



SERIES ON  
*Electrical Power Capacitors*

# **Reactive Power Management**

---

**D M TAGARE**



## Contents

<i>Foreword</i>	<i>vii</i>
<i>Preface</i>	<i>xi</i>

### **PART I—TERMS, POWER QUALITIES, LOADS AND LOAD MANAGEMENT**

<b>1. Reactive Power—Terms, Definitions and Meters</b>	<b>3</b>
Synopsis	3
Production and working of reactive power	3
An inductance: Series and parallel inductances	4
Series and parallel inductances	6
Stray reactance	6
Definition of terms used in reactive power control	7
Different types of power systems	8
Significance of various parameters	11
Meters on power systems	14
<i>References</i>	16
<b>2. Quality in Electric Power</b>	
<b>Supply—Part I: Quality Problems</b>	<b>18</b>
Synopsis	18
Role of Capacitors in Quality Control of Electric Power	18
Old system	19
New system	19
Disturbance	23
Steady state variations	27
Effects of under voltages	29
Prescribed limits for voltage regulation	30
System frequency	32
Harmonic as a problem area: Generation and harmful effects	34
Radio Frequency Interference: (RFI)	37

Electromagnetic Interference: EMI	38
Telephone Interference Factor: TIF	38
Flickers	39
Neutral grounding systems—safety, power quality	41
Power factor	44
<i>References</i>	44
Annexure 1: Frequency Limits for BHEL	
Thermal/Nuclear Turbine-Generator set operations	48
<b>3. Quality in Electric Power</b>	
<b>Supply—Part II: Indices and Cost of</b>	
<b>Power Quality Justification for Capital Costs</b>	<b>49</b>
Synopsis	49
Reliability	49
Interruptions and outages	50
Interruption	50
Duration of an outage	51
Cost of outages	53
Methods of calculating losses	53
Harmonics: surveying, indices and mitigation and costs of harmonics damages	57
Surveying for harmonics presence	57
Harmonic distortion indices	60
Harmonic measurement in the Indian scenario	60
Responsibilities for mitigating harmonic problems	60
Utility side	60
Consumer side	61
Costing of harmonics	62
Cost of loss in capacity	63
<i>References</i>	64
<b>4. Costing of Reactive Power—Under a Changing</b>	
<b>    Scenario Justification for Tariffs</b>	<b>67</b>
Synopsis	67
Old Method of Costing	67
Changing scenario	68
Responsibilities for supplying reactive power	68
Deeper considerations under Reactive Power Dispatch: (RPD)	69
Objectives served by costing of reactive power	70
Sources for reactive power	71

Costing of reactive power	71
The marginal costs	72
Opportunity costs with varying marginal costs	74
Reactive power costs of transmission	75
Costs of switchable items	76
Operating costs of an LTC and its transformer	77
<i>References</i>	81
<b>5. Load Patterns and Sectorial Distribution of Loads Demand Side Management</b>	<b>83</b>
Synopsis	83
Pattern of an electrical power system	83
The load pattern	83
Sectorial patterns of load	85
Residential/Commercial locality load pattern	87
Industrial load pattern	87
Agricultural pattern	87
Bulk loads	88
Sectorial distribution of Load	88
Division of capacitor requirement on the energy consumption basis (User side)	91
Importance of load patterns	91
Demand Side Management (DSM) load shaping	92
Retrofitting as a part of Demand Side Management (DSM)	96
DSM and Reactive Power Management	98
Forecasting of load patterns	99
Line losses	99
<i>References</i>	101
<b>6. Power Tariffs and Market Forces Shaping of Reactive Power</b>	<b>104</b>
Synopsis	104
Introduction	104
Power tariffs	105
Old power systems and basis for tariffs	105
Customer categories	106
Trend of changes in tariff in India:	
The Electricity Regulatory Commission	110
KVAR-based tariffs	111

The BEST proposal	111
New power systems: Revised structures and tariffs	112
Nature of Transactions	112
Some additional tariff features in aid of demand side management	114
Penalties for voltage flicker and harmonic voltage levels	115
<i>References</i>	121
Annexure 1: Maharashtra State Electricity Board Existing Tariff for 1999-2000	123
Annexure 2: A Typical Electricity Bill for a Residential Customer in the USA	128
<p style="text-align: center;"><b>PART II—UTILITY SIDE REACTIVE POWER SCENARIO</b></p>	
<b>7. Reactive Power Requirement of the Utilities—Own and Network Projections</b>	<b>133</b>
Synopsis	133
Introduction	133
Reactive requirements of a transformer	135
Magnetizing KVAR requirements of transformers	137
Tap changing in transformers	138
Effect of reactive loading on a distribution transformer	139
Generation of harmonics	140
Reactive power requirements of the transformers for carrying the load current	142
Distribution lines	143
Ratio of HT: LT lines—Impact on losses	148
Total KVAR requirements: Projections for a zone—topside to bottom approach	149
Reactive power requirements of distribution feeders: Bottom to topside approach	152
<i>References</i>	155
<b>8. Reactive Power Supply by the Utilities Synchronous Generators, Synchronous Condensers, Synchronous Motors, EHV Transmission Lines and Capacitors</b>	<b>158</b>
Synopsis	158
Introduction	159
Reactive power flow circuit	159

Synchronous generators	160
Reactive capability of a synchronous generator	160
Synchronous machines and capacitors	162
Synchronous machines	162
Capacitors	163
Synchronous machines—Disadvantages	164
Working of a synchronous condensor	164
Working of a synchronous motor	165
Effect of system parameters on the working of synchronous machines	167
Application of synchronous condensers	167
Application of synchronous motors	168
STATCONS: Static convertors	169
Reactive power and transmission lines	169
Surge impedance and charging KVA of a line	171
Voltage drop along an EHV line	174
Supply of reactive power by utilities in India	175
<i>References</i>	176
<b>9. Reactive Power Requirements Under Steady State Voltage Stability and Dynamic Voltage Stability</b>	<b>179</b>
Synopsis	179
Stability	179
Behaviour of system voltages	180
Stable voltages	180
Transmission feeder	183
Stability of a power system	184
Criteria for stability	184
Effect of capacitors on stability	185
Equal area considerations	185
Loadability of a line: Effect of capacitors	187
Calculation of critical points and security reserves	188
Dynamic voltage stability	188
Universal radial voltage stability limit curves	190
<i>References</i>	194
Annexure 1: Some Important Reference Parameters Relative to Indian Conditions	198
<b>10. Reactive Power Requirements to Cover Transient Voltage Instability</b>	<b>200</b>
Synopsis	200

Transient stability	200
Basic causes for transient instabilities	201
Transient instability for a feeder	203
Transient instability for a generator	204
Transient stability for a generator	205
A typical complex load	208
Dynamics of load characteristics	208
Importance of switching time constants:	
Protective vs corrective measures	211
Varieties of static var controllers (SVC)	211
SVC's instant response to a fault	212
<i>References</i>	217
<b>11. System Losses and Loss Reduction Methods</b>	<b>221</b>
Synopsis	221
Losses in electrical power systems	221
Determining losses in distribution systems	222
Daily load cycle	222
The losses in a system have two components	223
Sequential Switch Opening Method—SSOM	237
Liberalized transshipment method	237
Evaluation of losses	240
Incremental losses	240
Demand loss multiplier	241
<i>References</i>	243
Annexure 1: Environmental Measures for Improving Energy Efficiencies	248
<b>12. Reactive Power Planning in Distribution Systems</b>	<b>251</b>
Synopsis	251
Introduction	251
Complexity of today's power distribution systems	252
Planning of distribution system	252
Objectives in planning	253
Economically optimum investment of power factor correction	254
Economic justification for reactive power planning	254
Methods followed by the Electricity Boards in India	265
Zonal reactive power requirements—EHV and MV	266
Low tension capacitors, placement in distribution	266

Line capacitors	266
Substation and upside capacitors	267
Standards on capacitor sizes in other countries	269
Technical considerations for optimization	269
Retrofitting of capacitor banks	270
References	272
Annexure 1: Improved Load Flow—Newtons Method	277
<b>13. LT Distribution Systems—Rural and Urban</b>	<b>278</b>
Synopsis	278
An historical review	278
The North American systems	279
Advantages of the North American system	280
Neutral grounding problem	281
The European systems	283
Rural systems in India	286
Loadshedding on rural electric power lines	287
Distributed generation	290
References	291
<b>PART III—UTILITY SIDE SYSTEMS AND TOOLS FOR MANAGEMENT, OLD AND NEW</b>	
<b>14. High Voltage DC Transmission—HVDC</b>	<b>297</b>
Synopsis	297
What is HVDC?	297
Components of an HVDC system	299
Progress of rectifiers and invertors	299
Rectifiers	299
Thyristors	301
Invertors	301
Instabilities in the HVDC thyristorized system	302
Instability on the convertor side	302
Instability on the inverter side	302
Harmonics: Types and generation	302
Harmonics on the ac side	302
Characteristic Harmonics (CH)	303
Damaging effects of harmonics	303
Nons-Characteristic Harmonics (NCH)	303
NCH produced on the ac side	303



Harmonics on the dc side	305
Interference with telephone systems	305
Shunt capacitors and harmonic filters	308
Supporting RKVA supplies: Capacitors and filters	311
Active Filters	315
References	319
<b>15. Static VAR Controller—SVC</b>	<b>325</b>
Synopsis	325
What is a static VAR controller?	325
Working of an SVC	326
Various types of SVCs advantages and disadvantages	330
Transients produced on switching in three-phase capacitor:	
Different types of arrangements	337
Losses in an SVC	339
Prospective applications of an SVC	341
Dynamic instability in a network	342
References	343
Annexure 1: IEEE Benchmark Model for Static Var Compensator	348
Annexure 2: Multiple Thyristor Switching Systems for Three-Phase Capacitors	350
<b>16. Series Capacitors</b>	<b>356</b>
Synopsis	356
Basic working of a series capacitor	356
Working of a mechanically switched capacitor	358
Flip-flop arrangement for a series capacitor	361
Basic idea	361
Types of faults and their influence on the ratings of a series capacitor system	361
Ratings of the components of a series capacitor bank	363
Capacitor bank	363
Current ratings	364
Capacitors	364
Triggered air gaps	366
Damping reactor	366
Current transformers (CT <sub>1</sub> )	367
Metal Oxide Varister (MOV) supported series capacitor banks	367
Thyristor-Controlled Series Capacitors (TCSC)	369

Steady state series capacitor control	370
Grey areas in the operation of varnir control	375
Plus points of TCSC	375
Limiting conditions on TCSC	376
Losses in a module	379
<i>References</i>	380

<b>17. Phase Angle Regulators: Inter-phase Controllers</b>	<b>383</b>
Synopsis	383
Old type power flow controllers	383
Overloading of feeders	383
Regulation of power flow	384
Series transformer	387
Thyristorized Control of Phase Angle Regulators (TC – PAR)	388
EPRI Survey on TC-PAR	389
Limitations of TC-PAR	390
IPC-120	394
Inter-phase power control with voltage injection	395
Phase shifters and the French networks	397
Conclusion	397
<i>References</i>	398

<b>18. Flexible AC Transmission Systems (FACTS): An Introduction</b>	<b>400</b>
Synopsis	400
Transformation of the electric power systems	400
Problems arising out of quality constraints and solutions in the earlier transmission systems in the 1960's and before	401
Steady state operation	401
Operation under transient conditions	401
Further evolutions in reactive power management	402
Thyristors on the scene	405
Latest practices in reactive power management	406
Invertors	406
FACTS system	408
<i>References</i>	410

<b>19. Static Compensators for Shunt Reactive Power—STATCONS</b>	<b>413</b>
Synopsis	413
Working of an invertor	413

A three-level inverter pole	413
A six-pulse inverter with three level poles	414
Reducing the harmonics in an inverter output	416
Selective harmonic elimination modulation (SEHM)	419
Characteristics of SEHM	420
Voltage-sourced inverters become a powerful and flexible tool	420
Harmonics and transients on the DC side	421
Inverter as a fast acting switch	424
Working of a STATCON	424
STATCON vs SVC	426
<i>References</i>	431
<b>20. Static Series Compensation and Unified Power Flow Controllers (UPFC)</b>	<b>434</b>
Synopsis	434
Manipulating a transmission line for flexibility: Old methods	434
Power flow along a single transmission line manipulating a transmission line for flexibility: New methods	435
How does a series controller work?	436
Fixed series capacitor	438
SSS 'Capacitor'	438
Difference between maximum power obtainable with a series capacitor and that with an SSSC	440
Sub Synchronous Resonance (SSR)	442
Response to a contingency/dynamic response	442
Rating of an SSSC 'bank'	443
Unified Power Flow Controller (UPFC)	443
Functions of Unified Power Flow Controller: (UPFC)	443
Power circle diagrams	445
UPFC in a line at the sending end	447
Sending end power $Q_s$ -vs- $P_s$	449
Modes of operation and controls	451
Customs Power	453
<i>References</i>	456
<b>21. FACTS—Present and Future</b>	<b>459</b>
Synopsis	459
FACTS—A leader in transmission technology	459

Changing scenario in power systems parameters: FACTS	461
prospects for FACTS devices in India	463

## **PART IV—REACTIVE POWER MANAGEMENT—USER SIDE**

### **(A) APPLIANCES WITH INTEGRAL POWER FACTOR COMPENSATION**

#### **(B) SYSTEM WITH EXTERNAL POWER FACTOR COMPENSATION**

<b>22. Reactive Power Compensation through the Integral Part of an Apparatus: Residential Appliance</b>	<b>467</b>
Synopsis	467
Overall picture of the power requirement in India	467
Lighting loads	468
General lighting	468
Working of a fluorescent lamp	470
Ballasts for fluorescent tubes	470
Street lights	471
Total reactive power requirement of the lighting load in India	471
Harmonics	473
Other loads	474
Conclusion	482
References	484
Annexure 1: Estimated Electricity Used by End-Use in India 1989-90	488
<b>23. Reactive Power Compensation through the Integral or a Complimentary Part of an Apparatus: Industrial-Motors</b>	<b>490</b>
Synopsis	490
Induction motors	490
Adjustable speed drives—ASDs and motors	492
ASDs making inroads	492
Working of an ASD	493
The voltage boost	494
Effects of the high frequency output from the inverter	495
Power factor correction and harmonic control for ASDs	496
Some other considerations for ASDs	497
Efficiencies of induction motors and inductive motor drives	497
Standard motors	497
Energy-efficient motors	498
Features of energy efficient motors	498

Performance trade-off: Efficiency and power factor	498
Saturation factor	499
Operation at high and low voltages	500
Surge withstand capacity of induction motors	500
Surge protection capacitors for induction motors	504
Reliability of surge protection capacitors	505
ASDs and surge capacitors	506
Reactive power demand by induction motors on the networks in India	508
<i>References</i>	509
<b>24. Reactive Power Planning: User Side Selection of Capacitors</b>	<b>512</b>
Synopsis	512
Purpose of using capacitors	512
How to select a capacitor: Deciding factors	516
Types of capacitors available, their characteristics and limitations	522
Metallized polypropylene or self-healing type of capacitors (MPP or SH)	522
Metallized polypropylene type	522
Characteristics of MPP capacitors	523
Double metallized paper type of capacitors	523
Life of MPP capacitors	524
Mixed dielectric capacitors	524
All polypropylene—Separate aluminum foil type of capacitors	524
<i>References</i>	525
Annexure 1: How to Select Capacitor	527
Illustrative Example	527
Annexure 2: Capacitor Ratings for Direct Connection Across Induction Motors	530
<b>25. Reactive Power Planning: User Side System Design, Controls and Protection</b>	<b>531</b>
Synopsis	531
LT capacitors: Position in the scenario and standard sizes	531
Controls of LT capacitor bank	532
Manual control of capacitors	532
Automatic control of capacitors	533
Types of automatically controlled relays	533

Current sensing relay	533
Power factor sensing relay	534
Basic disadvantages by power factor of control	534
KVAR sensing relay	535
Voltage sensing relay	536
Common features of automatic relays	536
Susceptibilities of APFC relays	539
P.F. relays with special features	542
<i>References</i>	542
Annexure 1: Current Sensing Relay Used in Rural Agricultural Transformers	545
Annexure 2: Main Accessories for APFC Panels	549
<b>26. Reactive Power Planning—User Side Harmonics, Effects and Control</b>	<b>550</b>
Synopsis	550
Design considerations	550
IEC—61642 defines various terms	551
Different methods for harmonic reduction	554
Shunt capacitors	555
Tuned capacitor filters	555
De-tuned/damped filters	556
Filtering efficiencies	557
Components of a filter	558
Capacitors	558
Reactors	559
Resistance	559
Ripple frequency controls and filters	559
Filters LT voltage networks (upto 1000 V)	561
Filters on HT networks (for Voltages above 1000 V)	562
<i>References</i>	563
<b>27. Reactive Power Considerations—Petroleum Industries</b>	<b>566</b>
Synopsis	566
Special features of petroleum industries	566
The production centres and pipelines	567
The refineries	567
The induction motors	568
Energy efficiencies of motors	568
Starting of large induction motors	570

Capacitors connected directly across the motors	572
Surges on large motors	573
Typical causes for surge generation	574
Parameters affecting the peak and rise time of surge voltages	574
Surge protection	576
Adjustable speed drives (ASDs) for large sized motors	577
ASDs and flexible coupling devices	580
<i>References</i>	580
<b>28. Reactive Power Management in Industries: Cement Industry, Pulp and Paper Industries</b>	<b>586</b>
Section I: Cement Industries	586
Synopsis	586
Special features of cement industries	586
A general layout and the process flow	587
Roller mills	588
Major components of electrical systems	588
<i>References</i>	592
Annexure 1: Environmental Hazards	594
Section II: Pulp, Paper and Printing Industries	595
Synopsis	595
Nature of electrical load	595
<i>References</i>	601
<b>29. Reactive Power Management in Industries: Coal Mining, Glass, Textile, and Plastic Industries</b>	<b>604</b>
Section I: Coal Mining	604
Synopsis	604
Mining processes	604
Perspective of coal mining	604
Future course for reactive power control	609
<i>References</i>	613
Section II: Glass, Textiles, Plastic and Rubber Industries	616
Synopsis	616
Glass industry	616
Textile industries	619
Some useful hints for a harmonic survey	620
Remedial actions suggested	620

Rubber and plastic film industries	621
<i>References</i>	623
<b>30. Reactive Power Management in Industries: Industrial Arc Furnaces Rolling Mills and Other Major Power Consumers</b>	<b>625</b>
<b>Section I: Industrial Arc Furnaces</b>	<b>625</b>
Synopsis	625
Electric arc furnaces	625
Basic objectives of a steel plant	626
Pre-requisites for achieving these objectives	627
Operations of a furnace transformer	631
Amplification of harmonics and surges	631
The inductances	631
The capacitances	631
Filters for control of harmonics	632
De-tuning of a filter	632
Remedial measures	633
Power factor of an arc furnace	636
Operation of a bulk capacitor bank	639
Filters on a steel plant	639
Induction melting furnaces	642
<i>References</i>	645
Annexure 1: Measures to Improve Electric Arc Furnace Efficiency in India	647
<b>Section II: Rolling Mills</b>	<b>648</b>
<b>Section III: Other Major Power Consumers</b>	<b>651</b>
Reactive power demands	652
Special industry group	652
<i>References</i>	652
<b>31. Reactive Power Management in Industries: Railway Electric Traction Systems</b>	<b>654</b>
Synopsis	654
Nature of railway electric load	654
Types of railway electric systems	655
Details of a 25 kV traction system	656
Distribution transformer for railroad supply	659
Single phase transformers	660
Transformer type and voltage unbalance	660



Harmonics in railways	662
Sources of harmonics	662
Flow of harmonics	663
<i>References</i>	671
Annexure 1: Synchronous Condensor Across an Unbalanced Load	675
Annexure 2: SVC Application Study Notes on Railway Traction Systems	676
<b>32. Reactive Power Management under Distributed Generation</b>	<b>678</b>
Synopsis	678
Introduction	678
Power systems become larger and larger	678
Fossil-based fuels pollute the atmosphere: Greenhouse effect	678
The Kyoto protocol	679
Birth of distributed generation	679
Induction generators: Asynchronous generators	679
Synchronous generators	680
Seasonal variation in wind power	680
Extreme ratios between peak: Minimum powers in wind energy	681
Problems with wind energy	681
Grid-side problems faced by generators	683
Role of capacitors in a windmill generator: Minimum capacitance is necessary	685
Minimum capacitance required for excitation	685
Voltage regulation of a wind generator	686
Connections of capacitors across a wind generator	686
Compound connections	689
A wind generator branch gets disconnected from the grid: Safety measures	690
A running inductance generator is switched on against the grid supply	692
A suggested method for capacitor deployment in a wind farm	692
<i>References</i>	693
<b>33. Reactive Power Management—Future Projections</b>	<b>697</b>
Synopsis	697
A birds eye view	697
Primary energy sources of the world	698

Growth in power capacity	699
With oil unreliability, the electric power industry looks inwards	700
Vertical structure of electric power industry undergoes a change	700
Renewable energy sources	701
Primary energy sources for the future	702
Transmission growth under the old system	704
Future growth in transmission	705
Technological developments in transmission	706
Changing nature of electric power consumers	708
<i>References</i>	709
<b>Index</b>	<b>713</b>