

TABLE OF CONTENTS

0. PREFACE	III
HOW TO USE THE MANUAL	V
1. INTRODUCTION AND OVERVIEW	1
2. THE CONCEPT OF INDUCTION MOTORS USED AS GENERATORS	
2.1 Introduction.....	3
2.2 Induction versus Synchronous Generator	
2.2.1 Working Principle of a Synchronous Generator	3
2.2.2 Working Principle of an Induction Machine	5
2.3 System Components of an MHP with Stand-alone Electricity Generation.....	7
2.3.1 Possible Applications of Induction Motors as Generators in MHPs	8
2.3.2 The Hydraulic System and its Effect on the Choice of the Generator	9
2.3.3 The Consumer System and its Effect on the Choice of the Generator	10
2.3.4 Governors and Controllers Required by Synchronous or Induction Generators.....	10
2.4 Pros and Cons of Induction Motors Used as Generators	12
2.5 Suitable IMAGs.....	14
2.6 Conclusions	14
3. THEORY OF THE THREE-PHASE INDUCTION MACHINE	
3.1 General Design Features of the Induction Machine	15
3.2 Working Principle of an Induction Machine	
3.2.1 The Rotating Magnetic Field	17
3.2.2 Slip and Rotor Speed	18
3.2.3 Induced Voltage and Frequency	19
3.2.4 The Equivalent Circuit	19
3.2.5 Operation at no Load	22
3.2.6 Operation under Load.....	22
3.2.7 The Flow of Power of an Induction Machine in Motor Operation.....	24
3.3 The Induction Machine in Generator Mode	
3.3.1 General	26
3.3.2 Reactive Power Requirement and $\cos\phi$ in Generator Operation.....	27
3.3.3 The Effect of Saturation.....	28
3.3.4 The Self-Excited Generator	29
3.3.5 The Problem of Voltage and Frequency Control of the Induction Generator in Isolated Operation.....	30
3.4 Induction Machine Characteristics	
3.4.1 Torque.....	32
3.4.2 Rotor bar construction	33
3.4.3 Presentation of Induction Machine Performance	35
3.4.4 The Circle Diagram.....	37
4. SELECTING AN INDUCTION MOTOR TO BE USED AS A GENERATOR	
4.1 Mechanical Design and Rating Plate Data of Induction Motors	
4.1.1 Motor Size and Standard Mounting Designs.....	39
4.1.2 Rating Plate.....	40
4.2 General Considerations on Selection.....	43
4.3 Practical Selection Methods	
4.3.1 Selection Criteria - Suitable Machines	45
4.3.2 Selection Procedure	47
a) electrical limit ($I < I_n$)	47
b) thermal limit (permissible temperature rise).....	48
4.3.3 Generator efficiency and power factor at part-load.....	51
4.3.4 Summary of the selection procedure	54
4.3.5 Example	55
4.4 Determination of IMAG performance from test results.....	56

5. OPERATION AND CONTROL

5.1 Operation in Parallel with a Large Grid	
5.1.1 Start-up	58
5.1.2 Compensation of the Reactive Power Demand	59
5.1.3 Example on power factor correction for parallel operation	60
5.1.4 Compensation at part-load operation	61
5.1.5 Safety and Control Equipment for parallel operation	
Grid Protection	62
Internal Protection and Control	62
Optimization of energy production - Water level control	65
5.2 Operation in Parallel with a Synchronous Generator (Minigrid)	66
5.3 Stand-alone Electricity Generation	
5.3.1 General	67
5.3.2 The Ungoverned Plant at Constant Load	69
Start-up	69
Sizing Capacitors	70
De-excitation	72
Protection Required	73
5.3.3 The hand-regulated plant with stepped capacitors	73
Sizing Capacitors	74
5.3.4 IMAG in Conjunction with a Load Controller	75
5.4 Three-Phase Motor as Single-Phase Generator	
5.4.1 General	78
5.4.2 Balancing the single-phase load over the three phases of the IMAG - the C-2C connection	78
5.5 What to do if the expected power output of the selected IMAG is not attained	
5.5.1 Parallel Operation	80
5.5.2 Stand-alone Electricity Generation	81
5.6 Overview of monitoring equipment and protection required in MHPs using an IMAG	83

6. SAFETY AND PROTECTION

6.1 General	86
6.2 The Danger of Electricity	
6.2.1 To People	86
6.2.2 To Installations	86
6.3 Responsibilities in case of electrical accidents and damage	87
6.4 Fault Conditions and Protective Measures	
6.4.1 Protection of People - System Earthing	87
6.4.2 Protection of the Electrical Installation	89
6.5. Equipment	
6.5.1 Switchgear	91
6.5.2 Overcurrent protection devices	91
6.5.3 Overvoltage protection devices	93
6.6 Particularities of IMAGs	
6.6.1 The problem of third-harmonic currents	94
6.6.2 System Earthing and Internal Connection of IMAGs (Y or D)	94
6.6.3 The IMAG - an inherently overload-safe generator	96

7. ECONOMIC CONSIDERATIONS

7.1 General	97
7.2 Simple Methods of Comparing Project Costs and Benefits	97
7.2.1 Identifying Project Costs	97
7.2.2 Identifying Project Benefits	100
A) Parallel Operation with a grid	100
B) Stand-alone electricity generation	102

8. WORKED EXAMPLES

8.1 Parallel operation	105
8.2 Stand-alone operation	111

Appendices:

Appendix A:

BASIC THEORY OF ELECTRICAL ENGINEERING

1. INTRODUCTION

1.1 Electrical Circuit	115
1.2 Voltage	115
1.3 Current	115
1.4 Effects of Current Flow	116
1.5 Power	116

2. DIRECT CURRENT (DC)

2.1 Resistance	
2.1.1 General Formulae	117
2.1.2 Ohm's Law	118
2.1.3 Power Losses - Joule's Law	118
2.1.4 Connection of Resistances	119
2.2 Capacitance of Capacitors	
2.2.1 General	121
2.2.2 Capacitance	121
2.2.3 Variation of Current and Voltage	121
2.2.4 Stored Energy of a Capacitor	123
2.2.5 Connection of Capacitors	124

3. MAGNETISM - ELECTROMAGNETISM

3.1 Effects of Magnetism	126
3.2 Magnetism and Electric Current	127
3.3 Magnetic Flux and Magnetic Flux Density	128
3.4 Magnetic Characteristic - Magnetization Curve	128
3.5 Generation of an Electromagnetic Force	130

4. INDUCED VOLTAGE

4.1 General	133
4.2 Self-Induction	136
4.3 Transformer Induced Voltage	136
4.4 Eddy Currents	138

5. INDUCTANCE

5.1 Definition	139
5.2 Connection of Inductances	141
5.2.1 Inductors in series	141
5.2.2 Inductors in parallel	141

6. DC GENERATORS AND MOTORS

6.1 Working Principle of a DC Generator	142
6.2 Working Principle of a DC Motor	143

7. ALTERNATING CURRENT (AC)

7.1 Advantages of Alternating Current	144
7.2 Characteristics of the AC signal	144
7.3 Phasor Diagrams	146
7.4 Notations and Definitions	147
7.5 Power in AC	148
7.6 Power factor, $\cos \phi$	152
7.7 Circuit Elements in AC	
7.7.1 Pure Resistive Circuit	154
7.7.2 Pure Inductive Circuit	155
7.7.3 Pure Capacitive Circuit	156
7.8 Impedance Z in Series Connections	157

7.9 Impedance Z in Parallel Connections	158
7.10 Resonance	
7.10.1 Resonance for series connection of L and C	161
7.10.2 Resonance for parallel connection of L and C	161
7.11 Correction of the Power Factor $\cos \phi$	
7.11.1 General.....	162
7.11.2 Calculation of the Compensating Capacitance	163
8. THREE-PHASE SYSTEM	
8.1 General.....	165
8.2 Generating Three-Phase Voltage and Current.....	165
8.3 Connections	
8.3.1 Definitions	166
8.3.2 Star or Wye Connection.....	167
8.3.3 Delta Connection.....	169
8.3.4 Power in three-phase systems	170
8.3.5 Conclusion	171
8.4 Rotor Speed and Generated Frequency.....	171
8.5 Three-Phase Systems and Consumer Load	172
8.6 Power Factor Correction in Three-Phase Systems.....	173
9. VOLTAGE DROP AND CONDUCTOR SIZE	
9.1 General.....	175
9.2 Voltage Drop in DC.....	175
9.3 Voltage Drop in Single-Phase AC	
9.3.1 Considering line resistance only	175
9.3.2 Considering resistance and inductance of a line.....	176
9.4 Voltage Drop in Three-Phase AC.....	177
10. ANSWERS TO THE EXAMPLES	
10.1 Example 1 / page 120	178
10.2 Example 2 / page 124.....	179
10.3 Example 3 / page 125	180
10.4 Example 4 / page 164	180
10.5 Example 5 / page 173.....	183
10.6 Example 6 / page 174.....	186
10.7 Example 7 / page 177.....	186
Appendix B:	
SELECTED DIAGRAMS AND TABLES FOR ELECTRICAL ENGINEERING DESIGN	
B1) Standard Wire and Cable Sections and Permissible Currents (Heating).....	188
B2) End-use appliances and their approximate power demand.....	189
B3) Efficiency and $\cos \phi$ versus power for induction motors	190
B4) Slip versus power for induction machines (non-saturated motors)	191
B5) General range of efficiencies for synchronous generators	192
B6) General range of efficiencies for transmission gearings (flat and V-belts, gear-boxes).....	193
B7) Turbine types and specific speeds in function of head and flow	194
B8) Turbine efficiencies (at nominal flow).....	195
B9) Turbine efficiencies (at part flow)	196

Appendix C:

NO-LOAD AND BLOCKED-ROTOR TESTS AND DETERMINATION OF THE CIRCLE DIAGRAM

1. General.....	197
2. Measurement of stator resistance	197
3. No-Load Test.....	197
4. Blocked-Rotor Test.....	199
5. Determination of the Circle	201
6. Example	
6.1 Motor data (from rating plate):	203
6.2 Motor resistances (using an Ω -meter)	203
6.3 No-load test.....	203
6.4 Blocked-rotor test	204
6.5 Determination of the circle	204

Appendix D:

MEASURING TECHNIQUES AND REQUIRED EQUIPMENT

1. Accuracy of Measurements	205
2. Voltage Measurement	205
3. Current Measurement	205
4. Active Power Measurement by Means of Wattmeters	
4.1 Principle of a Wattmeter.....	206
4.2 Current Transformer	207
4.3 The Constant of a Wattmeter	207
4.4 Active Power Measurement in a Three-Phase System	
4.4.1 By Means of a Single Wattmeter	208
4.4.2 By Means of Three Wattmeters	209
4.4.3 By Means of Two Wattmeters - Connection according to Aron.....	210
5. Active Power Measurement by Means of a kW-Hour Meter	210
6. Portable Instruments - Multimeters	211

Appendix E:

LIST OF MANUFACTURERS OF INDUCTION GENERATOR CONTROLLERS 212

Appendix F:

REFERENCES.....213