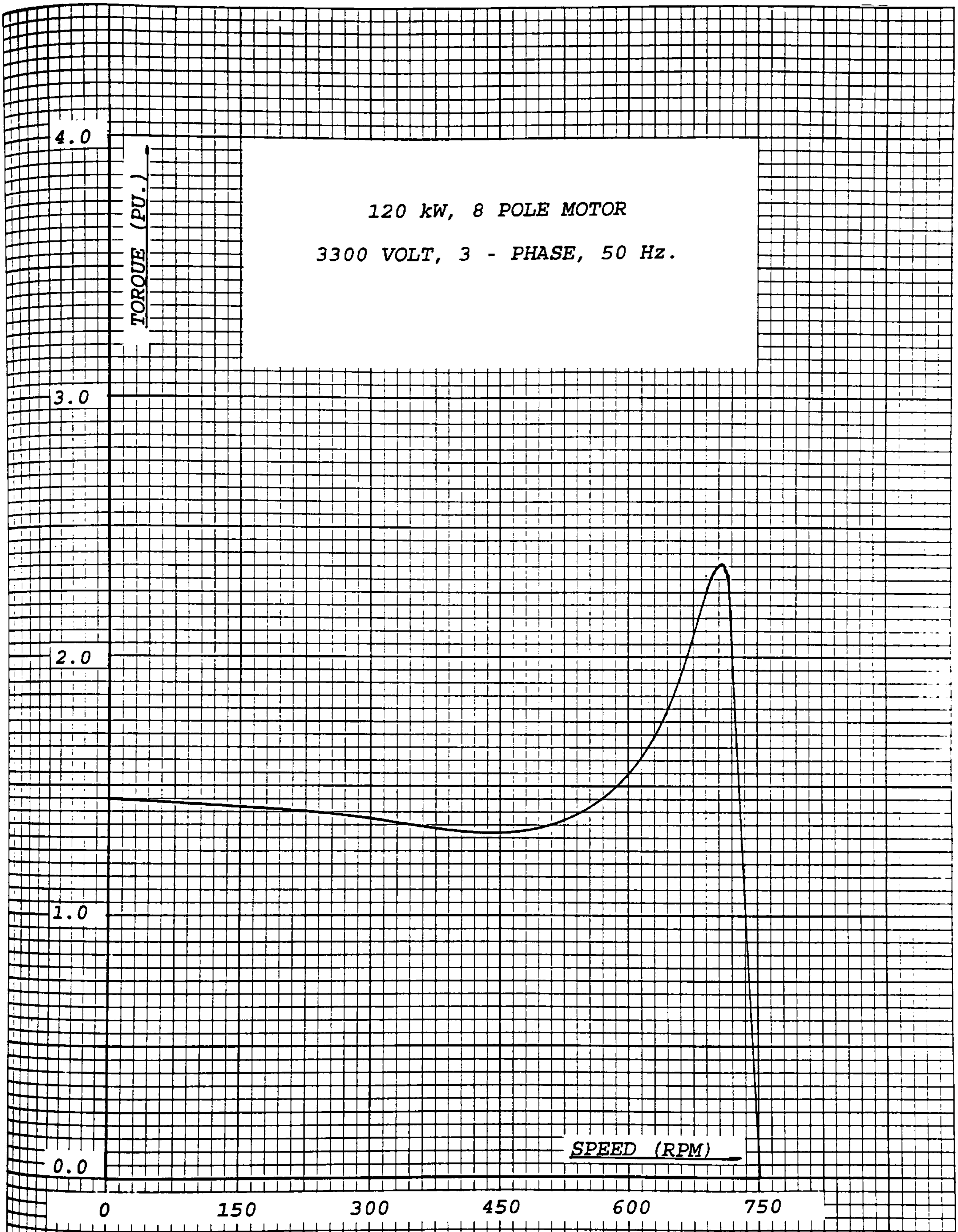



Fig A2.2 TORQUE/SPEED CHARACTERISTIC

Consider a 3.3kV, 120kW, 8 Pole motor driving a fan. The inertia of the rotating parts are:

Motor: 37 $kgm^2$

Fan: 342 $kgm^2$

By examination of the manufacturers published data, a set of torque/speed coordinates have been tabulated for both the motor and the fan. These coordinates are shown in table A2.1.

The data tabulated has been rearranged into more manageable form using a Neville-Aitken Interpolation program. The results of the rearrangement are shown in Tables A2.2 and A2.3. Table A2.2 details the nominal voltage case whilst Table A2.3 refers to the condition with minimum voltage applied to the motor.

An explanation of the table follows

Column 1 - RPM values

Column 2 - Motor Torque

Column 3 - Fan Torque

Column 4 - Accelerating Torque

Where Accelerating Torque = Motor Torque - Fan Torque

Column 5 - Average accelerating torque throughout RPM step

That is, typically 50-100 RPM step

$$Average\ Accelerating\ Torque = \frac{Torque\ at\ 100\ RPM - Torque\ at\ 50\ RPM}{2}$$

<u>**Table A2.1**</u>

| Motor | | Fan | |
|---|---|---|---|
| RPM | Torque pu | RPM | Torque pu |
| 0 | 1.45 | 0 | 0.0 |
| 50 | 1.44 | 75 | 0.02 |
| 100 | 1.425 | 150 | 0.04 |
| 150 | 1.415 | 225 | 0.085 |
| 200 | 1.4 | 300 | 0.155 |
| 250 | 1.38 | 375 | 0.25 |
| 300 | 1.365 | 450 | 0.355 |
| 350 | 1.34 | 525 | 0.49 |
| 400 | 1.325 | 600 | 0.64 |
| 450 | 1.32 | 675 | 0.815 |
| 500 | 1.345 | 750 | 1.0 |
| 550 | 1.41 | | |
| 600 | 1.54 | | |
| 650 | 1.82 | | |
| 700 | 2.32 | | |
| 710 | 2.35 | | |
| 750 | 0 | | |

Where: For the motor

$$Full\ load\ speed = 740\ RPM$$

$$1pu.\ Torque = \frac{120 \bullet 10^3 \bullet 60}{2 \bullet \Pi \bullet 740}$$

$$= 1549\ Nm$$

For the fan

$$1pu.\ Torque = 1329\ Nm$$

| R.P.M. | MOTOR TORQUE NM | FAN TORQUE NM | ACCEL. TORQUE NM | AV. ACCEL. TORQUE NM | Δ R.P.M. | ACCEL. TIME (S) |
|---|---|---|---|---|---|---|
| 0 | 2246 | 0.00 | 2246 | | | |
| 50 | 2230 | 19.02 | 2212 | 2229.0 | 50 | 0.89 |
| 100 | 2207 | 34.06 | 2173 | 2192.5 | 50 | 0.91 |
| 150 | 2192 | 53.00 | 2139 | 2156.0 | 50 | 0.92 |
| 200 | 2169 | 89.02 | 2080 | 2109.5 | 50 | 0.94 |
| 250 | 2138 | 140.18 | 1997 | 2038.5 | 50 | 0.97 |
| 300 | 2114 | 206.00 | 1908 | 1952.5 | 50 | 1.02 |
| 350 | 2076 | 288.11 | 1788 | 1848.0 | 50 | 1.07 |
| 400 | 2052 | 376.06 | 1676 | 1732.0 | 50 | 1.15 |
| 450 | 2045 | 472.00 | 1573 | 1624.5 | 50 | 1.22 |
| 500 | 2083 | 588.16 | 1495 | 1534.0 | 50 | 1.29 |
| 550 | 2184 | 714.97 | 1469 | 1482.0 | 50 | 1.34 |
| 600 | 2385 | 851.00 | 1534 | 1501.5 | 50 | 1.32 |
| 650 | 2819 | 1003.75 | 1815 | 1674.5 | 50 | 1.19 |
| 700 | 3594 | 1162.16 | 2432 | 2123.5 | 50 | 0.93 |
| 710 | 3640 | 1194.91 | 2445 | 2438.5 | 10 | 0.16 |
| 740 | ~1296 | ~1296 | 0 | 1222.5 | 30 | 0.97 |

TOTAL ACCELERATING TIME WITH 100% LINE VOLTS APPLIED = Σ COL 7 = 16.30 SECS

TABLE A2.2

| R.P.M. | MOTOR TORQUE NM | FAN TORQUE NM | ACCEL. TORQUE NM | AV. ACCEL. TORQUE NM | Δ R.P.M. | ACCEL. TIME (S) |
|---|---|---|---|---|---|---|
| 0 | 1819 | 0.00 | 1819 | | | |
| 50 | 1806 | 19.02 | 1781 | 1800.0 | 50 | 1.10 |
| 100 | 1788 | 34.06 | 1754 | 1767.5 | 50 | 1.12 |
| 150 | 1776 | 53.00 | 1723 | 1738.5 | 50 | 1.14 |
| 200 | 1755 | 89.02 | 1666 | 1694.5 | 50 | 1.17 |
| 250 | 1732 | 140.18 | 1592 | 1629.0 | 50 | 1.22 |
| 300 | 1712 | 206.00 | 1506 | 1549.0 | 50 | 1.28 |
| 350 | 1682 | 288.11 | 1393 | 1449.5 | 50 | 1.37 |
| 400 | 1662 | 376.06 | 1286 | 1339.5 | 50 | 1.48 |
| 450 | 1656 | 472.00 | 1184 | 1235.0 | 50 | 1.61 |
| 500 | 1687 | 588.16 | 1099 | 1141.5 | 50 | 1.74 |
| 550 | 1769 | 714.97 | 1054 | 1076.5 | 50 | 1.84 |
| 600 | 1932 | 851.00 | 1081 | 1067.5 | 50 | 1.86 |
| 650 | 2283 | 1003.75 | 1280 | 1180.5 | 50 | 1.68 |
| 700 | 2911 | 1162.16 | 1749 | 1514.5 | 50 | 1.31 |
| 710 | 2948 | 1194.91 | 1753 | 1751.0 | 10 | 0.23 |
| 737 | ~1285 | ~1285 | 0 | 875.5 | 27 | 1.22 |

TOTAL ACCELERATING TIME WITH 90% LINE VOLTS APPLIED = Σ COL 7 = 21.38 SECS

TABLE A2.3

Column 6 - RPM step length

Column 7 - Acceleration time in seconds for column 6. The step length is derived as stated previously from:

$$t = \frac{2 \bullet \Pi \bullet I}{60} \int_{o}^{N} \frac{1}{T}\, dN$$

Substituting we have

$$t = \Sigma t'$$

$$where\ t' = \frac{2 \bullet \Pi \bullet I}{60} \bullet \frac{(37 + 342) \bullet \Delta RPM}{Torque}$$

where t' is the accelerating time for Δ RPM step length considered

Torque means average accelerating torque.

## APPENDIX 3

### Harmonics in the Supply Voltage

When speed control of electric motors is considered, the modern approach is to incorporate some form of non-linear device in the control unit. These control units effect control over the motor by varying the output voltage or frequency or a combination of both, generally by utilising solid state thyristor type equipment. The object of the control philosophy is to determine the point on the waveform at which the devices are allowed to conduct, thus it can be seen that the resulting current flow is non-sinusoidal in nature.

It can be shown that any complex waveform may be considered as the addition of a number of sinusoidal waveforms comprising of a fundamental frequency and harmonic terms. If an examination of the complex wave reveals that the positive half cycle differs from the negative half cycle, then an even harmonic (for example, a second harmonic) will be present. Such is the case where rectifying equipment or speed control of motors by phase control of semiconductors is employed.

Consider a 3-phase supply with a second harmonic content

$$vr = VR1\,Sin\,(\omega t + \psi 1) + VR2\,Sin\,(2\omega t + \psi 2)$$

$$vy = VY1\,Sin\,(\omega t - \frac{2\pi}{3} + \psi 1) + VY2\,Sin\,(2(\omega t - \frac{2\pi}{3}) + \psi 2)$$

and

$$vb = VB1\,Sin\,(\omega t - \frac{4\pi}{3} + \psi 1) + VB2\,Sin\,(2(\omega t - \frac{4\pi}{3}) + \psi 2)$$

where

vr, vy and vb = Instantaneous voltage values

| | | |
|---|---|---|
| VR1, VY1 and VB1 | = | peak voltage values of the fundamental |
| VR2, VY2 and VB2 | = | peak voltage values of the second harmonic |
| $\omega$ | = | $2\pi f$, the angular frequency where f is Hertz |
| $\psi 1$ | = | Phase angle of the fundamental waveform |
| $\psi 2$ | = | Phase angle of the harmonic component |

reducing the above

$$vr = VR1\,Sin\,(\omega t + \psi 1) + VR2\,Sin\,(2\omega t + \psi 2)$$

$$vy = VY1\,Sin\,(\omega t - 120° + \psi 1) + VY2\,Sin\,(2\omega t - 240° + \psi 2)$$

$$vb = VB1\,Sin\,(\omega t - 240° + \psi 1) + VB2\,Sin\,(2\omega t - 120°) + \psi 2)$$

Fig. A3.1 depicts the above waveforms where it can be clearly seen that the second harmonic has a negative phase sequence.

Harmonics are also produced from other sources such as in the output of generators caused by for instance non-sinusoidal air gap flux distribution. Iron cored coils such as reactors or transformers are also harmonic generators owing to the non-linear characteristic of the B-H curve. The greater the saturation the more harmonic distortion will be present. The resultant waveforms will be symmetrical in nature which indicates that no even harmonic components are present. The resultant distortion being caused by odd harmonic values.

Consider a 3-phase supply with odd harmonic content (symbols as previous)

$$vr = VR1\,Sin\,(\omega t + \psi 1) + VR3\,Sin\,(3\omega t + \psi 3) + VR5\,Sin\,(5\omega t + \psi 5)$$

$$vy = VY1\,Sin\,(\omega t - \frac{2\pi}{3} + \psi 1) + VY3\,Sin\,(3(\omega t - \frac{2\pi}{3}) + \psi 3) + VY5\,Sin\,(5(\omega t - \frac{2\pi}{3}) + \psi 5)$$

$$vb = VB1\ Sin\,(\omega t - \frac{4\pi}{3} + \psi 1) + VB3\ Sin\,(3(\omega t - \frac{4\pi}{3}) + \psi 3) + VB5\ Sin\,(5(\omega t - \frac{4\pi}{3}) + \psi 5)$$

which reduces to

$$vr = VR1\ Sin\,(\omega t + \psi 1) + VR3\ Sin\,(3\,\omega t + \psi 3) + VR5\ Sin\ (5wt + \psi 5)$$

$$vy = VY1\ Sin\,(\omega t - 120^\circ + \psi 1) + VY3\ Sin\,(3\omega t + \psi 3) + Vr5\ Sin\ (5wt - 240^\circ + \psi 5)$$

$$vb = VB1\ Sin\,(\omega t - 240^\circ + \psi 1) + VB3\ Sin\,(3\,\omega t + \psi 3) + VB5\ Sin\ (5wt - 120^\circ + \psi 5)$$

From which it can be seen that the third harmonic is zero phase sequence in nature. This is illustrated in Fig. A3.2. Similarly it can be shown that the third and all triplen harmonics are co-phasal.

The fifth harmonic can be seen to have a negative phase sequence as was observed with the second harmonic. It can be shown that the 5th, 11th, 17th etc. harmonics all exhibit negative phase sequence characteristics.

The effect of negative phase sequence components in the supply is discussed in Appendix 4.

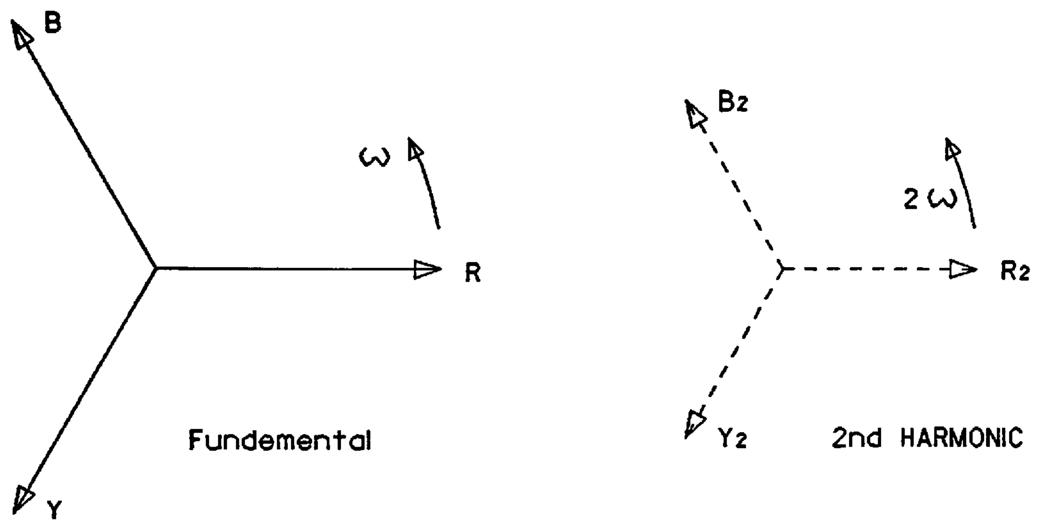



Fig A3.1 FUNDEMENTAL AND 2nd HARMONIC

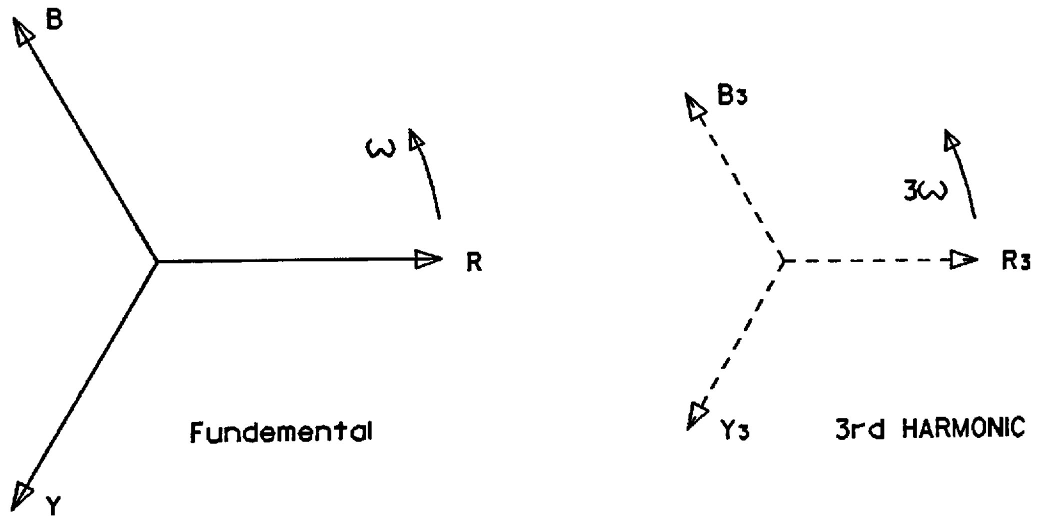



Fig A3.2 FUNDEMENTAL AND 3rd HARMONIC

## APPENDIX 4

### Effects of Unbalanced Supply Voltage

Consider the equivalent circuit diagram of an induction motor shown in Fig. A4.1. The positive phase sequence impedance of the motor equivalent circuit is:

$$Z = R_{S1} + jX_{S1} + R_{R1} + jX_{R1} + \frac{1-S}{S} R_{R1} \qquad \text{(A4.1)}$$

where: suffix R1 values are rotor values

suffix S1 refers to stator values

from which

$$Z = R_{S1} + R_{R1} + \frac{1-S}{S} R_{R1} + jX_{S1} + jX_{R1}$$

$$= R_{S1} + R_{R1} \left( \frac{S + (1-S)}{S} \right) + j(X_{S1} + X_{R1})$$

$$= R_{S1} + R_{R1}/S + j(X_{S1} + X_{R1})$$

$$Z = \sqrt{\left( (R_{S1} + R_{R1}/S)^2 + (X_{S1} + X_{R1})^2 \right)} \qquad \text{(A4.2)}$$

Differences will occur in individual equivalent circuit component values, mainly in rotor values. Disregarding the magnetising losses the circuit can be further simplified to that shown in Fig. A4.2.

In the case of negative sequence impedance of the motor equivalent circuit, the slip frequency seen by the rotor is again a function of rotor speed (see Fig. A.4.3). The slip value being 2-S pu. Note at rotor standstill slip = 2-1 = 1 pu. which is

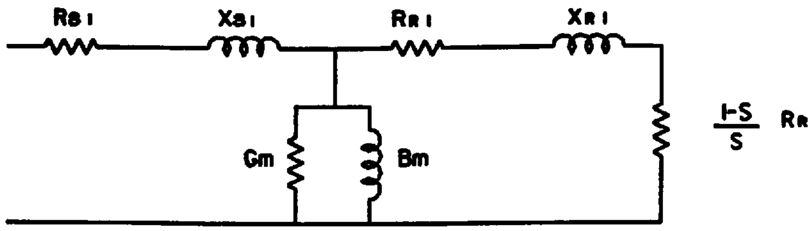



Fig A4.1 EQUIVALENT CIRCUIT REPRESENTATION OF A 3-PHASE INDUCTION MOTOR UNDER BALANCED CONDITIONS

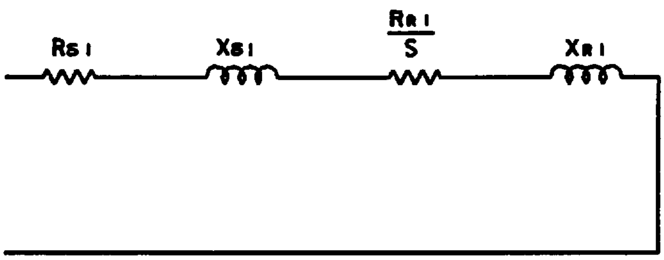



Fig A4.2 SIMPLIFIED 3-PHASE INDUCTION MOTOR PPS EQUIVALENT CIRCUIT

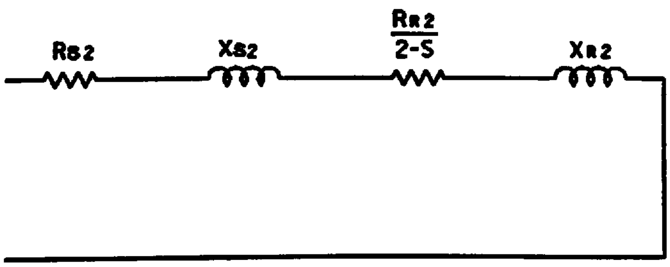



Fig A4.3 SIMPLIFIED 3-PHASE INDUCTION MOTOR NPS EQUIVALENT CIRCUIT identical with the slip seen by the positive sequence network under rotor standstill conditions.

The impedance of the negative phase sequence equivalent circuit is therefore

$$Z = \sqrt{\left( (R_{S2} + \frac{R_{R2}}{2-S})^2 + (X_{S2} + X_{R2})^2 \right)} \quad \textbf{(A4.3)}$$

from which under running conditions the negative phase sequence impedance approximates to:

$$Z = \sqrt{\left( (R_{S2} + \frac{R_{R2}}{2})^2 + (X_{S2} + X_{R2})^2 \right)} \quad \textbf{(A4.4)}$$

Now Starting phase current = Starting phase volts/Starting phase equivalent impedance
and Running phase current = Running phase volts/Running phase equivalent impedance.
from which

$$\frac{I_{start}}{I_{run}} = \frac{V_{ph}/\sqrt{((R_{S1} + R_{R1}*/S)^2 + (X_{S1} + X_{R1}*)^2)}}{V_{ph}/\sqrt{((R_{S1} + R_{R1}/S)^2 + (X_{S1} + X_{R1})^2)}} \quad \textbf{(A4.5)}$$

where $R_{R1}$ = PPS Rotor resistance in run mode

$X_{R1}$ = PPS Rotor reactance in run mode

$R_{R1}*$ = PPS Rotor resistance in starting mode

$X_{R1}*$ = PPS Rotor reactance in starting mode

Any slight variations in stators resistance and reactance values are of no consequence and are ignored in this analysis.

eliminating Vph in equation A4.5 gives:

$$\frac{Istart}{Irun} = \sqrt{\left( \frac{(R_{S1} + R_{R1}/S)^2 + (X_{S1} + X_{R1})^2)}{(R_{S1} + R_{R1}^*/S)^2 + (X_{S1} + X_{R1}^*)^2)} \right)} \qquad \textbf{(A4.6)}$$

Under normal running conditions

$$\frac{PPS\ Impedance}{NPS\ Impedance} = \sqrt{\left( \frac{(R_{S1} + R_{R1}/S)^2 + (X_{S1} + X_{R1})^2}{(R_{S2} + R_{R2}/(2-S))^2 + (X_{S2} + X_{R2})^2} \right)} \qquad \textbf{(A4.7)}$$

Comparing equations A4.6 and A4.7

It can be seen that the numerators in both equations are identical and in the denominators:

The stator components $R_{S1} = R_{S2}$

$X_{S1} = X_{S2}$ - Slip is identical in both cases

The rotor components $X_{R1}$ is of similar magnitude to $X_{R2}$

The only major difference is in the magnitudes of the rotor resistive components where

$$\frac{R_{R1}}{S} > \frac{R_{R2}}{2-S}$$

The resistive component, however, is small in comparison with $X_S + X_R$ and its effect may be neglected without detrimental effect on the result.

Hence it can be seen that

$$\frac{I_{start}}{I_{run}} \simeq \frac{Z_{PPS}}{Z_{NPS}}$$

Applying the previous theory to a practical example where unbalanced phase currents are due to unequal phase voltages. It should be noted that the current vectors sum to zero as no zero sequence currents are present.

A typical 3 phase 3300 volt balanced system would comprise of the following phase voltages

$$V_R = 3300/\sqrt{3}\ \angle 0^\circ = 1905\angle 0^\circ$$

$$V_Y = 3300/\sqrt{3}\ \angle 240^\circ = 1905\angle 240^\circ$$

$$V_B = 3300/\sqrt{3}\ \angle 120^\circ = 1905\angle 120^\circ$$

or expressed in symmetrical form

$$V_R = 1V+ \quad + 1V- \quad + 1Vo$$

$$V_Y = h^2 V+ \quad + hV- \quad + 1Vo$$

$$V_B = hV+ \quad + h^2V- \quad + 1Vo$$

$$\begin{matrix} V_R \\ V_Y \\ V_B \end{matrix} = \begin{matrix} 1 & 1 & 1 \\ h^2 & h & 1 \\ h & h^2 & 1 \end{matrix} \bullet \begin{matrix} V+ \\ V- \\ Vo \end{matrix}$$

| | | | | | |
|---|---|---|---|---|---|
| where | $h$ | = | $1\angle 120^\circ$ | Vector operator | |
| | $h^2$ | = | $1\angle 240^\circ$ | Vector operator | |
| | $V+$ | = | Positive sequence component of voltage | | = 1905 volts |
| | $V-$ | = | Negative sequence component of voltage | | = 0 volts |
| | $Vo$ | = | Zero sequence component of voltage | | = 0 volts |

If the system is required to supply a heavy single phase load such as a phase-phase load, then the unloaded phase would be at a higher phase-neutral potential than the loaded phases. The extent of the regulation being a function of load power factor and source impedance.

Consider a motor with equivalent circuit values as detailed in Appendix 7.

The motor is supplied with unequal voltages such that the negative phase sequence voltage is 5% of the positive sequence voltage. Such a system satisfying this criteria may comprise of the following set of symmetrical components.

Let the magnitude of the unloaded phase = 3300/√3 volts, this value being the result of the vector addition of the positive and negative phase sequence components. For ease of illustration consider the positive and negative phase sequence components to be in phase from which it follows that the unloaded phase comprises of:

$$\frac{100}{105} \bullet \frac{3300}{\sqrt{3}} = 1814.53\angle 0°V \quad \textit{Positive sequence component}$$

and

$$\frac{5}{105} \bullet \frac{3300}{\sqrt{3}} = 90.73\angle 0°V \quad \textit{Negative sequence component}$$

If the unloaded phase is $V_R$ then

| | Positive Sequence | | Negative Sequence | | Zero Sequence | |
|---|---|---|---|---|---|---|
| $V_R$ | = 1814.53 | + | 90.73 | + | 0 | = 1905.26∠0° |
| $V_Y$ | = 1814.53∠240° | + | 90.73∠120° | + | 0 | = 1770.91∠-122.54° |
| $V_B$ | = 1814.53∠120° | + | 90.73∠240° | + | 0 | = 1770.91∠+122.54° |

Consider the vector arrangement referred to in the above set of equations.

If the above voltages are applied to an induction motor represented by the equivalent circuit shown in Fig. A7.3.

Then for a running speed of 990 rpm

$$Slip = N_S - N_R/N_S = \frac{1000-990}{1000} = 0.01$$

Admittance of exiting component

$$= \; 0.000341 - j\,0.00672 \qquad \text{Siemens}$$

Admittance of rotor component for positive sequence network

$$= \frac{1}{0.539/0.01 + j6.237} = \frac{1}{53.9 + j6.237}$$

$$= \frac{1}{54.26\angle 6.6°} = 0.0184\angle -6.6°$$

$$= \; 0.018308 - j\,0.002118 \qquad \text{Siemens}$$

Total admittance of exiting component + rotor component

$$= \; 0.000341 - j0.00672 + 0.018308 - j0.002118$$

$$= \; 0.0186649 - j0.008838$$

$$= \; 0.020637\angle -25.36° \qquad \text{Siemens}$$

$$Equivalent\,Impedance = \frac{1}{0.020637\angle -25.36°}$$

$$= 48.456\angle 25.36°$$

$$= 43.787 + j20.753 \text{ Ohms}$$

Total Equivalent Impedance

= Stator Component + Rotor and Exiting Components

= 0.643 + j5.499 + 43.787 + j20.753

= 44.43 + j26.252

= $51.606\angle 30.58°$ Ohms

Similarly for the Negative Phase Sequence Network

Admittance of Rotor Component where Slip

$$= 2 - \frac{1000-990}{1000} = 1.99$$

$$= \frac{1}{3.234/1.99 + j4.5666}$$

$$= 0.2063\angle\text{-}70.41°$$

= 0.0692 - j0.1944 Siemens

Total Admittance of exiting component + rotor component

= 0.000341 - j0.00672 + 0.0692 - j0.1944

= 0.0695 - j0.2011

= $0.2128\angle\text{-}70.93°$ Siemens

$$Equivalent\,Impedance = \frac{1}{0.0695 - j0.2011} = 4.6996\angle 70.93°\,ohms$$

$= 1.5356 + j4.4416$ Ohms

Total Equivalent Impedance

= Stator Component + Rotor and Exiting Component

$= 0.643 + j5.499 + 1.5356 + j4.4416$

$= 2.1786 + j9.9406$

$= 10.1766\angle 77.64°$ Ohms

At Standstill Slip = 1

Admittance of rotor component

$$= \frac{1}{2.065/1 + j4.566} = 0.2\angle -65.7°$$

$= 0.082230 - j0.181821$ Siemens

Total Admittance of exiting component + rotor component

$= 0.000341 - j0.00672 + 0.082230 - j0.181821$

$= 0.082571 - j0.188541$

$= 0.205829\angle -66.35°$ Siemens

$$Equivalent\,Impedance = \frac{1}{0.205829\angle -66.35} = 4.85\angle 66.35°$$

$= 1.945 + j4.450$ Ohms

Total Equivalent Impedance

$$= \text{Stator Component} + \text{Rotor and Exciting Component}$$

$$= 0.643 + j5.499 + 1.945 + j4.450$$

$$= 2.592 + j9.949$$

$$= 10.281\angle 75.4°$$

Under balanced conditions

Current/phase at start = Vph/Zph at start = $V/Z_{Start}$

Current/phase run = Vph/Zph run = $V/Z_{Run}$

from which

$$\frac{Istart}{Irun} = \frac{Zrun}{Zstart}$$

$$= \left| \frac{51.606}{10.281} \right| = 5.02$$

and at full load speed

$$\frac{Z+}{Z-} = \frac{51.606}{10.177} = 5.07$$

which agrees with the generalised statement that:

$$\frac{Istart}{Irun} \simeq \frac{Z+}{Z-} \quad (5.07)$$

$$5.02 \simeq 5.07$$

The presence of this component although undesirable has little effect on the output of the motor as we will attempt to show.

Using data from the previous example, let the phase voltage supply to the motor be represented by the average value of $V_r$, $V_y$ and $V_b$.

$$Vaverage = \frac{1905.26 + 1770.91 + 1770.91}{3} = 1815.69\ Volt$$

Consider a balanced voltage supply of 1815.69 volts/phase applied to the motor then neglecting friction, windage and other losses

$$Output/Phase = I^2R\ \frac{(1-S)}{S}\ \ Watts$$

| | | | |
|---|---|---|---|
| where I | = | Rotor Current ≃ | Motor current |
| R | = | Rotor Resistance (0.539 ohms) | |
| S | = | Slip (0.01pu) | |

$$Now\ \ current/Phase = \frac{Voltage/Phase}{Equivalent\ Phase\ Impedance}\ (at\ slip\ S)$$

$$= \frac{1815.69}{51.606} = 35.18\quad Amp$$

then substituting in

$$Output/Ph = 35.18^2 \bullet 0.539\ \frac{(1-0.01)}{0.01} = 66055\ Watts/Phase$$

$$and\ Torque = \frac{I^2R}{S} = \frac{35.18^2 \bullet 0.539}{0.01} = 66708\ Synchronous\ Watts/Phase$$

$$Torque = \frac{I^2R}{S} \bullet \frac{1}{2\pi N} \, Nw-m$$

$$where\, N = Syn\, speed\, in\, rps\, (\frac{1000}{60})$$

$$= 66708 \bullet \frac{1}{2\pi N} \bullet \frac{60}{1000} = 637\, Nw-m/Phase$$

Consider now the case of an unbalanced voltage supply using the sequence voltage values previously determined. The behaviour of the motor to the positive sequence voltage is as normal motor running at slip S. In addition, the negative phase sequence component produces a reverse rotating field such that the rotor slip will be 2-S with respect to the positive sequence. The nett effect is that the motor behaves as the addition of two separate motors, one running of slip S with a terminal voltage of V+ (1814.53v)/phase, the other with slip (2-S) and a terminal voltage of 90.73 (V-)/phase.

For positive sequence component

$$Current/Phase = \frac{Voltage/Phase}{Equivalent\ Z/Phase}\ (at\ slip\ S)$$

$$= \frac{1814.53}{51.606} = 35.16\, Amp$$

Then substituting

$$Output/Phase = 35.16^2 \bullet 0.539 \bullet \frac{(1-0.01)}{0.01} = 65971\ Watt/Ph$$

and

$$Torque/Phase = \frac{35.16^2 \bullet 0.539}{0.01} = 66637\ Sync\ Watt/Phase$$

$$= 66637 \bullet \frac{1}{2\pi} \bullet \frac{60}{1000} = 636\, Nw-m/Phase$$

For negative phase sequence component

$$Current/Phase = \frac{Voltage/Phase}{Equivalent\ Z/Phase} \quad (at\ slip\ 2-S)$$

$$= \frac{90.73}{10.177} = 8.91\ Amp$$

Then substituting

$$Output/Phase = 8.91^2 \bullet 3.234 \bullet \left(\frac{1-0.01}{2-0.01}\right) = 127.9\ Watt/Phase$$

and

$$Torque/Phase = \frac{8.91^2 \bullet 3.234}{2-0.01} = 129.02\ Sync\ Watt/Phase$$

$$= 129.02 \bullet \frac{1}{2\pi} \bullet \frac{60}{1000} = 1.23\ Nw-m/Phase$$

From which it can be seen that the change in output power and torque due to negative phase sequence current in the motor generated by unbalanced supply voltages are so small that they may be neglected.

It can be seen that the power output of the machine is reduced when less than normal line voltages are supplied providing the speed of the motor is unchanged. In practice however, should the voltage supply to the motor fluctuate then the machine will modify its speed and hence its slip value until sufficient current is absorbed to satisfy the output demanded.

# APPENDIX 5

## Determination of terminal fault currents for typical transformer sizes

### A5.1 400kVA Transformer

Consider the 3300/431 Volt, 400kVA, Transformer Test Certificate shown in Fig. A5.1.

The Copper Loss ascribed to the transformer is 6250 Watts

From Test Certificate: % Z voltage = 4.85%

and % X voltage = 4.59%

Hence % R voltage = $\sqrt{(4.85^2 - 4.59^2)}$

= 1.567%

Referring the above percentage values to 415V and expressing in ohmic terms gives:

$$R = \frac{\%R \bullet kV^2}{0.4 \bullet 100} = \frac{1.567 \bullet 0.415^2}{0.4 \bullet 100} = 0.00674691 \ ohms$$

$$X = \frac{\%X \bullet kV^2}{0.4 \bullet 100} = \frac{4.59 \bullet 0.415^2}{0.4 \bullet 100} = 0.01976282 \ ohms$$

**For completeness**

Assume the primary cable to be 10 yds long typically 3.3/3.3kV insulation grade, 3 core, 0.1 $in^2$, PILC/SWA/SERVED with Stranded Copper conductors. The impedance would be:

$$0.31 + j0.072 \ ohms/1000\,yds$$

# TRANSFORMER TEST CERTIFICATE

Customer  Date
Customer's Order No  Our Order No
Inspection by
KVA 400  Phase 3  Freq. 50 c/s.  Rating Continuous  Type Outdoor

| | | | |
|---|---|---|---|
| Winding | HV | LV | |
| Volts | 3300 | 431 | |
| Amps | 70 | 535 | |
| Connection | Star | Star | with Delta tertiary |

Tappings on HV  Winding for full capacity
Controlled by Off circuit tapping switch
B.S.S. 171  Vector group ref. YY0D1
Cooling ON  Oil quantity 140 galls.  Cold oil depth  Conservator level inches
Voltage ratio, no load  3465 - 3382 - 3300 - 3218 - 3135 /431

| | | | | | |
|---|---|---|---|---|---|
| Transformer Serial No | | 60751C | | | |
| Winding referred to, at 75°C | | 3300/431 | | | |
| Iron loss | watts | 1560 | | | |
| Copper loss | watts | 6250 | | | |
| Impedance voltage | % | 4.85 | | | |
| % Efficiency at 1.0 P F. | 100% load | 98.09 | | | |
| | 75% load | 98.34 | | | |
| | 50% load | 98.45 | | | |
| | 25% load | 98.10 | | | |
| % Regulation at full load | 1.0 P.F. | 1.66 | | | |
| | 0.8 P.F. | 4.04 | | | |
| Temperature rise, °C after full load | Oil | 46.5 | | | |
| | H.V. | 59.5 | | | |
| | L.V. | 54.5 | | | |
| Insulation Resistance megohms, to other wdgs. & earth at 22°C | H.V. | 200+ | | | |
| | L.V. | 200+ | | | |

| | | | | | |
|---|---|---|---|---|---|
| Applied Voltage test at 22 °C | H.V. / Tertiary & Frame | 7.6 | kV for | 60 | secs |
| | L.V. / Frame | 2.0 | kV for | 60 | secs |
| | Tertiary / Frame | 2.0 | kV for | 60 | secs |

Induced Potential test at 22 °C  100 % at 150 c/s for 60 secs

Remarks,  Impedance of HV - Tertiary is 2% at 75°c & 100kva
Impedance of Sec - Tertiary is 0.86% at 75°c & 100kva

TYPICAL TEST CERTIFICATE FOR 400kVA TRANSFORMER

Fig A5J

referring to 415V gives

$$Impedance \quad Z = \frac{0.31 \bullet j0.072}{1000} \bullet 10 \bullet \left(\frac{0.415}{3.3}\right)^2 \; ohms/10\,yds$$

$$= 4.9026 \bullet 10^{-5} + j1.1387 \bullet 10^{-5} \; ohms$$

Typically a 3.3kV busbar would have a fault level of 7329A and an X/R ratio of 8.8529 (see calculation for 3.5 MVA, 11/3.4 kV transformer).

Hence Source impedance = Vph/Z

$$= \frac{3300}{\sqrt{3}} \bullet \frac{1}{7329\angle -83.56^\circ} = 0.25996\angle 83.56^\circ \, ohms$$

referring to 415V

$$Z\,Source = (0.029158 + j0.258320) \bullet \left(\frac{415}{3300}\right)^2$$

$$Z\,Source = 0.000467 + j0.004136$$

Assume the secondary side cables to be 10 yds long comprising two, three-core, 0.25 in$^2$, paper insulated, lead covered, single wire armoured, served overall (PILC/SWA/SERVED) with Stranded Copper conductors typically 660/1100 Volt grade

The impedance would be

$$0.14 + j0.063 \; ohms/1000\,yds$$

For two cables in parallel of length 10 yds, the impedance would be:

$$\frac{1}{2}\bullet(0.14 + j0.063)\bullet\frac{10}{1000}$$

$$= 7\bullet 10^{-4} + j3.14\bullet 10^{-4}\ ohms$$

Hence total impedance of transformer circuit comprising HV and LV cables all referred to 415 volt is:

| | | | |
|---|---|---|---|
| HV Source | 0.000467 | + | j 0.004136 |
| HV Cables | $4.9026\bullet 10^{-5}$ | + | $j\,1.1387\bullet 10^{-5}$ |
| Transformer | 0.00674691 | + | j 0.01976282 |
| LV Cables | $7.10^{-4}$ | + | $j\,3.14\bullet 10^{-5}$ |
| | | | |
| Total Impedance | 0.0079628 | + | j 0.0239417 |

For a three-phase fault on the LV busbars, the resulting current would be:

$$\frac{415}{\sqrt{3}\bullet(0.0079628 + j0.0239417)} = 9496\ \ Amp$$

$$with\,an\,\frac{X}{R}\,ratio\,of\ \ \frac{0.0239417}{0.0079628} = 3.0$$

## A5.2 800 kVA Transformer

Consider the 11000/431V, 800 kVA, Transformer Test Certificate shown in Fig. A5.2.

The load loss ascribed to the transformer is 10531 Watts.

From which:

$$Full\,Load\,\%R\ voltage = \frac{Load\,Loss}{Full\,Load\,Rating} \bullet 100\%$$

$$= \frac{10531}{800 \bullet 10^3} \bullet 100\%$$

$$= 1.3164\%$$

$$From\ Test\ Certificate\ \%Z\ voltage = 6.1\%$$

$$Hence\ \%X\ voltage = \sqrt{(6.1^2 - 1.3164^2)}$$

$$= 5.9563\%$$

Referring the above percentage values to 415V and expressing in ohmic terms gives:

$$R = \frac{\%R \bullet kV^2}{0.8 \bullet 100} = \frac{1.3164 \bullet 0.415^2}{0.8 \bullet 100} = 0.0028339\ ohms$$

$$X = \frac{\%X \bullet kV^2}{0.8 \bullet 100} = \frac{5.9563 \bullet 0.415^2}{0.8 \bullet 100} = 0.0128227\ ohms$$

# TRANSFORMER TEST CERTIFICATE

Customer — Date
Customer's Order No — Our Order No
Inspection by
kVA 800 Phase 3 Freq. 50 c/s. Rating Continuous Type Outdoor

| Winding | HV | LV |
|---|---|---|
| Volts | 11000 | 431 |
| Amps | 42 | 1072 |
| Connection | Star | Star with Delta tertiary |

Tappings on HV Winding for full capacity
Controlled by Off circuit tapping switch
B.S.S. 171 Vector group ref. YYODI
Cooling ON Oil quantity 282 galls. Cold oil depth Conservator level inches
Voltage ratio, no load 11550 - 11275 - 11000 - 10725 - 10450/431

| | | | | | |
|---|---|---|---|---|---|
| Transformer Serial No | | 60751C | | | |
| Winding referred to, at 75°C | | 11000/431 | | | |
| Iron loss | watts | 1554 | | | |
| Copper loss | watts | 10531 | | | |
| Impedance voltage | % | 6.1 | | | |
| % Efficiency at 1.0 P F. | 100% load | 98.48 | | | |
| | 75% load | 98.75 | | | |
| | 50% load | 98.80 | | | |
| | 25% load | 98.58 | | | |
| % Regulation at full load | 1.0 P.F. | 1.45 | | | |
| | 0.8 P.F. | 4.70 | | | |
| Temperature rise, °C after full load | Oil | 75 | | | |
| Insulation Resistance megohms, to other wdgs. & earth at 22°C | H.V. | 200+ | | | |
| | L.V. | 200+ | | | |

| | | | | | |
|---|---|---|---|---|---|
| Applied Voltage test at 22 °C | H.V. / LV Tert. & Earth | 28 | kV for | 60 | secs |
| | L.V. / Tertiary & Frame | 2.5 | kV for | 60 | secs |
| | Tertiary / Frame | 2.5 | kV for | 60 | secs |
| Induced Potential test at 22 °C | 200 % at | 100 | c/s for | 60 | secs |

TYPICAL TEST CERTIFICATE FOR 800kVA TRANSFORMER

Fig A5.2

**For completness**

Assume the primary cable to be 10 yds long, typically 6.35/11 kV grade, 3-core, 0.06 in$^2$, PILC/SWA/SERVED with Stranded Copper conductors. The impedance would be:

$$0.5 + j0.088 \ ohms \ /1000 \, yds$$

referring to 415 V gives

$$\frac{0.5 + j0.088}{1000} \bullet 10 \ \bullet \left(\frac{0.415}{11}\right)^2 \quad /10 \, yds$$

$$= 7.1167 \bullet 10^{-6} + j1.2525 \bullet 10^{-6} \ ohms$$

Assume the secondary side cables to be 10 yds long, typically 600/1000 V insulation grade, single core, 0.5 in$^2$, PILC/SERVED with Stranded Copper conductors using 2 Conductors /Phase and run in trefoil formation. The impedance would be:

$$0.064 + j0.079 \ ohms/core/1000 \, yds$$

For 2 cores in parallel

$$LV \ cable \ impedance = \frac{0.032 + j0.0395}{1000} \bullet 10 \quad ohms/10 \, yds$$

$$= 0.00032 + j0.000395 \ \ ohms/10 \, yds$$

Hence total impedance of transformer circuit comprising HV and LV cables all referred to 415V is:

| | | | | |
|---|---|---|---|---|
| HV cables | | $7.1167 \bullet 10^{-6}$ | + | $j\,1.2525 \bullet 10^{-6}$ |
| Transformer | | 0.0028339 | + | j 0.0128227 |
| LV cables | | 0.00032 | + | j 0.000395 |
| Total impedance | = | 0.0031610 | + | j 0.0132189 |

Assume an 11 kV Source fault level of 500 MVA and an X/R ratio of typically 10

Then expressed in ohmic form and referred to 415V

$$\text{The impedance} = \frac{kV^2}{MVA} = \frac{0.415^2}{500} = 3.4445 \bullet 10^{-4}\,ohms$$

From which

$$R_{500} = \sqrt{\left(\frac{(3.4445 \bullet 10^{-4})^2}{10^2 + 1}\right)} = 3.4274 \bullet 10^{-5}\,ohms$$

$$and\ X_{500} = 10 \bullet R_{500} = 3.4274 \bullet 10^{-4}\,ohms$$

Similarly for a 250 MVA source referred to 415V

$$R_{250} = 2 \bullet R_{500} = 6.8548 \bullet 10^{-5}\,ohms$$

$$and\quad X_{250} = 2 \bullet X_{500} = 6.8548 \bullet 10^{-4}\,ohms$$

Consider the case where a single 800 kVA transformer is connected to a 250 MVA source.

Total Impedance would be source + transformer + cable impedances

where.

$$\text{Source impedance} = 6.8548 \bullet 10^{-5} + j6.8548 \bullet 10^{-4}\,ohms$$

$$\text{Transformer + cable impedance} = 0.0031610 + j0.0132189\,ohms$$

$$= 0.0032296 + j0.0139044\,ohms$$

For a three phase fault on the LV busbars, the resulting current would be:

$$\frac{415}{\sqrt{3} \bullet (0.0032296 + j0.0139044)} = 16785\,Amp$$

$$with\,an\ \frac{X}{R}\ ratio\,of \qquad \frac{0.0139044}{0.00322296} = 4.3053$$

Next consider the case where two 800 kVA transformers are connected to a 500 MVA source

Equivalent impedance of two transformer circuits in parallel = Z/2

| | | | | |
|---|---|---|---|---|
| | = | 0.0015805 | + | j 0.0066094 |
| and Source | = | $3.4445 \bullet 10^{-4}$ | + | j $3.4274 \bullet 10^{-4}$ |
| | = | 0.0016147 | + | j 0.0069522 |

For a three phase fault on the LV busbars, the resulting current would be:

$$\frac{415}{\sqrt{3} \bullet (0.0016148 + j0.0069522)} = 33570\,Amp$$

$$with\,an\ \frac{X}{R}\ ratio\,of \qquad \frac{0.0069522}{0.0016148} = 4.3053$$

## A5.3 1.5 MVA Transformer

Consider the 11000/431V, 1.5 MVA Transformer equivalent circuit shown in Fig. A5.3.

The circuit may be simplified by considering the series elements only. Referring these values to 415V gives:

$$Resistive\,component = 1.066 \bullet \left(\frac{0.415}{11}\right)^2 = 1.5173 \bullet 10^{-3}\ ohms$$

$$Reactive\,component = 6.291 \bullet \left(\frac{0.415}{11}\right)^2 = 8.9543 \bullet 10^{-3}\,ohms$$

**For completeness**

Assume the primary cable to be 10 metres long, typically 6.35/11kV grade, 3-core, 150mm$^2$, XLPE/SWA/PVC with Stranded Aluminium conductors. The impedance would be:

$$0.264 + j0.09739 \quad ohms/km$$

referring to 415V gives

$$\frac{0.264 + j0.09739}{1000} \bullet 10 \bullet \left(\frac{0.415}{11}\right)^2 \quad ohms/10\ mtrs$$

$$= 6.9696 \bullet 10^{-4} + j1.38619 \bullet 10^{-6} \quad ohms/10\ mtrs$$

Assume the secondary side cables to be 10 yds long, typically 660/1100V grade, single core, 630mm$^2$, XLPE/PVC with Stranded Aluminium conductors using three conductors/phase and run in trefoil formation.

The impedance would be:

$$0.0618 + j\,0.078 \quad ohms/core/1000\,mtrs$$

For three cores in parallel and referring to 415V

$$\frac{0.0206 + j0.026}{1000} \bullet 10 \quad ohms/mtrs$$

$$= \quad 2.06 \bullet 10^{-4} + j\,2.6 \bullet 10^{-4} \quad ohms$$

Assume an 11kV Source fault level of 25kA and an X/R ratio of typically 10. Then expressed in ohmic form and referred to 415V.

$$The\,impedance = (11 \bullet 10^3/(\surd 3 \bullet 25 \bullet 10^3)) \bullet (0.415/11)^2 \; ohms$$

$$= 3.61578 \bullet 10^{-4} \, ohms$$

From which

$$Resistive\,component = \surd\left(\frac{(3.61578 \bullet 10^{-4})^2}{10^2 + 1}\right) = 3.5978 \bullet 10^{-5} \, ohms$$

$$Reactive\,component = 10 \bullet Resistive\,component = 3.5978 \bullet 10^{-4} \, ohms$$

Similarly for a 12.5kA Source fault level - again referred to 415V

$$R = R_{25ka} \bullet 2 = 7.1957 \bullet 10^{-5} \, ohms$$

$$X = X_{25ka} \bullet 2 = 7.1957 \bullet 10^{-4} \, ohms$$

Consider the case where a single 1.5 MVA transformer is connected to an 11kV source of 12.5kA fault level

Total Impedance would be:

| | | | | |
|---|---|---|---|---|
| | Source | + Transformer | + | Cable impedances |
| where: | Source | $7.1957 \bullet 10^{-5}$ | + | $j\,7.1957 \bullet 10^{-4}$ ohms |
| | Transformer | $1.5173 \bullet 10^{-3}$ | + | $j\,8.9543 \bullet 10^{-3}$ ohms |
| | HV Cable | $3.7576 \bullet 10^{-6}$ | + | $j\,1.38619 \bullet 10^{-6}$ ohms |
| | LV Cable | $2.06 \bullet 10^{-4}$ | + | $j\,2.6 \bullet 10^{-4}$ ohms |
| Total Impedance | = | $1.7990 \bullet 10^{-3}$ | + | $j9.9352 \bullet 10^{-3}$ ohms |

For a three phase fault on the LV busbars, the resulting current would be

$$\frac{415}{\sqrt{3} \bullet (1.799 \bullet 10^{-3} + j9.9352 \bullet 10^{-3})} = 23730 \quad Amp$$

$$with\,an\ \frac{X}{R}\ ratio\,of\ \frac{9.9352 \bullet 10^{-3}}{1.799 \bullet 10^{-3}} = 5.5226 \quad Amp$$

Next consider two 1.5 MVA transformers connected in parallel to a 25kA source. As the transformer impedance and source impedance are effectively halved.

The fault current will be $2 \bullet 23730$ = 47460 Amp

and X/R ratio = 5.5226

**Single Phase Faults**

Consider the associated Zero Phase Sequence equivalent circuit from which it can be seen that:

$$Z_0 = Z_{S2} + Z_{SE} = 0.00274 + j0.002865 \quad ohms$$

For a Reference Voltage of 431V

Referring $Z_0$ to 415V

$$\left(\frac{415}{431}\right)^2 \bullet 0.00274 + j0.002865 \quad ohms$$

$$= 0.00254 + j0.002656 \quad ohms$$

Previously we have calculated the Positive Sequence Impedance of:

HV Source + HV cable + transformer + LV cable which when referred to 415V was found to be:

$$Z_+ = 1.7970 \bullet 10^{-3} + j\,9.9352 \bullet 10^{-3} \text{ ohms}$$

Similarly for Negative Sequence Impedance

$$Z_- = Z_+$$

Hence Earth Fault Current at the LV Busbar/or Earth Bar = $I_{EF}$

where $I_{EF} = 3I_0$.

$$I_{EF} = \frac{3 \bullet V_{ph}}{Z_+ + Z_- + Z_o + 3Z_{for\ Earth\ Fault\ Path}}$$

Generally the transformer star point is connected by cable to either the 415V Neutral Busbar on the switchgear or to the Neutral busbar via a common earthing bar. In the latter case the connection between earth bar and neutral busbar may be neglected as all cables, switchgear etc are bonded directly to the earthbar. Consider the neutral cable to be 10 yds long, 600/1000V grade, single core, 630mm2, XLPE/PVC with Stranded Aluminium Conductors using two conductors in parallel. The usual approach is to use the dc. Resistance value as proximity effects are not present and skin effects are very small.

Hence Resistance of cable connection to star point

$$= \frac{0.0469}{2} \bullet \frac{10}{1000} = 0.000235\, ohms$$

where dc Resistance/core = 0.0469 ohms/km

Substituting gives

$$I_{EF} = \frac{3 \bullet (415/\sqrt{3})}{2(1.7990 \bullet 10^{-3} + j9.9352 \bullet 10^{-3}) + 0.00254 + j0.002656 + 3 \bullet 0.000235}$$

$$= \frac{\sqrt{3} \bullet 415}{6.843 \bullet 10^{-3} + j2.25266 \bullet 10^{-2}}$$

$$= \frac{\sqrt{3} \bullet 415 \angle 0°}{2.3543 \bullet 10^{-2} \angle 73.1°} = 30531.3 \angle -73.1° \; Amp$$

$$= 8874.2 - j29213.2 \quad Amp$$

or

$$30531.3\, Amp\ with\ an\ \frac{X}{R}\ ratio\ of\ tan\, 73.1° = 3.29192$$

Consider the case where two 1.5 MVA transformers are connected to a 25 kA source. As all impedances are effectively halved for identical circuits.

The fault current will be 2 • 30531 = 61062 Amp

and the X/R ratio = 3.29192

## A5.4 2.0 MVA Transformer

Consider the 11000/431V, 2.0 MVA Transformer equivalent circuit shown in Fig. A5.4.

Using only the series elements and referring the values to 415V gives

$$Resistive\,component = 0.6455 \bullet \left( \frac{0.415}{11} \right)^2 = 9.1877 \bullet 10^{-4}$$

$$Reactive\,component = 4.583 \bullet \left( \frac{0.415}{11} \right)^2 = 6.5232 \bullet 10^{-3}$$

**For completeness**

Assume primary cable to be 30 metres long, typically 6.35/11kV grade, 3-core, PILC/SWA/PVC with 240mm$^2$ Stranded Aluminium conductors. The impedance would be

$$0.149 + j\,0.0785 \text{ ohms/km}$$

referring to 415V gives

$$6.3624 \bullet 10^{-6} + j\,3.3537 \bullet 10^{-6} \text{ ohms}$$

Assume the LV cables to be 5 mtrs long, typically 660/1100V grade, single core, 630mm$^2$, PILC with Stranded Aluminium conductors using 4 conductors/phase and run in trefoil formation. The impedance would be:

$$0.0618 + j\,0.079 \text{ ohms /km}$$

For four conductors in parallel and referring to 415V

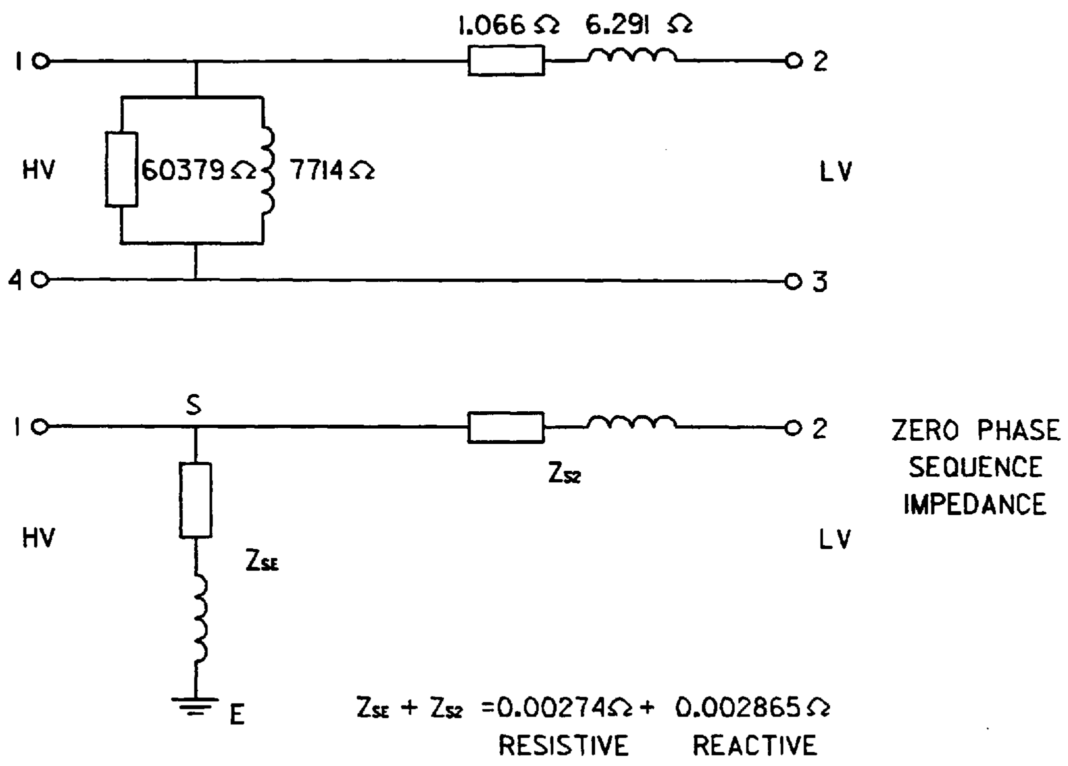



Fig A5.3 EQUIVALENT CIRCUIT FOR 1.5 MVA TRANSFORMER

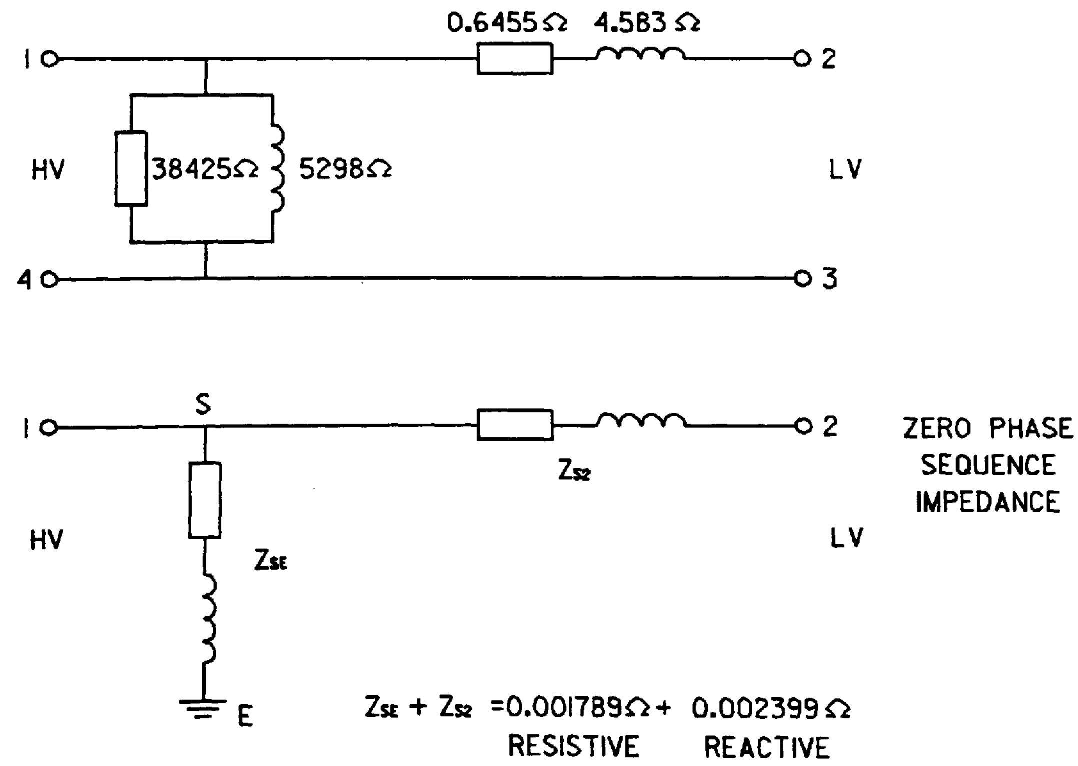



Fig A5.4 EQUIVALENT CIRCUIT FOR 2 MVA TRANSFORMER

$$\frac{0.0618 + j0.079}{4} \bullet \frac{5}{1000} \; ohms$$

$$= 7.725 \bullet 10^{-5} + j9.875 \bullet 10^{-5} \; ohms$$

Assuming an 11kV Source fault level of 25kA and an X/R ratio of typically 10. The equivalent source impedance will be as in the previous example.

$$Z_{25ka}\, source = 3.5978 \bullet 10^{-5} - j3.5978 \bullet 10^{-4} \; ohms$$

Similarly for a 12.5kA source

$$Z_{12.5kA}\, source = 7.1957 \bullet 10^{-5} - j7.1957 \bullet 10^{-4} \; ohms$$

Consider the case where a single 2 MVA transformer is connected to a 12.5kA source at 11kV

Total Impedance would be the sum of:

| | | | |
|---|---|---|---|
| Source | $7.1957 \bullet 10^{-5}$ | + | $j\,7.1957 \bullet 10^{-4}$ |
| Transformer | $9.1877 \bullet 10^{-4}$ | + | $j\,6.5232 \bullet 10^{-3}$ |
| HV Cable | $6.3624 \bullet 10^{-6}$ | + | $j\,3.3537 \bullet 10^{-6}$ |
| LV Cable | $7.7250 \bullet 10^{-5}$ | + | $j\,9.8750 \bullet 10^{-5}$ |

Total Impedance = $1.0743 \bullet 10^{-3}$ + $j\,7.34487 \bullet 10^{-3}$ ohms

For a three phase fault on the LV busbars, the resulting current would be:

$$\frac{415}{\sqrt{3} \bullet (1.0743 \bullet 10^{-3} + j7.34487 \bullet 10^{-3})} = 32278 \; Amp$$

$$with\; an\; \frac{X}{R}\; ratio\; of\; \frac{7.34487 \bullet 10^{-3}}{1.0743 \bullet 10^{-3}} = 6.8366$$

As two transformers in parallel would clearly exceed the 50kA symmetrical fault rating of the switchgear, the case is not considered. However, the effects of reducing the source fault level to 25kA should be known.

For a three phase fault on the LV busbars, the resulting current would be:

$$\frac{415}{\sqrt{3} \bullet (1.0386 \bullet 10^{-3} + j6.9851 \bullet 10^{-3})} = 33929\,Amp$$

$$with\,an\ \frac{X}{R}\ ratio\,of\ \frac{6.9851 \bullet 10^{-3}}{1.03836 \bullet 10^{-3}} = 6.7270$$

## A5.5 3.5 MVA Transformer

Consider the 11000/3400 V, 3.5 MVA Transformer Test Certificate shown in Fig. A5.5.

The Copper loss for the transformer is 27030 Watts

From which

$$Full\,load\,\%\,R\,voltage = \frac{Copper\,Loss}{Full\,Load\,Rating} \bullet 100\%$$

$$= \frac{27030}{3.500 \bullet 10^6} \bullet 100\%$$

$$= 0.7723\%$$

From Test Certificate

$$\%Z \text{ voltage} = 6.94\%$$

Hence

$$\%\,X\,voltage = \sqrt{(6.94^2 - 0.7723^2)}$$

$$= 6.8969\%$$

Expressing in ohmic terms and referring to 3300V gives

$$R = \frac{\%R \bullet kV^2}{3.5 \bullet 100} = \frac{0.7723 \bullet 3.3^2}{3.5 \bullet 100} = 2.4029 \bullet 10^{-2}$$

$$X = \frac{\%X \bullet kV^2}{3.5 \bullet 100} = \frac{6.8969 \bullet 3.3^2}{3.5 \bullet 100} = 2.1459 \bullet 10^{-1}$$

# TRANSFORMER TEST CERTIFICATE

Customer
Customer's Order No
Inspection by

Date
Our Order No

kVA 3500 Phase 3 Freq. 50 c/s. Rating Continuous Type Outdoor

| Winding | HV | LV |
|---|---|---|
| Volts | 11000 | 3400 |
| Amps | 184 | 594 |
| Connection | Delta | Delta |

Tappings on HV Winding for full capacity
Controlled by Off circuit tapping switch
B.S.S. 171 Vector group ref. Dd.0 Diag. of Connections Z60P62
Cooling ON Oil quantity 772 galls. Cold oil depth Conservator level inches
Voltage ratio,
no load 11550 - 11275 - 11000 - 10725 - 10450/3400

| | | | | | |
|---|---|---|---|---|---|
| Transformer Serial No | | 60751C | | | |
| Winding referred to, at 75°C | | 11/3.4kV | | | |
| Iron loss | watts | 4648 | | | |
| Copper loss | watts | 27030 | | | |
| Impedance voltage | % | 6.94 | | | |
| Resistance per phase, ohms | H.V. | 0.406 | | | |
| | L.V. | 0.0277 | | | |
| % Efficiency at 1.0 P F. | 100% load | 99.10 | | | |
| | 75% load | 99.25 | | | |
| | 50% load | 99.35 | | | |
| | 25% load | 99.28 | | | |
| % Regulation at full load | 1.0 P.F. | 1.01 | | | |
| | 0.8 P.F. | 4.88 | | | |
| Temperature rise, °C after full load | Oil | 46.5 | | | |
| | H.V. | 59.5 | | | |
| | L.V. | 54.5 | | | |
| Insulation Resistance megohms, to other wdgs. & earth at 22°C | H.V. | 200+ | | | |
| | L.V. | 200+ | | | |

Applied Voltage test at 22 °C — H.V. 28 kV for 60 secs
L.V. 16 kV for 60 secs

Induced Voltage test at 22 °C — 200 % at 100 c/s for 60 secs

Remarks.

TYPICAL TEST CERTIFICATE FOR 3500kVA TRANSFORMER

Fig A5.5

**For completeness**

Assume the primary cable to be 10 yds long, typically 6.35/11kV grade, 3-core, 0.25in², PILC/SWA/SERVED with Stranded Copper conductors. The impedance would be:

$$0.13 + j0.073\ ohms/1000\,yds$$

referring to 3300V gives

$$\frac{0.13 + j0.073}{1000} \bullet 10 \bullet \left(\frac{3.3}{11}\right)^2$$

$$= \quad 1.17 \bullet 10^{-4} + j\,6.57 \bullet 10^{-5}$$

Assume the secondary side cables to be 10 yds long, typically 3300/3300V grade, two 3 core cables, 0.25in² PILC/SWA/SERVED with Stranded Copper conductors. The impedance would be:

$$= \quad 0.14 + j\,0.066\ \text{ohms}/1000\ \text{yds}$$

For two cables in parallel

$$\frac{0.14 + j0.066}{2} \bullet \frac{10}{1000}$$

$$= \quad 7 \bullet 10^{-4} + j\,3.3 \bullet 10^{-4}\ \text{ohms}$$

Assuming an 11kV Source fault level of 500MVA and an X/R ratio of typically 10

Then expressed in ohmic form and referred to 3300V

$$Impedance = \frac{kV^2}{MVA} = \frac{3.3^2}{500} = 2.178 \bullet 10^{-2}\,ohms$$

$$From\ which\ R = \sqrt{\frac{(2.178 \bullet 10^{-2})^2}{10^2 + 1}} = 2.16719 \bullet 10^{-3}\,ohms$$

$$X = 10 \bullet R = 2.16719 \bullet 10^{-2}$$

Similarly for a 250 MVA 11kV source referred to 3300V

$$R = 4.33438 \bullet 10^{-3}$$

$$X = 4.33438 \bullet 10^{-2}$$

Consider the case where a single 3.5 MVA transformer is connected to a 250 MVA source

Total Impedance would be the sum of:

| | | | |
|---|---|---|---|
| Source | $4.33438 \bullet 10^{-3}$ | + | $j\,4.33438 \bullet 10^{-2}$ ohms |
| Transformer | $2.4029 \bullet 10^{-2}$ | + | $j\,2.1459 \bullet 10^{-1}$ ohms |
| HV Cable | $1.17 \bullet 10^{-4}$ | + | $j\,6.57 \bullet 10^{-5}$ ohms |
| LV Cable | $7.0 \bullet 10^{-4}$ | + | $j\,3.3 \bullet 10^{-4}$ ohms |

Total Impedance = $2.9181 \bullet 10^{-2}$ + $j2.58332 \bullet 10^{-1}$ ohms

For a three phase fault on the LV busbars, the resulting current would be:

$$\frac{415}{\sqrt{3} \bullet (2.91805 \bullet 10^{-2} + j2.58332 \bullet 10^{-1})} = 7329\,Amp$$

$$with\ an\ X/R\ ratio\ of\ \frac{2.58332 \bullet 10^{-1}}{2.918050 \bullet 10^{-2}} = 8.8529$$

Similarly for a three phase fault on the LV busbars with a 500 MVA source at 11kV

$$\frac{415}{\sqrt{3} \bullet (2.70138 \bullet 10^{-2} + j2.36659 \bullet 10^{-1})} = 7999\ Amp$$

$$with\ an\ X/R\ ratio\ of\ \ \frac{2.36659 \bullet 10^{-4}}{2.70133 \bullet 10^{-2}} = 8.7609$$

For two transformers in parallel on a 500 MVA supply, the LV (3.3 kV) fault current would be:

| | | | |
|---|---|---|---|
| | $2 \bullet 7329$ | = | 14658 Amp |
| with an | X/R ratio | = | 8.8529 |

## A5.6 4.0 MVA Transformer

Consider the 11000/3400V, 4MVA, DD0 Vector group transformer equivalent circuit shown in Fig. A.5.6.

Using the series element, converting to star configuration and referring the values to 3300V gives

$$Resistive\ component = \frac{0.796}{3} \bullet \left(\frac{3300}{11000}\right)^2 = 2.388 \bullet 10^{-2}$$

$$Reactive\ component = \frac{5.963}{3} \bullet \left(\frac{3300}{11000}\right)^2 = 1.7889 \bullet 10^{-1}$$

**For completeness**

Assume primary cable to be 10 metres long, typically 6.35/11kV grade, 3-core PILC/SWA/PVC with 240mm$^2$ Stranded Aluminium conductors. The impedance would be

$$0.161 + j\,0.090 \quad \text{ohms / 1000 mtrs}$$

referring a 10 metre length to 3300V

$$\frac{0.161 + j0.090}{1000} \bullet 10 \bullet \left(\frac{3300}{11000}\right)^2$$

$$= 1.449 \bullet 10^{-4} \quad + j\,8.1 \bullet 10^{-5} \text{ ohms}$$

Assume the secondary prime cable to be 10 yds long, typically 3.8/6.6kV grade, two 3-core, 240mm$^2$, XLPE/SWA/PVC with Stranded Aluminium conductors. The impedance would be:

$$0.162 + j\,0.0845 \quad \text{ohms / 1000 mtrs (1 cable)}$$

# TRANSFORMER TEST CERTIFICATE

Customer | Date
Customer's Order No | Our Order No
Inspection by

kVA 4000 Phase 3 Freq. 50 c/s. Rating Continuous Type Outdoor

| Winding | HV | LV |
|---|---|---|
| Volts | 11000 | 3400 |
| Amps | 209.95 | 679.2 |
| Connection | Delta | Delta |

Tappings on HV Winding for full capacity
Controlled by Off circuit tapping switch
B.S.S. 171 Vector group ref. Dd.0
Cooling ON Oil quantity 790 galls. Cold oil depth Conservator level inches
Voltage ratio, no load 11550 - 11275 - 11000 - 10725 - 10450/3400

| | | | | | |
|---|---|---|---|---|---|
| Transformer Serial No | | 60751C | | | |
| Winding referred to, at 75°C | | 11/3.4kV | | | |
| Iron loss | watts | 4362 | | | |
| Copper loss | watts | 32468 | | | |
| Impedance voltage | % | 6.92 | | | |
| Resistance per phase, ohms | H.V. | 0.406 | | | |
| | L.V. | 0.0277 | | | |
| % Efficiency at 1.0 P F. | 125% load | 98.91 | | | |
| | 100% load | 99.09 | | | |
| | 75% load | 99.25 | | | |
| | 50% load | 99.38 | | | |
| | 25% load | 99.37 | | | |
| % Regulation at full load | 1.0 P.F. | 1.05 | | | |
| | 0.8 P.F. | 4.95 | | | |
| Temperature rise, °C after full load | Oil | 60°C | | | |
| By resistance | | 65°C | | | |
| Insulation Resistance megohms, to other wdgs. & earth at 22°C | H.V. | 200+ | | | |
| | L.V. | 200+ | | | |

Applied Voltage test at 22 °C — H.V. 28 kV for 60 secs; L.V. 16 kV for 60 secs

Induced Voltage test at 22 °C — 200 % at 100 c/s for 60 secs

Remarks.

TYPICAL TEST CERTIFICATE FOR 4000kVA TRANSFORMER

Fig A5.6

For a 10 mtr length of two cables in parallel

$$\frac{0.162 + j0.0845}{2} \bullet \frac{10}{1000}$$

$$= 8.1 \bullet 10^{-4} + j\,4.225 \bullet 10^{-4} \text{ ohms}$$

Assuming an 11kV Source fault level of 25 kA and an X/R ratio of typically 10

Then impedance expressed in ohmic form and referred to 3300V

$$= \frac{kV\,source}{\sqrt{3} \bullet kA\,source} \bullet \left(\frac{3.300}{11000}\right)^2$$

$$= \frac{11}{\sqrt{3} \bullet 25} \bullet \left(\frac{3.300}{11000}\right)$$

$$= 2.2863 \bullet 10^{-2}\,ohms$$

From which

$$Resistive\,component = \sqrt{\frac{(2.2863 \bullet 10^{-2})^2}{10^2 + 1}} = 2.27496 \bullet 10^{-3}\,ohms$$

$$Reactive\,component = 10 \bullet Resistive = 2.27496 \bullet 10^{-2}\,ohms$$

Similarly for a 12.5kA source fault level, the impedance referred to 3300 volt would be double the values quoted above.

That is:

Resistive component = $4.54992 \bullet 10^{-3}$ ohms

Reactive component = $4.54992 \bullet 10^{-3}$ ohms

Consider the case where a single 4MVA transformer is connected to a 12.5kA source.

Total Impedance would be:

| | | | |
|---|---|---|---|
| Source | $4.54992 \bullet 10^{-3}$ | + | $j\,4.54992 \bullet 10^{-2}$ |
| Transformer | $2.388 \bullet 10^{-2}$ | + | $j\,1.7889 \bullet 10^{-1}$ |
| HV Cable | $1.449 \bullet 10^{-4}$ | + | $j\,8.1 \bullet 10^{-5}$ |
| LV Cable | $8.1 \bullet 10^{-4}$ | + | $j\,4.225 \bullet 10^{-4}$ |

Total Impedance = $2.93848 \bullet 10^{-2}$ + $j\,2.24893 \bullet 10^{-1}$

For a three phase fault on the 3300V busbars, the resulting current would be:

$$\frac{3300}{\sqrt{3} \bullet \sqrt{(2.93848 \bullet 10^{-2} + j2.24893 \bullet 10^{-1})^2}} = 8400\,Amp$$

$$with\ an\ X/R\ ratio\ of\ \frac{2.24893 \bullet 10^{-1}}{2.93848 \bullet 10^{-2}} = 7.6534$$

For two transformers in parallel on a 25 kA supply, the LV fault current (3.3kV) would be:

$2 \bullet 8400$ = 16,800 Amp

again with an X/R ratio = 7.6534

## APPENDIX 6

### Determination of Zero Sequence Impedance of a cable

Consider the Zero Sequence Resistance and Reactance of a three core PVC Insulated cable in 600/1000V grade with Extruded bedding, single wire armour and PVC Oversheath with Stranded Copper conductors.

The method adopted for this calculation was supplied by the cable manufacturers. BICC and AEI Ltd. The Resistance and Reactance values being calculated separately.

### A6.1 Zero Sequence Resistance

The Zero sequence resistance of the conductors per phase is equal to the maximum dc resistance of one conductor multiplied by (1 + 'Skin Effect' Factor) + 3 • Resistance of Armouring.

$$R_{ZERO} = R_{dc}(1 + Y_s) + 3 \bullet R_{swa}$$

where $Y_S$ = 'Skin Effect' factor

Consider a conductor of 240mm$^2$ CSA

| | | | | |
|---|---|---|---|---|
| $R_{dc}$ | = | 0.0754 ohms / km | ) | manufacturers |
| $R_{swa}$ | = | 0.6 ohms / km | ) | data |

A method of calculating the 'skin effect' factor is given in IEC publication 287. Using this method we have:

$$\text{'Skin effect' factor} = Y_s = \frac{xs^4}{192 + 0.8xs^4}$$

$$where\ xs^2 = \frac{8\pi f}{R'} 10^{-7} \bullet ks$$

| | | | |
|---|---|---|---|
| | f | = | 50Hz |
| | $k_s$ | = | 1 (an experimental value) |
| | R' | = | dc resistance of conductor at maximum operating temperature σ |
| Now | R' | = | Ro [1 + $\alpha_{20}$ (σ-20)] |
| where | Ro | = | dc Resistance of the conductor at 20°C |
| | | = | $0.0754 \bullet 10^{-3}$ ohms /metre |
| | $\alpha_{20}$ | = | Constant mass temperature coefficient at 20°C per Kelvin (IEC 287, p75, table 1) |
| | | = | $3.93 \bullet 10^{-3}$ |
| | σ | = | Maximum operating temperature of 70°C |

Substituting gives:

$$R' = 0.0754 \bullet 10^{-3} (1 + 3.93 \bullet 10^{-3} (70-20))$$

$$= 9.02161 \bullet 10^{-5}\ ohms/metre$$

$$xs^2 = \frac{8\pi 50 \bullet 10^{-7}}{9.02161 \bullet 10^{-5}}$$

$$= 1.3929$$

$$Y_s = \frac{1.3929^2}{192 + 0.8(1.3929)^2}$$

$$= 0.010024$$

$$Hence\, R_{zero} = 0.0754(1 + 0.010024) + 3 \bullet 0.6$$

$$= 1.87616\, ohms/km$$

## A6.2 Zero Sequence Reactance

The Zero sequence reactance is given by the following equation:

$$X_o = 0.434 \log_{10}(dL/GMD)\, ohms/km$$

where

| | | |
|---|---|---|
| dL | = | Mean diameter of armour layer in mm |
| GMD | = | Geometric mean diameter of armour layer |
| | = | 0.75 • diameter of circle circumscribing the three conductor |

As the conductors are sectoral in shape the fictitious diameter of any core is given by:

$D_c = d_L + 2t_1$ mm (Source IEC 502 page 85)

where

| | | |
|---|---|---|
| $d_L$ | = | 17.5mm for 240mm$^2$ conductors |
| $t_1$ | = | nominal thickness of insulation is 2.2mm |

Substituting

$$D_c = 17.5 + 2 \bullet 2.2 = 21.9 \text{ mm}$$

The fictitious diameter over laid up cores ($D_f$) is given by:

$$D_f = k.Dc$$

where

k = Assembly Coefficient value of 2.16

$$D_f = 2.16 \bullet 21.9 = 47.304 \text{ mm}$$

Hence mean diameter of armour layer

= Df + 2 • Bedding thickness + 2 • (0.5 • Armour diam)

$$= 47.304 + (2 \bullet 1.6) + 2.5$$

$$= 53.004 \text{ mm}$$

GMD = 0.75 • diameter of circle circumscribing the three conductors

$$= 0.75 \bullet (Df - (2 \bullet t1))$$

$$= 0.75 \bullet (47.304 - 2 \bullet 2.2)$$

$$= 32.178\text{mm}$$

$$Hence\ Xo = 0.434 \log_{10}\left(\frac{53.004}{32.178}\right)$$

$$= 0.09407 \ ohms$$

A short program using Lotus 123 has been written to construct tables A6.1 and A6.2 which follow. Table A6.1 gives the calculated values for Zero Sequence Resistance for the entire range under consideration, that is, from 1.5mm$^2$ to 400mm$^2$. Similarly Table A6.2 lists the calculated values for Zero Sequence Reactance together with the intermediate steps involved.

| CSA sq | CORES | DC 'R' Ohms/km | 'R' Ohms/m | Xs^2 | Xs^4 | SKIN EFF FACTOR | ARMOUR RESIST | ZERO SEQ RESIST |
|---|---|---|---|---|---|---|---|---|
| 1.5 | circ | 12.1000 | 0.01448 | 0.0086798 | 0.0000753396 | 0.0000003923939 | 10.20 | 42.70000 |
| 2.5 | circ | 7.4100 | 0.00887 | 0.0141736 | 0.0002008898 | 0.0000010463002 | 8.80 | 33.81001 |
| 4.0 | circ | 4.6100 | 0.00552 | 0.0227822 | 0.0005190300 | 0.0000027032755 | 7.00 | 25.61001 |
| 6.0 | circ | 3.0800 | 0.00369 | 0.0340994 | 0.0011627675 | 0.0000060560515 | 4.60 | 16.88002 |
| 10.0 | circ | 1.8300 | 0.00219 | 0.0573913 | 0.0032937615 | 0.0000171547721 | 3.70 | 12.93003 |
| 16.0 | circ | 1.1500 | 0.00138 | 0.0913270 | 0.0083406259 | 0.0000434392502 | 3.20 | 10.75005 |
| 25.0 | shape | 0.7270 | 0.00087 | 0.1444650 | 0.0208701466 | 0.0001086892289 | 2.40 | 7.92708 |
| 35.0 | shape | 0.5240 | 0.00063 | 0.2004315 | 0.0401727672 | 0.0002091981456 | 2.10 | 6.82411 |
| 50.0 | shape | 0.3870 | 0.00046 | 0.2713852 | 0.0736499391 | 0.0003834757538 | 1.90 | 6.08715 |
| 70.0 | shape | 0.2680 | 0.00032 | 0.3918884 | 0.1535764888 | 0.0007993660298 | 1.40 | 4.46821 |
| 95.0 | shape | 0.1930 | 0.00023 | 0.5441766 | 0.2961281573 | 0.0015404334619 | 1.20 | 3.79330 |
| 120.0 | shape | 0.1530 | 0.00018 | 0.6864450 | 0.4712067038 | 0.0024493925400 | 1.10 | 3.45337 |
| 150.0 | shape | 0.1240 | 0.00015 | 0.8469845 | 0.7173827868 | 0.0037252336044 | 0.74 | 2.34446 |
| 185.0 | shape | 0.0991 | 0.00012 | 1.0597990 | 1.1231739266 | 0.0058226149954 | 0.68 | 2.13968 |
| 240.0 | shape | 0.0754 | 0.00009 | 1.3929188 | 1.9402229190 | 0.0100242887250 | 0.60 | 1.87616 |
| 300.0 | shape | 0.0601 | 0.00007 | 1.7475221 | 3.0538336633 | 0.0157055415319 | 0.54 | 1.68104 |
| 400.0 | shape | 0.0470 | 0.00006 | 2.2345975 | 4.9934258624 | 0.0254773462025 | 0.49 | 1.51820 |

TABLE A6.1 ZERO SEQUENCE RESISTANCE CALCULATION

| CSA sq | INSUL mm | CORES | BED mm | SWA mm | FICT'D mm | Dc | Df | O/D mm | GMD mm | Xo Ohms/km |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.5 | 0.6 | circ | 0.8 | 0.9 | 1.4 | 2.6 | 5.616 | 8.116 | 3.312 | 0.16894 |
| 2.5 | 0.7 | circ | 0.8 | 0.9 | 1.8 | 3.2 | 6.912 | 9.412 | 4.134 | 0.15507 |
| 4.0 | 0.8 | circ | 0.8 | 0.9 | 2.3 | 3.9 | 8.424 | 10.924 | 5.118 | 0.14291 |
| 6.0 | 0.8 | circ | 0.8 | 1.3 | 2.8 | 4.4 | 9.504 | 12.354 | 5.928 | 0.13840 |
| 10.0 | 1.0 | circ | 0.8 | 1.3 | 3.6 | 5.6 | 12.096 | 14.946 | 7.572 | 0.12817 |
| 16.0 | 1.0 | circ | 0.8 | 1.3 | 4.5 | 6.5 | 14.040 | 16.890 | 9.030 | 0.11802 |
| 25.0 | 1.2 | shape | 1.0 | 1.6 | 5.6 | 8.0 | 17.280 | 20.880 | 11.160 | 0.11808 |
| 35.0 | 1.2 | shape | 1.0 | 1.6 | 6.7 | 9.1 | 19.656 | 23.256 | 12.942 | 0.11047 |
| 50.0 | 1.4 | shape | 1.0 | 1.6 | 8.0 | 10.8 | 23.328 | 26.928 | 15.396 | 0.10537 |
| 70.0 | 1.4 | shape | 1.2 | 2.0 | 9.4 | 12.2 | 26.352 | 30.752 | 17.664 | 0.10450 |
| 95.0 | 1.6 | shape | 1.2 | 2.0 | 11.0 | 14.2 | 30.672 | 35.072 | 20.604 | 0.10026 |
| 120.0 | 1.6 | shape | 1.2 | 2.0 | 12.4 | 15.6 | 33.696 | 38.096 | 22.872 | 0.09616 |
| 150.0 | 1.8 | shape | 1.4 | 2.5 | 13.8 | 17.4 | 37.584 | 42.884 | 25.488 | 0.09807 |
| 185.0 | 2.0 | shape | 1.4 | 2.5 | 15.3 | 19.3 | 41.688 | 46.988 | 28.266 | 0.09579 |
| 240.0 | 2.2 | shape | 1.6 | 2.5 | 17.5 | 21.9 | 47.304 | 53.004 | 32.178 | 0.09407 |
| 300.0 | 2.4 | shape | 1.6 | 2.5 | 19.5 | 24.3 | 52.488 | 58.188 | 35.766 | 0.09173 |
| 400.0 | 2.6 | shape | 1.6 | 2.5 | 22.6 | 27.8 | 60.048 | 65.748 | 41.136 | 0.08839 |

TABLE A6.2 ZERO SEQUENCE REACTANCE CALCULATION

## APPENDIX 7

### Typical Electric Motor Information

Table A7.1 shows a typical information listing supplied by a manufacturer for a 180kW, 3.3kV Induction motor. Item 17, listed on table A7.1, refers to the thermal withstand rating of the machine. This data is usually supplied in a graphical form. Fig. A.7.1 shows a typical characteristic which depicts the maximum withstand time under overload conditions for the machine at both ambient and running temperatures. Selected time/current values from these characteristics are used in the MPROT program. Item 18, listed on table A.7.1, refers to the Torque/Speed characteristic. A typical characteristic is shown in Fig. A7.2. This information is used in Appendix 2 to determine the acceleration period of the motor/drive unit. Fig. A7.3, the equivalent circuit of the motor, may also be used to determine acceleration times, but is more generally required for use in power-system study programs. Fig. A.7.4 is a typical test record supplied by the motor manufacturer. This certificate provides general data from which a circle diagram could be produced and also includes individual details of the motor heat run.

## TABLE A7.1

## INFORMATION REQUIREMENTS FOR ELECTRIC MOTORS

| | | |
|---|---|---|
| 1. | Rated Voltage | 3.3kV |
| 2. | Rated Output | 180kW |
| 3. | Synchronous Speed | 990rpm |
| 4. | Full Load Current | 40 Amp |
| 5. | Starting Current | 230 Amp |
| 6. | Max Stall time from Cold at 100% Volts | 23 Secs |
| 7. | Max Stall time from Hot at 100% Volts | 15 Secs |
| 8. | Max operating time at rated output on loss of 1 phase (cold) | 12 Min |
| 9. | Max operating time at rated output on loss of 1 phase (hot) | 10 Min |
| 10. | Max Stall time on loss of 1 phase (cold) | 14 Secs |
| 11. | Max Stall time on loss of 1 phase (hot) | 8 Secs |
| 12. | Min Delay before starting following a locked Rotor condition for max stall time | 1 hour |
| 13. | Max temperature rise at rated output | 60°C |
| 14. | Starting Secs from Cold condition | 50 Secs |
| 15. | Starting Secs from Hot condition | 28 Secs |
| 16. | $GD^2$ for motor | $41.2kgm^2$ |
| 17. | Hot and Cold Thermal Withstand Curves | Fig. A7.1 |
| 18. | Torque speed curve at 100%v | Fig. A7.2 |
| 19. | Equivalent Circuit Diagram for starting and running conditions | Fig. A7.3 |

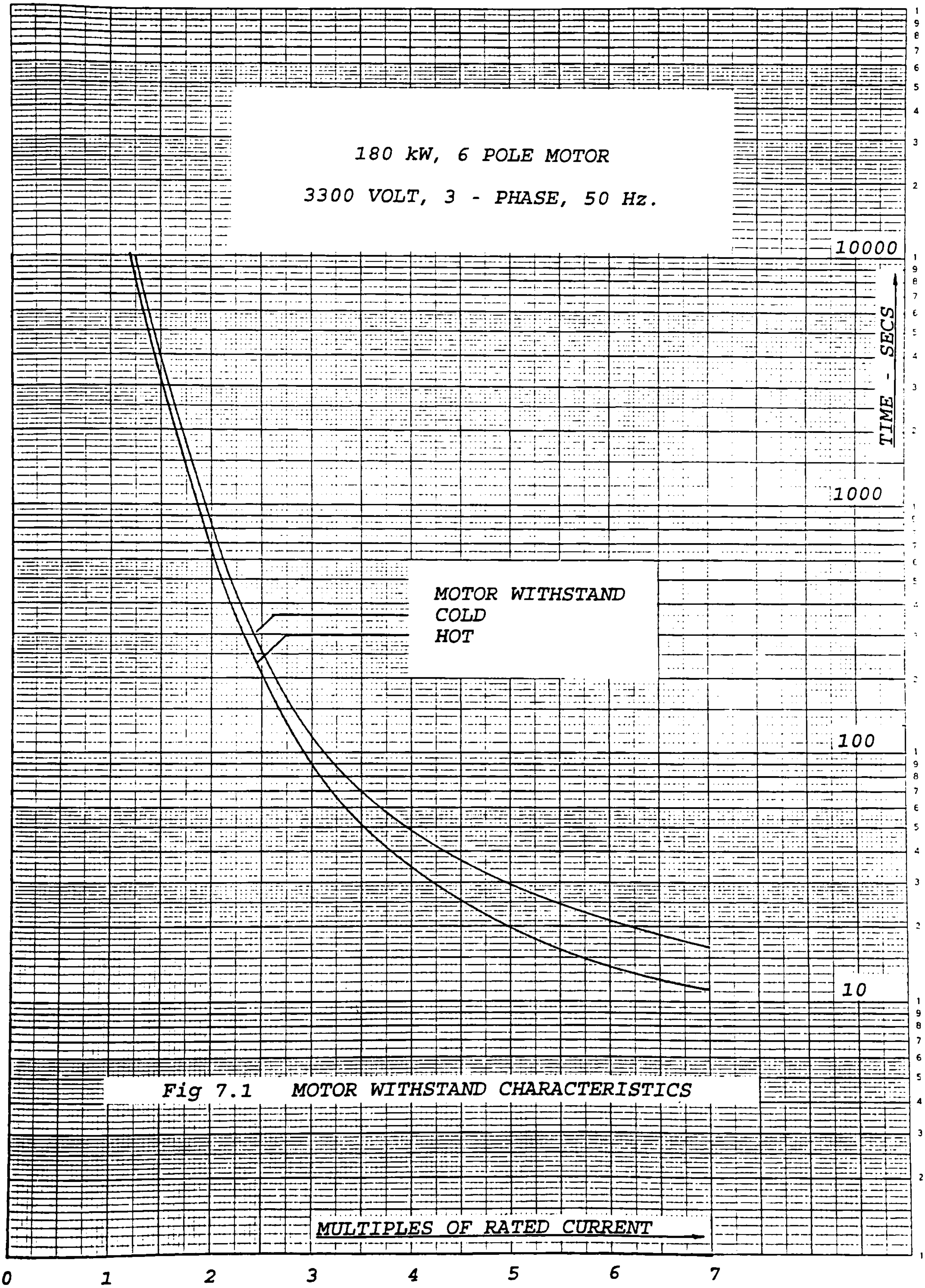



Fig 7.1 MOTOR WITHSTAND CHARACTERISTICS

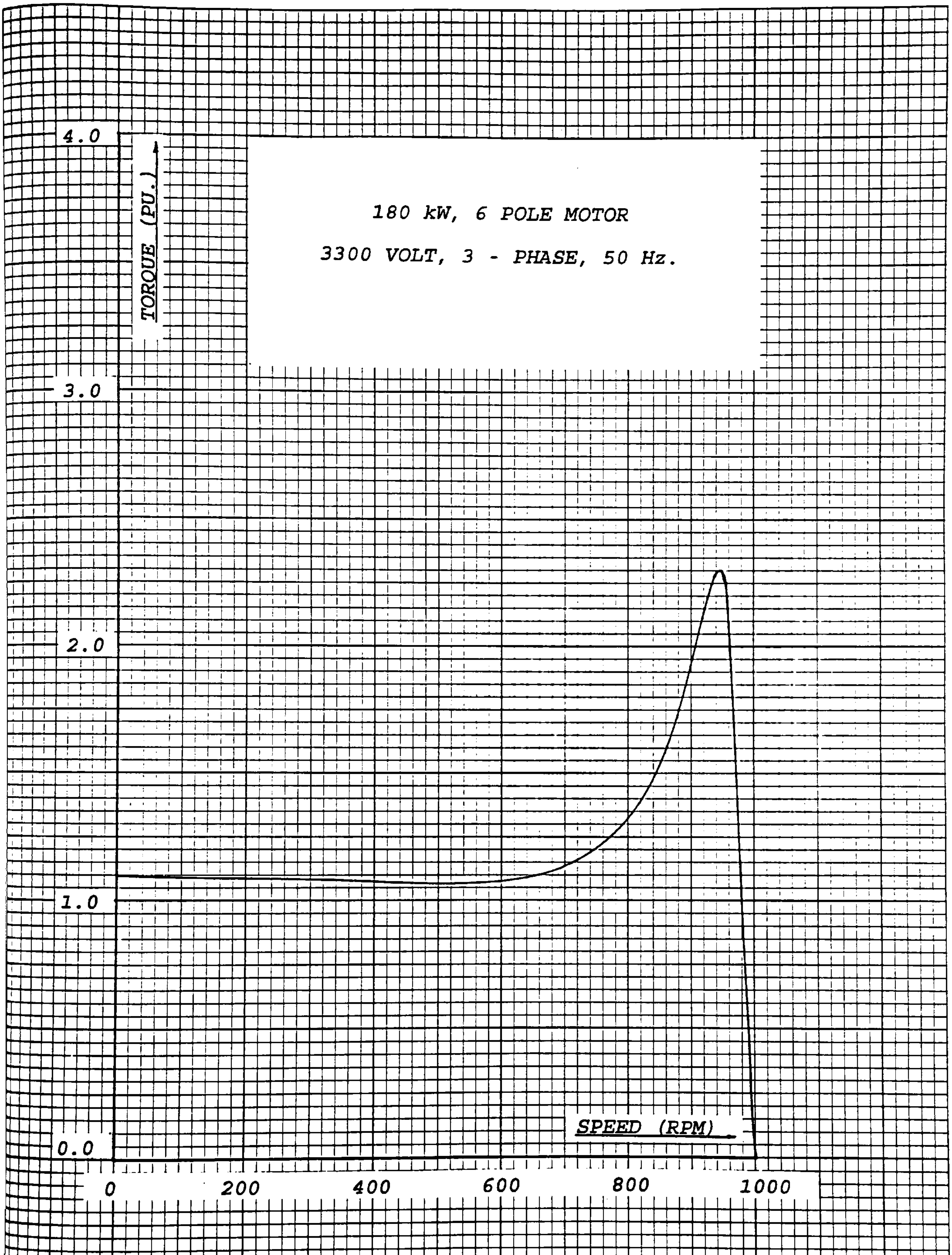
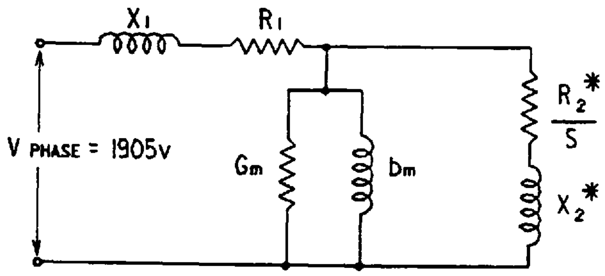



Fig 7.2 TORQUE/SPEED CHARACTERISTIC

VOLTAGE 3300 v
RATING 180 KW
POLES 6
FRAME D355-8B

EQUIVALENT CIRCUIT




| IDENTITY | P.P.S. START CONDITION | P.P.S. RUN CONDITION |
|---|---|---|
| $R_1$ | 0.643 Ω | 0.643 Ω |
| $X_1$ | 5.499 Ω | 5.499 Ω |
| Gm | 0.000341 SIEMENS | 0.000341 SIEMENS |
| bm | 0.00672 SIEMENS | 0.00672 SIEMENS |
| $R_2$* | 2.065 Ω | 0.539 Ω |
| $X_2$* | 4.566 Ω | 6.237 Ω |

* REFERRED TO STATOR

EQUIVALENT CIRCUIT PHASE VALUES

Fig A7.3

**OFFICIAL TEST RECORD OF** T/Encl. CACA Squirrel Cage **A.C. INDUCTION MOTOR No** 

**CUSTOMER** **SIZE** D355-8B

**OUTPUT :** 180 KW 3300 VOLTS 40 AMPS 990 R.P.M. 50 CYCLES 3 PHASE

| NO LOAD READINGS | | | | STARTING TORQUE | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Phase 1 | Phase 2 | Phase 3 | Volts | Amps | Nm | %F.L.T. | %F.L.C. | Conn. |
| Volts | 3300 | | 3300 | 3300 | 230 | 1633 | 94 | 5.75 | Y |
| Amps | 14.03 | | 14.03 | | | | | | |
| R.P.M. | | 1000 | | | SHORT CIRCUIT READING | | | | |
| Cycles | | 50 | | Volts | Amps | W1(x300) | W2 | | |
| (Watts x300) | 84 | | 67 | 577 | 40.9 | 73.3 | 37.1 | | |

No load loss = Total loss − $I^2R$ = 5102

| Time | Volts | Stator Amps | Cycles | R.P.M. | | KW | KVA | PF | | KW Output | Eff % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 7.00 | 3300 | 40.0 | 50 | 991 | | | | | | | |
| 7.30 | " | " | " | | | | | | | | |
| 8.00 | " | " | " | | | | | | | | |
| 8.30 | " | " | " | 990 | | | | | | | |
| 9.00 | " | " | " | | | | | | | | |
| 9.30 | " | " | " | | | | | | | | |
| 10.00 | " | " | " | 990 | | | | | | | |
| 10.30 | " | " | " | | | | | | | | |
| 11.00 | " | " | " | | | | | | | | |
| 11.30 | 3300 | 40.0 | 50 | 989 | | | | | | | |
| | | Stator winding temperature rise by resistance = 56° c | | | | | | | | | |
| | | | | | | | | | | | |
| 3/4 | 3300 | 29.75 | 50 | 992 | | 134.0 | 164.8 | .813 | | 126.8 | 94.6 |
| 1/2 | " | 20.25 | " | 994 | | 90.5 | 141.8 | .638 | | 83.0 | 91.7 |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| Calculated Pull-out Torque = 2.35 FLT | | | | | | | | | | | |
| | | | | | | | | | | | |
| Heater - 292 Watts at 110 volts | | | | | | | | | | | |

| RESISTANCE (OHMS) ACROSS TERMINALS | COLD 20° c | HOT 21°c |
|---|---|---|
| Stator | 1.53 | 1.83 |
| Conn. | 1.53 | 1.83 |
| Y | 1.53 | 1.83 |
| Rotor | | |
| Conn. | | |
| | | |

**HIGH PRESSURE INSULATION TEST**

**Stator flashed to earth for 1min. at 7600 V.A.C. Insulation Resistance 350 M**

**Heater flashed to earth for 1min. at 1200 V.A.C. Insulation Resistance 100 M**

Fig A7.4 MANUFACTURERS TYPICAL MOTOR TEST RECORD

## APPENDIX 8

### Typical Fuse Characteristics

The typical information supplied by manufacturers to describe their products is generally produced in a graphic form. The three basic requirements necessary to fingerprint each fuse are:

1. To establish the relationship between the pre-arcing time of the fuse and the rms symmetrical prospective fault current available at the point of connection. This relationship is shown in Fig. A8.1.

2. To establish the relationship between the rms symmetrical prospective fault current at the point of connection and the peak cut-off current of the fuse. This relationship is shown in Fig. A8.2

3. The manufacturers declaration of:

   (a) Minimum Pre-arcing $I^2t$ (Amp$^2$ seconds)

   (b) Maximum Total $I^2t$ (Amp$^2$ seconds)

   - for each fuse rating

   Typical information is shown in Table A8.1.

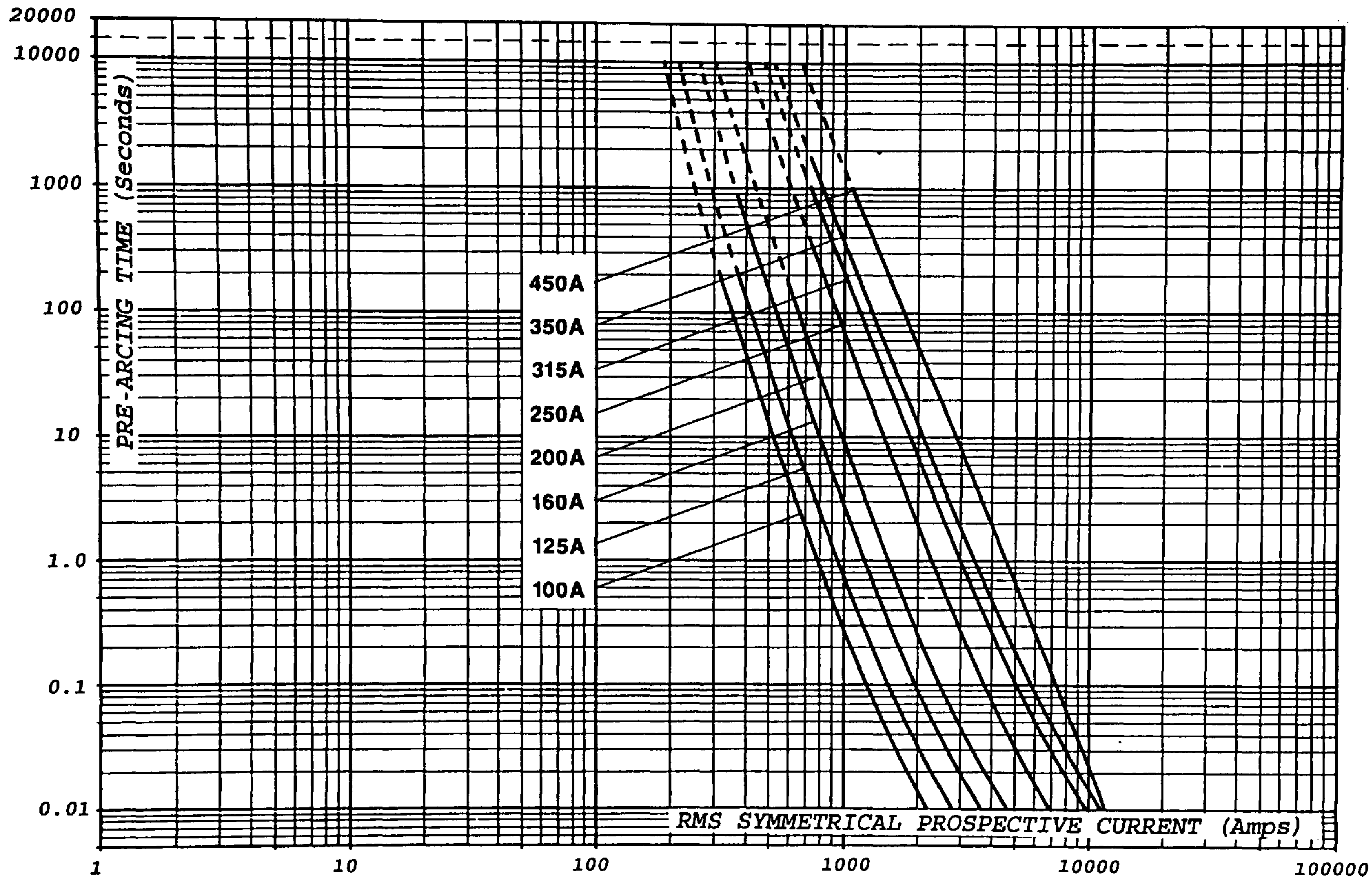



FIG A8.1 Typical Time/Current Characteristics

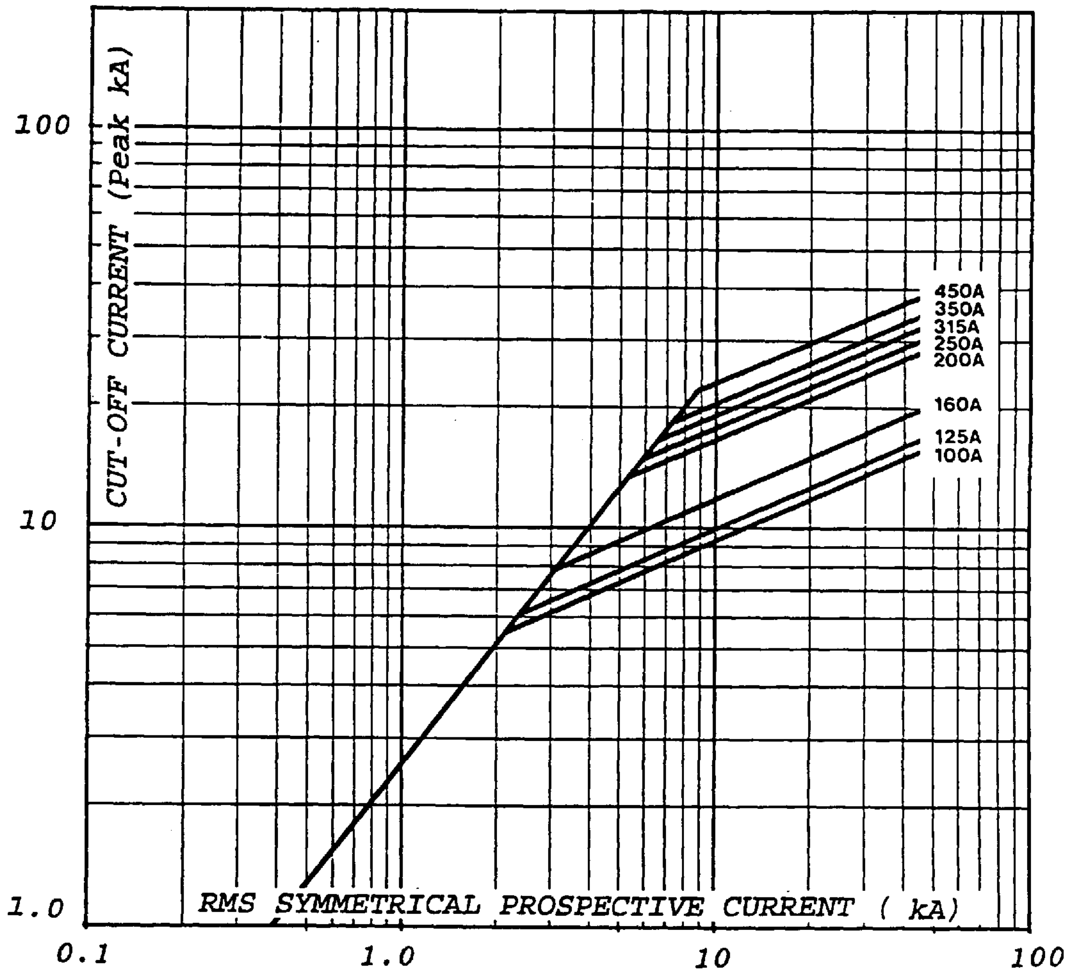



Fig A8.2 TYPICAL CUT-OFF CURRENT CHARACTERISTICS

| FUSE RATING Amps | MINIMUM PRE-ARCING $I^2t$ $A^2$ secs. $10^3$ | MAXIMUM PRE-ARCING $I^2t$ $A^2$ secs. $10^3$ |
|---|---|---|
| 100 | 23.0 | 270.0 |
| 125 | 33.0 | 340.0 |
| 160 | 59.0 | 570.0 |
| 200 | 92.0 | 770.0 |
| 250 | 235.0 | 1400.0 |
| 315 | 367.0 | 2200.0 |
| 350 | 540.0 | 3100.0 |
| 450 | 540.0 | 6400.0 |

TABLE A8.1 TYPICAL $I^2t$ CHARACTERISTICS

## APPENDIX 9

### Motor Protection Relay Thermal Characteristics

9.1 BS142, Section 2.3 refers to the specification for thermal electrical relays. Three relays are specified, they are:

2.1 Thermal electrical relays

2.2 Thermal electrical relays with total memory function

2.3 Thermal electrical relays with partial memory function

The relay specified in 2.2 is defined as:
"A thermal electrical relay which, in its operating characteristic, takes into account the thermal effects of the load and overload currents existing before the operation of the relay".

Both relays referred to in this work comply with this definition. the relays are equipped with a cold overload characteristic which is defined in BS 142, Section 2.3 as:

"Cold Curve - For a thermal electrical relay, the characteristic curve representing the relationship between specified operating time and current with the relay in a steady-state no-load condition before the overload occurs".

Let the relay operating characteristic be represented by a single time-constant exponential equation which will satisfy the motor thermal requirements derived in Appendix 1, then:

Actual temperature =

$$\textit{Final temperature} - \textit{Temperature difference} \bullet e^{-t/\tau}$$

$$\theta = \theta_f - (\theta_f - \theta_p) \bullet e^{-t/\tau}$$

where:

| | | |
|---|---|---|
| $\theta p$ | = | Starting temperature |
| t | = | Elapsed time |
| $\tau$ | = | Relay heating time constant |

Subtracting $\theta_p$ from both sides of the equation gives:

$$\theta - \theta_p = \theta_f - \theta_p - (\theta_f - \theta_p) \bullet e^{-t/\tau}$$

and simplifying

$$\theta - \theta_p = \theta_f - \theta_p \bullet (1 - e^{-t/\tau})$$

$$\frac{\theta - \theta_p}{\theta_f - \theta_p} = 1 - e^{-t/\tau}$$

$$e^{-t/\tau} = 1 - \frac{\theta - \theta_p}{\theta_f - \theta_p}$$

$$= \frac{\theta_f - \theta_p - (\theta - \theta_p)}{\theta_f - \theta_p}$$

$$= \frac{\theta_f - \theta}{\theta_f - \theta_p}$$

$$e^{t/\tau} = \frac{\theta_f - \theta_p}{\theta_f - \theta}$$

$$t = \tau \bullet \log_e \left( \frac{\theta_f - \theta_p}{\theta_f - \theta} \right) \qquad \text{(A9.1)}$$

Now final temperature $\theta_f \propto I^2$ where I = Relay current

and actual temperature $\theta \propto (k.I_B)^2$

starting temperature $\theta_p$ occurs when the relay current is zero

where $I_B$ is the basic current (1 or 5 Amp)

k is a constant by which $I_B$ is multiplied to obtain the current value to which the accuracy of the current is referred. As defined in Appendix A of BS 142, Section 2.3.

Substituting in equation A9.1 gives:

$$t = \tau \bullet \log_e \left( \frac{I^2}{I^2 - (k.IB)^2} \right) \qquad \text{(A9.2)}$$

which is the A.1 Cold characteristic referred to in Appendix A of BS 142, Section 2.3.

BS142, Section 2.3 defines the hot thermal characteristic as follows:
"Hot Curve - for a thermal electrical relay with a total memory function, the characteristic curve representing the relationship between specified operating time and current, taking account of the thermal effects of a specified steady-state load current before the overload occurs".

Hence referring to equation A9.1, $\theta_p$ is the steady-state temperature corresponding to the load current preceding the overload.

Let Ip be the load current proceeding the overload so that the steady-state temperature $\theta_p \propto Ip^2$.

Substituting for $\theta_p$ in equation A9.1 gives

$$t = \tau \bullet \log_e \left( \frac{I^2 - Ip^2}{I^2 - (k.I_B)^2} \right) \qquad \text{(A9.3)}$$

which is the B.1 Hot characteristic referred to in Appendix B of BS 142, Section 2.3.

By expanding equation A9.3, all equations referred to in BS 142, Section 2.3, Appendix B can be verified.

Dividing the Numerator and denominator by $(kIB)^2$ in equation (A9.3) gives:

$$t = \tau \bullet \log_e \left( \frac{\left(\frac{I}{k.I_B}\right)^2 - \left(\frac{Ip}{k.I_B}\right)^2}{\left(\frac{I}{k.I_B}\right)^2 - 1} \right)$$

$$= \tau \bullet \log_e \left( \left( \frac{\left(\frac{I}{k.I_B}\right)^2}{\left(\frac{I}{k.I_B}\right)^2 - 1} \right) - \left( \frac{\left(\frac{Ip}{k.I_B}\right)^2}{\left(\frac{I}{k.I_B}\right)^2 - 1} \right) \right)$$

$$= \tau \bullet \log_e \left| \frac{\left(\frac{I}{k.I_B}\right)^2}{\left(\frac{I}{k.I_B}\right)^2 - 1} \bullet \left( 1 - \frac{Ip^2}{I^2} \right) \right| \qquad \text{(A9.4)}$$

Since the actual temperature $\theta \propto (k.I_B)^2$

and $\theta p \propto Ip^2$

then

$$\frac{\theta p}{\theta} = \left(\frac{Ip}{k.IB}\right)^2$$

from which

$$Ip^2 = \frac{\theta p}{\theta} \bullet (k.IB)^2$$

Substituting for Ip in equation A9.4 gives:

$$t = \tau \bullet \log_e \left| \frac{\left(\frac{I}{k.IB}\right)^2}{\left(\frac{I}{k.IB}\right)^2 - 1} \bullet \left(1 - \frac{\frac{\theta p}{\theta} \bullet \left(k.IB)^2\right)}{I^2}\right) \right|$$

$$= \tau \bullet \log_e \left| \frac{\left(\frac{I}{k.IB}\right)^2}{\left(\frac{I}{k.IB}\right)^2 - 1} \bullet \left(1 - \frac{\theta p}{\theta\left(\frac{I}{k.IB}\right)^2}\right) \right| \qquad \text{(A9.5)}$$

From which it can be seen that equations A9.3, A9.4 and A9.5 comply with the relay characteristic hot curves stated in BS142, Section 2.3, Appendix B.

## 9.2 Derivation of P&B Microgolds Thermal Characteristic

The trip level of the relay is set at 105% of the nominal relay rating. This value may be varied by means of the Iθ/IN potentiometer which enables a variety of CT ratios to be accommodated and allows modification of the trip level to a user defined value.

Using P&B golds symbols we have

The Iθ/IN setting is determined as follows

$$\frac{I\theta}{IN} = \frac{S}{1.05} \bullet \frac{Motor\,FLC}{CT\,Primary\,RAtio}$$

where S is the required trip level.

From which it can be seen that

$$\theta_f \propto \left(\frac{Multiple\,of\,Motor\,FLC}{Overload\,Setting}\right)^2 = \left(\frac{P}{S}\right)^2$$

$$\theta = \frac{1 - The\,starting\,temperature}{Thermal\,capacity\,at\,overload\,setting\,S}$$

$$\theta_p \propto \left(\frac{1}{S} \bullet \frac{Motor\,Load}{Motor\,FLC}\right)^2 = \left(\frac{IL}{S}\right)^2$$

Substituting the above values in equation 9.1 gives:

$$t = \tau \bullet \log_e\left(\frac{(P/S)^2 - (IL/S)^2}{(P/S)^2 - 1}\right)$$

$$t = \tau \bullet \log_e \left( \frac{P^2/S^2 - I_L{}^2/S^2}{P^2/S^2 - S^2/S^2} \right)$$

$$t = \tau \bullet \log_e \left( \frac{P^2 - I_L{}^2}{P^2 - S^2} \right)$$

The relay characteristic considers the temperature of the machine on starting to be a function of (pre-start load current)$^2$ which may be any value from 0 to S • Full load current under normal conditions. In general terms this mean that the Cold thermal characteristic of the relay is based on a prefault current of 0 amp, that is, a stationary machine, whilst the hot thermal characteristic is calculated on the basis that the machine had been running at full load and had reached its full working temperature.

To achieve satisfactory compatibility between relay and machine characteristic curves a weighting factor is introduced to increase the relay operating times from the hot start condition. This factor has the effect of reducing the time margin between the hot and cold curves.

The equation of the modified relay thus becomes

$$t = \tau \bullet \log_e \left( \frac{(P/S)^2 - W(I_L{}^2/S)^2}{(P/S)^2 - 1} \right)$$

$$t = \tau \bullet \log_e \left( \frac{P^2 - W \bullet I_L{}^2}{P^2 - S^2} \right)$$

where W is a weighting factor of 0.5

## 9.3 Derivation of GEC Alsthom CTM(F) Thermal Characteristics

Referring to equation 4.1 where the cold operating characteristic is defined as:

$$t = \tau \bullet \log_e \frac{Ieq^2}{Ieq^2 - Is^2}$$

where the current

$$Ieq = \sqrt{(I^2 + 6I_2^2)}$$

which under balanced situations = $I_1$ ($I_{PPS}$). The equation can be seen to be of similar form to that derived in equation A9.1.

The trip level of the relay is set at 105% of the nominal relay rating. the value may be varied by means of the two faceplate mounted potentiometers to accommodate a variety of CT ratios and to allow modification of the trip level to a user defined value.

Using GEC-Alsthom symbols we have

$$Potentiometer\ setting = \frac{Is}{1.05} \bullet \frac{Motor\ FLC}{CT\ Ratio}$$

where IS is the desired trip level from which it can be seen that:

$$\theta_F \propto \left( \frac{\sqrt{(I_1^2 + 6I_2^2)}}{trip\ level} \right)^2 = \left( \frac{Ieq}{Is} \right)^2$$

$$\theta = 1 \ (max\ thermal\ capacity)$$

Substituting in equation A9.1.

$$t = \theta \bullet \log_e \frac{\left(\frac{Ieq}{Is}\right)^2}{\left(\frac{Ieq}{Is}\right)^2 - 1}$$

$$= \tau \bullet \log_e \frac{\left(\frac{Ieq}{Is}\right)}{\left(\frac{Ieq}{Is}\right)^2 - \left(\frac{Is}{Is}\right)^2}$$

$$t = \tau \bullet \log_e \frac{Ieq^2}{Ieq^2 - Is^2}$$

A typical value for $\tau$ is 88.7 seconds for the cold curve. This time constant value is directly modified to $\tau/3$ when the hot curve is considered.

Hence

$$t_{hot} = \frac{\tau}{3} \bullet \log_e \frac{Ieq^2}{Ieq^2 - Is^2}$$

## APPENDIX 10

## Current Transformers

### A.10.1 General Information

Current transformers like all transformers rely on the Ampere-Turn balance principle for their operation.

That is:

Primary Turns • Primary Amps = Secondary Turns • Secondary Amps + Losses

$$(N.I)_{primary} = (N.I)_{secondary} + (N.I)_{losses}$$

It can be seen that errors are introduced into the measuring process by the inclusion of a loss component. The losses are due to a requirement for the primary circuit to provide:-

(1) The Reactive Ampere-Turns necessary to excite the transformer core

(2) The Active Ampere-Turns necessary to supply the hysteris and eddy current losses in the iron core and the $I^2R$ losses in both the primary and secondary windings.

Current transformers fall into two distinct classifications, one for metering and measurement purposes, the other for protection duties. In the former case the accuracy up to full load is of paramount importance whilst for protection purposes the performance during the overload condition is the portion of interest. It is the protection current transformers which are of interest in this document. Protection current transformers may be subdivided into those conforming to Classes 5P and 10P and those conforming to Class X as referred to in BS 3938: 1973. Accuracy classes 5P and 10P define the limits of error for accuracy which the current transformer must comply with.

These are defined in BS 3938: 1973 as:

| Accuracy Class | Current Error at Rated Primary Current | Phase Displacement at Rated Primary Current | Composite Error at Rated Accuracy limit Primary Current |
|---|---|---|---|
| 5P | ±1% | ±60 mins; ±1.8 centi rad | 5% |
| 10P | ±3% | ±60 mins; ±1.8 centi rad | 10% |

Where: Percentage Current Error or Ratio Error

$$= \frac{(K_N \bullet I_S - I_P) \bullet 100}{I_P}$$

$K_N$ = Rated transformation ratio

$I_P$ = Actual primary current

$I_S$ = Actual secondary current when Ip is flowing

## Rated Primary Current

The current value upon which the performance of the transformer is based.

## Accuracy Limit Current

The accuracy limit current is the maximum current which the current transformer can deliver whilst connected to its rated burden without exceeding the declared composite error. The value is usually expressed as a ratio and included in the current transformer specification. The ratio is defined as the 'Accuracy Limit Factor' (ALF) where:

$$ALF = \frac{Maximum\ current\ output\ with\ rated\ burden}{Current\ Transformer\ secondary\ rating}$$

## Phase Displacement

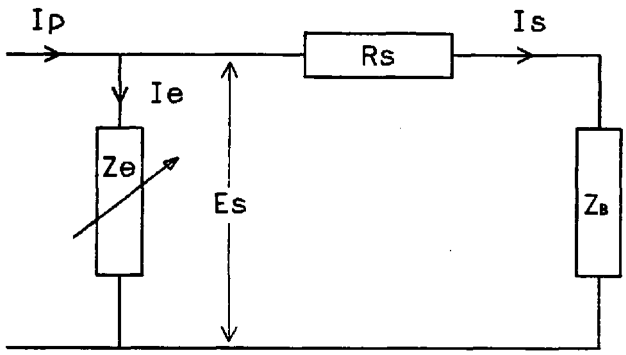
The displacement in phase between the primary and secondary current vectors. Phase displacement is considered positive if the secondary current vector leads the primary current vector and negative when it lags the primary current vector.

## Composite Error

A typical equivalent circuit diagram of a current transformer is as shown in Fig. A10.1 If the exciting impedance Ze is regarded as a linear value then the associated vector diagram would be as shown in Fig. A10.2. The error due to the exciting current is labelled Ie and is termed the composite error. The vector Ie comprises of components Ir and Iq which are in phase and in quadrature respectively with the primary current. The Ir vector represents the current error component and the Iq vector the phase error component.

Unfortunately the impedance Ze is not linear and results in the generation of harmonics in the exciting current Ie. The presence of these harmonics increases the rms value of Ie and as a consequence raises the value of the composite error.

CURRENT TRANSFORMER EQUIVALENT CIRCUIT




WHERE :

Ze IS THE EXCITING IMPEDANCE

Rs IS THE C.T. SECONDARY RESISTANCE

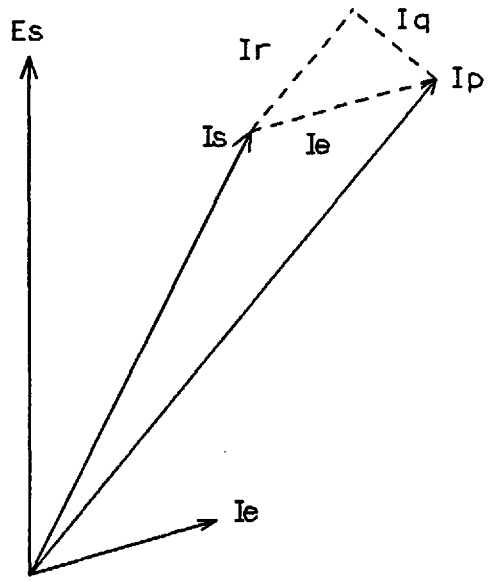
$Z_B$ IS THE IMPEDANCE OF THE SECONDARY BURDEN

Ip IS THE PRIMARY EQUIVALENT CURRENT

Is IS THE SECONDARY CURRENT

Ie IS THE EXCITING CURRENT

Fig A10.1




WHERE :

Ir IS THE CURRENT MAGNITUDE ERROR

Iq RESULTS IN THE PHASE ANGLE ERROR

Fig A10.2

Hence the composite error under steady state conditions may be defined as the rms value of the difference between:

(a) The instantaneous values of the Primary Current and

(b) The instantaneous values of the Secondary Current multiplied by the transformation ratio

The composite error, $e_c$ is generally expressed as a percentage of the rms value of the primary current in accordance with the expression

$$e_c = \frac{100}{Ip} \sqrt{\left( \frac{1}{T} \int_o^T (kN \bullet i_s - ip)^2 \, dt \right)}$$

| | | | |
|---|---|---|---|
| Where: | $k_N$ | = | related transformation ratio |
| | $i_p$ | = | the instantaneous value of the primary current |
| | $i_s$ | = | the instantaneous value of the secondary |
| | Ip | = | the rms value of the primary current |
| | T | = | the duration of one cycle |

Class X current transformers as defined in BS 3938: 1973, are essentially special purpose devices designed to produce a characteristic specified by the purchaser in the following terms.

1. Rated primary current.
2. Turns ratio
3. Rated knee-point emf at maximum secondary terms
4. Maximum exciting current at the rated knee-point emf and/or at a stated percentage thereof.

5. Maximum resistance of the secondary winding corrected to 75°C or the maximum service temperture whichever is the greater.

**Definition**

Knee-point emf:
That sinusoidal emf of rated frequence applied to the secondary teminals of the transformer, all other windings being open-circuited, which, when increased by 10% causes the exciting current to increase by 50%.

## A10.2 Modifying the Accuracy Limit Factor (ALF) for the MCGG Relay

A typical current transformer would be specified in accordance with a model specification contained in BS3938:1973 Current Transformers. The output, accuracy and ALF will typically be quoted in the form: 2.5VA 10P20.

Where 2.5 refers to the secondary burden at rated current
10P is the accuracy class
and 20 is the ALF

| | | |
|---|---|---|
| Rated Secondary burden | = | 2.5VA |
| Rated secondary current | = | 1 Amp |
| CT secondary resistance | = | 0.3 Ohm (typical value) |

Expressing the burden as an impedance

$$Z_B = \frac{VA\ of\ burden}{CT\ secondary\ rating}$$

$$Z_B = \frac{2.5}{1^2}$$

$$= 2.5 \text{ Ohm}$$

Then knee point voltage $> ALF$ (CT Resistance + Burden Impedance)

$> 20\,(0.3 + 2.5)$

$> 56$ Volts

If the case of the MCGG relay, the impedance of each element is 0.25 Ohm and is predominantly resistive.

Hence actual circuit resistance = CT resistance + relay resistance + lead resistance.

In the case where three CT phase conductors and a common return conductor are used, then only one lead resistance is required. Let the lead resistance be 0.1 ohm, then:

Actual circuit resistance $= 0.3 + 0.25 + 0.1$

$= 0.65$ ohm

From which, the maximum current that can be obtained before exceeding the prescribed error limit.

$$= \frac{\textit{knee point voltage}}{\textit{circuit resistance}}$$

$$= \frac{56}{0.65} = 86\,Amp$$

Therefore revised accuracy limit factor (ALF) = 86