

Table of Contents

Forewordxiii

Chapter • One **Introduction, 9**

1.1 Objectives of the Guide 1

Chapter • Two **Pumping System Hydraulic Characteristics, 3**

2.1 System Characteristics 3
2.2 Pump Curves 9
2.3 Pump Operating Point 10
2.4 Typical System Examples 11
 2.4.1 Pumping System with Open Reservoir for Pump Intake 11
 2.4.2 Parallel Pumps in Common Header 12
 2.4.3 Pumping System with Complex Piping System—Multiple
 Branches 13
 2.4.4 Pumping System with Complex Piping System—
 Multiple Loops 13

Chapter • Three **System and Process Introduction, 15**

3.1 Supply- and Demand-controlled Systems 15
3.2 Introduction to Variable Speed Concept 15
3.3 Process Requirements 16

Chapter • Four **Pumps, 19**

4.1 Classification of Pumps 19
4.2 Rotodynamic Pumps 19
 4.2.1 Pump Principles and Performance Characteristics 19
 4.2.2 Methods of Controlling Rotodynamic Pumps to Meet System
 Demands 25

4.3 Positive Displacement Pumps	37
4.3.1 Rotary Pumps	38
4.3.2 Reciprocating Positive Displacement Pumps	40
4.3.3 Applying Variable Speed to PD Pumps	46
4.3.4 Other Methods of Flow Control for PD Pumps	47

Chapter • Five

Concepts for Estimating Pumping Energy Costs, 49

5.1 Specific Energy Definition	49
5.2 Specific Energy Calculation	50
5.3 Flow Regulation by Varying Speed of a Rotodynamic Pump	50
5.4 Flow Regulated by Throttling	52
5.5 System Awareness—Notes of Caution	53
5.6 Worked Example	53

Chapter • Six

Motors, 59

6.1 Types of Electric Motors	59
6.2 Asynchronous Induction Motors	60
6.2.1 Main Types and Operating Principles	60
6.2.2 Motor Efficiency	62
6.2.3 Output Torque	65
6.2.4 Induction Motors Operated at Variable Speed	65
6.2.5 Special Motor Considerations for Motors Run on PWM Waveform	65
6.3 Alternative Electrical Designs of Motors	66
6.3.1 Synchronous Motors	66
6.3.2 Direct Current Motors	71
6.4 Motor Construction and Cooling	72
6.4.1 Dry Installed Motors	72
6.4.2 Submersible Pump Motors	72
6.4.3 Wet Rotor Motors (Canned Motors)	72
6.5 Motor Starting	73

Chapter • Seven

Variable Frequency Drives, 75

7.1 Types of Variable Frequency Drives	75
7.2 Variable Frequency Drives for Induction Motors	75

7.2.1	VFD Application Considerations for Positive Displacement Pumps	79
7.2.2	VFD Application Considerations for Rotodynamic Pumps	80
7.3	Extended Frequency (Speed) Operation.	81
7.4	VFD Motor Control Algorithms	82
7.5	Power Drive Systems	82
7.6	Integrated Motors and Drives	82
7.7	Variable Speed Drives for Other AC Motors	83
7.8	Variable Speed Drives for DC Motors	84

Chapter • Eight

Control Principles for Variable Speed Pumping, 85

8.1	Control Principles (Methods) for Variable Speed Pumping	85
8.1.1	Main Types of Variable Speed Control Methods.	85
8.2	Pressure Control.	87
8.2.1	Definition	87
8.2.2	P&ID (Process and Instrumentation Diagram).	88
8.2.3	Sensors/Transmitters/Transducers	89
8.2.4	System Considerations for Pressure Control.	89
8.2.5	Single Pump Variable Load	90
8.2.6	Multiple Pump Variable Load	91
8.3	Flow Control	96
8.3.1	Flow Control Definition	96
8.3.2	Piping and Instrumentation	97
8.3.3	Sensors/Transmitters/Transducers	98
8.3.4	Single Pump—Set Flow Rate	98
8.4	Level Control.	101
8.4.1	Definition	101
8.4.2	P&ID	102
8.4.3	Sensors/Transmitters/Transducers	103
8.4.4	Single-Pump Variable Load	103
8.4.5	Multiple-Pump Variable Load.	104
8.4.6	Cyclic-Based Collection Tank	104
8.5	Temperature Control	106
8.5.1	Definition	106
8.5.2	P&ID	107
8.5.3	Sensors/Transmitters/Transducers	108
8.5.4	Single-Pump Variable Load	108
8.5.5	Multiple-Pump Variable Load.	110
8.6	Pumping System Monitoring and Protection	110
8.7	Implementation of System Controls	111

8.8	Special Consideration for Positive Displacement Pumps	111
8.8.1	PD Pump Control.	111
8.8.2	PD Pump Starting Torque	111
8.8.3	PD Pump Operating Considerations	111

Chapter • Nine

Benefits, Drawbacks, and Operational Issues, 113

9.1	Introduction.	113
9.2	Tangible Benefits to the User.	113
9.2.1	Energy Savings	113
9.2.2	Improved Process Control.	113
9.2.3	Improving System Reliability	114
9.2.4	Importance of Maintenance.	114
9.3	Additional Benefits of Pulse Width Modulation Variable Frequency Drives	114
9.4	Potential Drawbacks of PWM VFDs	115
9.5	Operational Issues	117
9.5.1	General Precautions	117
9.5.2	Resonance and Rotordynamics	119
9.6	Power Drive System Integration	123
9.6.1	Operating Pump Motor Systems Above Base Speed.	123
9.7	Low Base Speed Motors	124
9.8	Motor Design	124

Chapter • Ten

Financial Justification, 127

10.1	Life Cycle Cost.	127
10.2	Life Time Energy Cost Reduction.	129
10.3	Capital Cost	135
10.4	Summary	136

Chapter • Eleven

Selection Process: New Systems, 137

11.1	Selection for Optimum Life Cycle Cost	137
11.2	Flowcharts	137

Chapter • Twelve

Selection Process: Retrofitting to Existing Equipment, 141

12.1 Justification	141
12.2 Motor Suitability and Derating	142
12.3 Flowchart	142
12.4 Retrofitting a Motor-Mounted VFD	143

Chapter • Thirteen

Case Studies, 144

13.1 Introduction	145
13.2 Case Study 1: Downsized Pump and Utilization of VFD for Cooling Water	145
13.3 Case Study 2: Boiler Feed Pumps Parallel Operation.	148
13.4 Case Study 3: Water Supply Pump—Eliminate Bypass Pressure Control	151
13.5 Case Study 4: Booster Pump Set with On/off and Bypass Pressure Control	154
13.6 Case Study 5: Water Distribution System	156
13.7 Case Study 6: Wastewater Lift Station Using Constant Speed vs. Variable Speed Driven Pumps	160
13.8 Case Study 7: Axial Flow Pumps with Eddy Current-Drive Retrofit . . 164	
13.9 Case Study 8: Variable Speed Drive on Raw Water–Transfer Pump . 167	
13.10 Case Study 9: Installing Variable Frequency Drives on a Potable Water Distribution System in the Caribbean	169

Appendix A

Electric Motors, 173

A.1 Energy Efficiency	173
A.2 Efficiency Labeling	174
A.2.1 Europe	174
A.2.2 United States of America	176
A.2.3 Global Regulation	177
A.3 Motor sizing	178

Appendix B

Variable Frequency Drives, 179

B.1 Inverter Designs	179
B.1.2 Current Source Inverter	181
B.1.3 Load-commutated Inverter	182
B.1.4 Matrix Style VFD	182
B.1.5 Switched Reluctance Drive	183
B.2 Rectifier Designs.	184
B.2.1 Diode Bridge Rectifier	184
B.2.2 Active Rectifier	185
B.3 Motor Control Strategies	186
B.3.1 Constant Torque V/Hz Control	187
B.3.2 Variable Torque V/Hz Control.	188
B.3.3 Load-Optimized V/Hz Control	190
B.3.4 Operating Above the Motor's Rated Frequency	190
B.4 Methods of Controlling Motor Voltage and Dynamic Response.	193
B.4.1 Scalar or Voltage/Frequency (U/F, V/Hz) Control	193
B.4.2 Flux Vector Control	193
B.4.3 Closed Loop Control	194
B.5 Factors to be Considered in Selecting Variable Frequency Drives.	194
B.5.1 Continuous Motor Current	194
B.5.2 Motor Load Torque Characteristic	195
B.5.3 Incoming Voltage	195
B.5.4 Selecting VFDs for Use with Single-Phase Input	195

Appendix C

Legal Obligations, 197

C.1 European Directives	197
C.1.1 The Machinery Directive	197
C.1.2 The EMC Directive.	198
C.1.3 The Low-voltage Directive	198
C.1.4 The ATEX Directives	198
C.1.5 The CE Marking Directive	200
C.2 United States Regulations and Standards.	200
C.2.1 Federal Regulations.	200
C.2.2 Safety Regulations and Standards	200

Appendix D

Power Line Harmonics, 203

D.1 Harmonic Current Distortion Limits.	203
D.2 Power Line Harmonics and Their Cause	204

D.3 Harmonic Mitigation Techniques	207
D.3.1 VFD with No Harmonic Mitigation	208
D.3.2 AC line Reactors or DC Chokes	209
D.3.3 Reduced DC Bus Capacitance	210
D.3.4 Passive Harmonic Filters	211
D.3.5 Multipulse Rectifiers and Phase-shifting Transformers	213
D.3.6 Active Rectifiers	214
D.3.7 Active Harmonic Filters	215
D.3.8 Matrix Style VFDs	216
D.4 General Summary	217

Appendix E

Effects of Pump Speed and Impeller Diameter on Magnetically Driven Pumps, 221

E.1 Introduction	227
E.2 Changes of Pump Speed	221
E.3 Change of Impeller Diameter	223

Appendix F

Non-VFD Drives, 225

F.1 Overview of Variable Speed Technologies	225
F.2 Eddy Current Drives	225

Appendix G

Instruments, 231

G.1 Instrumentation Fundamentals	231
G.1.1 Definitions	231
G.1.2 Selection Considerations	233
G.1.3 Pressure	233
G.1.4 Temperature	234
G.1.5 Level	235
G.1.6 Flow	235

Appendix H

Definitions, 237

H.1 Glossary	237
H.2 Nomenclature	252
H.3 Abbreviations of Terms	253
H.4 P&ID Terms	254

Appendix I
Bibliography, 257

Appendix J
Index, 261

List of Figures

1.1	Share of motor electricity consumption	1
2.1	Equation for pipeline flow	3
2.2	Equation for pumped system	5
2.3	Static head.	6
2.4	System curve.	6
2.5	Closed loop system	7
2.6	Friction head versus flow rate.	7
2.7	Pressurized tank	8
2.8	System curve.	8
2.9	Rotodynamic pump	9
2.10	Positive displacement pump	10
2.11	Rotodynamic pump and system curves	11
2.12	PD pump and system curves	11
2.13	Rotodynamic pump and minimum-maximum system curves	12
2.14	Typical curve for parallel pumps in common header.	12
2.15	Typical branch system with a single pump supplying three circuits, and each circuit has a separate destination	13
2.16	A looped system with a single pump and supplying three circuits in a closed loop	14
4.1	Classification of pumps	20
4.2	Example of pump performance curves	21
4.3	Example of speed variation affecting rotodynamic pump performance	22
4.4	Example of impeller diameter reduction affecting rotodynamic pump performance	23
4.5	Overplot of NPSHR and NPSHA	24
4.6	Illustration of wasted head by control method	24

4.7	Reducing the speed of the pump reduces both the pump's pressure and flow, which minimizes losses in the system	26
4.8	Example of the effect of pump speed change in a system with low static head	27
4.9	Example of the effect of pump speed change in a system with high static head	28
4.10	Selection of operating point to the right of BEP for static head system	29
4.11	Control of pump flow by changing the system resistance using a throttle valve	30
4.12	Bypass control for a constant speed pump in a chilled water system	31
4.13	When the bypass's resistance to flow is less than the load's resistance to flow, the operating point moves to the right on the pump curve	33
4.14	Typical curves for pumps in parallel	34
4.15	When additional pumps are added in parallel, the flow in each individual pump decreases	35
4.16	Typical curves for pumps in series, with a system curve	36
4.17	Slip flow	37
4.18	Volumetric efficiency	38
4.19	Typical power curves	39
4.20	Output characteristic of a single-cylinder pump	40
4.21	Output characteristic of a two-cylinder pump	41
4.22	Flow characteristic of a three-cylinder pump	42
4.23	Flow rate versus speed for a plunger pump	43
4.24	Power versus speed for a plunger pump	44
4.25	Efficiency versus speed for a plunger pump	44
5.1	System curves for Figure 5.2	51
5.2	Specific energy for three systems	51
5.3	Valve throttling losses	52
5.4	Specific energy curves	53
5.5	High static head examples	54
5.6	Low static head examples	54
5.7	High static head specific energy	55
5.8	Low static head specific energy	55

6.1	Classification of electric motors	59
6.2	Squirrel-cage induction motor cross section	60
6.3	Induced magnetic field in squirrel cage rotor bars	61
6.4	Motor efficiency versus speed (nominal 95% efficient motor).	64
6.5	Development of torque for permanent magnet motors.	68
6.6	Simple schematic of switched reluctance motor.	70
6.7	Cross-sectional drawing of a synchronous reluctance motor	71
6.8	Induction motor DOL starting characteristics	74
7.1	Types of variable frequency drives	76
7.2	Power ranges and application fields for electrical VFDs	77
7.3	Basic PWM VFD	78
7.4	Simplified PWM VFD output.	78
7.5	Speed/torque curves for positive displacement and rotodynamic pumps	79
7.6	Speed/torque curves for VFDs set up for constant torque	80
7.7	Speed/torque curves for VFDs set up for variable torque	81
7.8	Illustrations of integrated motor and VFD	83
8.1	Proportional integral and derivative control	86
8.2	Unstable controller (oscillation)	86
8.3	Stable controller.	87
8.4	Typical pressure control P&ID	88
8.5	Typical pressure transmitters	89
8.6	Pressure control system	90
8.7	Single pump variable speed constant pressure	91
8.8	Multiple pump skid for parallel operation	91
8.9	Multipump variable speed constant pressure control	92
8.10	Multiple pump single VFD and DOL starters	94
8.11	Multiple pumps with VFD for each pump	95
8.12	Staging example based on specific energy curves.	96
8.13	Flow control P&ID	97
8.14	Typical flow transmitter used	98
8.15	Control on constant flow	99
8.16	P&ID differential pressure flow control	100
8.17	Control by pump power algorithm	101

8.18	Continuous level control P&ID	102
8.19	Typical level transmitter used	103
8.20	Steam boiler feed application.	104
8.21	Lift station pump control application.	105
8.22	Continuous operation and cyclic operation to maximize specific energy.	106
8.23	P&ID temperature control system	107
8.24	Typical temperature transmitters	108
8.25	Temperature control downstream of load.	109
8.26	Differential temperature control	109
9.1	Typical vibration signature of discharge head/motor structure	121
9.2	Amplification chart	121
9.3	Campbell diagram	122
10.1a	High static head operation with flow frequency bins.	131
10.1b	High static head specific energy curves	131
10.2a	Low static head operation with flow frequency bins	133
10.2b	Low static head specific energy curves	133
11.1	Flowchart to assess the suitability of using a VSD in a rotodynamic pump system.	138
11.2	Flowchart to assess the suitability of using a VSD in a positive displacement pump system	139
11.3	Flowchart for selection of the correct drive and financial justification.	140
12.1	Flowchart to assess the suitability of retrofitting a VSD to an existing pump system	143
13.1	Initial installation and control diagram	146
13.2	Pump curve full speed operation	146
13.3	Pump and system curve variable speed operation.	147
13.4	Initial installation and control diagram	148
13.5	Motor current strip chart.	148
13.6	Operating condition before modification.	149
13.7	Operating conditions after modification	150
13.8	Initial installation and control diagram	151
13.9	Operating condition before modification.	152
13.10	Modified installation and control diagram	152

13.11 Average operating conditions	153
13.12 Variable speed operating range	153
13.13 Original installation and control diagram	154
13.14 Modified installation and control diagram	155
13.15 New pumps with integrated VFDs	155
13.16 Original installation and control diagram	157
13.17 Original pump system operation	157
13.18 Diurnal flow rate demand curve	158
13.19 Modified installation and control diagram	159
13.20 Comparison of power consumption	159
13.21 Average daily diurnal flow rate	161
13.22 Pumping system and control with constant speed drives	161
13.23 Pumping system and controls with variable speed drives	162
13.24 Pumping system energy consumption chart	163
13.25 Pumping system specific energy comparison	163
13.26 Variable speed new pump and system curves	165
13.27 Original installation and control diagram	168
13.28 Variable speed pump curve	168
13.29 Pump system layout	169
13.30 Pump installation, piping, and pressure-reducing valve	170
13.31 Histogram of total system flow during two-pump operation	170
13.32 Variable speed performance compared with system head	171
13.33 Pumping system and controls with variable speed drives	171
A.1 Typical life cycle cost of an electric motor	173
A.2 Efficiency comparison between premium and standard efficiency AC induction motors	178
B.1 Basic PWM VFD	181
B.2 Basic CSI main circuit	181
B.3 Basic LCI main circuit	182
B.4 Matrix style VFD main circuit	183
B.5 VFD for a switched reluctance motor	184
B.6 VFD with a diode bridge rectifier	184
B.7 VFD with diode bridge rectifier, braking resistor and braking chopper transistor	184

B.8	VFD with an active rectifier and input filter	185
B.9	Power diagram of the inverter section of a basic variable VFD	187
B.10	A constant ratio of voltage to frequency supplied to the motor	188
B.11	A constant V/Hz ratio from the drive	188
B.12	The low-speed torque requirements of variable torque and constant torque loads.	189
B.13	A variable torque V/Hz ratio matches the magnetizing current in the motor to the requirements of a typical variable torque load	189
B.14	By monitoring the load on the motor's shaft, a VFD can automatically adjust its output voltage	190
B.15	VFD output voltage	191
B.16	Motor operation above nameplate frequency relationship	192
B.17	Torque requirements	192
B.18	Power availability at the motor's shaft as the operating frequency extends above the rated value	193
C.1	EMC aspects of a power drive system	198
D.1	Three-phase input rectifier section for a PWM VFD	204
D.2	480-V AC sinusoidal voltage supplied to the VFD's input rectifier	204
D.3	Rectified AC voltage into DC from a single-phase power source	205
D.4	The DC voltage pulses for a VFD connected to a three-phase power source	205
D.5	The DC bus capacitors filter the DC bus voltage (in red) and store it for use by VFD's inverter section.	205
D.6	While a resistive load (blue) draws a peak current of about 30 A, the nonlinear load (red) of the same size draws a peak current of over 60 A	206
D.7	Single-phase undistorted AC current (in blue) and distorted AC current (in red)	206
D.8	Phase L1 current for a three-phase non linear load. The two peaks are for current L1 to L2 and L1 to L3. The area with no peak is when L2 is conducting L3	207
D.9	Current distortion can distort the voltage in the power source, as shown by the flattening of the voltage near its peak value	207
D.10	A VFD with no harmonic mitigation	208
D.11	A VFD with input AC line reactor	209

D.12 A VFD with input DC choke 209

D.13 Some VFDs use small DC bus capacitors to reduce their THiD. 210

D.14 A passive harmonic filter uses parallel capacitors to store energy that is used to provide peak current that the VFD requires 211

D.15 The contactors just above the capacitors are used to disconnect the capacitors when the system is lightly loaded 212

D.16 A 12-pulse rectifier with phase-shifting transformer 213

D.17 An 18-pulse rectifier with phase-shifting transformer 213

D.18 VFD with active rectifier for harmonic mitigation. 214

D.19 An active harmonic filter monitors a section of the AC power source and actively responds to correct power quality issues 215

D.20 A matrix style VFD uses a network of IGBT’s to directly switch current from the building’s power to the driven motor 216

F.1 Block diagram of an eddy current drive 228

List of Tables

4.1 Control methods overview 25

5.1a High static head, metric units 56

5.1b High static head, US customary units 56

5.2a Low static head, metric units 57

5.2b Low static head, US customary units 57

6.1 No-load (synchronous) speeds for typical motors with different pole numbers and supply frequencies 62

6.2 Insulation and temperature rise classes. 63

6.3 Typical motor losses 64

6.4 Motor frame output relationship for two typical motors 65

6.5 Performance compared to an inverter-fed induction motor. 69

6.6 Comparison of motor efficiencies. 73

7.1 Summary of drive applicability 83

8.1 Main PID tuning methods. 87

8.2 Configurations and control principles for multiple pump operation 92

8.3 Control methods for constant flow applications using a single pump 99

8.4 Common faults and causes 110

8.5	PD pump variables to be considered in speed control	111
9.1	Motor designs	125
10.1	Influence of VSD on LCC	125
10.2a	High static head life cycle energy cost results, metric units	132
10.2b	High static head life cycle energy cost results, US customary units	132
10.3a	Low static head life cycle energy cost results, metric units	134
10.3b	Low static head life cycle energy cost results, US customary units	134
13.1	Return on investment (ROI) calculation	147
13.2	ROI calculation	150
13.3	ROI calculation	154
13.4	ROI calculation	156
13.5	ROI calculation	160
13.6	ROI calculation	164
13.7	Capacity variation	165
13.8	Drive efficiency comparison.	166
13.9	Cost of energy comparison	166
13.10	Variable speed energy savings per pump	167
13.11	ROI calculation	167
13.12	ROI calculation	169
13.13	ROI calculation	172
A.1	EU MEPS implementation	175
A.2	Efficiency classes	175
A.3	Old versus new threshold.	175
B.1	Summary of inverter designs and characteristics.	179
D.1	Summary of harmonic mitigation methods for VFDs	218
F.1	Other types of variable speed drives	226