

List of Figures

SNo.	Title of the Figure	Figure No.	Page No.
1	Product – Process Matrix	Figure 1.1	2
2	Block Diagram of Inter-relation of Health-RCM-Maintenance	Figure 1.2	21
3	Block Diagram for Approach used in Reliability Assurance using PDM data and Fuzzy Logic	Figure 1.3	23
4	Block diagram of Prognostics Module of OSA-CBM	Figure 1.4	26
5	Evaluation of Predictive Maintenance Technology	Figure 2.1	32
6	P-F Interval Curve	Figure 2.2	38
7	Bearing Vibration Spectrums and Digital Image Bearing Cage	Figure 2.3	41
8	Thermal Image of Motor Stator	Figure 2.4	42
9	Motor Current Signatures and Digital Image of Defective Rotor Bars	Figure 2.5	43
10	Stressor – Degradation - Equipment Failure	Figure 3.1	49
11	Flow chart showing implementation of PDM in Process Plants	Figure 3.2	53
12	Variation of desirability ' d ' with emphasis ' r '	Figure 3.3	55
13	Trend of Condition Indicators and EHI of a Gearbox	Figure 3.4	59
14	EHI plot with different weights ($w_1:w_2:w_3$)	Figure 3.5	60
15	Trend plot of Equipment Health Index	Figure 3.6	62
16	Water fall (Trend) diagram of Gearbox Vibration in Axial	Figure 3.7	63
17	Digital Photograph of the Steel Mill Gearbox.	Figure 3.8	64
18	Bottom Casing of the Gearbox	Figure 3.9	64
19	Bearing Housing with Rub marks	Figure 3.10	65

20	Condition Indicating Parameter Level and Degradation Pattern	Figure 4.1	71
21	Flow chart Approach for assessing True Degradation	Figure 4.2	77
22	Vibration Trend of the Gearbox for various products	Figure 4.3	79
23	Digital Images of Rolling Mill Stand and Gearbox	Figure 4.4	80
24	Subset of Rule Base for aggregating – FIS-I -Dynamic Load	Figure 4.5	83
25	FIS-II (Equipment Health Index) Membership Functions	Figure 4.6	84
26	Surface view of the dynamic load	Figure 4.7	85
27	FIS -Dynamic Load Input – Output membership functions	Figure 4.8	87
28	Health Index with and without Dynamic load consideration	Figure 4.9	89
29	Health Index and Dynamic Load	Figure 4.10	92
30	Fuzzy Probability Number (Trapezoidal Representation)	Figure 5.1	98
31	Electro-magnetic Sub System and Constituent materials	Figure 5.2	102
32	Power Transmission Sub System and its parts	Figure 5.3	103
33	Ventilation Sub System	Figure 5.4	104
34	Support Sub-System	Figure 5.5	105
35	Degradation - Failure progression of Electro-magnetic Sub System	Figure 5.6	106
36	Degradation - Failure progression Diagram for failure of Power Transmission Sub System	Figure 5.7	107
37	Degradation - Failure progression Diagram for failure of Ventilation Sub System	Figure 5.8	108
38	Degradation - Failure progression Diagram for failure of Support Sub System	Figure 5.9	109
39	Fault Tree for failure of Electro-magnetic motor sub system	Figure 5.10	113
40	Fault tree for failure of Power Transmission sub system	Figure 5.11	114

41	Fault tree for failure of Ventilation motor sub system	Figure 5.12	115
42	Fault tree for failure of Support motor sub system	Figure 5.13	116
43	Block diagram of Bottom Up relation of Sub-functions and Function	Figure 6.1	133
44	Uncertainty in PF interval	Figure 6.2	136
45	Fuzzy Sets for Condition Indicator Level (Normalized)	Figure 6.3	138
46	Elements of Fuzzy Inference System	Figure 6.4	138
47	Fuzzy Sets for Possibility of Failure Mode Detection	Figure 6.5	144
48	Firing of Rules on Inputs - Aggregation of output (POD)	Figure 6.6	144
49	Surface View of POD - Operating Context – Condition Indicator Level	Figure 6.7	145
50	Firing of Rubes – Output Aggregation with MATLAB	Figure 6.8	147
51	Membership functions of Freq. of Occurrence and RPN	Figure 6.9	148
52	Bearing Temperature Trend	Figure 7.1	154
53	Bearing Vibration Trend Temperature	Figure 7.2	154
54	DM between Field data and Expert Fuzzy Set	Figure 7.3	157
55	Flow Chart showing development of Hierarchical Equipment	Figure 7.4	160
56	Hierarchical Fuzzy Health Assessment scheme for Electric Motor	Figure 7.5	161
57	Degree of Match for Health Indicators for Electro Magnetic System	Figure 7.6	165
58	Degree of Match for Health Indicators for Power Transmission System	Figure 7.7	166
59	Degree of Match for Health Indicators for Ventilation System	Figure 7.8	167
60	Degree of Match for Health Indicators for Support System	Figure 7.9	168

List of Tables

SNo.	Title of the Table	Table No.	Page No.
1	Some Differences between Process Industry and Discrete Industry	Table 1.1	3
2	Failure Modes of Two Motors operating in different conditions	Table 1.2	15
3	Summary of Health Monitoring Practices	Table 2.1	33
4	Population of Electric Motors in an Integrated Steel Plant (3.0 MT)	Table 2.2	36
5	Classification of Motors according to Physical Aspects	Table 2.3	36
6	Condition Indicator-PDM Techniques – Large Motor Components	Table 2.4	39
7	Application of PDM Strategy on Large Electric Motors	Table 2.5	40
8	Gearbox Technical Data	Table 3.1	57
9	PDM data of a Rolling Mill Gearbox	Table 3.2	58
10	Component - Degradation and Indicating Parameter - Measurement	Table 4.1	72
11	Some Component Degradation and Predictive Indicators	Table 4.2	73
12	Parameter Setting Details and Firing of Rules of Fuzzy Inference System FIS-1 (Dynamic Load)	Table 4.3	82
13	Dynamic Load with Trapezoidal and Triangular Membership Functions	Table 4.4	88
14	Acceptability Criteria for Equipment Health Index versus Product	Table 4.5	92
15	Some constructional differences between small and large motors	Table 5.1	101
16	Condition Monitoring Scheme for Electric Motor of capacity 900.0 kW, 6.6 kV, 1480 RPM	Table 5.2	111
17	HAZOP worksheet for Large Squirrel Cage Induction Motor EMS	Table 5.3	117
18	HAZOP worksheet for Large Squirrel Cage Induction Motor PTS	Table 5.4	118

19	HAZOP worksheet for Large Squirrel Cage Induction Motor VS	Table 5.5	119
20	HAZOP worksheet for Large Squirrel Cage Induction Motor SS	Table 5.6	119
21	Failure Mode and Effect Analysis of Motor Electro-Magnetic System	Table 5.7	120
22	Failure Mode and Effect Analysis of Motor Power Transmission System	Table 5.8	121
23	Failure Mode and Effect Analysis of Motor Ventilation System	Table 5.9	122
24	Failure Mode and Effect Analysis of Motor Support System	Table 5.10	123
25	Probability bounds for Basic Failure Events of an Electro-Magnetic Sub System	Table 5.11	124
26	Comparison of Top Event Probabilities of FTA and FFTA	Table 5.12	126
27	Fuzzy Top Event Probabilities for Large Electric Motor Sub-Systems	Table 5.13	128
28	Expected Motors Failures and RCM Resource Requirements	Table 5.14	129
29	Classification of Operating Context in Process Industries	Table 6.1	135
30	Fuzzy set details for estimating POD with PDM data	Table 6.2	137
31	Typical variation of Possibility of Detection computed with FIS	Table 6.3	139
32	Details of Fuzzy Sets for Estimation of RPN	Table 6.4	141
33	Gearbox Specifications	Table 6.5	142
34	Relationship of Failure Mode – Predictive Monitoring	Table 6.6	143
35	Results of ‘FIS-Possibility of Detection’ on Gearbox	Table 6.7	146
36	Failure Modes and Fuzzy sets of Input Variable of FIS - I	Table 6.8	146
37	Results of FIS-RPN on Gearbox Failure Modes	Table 6.9	149
38	Classification of Operating Context in Process Industries	Table 7.1	162
39	Sub-System Condition Monitoring Parameters	Table 7.2	163

40	Sample Rule-Base for Power Transmission System	Table 7.3	164
41	Degree of Match values for Power Transmission System Under 'Hostile' Operating Context	Table 7.4	164
42	Health Assessment of the motor under 'Hostile' Operating Context.	Table 7.5	168
43	Health Assessment of the motor under 'Marginal' Operating Context	Table 7.6	168
44	Health Assessment of the motor under 'Normal' Operating Context	Table 7.7	169
45	Summary Health Status for Motors of case study Under various Operating Contexts	Table 7.8	169