POWER QUALITY IMPROVEMENTS IN LOW VOLTAGE DISTRIBUTION NETWORKS CONTAINING DISTRIBUTED ENERGY RESOURCES

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Single phase PV
UPS
UPQC
Stochastic analysis
ABSTRACT

The emergence of renewable energy has opened a new horizon to the generation, transmission and distribution of the electrical power. Due to environment friendliness and commitment of countries around the world to lessen the emission greenhouse gas, the distributed generation (DG) based on renewable sources (Solar, wind, biogas etc.) are very mainstream now-a-days. Among them solar photovoltaic cell (PV) is the most popular. PVs are mostly integrated on rooftop of residential houses in the countries where the sun shines for long period like Australia. Its compact size, easy installation and low maintenance convinced the residential customers to invest on this. But integration of DGs to the existing network creates power quality issues. This thesis addresses some of the power quality issues and investigates possible solutions to those problems in order to increase the ability to use of renewable energy sources.

A typical distribution network is random in nature. The power consumption in each bus as well as PV location and rating is random. Due to this uncertainty, it can happen that one phase has more than enough of PV injection; while another phase may have no PV at all. This excess power will flow back to upstream network and can create unbalance. In this thesis, a power circulation technique with custom power devices (CPD) is investigated. The excess power generated by PVs can be circulated amongst phases to prevent the backflow of the power. A single distribution static compensator (DSTATCOM) connected at the beginning of the network working in current control mode is capable of circulating power.

To enable islanding operation of the system a voltage controller mode of DSTATCOM is investigated as current controller fails due to lack of source power.
This voltage controller holds the voltage at the point of common coupling (PCC) and supplies/absorb necessary power to keep the system stability. The DSTATCOM is assumed with a battery to enable this facility. However, correcting the PCC voltage to 1 per-unit (pu) cause a large amount of reactive power to/from the utility substation. This increases the current flow in the system and increases the line loss where the R/X ratio is high. It is desired to have the least reactive power from the utility substation. A modified voltage magnitude controller can solve this problem though it changes the voltage of buses. Fixed transformer tap setting can only complicate the problem further as the downstream buses may/may not have PVs. A unified power quality compensator (UPQC) isolates the PCC voltage and the load bus voltage and thus these two voltages can be independently controlled.

Due to the power injection at upf by the PVs, the voltage at the connecting bus increases. While in the evening time, the generation is almost zero and the bus voltages are dipped due to heavy load consumption. If the loads are RL load, the power consumption is heavily depended on the bus voltage. Reactive power consumption or absorption can correct the bus voltage but it increases the line loss significantly when R/X ratio is high. A Stochastic analysis of a standard low voltage (LV) network shows the most affected node/bus and trends of line loss with the change of load power consumption, reactive power compensation by PVs and the variation of the 1st bus voltage. The 1st bus voltage has been considered as dummy bus where there is no load connected.

Every phase of the LV distribution network has different voltage levels and it is not possible to correct the voltage just judging the feedback from one phase. As a decision for three phases are taken together in UPQC will not be helpful to improve the power quality as it can improve the voltage in one phase while it can deteriorate
the quality in other phase. As a solution single phase dynamic voltage restorers (DVR) are used to control phases individually. A DSTATCOM is connected at the beginning of the medium voltage (MV) network that facilitate power circulation among the phases while single-phase individual DVRs can correct the voltages of each phase according to its status.

All of these proposed schemes are simulated in PSCAD and MATLAB. There have been several cases considered and the results are presented in various examples to verify the proposals.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of figures</td>
<td>xiii</td>
</tr>
<tr>
<td>List of tables</td>
<td>xxiii</td>
</tr>
<tr>
<td>List of principal symbols and abbreviation</td>
<td>xxv</td>
</tr>
<tr>
<td><strong>Chapter-1: Introduction</strong></td>
<td></td>
</tr>
<tr>
<td>1.1. Distributed energy resources</td>
<td>1</td>
</tr>
<tr>
<td>1.2. Power quality problems</td>
<td>7</td>
</tr>
<tr>
<td>1.3. Solar energy and load management</td>
<td>9</td>
</tr>
<tr>
<td>1.4. Custom power devices (cpds)</td>
<td>13</td>
</tr>
<tr>
<td>1.4.1. Distributed statcom (dstatcom)</td>
<td>14</td>
</tr>
<tr>
<td>1.4.2. Dynamic voltage restorer (dvr)</td>
<td>16</td>
</tr>
<tr>
<td>1.4.3. Unified power quality conditioner (upqc)</td>
<td>17</td>
</tr>
<tr>
<td>1.5. Objectives of the thesis and specific contribution</td>
<td>18</td>
</tr>
<tr>
<td>1.6. Organization of the thesis</td>
<td>20</td>
</tr>
<tr>
<td><strong>Chapter-2: Power circulation using current controlled DSTATCOM</strong></td>
<td></td>
</tr>
<tr>
<td>2.1. Explanation of excess power circulation</td>
<td>23</td>
</tr>
<tr>
<td>2.2. Delta connected DSTATCOM</td>
<td>25</td>
</tr>
<tr>
<td>2.2.1. Compensation using fixed susceptibility</td>
<td>25</td>
</tr>
<tr>
<td>2.2.2. Compensation using DSTATCOM</td>
<td>29</td>
</tr>
<tr>
<td>2.2.3. Simulation results with -connected DSTATCOM</td>
<td>31</td>
</tr>
<tr>
<td>2.3. Y-connected DSTATCOM</td>
<td>35</td>
</tr>
<tr>
<td>2.3.1. DSTATCOM switching control</td>
<td>36</td>
</tr>
<tr>
<td>2.3.2. DSTATCOM current control strategy</td>
<td>38</td>
</tr>
<tr>
<td>2.4. Load voltage correction</td>
<td>50</td>
</tr>
<tr>
<td>2.4.1. DVR connection at node-16</td>
<td>55</td>
</tr>
<tr>
<td>2.4.2. DSTATCOM connection at node-14</td>
<td>57</td>
</tr>
<tr>
<td>2.5. Conclusion</td>
<td>60</td>
</tr>
</tbody>
</table>
Chapter-3: Power circulation using voltage controlled DSTATCOM

3.1. Failure of islanded operation using current controlled DSTATCOM........... 62

3.2. Voltage controlled DSTATCOM ................................................................. 65
   3.2.1. DSTATCOM structure ................................................................. 65
   3.2.2. DSTATCOM voltage control ...................................................... 66

3.3. Voltage controlled DSTATCOM in grid connected mode ................. 68

3.4. Voltage controlled DSTATCOM in islanded mode ............................ 83

3.5. Conclusion ............................................................................................... 95

Chapter-4: Voltage quality improvement in distribution networks containing DERs using UPQC

4.1. Distribution system structure ................................................................. 97

4.2. Compensation using DSTATCOM ....................................................... 99
   4.2.1. Reactive power consideration ....................................................... 101
   4.2.2. Using PI controller .................................................................... 103
   4.2.3. Through equation solving ......................................................... 105

4.3. Transformer tap setting ......................................................................... 106

4.4. Compensation using UPQC .................................................................. 110

4.5. Conclusion ............................................................................................. 119

Chapter-5: Stochastic analysis of an LV network

5.1. Distribution system structure ............................................................... 120

5.2. Monte-Carlo analysis .......................................................................... 122

5.3. Kernel distribution ............................................................................... 123
   5.3.1. Kernel density function .............................................................. 123
   5.3.2. Kernel smoothing function ....................................................... 123

5.4. Results of Monte-Carlo analysis ......................................................... 125
   5.4.1. Simulation results .................................................................... 125

5.5. Conclusion ............................................................................................. 147
Chapter-6: Use of custom power devices for power quality improvement in an LV network

6.1. Distribution system structure ................................................................. 148
6.2. Line loss of the network ........................................................................ 149
6.3. Regulating dummy bus voltage ........................................................... 153
6.4. LV individual bus voltage system study with DSTATCOM .......... 164
6.5. LV bus voltage regulation using DVR .............................................. 170
6.6. Setting voltage magnitude for DVR .................................................. 172
   6.6.1. Using real time feedback ......................................................... 172
   6.6.2. Using worst voltage feedback ................................................. 173
6.7. Conclusion ......................................................................................... 182

Chapter-7: General conclusions and scopes for future research

7.1. General conclusion ............................................................................. 184
7.2. Scopes of future work ........................................................................ 186

Appendix

List of publications .................................................................................. 188

References ............................................................................................... 189
LIST OF FIGURES

Fig. 1.1. Electricity generation through conventional sources of energy…………….3
Fig. 1.2. Electricity generation through renewable sources of energy……………3
Fig. 1.3. Schematic diagram of DSTATCOM………………………………………14
Fig. 1.4. Current correction by DSTATCOM……………………………………15
Fig. 1.5. Schematic diagram of DVR……………………………………………………17
Fig. 1.6. Voltage correction by DSTATCOM……………………………………17
Fig. 1.7. Schematic diagram of UPQC…………………………………………………18
Fig. 2.1. DSTATCOM connection for excess power circulation…………………...23
Fig. 2.2. Power flow in the compensated network…………………………………23
Fig. 2.3. A simple network with delta connected load and DSTATCOM………26
Fig. 2.4. Distribution network with Δ-connected DSTATCOM…………………30
Fig. 2.5. Δ-connected DSTATCOM structure……………………………………30
Fig. 2.6. Upstream network currents before and after Δ-connected DSTATCOM connection (Example 2.4)……………………………………………………………32
Fig. 2.7. PCC voltages before and after Δ-connected DSTATCOM (Example 2.4)…32
Fig. 2.8. Unbalance in upstream network currents before and after Δ-connected DSTATCOM connection (Example 2.4)……………………………………………………………32
Fig. 2.9. THD in upstream network currents and PCC voltages (Example 2.4)……33
Fig. 2.10. Unity power factor operation due to DSTATCOM operation (Example 2.4)…………………………………………………………………………………………34
Fig. 2.11. Upstream phase power before and after DSTATCOM connection (Example 2.5)…………………………………………………………………………………………35
Fig. 2.12. Upstream phase currents before and after DSTATCOM connection (Example 2.5)…………………………………………………………………………………………35
Fig. 2.13. Y-connected DSTATCOM structure……………………………………36
Fig. 2.14. Equivalent circuit of one phase of the compensated system……………36
Fig. 2.15. Distribution system with DER and DSTATCOM……………………39
Fig. 2.16. Source current after the time of DER connection (Example 2.6)………41
Fig. 2.17. Source power before and after the time of DER connection (Example
2.6)........................................................................................................42
Fig. 2.18. Source current after the time of DSTATCOM connection (Example
2.6)........................................................................................................43
Fig. 2.19. PCC voltage before and after the time of DSTATCOM connection (Example 2.6)........................................................................................................43
Fig. 2.20. Source power before and after the time of DSTATCOM connection (Example 2.6)........................................................................................................44
Fig. 2.21. Current tracking performance (Example 2.6)...............................44
Fig. 2.22. A distribution system consisting of two load buses.....................45
Fig. 2.23. Source power in the three phases (Example 2.7).........................46
Fig. 2.24. Positive sequence PCC voltage angle (Example 2.7)....................47
Fig. 2.25. PCC voltage and source current for UPF operation (Example 2.7)....47
Fig. 2.26. Steady state PCC voltage (Example 2.7)....................................48
Fig. 2.27. Steady state source current (Example 2.7)....................................48
Fig. 2.28. Source power in the three phases (Example 2.8).........................49
Fig. 2.29. Steady state source current (Example 2.8)....................................49
Fig. 2.30. A distribution system consisting of 27 nodes.............................50
Fig. 2.31. Voltage unbalance profile along the LV network......................52
Fig. 2.32. VU at PCC before and after the time of DSTATCOM connection..........................................................53
Fig. 2.33. Source power in the three phases..............................................53
Fig. 2.34. Source current in the three phases...........................................54
Fig. 2.35. VU at Node-16 before and after the time of DSTATCOM connection

Fig. 2.36. DVR connection for single load

Fig. 2.37. VU at node-16 after the time of DVR connection

Fig. 2.38. RMS voltage at node-16 after the time of DVR connection

Fig. 2.39. Voltage injected by DVR

Fig. 2.40. Voltage controlling DSTATCOM connection at node-14

Fig. 2.41. VUs in nodes 11-16 after the time of DSTATCOM connection

Fig. 2.42. Phase-a rms voltage in three neighboring nodes

Fig. 3.1. Source currents before and after islanding with current controlled DSTATCOM

Fig. 3.2. PCC voltages before and after islanding with current controlled DSTATCOM

Fig. 3.3. Simple equivalent circuit to explain islanded operation

Fig. 3.4. DSTATCOM structure for voltage control mode

Fig. 3.5. Distribution system with DER and voltage controlled DSTATCOM

Fig. 3.6. Source current before and after DER connection in Example 3.1

Fig. 3.7. Phase-a current angle before and after DER connection in Example 3.1

Fig. 3.8. Phase source power before and after DER connection in Example 3.1

Fig. 3.9. Source active power before and after DSTATCOM connection in Example 3.2

Fig. 3.10. Terminal (PCC) voltage after DSTATCOM connection in Example 3.2

Fig. 3.11. PCC voltage angle in Example 3.2

Fig. 3.12. Source current after DSTATCOM connection in Example 3.2
Fig. 3.13. DSTATCOM active power in Example 3.2………………………………75
Fig. 3.14. A distribution system consisting of four load buses…………………77
Fig. 3.15. Source active power in the three phases in Example 3.3………………78
Fig. 3.16. PCC or terminal voltage angle in Example 3.3………………………78
Fig. 3.17. DSTATCOM power in Example 3.3…………………………………79
Fig. 3.18. RMS bus voltages without DER connection in Example 3.4………80
Fig. 3.19. RMS bus voltages with DER connection in Example 3.4……………80
Fig. 3.20. RMS bus voltages after reactive power control in Example 3.4……..81
Fig. 3.21. Reactive power injection/absorption in the three buses in Example 3.4…82
Fig. 3.22. RMS bus voltages without reactive power control for a short feeder in Example 3.4…………………………………………………………………………83
Fig. 3.23. Three phase source power in Example 3.5……………………………84
Fig. 3.24. DSTATCOM power in Example 3.5…………………………………85
Fig. 3.25. PCC voltage angle in Example 3.5……………………………………85
Fig. 3.26. PCC voltage angle in Example 3.6……………………………………86
Fig. 3.27. DSTATCOM power in Example 3.6…………………………………86
Fig. 3.28. PCC voltage angle in Example 3.6……………………………………87
Fig. 3.29. DSTATCOM power in Example 3.7…………………………………88
Fig. 3.30. Power supplied to the load by the DERs, utility/DSATAacom in Example 3.7…………………………………………………………………………88
Fig. 3.31. DSTATCOM power for the brown out Example 3.8…………………90
Fig. 3.32. PCC Voltage for the brown out Example 3.8…………………………90
Fig. 3.33. DSTATCOM power for the load shedding Example 3.9……………92
Fig. 3.34. PCC Voltage for the load shedding Example 3.9……………………92
Fig. 3.35. Three-phase source powers for the load shedding Example 3.9………93
Fig. 3.36. Bus voltages for the power surplus Example 3.10
Fig. 3.37. DSTATCOM power for the power surplus Example 3.10
Fig. 4.1. Distribution system structure for the study
Fig. 4.2. Schematic distribution system with DSTATCOM
Fig. 4.3. Three phase source power in Example 4.1
Fig. 4.4. System reactive power in Example 4.1
Fig. 4.5. PCC voltage angle in Example 4.1
Fig. 4.6. System reactive powers in Example 4.2
Fig. 4.7. The output of voltage magnitude controller in Example 4.2
Fig. 4.8. The output of angle controller in Example 4.2
Fig. 4.9. The rms bus voltages in Example 4.2
Fig. 4.10. System reactive powers in Example 4.3
Fig. 4.11. Bus voltage magnitudes for upf operation and high load with no transformer tap setting
Fig. 4.12. Bus voltage magnitudes for upf operation and high load with transformer tap setting
Fig. 4.13. Bus voltage magnitudes for upf operation and low load with transformer tap setting and DER injection
Fig. 4.14. PSCAD simulation result of variation in bus voltage magnitudes with and without transformer tap settings
Fig. 4.15. Distribution system with UPQC connection
Fig. 4.16. Three phase source power with UPQC in Example 4.4
Fig. 4.17. RMS load bus voltages in phase-a in Example 4.4
Fig. 4.18. PCC voltage magnitude in Example 4.4
Fig. 4.19. Reactive power flowing in various parts of the system in Example 4.4
Fig. 4.20. Real power flowing in various parts of the system in Example 4.4……115
Fig. 4.21. Real power flowing in various parts of the system with DVR angle controller…………………………………………………………………………117
Fig. 4.22. Real powers in Example 4.5……………………………………………117
Fig. 4.24. PCC voltage magnitude in Example 4.5……………………………118
Fig. 4.25. RMS load bus voltages in phase-a in Example 4.5…………………119
Fig. 5.1. A 28-node distribution network………………………………………121
Fig. 5.2. Probability density function (pdf) of line loss in Example 5.1………126
Fig. 5.3. Histogram of the nodes with the highest voltage in Example 5.1……127
Fig. 5.4. Pdf of five node voltages in Example 5.1……………………………127
Fig. 5.5. Histogram of the node-17 PV ratings in Example 5.1………………128
Fig. 5.6. Probability Density Function (PDF) of total phase-a load Example 5.1…129
Fig. 5.7. Probability Density Function (PDF) of line loss in Example 5.2………130
Fig. 5.8. Probability Density Function of node-17 voltage in Example 5.2…….130
Fig. 5.9. Probability Density Function (PDF) of node-23 voltages in Example
5.2………………………………………………………………………………….131
Fig. 5.10. Probability Density Function (PDF) of node-4 voltages in Example
5.2………………………………………………………………………………….132
Fig. 5.11. Probability Density Function (PDF) of node-6 voltages in Example
5.2………………………………………………………………………………….132
Fig. 5.12. Probability Density Function (PDF) of node-16 in Example 5.2…….133
Fig. 5.13. Probability Density Function (PDF) of load power in Example 5.2……133
Fig. 5.14. Probability Density Function (PDF) of line loss in Example 5.3………135
Fig. 5.15. Probability Density Function (PDF) of node-17 volt. in Example 5.3…136
Fig. 5.16. Probability Density Function (PDF) of node-16 volt. in Example 5.2…136
Fig. 5.17. Probability Density Function (PDF) of node-23 volt. in Example 5.3…137
Fig. 5.18. Probability Density Function (PDF) of node-4 volt. in Example 5.3…..137
Fig. 5.19. Probability Density Function (PDF) of node-6 voltage with reactive absorption in Example 5.3………………………………………………………………138
Fig. 5.20. Probability Density Function (PDF) of phase-a load power in Example 5.3……………………………………………………………………………138
Fig. 5.21. PDF of line loss with graded non-essential PQ load in Example 5.4…..140
Fig. 5.22. PDF of load power with graded non-essential PQ load in Example 5.4..141
Fig. 5.23. PDF of node-17 voltage with graded non-essential PQ load in Example 5.4……………………………………………………………………………142
Fig. 5.24. PDF of node-23 voltage with graded non-essential PQ load in Example 5.4……………………………………………………………………………142
Fig. 5.25. PDF of line loss with graded non-essential P-Q load in Example 5.6……………………………………………………………………………144
Fig. 5.26. PDF of node-17 voltage with graded non-essential P-Q load in Example 5.6……………………………………………………………………………145
Fig. 5.27. PDF of node-23 voltage with graded non-essential P-Q load in Example 5.6……………………………………………………………………………145
Fig. 6.1. Distribution network structure considered in chapter 6……………...…...149
Fig. 6.2: Simple network for analyzing line loss along with phasor diagrams of different cases in Example 6.1………………………………………………………151
Fig. 6.3: Line loss and bus voltage variation with the variation of reactive power injection/absorption by DER……………………………………………………152
Fig. 6.4. PDF of lineloss with R-L load in Example 6.2……………………………154
Fig. 6.5. PDF of node-17 voltage with RL load in Example 6.2…………………..154
Fig. 6.6. PDF of node-23 voltage with RL load in Example 6.2..............................155
Fig. 6.7. PDF of node-2 voltage with R-L load in Example 6.2..............................155
Fig. 6.8. PDF of line loss with PQ load in Example 6.3.................................157
Fig. 6.9. PDF of load with PQ load in Example 6.3......................................157
Fig. 6.10. PDF of node-17 voltage with P-Q load in Example 6.3....................158
Fig. 6.11. PDF of node-23 voltage with P-Q load in Example 6.3....................159
Fig. 6.12. PDF of node-2 voltage with P-Q load in Example 6.3....................159
Fig. 6.13. PDF of line loss with P-Q load in Example 6.4.................................161
Fig. 6.14. PDF of node-17 voltage with P-Q load in Example 6.4....................162
Fig. 6.15. PDF of node-23 voltage with P-Q load in Example 6.4....................163
Fig. 6.16. PDF of node-2 voltage with P-Q load in Example 6.4....................163
Fig. 6.17. Random DER connections in LV distribution network…………………165
Fig. 6.18. Voltage in pu for some critical nodes in phase-a in Example 6.5……166
Fig. 6.19. Voltage in pu for some critical nodes in phase-b in Example 6.5……166
Fig. 6.20. Voltage in pu for some critical nodes in phase-c in Example 6.5……166
Fig. 6.21. MV side voltage of the buses in Example 6.5…………………………..167
Fig. 6.22. Voltage peak set by DSTATCOM at PCC in Example 6.5…………….167
Fig. 6.23. Three phase source power in Example 6.5…………………………….168
Fig. 6.24. Voltage in pu for some critical nodes in phase-a in Example 6.6……169
Fig. 6.25. Voltage in pu for some critical nodes in phase-b in Example 6.6……170
Fig. 6.26. Voltage in pu for some critical nodes in phase-c in Example 6.6……170
Fig. 6.27. DVR connection for per phase voltage control…………………………171

Fig. 6.28. Flowchart of $V_{41}^*$ setting algorithm……………………………………..173

Fig. 6.29. Bus voltages after DVR set in phase b for high load and no generation for Example 6.5………………………………………………………………………..179

Fig. 6.30. Bus voltages after DVR set in phase c for high load and no generation for Example 6.5………………………………………………………………………..179

Fig. 6.31. Bus voltages after DVR set in phase a for low load and high generation for Example 6.6………………………………………………………………………..181

Fig. 6.32. Bus voltages after DVR set in phase b for low load and high generation for Example 6.6………………………………………………………………………..181

Fig. 6.33. Bus voltages after DVR set in phase c for low load and high generation for Example 6.6………………………………………………………………………..182
LIST OF TABLES

Table 1.1. Capabilities of power generation for the various technologies of DGs……4
Table 2.1. System parameters with Δ connected DSTATCOM……………………31
Table 2.2. System parameters for Y connected DSTATCOM studies…………..40
Table 2.3. 27 Node system parameters……………………………………………51
Table 3.1. System parameters for example 3.1………………………………………69
Table 3.2. Load and DER parameters………………………………………………76
Table 4.1. System parameters………………………………………………………98
Table 4.2. Converter parameters…………………………………………………112
Table 5.1. Standard deviation and mean of parameters in example 5.1…………129
Table 5.2. Standard deviation and mean of parameters for reactive power injection in example 5.2……………………………………………………………………134
Table 5.3. Standard deviation and mean of parameters for reactive power absorption in example 5.3……………………………………………………………………139
Table 5.4. Standard deviation and mean of parameters for P-Q load in example 5.4…………………………………………………………………………………143
Table 5.5. Standard deviation and mean of parameters for P-Q load in example 5.5…………………………………………………………………………………146
Table 6.1. Standard deviation and mean of parameters for R-L load in example 6.1…………………………………………………………………………………156
Table 6.2. Standard deviation and mean of parameters for P-Q load in example 6.3…………………………………………………………………………………160
Table 6.3. Standard deviation and mean of parameters for P-Q load in example 6.4…………………………………………………………………………………162
Table 6.4. Sample data to obtain the value of K……………………………………174
Table 6.5. Sample data to obtain $\alpha$.

Table 6.6. Node voltage values obtained from the worst voltage feedback in low generation.

Table 6.7. Node voltage values obtained from the worst voltage feedback in high generation.
# LIST OF PRINCIPAL SYMBOLS AND ABBREVIATION

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSTATCOM</td>
<td>Distributed Static Compensator</td>
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<tr>
<td>DVR</td>
<td>Dynamic Voltage Restorer</td>
</tr>
<tr>
<td>CPD</td>
<td>Custom Power Device</td>
</tr>
<tr>
<td>DG</td>
<td>Distributed Generation</td>
</tr>
<tr>
<td>DER</td>
<td>Distributed Energy Resources</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic cells</td>
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<tr>
<td>VSC</td>
<td>Voltage Source Controller</td>
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<tr>
<td>PDF</td>
<td>Probability Density Function</td>
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<tr>
<td>LV</td>
<td>Low Voltage</td>
</tr>
<tr>
<td>THD</td>
<td>Total Harmonic Distortion</td>
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<tr>
<td>UPQC</td>
<td>Unified Power Quality Compensator</td>
</tr>
<tr>
<td>PCC</td>
<td>Point of Common Coupling</td>
</tr>
<tr>
<td>EV</td>
<td>Electric Vehicles</td>
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<tr>
<td>OLTC</td>
<td>Online Tap Changer</td>
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<tr>
<td>KCL</td>
<td>Kirchoff’s Current Law</td>
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<tr>
<td>RMS</td>
<td>Root mean square</td>
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</tbody>
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\[
v \quad \text{Instantaneous voltage} \\
i \quad \text{Instantaneous current} \\
V \quad \text{RMS voltage} \\
I \quad \text{RMS current} \\
P \quad \text{Real power} \\
Q \quad \text{Reactive power} \\
R \quad \text{Resistance} \\
L \quad \text{Inductance} \\
C \quad \text{Capacitance} \\
Z \quad \text{Impedance} \\
X \quad \text{Reactance} \]
STATEMENT OF ORIGINAL AUTHORSHIP

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written except where due reference is made.

QUT Verified Signature

Signature........... ............

Date..............................January 2015...............
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CHAPTER 1
INTRODUCTION

Electric power distribution networks are extensive and are a key part of the infrastructure that supports commercial, residential and industrial facilities. These networks are always evolving, which is driven by a need for age-related renewal, application of clean and renewable sources of energy, power industry deregulation and increased or decreased demand [1]. These issues have resulted in proposing new structures, devices, control systems, management methods and even power distribution system restructuring, where sometimes new network architecture has been proposed or sometimes new devices have been installed. Moreover in recent years, installation of photovoltaic cells (PVs) has been significantly increased, which has a strong impact on radial distribution networks. Therefore it is a necessity to look at the renewable integration issues for efficient and safe power system operation and maintenance, while keeping track of modernization.

1.1. DISTRIBUTED ENERGY RESOURCES

Distributed energy resource (DER) is an umbrella term, which envelops different energy resources such as renewable energy generators, batteries and electric vehicles (EVs). These resources are distributed throughout low voltage feeders at customer premises. While the term distributed generator (DG) defines an electric power source connected directly to the distribution network or on the customer side of the meter. It is being very popular due to cost effectiveness and world-wide environment awareness. As a result, the operational structure of low voltage distribution networks is changing. Though from current statistics, the DG connection
is between 0.45% and 10.86% of the average load, DG penetration in LV network may even exceed 100% of average load in the next couple of decades [2]. It is estimated that between 2010 and 2020, photovoltaic (PV) cells will become the major mode of distributed generation, followed by reciprocating engines and wind turbines [2]. Along with these, other forms of distributed generators such as micro-turbines, biogas engines and fuel cells will be also available in large numbers [2]. The installation of these will change the nature of the LV networks completely as each LV segment will resemble a mini power system. Furthermore these networks will also not remain radial requiring extensive change in their protection hardware and strategies.

The major source of power generation is still conventional fossil fuel based (e.g., coal, natural gas), even though there is a significant mix of nuclear, hydro and wind available. Of these coal and gas plants emit green house gases, while nuclear is considered hazard prone. Moreover, hydro plants are highly dependent on geographical topography. On the other hand, electric power generation based on renewable sources is usually called environmentally friendly green power. The diagram of electricity generation through conventional and the green power are shown in Figs. 1.1 and 1.2 respectively. The capabilities of power generation are listed in Table 1.1.

DG units are utilized for several different applications in the electrical systems which depend on the structure of the system; such as:
Fig. 1.1. Electricity generation through conventional sources of energy.

Fig. 1.2. Electricity generation through renewable sources of energy.
### TABLE 1.1: CAPABILITIES OF POWER GENERATION FOR THE VARIOUS TECHNOLOGIES OF DGs

<table>
<thead>
<tr>
<th>DG Technology</th>
<th>Typical Capability Ranges</th>
<th>Utility Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar, Photovoltaic</td>
<td>A few W to several hundred kW</td>
<td>DC-AC Converter</td>
</tr>
<tr>
<td>Wind</td>
<td>A few hundred W to several hundred MW</td>
<td>Asynchronous Gen, DC-AC or AC-DC-AC Converter</td>
</tr>
<tr>
<td>Geothermal</td>
<td>A few hundred W to several hundred MW</td>
<td>Synchronous Generator</td>
</tr>
<tr>
<td>Ocean</td>
<td>A few hundred W to several hundred MW</td>
<td>Synchronous Machine</td>
</tr>
<tr>
<td>Internal combustion engine</td>
<td>A few kW to tens of MW</td>
<td>Synchronous Generator, AC-AC Converter</td>
</tr>
<tr>
<td>Combustion Turbines</td>
<td>A few kW to a few MW</td>
<td>Synchronous Generator</td>
</tr>
<tr>
<td>Micro Turbines</td>
<td>A few kW to a few MW</td>
<td>AC-AC Converter</td>
</tr>
<tr>
<td>Fuel Cells</td>
<td>A few kW to a few MW</td>
<td>DC-AC Converter</td>
</tr>
</tbody>
</table>

- Standby power: This sort of generation is used where outage costs are unacceptably high (e.g. hospitals, water pumping stations, electronic-dependent manufacturing facilities, etc.).
- **Combined heat and power (CHP):** During the power generation with conventional energy sources, a large amount of heat is produced. This heat can be used cogeneration applications. This system can be used for customers such as process industries, large office buildings, hospitals, etc.

- **Peak shaving:** Depending on demand and generation of power, the cost fluctuates hour by hour. Use of DG during relatively high-cost on-peak periods is called peak shaving.

The utilization of DG units can have great advantages in the network including [3]:

- Lower power cost local electricity generation.
- Reduction of power outages and end-user satisfaction due to reduction of faults in the network.
- Improving the voltage profile in the network.

In recent years, low voltage dc distribution system is emerging as a solution to ensure premium power quality to the sensitive customers. This LV dc system combines the advantages of the equipments used for improving the voltage quality, supply continuity and uses sustainable power generating units [4]. For ac systems, smaller diesel based DG units can quickly takeover when the system is facing an interruption. Study has been done to confirm this transition smoothly [5].

However DGs can also cause power quality and power factor related problems for the network if inappropriate interface or non-suitable and weakly controlled technologies are utilized, like [6, 7]:

• High rate of harmonics penetrated to the network.
• Power fluctuation.
• Increase of the short circuit level of the network.
• Complex fuse coordination.
• Voltage regulation and power flow complications.
• Feeding fault after utility protection opens.
• Relay desensitizing.
• Increasing vulnerability.
• Overvoltage due to islanding.

Distributed Generation (DG) has also impacts on the performance of connected distribution network, especially in terms of power quality issues. Study results show that depending on the electrical distance between the buses, there is great influence of the location of fault on the voltage sag of the buses. It has also been shown that synchronous generator based DG has poor performance on correcting voltage profile. On the other hand, voltage source converter (VSC) based DGs have are capable for their special control mode, fast response time and separated regulation algorithm for active and reactive power [8]. Voltage profile in a network can be improved by keeping a reactive power reserve for the DGs. DGs usually do not take part in the voltage regulation of the distribution network. Restructuring this distribution network to microgrids may solve this problem. Restructuring enables DG to maintain its capability for suppressing voltage dips.
1.2. POWER QUALITY PROBLEMS

Power quality is defined as “the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment” by Institute of Electrical and Electronic Engineers Standard (IEEE Std 1100) [9]. A simpler and concise definition is “Power Quality is a set of electrical boundaries that allows a piece of equipment to function in its intended manner without significant loss of performance or life expectancy” [10]. Primarily power quality at the transmission and distribution level refers to the voltage staying within plus or minus 5 percent [11]. It is recommended that the voltage violation should be cleared up within 2 s from the time of occurrence [12]. Poor power quality affects the performance and life expectancy of an electrical device. Both of them are strictly related to the voltage, current and frequency applied to the electrical device [10].

An ideal distribution system is expected to have pure sinusoidal voltage and current waveforms of fundamental frequency, where the voltage magnitude remains within some pre-specified bounds. Most of the power quality problems occur in the distribution system network, especially where the major portion of the system has overhead lines rather than underground cables. There may be several natural reasons for the disturbance like contact of the lines with each other especially in windy days or due to birds or the contact of tree branches to lines, severing of the lines due to the falling trees or branches, lightings, etc. All these cause power quality issues in the network. Notable man made reasons can be switching on and off large loads, especially large electrical motors in industry, power electronic equipment used in electronic devices, operation and switching of capacitor or inductive banks, transformers etc. [10, 13].
Some of the power quality events considered in this thesis is:

- **Voltage Variation:** Voltage variation (like sag, swell or interruption) with a duration not exceeding one minute is categorized as short time voltage variation, while those with time duration above one minute are categorized as long time voltage variation [10, 13]. The voltage variation can result damage in customer appliances and other power quality problems as by-products.

- **Power Factor and Reactive Power:** As per IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems, all PVs must inject power at unity power factor [14]. This PV injection increases the voltage at the connection point and adds non-linearity to the system. However with reactive power control of the PVs the voltage at the connecting point can be controlled. Ideally, reactive power should be generated at places close to load to compensate it in order to free more capacity of the conductors and transformers in the network [10].

Even though some of the power qualities problems are created by power electronic loads, the use of power electronics as solutions to these problems is also very popular [10]. In this study, the above mentioned problems will be addressed and their mitigation techniques will be proposed. The devices that will be used in mitigation are all VSC based. It is to be noted that as PV is currently the most popular form of small scale DG units. Therefore, in this thesis, the terms DER, DG and PV are used interchangeably.
1.3. SOLAR ENERGY AND LOAD MANAGEMENT

Solar energy is utilized in two ways – solar photovoltaic (PV) or solar thermal. PV is the most prominent renewable energy sources used in low voltage feeders. A PVs cell work on the $I-V$ characteristics of the elements used in their production. The $I-V$ characteristic PV system can be expressed as [16]:

$$I(V) = \frac{aI_{max}(1 - e^b)}{V}$$

$$\beta = \frac{1}{b(\alpha \gamma + 1 - \gamma)V_{max}^2 - b}$$

(1.1)

where, $V$ and $I(V)$ are the output voltage and current of the photovoltaic array; $V_{max}$ is the rated open circuit voltage of PV array when the light amount is the highest, $I_{max}$ is the maximum current; $b$ is the index constants; $\alpha$ is the light intensity percentage of photovoltaic cells; $\gamma$ is a linear factor dependent on $V_{max}$. PV can be off grid, grid connected or grid-connected centralized. Regardless of the connection strategy they follow, power electronic interface is needed for PVs for network connection. Usually both dc-dc and dc-ac converters are used. Among the inverters used, the popular types are “central inverters”, “Module integrated or module oriented inverters”, “String inverters” and “Multi string inverters” [17].

From the $I-V$ characteristic relation, it can be seen that the output power of PV is not controlled. Rather it is dependent on instantaneous power from the sun. Though advantageous, integration of PV creates several technical problems to the existing network such as harmonics, voltage profile and power loss. Some of these are investigated in [18-20]. Several studies on the voltage violation due to PV integration have been conducted [21-24]. The studies have been carried out at different countries on different geographic location. From all these studies it is found that distributed networks with PVs faces two types of voltage problems. In the
evening when network is in peak hour, the residential load increases while the power output of PVs diminishes. As a result, voltage drop occurs throughout the network. On the other hand, at noon, the PVs are at the peak of their power generation, while the residential loads are at their minimum level. This may lead to an increase in voltage.

In [25], it has been found that if the PV rating does not exceed 2.5 kW, the voltage in the network is not adversely affected even with the worst case scenario. But it is not practical to restrict the PV rating because PV rating will be bigger with the advancement of technology and the increased market availability. A comprehensive study on Australian network is reported in [26] and the results show that there is significant voltage rise, feeder loss, voltage unbalance and reverse power flow during midday. A mitigation strategy for neutral current is proposed in [27] using energy storage to balance the power injections into the grid and the power imports from the grid in the three phases. Along with changing the voltage level of the network, high (20% or higher) penetration of PV increases voltage imbalance. In [28–30], different VU measurement and calculation methods based on line or phase voltages in three phase and three- and four-wire systems were investigated. From [31], the voltage unbalance can be calculated as

\[
\%\text{Unbalance} = \left| \frac{V_2}{V_1} \right| \times 100
\]  

(1.2)

where \( V_1 \) and \( V_2 \) respectively are the positive and negative sequence voltages.

If the system has mostly single phase loads, then minor voltage unbalance may be overlooked. However it may cause serious problem for three-phase loads (motors for pumps, elevator etc). In [32], voltage unbalance has been studied with PV installed on one feeder. The result shows that the PV installation has minor effect on the voltage imbalance at the beginning of an LV feeder. However it increases at
the end of the feeder to more than 2%, which is unacceptable by most standards. Some studies proposed solutions to mitigate this unbalance problem. In [33], energy storage based control algorithm is applied in a distribution network to mitigate to voltage unbalance. A method of analyzing voltage variation sensitivity due to PV power fluctuations in an unbalanced network and its solution utilizing the unbalanced line characteristics and realizing the potential of the network is proposed in [34]. It is to be noted that voltage/current imbalance is defined with the voltage quantity, it is indirectly related the bus voltages where the PVs are connected. That is why in this thesis, voltage quality control has been the primary focus. With the application of various mitigation schemes, the voltages are tried to be kept within the acceptable limits of ± 0.05 per unit (pu).

For a usual residential distribution network, the rooftops PVs are installed randomly across distribution systems. In [35] stochastic analysis of two real LV networks in the North West of England is carried out for different PV penetration level. It is found that for long feeders with high load, voltage problems can start in average at 40% of PV penetration. This picture can change depending on geographic location and demography of the place.

Several methods have already been discussed and investigated for the reduction of voltage rise due to PV penetration. Some of them are:

- Distribution transformers tap changing [36-38]. In [37], it is proposed to switch the distribution transformer between two pre-defined tap set. But it is based on historical loading data which is not at all a reliable process. In [38] a coordinated control of energy storage with on-line tap changer (OLTC) is studied. Though OLTC is feasible, it does not facilitate a continuous voltage
adjustment. Moreover, some countries discourage installation of energy storage.

- Upgrading distribution feeder’s cross-section [36]. However relaying of all the distribution lines can be very expensive.

- Curtailing the active power output [39-42]. In [39], it is recommended to allow generation curtailment in large DG concentration for limited periods of time. A droop based active power curtailment scheme is presented in [40]. This study is done on a typical Canadian suburban network. In [41], a distribution network in Taiwan is simulated and proposal is made limiting the PV generation by moving it from Maximum Power Point Tracking (MPPT). An algorithm based of power flow management is developed in [42] to reduce this power curtailment. But active power curtailment is counterproductive and violates the actual reason of PV installation, which is to generate maximum power from sunshine. It can also create dissatisfaction to the customers as they invest their money on installing PVs and can generate revenues by selling extra generated power to the grid.

- Allowing PV to inject/absorb reactive power [43-50]. In [43], droop controlled reactive power compensation is proposed. A voltage control loop is implemented within PV inverters by absorbing or supplying reactive power in [44]. A location-dependent power factor set value is proposed to each inverter to control voltage rise in [45]. A reactive power control strategy is discussed in [46], which is based on latent reactive power capability of the PV inverter. A combined central and local active and reactive power control in proposed in [47]. In [48], a Taiwanese distribution network is studied with reactive power control by integration a distribution static compensator
(DSTATCOM), which increases the PV penetration level. Some other reactive power compensation strategies are discussed in [49, 50].

In addition to these, smart load management is another option to manage the voltage/power quality in distribution network [51]. In general sense, there are two types of load management schemes – direct and indirect. Typically the direct demand makes use of a control signal from utility to directly control loads. Using a real time price as the control signal, it triggers an automated action from home automation controller [52]. The indirect demand schemes use price as a control variable to influence consumers’ behavior and thus indirectly control the load. For example, time of use tariffs typically increase the price of power during peak periods thus encouraging consumers to shift their consumption to off-peak periods [52, 53]. To support high penetration of intermittent solar and wind power generation, digital grid is introduced in [54]. Here large networks can be segmented into smaller grids, which are connected asynchronously via multi-leg IP addressed ac/dc/ac converters. These are called digital routers. The routers communicate with each other and send power among the segmented grids through existing transmission lines.

1.4. CUSTOM POWER DEVICES (CPDs)

There are two basic models of CPDs – one is connected in shunt and the other one connected in series [10]. The device which is connected in shunt is named as a distribution static compensator (DSTATCOM) and the series connected device is named a dynamic voltage restorer (DVR). Voltage source converter (VSC) is the basic building block of both these devices.

The dc bus of the DSTATCOM VSC is equipped with a dc storage capacitor, while the dc bus of the DVR can have a storage capacitor. In this study, it is assumed
that CPDs can supply some amount of power to the system. So instead of a capacitor, a battery has been used. It serves two purposes – its more easy control and can supply/absorb real power. The batteries can be kept fully charged by drawing a predefined amount of power from the grid.

1.4.1. DISTRIBUTED STATCOM (DSTATCOM)

The schematic diagram of a DSTATCOM structure is shown in Fig. 1.3. This can perform, power factor correction, load compensation load balancing and harmonic filtering. The DSTATCOM can be operated in current control mode or voltage control mode. These are discussed briefly below:

Fig. 1.3. Schematic diagram of DSTATCOM.

**Current Control Mode:** In the current control mode, the DSTATCOM injects an unbalanced and harmonically distorted current to eliminate unbalance or distortions in the source current [55]. In Fig. 1.3, $i_s$ is the source current, $i_L$ is the load.
current and $i_f$ is the current injected by the DSTATCOM. The voltage at point of common coupling (PCC) is $v_p$. KCL at PCC gives

$$i_s = i_L - i_f$$

(1.3)

If there is unbalance and harmonics in $i_L$, the source current $i_s$ will be also unbalanced and have harmonics. However if a current with the harmonic components of the load is injected by the DSTATCOM ($i_f$), the source current will be harmonics free and will have only fundamental component. This is shown in Fig. 1.4. In addition, through injection of $i_f$, the power factor corrections and current balancing can also be achieved.

![Fig. 1.4. Current correction by DSTATCOM.](image)

Now if the source voltage ($v_s$) is fundamental and the DSTATCOM makes $i_s$ fundamental, the PCC voltage ($v_p$) will be also fundamental and free of harmonics. If the load is connected through a feeder with source, the current and voltage at PCC will have harmonics due to DSTATCOM VSC switching. To avoid this, suitable passive filters need to be added and the control scheme need to be modified [56].
Two different multi-level inverter structures are presented for high power DSTATCOM applications [57].

**Voltage Control Mode:** In voltage control mode the PCC voltage \((v_p)\) is controlled and made balanced. As a result, the current in between the source and the PCC, \(i_s\) also becomes balanced [58]. It is shown in [59] that DSTATCOM can be flexibly operated in both voltage and current control mode. Necessary hardware topology and control algorithm is derived for that. The concept of custom power park where voltage is tightly regulated by a diesel-generator backed DSTATCOM is discussed in [60]. This also enables supplying sensitive load during outage and increase reliability. Both of these modes of operation are discussed in detailed in later chapters.

### 1.4.2. DYNAMIC VOLTAGE RESTORER (DVR)

A DVR is a series connected device that has a structure as shown in Fig. 1.5. DVR is used to protect sensitive loads from sag/swell and interruptions from the supply side. Instantaneous series voltage injection is the way to accomplished this. A DVR can tightly regulate the voltage at the load side [61]. It can also act as an active filter in medium voltage level [62]. If there is an unbalanced sag/swell in the supply side, the DVR may have to inject unbalanced voltages to maintain the voltage at the load. It can also inject a distorted voltage to counteract voltage harmonics. Typical voltage waveforms with DVR application are shown in Fig. 1.6.

A DVR can be supplied by a DC capacitor instead of a DC source to nullify any power supply or absorption by DVR [63]. Performance of VSC based shunt and series compensator is compared in [64]. It is found that DVR has good bandwidth
and attenuation properties and with strong stiff source, the DSTATCOM cannot compensate the load bus voltage in this case.

**Fig. 1.5. Schematic diagram of DVR.**

![Schematic diagram of DVR](image)

**Fig. 1.6. Voltage correction by DSTATCOM.**

![Voltage correction by DSTATCOM](image)

### 1.4.3. UNIFIED POWER QUALITY CONDITIONER (UPQC)

The schematic diagram of a UPFC is shown in Figure 1.7. This is a combination of DSTATCOM and DVR connected at the common DC bus. UPQC is a very versatile device that can inject current in shunt and voltage in series simultaneously in a dual control mode. Therefore it can compensate the load and
control the voltage at the same time. Just like DSTATCOM or DVR, the UPQC can also inject unbalanced and distorted voltages and currents.

![Schematic diagram of UPQC.](image)

**Fig. 1.7. Schematic diagram of UPQC.**

### 1.5. OBJECTIVES OF THE THESIS AND SPECIFIC CONTRIBUTION

Based on the literature review some gaps have been identified. These gaps have been focused and directed the objectives:

- Due to high penetration of PV, there might be more generation than the power consumption in the system at times. No literature so far has proposed any scheme to handle this excess power.

- This generated excess power can flow back to the upstream network and create severe phase unbalance. Some of the literatures have addressed the issues regarding phase unbalance in downstream network, but no work has been reported yet about the upstream network.

- Many papers in the literatures have proposed reactive power compensation for voltage mitigation due to PV injection. However, little attention have been paid on the line loss that might be significant, especially in distribution systems with high R/X ratio.
• As mentioned before, OLTCs cannot provide a smooth load bus voltage control. This however can be performed by A DVR or several DVRs. Such operations of DVRs have not been studied before.

• The integration of all three types of CPDs mentioned above for excess power circulation, line loss minimization and voltage quality improvement.

Working towards the above-mentioned objectives, the specific contributions of the thesis are listed below.

• A current control algorithm of DSTATCOM operation is developed to circulate the excess power amongst the feeder. The DSTATCOM injects current to the PCC for eliminating harmonics in the upstream network. As a result balanced set of power is drawn from or supplied to the source.

• The current control mode fails to circulate the power for an islanded operation of the network. A voltage control algorithm is developed that can work in both grid-connected and islanded modes.

• It is desirable that the source works at unity power factor (upf), that means no reactive power is drawn from the source. It is achieved by another control algorithm for controlling the PCC voltage magnitude.

• Except for some pathological case, it is highly unlikely to keep PCC voltage at 1 per unit (pu) in the case of upf operation. As a result the bus voltages are affected. So a UPQC integrated scheme is presented to facilitate upf operation and voltage correction.

• Line loss and voltage profile have been analyzed in the case of reactive power compensation by PVs. It is found that line loss increases with the absorption
and injection of reactive power, though reactive power absorption can reduce the voltage.

- A combined operation of DSTATCOM and DVR is implemented in a large distribution network where the PVs inject power at upf to keep the line loss minimum. Individual single-phase DVRs have been implemented to restrict downstream bus voltages within acceptable limits. This operation of DVR is much more efficient than an OLTC and is also cheaper.

1.6. ORGANIZATION OF THE THESIS

This thesis has been divided in seven chapters. The breakdown of the remaining six chapters is given below.

Chapter 2: The current control algorithm for DSTATCOM for circulating excess power generated by the distributed energy resources is discussed in this chapter. The control algorithm addresses both delta and Y connected DSTATCOM topologies. Several case studies have been carried out and it is found that a single DSTATCOM connected at the beginning of the network is able to circulate the power amongst the phases and balance the upstream currents.

Chapter 3: In this chapter, a voltage control algorithm of DSTATCOM for excess power circulation is discussed. This control can withstand the islanded operation of the network, which is not possible by current control. Several case studies are performed for both grid-connected and islanded mode operations.

Chapter 4: This chapter discusses a modified voltage control of the DSTATCOM to achieve an upf operation at the PCC. This modified algorithm changes the PCC voltage which consequently affects the downstream load bus voltages. To isolate the PCC voltage from the load bus voltage a UPQC is utilized.
The shunt VSC of the UPQC performs the excess power circulation and upf operation, while the series VSC of the UQPC tightly regulates the load bus voltage. Case studies are performed to verify the operation of the UPQC.

**Chapter 5:** The load in a suburban residential distribution network can vary randomly. Also the PVs in such networks are connected in random fashion, both in terms of the sites and size. A stochastic analysis of a realistic low voltage (LV) network is carried out in this chapter. Through the analysis, the trend of line loss, bus voltages and power consumption are studied. Such a study can give guidelines for the connection and operating ranges of CPDs.

**Chapter 6:** In this chapter, schemes for power quality improvement in LV networks are presented. This chapter draws upon the results from all the previous chapters. A large network with high level of PV penetration is simulated to study the schemes. A decision is made from these results that a single DSTATCOM at the beginning of the network can perform power circulation in any stance, while single phase small-rated DVRs, connected to every LV phase, is the optimum option to correct the LV distribution network voltage profile. Though some of the farthest LV node voltages cannot be fixed properly but their voltage limit violations are kept minimal by the proposed schemes. It is concluded that a combined operation of power curtailment and smart load management, along with proposed schemes, can keep the voltage profile within acceptable limit.

**Chapter 7:** The thesis concludes in this chapter, where some scopes of future research are also mentioned.
CHAPTER 2

POWER CIRCULATION USING CURRENT
CONTROLLED DSTATCOM

The presence of large number of single-phase distributed energy resources (DERs) can cause severe power quality problems in distribution networks. The DERs can be installed in random locations. This may cause the generation in a particular phase to exceed its load demand. Therefore the excess power in that phase will be fed back to the upstream network, resulting in unbalance in the transmission system.

This chapter presents an approach to circulate this excess power among the phases. Consider the system shown in Fig. 2.1, which shows a substation that is connected to a low voltage (LV) feeder with a voltage rating of 0.415 kV (L-L) through a medium voltage (MV) feeder (11 kV, L-L) and a $\Delta$-Y transformer. The LV feeder has random connection of domestic loads and DERs.

A DSTATCOM is connected to the MV feeder at the point of common coupling (PCC). The DSTATCOM can either be connected in $\Delta$ (in between lines) or in shunt at the PCC. Each of these connections has different control schemes. When operated properly, the DSTATCOM can facilitate a set of balanced current flow from the substation, even when excess power is generated by DERs. Furthermore it can supply a portion of the load reactive power. In this chapter, the operation, advantages and disadvantages of both these topologies are discussed.
2.1. EXPLANATION OF EXCESS POWER CIRCULATION

Fig. 2.2 shows the detailed three-phase connection of the DSTATCOM at PCC, where the subscript $a$, $b$ and $c$ denote the phases. The upstream power, the load power and the power supplied by the DSTATCOM are respectively denoted by $P_{\text{Source}}$, $P_{\text{Load}}$ and $P$. It is assumed that the power in phase-c is in the reverse direction, due to high number of single-phase DERs in this phase. It is obvious that before DSTATCOM connection, $P_{\text{Source}} = P_{\text{Load}}$; and therefore, the upstream currents are unbalanced due to this reverse power in one of the phases. A proper power circulation from phase-c to other phases, by the help of the DSTATCOM, eliminates this unbalance.

Fig. 2.2. Power flow in the compensated network.
It is desired that after DSTATCOM connection, \( P_{\text{Source}} \) is balanced, i.e.,

\[
P_{a}^{\text{Source}} = P_{b}^{\text{Source}} = P_{c}^{\text{Source}} = \frac{P_{a}^{\text{Load}} + P_{b}^{\text{Load}} - P_{c}^{\text{Load}}}{3} \tag{2.1}
\]

Then from the connections shown in Fig. 2.2, we get

\[
\begin{bmatrix}
  f \\
  P_{a} \\
  P_{b} \\
  P_{c}
\end{bmatrix} = \begin{bmatrix}
  P_{a}^{\text{Load}} \\
  P_{a} \\
  P_{b} \\
  -P_{c}
\end{bmatrix} - \begin{bmatrix}
  P_{a}^{\text{Source}} \\
  P_{b}^{\text{Source}} \\
  P_{c}^{\text{Source}}
\end{bmatrix} \tag{2.2}
\]

Substituting (2.1) in (2.2), the DSTATCOM output powers are expressed in terms of the downstream powers as

\[
\begin{bmatrix}
  f \\
  P_{a} \\
  P_{b} \\
  P_{c}
\end{bmatrix} = \frac{1}{3} \begin{bmatrix}
  2 & -1 & 1 \\
  -1 & 2 & 1 \\
  -1 & -1 & -2
\end{bmatrix} \begin{bmatrix}
  P_{a}^{\text{Load}} \\
  P_{a} \\
  P_{b}
\end{bmatrix} \tag{2.3}
\]

Simplifying (2.3), the relationship between the compensator output powers are expressed as

\[
P_{c}^{f} = -(P_{a}^{f} + P_{b}^{f}) \tag{2.4}
\]

This shows that, to satisfy (2.1), the DSTATCOM will have to circulate power, from the phase with reverse power flow (in this case, phase-c) to the other phases. This proves that if proper power circulation occurs, the DSTATCOM will be able to balance the upstream powers.

Let us consider an example. Assume that the load powers are \( P_{a}^{\text{Load}} = 8 \) kW, \( P_{b}^{\text{Load}} = 3 \) kW and \( P_{c}^{\text{Load}} = -5 \) kW. From (2.1), the desired upstream power in each phase will be 2 kW after the DSTATCOM connection. From (2.3), the DSTATCOM output powers are required to be \( P_{a}^{\text{Load}} = 6 \) kW, \( P_{b}^{\text{Load}} = 1 \) kW and \( P_{c}^{\text{Load}} = -7 \) kW. Therefore the DSTATCOM needs to circulate 7 kW from phase-c to phase-a and b.
2.2. DELTA CONNECTED DSTATCOM

In this section, the operation and control of a delta connected DSTATCOM is discussed. Since most of the distribution transformers have delta connection on their primary MV side, the load on a medium voltage feeder which supplies several distribution transformers can be assumed as an unbalanced three-phase delta connected load. Thus installation of the proposed compensator on a medium voltage distribution feeder can easily restrict and limit the current and voltage unbalance in these networks.

Before the application of DSTATCOM is presented, a review of the fixed susceptance based compensation is discussed, especially for non-stiff system in which the load is connected to the substation through a feeder.

2.2.1. COMPENSATION USING FIXED SUSCEPTANCE

Let us consider the power system structure shown in Fig. 2.3. It is assumed a three-phase balanced voltage source \((V_a, V_b, V_c)\) is connected through feeder impedance \((Z_F)\) to the three unbalanced loads connected in delta \((Z_{ab}, Z_{bc}, Z_{ca})\). This will result in unbalanced load \((i_L)\) and source \((i_s)\) to be unbalanced. To fix this problem, we can connect a set of fixed susceptances in parallel with delta-connected load. This theory is well established [65], and the mains results are presented below.

Let us first ignore the feeder impedance and assume that the PCC is directly connected to a stiff voltage source. Therefore, the phase voltages are

\[
V_a = V \angle 0 \\
V_b = V \angle -120^\circ \\
V_c = V \angle +120^\circ
\]  

(2.5)

Consequently, the line voltages are given by
The source current can be made balanced if a compensator, composed of three unbalanced impedances \((X_{ab}, X_{bc}, X_{ca})\), is connected in parallel with the load in such a way that

\[
Z_{ab} \parallel X_{ab} = Z_{bc} \parallel X_{bc} = Z_{ca} \parallel X_{ca}
\]  

(2.7)

The susceptances are calculated from [65]

\[
B_{ab}^{\text{comp}} = -\frac{1}{3V} \text{Im}[I_{La} + aI_{Lb} - a^2I_{Lc}]
\]

(2.8)

\[
B_{bc}^{\text{comp}} = -\frac{1}{3V} \text{Im}[-I_{La} + aI_{Lb} + a^2I_{Lc}]
\]

\[
B_{ca}^{\text{comp}} = -\frac{1}{3V} \text{Im}[I_{La} - aI_{Lb} + a^2I_{Lc}]
\]

where \(a = e^{j120^\circ}\). Then, the load and compensator combination will look like a unity power factor load.

**Example 2.1 (Without Source Impedance):** Let us consider an example in which a balanced three-phase 11 kV (L-L, rms) source is connected to a three-phase delta load with unequal impedances of
\[ Z_{ab} = 20 + j20 \Omega \]
\[ Z_{bc} = 20 \Omega \]
\[ Z_{ca} = 40 + j10 \Omega \]

Hence the load currents are equal to

\[ I_{la} = 635.49 \angle -26.7^\circ \ A \]
\[ I_{lb} = 585.68 \angle -129.8^\circ \ A \]
\[ I_{lc} = 760.04 \angle +104.6^\circ \ A \]

Then from (2.9), the compensating susceptances are

\[ B_{ab}^{\text{comp}} = 0.0097 \ \text{mho} \]
\[ B_{bc}^{\text{comp}} = 0.00084904 \ \text{mho} \]
\[ B_{ca}^{\text{comp}} = 0.0203 \ \text{mho} \]

The connection of these susceptances in parallel with the load admittances will result in the following source currents

\[ i_a = 625.74 \angle 0^\circ \ A \]
\[ i_b = 625.74 \angle -120^\circ \ A \]
\[ i_c = 625.74 \angle +120^\circ \ A \]

As can be seen, the source currents are now balanced and in phase with the source voltages. Let us now see what happens if the source impedance is present.

**Example 2.2 (With Source Impedance):** Let us now assume that feeder impedance is present. Therefore even if the phase-\( a \) source voltage has an angle of 0\(^\circ\), the angle of \( V_{PCCa} \) (see Fig. 2.3) is not zero. Let us assume this angle to be 20\(^\circ\), i.e., the angle of \( V_{PCCab} \) is 50\(^\circ\). Using the parallel combination of the susceptances given in Example 2.1 and the load admittances will result in the following source currents

\[ I_{sa} = 628.08 \angle 0.34^\circ \ A \]
\[ I_{sb} = 686.29 \angle -117.24^\circ \ A \]
\[ I_{sc} = 682.91 \angle +117.37^\circ \ A \]

It can be seen that the theory fails here.
The reason for this failure is that the derivation of (2.8) is dependent on the L-L PCC voltage $V_{ab}$ to have a phase of 30°. Otherwise, the derivations presented in [65] are not valid. To overcome this problem, we first determine the phase of the PCC voltage $V_{PCCab}$. Let this be given by $\phi$. We know the computation is based on this being equal to 30°. We therefore define

$$\delta = \phi - 30^\circ$$  \hspace{1cm} (2.9)

In this case, the susceptances can be modified by multiplying them by $e^{-j\delta}$, i.e.,

$$B_{comp}^{ab} = -\frac{1}{3V} \text{Im}\left[I_{La} + aI_{Lh} - a^2I_{Le} e^{-j\delta}\right]$$

$$B_{bc}^{comp} = -\frac{1}{3V} \text{Im}\left[-I_{La} + aI_{Lh} + a^2I_{Le} e^{-j\delta}\right]$$

$$B_{ca}^{comp} = -\frac{1}{3V} \text{Im}\left[I_{La} - aI_{Lh} + a^2I_{Le} e^{-j\delta}\right]$$  \hspace{1cm} (2.10)

**Example 2.3 (With Source Impedance and angle correction):** For the same value of phase angle given in Example 2.2, the susceptances are then computed to be the same as those given in Example 2.1. The computed source currents are then

$$I_{sa} = 625.74 \angle 20^\circ \text{ A}$$

$$I_{sb} = 625.74 \angle -100^\circ \text{ A}$$

$$I_{sc} = 625.74 \angle +140^\circ \text{ A}$$

It is expected that by adding the above mentioned compensator into the network, the source currents become balanced. In addition, the compensator will supply all the reactive power demand of the load and the PCC will look like a unity power factor. This is because the compensator only consists of susceptances, and hence will not consume any active power. The main problem with a fixed compensation is that it becomes ineffective when the load changes. Moreover, when DERs cause reverse power flow intermittently, the susceptances need to be changed.
to accordance with that. A DSTATCOM is capable of performing this. This is discussed below.

### 2.2.2. COMPENSATION USING DSTATCOM

Fig. 2.4 shows an MV distribution feeder that supplies two Δ/Y-connected distribution transformers. Each distribution transformer supplies a group of three-phase unbalanced wye-connected loads and single-phase rooftop PVs. The DSTATCOM structure is shown in Fig. 2.5. It is composed of three single-phase voltage source converters (VSCs) that are connected to a common DC bus, with a voltage of $V_{dc}$. Each VSC has an H-bridge configuration, composed of insulated gate bipolar transistors (IGBTs) with anti-parallel diodes. A single-phase transformer, with turns ratio of 1: $n$, is connected to the output of each VSC to provide galvanic isolation and voltage boosting [66]. In addition, they act as filters in the output of the VSCs to regulate the output current. The ratio $n$ is selected based on the line voltage of the MV network, in which the DSTATCOM is to be installed. Another advantage of using transformers is that the VSCs can have a lower voltage rating. As can be shown from the DSTATCOM structure in Fig. 2.5, the transformers in the PCC side are connected in Δ. The transformer leakage inductances provide L-filter to compensate for switching harmonics. No other filter has been used. Since the distribution transformers are also Δ/Y-connected, there is no need to compensate the zero-sequence components.
Each VSC is controlled such that it acts as a capacitance with a susceptance equal to the value calculated in (2.10). A per-phase control technique is deployed, in which the same control principle is applied separately for each VSC. The main aim of the switching control is to minimize the tracking error. In this connection style, a hysteresis reference current tracking control method is utilized to generate the appropriate bipolar switchings of the IGBTs. For this, let the output current tracking error, $e$, be defined as

$$e = i_{f,\text{ref}} - i_f$$

(2.11)

where $i_{f,\text{ref}}$ is the per phase reference DSTATCOM current.
Then the control hysteretic control law is

\[
\begin{align*}
\text{if} & \quad e > h \quad \text{then turn on } S_1 \text{ and turned off } S_2 \\
\text{if} & \quad -h \leq e \leq h \quad \text{No change in switching status} \\
\text{if} & \quad e < h \quad \text{then turn off } S_1 \text{ and turn off } S_2
\end{align*}
\]

(2.12)

where \( h \) is a small positive value. It is to be noted that the value of this constant must be chosen carefully. A smaller value will reduce the tracking error, but it will also increase the switching frequency and the power losses. Therefore, the value of \( h \) is to be chosen as a compromise between the reference tracking and power losses [10].

### 2.2.3. SIMULATION RESULTS WITH \( \Delta \)-CONNECTED DSTATCOM

In this section some simulation results are presented. The data used in these studies are given in Table 2.1.

**TABLE 2.1. SYSTEM PARAMETERS WITH \( \Delta \)-CONNECTED DSTATCOM.**

<table>
<thead>
<tr>
<th>System Quantities</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source voltage</td>
<td>11 kV (L-L, rms), 50 Hz</td>
</tr>
<tr>
<td>MV Feeder impedance</td>
<td>( Z_{F1} = 1.08 + j 0.302 , \Omega )</td>
</tr>
<tr>
<td>LV Feeder impedance</td>
<td>( Z_F = 0.02 + j 0.01 , \Omega )</td>
</tr>
<tr>
<td>Distribution transformer</td>
<td>11( \Delta )/0.4Y kV, 100 kVA, ( Z_I = 5% )</td>
</tr>
<tr>
<td>Equivalent LV wye-connected load</td>
<td>( Z_a = 0.0964 + j 18.84 , \Omega )</td>
</tr>
<tr>
<td></td>
<td>( Z_b = 0.0482 + j 12.56 , \Omega )</td>
</tr>
<tr>
<td></td>
<td>( Z_c = 0.0241 + j 6.28 , \Omega )</td>
</tr>
<tr>
<td>DSTATCOM parameters</td>
<td>( V_{dc} = 1 , \text{kV}, )</td>
</tr>
<tr>
<td></td>
<td>Transformer: 100 kVA, ( n = 11, Z_I = 5% )</td>
</tr>
</tbody>
</table>
Example 2.4: To start with, it is assumed that the DERs are not connected. Therefore, there is no reverse power flow in the network. Assuming the network in steady-state condition, the DSTATCOM is connected at 0.5 s. The instantaneous upstream current waveforms and PCC voltage waveforms are shown in Figs. 2.6 and 2.7 respectively. It can be seen that the upstream currents get balanced once the DSTATCOM is connected. The upstream current unbalance before and after DSTATCOM connection is shown in Fig. 2.8, where the unbalance value is calculated as the ratio of the negative sequence to the positive sequence of the current [31]. It can be seen that the current unbalance is reduced from 38% to almost zero, once the DSTATCOM is connected.

Fig. 2.6. Upstream network currents before and after Δ-connected DSTATCOM connection (Example 2.4).

Fig. 2.7. PCC voltages before and after Δ-connected DSTATCOM (Example 2.4).
Since the delta-connected DSTATCOM uses a hysteresis current control, it is expected that some harmonics are added to the network current and voltage. This is evident from Figs. 2.6 and 2.7. To check whether the total harmonic distortion (THD) of the upstream current and PCC voltage are within acceptable limits, these are computed and plotted in Fig. 2.9. It can be seen that THD of voltage and current are both below 1%, which is within the acceptable limits of power quality based on [31]. Please note that the THD before DSTATCOM connection is zero since the harmonic components are present in the load. Also, the DSTATCOM successfully delivers the required reactive power for its downstream loads and, as a consequence, the upstream current and voltage in its PCC are in phase. This is shown in Fig. 2.10.
Example 2.5: In this study, the capability of this DSTATCOM for circulating the excess power is investigated. It is assumed that 20 single-phase DERs, with a total power generation capacity of 100 kW, are connected. These are injecting power at unity power factor (upf) to phase-a of the LV networks. This amount of generation exceeds the total load demand in all three phases. Also, the excess generation in phase-a of the LV feeders causes a reverse power flow in phases a and b of the MV feeder due to Δ-Y connected transformers. A DSTATCOM, with the structure of Fig. 2(a), is installed in the MV feeder and connected between the phases.

Assuming that the network in steady-state, the DSTATCOM is connected to the network at 0.5 s. Fig. 2.11 shows the instantaneous three-phase powers drawn from the source. Note that these are computed by multiplying the instantaneous voltage of a phase with its instantaneous current. The product is the passed through a lowpass filter (LPF) to obtain the dc value. After DSTATCOM connection, the power in all three phases becomes equal, except that they now feed equal amount of power back to the upstream network. The upstream currents are shown in Fig. 2.12. It can be seen that they get balanced as the DSTATCOM is connected.
2.3. Y-CONNECTED DSTATCOM

The structure of the VSC realizing the DSTATCOM is shown in Fig. 2.13. It is very similar to the one given in Fig. 2.5 except that the three single-phase transformers are connected in wye in the secondary (PCC) side. Also a T-filter, consisting of an inductor ($L_f$), a capacitor ($C_f$) and the single-phase transformer leakage reactance ($L_t$) are connected to the output of each VSC. The resistance $R_f$ in the figure represents the switching and transformer losses. The DSTATCOM is connected in shunt with the system, where it injects the current $i_i$. 
2.3.1. DSTATCOM SWITCHING CONTROL

Referring all the quantities to the secondary of the transformer, the equivalent circuit of one phase of the compensated system is shown in Fig. 2.14, where \( n \) is the transformer turns ratio and

\[
V_{dcn} = n \times V_{dc}, \quad R_{fn} = n^2 \times R_f, \quad L_{fn} = n^2 \times L_f, \quad C_{fn} = \frac{C_f}{n^2}
\]

Also \( u_c \) is the control law from which the switching will be generated and \( v_P \) is the PCC voltage.

Fig. 2.14. Equivalent circuit of one phase of the compensated system.
Let us define the following state vector

\[ x^T = [i, i_f, v_{cf}] \]

The state space equation of the system is then given by

\[ \dot{x} = Fx + Gz \]
\[ y = Hx \quad (2.13) \]

where

\[
F = \begin{bmatrix}
0 & 0 & \frac{1}{L_T} \\
0 & -\frac{R_f}{L_f} - \frac{1}{n^2 L_f} & 0 \\
-\frac{n^2}{C_f} & -\frac{n^2}{C_f} & 0
\end{bmatrix}, \quad G = \begin{bmatrix}
0 & -\frac{1}{L_T} \\
V_{dc} & 0 \\
0 & 0
\end{bmatrix}
\]

\[ H = [1 \ 0 \ 0], \quad z^T = [u_c \ v_c] \]

Assuming the PCC voltage as a disturbance input, the state equation (2.13) is converted into a discrete-time input-output equation as

\[ A(z^{-1})y(k) = B(z^{-1})u_c(k) \quad (2.14) \]

where \( A \) and \( B \) are polynomials given by

\[ A(z^{-1}) = 1 + a_1 z^{-1} + a_2 z^{-2} + a_3 z^{-3} \]
\[ B(z^{-1}) = b_1 z^{-1} + b_2 z^{-2} + b_3 z^{-3} \]

In the pole-shift control, the closed loop poles are obtained by radially shifting the open loop poles to a more stable location. The closed loop poles are then given by the polynomial [67]
\[ T(z^{-1}) = A(\lambda z^{-1}) = 1 + a_1 \lambda z^{-1} + a_2 \lambda^2 z^{-2} + a_3 \lambda^3 z^{-3} \]  

(2.15)

for \( 0 < \lambda < 1 \), \( \lambda \) being a scalar. The control law is then

\[ u_c(k) = \frac{S(z^{-1})}{R(z^{-1})} \left[ v_{\text{ref}}(k) - y(k) \right] \]  

(2.16)

The polynomials \( R \) and \( S \) are obtained from the solution of the equation

\[ T(z^{-1}) = A(z^{-1})R(z^{-1}) + B(z^{-1})S(z^{-1}) \]  

(2.17)

Based on this control law, the switching actions are taken as

\[
\begin{align*}
\text{If } u_c & > h \text{ then } u = +1 \\
\text{elseif } u_c & < -h \text{ then } u = -1
\end{align*}
\]  

(2.18)

where \( h \) is a small number.

### 2.3.2. DSTATCOM CURRENT CONTROL STRATEGY

The DSTATCOM needs to circulate excess power generated by a phase to the remaining phase such that a set of balanced currents are drawn from the source. For this purpose, this device needs to be connected at the very first node following the substation. Moreover, if a single DSTATCOM can balance the source currents, no additional DSTATCOM will be required.

The distribution system under consideration is shown in Fig. 2.15, in which \( v_s \) indicates the utility supply. The feeder impedance is denoted by \( R_s \) and \( L_s \). The source and load currents are denoted by \( i_s \) and \( i_l \) respectively, while the DSTATCOM injects a current \( i_t \). We first assume that the DER is not connected to the system (switch \( S \) is open).
Fig. 2.15. Distribution system with DER and DSTATCOM.

For distribution system compensation, we shall use the theory of instantaneous symmetrical component [55]. The main aim here is to balance the source currents and make them in phase with the PCC voltages (Unity power factor). To apply the theory, first the fundamental positive sequence of the PCC voltage has to be obtained [56]. Let the instantaneous positive sequence voltages be denoted by \( v_{pa} \), \( v_{pb} \), and \( v_{pc} \). The reference currents are given by

\[
\begin{align*}
    i_{a,\text{ref}} &= i_a - \frac{v_{pa}}{M} P_{av} \\
    i_{b,\text{ref}} &= i_b - \frac{v_{pb}}{M} P_{av} \\
    i_{c,\text{ref}} &= i_c - \frac{v_{pc}}{M} P_{av}
\end{align*}
\]  
\tag{2.19}

where

\[
M = \sum_{i=a,b,c} v_{pi}^2
\]

The quantity \( P_{av} \) is the average load power, which is obtained by the average of the instantaneous load power given by

\[
P_l = v_{pa}i_{a} + v_{pb}i_{b} + v_{pc}i_{c}
\]  
\tag{2.20}
TABLE 2.2. SYSTEM PARAMETERS FOR Y-CONNECTED DSTATCOM STUDIES.

<table>
<thead>
<tr>
<th>System Quantities</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systems frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Source voltage</td>
<td>11 kV (L-L, rms)</td>
</tr>
<tr>
<td>Feeder impedance</td>
<td>( R_s = 3.025 , \Omega, , L_s = 57.8 , \text{mH} )</td>
</tr>
</tbody>
</table>
| Load impedance    | Phase-a: 100 + j157.1 \, \Omega  
                           Phase-b: 150 + j235.62 \, \Omega  
                           Phase-c: 200 + j157.1 \, \Omega  |
| DSTATCOM parameters | \( R_f = 9.68 \, \text{m} \Omega \)  
                           \( L_f = 61.625 \, \mu \text{H} \)  
                           \( C_f = 2348.8 \, \mu \text{F} \)  
                           \( V_{dc} = 1.5 \, \text{kV} \)  
                           Transformer: 1 MVA, \( n = 25 \), 10% leakage |

It can be seen from Fig. 2.15 that the \( i_l \) is the current supplied to the load minus the current injected by the DER when the switch \( S \) is closed. Therefore the formulation (2.19) is general and will work even when the net power injected by the DERs is negative. The current references generated through (2.19) will now be tracked using the output feedback control given in the previous section. Some
numerical examples are now presented for which the system parameters for these are given in Table 2.2.

**Example 2.6:** In this example, it is assumed that the DER is connected to phase-a only at 0.2 s and the DSTATCOM is connected at 0.8 s in the network of Fig. 2.15. The DER injects 150 kW and 5 kVar. The source currents before the DSTATCOM connection are shown in Fig. 2.16. It can be seen that they are unbalanced and the angle difference between the phases a and b is much less than 120°. The power drawn from the source by each phase before and after DER connection is shown in Fig. 2.17. It can be seen that phase-a has been drawing 100 kW power before the DER connection, which then becomes negative 50 kW once the DER injects 150 kW power.

![Source Currents](image)

Fig. 2.16. Source current after the time of DER connection (Example 2.6).
Fig. 2.17. Source power before and after the time of DER connection (Example 2.6).

The results with when the DSTATCOM is connected at 0.8 s are shown in Figs. 2.18 to 2.21. Fig. 2.18 shows the source currents, which are balanced. Since the excess power is now distributed in the other two phases, the source current magnitude has reduced (see Fig. 2.16). The PCC voltage before and after DSTATCOM connection is shown in Fig. 2.19. It can be seen that the voltage magnitude has increased slightly (about 5.5%).
Fig. 2.18. Source current after the time of DSTATCOM connection (Example 2.6).

Fig. 2.19. PCC voltage before and after the time of DSTATCOM connection (Example 2.6).

The power supplied by each phase of the source is shown in Fig. 2.20. It can be seen that they become equal as the DSTATCOM is connected indicating that the DSTATCOM is circulating power between the phases. The tracking performance is shown in Fig. 2.21, which shows both the reference and actual currents before and
after DSTATCOM connection. It can be seen that the current tracking is very accurate.

Fig. 2.20. Source power before and after the time of DSTATCOM connection (Example 2.6).

Fig. 2.21. Current tracking performance (Example 2.6).
Example 2.7: In this example, we consider the extension to the distribution system of Fig. 2.15, as shown in Fig. 2.22. In this, Feeder-2 parameters are the same as \( R_s \) and \( L_s \) of Table 2.2. Load-1 impedance is also same as given in Table 2.2, whereas Load-2 impedances are \( 150 + j235.62 \Omega \), \( 200 + j157.1 \Omega \) and \( 100 + j157.1 \Omega \) in phases a, b and c respectively.

![Distribution System Diagram](image)

Fig. 2.22. A distribution system consisting of two load buses.

All the DERs inject a reactive power of 5 kVar. DER-1 is connected to phase-a at 0.2 s supply 300 kW. DER-2 consists of two separate DERs that are connected to phases b and c independently. Phase-b DER-2 is connected at 0.4 s supplying 150 kW, while that is connected in phase-c at 0.5 s is supplying 250 kW. The DSTATCOM is connected at 1.75 s.

The power in the three phases is shown in Fig. 2.23. It can be seen that, before that DSTATCOM connection, power in two phases are negative. The power
supplied by the phases becomes balanced once the DSTATCOM is connected, except that the total power is negative. This implies that the DERs are supplying power to the source. To verify this point, the angle of the positive sequence of the PCC voltage is shown in Fig. 2.24. When no DER is connected, this angle is negative, indicating that power is flowing from the source to the load. Once the DERs start getting connected this angle becomes positive indicating a reverse power flow. Once the DSTATCOM gets connected, this angle again changes as zero and negative sequence components vanish. A scaled ($\times 10^{-3}$) PCC phase-a voltage and current are shown in Fig. 2.25. It can be seen that they have a phase difference of $180^\circ$, which is implies that a unity power factor current is now flowing from the PCC to the source. The PCC voltage and source current in the steady state are shown in Figs. 2.26 and 2.27.

![Source Powers](image)

**Fig. 2.23.** Source power in the three phases (Example 2.7).
Fig. 2.24. Positive sequence PCC voltage angle (Example 2.7).

Fig. 2.25. PCC voltage and source current for UPF operation (Example 2.7).
Example 2.8: In this example, we consider the same system as given in Example 2.7, except that we connect the DSTATCOM to Load Bus-2 at 1.75 s. The power supplied by the three phases of the source is shown in Fig. 2.28. It can be seen that the DSTATCOM cannot influence the power from DER-1 since it is connected
downstream from Load Bus-1. Similarly, DSTATCOM cannot influence the phase-a source current, which has a negative polarity as shown in Fig. 2.29. The DSTATCOM however tries to balance the current upstream from Load Bus-2 and hence the current in phases b and c are balanced.

Fig. 2.28. Source power in the three phases (Example 2.8).

Fig. 2.29. Steady state source current (Example 2.8).
The above examples clearly demonstrate that a single DSTATCOM connected at the first bus itself can circulate power in all the three phases. However, if the DSTATCOM is connected at any other bus, this will not be possible. It is to be noted that the DSTATCOM can only prevent unbalanced current from flowing in the upstream network and cannot influence the downstream current. In the next section, we shall discuss a strategy that can be employed if a particular three-phase load amidst unbalanced loads and single-phase DERs required a set of balanced voltages.

### 2.4. LOAD VOLTAGE CORRECTION

So far only simple distribution systems have been considered. In this section, a segment of a practical distribution system has been considered. This has 27 nodes as shown in Fig. 2.30. The system is connected with the substation through a 11/0.415 kV Δ-Y transformer. As can be seen, the LV side of the system is not purely radial.

![Fig 2.30. A distribution system consisting of 27 nodes.](image)
Every three-phase node is assumed to be consuming 6 kW power. However the loads at each node are assumed to be unbalanced. We have considered uniform length between two nodes and equal load at each node. The system data are shown in Table 2.3. In addition 19 PVs in phase a are injecting power at unity power factor are connected to the system. Four of these PVs have a rating of 5 kW and the rest have a rating of 10 kW.

**TABLE-2.3: 27-NODE SYSTEM PARAMETERS**

<table>
<thead>
<tr>
<th>System Quantities</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systems frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Source (feeder) impedance</td>
<td>( R_s = 3.025 , \Omega, \quad L_s = 57.8 , \text{mH} )</td>
</tr>
<tr>
<td>Load impedance of each node</td>
<td>Phase-a: ( 51.81 + j17.03 , \Omega )</td>
</tr>
<tr>
<td></td>
<td>Phase-b: ( 25.9 + j8.52 , \Omega )</td>
</tr>
<tr>
<td></td>
<td>Phase-c: ( 17.27 + j5.68 , \Omega )</td>
</tr>
<tr>
<td>Impedance of line segment between nodes</td>
<td>( 0.02 + j0.01 , \Omega )</td>
</tr>
</tbody>
</table>

The voltage profile of the system before and after the PV connection is at first investigated. A load flow program is developed in MATLAB for the unbalanced network including the return neutral wire. Voltage unbalance at each of the 27 nodes of the system is shown in Fig. 2.31. It can be seen that the unbalance increases significantly after the PV connections. It is not surprising that the voltage unbalance is higher in the nodes that are further from the substation (e.g. nodes 15 and 16).
A DSTATCOM is now connected at the MV side of the delta-wye transformer, at PCC. The rating of the DSTATCOM is the same as that given in Table 2.2. In this case, the PVs are connected at 0.2 s, while the DSTATCOM is connected at 0.5 s. The unbalance in PCC voltage is shown in Fig. 2.32. Before PV connection, the unbalance is less than 1%, which reaches to 3.0% after PV connection. But after DSTATCOM connection it decreases rapidly to almost zero indicating that the DSTATCOM balances the PCC voltage. The power supplied by each of the three phases of the source is shown in Fig. 2.33, while the source currents are shown in Fig. 2.34. It can be seen that the source power and the source currents almost become zero. Therefore the PVs support all the loads of the network.
Fig 2.32. VU at PCC before and after the time of DSTATCOM connection.

Fig 2.33. Source power in the three phases.
Fig. 2.34. Source current in the three phases.

However, the VU at the node furthest away from the substation (i.e., node-16), remains at a very high level despite the DSTATCOM connection (see Fig. 2.35). Usually the single-phase loads do not get affected by the voltage unbalanced in the LV feeders. However, if there are three-phase loads (e.g., elevators and pumps) amidst single-phase loads, large negative phase sequence (NPS) voltage can affect their performance. Let us assume that one such load is connected to node-16. There are two possible solutions to this problem – the connection of a DVR at node-16 or a DSTATCOM connection between nodes 8 and 16.
2.4.1. DVR CONNECTION AT NODE-16

A DVR can fix the voltage downstream and hence it can be connected between node-16 and its load. The DVR connection is shown in Fig. 2.36. Its structure is essentially the same as that of a DSTATCOM structure shown in Fig. 2.13, except that the capacitor is connected on the secondary of the transformer and the voltage across the capacitor is controlled in the output feedback scheme. This will be discussed in details in Chapter 4. Fig. 2.37 shows the VU across the load connected in node-16. The DVR is connected from the beginning, while the PVs and DSTATCOM are connected at 0.2 s and 0.5 s respectively. It can be seen that the VU has been reduced to around 0.5%. The rms voltages of the three phases at node-16 are shown in Fig. 2.38. It can be seen that these voltages are very close to each other and are close to 1 per unit (239.6 V). The voltages injected by the DVR are shown in Fig. 2.39. It can be seen that the maximum peak voltage is around 75 V (50 V rms).
This means that the DVR needs to inject only a small amount voltage and hence its rating can be small.

Fig. 2.36. DVR connection for single load

Fig. 2.37. VU at node-16 after the time of DVR connection.
2.4.2. DSTATCOM CONNECTION AT NODE-14

The DSTATCOM in this case has only an LC filter, where the filter capacitor is connected in the secondary side of the transformer in shunt with the node to which it is connected. It is shown in Fig. 2.40. The voltage control using DSTATCOM will
be discussed in Chapter 3. The rating of the DSTATCOM however is much smaller than that of the primary current balancing one since it is connected at the LV side. For this case, the DSTATCOM is connected at node-14, which is 2 nodes upstream from node-16. If this voltage is regulated close to 1 per unit, a few bus voltages up or downstream will also rise close to 1 per unit. The voltage across filter capacitor is controlled in an output feedback voltage control. It has been assumed that the DSTATCOM remains connected to node-14 from the beginning.

![DSTATCOM Diagram](image)

Fig. 2.40. Voltage controlling DSTATCOM connection at node-14.

Since the DSTATCOM balances the voltage across node-14, it will also have a positive impact on the voltages of the neighboring nodes. Fig. 2.41 shows the VU in buses 11 to 16 with this DSTATCOM. The VU in all these nodes was more than 10% after PV connection, with or without the main (outer) DSTATCOM. It can be seen that this inner (smaller) DSTATCOM reduces all the VUs to less than 3%. Another important thing is to be noted that the VUs in the upstream nodes reduce after the outer DSTATCOM connection, while the VUs increase in node-14 and the downstream nodes. This is in agreement with what has been reported in [68].
Fig. 2.41. VUs in nodes 11-16 after the time of DSTATCOM connection.

The DSTATCOM regulates node-14 voltage at 0.97 per unit (232.4 V). This is intentionally chosen to prevent voltage rise in the upstream network due to DERs connections. The voltages of three neighboring nodes from the inner DSTATCOM connection bus are shown in Fig. 2.42 (phase-a only). It can be seen that the upstream voltage has a tendency to rise. Therefore the regulated voltage set point has to be carefully chosen. This will be discussed in Chapters 4 to 6.
2.5. CONCLUSION

In this chapter, the power circulation capability of DSTATCOM, operating in current control mode, is investigated. It is proved that a single three-phase DSTATCOM installed in MV network with the proposed topology, can circulate power from one phase to the other phases. This is a very important method of preventing reverse current/power flow some of the phases, due to the presence of single-phase DERs. The DSTATCOM provides a path for the power to flow among its phases, through its DC bus and by the help of the transformers connections and switches in the VSCs. The DSTATCOM can be connected both in delta and in Y connection. However, each connection style has a different control algorithm.

The main objective of the DSTATCOM is to circulate excess power amongst the phases to improve power quality. At the same time it is expected to enable unity power factor operation for sources. Through several simulation studies, it is shown
that the DSTATCOM responds appropriately to the load/DER variations in the network. The DSTATCOM is capable of performing the power circulation regardless the generation amount of the DER.

In the next chapter it will be shown that the current controlled DSTATCOM will not work properly if accidental or intentional islanding occurs. If the DSTATCOM dc bus is operated from a battery, then it will be able to supply or absorb excess power. In that case, the DSTATCOM will be able to support the network even if it is islanded. This is discussed in the next chapter.
CHAPTER 3

POWER CIRCULATION USING VOLTAGE CONTROLLED DSTATCOM

In the previous chapter, it has been shown that a current controlled DSTATCOM can inject current to cancel the effects of large number of single-phase DERs. The DERs can cause severe power quality problems in distribution networks including reversal of excess DER generated power and voltage/current imbalance. The current controlled DSTATCOM can not only circulate the excess power through its dc bus, but can also perform power factor correction, which will reduce the line losses. However, this topology is not suitable if the distribution network gets disconnected from the utility, either through intentional or accidental islanding.

In this chapter, the suitability of a voltage controlled DSTATCOM for excess power circulation is investigated. The DSTATCOM must operate such that it can supply/absorb power during islanded operation. Suitable control techniques are developed for this purpose.

3.1. FAILURE OF ISLANDED OPERATION USING CURRENT CONTROLLED DSTATCOM

It has been showed previously that DSTATCOM in current control mode can circulate the excess power amongst the phases regardless delta and Y-connection of DSTATCOM and the load. So if the DER generation is adequate to support the loads, the network can work as a stand-alone or islanded microgrid mode. To investigate the suitability of Y-connected DSTATCOM, a simulation study is carried
out in which the LV system is islanded at 2.25 s, when the system is operating at steady state with the DSTATCOM injecting current to circulate the excess power. The source currents are shown in Fig. 3.1. It can be seen that these currents become zero once the islanding occurs. However the PCC voltages rise to abnormal high values as shown in Fig. 3.2. In fact this will not acceptable in practice and the DSTATCOM protection devices will block the switches causing a total chaos and system collapse.

Fig. 3.1. Source currents before and after islanding with current controlled DSTATCOM.
Fig. 3.2. PCC voltages before and after islanding with current controlled DSTATCOM.

To explain the situation, consider the circuit shown in Fig. 3.3. When the switch $SW$ is closed, the DSTATCOM circulates excess power based on the algorithms presented in Chapter 2. When the switch opens, the KCL dictates that

\[ i_{jk} = i_{Lk}, \quad k = a, b, c \]  

(3.1)

Therefore the DSTATCOM must inject the same amount of current that is needed by the load. While, by itself, this can be an acceptable strategy, from the point of view of power circulation or voltage rise or fall compensation, this is rather useless. Therefore alternate control strategy for the DSTATCOM is needed to tackle this situation.
3.2. VOLTAGE CONTROLLED DSTATCOM

In this section, the structure and control of voltage controlled DSTATCOM are discussed.

3.2.1. DSTATCOM STRUCTURE

The DSTATCOM structure is shown in Fig 3.4. This is essentially the same as shown in Fig. 2.12, except that an LC-filter is utilized instead of the LCL-filter in that figure. Furthermore, the filter capacitor $C_f$ is placed in the secondary (grid) side. The transformer leakage reactance ($L_T$) and the capacitor together form the LC filter. Transformer losses and switching losses are denoted as $R_f$. 
3.2.2. DSTATCOM VOLTAGE CONTROL

A typical voltage controlled DSTATCOM connected distribution system with DER is shown in Fig 3.5. Here the DSTATCOM is represented by the voltage source $|V| \angle \delta$. The DSTATCOM is connected at the first node of the network so that it can balance the upstream current. $L_s$ and $R_s$ represent the feeder impedance. It is be noted from Fig. 3.5 that the average real power entering the PCC must be equal to the sum of average load power and power flowing into the DSTATCOM. Otherwise the battery connected to the dc bus of the DSTATCOM will continuously charge or discharge.
Let us assume that the DSTATCOM regulates the magnitude of the PCC voltage. Therefore the angle of this voltage must be set such that the power balance in the circuit occurs. Referring to Fig. 3.5, the instantaneous power flow from the PCC to DSTATCOM is given by

\[ P_f = v_{p_a}i_{fa} + v_{p_b}i_{fb} + v_{p_c}i_{fc} \]  \hspace{1cm} (3.2)

where, \( v_{p_a}, v_{p_b} \) and \( v_{p_c} \) are PCC voltages of phases a, b and c respectively and \( i_{fa}, i_{fb} \) and \( i_{fc} \) are three respective currents flowing to the DSTATCOM. The instantaneous measurement is averaged using a lowpass filter to obtain \( P_{fav} \). Then the PCC voltage angle (\( \delta \)), which is referred from voltage angle of \( v_s \) is obtained by a PI controller, given by

\[ \delta = K_{p\delta}e_p + K_{i\delta} \int e_p \, dt \]  \hspace{1cm} (3.3)

where \( P_{ref} \) is the reference value of \( P_f \), the proportional and integral gains of PI controller are denoted by \( K_{p\delta} \) and \( K_{i\delta} \) respectively.

Ordinarily, without any DER injection, the power flows from source to the load. If the source voltage angle is taken as the reference angle, then PCC voltage angle should lag the source one to make the angle difference positive. It is assumed
that the source voltage angle is $0^\circ$. Therefore, the constants $K_p\delta$ and $K_I\delta$ are chosen negative.

Once its angle is obtained from (3.3), the instantaneous PCC reference voltages of the three phases are obtained from

\[ v_{p_{ref}} = \frac{|V_s|}{\sqrt{2}} \sin(\omega t + \delta) \]

\[ v_{ph_{ref}} = \frac{|V_s|}{\sqrt{2}} \sin(\omega t + \delta - 120^\circ) \]

\[ v_{pc_{ref}} = \frac{|V_s|}{\sqrt{2}} \sin(\omega t + \delta + 120^\circ) \]

(3.4)

In these, the voltage $|V_s|$ is a pre-specified value that is usually chosen as 1.0 per unit. These reference voltages are then tracked by output-feedback pole shift control in the same manner as that discussed in Chapter 2.

3.3. VOLTAGE CONTROLLED DSTATCOM IN GRID CONNECTED MODE

In this mode, the distribution network is connected with the source utility supply. The DSTATCOM has some losses associated with its transformers and switches. These losses are termed as $P_{loss}$ here. Unless these losses are absorbed from the supply, the batteries supplying the dc bus of the DSTATCOM will discharge continuously. Therefore the PCC voltage angle must be set such that $P_{loss}$ is drawn from the supply. Therefore $P_{pref}$ is set equal to $P_{loss}$ for this mode. Since the DSTATCOM balances the PCC voltage and the source voltage $v_s$ is balanced, the source current, which is in between these two nodes, will also be balanced. Therefore
the DSTATCOM circulates the excess phase power amongst the other phases. However, when the utility is absent, the DSTATCOM is unable to get power from the utility. Therefore the reference needs to be calculated differently. This will be discussed in the next section.

**Example 3.1 (System Response without DSTATCOM):** For this case study, the system in Fig. 3.5 has been considered. The system parameters used for this study are listed in Table 3.1. It is assumed that a single DER is connected to phase-a, which is activated at 0.3 s. The DER is injects 100 kW and 1 kVAr. The DSTATCOM remains switched off.

<table>
<thead>
<tr>
<th>Table-3.1: System Parameters for Example 3.1.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System Quantities</strong></td>
</tr>
<tr>
<td>Systems frequency</td>
</tr>
<tr>
<td>Source voltage</td>
</tr>
<tr>
<td>Feeder impedance</td>
</tr>
</tbody>
</table>
| Load impedance | Phase-a: $400 + j131.48 \, \Omega$  
| | Phase-b: $640 + j210.36 \, \Omega$  
| | Phase-c: $2400 + j788.85 \, \Omega$  
| DSTATCOM parameters | $R_f = 1.0 \, \Omega$  
| | $C_f = 50 \, \mu\text{F}$  
| | $V_{dc} = 2.5 \, \text{kV}$  
| | Transformer: 1 MVA, $n = 7.33$, 2.5% leakage |

The three phase source currents, before and after DER connection, are shown in Fig. 3.6. It can be seen that the peak of phase-a current reduces from 21 A to 5.5 A after the DER connection. The angle of this phase current shifts from $-21^\circ$ to $-111^\circ$, ...
as shown in Fig. 3.7. After DER connection the angle shifts to the 3\textsuperscript{rd} quadrant, indicating a reversal in direction of current flow. The active power supplied by the three phases of the source before and after DER connection is shown in Fig. 3.8. It can be seen that phase-a was drawing 90 kW power before the DER connection, which then becomes – 10 kW once the DER injects 100 kW. The other two phases remain same as before.

Fig 3.6. Source current before and after DER connection in Example 3.1.
Example 3.2 (System Response with DSTATCOM): This example is an extension of the previous example. Here a DSTATCOM is connected at 0.8 s. The peak magnitude reference PCC voltage is chosen as 8.98 kV (i.e., $|V| = 6.35$ kV rms). The angle of the PCC voltage is adjusted by the PI controller for which the
power reference $P_{ref}$ is chosen as 10 kW (equal to the loss in the DSTATCOM circuit).

The source power for the three phases is shown in Fig. 3.9. It can be seen they become balanced within 0.1 s and attain steady state within 0.3 s. After 1.1 s, the power supplied by the three phases becomes constant and equal to 22 kW. The three phase PCC voltage is shown in Fig. 3.10. It can be seen that these voltages are balanced once the DSTATCOM is operational and has a peak of 9 kV. The PCC voltage angle obtained from the PI controller is shown in Fig. 3.11. Since the total power flows from the utility to the network, the voltage angle settles to a negative value. This angle however remains zero before the DSTATCOM connection since the DSTATCOM angle controller remains inactive. When the PCC voltage becomes balanced, the source current also gets balanced as shown in Fig. 3.12. The active power consumed by the DSTATCOM is shown in Fig. 3.13. It can be seen that this is zero before the DSTATCOM connection but settles to its reference value of 10 kW once it is connected.
Fig 3.9. Source active power before and after DSTATCOM connection in Example 3.2.

Fig. 3.10. Terminal (PCC) voltage after DSTATCOM connection in Example 3.2.
Fig. 3.11. PCC voltage angle in Example 3.2.

Fig. 3.12. Source current after DSTATCOM connection in Example 3.2.
Example 3.3 (DSTATCOM Connection to a 4-Bus System): For this example, a 4-bus distribution system is considered. This is shown in Fig. 3.14. The source voltage and feeder impedance are the same as those used in previous studies. The load impedances and the DER ratings that are connected to the four load buses are given in Table 3.2. It is assumed that all the DERs are connected to phase-a. This is intentionally chosen to consider the worst case scenario.
# TABLE-3.2: LOAD AND DER PARAMETERS

<table>
<thead>
<tr>
<th>System quantities</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus-1: Load impedances</td>
<td>Phase-a: $400 + j131.48 , \Omega$</td>
</tr>
<tr>
<td></td>
<td>Phase-b: $640 + j210.36 , \Omega$</td>
</tr>
<tr>
<td></td>
<td>Phase-c: $2400 + j788.85 , \Omega$</td>
</tr>
<tr>
<td>DER</td>
<td>300 kW, 1 kVAr</td>
</tr>
<tr>
<td>Bus-2: Load impedances</td>
<td>Phase-a: $300 + j98.605 , \Omega$</td>
</tr>
<tr>
<td></td>
<td>Phase-b: $560 + j184.06 , \Omega$</td>
</tr>
<tr>
<td></td>
<td>Phase-c: $2200 + j723.11 , \Omega$</td>
</tr>
<tr>
<td>DER</td>
<td>250 kW, 1 kVAr</td>
</tr>
<tr>
<td>Bus-3: Load impedances</td>
<td>Phase-a: $200 + j65.737 , \Omega$</td>
</tr>
<tr>
<td></td>
<td>Phase-b: $480 + j157.77 , \Omega$</td>
</tr>
<tr>
<td></td>
<td>Phase-c: $2000 + j657.37 , \Omega$</td>
</tr>
<tr>
<td>DER</td>
<td>300 kW, 1 kVAr</td>
</tr>
<tr>
<td>Bus-4: Load impedances</td>
<td>Phase-a: $100 + j38.868 , \Omega$</td>
</tr>
<tr>
<td></td>
<td>Phase-b: $400 + j131.47 , \Omega$</td>
</tr>
<tr>
<td></td>
<td>Phase-c: $1800 + j591.63 , \Omega$</td>
</tr>
<tr>
<td>DER</td>
<td>350 kW, 1 kVAr</td>
</tr>
</tbody>
</table>
Fig. 3.14. A distribution system consisting of four load buses.

In this case, the DERs are connected at 0.3 s simultaneously, while the DSTATCOM is connected at 1.0s. The source phase powers are shown in Fig 3.15. It can be seen that phase-a sends over 400 kW power back to the utility before the DSTATCOM connection as all DERs are injecting power to this phase. However once the DSTATCOM is connected, the power gets circulated among phases. Each of them sends back about 25 kW power back to the grid. This is also obvious from the PCC voltage angle shown in Fig. 3.16. The angle settles to 0.5°, which is positive. It indicates a power flow from the PCC to the utility as the source voltage angle is considered the reference angle and the angle difference is positive from PCC to source. The power consumed by the DSTATCOM is shown in Fig. 3.17 which is on average 10 kW, as is expected.
Fig 3.15. Source active power in the three phases in Example 3.3.

Fig 3.16. PCC or terminal voltage angle in Example 3.3.
Example 3.4 (Bus Voltage Control): This example uses the same configuration as given in Example 3.3, where it is first assumed that the DERs are not connected, while the DSTATCOM gets connected at 1 s. The phase-a rms voltages of the four load buses after the system reaches steady state with DSTATCOM connection are plotted in Fig. 3.18. It can be seen that the voltage of Bus-1 ($V_{ba1}$) is tightly regulated as the DSTATCOM is connected to this bus. However, the bus voltages drop progressively as they move away from Bus-1. Since the DERs are not connected for this case the voltage of Bus-4 drops to 4.6 kV, which is unacceptable. The same study if performed, now with DERs being connected. The rms bus voltages are shown in Fig. 3.19. The DERs inject active power in a near unity power factor (upf) condition. They are not allowed to perform bus voltage control. Therefore, bus voltages drop progressively despite the DER injection.
If DERs are allowed to inject/absorb some amount of reactive power, the bus voltages can be regulated. This can be achieved by using a simple PI controller. One such controller is used at each bus that track a reference voltage to generate reactive power. The controller has to form
where \( V_{hai, \text{ref}} \) is the rms reference voltage of \( i^{th} \) bus. Note that this PI controller is not used for the first bus since this voltage is controlled by the DSTATCOM itself. So introducing another voltage controller may cause system instability. Therefore DER at this bus has been precluded from reactive control. The parameter values are as chosen as

\[
K_{pQi} = 2.0, \quad K_{iQi} = 125, \quad V_{hai, \text{ref}} = 6.35 \text{ kV}
\]

The rms bus voltages with reactive power control are shown in Fig. 3.20. It is assumed that the reactive power control occurs as soon as the DERs are connected (i.e., at 0.3 s). It can be seen that the bus voltages are constant irrespective of DSTATCOM connection at 1.0 s. The reactive power injection/absorption by the three DERs is shown in Fig. 3.21. It can be seen that DER at Bus-4 needs to inject more reactive power since it is the furthest and it had the lowest voltage before this controller come to action. As a consequence, Buses 2 and 3 absorb reactive power. It is to be noted that reference voltages are not drooped to find the setting of ideal reactive power compensation.

It is to be noted that this reactive power control may not always be desirable. For example, the bus voltages in Fig. 3.22 are obtained when the feeder impedances joining the buses are small. In this case, the DSTATCOM itself is able to regulate all the bus voltages. The effect of reactive power injection on bus voltage line loss will be discussed in detail in Chapter 5.
Fig 3.20. RMS bus voltages after reactive power control in Example 3.4.

Fig 3.21. Reactive power injection/absorption in the three buses in Example 3.4.
3.4. VOLTAGE CONTROLLED DSTATCOM IN ISLANDED MODE

When an islanding occurs, the DSTATCOM should not only circulate the excess power from one phase to the others, but also should either supply the balance load power or absorb any excess power that is generated by DERs. In addition, it should hold the PCC voltage constant. In order to achieve this, the power reference \( P_{fref} \) needs to be changed. Note from Fig. 3.3 that

\[
\begin{align*}
    P_L &= v_{p_a}i_{La} + v_{p_b}i_{Lb} + v_{p_b}i_{Lb} \\
    &= v_{p_a}i_{La} + 2v_{p_b}i_{Lb} \\
    &= 2v_{p_a}i_{La} + v_{p_b}i_{Lb}
\end{align*}
\]

This instantaneous load power is passed through the moving average filter to get the average load power \( P_{Lav} \) over a cycle. Therefore in order for the DSTATCOM to supply or absorb power, the following condition must be satisfied

\[
    P_{fref} = -P_{Lav}
\]
Note that no fault studies are performed here and it is assumed that the source disconnects inadvertently. The islanding condition is detected when the absolute values source currents in all the three phases fall below a small number.

**Example 3.5 (Islanding Operation with Power Surplus):** This example uses the same configuration as in Example 3.3. The study starts once the system reaches steady state. At 2.5 s, the upstream utility system is disconnected. The three phase source powers are shown in Fig. 3.23. As expected they become zero at 2.5 s. Before islanding, each phase supplied around 25 kW back to the utility. Once the utility disconnects, the DSTATCOM must absorb the total amount of power. This is shown in Fig. 3.24, where it can be seen that the average power consumed by the DSTATCOM is 80 kW. The PCC voltage angle is shown in Fig. 3.25. It is rather difficult to comment on the nature of this angle since the source is not present.

![Source Powers](image)

**Fig 3.23.** Three phase source power in Example 3.5.
Example 3.6 (Islanding Operation with Power Shortfall): This example is similar to Example 3.5, except that the four DERs are now supplying 200 kW, 250 kW, 300 kW and 250 kW (altogether 1000 kW instead of 1200 kW for the prior case). The utility is disconnected at 2.5s. The three phase source powers for this case are shown in Fig. 3.26. Each phase supplies around 40 kW from the utility before
disconnection. To meet the load demand the DSTATCOM must supply around 120 kW once the utility disconnects. This is shown in Fig. 3.27. The PCC voltage angle is shown in Fig. 3.28. This angle is negative before the disconnection of the utility since the power must flow from the utility to the PCC. However, this angle increases to accommodate power flow from the DSTATCOM to the loads.

Fig 3.26. PCC voltage angle in Example 3.6.

Fig 3.27. DSTATCOM power in Example 3.6.
Example 3.7 (Islanding Operation with Power Shortfall for a 6-Bus Network): For this example, a 6-bus system has been considered. The load in every bus is composed of 40% non-essential and 60% essential load. In every bus there is a DER connected to phase-a. Each of the DER is capable of injecting 30 kW at upf. Altogether there is 180 kW DER generation. The system total load consumption is 1000 kW. As a result of the DER generation, around 825 kW of power is being drawn from the system. The DERs are connected at 0.35 s, while the DSTATCOM is connected at 0.5 s. The utility is disconnected at 0.85 s.

The DSTATCOM power is shown in Fig. 3.29. It can be seen that after the DSTATCOM connection it starts to consume 10 kW as directed. As soon as the islanding occurs, it starts to provide the required 845 kW power to the load to hold the voltage. The three phase power supplied to the load by the DERs, utility/DSTATCOM is shown Fig. 3.30. Before the DER connections at 0.35 s, the load consumes around 1000 kW. Once the DERs are connected, they are supplying
180 kW and, as a result, the power supplied by the utility reduces to 825 kW. The DSTATCOM connection or islanding event do not change the supplied power.

Fig 3.29. DSTATCOM power in Example 3.7.

Fig 3.30. Power supplied to the load by the DERs, utility/DSTATCOM in Example 3.7.
Example 3.8 (Islanding Operation with Brown Out): This example uses the same configuration as the previous one except the DSTATCOM is assumed have steady state limit of 300 kW. In this example, all the DERs are connected at 0.1 s and the DSTATCOM is connected at 0.25 s. When the utility is cut at 0.5 s, total load consumption is 940 kW, which is now required to be supplied by the DSTATCOM. This is much above its steady state limit.

Once the islanding occurs, the DSTATCOM holds the PCC voltage for 0.3 s by supplying entire amount of power shortfall of 940 kW. Thereafter, it starts to dip the PCC voltage (brown out) until it reaches to its limit of power supply. The brown out scheme is governed by the following equation

\[
\begin{align*}
    e_p &= P_{\text{ref}} - P_l \\
    |V_t| &= G_p e_p + G_f \int e_p \, dt
\end{align*}
\]  

(3.8)

The rms voltage \(|V_t|\) is then used in (3.4). The DSTATCOM reference \(P_{\text{ref}}\) in this case is chosen as \(-300\) kW. With this controller, the power supplied by the DSTATCOM power is shown in Fig. 3.31. The PCC rms voltage is shown in Fig. 3.32. It can be seen that this voltage drops very low to limit the DSTATCOM power supply. This is unacceptable.
Example 3.9 (Islanding Operation with Load Shedding): In the previous example it is shown that the PCC voltage drops to a very low value to restrict the DSTATCOM supply in an islanding event. A better strategy is load shedding. In this example, a load shedding strategy is employed. It is assumed that the DSTATCOM
has a steady state supply capacity of 400 kW. The DERs are connected at 0.1 s and DSTATCOM is connected at 0.25 s. The utility is disconnected at 0.55 s.

Once islanding occurs, the DSTATCOM holds the PCC voltage for 10 cycles by supplying the necessary 850 kW power to the load. Thereafter, a broadcast signal is sent to disconnect all the non-essential loads. However, even after the disconnection of all the non-essential loads, the DSTATCOM still needs to supply 480 kW power, which is more than its capacity. After waiting further 10 cycles, it starts brown out by dipping its PCC voltage. This voltage gradually dips to 0.96 pu. It holds the voltage at this level cause, since further dip is not permissible. At this instant, the DSTATCOM still needs to supply around 440 kW power. Another broadcast signal can be sent to disconnect some more loads or to increase DER generation. This has not been investigated here. At 2 s, the utility is connected back and the system quantities revert back to their pre-islanding levels.

The DSTATCOM power and the PCC peak voltage are shown in Figs. 3.33 and 3.34 respectively. It can be seen from Fig. 3.34 that peak voltage is held steady at 0.97 pu (8.7 kV) till the utility is reconnected back. The three phase source powers are shown in Fig.3.35. It can be seen that they come back to their pre-islanding operating point once the utility is reconnected.
Fig 3.33. DSTATCOM power for the load shedding Example 3.9.

Fig 3.34. PCC Voltage for the load shedding Example 3.9.
Example 3.10 (Islanding Operation with Power Surplus for the 6-Bus Network): In this example the DSTATCOM capacity has been defined as 200 kW. The load consumption is 136 kW in total. Each DER is injecting 75 kW. So together they are contributing 450 kW and all are connected at 0.1 s. Note that in this case there is more generation than consumption in this case. The DSTATCOM is connected at 0.35 s and the utility is disconnected at 0.75 s. This time DSTATCOM needs to absorb the excess power generated after the load power requirement is met by the DERS. This amount is about 310 kW if the PCC voltage is held constant at 1 pu. However it is preferable that the DSTATCOM only absorbs 200 kW. Therefore it waits 20 cycles, after which it sends a broadcast signal to connect the non-essential loads. Once these loads are connected, the DSTATCOM still absorbs 300 kW. Therefore after waiting another 10 cycles, it starts to raise the PCC voltage. The upper voltage threshold is set at 1.03 pu. The bus voltages are shown in Fig. 3.36 and the DSTATCOM power is shown in Fig. 3.37. It can be seen from Fig. 3.36 that after 1.35 s, the voltages start to ramp but at 1.8 s, it reaches to 1.03 pu and thereafter the
DSTATCOM holds the PCC voltage at that value. However the DSTATCOM still absorbs around 245 kW power. Therefore either some more non-essential loads can be connected or DER power curtailment may be required. These are not shown here.

Fig 3.36. Bus voltages for the power surplus Example 3.10.

Fig 3.37. DSTATCOM power for the power surplus Example 3.10.
3.5. CONCLUSION

In this chapter, the power circulation capability of the DSTATCOM in voltage angle control has been investigated. Various simulation studies have been undertaken to verify the proposed scheme. It is shown that if one or more phase has excess power generation than the load demand due to large number of single phase DER presence, a single DSTATCOM with voltage angle controller is capable of circulating this extra power to other phases to make the source components balanced. Thus it can also prevent flow of large unbalanced current upstream.

Furthermore, the capability of this voltage controlled DSTATCOM for supplying/absorbing active power in the absence of the utility source has been studied. It is shown that the DSTATCOM is able to hold the PCC voltage constant by either absorbing or supply power, while the current control algorithm fails for islanding operation. So this can be successfully implemented for islanding operation of a microgrid.

Also a reactive power control scheme based on PI controller is developed for the DERs to regulate the load bus voltages. It has been shown that without these controllers the load bus voltages drop (or rise) from their nominal values.
CHAPTER 4

VOLTAGE QUALITY IMPROVEMENT IN DISTRIBUTION NETWORKS CONTAINING DERS USING UPQC

Single phase distributed energy resources (DERs) can cause voltage rise along distribution feeder and power imbalance among the phases. Usually transformer tap setting are used to mitigate voltage drop along feeders. However this can aggravate the voltage rise problem when DERs are connected. Moreover if the power generation in a phase is more than its load demand, the excess power in that phase will be fed back to the transmission network. In previous chapters and some literatures [69,70], it has been discussed how a single DSTATCOM connected at the connection point (PCC) of MV and LV feeders can circulate the excess power among the phases both in current control and voltage control mode. It is desirable for a DSTATCOM to supply the load reactive power demand such that the source injects power at unity power factor.

In this chapter, a mode of operation of unified power quality conditioner (UPQC) is discussed. The UPQC is able to

- inject power to PCC from the source at unity power factor (upf),
- PCC and load bus voltage regulation and balancing
- circulate excess power

These are achieved by isolating the voltage at the point of common coupling (PCC) from the load bus voltage though the UPQC. Extensive digital computer simulation studies using PSCAD and load flow solutions using MATLAB are presented.
4.1. DISTRIBUTION SYSTEM STRUCTURE

The structure of the distribution system under consideration is shown in Fig. 4.1. This contains a substation that is connected to 4 distribution buses through an 11 kV feeder. Note that the feeder shown in this figure is the 11 kV backbone. Each bus has 11 kV/415 V Y-Y transformer supplying domestic loads. Domestic customers may have single-phase DERs connected in parallel with its load. The cumulative effects of the loads and DERs on the 11 kV bus are shown in the figure for one bus only. Similar loads and DERs are connected in the other buses as well. The point of common coupling is denoted by PCC where the UPQC will be connected. The line impedance between the substation and the PCC is denoted by $R + jX$, while the line impedance between buses is assumed to be equal ($Z_f$). The data used for the distribution system are listed in Table 4.1.

![Diagram of distribution system structure](image)

Fig. 4.1. Distribution system structure for the study.

Usually the DERs are solar PVs, which can inject power during the daytime. As per the current practice, they can inject power at unity power factor. Also the feed in tariff and/or government rebate scheme prohibits the use of storage devices.
Therefore the DERs inject power during a time when the domestic consumption is the minimum. It has been shown in [70] and discussed in previous chapters about the circulation of this excess single phase power among the phases using a DSTATCOM connected at the PCC. In the next section the effect of connecting a DSTATCOM at the PCC has been analyzed.

**TABLE-4.1: SYSTEM PARAMETERS**

<table>
<thead>
<tr>
<th>System Quantities</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power consumption in high load (PCC voltage=1 PU)</td>
<td></td>
</tr>
<tr>
<td>Phase A</td>
<td>1038 kW</td>
</tr>
<tr>
<td>Phase B</td>
<td>1210 kW</td>
</tr>
<tr>
<td>Phase C</td>
<td>908 kW</td>
</tr>
<tr>
<td>Power consumption in low load (PCC voltage=1 PU)</td>
<td></td>
</tr>
<tr>
<td>Phase A</td>
<td>421 kW</td>
</tr>
<tr>
<td>Phase B</td>
<td>514 kW</td>
</tr>
<tr>
<td>Phase C</td>
<td>357 kW</td>
</tr>
<tr>
<td>Feeder impedance</td>
<td>2.42+j4.8381</td>
</tr>
<tr>
<td>Line impedance</td>
<td>0.6712+j0.2887</td>
</tr>
<tr>
<td>Systems frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Source voltage</td>
<td>11 kV (L-L, rms)</td>
</tr>
<tr>
<td>DER rating (in Unity Power Factor and low load condition)</td>
<td></td>
</tr>
<tr>
<td>Bus 1= 625 kW</td>
<td></td>
</tr>
<tr>
<td>Bus 2= 625 kW</td>
<td></td>
</tr>
<tr>
<td>Bus 3= 625 kW</td>
<td></td>
</tr>
<tr>
<td>Bus 4= 625 kW</td>
<td></td>
</tr>
</tbody>
</table>
4.2. COMPENSATION USING DSTATCOM

This study has been already discussed in previous chapters. In this chapter it is done with a different set of parameters and to introduce the problem involving this. The schematic diagram of the scheme is shown in Fig. 4.2, in which the DSTATCOM is supplied by a battery bank with a dc voltage of $V_{dc}$. The DSTATCOM is connected through an LC filter ($L_f, C_f$) to the PCC to suppress switching harmonics. The resistor $R_f$ represents the switching losses.

![Fig. 4.2. Schematic distribution system with DSTATCOM.](image)

The purpose of the DSTATCOM is to hold the PCC voltage magnitude constant at $V_p$, while angle is obtained through the PI controller. The function of the angle controller is to supply required amount of real power from the DSTATCOM. The DSTATCOM parameters are $R_f = 1.0 \, \Omega$, $C_f = 50 \, \mu F$ and $V_{dc} = 2.5$ kV.
**Example 4.1:** Let us consider a case in which none of the DERs are injecting power, while the load consumption is high (evening peak time). The DSTATCOM is connected at 0.5 s. The power drawn from the source is unbalanced before the DSTATCOM connection, but gets balanced once the DSTATCOM is connected. The reference real power for DSTATCOM \((P_f^*)\) is chosen as \(-5 \text{ kW}\). Here negative means it is expected to draw power from the system to account for the DSTATCOM losses and the DSTATCOM is required to hold the PCC voltage \(V_P\) at 1 pu (11 kV). The three single phase power supplied by the source \((P_s)\) are shown in Fig. 4.3. Even though the real power gets balanced, problem occurs with the reactive power. As shown in Fig. 4.4, that the DSTATCOM sends a large amount (4.5 MVAR) reactive power back towards the source, which is undesirable. The PCC voltage angle is shown in Fig. 4.5. Since the source voltage angle is assumed to be the reference \(0^\circ\), this angle settles to negative value to draw power from the source.

![Source Power](image)

*Fig. 4.3. Three phase source power in Example 4.1.*
4.2.1. REACTIVE POWER CONSIDERATION

As can be seen from Fig. 4.4, the DSTATCOM injects a large amount of reactive power, much more than is required by the load. Therefore, the balance amount of reactive power is being fed back towards the source. It will cause a large current to flow from/to the source, which will increase the line drop. This is analyzed in the next chapter. Therefore it may be desirable to have a upf injection of power at the PCC. However, the DSTATCOM angle controller has only a single degree of freedom. Therefore the degree of freedom must be increased.
From Fig. 4.2, the following expression can be written

\[
I_s = \frac{V - V_p \angle - \delta}{R + jX} \quad (4.1)
\]

Therefore the complex power inject at the PCC from the source is

\[
P_s + jQ_s = (V_p \angle - \delta) \times I_s^* \quad (4.2)
\]

where \( I_s^* \) is the complex conjugate of the source current \( I_s \). The above equation can be expanded as

\[
P_s = \frac{1}{R^2 + X^2} \left[ VV_p R \cos \delta + VV_p X \sin \delta - V_p^2 R \right] \quad (4.3)
\]

\[
Q_s = \frac{1}{R^2 + X^2} \left[ VV_p X \cos \delta - VV_p R \sin \delta - V_p^2 X \right] \quad (4.4)
\]

In Example 4.1 and in Chapter 3, the PCC voltage magnitude \( V_p \) is assumed to be 1 pu, while its angle \( \delta \) is obtained by a PI controller by real power feedback. From (4.4), it can be seen that the reactive power injected at the PCC \( Q_s \) cannot be made equal to zero by controlling \( \delta \) only. In Moreover from (4.3), it is evident that the real power injection \( P_s \) will depend on both \( V_p \) and \( \delta \), given that \( V, R \) and \( X \) are constant. Therefore, the reactive power control can be achieved without sacrificing the real power control.

From (4.4), it can be seen that when \( Q_s = 0 \) when

\[
V_p = V \cos \delta - \frac{VR}{X} \sin \delta \quad (4.5)
\]

Therefore the reactive power can be forced to zero by controlling the voltage magnitude. Two different controllers are employed to achieve zero reactive injection. These are discussed below.
4.2.2. USING PI CONTROLLER

Let us assume that $V$ is 1 pu (11/√3 kV). Then from (4.5), it is evident that the reactive power $Q_s = 0$ only when the magnitude of $V_P$ is less than 1 pu for positive values of $\delta$. Therefore it is not possible to regulate the PCC voltage close to 1 pu without sending reactive power back to the source. As a solution to this problem the reference for the PCC voltage magnitude can be set through another PI controller. This new PI controller with set the voltage magnitude and the DSTATCOM will tune the angle to achieve unity power factor (upf) at PCC. This is given by

$$e_r = 0 - Q_s$$

$$V_P^* = K_{pv}e_r + K_{pv} \int e_r \, dt$$

where $V_P^*$ is the reference voltage that is used in conjunction with the angle controller.

**Example 4.2:** This is an extension of Example 4.1, where the DSTATCOM with its angle controller is connected at 0.3 s and the voltage magnitude controller is connected at 0.8 s. The system reactive powers are shown in Fig. 4.6. It can be seen that once the voltage magnitude controller is connected, the DSTATCOM starts supplying the entire reactive power requirement and therefore the source does not supply any reactive power to the PCC. The voltage controller output is shown in Fig. 4.7. Before the voltage magnitude controller is connected, the DSTATCOM holds the PCC voltage to 1 pu (9 kV), which drops to 8.2 kV in the steady state. The angle controller is
shown in Fig. 4.8. Once the PCC drops, the load power consumption drops since the loads are passive RL-type. Therefore the angle also reduces. The rms voltages of the four buses are shown in Fig. 4.9. They follow the same pattern as the voltage magnitude controller.

![Fig. 4.6. System reactive powers in Example 4.2.](image)

![Fig. 4.7. The output of voltage magnitude controller in Example 4.2.](image)
4.2.3. THROUGH EQUATION SOLVING

An alternative way is to use (4.5) directly. This will work if the source voltage, $R$ and $X$ are known exactly. In that event, $V_p$ can be calculated by substituting these values along with the output of angle controller ($\delta$).
Example 4.3: For the system described in Example 4.1, the DSTATCOM, along with its angle controller and equation based voltage magnitude controllers are employed at 0.5. The reactive powers for this case are shown in Fig. 4.10. It can be seen that this controller settles quickly. However the source reactive power does not become exactly equal to zero. Therefore the PI based controller is preferable even if it causes larger transients.

![Source, Load and DSTATCOM Reactive Powers](image)

Fig. 4.10. System reactive powers in Example 4.3.

4.3. TRANSFORMER TAP SETTING

Utility companies usually use fixed transformer tap settings to prevent voltage drop during evening peak hours. In this section, some studies are conducted using MATLAB to find the effect of fixed transformer tap settings when the DSTATCOM is operated in upf.

First a situation is considered in which the system load is high with no DER injection. For this case, the PCC voltage is step by step till the upf operation is
achieved, i.e., the reactive power injected to the PCC by the source is zero. The resulting voltage distribution is shown in Fig. 4.11. It can be seen that the voltage of Bus-1 itself is around 0.87 pu and it progressively deteriorates for the downstream buses.

Fig. 4.11. Bus voltage magnitudes for upf operation and high load with no transformer tap setting.

To fix this problem, fixed tap settings are used. Setting of 1:1.15, 1:1.18, 1:1.19 and 1:1.2 are used for buses 1 to 4 respectively. The bus voltages are shown in Fig. 4.12. This tap setting improves the bus voltages. It can be seen that the voltages are now within the acceptable limits.
Fig. 4.12. Bus voltage magnitudes for upf operation and high load with transformer tap setting.

Fig. 4.12 shows the effect of the fixed tap changers when the load is high, while the DERs are off. The effect of these tap settings are now investigated for the case when the load is low. Typically when the load is low, the PV generation is the highest. It is assumed that the DERs are only connected to phase-a. With the tap setting given above, the phase-a bus voltages will rise as shown in Fig. 4.13. In fact the last two bus voltages are above the stipulated limit of 1.04 pu.

A PSCAD study is performed in which rms voltages of all the four buses are plotted. This is shown in Fig. 4.14. In this, it is assumed that the transformer tap settings are 1:1 at the beginning and the load is low. The DSTATCOM, with both its voltage magnitude and angle controllers, is connected at 0.3 s. To achieve the upf operation, the DSTATCOM raises the PCC voltage and hence there is a rise in the bus voltages. The DERs are connected at 0.6 s, which causes the bus voltages to rise even further. Subsequently, the transformer tap settings are changed to 1:1.15,
1:1.18, 1:1.19 and 1:1.2 are used for buses 1 to 4 respectively. It can be seen, that it causes further rise in the bus voltages. This situation is also evident in Australian distribution network [71].

Fig. 4.13. Bus voltage magnitudes for upf operation and low load with transformer tap setting and DER injection.

Fig. 4.14. PSCAD simulation result of variation in bus voltage magnitudes with and without transformer tap settings.
The results of this section are summarized below

- If the PCC voltage magnitude is held at 1 pu, a large amount of reactive power is fed back to the source.
- To have upf operation, the PCC voltage magnitude needs to be reduced causing voltage drop in buses.
- Fixed tap setting can be used. This will solve the voltage drop problem during high load but will cause voltage rise problem during light load with DER generation.

4.4. COMPENSATION USING UPQC

To solve the problem of PCC voltage drop for upf operation, a unified power quality conditioner (UPQC) is used. A UPQC contains a shunt voltage source converter (VSC) and a series VSC, both connected to a common dc bus as shown in Fig. 4.15. The shunt VSC is termed a DSTATCOM and the series VSC is termed as a DVR here for brevity. The a common dc bus is assumed to be battery stack. To bypass the DVR, the switch $S_{BP}$ is closed. During this time, the DVR switches are also blocked. From Fig. 4.13 it can be seen that if no tap setting is used and if the load voltage $V_L$ can be controlled independently, then the bus voltages can be kept with the limits of 0.95 pu and 1.04 pu. This can be achieved through the UPQC, in which the DSTATCOM controls the PCC voltage $V_P$, while the DVR controls the load voltage $V_L$ and these two voltages are not the same (see Fig. 4.15).
The DVR injects a voltage $V_d$ in series such that the load voltage is given by
\[ V_L = V_p + V_d \]  
(4.7)

Note that if the DSTATCOM is able to follow the voltage reference accurately, the PCC voltage will be given by (4.6) and the angle controller as
\[ V_p = V_p^* \angle -\delta \]  
(4.8)

To restrict the injection by the DVR to a minimum, the angle of the load voltage is fixed as $-\delta$. Now if the magnitude of the load voltage is fixed as $V_L^*$, the DVR injects a voltage $V_d^*$, the reference for which can be determined from (4.7) and (4.8) as
\[ V_d^* = (V_L^* - V_p^*) \angle -\delta \]  
(4.9)

Equations (4.6) and (4.7) respectively give the reference voltages for the DSTATCOM and DVR. These are then followed by the voltage source converters realizing these two devices. The UPQC parameters are given in (Table 4.2).
TABLE-4.2: CONVERTER PARAMETERS

<table>
<thead>
<tr>
<th>Converter and Controller Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DSTATCOM</strong></td>
<td>$R_f = 1.0 , \Omega$</td>
</tr>
<tr>
<td></td>
<td>$C_f = 50 , \mu F$</td>
</tr>
<tr>
<td></td>
<td>$V_{dc} = 2.5 , kV$</td>
</tr>
<tr>
<td>DVR (in each phase)</td>
<td>$C_s = 50 , \mu F$</td>
</tr>
<tr>
<td></td>
<td>$V_{dc} = 2.5 , kV$</td>
</tr>
<tr>
<td><strong>Angle Controller</strong></td>
<td>$K_{\delta} = -0.01$</td>
</tr>
<tr>
<td></td>
<td>$K_{I\delta} = -2$</td>
</tr>
<tr>
<td><strong>Voltage Magnitude Controller</strong></td>
<td>$K_{pV} = -0.05$</td>
</tr>
<tr>
<td></td>
<td>$K_{IV} = -12.5$</td>
</tr>
</tbody>
</table>

**Example 4.4 (UPQC with High Load):** This is the high load case in which there is no DER injection. The DSTATCOM is connected at 0.2 s while the DVR is connected at 1.0 s. The three single phase source powers are shown in Fig. 4.16. It can be seen that the powers become equal after the DSTATCOM gets connected. Also the DVR raises the load voltage and hence the power drawn from the source increases once the DVR gets connected.
The rms bus voltages of phase-a and the magnitude of PCC voltage \( V_P \) (i.e., the output of the voltage magnitude controller) are shown in Figs. 4.17 and 4.18 respectively. Fig. 4.17 shows that the bus voltages are below 1 pu due to upf operation before the DVR connection, while after DVR connection, the bus voltages are corrected and are restored to near 1 pu. It is interesting to note that the PCC voltage dips a little after the DVR connection. This is caused by the increase in power flow with the DVR connection.

The reactive power flowing through the various parts of the system is shown in Fig. 4.19. The reactive power injected from the source remains zero despite the UPQC operation.
Fig. 4.17. RMS load bus voltages in phase-a in Example 4.4.

Fig. 4.18. PCC voltage magnitude in Example 4.4.
The real powers flowing from the source, from DSTATCOM and to the load are shown in Fig. 4.20. It can be seen that the DVR supplies a slight amount of real power after its connection, while $P_f$ is nearly equal to zero. In fact, the power sharing between the source and UPQC can be regulated, this is discussed next.
The power supplied by the DVR \((P_{dvr})\) is not desirable since this will discharge the battery stack. Therefore this power must also be forced to zero. In order to accomplish this, another PI controller is used that is given by

\[
e_{dvr} = 0 - P_{dvr} \\
\phi = K_{p_{dvr}} e_{dvr} + K_{i_{dvr}} \int e_{dvr} \, dt
\]  

(4.10)

The DVR reference voltage is then obtained as

\[
V_d^* = |V_L^* - V_p^*| \angle - (\delta + \phi)
\]  

(4.11)

In Fig 4.21, the source, DSTATCOM, load and DVR power is shown together. As it is expected, the DVR power is force to zero due to its angle controller (4.10).

Example 4.5 (UPQC with Low Load): In this case, it is assumed that the load power requirement is minimum, while the DER injection is at its maximum. All the DERs are injecting power at unity power factor and are connected to phase-a. The
DSTATCOM and the DERs are connected at 0.2 s, while the DVR is connected at 1 s. Fig. 4.22 shows the real power. It can be seen that $P_f$ and $P_{dvr}$ remain zero, while a large amount of power is flowing back to the source. Fig. 4.23 shows the reactive power, which confirms the upf operation enforced by the UPQC.

Fig. 4.22. Real powers in Example 4.5.

Fig. 4.23. Reactive powers in Example 4.5.
The PCC voltage is shown in Fig. 4.24. It can be seen that this voltage rises over 1 pu (8.98 kV peak for 11 kV L-L), and rises further after DVR connection. However the phase-a load bus voltages remain within the specified limits once the DVR is connected, as shown in Fig. 4.25. This validates the proposed scheme.

![Fig. 4.24. PCC voltage magnitude in Example 4.5.](image1)

![Fig. 4.25. RMS load bus voltages in phase-a in Example 4.5.](image2)
4.5. CONCLUSION

This chapter presents the application of UPQC in a distribution system that contains several single-phase DERs. The DERs can cause voltage rise along the feeder if they inject power at unity power factor when the load consumption is low. Moreover the random placement of these single-phase DERs can cause power imbalance in the circuit that can flow upstream in the transmission network.

A DSTATCOM can be used for voltage regulation and power balancing in such networks. However it has been shown that the DSTATCOM can cause substantial amount of reactive power to flow back to the substation, increasing line losses. The most desirable situation is the one in which the DSTATCOM supplies the reactive power requirement of the load, while the source injects real power at unity power factor. This however will cause severe voltage drop at the PCC, especially when the load is high and the DER injection is zero. Tap changing transformers can solve this problem, but this can cause severe voltage rise for full DER injection at low loads.

To solve this problem, a UPQC is used that can isolate the PCC voltage from the load bus voltage. In this scheme, the shunt converter can supply the entire load reactive power requirement, while the series converter can regulate the load bus voltage magnitude against voltage rise or fall of PCC bus voltage magnitude. The scheme is validated through PSCAD simulation studies. However it will be shown in Chapter 6 that this configuration may lead to some undesirable operation.
CHAPTER 5

STOCHASTIC ANALYSIS OF AN LV NETWORK

In a practical low voltage distribution network, the ratings of the DERs, which are mostly PVs that are integrated to the network at the consumer premises, will be random. At the same time, the load will also be random. In some countries, a utility can restrict the maximum rating of a DER that a domestic consumer can install. Also in some countries the maximum power that a customer can consume can be limited. However the location of DER installation, power injection from DER and load consumption in the network is random in nature. So a deterministic analysis may not be suitable to predict the voltages and load pattern of the network. As a solution, stochastic method based on Monte Carlo analysis is performed on a real life network for finding its characteristics.

In this chapter, a suburban distribution network is been studied through Monte Carlo analysis. Random variations are imposed on system variables and the network load flow is performed with these variations. The results obtained are then fitted into suitable distribution functions to obtain the general characteristics of the network. At the same time, the best and worst case scenarios are also predicted.

5.1. DISTRIBUTION SYSTEM STRUCTURE

The distribution system studied has been shown in Fig. 5.1. It is a 28 bus low voltage distribution network. The network spreads into several branches. As a result, it is not purely radial in nature. The network is connected to the MV network through an 11/0.415 kV ∆-Y transformer. Since the LV side is connected in Y, each phase of
the network can be treated independently assuming that the neutral wire has zero impedance.

In the network of Fig. 5.1, the 1st bus is assumed to be the dummy bus. No load or DER is connected to it. The rest 27 nodes have single phase loads of different power consumption levels connected. These buses may or may not have single-phase DERs be connected to then. The line impedance between two consecutive buses is taken as $0.02 + j 0.01 \, \Omega$. Therefore the R/X ratio is 2.
5.2. MONTE-CARLO ANALYSIS

Monte-Carlo method relies on repeated random sampling to obtain generalized results. In this method, simulation is performed several times to obtain the distribution of an unknown probabilistic entity. A domain of possible input is defined. Then random input is generated and a deterministic computation is performed. At the end, the results are aggregated to get an overall expected value and the probability density function (pdf). The simulation number is depended on the characteristics of the input domain and the range.

The study only considers one phase (phase-a) of the network. It is because if the loads are grounded, each phase can act independently. The input random variables considered are

- PV maximum power output
- Load consumption
- PV reactive power injection/absorption

The output variables are

- Line loss
- Bus voltages

All the simulations have been carried out $10^4$ times. No breaking rule has been employed since the expected values of the outputs are unknown. These random samples have been further analyzed to fit into standard probability distribution to obtain the mean and standard deviation. To find the probability density function, kernel density estimator technique has been used. This is discussed next.
5.3. KERNEL DISTRIBUTION

A kernel distribution is a nonparametric representation of the probability density function (pdf) of a random variable. It is usually used when

- a parametric distribution cannot properly describe the data
- and/or when making assumptions about the distribution of the data cannot be made.

A smoothing function and a bandwidth value that controls the smoothness of the resulting density curve define this distribution.

5.3.1. KERNEL DENSITY FUNCTION

Let \((x_1, x_2, \ldots, x_n)\) be an independent and identically distributed sample drawn from some distribution with an unknown density \(f\). The kernel density estimator is then defined for bounded values of \(x\) as

\[
\hat{f}_h(x) = \frac{1}{nh} \sum_{i=1}^{n} K\left(\frac{x-x_i}{h}\right), \quad -\infty < x < \infty
\]  (5.1)

where \(n\) is the sample size, \(h\) is the bandwidth and \(K(.)\) is the kernel smoothing function which is a symmetric. Note that this function is not necessarily positive, but it integrates to one.

5.3.2. KERNEL SMOOTHING FUNCTION

The shape of the curve that is used to generate the pdf is the kernel smoothing function. The probability distribution is found by establishing bins and placing each data value in the appropriate bin in a histogram. Kernel distribution also builds a
function to represent the probability distribution using the sampled data. But unlike a histogram, a kernel distribution sums the component smoothing functions for each data value to produce a smooth, continuous probability curve.

There is range of commonly used kernel functions, such as

- Uniform
- Triangular
- Biweight
- Triweight
- Epanechnikov
- Normal

Due to its convenient mathematical properties, the normal kernel is often used. The mathematical expression is

$$K(x) = \phi(x)$$  \hspace{1cm} (5.2)

where $\phi$ is the standard normal density function.

The probability density $f(x)$ of a continuous variable $x$ has the units and dimensions of the reciprocal of $x$. For example, if $x$ is measured in meters, $f(x)$ has the unit of $1$/meter. Thus the density is not measured on a probability scale, and therefore it is possible for $f(x)$ to exceed 1. However the area under the curve will always be equal to 1 as it is the total probability of the system. All the simulations of this chapter have been carried out in MATLAB using its default functions and default parameter values.
5.4. RESULTS OF MONTE-CARLO ANALYSIS

Several Monte-Carlo trials are performed on the distribution network of Fig. 5.1. In particular, the following cases are considered.

- Random PV generation in upf with fixed passive RL load.
- Random PV generation with reactive power injection and absorption with fixed RL load.
- Random PV generation in upf with PQ essential and non-essential loads. The ratio of essential and non-essential loads is varied.
- No PV generation in upf with PQ essential and non-essential loads. The ratio of essential and non-essential loads is varied.

The case studies are presented below.

5.4.1. SIMULATION RESULTS

Example 5.1 (Random PV injection at upf with RL loads): For this case, all the loads of phase-a are constant and equal to $69.0800 + j 22.7451 \, \Omega$. Without any PV generation and for a dummy bus voltage of 1 pu, the power consumption for this load is 831 W. This gives the total power consumption of 19.75 kW and line loss 439.74 W.

The PV generation is now included, where the PV injections (at upf) are varied between 0 to 5 kW with a grading of 0.25 kW. They are randomly distributed in load buses barring the dummy bus. It is to be noted that the random PV injections depend on the PV rating and solar insolation assuming that the PVs operate at MPPT. Also note that the PV injection is usually maximum during noon/afternoon hours.
when the load consumptions are minimum. The Monte Carlo trial is run 10,000 times with random PV ratings in each bus for every trial. The probability density function (pdf) of line loss is shown in Fig. 5.2.

![Pdf of Line Loss During upf Operation of PVs](image)

**Fig. 5.2.** Probability density function (pdf) of line loss in Example 5.1.

The histogram of the nodes with the highest voltage is shown in Fig. 5.3. It can be seen that node-17 has the highest voltage for the most of the time while node-23 and node-16 are the next two worst nodes as voltage rise is concerned. On the other hand, node-4 and node-6 are the two nodes in which voltage violation rarely occurs (not shown in Fig. 5.3). The pdf of these 5 node voltages are shown in Fig. 5.4. It can be seen from this figure that the voltages of nodes 17 and 16 have more than 50% of the samples above 1.05 pu limit, while the voltage of node-23 has 50% of the data below the 1.05 pu limit.
From Fig. 5.4, it can be seen that though node-16 has more data above the upper limit, it has relatively low occurrence compared than node-23. So primarily, node-17 and node-23 are the two worst nodes. Almost one-third of the samples are above the 1.05 limit for node-6 while for node-4 almost all the samples are within limit. The histogram of PV ratings connected to node-17 is shown in Fig. 5.5. The
distribution is almost uniform between 0 to 5 kW which demonstrates a fair
distribution in the randomization process. Fig. 5.6 shows the pdf of the total load
consumption. The standard deviation and mean of line loss, phase-a load
consumption and mentioned five node voltages are listed in Table 5.1.

Fig. 5.5. Histogram of the node-17 PV ratings in Example 5.1.

Fig. 5.6. Probability Density Function (PDF) of total phase-a load in Example 5.1.
TABLE-5.1: STANDARD DEVIATION AND MEAN OF PARAMETERS IN EXAMPLE 5.1.

<table>
<thead>
<tr>
<th>Random PV Generation</th>
<th>Standard Deviation</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lineloss</td>
<td>0.6441838 W</td>
<td>2.0741 kW</td>
</tr>
<tr>
<td>Load power</td>
<td>0.3073799 W</td>
<td>21.91 kW</td>
</tr>
<tr>
<td>Voltage of Node-17</td>
<td>0.0124 pu</td>
<td>1.0581 pu</td>
</tr>
<tr>
<td>Voltage of Node-16</td>
<td>0.0122 pu</td>
<td>1.0576 pu</td>
</tr>
<tr>
<td>Voltage of Node-23</td>
<td>0.0106 pu</td>
<td>1.0509 pu</td>
</tr>
<tr>
<td>Voltage of Node-4</td>
<td>0.0062 pu</td>
<td>1.0345 pu</td>
</tr>
<tr>
<td>Voltage of Node-6</td>
<td>0.0082 pu</td>
<td>1.0432 pu</td>
</tr>
</tbody>
</table>

Example 5.2 (Random PV injection with reactive power injection for RL loads): This is an extension of the previous example. The system configuration remains unchanged. The PVs are not operating at upf and are capable of injecting or absorbing some reactive power to the bus. For this example, it is assumed that PVs inject four sets of reactive power, which are 20%, 40%, 60%, and 80% of the PV real power injection. Simulations are carried out with each of the four sets and random set of PVs. The pdf of the line loss is shown in Fig. 5.7 where it increases with the increment of reactive power injection. In high reactive power injection, the samples are more spread, which contributes to more uncertainty. Node-17 voltage is shown in Fig. 5.8. It can be seen that in almost all cases, the sample data are beyond the upper threshold of 1.05 pu. The same can also be said about the voltage of node-23 that is shown in Fig. 5.9. For node-4, which is one of the least affected nodes, half of the
samples for 60% reactive power injection are above the threshold, as shown in Fig. 5.10. The situation worsens as injection increases.

Fig. 5.7. Probability Density Function (PDF) of line loss in Example 5.2.

Fig. 5.8. Probability Density Function of node-17 voltage in Example 5.2.
Fig. 5.9. Probability Density Function (PDF) of node-23 voltages in Example 5.2.

The pdf of node-6 voltages is shown in Fig. 5.11. Even with 20% reactive power injection, half of the samples cross the upper limit of acceptable voltage. Node-16, due to its proximity of node-17 shows almost same characteristic; its pdf is been shown in Fig. 5.12. The pdf of load power is shown in Fig. 5.13. The load consumption increases with the increasing penetration level of reactive power. The mean and standard deviation of line loss, load, and voltages for this example are listed in Table 5.2.
Fig. 5.10. Probability Density Function (PDF) of node-4 voltages in Example 5.2.

Fig. 5.11. Probability Density Function (PDF) of node-6 voltages in Example 5.2.
Fig. 5.12. Probability Density Function (PDF) of node-16 in Example 5.2.

Fig. 5.13. Probability Density Function (PDF) of phase-a load power in Example 5.2.
### TABLE-5.2: STANDARD DEVIATION (σ) AND MEAN (µ) OF PARAMETERS FOR REACTIVE POWER INJECTION IN CASE- B

<table>
<thead>
<tr>
<th>Reactive power injected by DER</th>
<th>20% injection</th>
<th>40% injection</th>
<th>60% injection</th>
<th>80% injection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>σ</td>
<td>μ</td>
<td>σ</td>
<td>μ</td>
</tr>
<tr>
<td>Lineloss (kW)</td>
<td>0.6378</td>
<td>2 kW</td>
<td>0.708</td>
<td>2.005</td>
</tr>
<tr>
<td>Load power (kW)</td>
<td>0.3387</td>
<td>22.17</td>
<td>0.3676</td>
<td>22.43</td>
</tr>
<tr>
<td>Node-17 volt (pu)</td>
<td>0.0136</td>
<td>1.067</td>
<td>0.0147</td>
<td>1.076</td>
</tr>
<tr>
<td>Node-16 volt (pu)</td>
<td>0.0134</td>
<td>1.066</td>
<td>0.0145</td>
<td>1.075</td>
</tr>
<tr>
<td>Node-23 volt (pu)</td>
<td>0.0116</td>
<td>1.059</td>
<td>0.0124</td>
<td>1.066</td>
</tr>
<tr>
<td>Node-4 volt (pu)</td>
<td>0.0068</td>
<td>1.04</td>
<td>0.0073</td>
<td>1.045</td>
</tr>
<tr>
<td>Node-6 volt (pu)</td>
<td>0.009</td>
<td>1.05</td>
<td>0.0096</td>
<td>1.056</td>
</tr>
</tbody>
</table>
Example 5.3 (Random PV injection with reactive power absorption for RL loads): In this case, the reactive power absorption is considered instead of injection. The same set of percentage absorption with respect to power injection as discussed in Example 5.2 has been used and simulations have been carried out considering these four sets. The pdf of the line loss for this case is shown in Fig. 5.14. It can be noted that even with reactive power absorption, the line loss increases as the level of absorption increases. This will be discussed further in Chapter 6. Pdf of node-17 voltage is shown in Fig. 5.15. With 40% absorption, around two-third of the samples are within acceptable limit, while with 60% absorption, most of the sample data are within limit. The behavior is similar for node-16, as shown in Fig. 5.16. In Fig. 5.17, the pdf of node-23 voltage is shown. With only 20% absorption, most of the samples are within the specified limits.

![Fig. 5.14. Probability Density Function (PDF) of line loss in Example 5.3.](image-url)
Fig. 5.15. Probability Density Function (PDF) of node-17 voltage in Example 5.3.

Fig. 5.16. Probability Density Function (PDF) of node-16 voltage in Example 5.2.
Pdfs of voltages of nodes 4 and 6 are shown in Fig. 5.18 and 5.19 respectively. These are least affected due to their proximity to the dummy bus, which is considered as a strong bus. All data samples of node-4 and significant portion of samples of node-6 are within the stipulated limit. In Fig. 5.20, pdf of load
consumption is shown. As the node voltages decreases with the reactive power injection, the consumption of the R-L load also decreases. The mean and standard deviation of line loss, load, and voltages are listed in Table 5.3.

Fig. 5.19. Probability Density Function (PDF) of node-6 voltage with reactive absorption in Example 5.3.

Fig. 5.20. Probability Density Function (PDF) of phase-a load power in Example 5.3.
TABLE-5.3: STANDARD DEVIATION (σ) AND MEAN (μ) OF PARAMETERS FOR REACTIVE POWER ABSORPTION IN EXAMPLE 5.3.

<table>
<thead>
<tr>
<th>Reactive power absorption by DER</th>
<th>20% absorption</th>
<th>40% absorption</th>
<th>60% absorption</th>
<th>80% absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>σ</td>
<td>μ</td>
<td>σ</td>
<td>μ</td>
</tr>
<tr>
<td>Lineloss (kW)</td>
<td>0.72</td>
<td>2.493</td>
<td>0.8954</td>
<td>3.277</td>
</tr>
<tr>
<td>Load power (kW)</td>
<td>0.2692</td>
<td>21.63</td>
<td>0.2337</td>
<td>21.35</td>
</tr>
<tr>
<td>Node-17 Volt (pu)</td>
<td>0.111</td>
<td>1.049</td>
<td>0.0099</td>
<td>1.039</td>
</tr>
<tr>
<td>Node-16 Volt (pu)</td>
<td>0.0109</td>
<td>1.049</td>
<td>0.0097</td>
<td>1.039</td>
</tr>
<tr>
<td>Node-23 Volt (pu)</td>
<td>0.0094</td>
<td>1.043</td>
<td>0.0082</td>
<td>1.034</td>
</tr>
<tr>
<td>Node-4 Volt (pu)</td>
<td>0.0054</td>
<td>1.029</td>
<td>0.0047</td>
<td>1.023</td>
</tr>
<tr>
<td>Node-6 Volt (pu)</td>
<td>0.0072</td>
<td>1.036</td>
<td>0.0063</td>
<td>1.029</td>
</tr>
</tbody>
</table>
Example 5.4 (Random PV upf injection with essential and non-essential loads): In case, it is assumed that the loads are two types – essential and non-essential. Ordinarily, the system runs with only the essential loads. However if the voltage rise occurs, the non-essential loads are connected to depress the bus voltages. Only PQ type loads are considered here. Four discrete steps of non-essential loads are considered – which are 10%, 20%, 30% and 40% of essential load. Note that, in general, the non-essentials loads are about 33% of the total load [72].

The line loss pdf is shown in Fig. 5.21. It can be seen that the line loss reduces slightly when non-essential loads get connected. This is obvious as the real power injection in the bus reduces, thereby reducing the line loss.

Fig. 5.21. PDF of line loss with graded non-essential PQ load in Example 5.4.

The pdf of load power of is shown in Fig 5.22. The power consumption increases with every increment of non-essential loads, which is expected. The pdf of
node-17 voltage is shown in Fig. 5.23. It can be seen that the voltage reduces with every increment of non-essential load percentage. However, there are significant amount of sample data above the upper threshold even with 40% non-essential loads. The situation for node-23 voltage is slightly better, as shown in Fig. 5.24. With 40% of non-essential load, 2/3rd of the sample data are within the acceptable limit. The standard deviation and mean of line loss, load power, node-17 voltage and node-23 voltage are listed in Table 5.4.

![Fig. 5.22. PDF of load power with graded non-essential PQ load in Example 5.4.](image)

Fig. 5.22. PDF of load power with graded non-essential PQ load in Example 5.4.
Fig. 5.23. PDF of node-17 voltage with graded non-essential PQ load in Example 5.4.

Fig. 5.24. PDF of node-23 voltage with graded non-essential PQ load in Example 5.4.
### TABLE-5.4: STANDARD DEVIATION (σ) AND MEAN (µ) OF PARAMETERS FOR P-Q LOAD IN EXAMPLE 5.4

<table>
<thead>
<tr>
<th>P-Q Load with non-essential portion</th>
<th>Full essential</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>σ</td>
<td>µ</td>
<td>σ</td>
<td>µ</td>
<td>σ</td>
</tr>
<tr>
<td>LineLoss (kW)</td>
<td>0.74604</td>
<td>2.6979</td>
<td>0.72402</td>
<td>2.6067</td>
<td>0.70149</td>
</tr>
<tr>
<td>Node-17 Volt(pu)</td>
<td>0.0135</td>
<td>1.0574</td>
<td>0.0136</td>
<td>1.0538</td>
<td>0.0138</td>
</tr>
<tr>
<td>Node-23 Volt(pu)</td>
<td>0.0113</td>
<td>1.0502</td>
<td>0.0114</td>
<td>1.047</td>
<td>0.0115</td>
</tr>
</tbody>
</table>
Example 5.5 (No PV injection with essential and non-essential loads): In this example, a typical evening time peak load scenario is considered where there is no PV generation but the load is the highest. The loads considered here are PQ loads that ranges from 1 kW to 3 kW. As a result the bus voltages drop significantly. If the non-essential loads are disconnected during this time, the voltage profile of the system may improve.

Like in Example 5.4, it the non-essential loads are considered in four discrete steps of 10%, 20%, 30% and 40% of essential loads. The pdf of line loss is shown in Fig. 5.25. The loss drops significantly once non-essential loads start to disconnect. The pdf of node-17 voltage is shown in Fig. 5.26. Though voltage improves with the disconnection of non-essential load, it is still below the acceptable limit. The node-23 voltage also has some characteristic as node-17 voltage, which is shown in Fig. 5.27. The standard deviation and mean of line loss, node-17 and node-23 voltage are listed in Table 5.5

![Pdf of Line Loss for High Load Condition](image)

Fig. 5.25. PDF of line loss with graded non-essential P-Q load in Example 5.6.
Fig. 5.26. PDF of node-17 voltage with graded non-essential P-Q load in Example 5.6.

Fig. 5.27. PDF of node-23 voltage with graded non-essential P-Q load in Example 5.6.
TABLE-5.5: STANDARD DEVIATION (σ) AND MEAN (µ) OF PARAMETERS FOR P-Q LOAD IN EXAMPLE 5.5

<table>
<thead>
<tr>
<th>P-Q Load with non-essential portion</th>
<th>Full essential</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>σ</td>
<td>µ</td>
<td>σ</td>
<td>µ</td>
<td>σ</td>
</tr>
<tr>
<td>Lineloss (kW)</td>
<td>0.93913</td>
<td>7.12</td>
<td>0.72723</td>
<td>5.6165</td>
<td>0.55076</td>
</tr>
<tr>
<td>Load Power (kW)</td>
<td>2.9859</td>
<td>54</td>
<td>2.6873</td>
<td>48.6</td>
<td>2.3887</td>
</tr>
<tr>
<td>Voltage of Node-17 (pu)</td>
<td>0.0104</td>
<td>0.8663</td>
<td>0.0091</td>
<td>0.8814</td>
<td>0.0078</td>
</tr>
<tr>
<td>Voltage of Node-23 (pu)</td>
<td>0.0085</td>
<td>0.8846</td>
<td>0.0074</td>
<td>0.8976</td>
<td>0.0064</td>
</tr>
</tbody>
</table>
5.5. CONCLUSION

In this chapter, Monte-Carlo analysis of a real-life low voltage distribution network has been performed with various random inputs. Four different cases are studied to get a general idea about the network characteristic.

It has been observed that the line loss is the minimum when DERs are working near upf. This will be further elaborated in the next chapter. Reactive power injection by the DER increases both the node voltages and line loss. On the contrary, reactive power absorption by the DERs improves the voltage profile, but also increases the line loss. Therefore, it may be desirable for the DERs to work in upf.

If the loads are graded into essential and non-essential, manipulating them can also result in voltage control. Connecting non-essential loads in high generation-low load periods and disconnecting them in no generation-peak load periods can improve the voltage profile to some extents, if not fully. Even with 40% non-essential load, the voltage profile was not acceptable for some of the buses all the time.
CHAPTER 6

USE OF CUSTOM POWER DEVICES FOR POWER QUALITY IMPROVEMENT IN AN LV NETWORK

In the previous chapter, stochastic analysis has been performed for a low voltage distribution network. It is obvious from the results that the node, which is situated furthest from the dummy bus, is the most affected by voltage rise and fall. Reactive power injection or absorption is not always viable as this can lead to an increase in the line loss, especially in networks with high R/X ratio. For a Y-connected LV network, the power supply to a phase is independent of the other two phases. Since the PV number and ratings are random in the network, it is a possibility that one phase faces voltage rise due to PV injection while some other phase can have voltage fall at the same time.

In this chapter a solution is proposed in which each phase is treated independently to correct any voltage rise/fall problem to any of the nodes connected the phase. This is accomplished by the use of single-phase DVRs, connected to each phase near the PCC along with a single DSTATCOM, connected to the PCC.

6.1. DISTRIBUTION SYSTEM STRUCTURE

The system under study is shown in Fig. 6.1. In this structure, a substation is connected to four distribution buses through an 11 kV feeder with an impedance of \( R + jX \). Each bus supplies residential (domestic) loads through 11 kV/415 V, \( \Delta/Y \) transformers. The feeder impedances between the buses are assumed to be same \((Z_f)\). The value of \( Z_f (2.42+j \ 4.838i) \) is the same as mentioned in Chapter 4. The LV voltage distribution network connected to it has same configuration like the 28 node
network discussed in previous chapter. The transformer is rated 500 kVA with 5% leakage inductance.

Fig. 6.1. Distribution network structure considered in chapter 6

6.2. LINE LOSS OF THE NETWORK

In previous chapter it is shown that the line loss of the system increases with the DER power injection. Furthermore both reactive power injection and absorption by the DERs increase the line loss. Consider the system shown in Fig. 6.2 (a). In this, a source ($V_s$) supplies a load through a feeder of impedance $R + jX$. The source voltage has a magnitude of $V$, while the load voltage ($V_L$) is $V_1 \angle \delta$. The real and reactive components of the load current are denoted by $I_{RL}$ and $I_{XL}$ respectively. The PV injects a real current of $I_{RPV}$ and a reactive current of $I_{XPV}$. This line loss and voltage rise/fall phenomena are discussed through phasor diagrams and a numerical example, given below.

**Example 6.1:** In these phasor diagrams shown in Fig. 6.2, the magnitude of the load voltage is assumed to be constant, while the magnitude of the source voltage
is allowed to vary. In practice however, the source voltage magnitude remains constant and that of the load voltage vary. However the relative magnitude difference in these diagrams indicates the rise and fall of the load bus voltage. For example, a bigger magnitude of $V_s$ signifies a decrease in the magnitude of $V_L$ and vice versa. Also note that the line drop is proportional to $I^2$ and hence for an increase in $I$, there is a quadratic increase in the line loss.

For the system in Fig. 6.2(a), the following parameters are considered

$$V_s = \frac{415}{\sqrt{3}} = 239.6 \text{ V}, \quad R = 0.02 \Omega, \quad X = 0.01 \Omega$$

A constant PQ load with real power of 800 W at a power factor of 0.95 is considered. Four different cases are considered. These are discussed below.

**Case-a (No PV injection):** The load voltage is found to be $V_L = 239.52\angle -0.0027^\circ$ and the line current is $I = 3.53\angle -18.19^\circ$. This is shown in Fig. 6.2 (b). In this figure, $I_{RL}$ and $I_{XL}$ respectively denote the real and reactive parts of the line current.

**Case-b (Low PV injection at upf):** In this case, the PV is assumed to be injecting 400 W power at unity power factor. The load voltage is found to be $V_L = 239.56\angle 0.0013^\circ$ and the line current is $I = 2\angle -33.32^\circ$. This is shown in Fig. 6.2 (c). From this figure, it is evident that the magnitude of the current, and therefore the line loss, will be minimum only when $I_{RPV} = I_{RL}$.

**Case-c (High PV injection at upf):** The PV now is assumed to be injecting 4 kW power at unity power factor. The load voltage is found to be $V_L =$
239.86V∠0.037° and the line current is \( I = 13.39A∠-175.26° \). This is shown in Fig. 6.2 (d). It is also evident that the magnitude of the current increase and \( V_s \) reduces, thereby indicating a rise in \( V_L \).

**Fig. 6.2:** Simple network for analyzing line loss along with phasor diagrams of different cases in Example 6.1.

**Case-d (High PV and reactive power injection):** The PV still assumed to be injecting 4 kW power and absorbing 50% reactive power (i.e., 2 kVar). The load voltage is found to be \( V_L = 239.77V∠0.077° \) and the line current is \( I = \)
16.35A∠−144.66°. This is shown in Fig. 6.2 (e). Even though the magnitude of the load voltage drops, $I$ increases causing an increase in the line loss.

![Graphs of line loss and bus voltage variation with reactive power](image)

**Fig. 6.3**: Line loss and bus voltage variation with the variation of reactive power injection/absorption by DER.

Fig. 6.3 shows the variations in the line loss and bus voltage with the variation in the reactive power. The real power injection from the PV is assumed to be 5 kW. The reactive power is varied from −100% to 100% times the real power, i.e., −5 kVar to 5 kVar. Fig. 6.3 (a) shows that the line loss rises faster with reactive absorption even though it helps in reducing the bus voltage, as shown in Fig. 6.3 (b).

An increase in line loss will cause unnecessary heating in the distribution feeder, which already are stressed due to PV injection. Furthermore the PV converter size needs to be higher for reactive power absorption. Therefore an alternate strategy needs to be devised that can decrease (or increase) the voltage of LV bus-1 depending on the PV injection or load. This is discussed next.
6.3. REGULATING DUMMY BUS VOLTAGE

One of the ways to regulate the bus voltage is to manipulate the dummy bus voltage of the LV network. It is assumed the LV network is connected to the 4th bus of the MV network in Fig. 6.1. A similar MATLAB stochastic analysis like previous chapter for one phase of the LV network is carried out. The simulation has been carried out in two set of loads which are discussed in the below.

**Example 6.2 (Random PV injection with varying dummy bus voltage for RL loads):** In this example, the RL load in each bus has a nominal power consumption of 831 W. The PV generation has been randomized from 0 to 5 kW with a separation of 250 W. The dummy bus voltage has been decreased in 4 steps to observe the effect of dummy bus voltage reduction on the downstream voltages. In the previous chapter, it was identified that nodes 17 and 23 are the two most affected nodes of the network. Therefore the pdf of the voltages of these two nodes, along with that of node-2 are considered in this example. The voltage of node-2 is checked to ensure that this does not fall below the lower limit of 0.95 pu.

The pdf of line loss is shown in Fig. 6.4. It is observed that the line loss increases a little with the decrement of the dummy bus voltage from 1 pu. The node-17 voltage distribution is shown in Fig. 6.5. With the dummy voltage set to 0.96 pu, 2/3rd of the sample data lies within the limit. When the voltage is decreased further to 0.94 pu, almost all of the sample data are within the stipulated limit. In case of pdf of node-23 voltage shown in Fig. 6.6, when dummy bus voltage is at 0.96 pu, all the data are within limit. As the occurrence of the voltage limit violation in node-23 much less compared to that of node-17, node-17 data give a better picture of voltage limit violation. The pdf of node-2, shown in Fig. 6.7, shows a non-overlapping
distribution which is more or less identical with the dummy bus voltage. For all the cases, the 2\textsuperscript{nd} bus voltage is within limit. The standard deviation and mean of line loss, load and voltages of nodes 17, 23 and 2 are listed in Table 6.1. An average value and trend of voltage can be obtained from these.

![Fig. 6.4. PDF of line loss with R-L load in Example 6.2.](image)

![Fig. 6.5. PDF of node-17 voltage with RL load in Example 6.2.](image)
Fig. 6.6. PDF of node-23 voltage with RL load in Example 6.2.

Fig. 6.7. PDF of node-2 voltage with R-L load in Example 6.2.
TABLE 6.1: STANDARD DEVIATION (σ) AND MEAN (µ) OF PARAMETERS FOR R-L LOAD IN EXAMPLE 6.1

<table>
<thead>
<tr>
<th>R-L Load</th>
<th>V1=1 pu</th>
<th>V1=0.98 pu</th>
<th>V1=0.96 pu</th>
<th>V1=0.94 pu</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>σ</td>
<td>µ</td>
<td>σ</td>
<td>µ</td>
</tr>
<tr>
<td>Line loss (kW)</td>
<td>0.7804</td>
<td>2.982</td>
<td>0.8177</td>
<td>3.126</td>
</tr>
<tr>
<td>Load (kW)</td>
<td>0.1543</td>
<td>11.20</td>
<td>0.1559</td>
<td>10.81</td>
</tr>
<tr>
<td>Node-17 Volt (pu)</td>
<td>0.0124</td>
<td>1.075</td>
<td>0.0128</td>
<td>1.056</td>
</tr>
<tr>
<td>Node-23 Volt (pu)</td>
<td>0.0105</td>
<td>1.065</td>
<td>0.0106</td>
<td>1.047</td>
</tr>
<tr>
<td>Node-2 Volt (pu)</td>
<td>0.0024</td>
<td>1.018</td>
<td>0.0024</td>
<td>0.998</td>
</tr>
</tbody>
</table>

Example 6.3 (Random PV injection with varying dummy bus voltage for PQ loads): This example uses the same configuration except the loads are considered are constant PQ load instead of RL load. Unlike an RL load, the power consumption for a PQ load is not depended on the bus voltage. The ratings of loads are randomly varied between 300 W to 1 kW randomly. Like previous case, no load is connected at the dummy bus. The pdf of line loss is shown in Fig. 6.8. The line loss is more tightly regulated – it does not change much with the change in the
dummy bus voltage. The pdf of the load consumption is is shown in Fig. 6.9. It can be seen that this does not change with the dummy bus voltage as the load is taken as constant PQ.

Fig. 6.8. PDF of line loss with PQ load in Example 6.3.

Fig. 6.9. PDF of load with PQ load in Example 6.3.
The pdf of node-17 voltage is shown in Fig. 6.10. It can be seen that by lowering the dummy bus voltage to 0.98 pu, a reasonable amount of sample data belongs within the acceptable limits. Note that for RL load, the dummy bus voltage was decreased to 0.96 pu to get a comparable result. The pdf of node-23 voltage is shown in Fig. 6.11. In case of the node-23 voltage, at 0.98 pu setting for dummy bus voltage, almost all the sample data are within the band of 0.95 pu to 1.05 pu. The pdf of node-2 voltage is pretty straightforward shown in Fig. 6.12. This is non-overlapping and has almost identical distribution due to its proximity with the dummy bus. The standard deviation and mean of line loss, load and voltages of nodes 17, 23 and 2 are listed in Table 6.2.

![Fig. 6.10. PDF of node-17 voltage with P-Q load in Example 6.3.](image-url)
Fig. 6.11. PDF of node-23 voltage with P-Q load in Example 6.3.

Fig. 6.12. PDF of node-2 voltage with P-Q load in Example 6.3.
TABLE-6.2: STANDARD DEVIATION ($\sigma$) AND MEAN ($\mu$) OF PARAMETERS FOR P-Q LOAD IN EXAMPLE 6.3

<table>
<thead>
<tr>
<th>P-Q Load</th>
<th>V1=1 pu</th>
<th>V1=0.98 pu</th>
<th>V1=0.96 pu</th>
<th>V1=0.94 pu</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma$</td>
<td>$\mu$</td>
<td>$\sigma$</td>
<td>$\mu$</td>
</tr>
<tr>
<td>Lineloss (kW)</td>
<td>0.7331</td>
<td>2.677</td>
<td>0.7518</td>
<td>2.764</td>
</tr>
<tr>
<td>Load (kW)</td>
<td>0.2045e-15</td>
<td>18.39</td>
<td>0.2045e-15</td>
<td>18.39</td>
</tr>
<tr>
<td>Node-17 Volt (pu)</td>
<td>0.0131</td>
<td>1.057</td>
<td>0.0133</td>
<td>1.038</td>
</tr>
<tr>
<td>Node-23 Volt (pu)</td>
<td>0.0109</td>
<td>1.048</td>
<td>0.0112</td>
<td>1.029</td>
</tr>
<tr>
<td>Node-2 Volt (pu)</td>
<td>0.0025</td>
<td>1.013</td>
<td>0.0025</td>
<td>0.993</td>
</tr>
</tbody>
</table>

Example 6.4 (No PV injection with varying dummy bus voltage for PQ loads): This example uses the same configuration like previous example except the loads range from 1 kW to 3kW. As a result it is expected that downstream voltages will dip. The dummy bus voltage is increased from 1 pu in 4 steps of 1, 1.02, 1.04 and 1.06 pu to observe the effects on line loss and bus voltage. Note that as dummy bus does not contain any load, it can be increased above the upper limit (1.05 pu) as
long as the 2nd bus voltage, where load is connected, in within the stipulated limit.
The pdf of line loss is shown in Fig. 6.13. The line loss slightly decreases with the voltage increment.

Fig. 6.13. PDF of line loss with P-Q load in Example 6.4.

The probability distribution of node 17 voltage is given in Fig. 6.14. In this case, it can be seen that by increasing the dummy bus voltage even to 1.06 pu, the node-17 voltage samples are below the acceptable level. The pdf of node-23 voltage is shown in Fig. 6.15. With the dummy bus at 1.06 pu, some samples lie inside the acceptable range. The pdf of node-2 voltage is shown in Fig. 6.16. These are non-overlapping almost identical distributions which pretty much follows the 1st node voltage due its proximity. The standard deviation and mean of line loss, load and voltages of nodes 17, 23 and 2 are listed in Table 6.3.
TABLE-6.3: STANDARD DEVIATION (σ) AND MEAN (µ) OF PARAMETERS FOR P-Q LOAD IN EXAMPLE 6.4

<table>
<thead>
<tr>
<th>P-Q Load</th>
<th>( V_1=1) pu</th>
<th>( V_1=1.02) pu</th>
<th>( V_1=1.04) pu</th>
<th>( V_1=1.06) pu</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \sigma )</td>
<td>( \mu )</td>
<td>( \sigma )</td>
<td>( \mu )</td>
</tr>
<tr>
<td>Lineloss (kW)</td>
<td>0.944</td>
<td>7.125</td>
<td>0.898</td>
<td>6.773</td>
</tr>
<tr>
<td>Node-17 voltage (pu)</td>
<td>0.01</td>
<td>0.866</td>
<td>0.01</td>
<td>0.89</td>
</tr>
<tr>
<td>Node-23 voltage (pu)</td>
<td>0.008</td>
<td>0.885</td>
<td>0.008</td>
<td>0.907</td>
</tr>
<tr>
<td>Node-2 voltage (pu)</td>
<td>0.002</td>
<td>0.969</td>
<td>0.002</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Fig. 6.14. PDF of node-17 voltage with P-Q load in Example 6.4.
Fig. 6.15. PDF of node-23 voltage with P-Q load in Example 6.4.

Fig. 6.16. PDF of node-2 voltage with P-Q load in Example 6.4.
6.4. LV INDIVIDUAL BUS VOLTAGE SYSTEM STUDY WITH DSTATCOM

From previous section, it is understood that the voltage of the buses can be controlled by controlling the dummy bus voltage. Again from Figs. 6.1, it can be seen that the voltage of bus-\(k\) (where \(1 \leq k \leq 4\)) is set by the reactive power control by the DSTATCOM. This voltage, in turn, is related to dummy bus voltage (\(V_{41}\)) by the transformer turns ratio. Therefore to control \(V_{41}\) according to PV injection, it needs to be separated from the voltage of bus-\(k\). This can be done using an UPQC at that point as discussed in Chapter 4. The problem in this approach is the lack of individual phase control. As shown in Fig. 6.17, the DERs are installed randomly throughout the three phase network. In some case, there may be no DER in one phase. So while one phase has high bus voltages, the voltage some other phase may dip. If an UPQC is used, the DVR in that might decrease the dummy bus voltage in three phase considering feedback from that particular phase. As a result, the phase with no DER will face severe voltage dip problem. In addition to that if the UPQC is connected at the beginning of the MV network, the DSTATCOM of the UPQC can circulate the power but the voltage correction by the DVR can be a real problem. An MV network will have several LV networks with different rating connected to it. Each of these LV networks will have different voltage profile, loads and DER connections. Therefore their requirements will be different. Therefore the use of a UPQC might ultimately cause severe voltage problem. This is illustrated by the following examples.
Example 6.5 (No PV injection with RL loads): For this study, the system shown in Fig. 6.1 is used. It has been assumed that the detailed LV network of Fig. 5.1 is connected to bus. Equivalent loads are connected to the other three buses. Each LV system consumes 150 kW of load. For bus-4, phase-a consumes around 22 kW power, phase-b 44 kW and phase-c consumes around 66 kW power. There is no PV generation during this time. The DSTATCOM, with its power-angle controllers, is connected to the MV system at 0.3 s. At 0.8 s, the reactive power controller is switched on.

The voltages of critical nodes at phase-a, phase-b and phase-c are shown in Figs. 6.18, 6.19 and 6.20 respectively. It can be seen from the figures that phase-a voltages are within acceptable limit while the voltages of phases b and c have fallen below the limit. Therefore there is no need for voltage correction in phase-a, while the dummy bus voltages in phases b and phase need to be raised. Note that the lowest voltage in phase-b is around 0.92 pu and in phase-c, it is less than 0.9 pu.
Fig. 6.18. Voltage in pu for some critical nodes in phase-a in Example 6.5.

Fig. 6.19. Voltage in pu for some critical nodes in phase-b in Example 6.5.

Fig. 6.20. Voltage in pu for some critical nodes in phase-c in Example 6.5.
The MV side voltages of all the four buses are shown in Fig. 6.21. It can be seen that they are all in acceptable limit. The voltage peak set by DSTATCOM to facilitate upf operation at PCC is shown in Fig. 6.22. It can be seen that this voltage dips only slightly to accommodate upf operation. The three phase source power drawn from substation is shown in Fig. 6.23. It is found that proper power circulation occurs.

![MV side RMS voltage (pu) in four buses](image1)

**Fig. 6.21.** MV side voltage of the buses in Example 6.5.

![Voltage peak set by DSTATCOM at PCC](image2)

**Fig. 6.22.** Voltage peak set by DSTATCOM at PCC in Example 6.5.
**Example 6.6 (PV injection with RL loads):** This is a system study with same configuration like previous example, but with PV injection. To test the maximum PV injection during low load period, all the loads have been reduced to $1/3^{rd}$ of the high load values used in Example 6.5. There are 15 PVs in phase-a, 9 PVs in phase-b and 5 PVs in phase-c of the detailed network. All of the PVs are assumed to be injecting 5 kW at upf. In the equivalent buses of 1 to 3, the following PV injections at upf are considered:

- Bus-1: 150 kW PV generation in phase-b only;
- Bus-2: 100 kW PV generation in phase-c only;
- Bus-3: 250 kW PV generation in phase-a only.

The power controller of DSTATCOM is connected at 0.8s and the reactive power controller is connected at 1.2s. The node voltages in phases a, b and c are shown Figs. 6.24, Fig. 6.25 and Fig. 6.26 respectively. The phase-a bus voltages are the most affected in this case, while phase-c is the least affected. This is because the

![Source power in three phases](image)

Fig. 6.23. Three phase source power in Example 6.5.
The highest number of PVs is connected to phase-a with the lowest power consumption. On the other hand, phase-c has the highest load consumption whereas it has the least number of PV connections. The worst voltage at node-17 in phase-a reaches around 1.15 pu and even node-2 voltage rises to 1.05 pu. The downstream voltages are mostly in between 1.05 to 1.15 pu. The phase-b bus voltages are in a moderate position with some extreme downstream voltage above the upper limit. In phase-c, the voltages are more or less in the acceptable limit. Note that after reactive controller takes action, the bus voltages increase in all phases. This is because the Q-controller of DSTATCOM increases the PCC voltage to facilitate upf operation. As a result the downstream MV bus voltages also increase and, as a consequence, the LV bus voltages also increase.

![Source Power in Phase-a for Low Load and High DER Generation](image)

Fig. 6.24. Voltage in pu for some critical nodes in phase-a in Example 6.6.
Fig. 6.25. Voltage in pu for some critical nodes in phase-b in Example 6.6.

Fig. 6.26. Voltage in pu for some critical nodes in phase-c in Example 6.6.

6.5. LV BUS VOLTAGE REGULATION USING DVR

From these two examples, it can be seen that the phase-a does not face any voltage violation during no PV generation but has the highest voltage rise during PV generation. Phase-c behaves exactly in the opposite fashion. So voltage correction requirement for a phase is different from the others. The DSTATCOM keeps circulating power and regulates the MV side voltage for upf operation.
Since the MV system supplies several LV systems with different load and PV injection levels, a UPQC may not be able to provide voltage correction to all the buses. Moreover, as can be seen from the above examples that the requirements of each phase are different. A solution of this problem is to use independent individual DVRs in each phase, along with the DSTATCOM at the PCC. This is shown in Fig. 6.27. The DSTATCOM circulates power amongst the phases while the DVRs inject voltage to a phase independent to the other two phases. All the three DVRs are however connected to a common dc bus.

![Diagram of DVR connection for per phase voltage control.](image)

Note that bus-1 is considered as the dummy bus in the Example 6.5 and 6.6. This voltage now can be defined using the DVRs as

$$V_{41k} = V_{4k} + V_{dvrk}, \quad k = a, b, c$$

The DVR reference voltages are then generated from

$$
\begin{align*}
V_{dvr_a} &= V_{4ka} - (\delta_L - \delta) \\
V_{dvr_b} &= (\delta_L - 120^\circ) - V_{4b} - (\delta - 120^\circ) \\
V_{dvr_c} &= (\delta_L + 120^\circ) - V_{4c} - (\delta + 120^\circ)
\end{align*}
$$

(6.2)
where \( \delta_i \) is the angle of \( V_4 \) and \( \delta_L \) is the angle that is obtained through the DVR power controller discussed in Chapter 4. Since only the voltage magnitude needs to be adjusted separately for the three phases, their angle can be 120\(^\circ\) apart.

### 6.6. SETTING VOLTAGE MAGNITUDE FOR DVR

The setting of the DVR reference magnitude is crucial for its efficient operation. An unnecessary dipping or swelling the dummy voltage can increase the line loss and affect life length of the attached equipments. Two different approaches are proposed to find the optimum voltage level for the dummy bus. These are discussed below.

#### 6.6.1. USING REAL TIME FEEDBACK

This proposal assumes that a two-way communication system for obtaining a feedback from each bus. A master controller, which sets the voltage \( V_{41}^* \) of each phase, collects the voltage magnitude measurements of all nodes of that phase. This operation takes place based on a fixed sampling time. If voltage of a node rises above 1.05 pu, the master controller reduces \( V_{41}^* \) by 0.0025 pu and samples all the bus voltages again. This process continues till all the bus voltages are within the specified ranges. However, the process terminates if, as a consequence of reduction in \( V_{41}^* \), one of the bus voltages falls below 0.94 pu. In that case, a request is sent to the buses with voltage violation to switch on auxiliary loads through their home area networks.

A flowchart of the process is given in Fig. 6.28. Since a bus voltage does not vary very rapidly, the sampling time can be chosen around 0.5 s to accommodate the collection of data from all 28 buses. Also note that synchronized sampling of all
nodes is not essential and the controller can sequentially poll all the nodes in a half duplex communication. The bandwidth requirement for this will be very low.

**Fig. 6.28. Flowchart of $V_{41}^*$ setting algorithm.**

### 6.6.2. USING WORST VOLTAGE FEEDBACK

This is a recursive method that uses the average data already been obtained from the Monte Carlo analysis. For example, from this analysis, it has been already established that the worst voltage limit violation occurs in node-17. The average voltage for this node during no PV generation and high load is 0.866 pu. Let the target be to improve this magnitude to 0.95 pu. Let the new dummy bus voltage for this purpose is
\[ V_{new1} = \frac{A - V_{17\text{mean}}}{V_{old1}} + V_{old1} \]  

(6.3)

where \( V_{new1} \) is the new desired dummy bus voltage, \( V_{old1} \) is the existing dummy bus voltage (typically 1 pu), \( V_{17\text{mean}} \) is the mean node-17 voltage obtained from the Monte Carlo analysis. For a desired operating voltage of \( V_{new17} \) for node-17, \( A \) is defined as \( V_{new17}/K \) for a constant \( K \). The value of \( K \) depends on the characteristic of the network and can be obtained through random sample data. To find the value of \( K \), the system is tested with some arbitrary sample values. The “goal seek” tool in MS excel, which is very powerful tool, is used to find the value. The sample data are listed in Table 6.4. Note that the study has considered high load and no PV generation scenario.

### TABLE-6.4: SAMPLE DATA TO OBTAIN THE VALUE OF \( K \).

<table>
<thead>
<tr>
<th>Entities</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A )</td>
<td>( V_{new17} )</td>
</tr>
<tr>
<td>0.8</td>
<td>0.8128</td>
</tr>
<tr>
<td>0.92</td>
<td>0.9647</td>
</tr>
<tr>
<td>1</td>
<td>1.0589</td>
</tr>
<tr>
<td>1.1</td>
<td>1.183</td>
</tr>
</tbody>
</table>

As it can be seen that the value for \( K \) is not constant. So the square root operation is repeatedly done until a constant/near constant value is obtained. After doing double square root, the value come close to 1.01*.

The value of \( K \), obtained from Table 6.4, is substituted in (6.3). This will give an expected value of \( V_{new1} \). Once this value is used as the dummy bus voltage in a
load flow program, a different value of $V_{new17}$ is obtained. To get the desired $V_{new17}$ voltage, the dummy bus voltage in load is varied. This is then substituted in (6.3) to obtain a new value of $K$. The dummy bus voltage and the corresponding expected value of $K$ are listed in Table 6.5. As the value of $K$ does not vary linearly with the change in dummy bus voltage, its rms value is computed as 1.014141611. As shown in Table 6.5, that the difference between this value and the expected value of $K$ changes proportionally with the deviation of dummy bus voltage from 1 pu.

For further derivation the following two quantities are defined

$$K_{diff} = K_{exp} - K_{rms}$$  \hspace{1cm} (6.4)

$$V_{diff} = V_{exp} - 1$$  \hspace{1cm} (6.5)

where $K_{exp}$ is the expected value of $K$, $K_{rms}$ is its rms value and $V_{exp}$ is the expected value of the dummy bus voltage. From these two quantities, an error constant is defined as

$$\alpha = \frac{K_{diff}}{V_{diff}}$$  \hspace{1cm} (6.6)

This constant has an rms value of 0.048234727 $\approx$ 0.05. With this, (6.3) is further modified to

$$V_{new1} = \frac{(V_{new17}^2/(V_{old1} + (V_{new17} - 1) \times 0.05)^2) - V_{mean17}}{V_{old1}} + V_{old1}$$ \hspace{1cm} (6.7)

With the help of (6.7), the reference voltage magnitude of the dummy bus can be set taking the feedback from the worst node voltage. The bus voltage values are listed in Table 6.6. However it is needed to check the 2nd node voltage. If it is more than the acceptable value, the voltage cannot be further modified. Sample iteration is done in MATLAB with this relation deployed and the voltage data is listed in Table 6.6. It is
found that after the 3rd iteration, the 2nd voltage is close to the upper limit and at 4th iteration it has crossed the limit. So the DVR voltage will be the value obtained from the 3rd iteration.

**TABLE-6.5: SAMPLE DATA TO OBTAIN α.**

<table>
<thead>
<tr>
<th>Expected pu</th>
<th>$K_{exp}$</th>
<th>$K_{diff}$</th>
<th>α</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.05</td>
<td>1.016746234</td>
<td>0.002604623</td>
<td>0.052092454</td>
</tr>
<tr>
<td>1.04</td>
<td>1.016297455</td>
<td>0.002155844</td>
<td>0.053896105</td>
</tr>
<tr>
<td>1.03</td>
<td>1.015888699</td>
<td>0.001747088</td>
<td>0.05823626</td>
</tr>
<tr>
<td>1.02</td>
<td>1.015379854</td>
<td>0.001238243</td>
<td>0.061912163</td>
</tr>
<tr>
<td>1.01</td>
<td>1.014908505</td>
<td>0.000766893</td>
<td>0.076689332</td>
</tr>
<tr>
<td>1</td>
<td>1.014428854</td>
<td>0.000287243</td>
<td>0</td>
</tr>
<tr>
<td>0.99</td>
<td>1.013940682</td>
<td>-0.000200929</td>
<td>0.020092941</td>
</tr>
<tr>
<td>0.98</td>
<td>1.013443757</td>
<td>-0.000697854</td>
<td>0.034892713</td>
</tr>
<tr>
<td>0.97</td>
<td>1.012937841</td>
<td>-0.00120377</td>
<td>0.040125674</td>
</tr>
<tr>
<td>0.96</td>
<td>1.012422931</td>
<td>-0.001718681</td>
<td>0.042967016</td>
</tr>
<tr>
<td>0.95</td>
<td>1.01189744</td>
<td>-0.002244171</td>
<td>0.044883418</td>
</tr>
<tr>
<td>0.94</td>
<td>1.011390209</td>
<td>-0.002751403</td>
<td>0.045856712</td>
</tr>
<tr>
<td><strong>RMS of K</strong></td>
<td><strong>1.014141611</strong></td>
<td><strong>RMS of α</strong></td>
<td><strong>0.048234727</strong></td>
</tr>
</tbody>
</table>
TABLE-6.6: NODE VOLTAGE VALUES OBTAINED FROM THE WORST VOLTAGE FEEDBACK IN LOW GENERATION

<table>
<thead>
<tr>
<th>Node</th>
<th>1st iteration</th>
<th>2nd iteration</th>
<th>3rd iteration</th>
<th>4th iteration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1.033</td>
<td>1.0649</td>
<td>1.0959</td>
</tr>
<tr>
<td>2</td>
<td>0.9745</td>
<td>1.0084</td>
<td>1.0412</td>
<td><strong>1.073</strong></td>
</tr>
<tr>
<td>15</td>
<td>0.8968</td>
<td>0.9337</td>
<td>0.9692</td>
<td>1.0034</td>
</tr>
<tr>
<td>16</td>
<td>0.8947</td>
<td>0.9318</td>
<td>0.9673</td>
<td>1.0015</td>
</tr>
<tr>
<td>17</td>
<td>0.8937</td>
<td>0.9307</td>
<td><strong>0.9663</strong></td>
<td>1.0006</td>
</tr>
<tr>
<td>23</td>
<td>0.9076</td>
<td>0.9441</td>
<td>0.9792</td>
<td>1.013</td>
</tr>
<tr>
<td>24</td>
<td>0.9694</td>
<td>1.0035</td>
<td>1.0364</td>
<td>1.0683</td>
</tr>
<tr>
<td>25</td>
<td>0.9665</td>
<td>1.0008</td>
<td>1.0338</td>
<td>1.0658</td>
</tr>
<tr>
<td>26</td>
<td>0.9647</td>
<td>0.999</td>
<td>1.0321</td>
<td>1.0641</td>
</tr>
</tbody>
</table>

This relation can also be applied when there is high DER generation and low load consumption. For example, a simulation was carried out in the LV network considering random PQ load ranging from 300 W to 1 kW and random PV generation from 0 kW to 5 kW. The voltage is increased and the dummy bus needs to be dipped for this case. The voltage data are listed in Table 6.7. It can be seen that the DVR set point can be obtained in the 2nd iteration as all the voltages are in the range. Though the dummy bus can be further dipped but the 2nd node voltage falls below the acceptable limit in the 3rd iteration. So the DVR is set with the value of the 2nd iteration.
TABLE-6.7: NODE VOLTAGE VALUES OBTAINED FROM THE WORSTNODE VOLTAGE FEEDBACK IN HIGH GENERATION

<table>
<thead>
<tr>
<th>Node</th>
<th>1st iteration</th>
<th>2nd iteration</th>
<th>3rd Iteration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.9347</td>
<td>0.8648</td>
</tr>
<tr>
<td>2</td>
<td>1.0163</td>
<td><strong>0.952</strong></td>
<td><strong>0.8833</strong></td>
</tr>
<tr>
<td>15</td>
<td>1.0638</td>
<td>1.0024</td>
<td>0.9372</td>
</tr>
<tr>
<td>16</td>
<td>1.0643</td>
<td>1.0029</td>
<td>0.9378</td>
</tr>
<tr>
<td>17</td>
<td>1.0647</td>
<td><strong>1.0033</strong></td>
<td>0.9382</td>
</tr>
<tr>
<td>18</td>
<td>1.0531</td>
<td>0.9911</td>
<td>0.9251</td>
</tr>
<tr>
<td>19</td>
<td>1.0521</td>
<td>0.9899</td>
<td>0.9239</td>
</tr>
<tr>
<td>20</td>
<td>1.0523</td>
<td>0.9902</td>
<td>0.9241</td>
</tr>
<tr>
<td>21</td>
<td>1.0524</td>
<td>0.9903</td>
<td>0.9243</td>
</tr>
<tr>
<td>22</td>
<td>1.0526</td>
<td>0.9905</td>
<td>0.9245</td>
</tr>
<tr>
<td>23</td>
<td>1.0526</td>
<td>0.9905</td>
<td>0.9245</td>
</tr>
</tbody>
</table>

Some PSCAD simulations are carried out and the results are shown below. The system of Example 6.5 is considered, albeit with DVR connection. Since there is no voltage violation in phase-a, the DVR injection for this phase is negligible. The bus voltages of phases b and c are shown in Figs. 6.29 and 6.30 respectively. The DVR comes to action at 1.5 s. At first, the reference for the dummy bus voltage magnitude is set arbitrarily at 1.1 pu. It can be seen that the 2nd bus voltage is way above the acceptable limit of 1.05 pu. Thereafter a reasonable set point is found (6.7)
at 2 s. For phases b and c, the values are calculated as 1.058 pu and 1.08 pu respectively. Therefore at 2 s, both phase-b and phase-c is reset to the calculated set point. As a result both the 2nd voltage ($V_2$) and the worst voltage ($V_{17}$) are within acceptable limits. Note that the DVR set points are different in the phases. So it clearly justifies the use of single phase DVRs.

![Bus Voltage after DVR Connection with Arbitrary and Defined Set Point](image)

Fig. 6.29. Bus voltages after DVR set in phase b for high load and no generation for Example 6.5

![Bus Voltage after DVR Connection with Arbitrary and Defined Set Point](image)

Fig. 6.30. Bus voltages after DVR set in phase c for high load and no generation for Example 6.5
For the system of Example 6.6, phase-c has a fairly acceptable bus voltages, but phases a and b are badly affected and their dummy bus voltages need to be dipped. The bus voltage profile of phase-a is shown in Fig. 6.31. As it can be seen, the voltages are very high before the DVR connection at 0.8 s. The DVR sets dummy bus voltage to 0.89 pu. The voltages of the furthest nodes fall within the acceptable range, but a violation of the 2nd node voltage occurs. However a set point is changed at 1.2 s using (6.7). This is computed as 0.94 pu. It can be seen that this results in a voltage rise in the furthest nodes.

The bus voltages for phase-b are shown in Fig. 6.32. Similar characteristic is observed, even though the voltages are not as bad as phase-a due to less number of PVs in this phase. The DVR is connected at 0.8 s with 0.9 pu set point. It is reset with a value of 0.92 pu at 1.2 s using (6.7). However the 2nd node voltage did not pass the lower limit. So the dummy bus can be increased even further. It is to be noted that (6.7) does not work very well when the generation is high as bus voltages are very much dependent on the PV generation. In addition to that the presence of pure RL loads makes the troubleshooting complicated. So the communication based scheme proposed in section 6.5.1 is the best suited for this case. The bus voltages of phase c are shown in Fig. 6.33. Though there is no need for DVR action, the dummy bus was set to 1 pu for optimum operation. However if it causes voltage violation, it should be avoided.
Fig. 6.31. Bus voltages after DVR set in phase a for low load and high generation for Example 6.6

Fig. 6.32. Bus voltages after DVR set in phase b for low load and high generation for Example 6.6
As can be seen from the results that during high PV generation, DVR operation alone may not be successful to keep the voltage quality within limits. A solution to this problem is a coordinated combined operation of essential-non-essential load, active power curtailment or integration of power storage on per-customer or community basis can be applied. These have not been attempted here.

6.7. CONCLUSION

In this chapter, first the line loss characteristic with the active and reactive power of the DER generation is discussed. Analysis has been performed with phasor-diagram and Newton-Rhapson method to find the minimum line loss situation. It has been found that line loss is the minimum when the DER generates same amount of active power that is needed for the load connected to it. As it is quite unpractical, so to operate them at upf is the optimum solution.
Also the probability distribution of node voltages and line loss with controlling the dummy bus voltage is obtained through Monte-Carlo analysis. From there a network strategy with separate DSTATCOM and single-phase individual DVR is studied. A mathematical relation for the DVR set is proposed considering the worst voltage feedback. A particular very large network is simulated in PSCAD to verify the proposals. It is understood that single-phase DVR is the optimum choice for controlling downstream node voltages regardless the DER presence and penetration level. However a communication channel is still needed for finer operation with load curtailment and smart load management.
CHAPTER -7
GENERAL CONCLUSIONS AND SCOPES FOR
FUTURE RESEARCH

The general conclusions of the thesis and some future scopes of work are
presented in this chapter

7.1. GENERAL CONCLUSION

The thesis mainly addresses some topical problems that arise due to large
uptake of single-phase DERs in distribution networks. This can cause reverse power
flow towards the upstream transmission system [71], can cause voltage fluctuation
and can increase line loss. Some measures using different types of CPDs can be
taken to alleviate these problems. Based on the investigation reported in the earlier
chapters to address these problems, some general conclusions are drawn. These are
listed below.

- A single DSTATCOM connected at the point of common coupling (PCC)
between MV and LV sections of a distribution network, when operated in
current control mode, is capable of circulating the excess power amongst the
phases. This way, the reverse power flow in the system can be reduced. The
DSTATCOM provides a path for the power to flow through its DC bus. Both
delta and Y-connected DSTATCOM topologies can be used. However the delta-
connected DSTATCOM can only be used when it is connected upstream from a
delta-connected transformer, since it does not have the ability to cancel zero-
sequence currents. Regardless the transformer connection, a y-connected
DSTATCOM can circulate the power, even with the change in generation
condition. However a current controlled DSTATCOM is not suitable when the system gets islanded. In this case, the current control fails.

- A voltage controlled DSTATCOM, connected at the PCC, on the other hand, can operate in both grid connected and islanded modes. The DSTATCOM in this acts as a shunt connected source, which holds the PCC voltage constant to a pre-specified value. The angle of the voltage is obtained from a power flow relation. In the islanded mode, the DSTATCOM is able to supply power shortfall or absorb excess power.

- The DSTATCOM can fix the PCC voltage to predefined value. However fixing it to 1 per unit can cause a large amount of reactive power to/from the utility substation. This will result in excessive current and therefore large line loss, which is undesirable. To avoid this, it is prudent to set the PCC voltage magnitude such that the current from the utility flows in the PCC at unit power factor (upf). This is achieved by a voltage magnitude controller that set the reactive power drawn/supplied to the source to zero. This might however result in the decrease/increase of the downstream load bus voltages. Since the LV network may or may not have DERs (depending on the DER type), fixed transformer tap setting can only complicate the problem further. To isolate the PCC voltage from the load bus voltages, a UPQC is used. The shunt controller in this case performs the power circulation and reactive compensation, while the series controller set the load bus voltage.

- LV distribution network may contain both RL and PQ loads. The power consumption of the loads are random in nature, as well as the installed DER ratings and locations. Stochastic analysis of a standard large network shows that the most affected node is always furthest from the distribution transformer. It
also shows that both reactive power injection/absorption by the DERs increases the line loss though absorbing reactive power can reduce the bus voltages. The bus voltages can be also controlled by connecting/disconnecting non-essential loads. A UPQC can manipulate the first (dummy) load bus voltage. Therefore using this device, the bus voltages can nearly be kept near within the specified lower and upper limits.

- Due this randomness of loads and DER injections in any LV distribution network, every phase will have different voltage levels and power requirements. This will render the installation of a single UPQC useless. It may improve voltage in one phase, while degrade voltage in the other two phases since a decision regarding all the three phases are taken together. To control the voltage of each phase individually, single phase DVR in every phase can be installed for all the load buses. In this configuration, a single DSTATCOM connected at the PCC can circulate power among the phases of every load bus while individual the DVRs can correct the LV bus voltages of each phase. This will work in most of the cases. However in some cases, especially if there are a large number of PVs connected to one phase or load in one phase is significantly heavier than the other phases. In such case, nonessentials loads need to be connected or disconnected to maintain the voltage within specified limits.

### 7.2. SCOPES OF FUTURE WORK

Some scopes of future work can be identified as given below.

- The coordination of active power curtailment of DER and smart load management can be investigated. Power curtailment, especially from non-dispatchable sources, is never a desired option and therefore it should be kept at
a minimum. Therefore to improve the voltage profile, smart load management strategies need to be designed.

- The operation of multiple DSTATCOMs and/or CPDS is another area of study. It has been found that connecting two DSTATCOMs on the same network without much electrical isolation can lead to instability. Therefore, coordination strategies for such devices with much smaller ratings can be investigated.
APPENDIX

LIST OF PUBLICATIONS

The following papers are published (or under publication process) from the work described in the thesis.

**Journal papers:**


**Conference papers:**


REFERENCES


A. Ghosh, A.K. Jindal and A. Joshi, "Design of a capacitor-supported
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T. J. E. Miller, Reactive power control in electric systems, Wiley, 1982.

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feedback for power compensating devices.", TENCON 2003 IEEE 
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S. Mazumder, A. Ghosh, and F. Zare. "Improving Power Quality in Low-
Voltage Networks Containing Distributed Energy Resources." 
67-78.

S. Mazumder, A. Ghosh, F. Shahnia, F. Zare, and G. Ledwich. "Excess 
power circulation in distribution networks containing distributed energy
