

# **Reactive Power Support**

## Planning, Design and Operation

**J.ARRILLAGA**

**EPECentre Series- 2  
University of Canterbury  
New Zealand**

All rights reserved. No reproduction, copy or transmission of this publication may be made without written permission.

Electric Power Engineering Centre, University of Canterbury 2009

Published by  
The EPECentre  
Dept. of Electrical and Comp. Engineering  
University of Canterbury  
Private Bag 4800  
Christchurch 8013  
New Zealand  
[www.epicentre.ac.nz](http://www.epicentre.ac.nz)

Printed in New Zealand by  
Microfilm Digital Print, Christchurch

Cover design by John Arrillaga

**“Reactive Power Support- Planning, Design and Operation”**

This book, the second in the EPECentre series, is based on the CIGRE Joint AP-B4/C1 two-day Seminar held in Brisbane (Australia) in 8-9 May 2008. The contributors and titles of the Seminar presentations were:

- Carson Taylor (ex-BPA, USA)  
*Voltage Stability - An old problem and new thinking*
- Nalin Pahalawaththa (Transpower NZ)  
*Behaviour and modelling of loads*
- Tom Percy (Western Power, AU)  
*Shunt reactive compensation*
- Michael Redpath (Vencorp, AU)  
*Series reactive compensation*
- Colin Parker (TransGrid, AU)  
*Voltage instability mechanisms and assessment*
- Nalin Pahalawaththa and Tim George (Transpower NZ)  
*Dynamic voltage instability*
- Jennifer Crisp (NEMMCO, AU)  
*Planning standards, guidelines and emerging trends, Australian perspective*
- Carson Taylor (ex-BPA, USA)  
*Planning standards, guidelines and emerging trends, An international Perspective*
- Peter Biddle (NEMMCO, AU)  
*Operational aspects of voltage control*
- Keith Frearson (SKM)  
*Synchronous condensers and synchronous generators*
- Peeter Muttik (AREVA)  
*Shunt capacitors*
- Bo Nilsson, Leif Andreasson and Anders Bostrom (ABB)  
*Series capacitors*
- Claus Matthias (SIEMENS)  
*SVCs*
- Narend Reddy (American Superconductors)  
*STATCOMs*
- Carson Taylor (ex-BPA, USA)  
*A critical comparison of technologies*
- John Mouatt (TransGrid, AU)  
*Operational experiences of SVC installations in TransGrid*
- Tuan Vu (Powerlink, AU)  
*Specification, design and refurbishment of SVC installations*
- Tim George (Transpower NZ) and Marian Piekutowski (Hydro Tasmania)  
*Reactive power control*

## CONTENTS

<i>PREFACE</i>	X
<b>CHAPTER 1- VOLTAGE STABILITY-GENERAL PRINCIPLES AND NEW THINKING</b>	<b>1</b>
1.1 INTRODUCTION	1
1.2 VOLTAGE STABILITY DEFINITIONS	1
1.3 AIDS TO VOLTAGE STABILITY STATIC ASSESSMENT	4
1.4 AIMS OF VOLTAGE AND REACTIVE POWER CONTROL	9
1.5 VOLTAGE INSTABILITY TIME FRAMES	9
1.6 NEW THINKING IN VOLTAGE STABILITY CONTROL	14
1.7 CONCLUSION	19
References	20
<b>CHAPTER 2- BEHAVIOUR AND MODELLING OF LOADS</b>	<b>22</b>
2.1 INTRODUCTION	22
2.2 CHANGING LOAD COMPOSITION	22
2.2.1 Compact Fluorescent Lamps	22
2.2.2 Induction motors	22
2.2.3 Power Electronic drives	24
2.2.4 IT and Entertainment systems	24
2.3 LOAD MODELLING	26
2.3.1 Steady state modelling	26
2.3.2 Dynamic modelling	26
2.4 LOAD COMPOSITION ASSESSMENT	31
2.4.1 Customer survey	31
2.4.2 GXP load by customer class	32
2.4.3 Results from load surveys	35
2.4.4 Equivalent dynamic model	36
2.4.5 Load model calibration	36
2.5 MAIN CONCLUSIONS	39
Bibliography	39

<b>CHAPTER 3- SHUNT REACTIVE COMPENSATION</b>	<b>40</b>
3.1 INTRODUCTION	40
3.2 DYNAMIC COMPENSATORS	40
3.2.1 Synchronous Generators	40
3.2.2 Synchronous Compensators	41
3.3 TYPES AND BASIC FUNCTION OF STATIC SHUNT COMPENSATION DEVICES	41
3.4 CHARACTERISTICS OF MSC AND MSR COMPENSATION	42
3.5 STATIC VAR COMPENSATION (SVC)	43
3.6 STATCOM	46
3.7 PERFORMANCE OF SHUNT REACTIVE COMPENSATION	47
3.7.1 Compensation requirements for line outages	57
3.8 SYNCHRONOUS COMPENSATORS VERSUS SVCs FOR SYSTEM RESTORATION	59
3.9 STATCOM VERSUS SVC PERFORMANCE	62
3.10 OTHER CONSIDERATIONS	63
References	64
<b>CHAPTER 4- SERIES REACTIVE COMPENSATION</b>	<b>65</b>
4.1 FUNDAMENTALS OF SERIES COMPENSATION	65
4.1.1 Effect on Power Transfer	65
4.1.2 Series Capacitance and voltage stability	69
4.1.3 Connection of a series capacitor bank	69
4.2 CONTROLLED SERIES COMPENSATION	71
4.3 THE POSSIBILITY OF SUBSYNCHRONOUS RESONANCE (SSR)	74
4.4 CHARACTERISTICS OF SERIES COMPENSATION	75
4.5 A SUMMARY OF SERIES CAPACITIVE COMPENSATION PROPERTIES	76
Bibliography	76
<b>CHAPTER 5- VOLTAGE STABILITY MECHANISMS AND ASSESSMENT</b>	<b>77</b>
5.1 THE MAIN NSW SYSTEM	77
5.2 MECHANISMS	79
5.2.1 Characteristic Time Domain	79
5.2.2 Mechanisms events	79
5.3 STATIC AND DYNAMIC RESPONSE	80
5.3.1 Case 1	81
5.3.2 Case 2	84

5.3.3	Case 3	87
5.4	COORDINATION OF TAP-CHANGERS	89
5.5	DYNAMIC RESPONSE OF LOADS	91
5.6	VOLTAGE RESPONSE TO A BUS FAULT IN THE NSW QUEENSLAND CONNECTION	93
5.7	SLOW VOLTAGE COLLAPSE SIMULATION	95
5.8	STATIC ASSESSMENT TOOLS	96
5.8.1	Power flow	96
5.8.2	PV curves	97
5.8.3	QV curves	98
5.8.4	Optimal power flow	99
5.8.5	Contour plotting	100
5.8.6	Analysis of the power flow Jacobian matrix- Voltage Modal Analysis (VMA)	101
5.8.7	Singular Value Decomposition (SVD)	101
5.9	TRANSGRID REACTIVE PLANNING	103
	Bibliography	103
 <b>CHAPTER 6- DYNAMIC VOLTAGE INSTABILITY</b>		<b>104</b>
6.1	INTRODUCTION	104
6.2	REACTIVE POWER CONSUMERS AND SUPPLIERS	104
6.3	VOLTAGE REGULATION AND VOLTAGE STABILITY	104
6.4	DYNAMIC VOLTAGE STABILITY MODELLING	111
6.4.1	Reactive power support	111
6.5	CASE STUDY	115
6.6	FUTURE TRENDS	118
	Bibliography	118
	APPENDIX-Small signal analysis of voltage stability	119
 <b>CHAPTER 7- SHUNT CAPACITORS</b>		<b>122</b>
7.1	INTRODUCTION	122
7.2	SHUNT CAPACITOR TECHNOLOGY	122
7.3	REACTIVE POWER SUPPORT	125
7.3.1	Under and overvoltage performance of shunt capacitors	125
7.3.2	Fast switching of shunt capacitors	126
7.3.3	Limitations and benefits of post contingency shunt capacitor switching	127
7.4	DESIGN AND IMPLEMENTATION ISSUES	128
7.4.1	Voltage step changes and transients	128

7.4.2	Point on wave (POW) switching	129
7.4.3	Back to back shunt capacitor switching transients	131
7.4.4	Harmonic resonances	133
7.4.5	Harmonic impedances	137
7.4.6	Capacitor protection issues	138
7.4.7	Capacitor switching device requirements	140
7.4.8	Other considerations	141
7.5	PLANNING AND DESIGN STANDARDS	141
7.6	PRESENT PRACTICES AND FUTURE TRENDS	141

## CHAPTER 8- SERIES CAPACITORS 143

8.1	INTRODUCTION	143
8.2	SERIES CAPACITOR - DESIGN ASPECTS	143
8.3	PROTECTION OF SERIES COMPENSATED SYSTEMS	145
	8.3.1 Series capacitor overvoltage and surge protection	146
	8.3.2 Protection of the series compensated line	153
8.4	EXPERIENCE WITH SERIES CAPACITOR COMPENSATION IN THE VICTORIA POWER SYSTEM	154
	8.4.1 System capability with compensation	155
	8.4.2 Other Effects	160
8.5	SUMMARY	164
	References	164

## CHAPTER 9- SVC AND STATCOM 165

9.1	INTRODUCTION	165
9.2	SVC TECHNOLOGY	165
	9.2.1 Filter design considerations	167
	9.2.2 Voltage control considerations	169
	9.2.3 Protection System	172
	9.2.4 SVC Losses	173
9.3	SVC DYNAMIC RESPONSE AND EFFECT ON SYSTEM PERFORMANCE	175
9.4	POWERLINK DESIGN EXPERIENCE WITH SVCs	179
9.5	STATCOM TECHNOLOGY	181
	9.5.1 Examples of Application	183
	9.5.2 STATCOM control	184
	9.5.3 Modelling and Validation	186
9.6	H-BRIDGE BASED STATCOM	189
9.7	SUMMARY	191
	References	192

<b>CHAPTER 10- OPERATIONAL EXPERIENCES OF SVC INSTALLATIONS</b>	<b>193</b>
<b>10.1 THE NSW TRANSMISSION SYSTEM</b>	<b>193</b>
<b>10.1.1 Broken Hill</b>	<b>194</b>
<b>10.1.2 Kemps Creek</b>	<b>195</b>
<b>10.1.3 Lismore</b>	<b>196</b>
<b>10.1.4 Armidale</b>	<b>198</b>
<b>10.1.5 Sydney West</b>	<b>199</b>
<b>10.2 COMMISSIONING, SERVICE AND MAINTENANCE ISSUES</b>	<b>201</b>
<b>10.3 TRANSGRID'S SVC SPECIFICATION</b>	<b>206</b>
<b>10.4 NSW SVC PLANT ASSESSMENT</b>	<b>208</b>
<b>CHAPTER 11- CRITICAL COMPARISON OF TECHNOLOGIES AND SUGGESTED CONTROL STRATEGIES</b>	<b>209</b>
<b>11.1 STATIC VAR (SVC) VERSUS MECHANICAL SWITCHING (MSC) COMPENSATION</b>	<b>209</b>
<b>11.2 CAPACITOR/REACTOR BANKS SWITCHED COMPENSATION</b>	<b>210</b>
<b>11.3 CAPACITOR BANK SHORTING</b>	<b>212</b>
<b>11.3.1 BPA's CAPS installation at the Olympia substation</b>	<b>213</b>
<b>11.4 TAP CHANGER CONTROL STRATEGIES</b>	<b>214</b>
<b>11.5 SUGGESTION TO REDUCE STATIC VAR SYSTEMS COSTS</b>	<b>215</b>
<b>11.6 TRANSMISSION VERSUS DISTRIBUTED DISTRIBUTION SVCS/STATCOMS</b>	<b>216</b>
<b>11.7 GENERATOR LDC AND HIGH SIDE VOLTAGE CONTROL</b>	<b>216</b>
<b>11.8 WIDE AREA CONTROLS</b>	<b>218</b>
<b>Bibliography</b>	<b>221</b>
<b>CHAPTER 12- REACTIVE POWER CONTROLLERS</b>	<b>223</b>
<b>12.1 NEMMCOs OVERVIEW</b>	<b>223</b>
<b>12.2 THE BASSLINK HVDC CONNECTION</b>	<b>225</b>
<b>12.3 TASMANIA AC TRANSMISSION SYSTEM</b>	<b>225</b>
<b>12.4 REACTIVE POWER CONTROLLER (RPC)</b>	<b>226</b>
<b>12.5 A NEMMCO ASSESSMENT OF THE VOLTAGE BEHAVIOUR AT GEORGE TOWN</b>	<b>227</b>
<b>12.6 FILTER ISSUES</b>	<b>227</b>
<b>12.7 BASSLINK RPC EXPERIENCE</b>	<b>229</b>



<b>12.8</b>	<b>GEORGE TOWN VOLTAGE CONTROL SCHEME</b>	<b>230</b>
<b>12.9</b>	<b>FUTURE TRENDS</b>	<b>231</b>
	<b>Bibliography</b>	<b>231</b>
	<b>CHAPTER 13- PLANNING STANDARDS AND GUIDELINES</b>	<b>232</b>
<b>13.1</b>	<b>AN AUSTRALIAN PERSPECTIVE</b>	<b>232</b>
	<b>13.1.1 Systems standards for voltage control and stability</b>	<b>233</b>
	<b>13.1.2 Planning Standards across Australia</b>	<b>234</b>
	<b>13.1.3 Recent Developments</b>	<b>238</b>
	<b>References</b>	<b>239</b>
<b>13.2</b>	<b>A NORTH AMERICAN PERSPECTIVE</b>	<b>239</b>
	<b>13.2.1 Best Practices Implementation</b>	<b>239</b>
	<b>13.2.2 NERC Reliability Standards</b>	<b>240</b>
	<b>13.2.3 A selection from 55 best practices</b>	<b>243</b>
	<b>References</b>	<b>244</b>
	<b>APPENDIX to Section 13.2</b>	<b>245</b>
	<b>ABBREVIATIONS</b>	<b>247</b>
	<b>INDEX</b>	<b>248</b>

## Preface

In his opening address to the Brisbane Seminar, Simon Bartlet, CIGRE ANC Director, referred to the growing demand and the use of new generation sources located remotely from load centres, coupled with the community opposition to new transmission lines. To try and reduce these problems the transmission lines needed to be operated at increasingly higher power levels, often above their surge impedance loading. This makes the long transmission systems more vulnerable to voltage instability. The problem is more critical in long and narrow countries, such as New Zealand and to large countries, such as Australia, where remote loads are supplied through weak transmission links. Mr Bartlet also indicated the increasing consumption of reactive power (especially when lines trip), the need to provide more reactive power locally and the increasing part that renewable generation can make in this respect.

The availability of turn off semiconductors of large power ratings, coupled with the development of a Flexible AC System Transmission (FACTS) technology has made a great impact in the area of power system reactive power support. To review the state of the art, the Australasian sections of CIGRE Study Committees B4 and C1 held a two day seminar in Brisbane in May 2008. The comprehensive coverage and high standard of the contributions prompted the preparation of this book, the second in the New Zealand EPECentre Power and Energy series, in order to make the information generally available.

Subject to some introductions and clarifications, the material in the book comes largely from the seminar presentations and is somewhat based on the experience of the Australia and New Zealand power systems. However, the involvement of the main international power companies in the seminar presentations, ensures that the coverage reflects the global state of the art on the subject. The editor wishes to thank the support received from all the seminar contributors, especially Carson Taylor, the main international contributor and Nalin Pahalawaththa (chairman of the PLB4 Study Committee) and also the main local contributor. It is also appreciated the backing and financial assistance of the EPECentre (NZ), and specially Joseph Lawrence its manager, for his enthusiastic support. The editor also wishes to acknowledge the help received from Greta Arrillaga in the preparation of the manuscript and of John Arrillaga and John Mouatt for their part in the cover design

Last but not least, the author wishes to acknowledge the Members of the Power Engineering Excellence Trust (PEET), the NZ Electricity Engineers' Association (EEA) and the University of Canterbury Press for their support.