Power quality improvement using adaptive unified power quality conditioner

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POWER QUALITY IMPROVEMENT USING ADAPTIVE UNIFIED POWER QUALITY CONDITIONER

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SUMMARY

In recent years, the prolific use of power electronics devices to improve the overall energy efficiency for electrical systems has led to the deterioration of power quality (PQ) due to harmonic generation. These PQ problems, such as a distorted supply current drawn and a poor power factor at the supply side, have led to severe technical mishaps and substantial economical losses. Likewise, a stable supply voltage has always been desired for smooth operations of many industrial power plants, for example, a petrol chemical plant and a semiconductor plant. Various PQ standards have also been developed to serve as guidelines for stakeholders to adhere to. Compensating devices such as dynamic voltage restorers, uninterruptible power supplies, and active filters are also proposed to handle these PQ problems. Nonetheless, each of these devices has limited capabilities such that they can only handle one or two problems.

One of the more comprehensive devices is the Unified Power Quality Conditioner (UPQC), an integration of series and shunt active filters. The series active filter of the UPQC is employed to compensate for any distortions in the supply voltage, while the shunt active filter of the UPQC can be used to compensate for current harmonics in the load current, as well as to correct the power factor of the supply side near to unity. However, the configuration, implementation and maintenance of an effective UPQC can be complex and costly due to its enhanced capabilities. As such, this research

seeks to develop adaptive, robust and cost-effective UPQCs that can not only be implemented easily, but also be fully utilized to solve a wide range of PQ problems concurrently and efficiently.

Specifically, 2 model-based controlled UPQCs, namely the Multi-variable regulator (MVR) controlled UPQC and the H_∞ controlled UPQC, are proposed and developed in this thesis. Their control strategy will also be direct, i.e., by making the outputs of the network (load voltage and supply current), to track certain desired waveforms directly. This approach provides direct feedback to the controller and shows how well the PQ of the network outputs can be improved. Zero steady-state tracking error can be ensured if there is no modeling error. Otherwise, the controllers will seek to mitigate the negative effects introduced by any modeling error. The coupling effect between the series and shunt filters is also taken care of by the controller to enhance the robustness of the UPQC. To reduce implementation cost and complexity, digital Kalman filters are implemented in place of hardware sensors, while any control gains are calculated offline and then implemented as constant gains online. All in all, the proposed UPQCs are able to handle most power quality problems such as issues harmonic distortions, power factor correction and voltage sags/swells satisfactorily and concurrently.

Furthermore, to address increasing concerns over climate changes and energy security, this research proposes and develops a proton exchange membrane fuel cell (PEMFC) with ultra-capacitor based UPQC. This UPQC will not only handle most PQ problems but also perform load sharing with the grid supported by a hybrid

system of the PEMFC and ultra-capacitor. Another model-based controller based on the Model Predictive Control theory is also developed to control the UPQC. This results in a comprehensive UPQC that operates in a clean and green way to achieve energy efficiency, power quality, availability and reliability of the network.

TABLE OF CONTENTS

ACKNOWLEDGMENTS

SUMMARY

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

1.	INTRODUCTION	1
1.1	Motivation	1
1.2	Objectives	8
1.3	Major Contributions of the Thesis	9
1.4	Organization of the Thesis	14
2	POWER QUALITY PROBLEMS AND THEIR SOLUTIONS	17
2.1	Introduction	17
2.2	Supply Voltage Sags and Swells	19
2.2.1	Causes and effects of voltage sags	19
2.2.2	Causes and effects of voltage swells	21
2.2.3	Standards on the ride-through capability of equipment during voltage sags/swells	22

2.2.4	Solutions to voltage sags/swells and their limitations	25
2.2.5	Limitations of Dynamic Voltage Restorers.	27
2.3	Harmonic Generation and Distortions	27
2.3.1	Causes and effects of harmonics	28
2.3.2	Harmonic indices	31
2.3.3	Harmonic standard	33
2.3.4	Solutions to harmonic distortions and their limitations.	34
2.4	Supply Frequency Drifts	41
2.5	Poor Power Factor Loads	42
2.5.1	Causes and effects of poor power factor loads	42
2.5.2	Solutions to loads with poor power factor	44
2.5.3	Limitations of power factor correction devices	47
3	UNIFIED POWER QUALITY CONDITIONER	48
3.1	Introduction	48
3.2	Configuration of the UPQC	49
3.2.1	Right-shunt and Left-shunt UPQC	49
3.2.2	Inverter structure of the series and shunt active filters of the UPQC	51
3.2.3	Low-pass interfacing filters	53
3.3	Control of the UPQC	58
3.3.1	Extraction and injection of distorted components	58
3.3.1.1	A general control of the shunt active filter of the UPQC	60
3.3.1.2	A general control of the series active filter of the UPQC	64

3.3.2	Model-based control	66
4	MVR CONTROLLED UPQC WITH KALMAN FILTERS	68
4.1	Introduction	68
4.2	Modeling of the Plant	70
4.3	Control Design	74
4.3.1	Construction of the desired references	75
4.3.2	Modeling of the exogenous signals	78
4.3.3	Multi-Variable Regulator (MVR)	80
4.3.4	Kalman filters as extraction circuits and state observers	82
4.3.5	Self-charging circuit	86
4.4	Injection Circuit	90
4.5	Overall Control Configuration	91
4.5.1	Illustration of the operation of the UPQC	95
5	MODEL-BASED H_{∞} CONTROLLED UPQC	101
5.1	Introduction	101
5.2	Control Design	103
5.2.1	Design of feedforward control	105
5.2.2	Design of feedback control	109
5.3	Overall Control Configuration	117
6	A PEMFC WITH UC BASED MPC CONTROLLED UPQC	120
6.1	Introduction	120

6.2	Modeling of the Ultra-capacitor	123
6.3	Modeling of the Proton Exchange Membrane Fuel Cell	125
6.4	Model Predictive Control	129
6.5	Hybrid System of the PEMFC/UC and its Modes of Operation	133
6.5.1	Mode 1: Steady state condition	135
6.5.2	Mode 2: Sudden dip in V_{dc}	136
6.5.3	Mode 3: Sudden surge in V_{dc}	137
6.6	Overall Control Configuration	138
7	SIMULATION AND EXPERIMENTAL STUDIES	142
7.1	Introduction	142
7.1.1	Setup for simulation studies	143
7.1.2	Setup for experimental studies	145
7.2	MVR Controlled UPQC	146
7.2.1	Simulation studies	146
7.2.1.1	Simulation Test Case 1: Harmonic compensation in the supply voltage and load current with power factor correction at the supply side and the Model-based H_∞ - controlled UPQC	148
7.2.1.2	Simulation Test Case 2: Disturbances in the supply voltage	150
7.2.1.3	Simulation Test Case 3: Variations in the load demand	153
7.2.1.4	Simulation Test Case 4: Slight and unknown frequency Variations in the supply voltage	154

7.2.2	Experimental studies	158
7.2.2.1	Experimental Test Case 1: Harmonics compensation in the supply voltage and load current with power factor correction at the supply side	158
7.2.2.2	Experimental Test Case 2: Disturbances in the supply voltage	160
7.2.2.3	Experimental Test Case 3: Variations in the load demand	162
7.2.2.4	Experimental Test Case 4: Slight and unknown frequency variations in the supply voltage	163
7.3	H_{∞} controlled UPQC	165
7.3.1	Simulation studies	165
7.3.1.1	Simulation Test Case 1: Harmonics compensation in the supply voltage and load current with power factor correction at the supply side and the Model-based H_{∞} - controlled UPQC	166
7.3.1.2	Simulation Test Case 2: Disturbances in the supply voltage	167
7.3.1.3	Simulation Test Case 3: Variations in the load demand	169
7.3.1.4	Simulation Test Case 4: Slight and unknown frequency variations in the supply voltage	170
7.3.2	Experimental studies	173
7.3.2.1	Experimental Test Case 1: Harmonics compensation in the supply voltage and load current with power factor correction at the supply side	174
7.3.2.2	Experimental Test Case 2: Disturbances in the supply	174

	voltage	
7.3.2.3	Experimental Test Case 3: Variations in the load demand	175
7.3.2.4	Experimental Test Case 4: Slight and unknown frequency	176
	variations in the supply voltage	
7.4	Comparison Studies	178
7.4.1	Steady state performance	178
7.4.2	Performance under the presence of modeling errors	181
7.5	PEMFC/UC based MPC controlled UPQC	186
7.5.1	Test case 1 (Mode 1): Harmonic compensation in supply	186
	voltage and load current with power factor correction at the	
	supply side, and load sharing with the grid	
7.5.2	Test Case 2 (Modes 2 and 3): Sag in the supply voltage	191
8	CONCLUSIONS AND RECOMMENDATIONS	201
8.1	Conclusions	201
8.2	Recommendations for Further Research	206

BIOGRAPHY

LIST OF PUBLICATIONS

BIBLIOGRAPHY

APPENDICES

LIST OF FIGURES

Figure 2.1	Waveform for supply voltage sag.	19
Figure 2.2	Waveform for supply voltage swell.	22
Figure 2.3	(a) CBEMA curve, (b) ITI curve and (c) SEMI F47.	23
Figure 2.4	A DVR in a power network.	26
Figure 2.5	Supply Network with harmonic distortions.	29
Figure 2.6	IEEE Standard 519-1992 Table 10.3.	33
Figure 2.7	IEEE Standard 519-1992 Table 10.2.	34
Figure 2.8	Phase multiplication technique for harmonic compensation in the load current.	36
Figure 2.9	Shunt passive filter installed in a network	37
Figure 2.10	Shunt active filter installed in a network	38
Figure 2.11	Series active filter installed in a network	40
Figure 2.12	Waveform for frequency drift in supply voltage.	42
Figure 2.13	(a) Power factor correction at the supply side via the injection of reactive power, (b) Phasor diagram depicting the real and reactive powers of the network.	45
Figure 3.1	Simplified diagram of a UPQC.	48
Figure 3.2	Right-shunt UPQC topology.	50
Figure 3.3	Left-shunt UPQC topology.	50
Figure 3.4	(a) Topology of a half-bridge inverter; and (b) full-bridge inverter.	52

Figure 3.5	VSI of an active filter.	53
Figure 3.6	VSI with a 1 st order low pass interfacing filter.	54
Figure 3.7	A 2 nd order low pass interfacing filter.	55
Figure 3.8	Figure 3.8: An n-order LC filter.	56
Figure 3.9	Typical frequency responses of a 1 st , 2 nd and 3 rd order low pass filter with a cut-off frequency at 5000Hz.	57
Figure 3.10	General control of a UPQC in a power distribution plant.	59
Figure 3.11	Classical control approach for the series active filter of the UPQC.	60
Figure 3.12	A PI-based controller for the shunt active filter.	62
Figure 3.13	A PI-based controller to regulate the DC link of the UPQC.	63
Figure 3.14	A PI-based controller for the series active filter.	66
Figure 4.1	Equivalent single-phase representation of a power distribution plant and the UPQC.	72
Figure 4.2	MVR controller.	82
Figure 4.3	Kalman Filters as Extraction Circuits and State Observers.	85
Figure 4.4	MVR controller with Kalman Filters as Extraction Circuits and State Observers.	86
Figure 4.5	A LQR control topology for the regulation of the dc link voltage of the UPQC.	89
Figure 4.6	System block diagram of MVR-controlled UPQC with Kalman filters.	92

Figure 4.7	3-phase UPQC Configuration.	94
Figure 4.8	Switching and self-charging sequences of the UPQC.	97
Figure 5.1	FF control for the UPQC, with K/F denoting the Kalman filter.	109
Figure 5.2	Combining the pre-compensator, $W_1(s)$, the post-compensator, $W_2(s)$, and the stabilizing controller, $K_\infty(s)$, into an overall feedback controller.	110
Figure 5.3	Magnitude plot of $W_2(s)$ with 3 peaks at 50Hz, 150Hz and 250Hz.	112
Figure 5.4	Robust stabilization of the weighted plant in H_∞ loop-shaping	114
Figure 5.5	FB control for the UPQC, with FB/C denoting the FB controller.	115
Figure 5.6	Overall FF/FB control for the UPQC.	116
Figure 5.7	Overall configuration of the UPQC, with K/F denoting the Kalman filter and FB/C denoting the feedback controller.	118
Figure 6.1	An ultra-capacitor model.	123
Figure 6.2	A PEMFC model.	126
Figure 6.3	PEMFC polarization curve (top) and power curve (bottom).	129
Figure 6.4	The hybrid system of PEMFC/UC.	134
Figure 6.5	Mode 1 operation of the hybrid system.	136
Figure 6.6	Mode 2 operation of the hybrid system.	137
Figure 6.7	Mode 3 operation of the hybrid system.	138

Figure 6.8	System block diagram of MPC-controlled UPQC with dc link supported by the hybrid system of PEMFC/UC.	140
Figure 7.1(a)	A single phase power distribution system with UPQC installed.	145
Figure 7.1(b)	A hardware development of a single-phase power distribution system with UPQC installed.	146
Figure 7.2	Charging of the dc link voltage.	147
Figure 7.3	Simulation Test Case 1: Voltage waveforms under a distorted supply voltage with a nonlinear load under steady state condition.	149
Figure 7.4	Simulation Test Case 1: Actual harmonic spectrums of the supply voltage and load current (shaded bars) and the harmonic spectrums extracted by the exogenous Kalman filter (non-shaded bars).	150
Figure 7.5(a)	Simulation Test Case 2: Voltage waveforms under sag and swell conditions.	152
Figure 7.5(b)	Simulation Test Case 2: Injected voltage and current waveforms under sag and swell conditions.	152
Figure 7.6(a)	Simulation Test Case 3: Voltage and current waveforms under variations in the load demand.	154
Figure 7.6(b)	Simulation Test Case 3: Injected voltage and current waveforms under variations in the load demand.	154
Figure 7.7	Simulation Test Case 4: Voltage and Current waveforms under frequency variations in the Supply Voltage.	156

Figure 7.8	Simulation Test Case 4: Harmonics Spectrum of voltages & currents when v_s is at 47Hz.	156
Figure 7.9	Simulation Test Case 4: Harmonics Spectrum of voltages & currents when v_s is at 53Hz.	157
Figure 7.10	Experimental Test Case 1: Voltage waveforms under a distorted supply voltage with a nonlinear load under steady state condition.	159
Figure 7.11	Experimental Test Case 1: DC link voltage.	159
Figure 7.12	Experimental Test Case 1: Actual harmonic spectrums of the supply voltage and load current (shaded bars) and the harmonic spectrums extracted by the exogenous Kalman filter (non-shaded bars).	160
Figure 7.13	Experimental Test Case 2: Voltage waveforms under sag and swell conditions.	161
Figure 7.14	Experimental Test Case 3: Load current (top) and supply current (bottom) waveforms for various load demands.	162
Figure 7.15	Experimental Test Case 4: Voltage and Current waveforms under frequency variations in the Supply Voltage.	164
Figure 7.16	Experimental Test Case 4: Harmonics Spectrum of voltages & currents when v_s is at 47Hz.	164
Figure 7.17	Experimental Test Case 4: Harmonics Spectrum of voltages & currents when v_s is at 53Hz.	165
Figure 7.18	Simulation Test Case 1: Voltage waveforms under a	167

	distorted supply voltage with a nonlinear load under steady state condition.	
Figure 7.19(a)	Simulation Test Case 2: Voltage and current waveforms under sag and swell conditions.	168
Figure 7.19(b)	Simulation Test Case 2: Injected voltage and current waveforms under sag and swell conditions.	168
Figure 7.20(a)	Simulation Test Case 3: Voltage and current waveforms under variations in the load demand.	169
Figure 7.20(b)	Simulation Test Case 3: Injected voltage and current waveforms under variations in the load demand.	170
Figure 7.21	Simulation Test Case 4: Voltage and Current waveforms under frequency variations in the Supply Voltage.	172
Figure 7.22	Simulation Test Case 4: Harmonics Spectrum of voltages & currents when v_s is at 47Hz.	172
Figure 7.23	Simulation Test Case 4: Harmonics Spectrum of voltages & currents when v_s is at 53Hz.	173
Figure 7.24	Experimental Test Case 1: Voltage waveforms under a distorted supply voltage with a non-linear load under steady state condition.	174
Figure 7.25	Experimental Test Case 2: Voltage waveforms under sag and swell conditions.	175
Figure 7.26	Experimental Test Case 3: Load current (top) and supply current (bottom) waveforms for various load demands.	176
Figure 7.27	Experimental Test Case 4: Voltage and Current	177

waveforms under frequency variations in the Supply
Voltage.

Figure 7.28	Figure 6.28: Experimental Test Case 4: Harmonics Spectrum of voltages & currents when v_s is at 47Hz.	177
Figure 7.29	Experimental Test Case 4: Harmonics Spectrum of voltages & currents when v_s is at 53Hz.	178
Figure 7.30	Simulation Test Case 1: Voltage and current waveforms.	187
Figure 7.31	Simulation Test Case 1: Real power waveforms.	189
Figure 7.32	Simulation Test Case 1: Ultra-capacitor power waveform.	190
Figure 7.33	Simulation Test Case 1: DC link voltage.	190
Figure 7.34	Simulation Test Case 2: Supply voltage and load current waveforms.	195
Figure 7.35	Simulation Test Case 2: Load voltage waveforms.	196
Figure 7.36	Simulation Test Case 2: Supply current waveforms.	197
Figure 7.37	Simulation Test Case 2: DC link voltage waveforms.	198
Figure 7.38	Simulation Test Case 2: PEMFC power waveforms.	199
Figure 7.39	Simulation Test Case 2: UC power waveform.	200

LIST OF TABLES

Table 2.1	Harmonic voltage spectrum of a typical distorted voltage waveform	32
Table 6.1	System Parameters of the UC Bank	124
Table 6.2	Fuel Cell and Operating Parameters	128
Table 7.1	Values of the components of the UPQC	144
Table 7.2	Line impedance and VSI impedances of the UPQC	144
Table 7.3	Steady state performance in harmonics compensation for the different UPQCs	180
Table 7.4	Steady state performance in harmonics compensation for the different UPQCs under modeling errors	182
Table 7.5	Actual Values of the Components of the UPQC	183
Table 7.6	Actual Line Impedance and VSI Impedances of the UPQC	183
Table 7.7	Power Quality Fluctuations During Frequency Variations	185
Table 7.8	Different Control Configurations of UPQC	191

LIST OF SYMBOLS AND ABBREVIATIONS

The following symbols and abbreviations are used throughout the thesis:

C	Capacitor of the dc link
C_{sh}	Capacitor of the shunt low-pass interfacing filter
C_{se}	Capacitor of the series low-pass interfacing filter
d	Reference signals for y to track
e	Tracking error between y and d
f	Fundamental frequency, 50Hz
F	Feedback gain of the MVR control law
H_∞	H-infinity
$i_{C_{sh}}$	Leakage capacitor current of the shunt low-pass interfacing filter
i_{dc}	Charging current for the regulation of the dc link voltage
i_{inj}	Instantaneous injected component of the shunt active filter of the UPQC
i_{inj}^*	Reference for the instantaneous injected current component of the shunt active filter of the UPQC
i_L	Instantaneous load current of a power distribution system
i_{L_f}	Instantaneous fundamental component of i_L
I_{L_f}	Amplitude of i_{L_f}
$i_{L_f,p}$	Load instantaneous fundamental phase current

$i_{L_f,q}$	Load instantaneous fundamental quadrature current
$I_{L_f,p}$	Amplitude of $i_{L_f,p}$
$I_{L_f,q}$	Amplitude of $i_{L_f,q}$
i_{L_h}	Instantaneous harmonic component of i_L
I_{L_h}	Amplitude of i_{L_h}
i_S	Instantaneous supply current of a power distribution system
i_S^*	Reference for i_S to track
$K_\infty(s)$	Stabilizing controller of u_{fb}
L_l	Line inductor of a power distribution system
L_{se}	Inductor of the series low-pass interfacing filter
L_{sh}	Inductor of the shunt low-pass interfacing filter
LQR	Linear Quadratic Regulator
MPC	Model predictive control
MVR	Multi-variable regulator
PEMFC	Proton exchange membrane fuel cell
P_L	Fundamental real power consumed by load
P_S	Fundamental real power delivered by supply side
P_{FC}	Real power delivered by fuel cell
P_{UC}	Real power delivered by Ultra-capacitor
Q_L	Fundamental reactive power consumed by load
Q_S	Fundamental reactive power delivered by supply side

R_l	Line resistance of a power distribution system
R_{se}	Inverter losses of series active filter of UPQC
R_{sh}	Inverter losses of shunt active filter of UPQC
THD	Total Harmonic Distortion
u_1	Control signal for the series active filter of the UPQC
u_2	Control signal for the shunt active filter of the UPQC
U	Feedforward gain of the MVR control law
UC	Ultra-capacitor
u_{ff}	Feedforward control law of the H_∞ controlled UPQC
u_{fb}	Feedback control law of the H_∞ controlled UPQC
u_{inj}	Actual control signals for the UPQC
V_{dc}	DC link voltage of the UPQC
V_{dc}^*	Reference DC link voltage of the UPQC
v_{inj}	Instantaneous injected component of the series active filter of the UPQC
v_{inj}^*	Reference for the instantaneous injected voltage component of the series active filter of the UPQC
v_L	Instantaneous load voltage at the point of coupling (PCC) of a power distribution system
v_L^*	Reference for v_L to track
v_S	Instantaneous supply voltage of a power distribution system
v_{S_f}	Instantaneous fundamental component of v_S
V_{S_f}	Amplitude of the v_{S_f}

v_{S_h}	Instantaneous harmonic component of v_S
V_{S_h}	Amplitude of the harmonic component of v_S
VSI	Voltage source inverter
v_z	Instantaneous voltage drop across the line impedance of a power distribution system
$W_1(s)$	Pre-compensator of u_{fb}
$W_2(s)$	Post-compensator of u_{fb}
x	State of the UPQC model
X	Regulator gain of the MVR control law
y	Outputs of the UPQC model
ξ	Exogenous state vector
ξ_w	Exogenous state vector of v_S and i_L
ξ_d	Exogenous state vector of the reference signals d
θ_{L_f}	Phase angle difference between v_{S_f} and i_{L_f}
θ_{L_h}	Phase angle difference between v_{S_f} and i_{L_h}
θ_{S_h}	Phase angle between v_{S_f} and v_{S_h}
ω	Supply frequency, $2\pi f$
ω_{co}	Cut-off frequency

CHAPTER 1

INTRODUCTION

1.1 Motivation

Today, the employment of advanced power electronics for industries, services and products has been increasing rapidly [1-3]. With the increasing use of power electronics, certain power quality problems due to the generation of harmonics occur in power distribution systems [4-7]. For example, the result of switching actions of power converters is a distorted supply current experienced. The distortion of the supply voltage at the Point of Common Coupling (PCC) also occurs because the supply voltage at the PCC, being the difference between the source voltage and the voltage across the source impedance, becomes distorted when a nonlinear load connected at the PCC injects a distorted current into the supply network. Customers at the PCC will experience this distorted voltage. Overheating of power factor correction capacitors, motors, transformers and cables, and thermal tripping of protective devices may occur. In addition, a device that requires a sinusoidal voltage waveform for the proper operation on its circuitry when installed at the PCC may mal-operate. Furthermore, the growth in the use of nonlinear power electronics loads, such as static rectifiers, adjustable speed drives, dc/ac converters, etc., has indiscriminately increased the amount of voltage and current distortions in power distribution systems, which in turns degrades the power quality of power supply. Power factor at the supply side is affected as well.

Likewise, the operation of manufacturing plants like petrochemical plants and semiconductor plants is highly dependant on a stable supply voltage. The supply voltage has to be free from any voltage sag or swell [8], while concurrently, be maintained at a normally fixed frequency. Voltage sags, which can be caused by a short circuit in the power system or energization of heavy loads, etc., can cause disruptions to manufacturing plants, bringing about substantial financial losses [9-13].

Similarly, voltage swells [8], [14], though not as common as voltage sags, which can be caused by system faults, may cause memory or data loss, shut down or damage to equipment. Frequency drift of the supply voltage, due to loading or unloading and erratic operations of generators, may result in data corruption, hard drive crash or program failure in computers. All in all, these power quality problems have become a great concern for both utilities and customers [15]-[17].

To tackle these problems (so that adherences to power quality standard, i.e., IEEE Standard [18]-[19] can be achieved), there is a need to install compensating devices. Uninterruptible power supplies [20]-[21], and dynamic voltage restorers [22-23] can be used to compensate for any sags/swells or distortions in the supply voltage; the passive [24]-[25] and active filters [26]-[27] can be used to compensate for harmonic distortions inherent in the supply voltage and load current; capacitors banks can be installed at the load side to correct the power factor at the supply side. As illustrated, the capabilities of these devices are usually limited as they can only solve one or two of the power quality problems. Hence, it may be costly and inefficient for a consumer to install each of these devices to improve the power quality. Even though one may

choose to install all these compensating devices to solve these power quality problems concurrently, the inherent coupling effects between all these devices when installed together cannot be neglected.

The Unified Power Quality Conditioners (UPQC) [28]-[29], which is an integration of series and shunt active filters, has the capability of improving power quality at the point of installation in power distribution systems or industrial distribution systems. The series active filter of the UPQC is employed to compensate for any distortions in the supply voltage, while the shunt active filter of the UPQC is used to compensate for current harmonics in the load current, as well as to correct the power factor of the supply side near to unity.

Furthermore, recent research works [30]-[36] have also shown that the UPQC can be utilized to solve most of the power quality problems. The objectives now are to obtain reliable control algorithms and fast response procedures to get the proper switch control signals so that the UPQC can be optimized to eliminate most of the power quality problems in a power distribution system. To remain competitive, the employment of UPQC has to be cost effective, while maintaining their robustness and efficiency. As a result, modern control theories are considered and adopted to design control circuits for power quality devices.

To date, different control approaches for the UPQC have been proposed. The most common approach [30]-[36] focuses on extracting and injecting distorted components, e.g., harmonics, (from sampled supply voltage and load current) into the network. This

aims to make the load voltage and supply current undistorted in an indirect approach. However, there is no feedback of the load voltage and supply current in these designs to show that they are undistorted. From this point of view, these designs are open-loop control. Hence, most of these schemes, such as proportional–integral (PI)/proportional–integral–derivative (PID), hysteresis control, are not supposed to eliminate the steady-state error totally when the system is subjected to periodic references and disturbances.

Also, for this control approach (i.e., the approach that focuses on extracting and injecting distorted components, e.g., harmonics, into the network), the shunt and series filters of the UPQC are usually controlled independently by their individual controllers. However, the UPQC is a coupled system, such that there is a coupling effect between its series and shunt active filter. As such, controlling the series and shunt active filter separately may cause the performance of the UPQC to suffer. In addition, if there is a drift in the operating frequency, the extraction of the harmonic components can become inaccurate. Furthermore, this control approach often neglects any voltage drop across the line impedance and the voltage source inverters (VSIs) of the active filters. This can result in the injection of inaccurate distorted components. For these reasons, this type of control approach might not result in the best performance of the UPQC.

Another approach is the model-based control [38]–[41]. In this approach, the UPQC is modeled and is controlled by a coordinated model-based controller. The coupling effect between the active filters of the UPQC as well as any voltage drop is modeled into the UPQC model. This can result in the optimization of the performance of the UPQC in

principle. However, the cost and complexity of the UPQC will increase due to the additional sensors or high-speed digital signal processor (DSP) needed. Moreover, any modeling error can be detrimental to its performance. Also, zero steady-state error cannot be guaranteed in some of these model-based control schemes.

In view of the above, the author is motivated to develop UPQC that has the capabilities to solve a wide range of power quality problems, which include:

- 1) Harmonic generation due to a non-linear load current drawn;
- 2) A distorted load voltage, experienced by consumers at the PCC;
- 3) Voltage sags/swells;
- 4) Poor power factor at the supply side; and
- 5) Frequency drifts in the supply voltage.

Concurrently, the proposed UPQC, when installed, should also **help to** ensure that network stability can be maintained satisfactorily. It should facilitate periodic reference tracking and disturbance rejection as well so that it can be used to solve most of the power quality problems concurrently. The proposed UPQC should also take into account the coupling effect between the series and shunt active filters as well as any voltage drop in the system, to generate accurate switching signals for its active filters, so that its performance can be optimized.

By incorporating many functions into the UPQC, the UPQC may be costly and inefficient to be maintained. Nonetheless, the thesis discusses methodologies that seek to optimize the capabilities and performance of the UPQC, while minimizing its cost.

In view of all the above, this thesis first employs a model-based controller – the multi-variable regulator (MVR) [42]-[43] with Kalman filters [44]-[46] to generate the control signals for the series and shunt active filters of the UPQC. The MVR controller will ensure the global stability for the plant, and also facilitates periodic reference tracking and disturbance rejection. In this way, the load voltage and supply current of the plant can be made to track desired sinusoidal waveforms (for harmonic compensation and power factor correction). Disturbances such as variations in the supply and load sides will also be rejected. The UPQC is also highly responsive to abrupt changes in the operating conditions, i.e., voltage sag/swell as well as changes in the load demand. Furthermore, the use of Kalman filter as a state observer relaxes the requirement of numerous state measurements. This reduces sensory circuit hardware and manufacturing and maintenance costs. To minimize the complexity of the UPQC, the gains of the controller and the Kalman filters are calculated offline and then implemented as constant gains online. This coordinated controller is able to handle the coupling effect between the active filters as well as any voltage drop in the system. However, certain modeling error, like frequency drift of the supply voltage, can be detrimental to the performance of the UPQC.

As such, this thesis further extends the above work to develop a H_∞ [47]-[48] model-based feedforward/feedback controller for the UPQC. Then, the feedforward control is applied to make the model outputs, i.e., the load voltage and the supply current, to track certain desired waveforms. It can ensure zero steady-state tracking error if there is no modeling error. Otherwise, the negative effects introduced by any modeling error can be mitigated by the feedback control simultaneously. In other words, it has the

advantages of the above method while is also capable to mitigate the negative effects of any modeling error.

Thus, this thesis provides modelling of the UPQC from the theoretical point of view using multi-input mutli-output (MIMO) state-space representation. The developed models provide the basis for controller design of UPQC, thus providing an overall solution to a variety of power quality problems encountered in a power distribution system. All in all, this research proposes 2 model-based controlled UPQCs, which are called the MVR controlled UPQC and the H_∞ controlled UPQC in this thesis.

In addition, increasing oil prices and concerns over climate changes and energy security warrants the need for sustainable energy technologies. One of these technologies is the proton exchange membrane fuel cell (PEMFC) [49]-[52]. PEMFC which chemically combines the hydrogen and oxygen to produce electrical power is hybridized with secondary storage devices [52]-[53] like the flywheel, battery and ultra-capacitor (UC) are being deployed as transporters and uninterruptible power supplies today. Among these storage devices, UC [54]-[55] promises one of the best dynamic responses and can be charged and discharged instantly and over numerous cycles.

To enhance the performance of the UPQC and in a clean and greener way, this research proposes the incorporation of a hybrid system of the PEMFC and the UC with the UPQC. The overall UPQC will be able to concurrently achieve power quality improvement and perform load sharing with the incoming grid. Adopting the multi-

input-multi-output (MIMO) model of the UPQC, Model Predictive Control (MPC) [56] which has the capability to handle hard constraints is designed as a controller for the UPQC. This results in a comprehensive solution to improve the energy efficiency, power quality, availability and reliability of the network in a cleaner and greener approach.

1.2 Objectives

The objective of this research is to design and develop a UPQC that is capable to concurrently handle a wide range of power quality problems. To achieve this objective, the proposed UPQC is robust and adaptive to variations and disturbances in the supply side and load demand. The proposed UPQC is also cost effective and requires minimal maintenance.

The first stage of the research is to perform literature review on the various power quality problems and their causes and effects. Developments in the standards for the mitigations of these problems are also discussed. Solutions to solve these power quality problems are also reviewed. The performances and limitations of these solutions are also studied to understand the need to develop a single comprehensive solution – UPQC, to handle these power quality problems concurrently. All these factors are used to understand power quality and to define the scope of compensating capabilities of the proposed UPQC in this research.

The second stage of the thesis reviews the UPQC comprehensively. The different topologies, and associated devices, such as the different low pass interfacing filters and the UPQC structures, are reviewed. The different control approaches are also studied to understand their strengths and weaknesses. All these factors are used to define the UPQC topologies as well as the control strategies/schemes for the UPQC.

The third stage of the thesis discusses the research and development works on UPQC. These include:-

1. Mathematical modeling of the UPQC;
2. Development of the MVR controlled and the H_∞ controlled UPQCs;
3. Development of the MPC PEMFC/UC based UPQC;
4. Simulation studies of the UPQCs;
5. Hardware prototyping of a 1kVA power distribution plant (with both linear and non-linear loadings) and the UPQC topology;
6. Experimental verifications of the UPQCs; and
7. Comparison studies of the proposed UPQCs and the PI controlled UPQC.

1.3 Major Contributions of the Thesis

The main contributions of this thesis are:

- 1) Modeling of the UPQC - In most existing models of the UPQC, a 1st order low-pass interfacing filter is usually adopted together with an isolation transformer for

the shunt active filter, while a 2nd order low-pass interfacing filter is used for the series active filter.

In this thesis, 2nd order low-pass interfacing filters for both the series and shunt active filters are proposed. This will eliminate the need for the isolation transformer and also enhance the capability of the UPQC to handle higher order of harmonics that may be present in the network. This thesis also further develops a single-phase representation and a mathematical model for the proposed UPQC. This mathematical model will be used to design model-based controllers to provide a coordinated and robust control for the UPQC. Furthermore, this mathematical model may also be used as a framework for future researches on the UPQC.

- 2) The development of the MVR controlled UPQC - A Multi-variable regulator (MVR) as a model-based state-feedback controller is designed and developed for the control of the UPQC. Most conventional designs focus on extracting and injecting distortions, e.g., harmonics, in order to ‘clean’ the load voltage and supply current in an indirect approach. However, the strategy of this controller facilitates periodic reference tracking and disturbance rejection, while ensuring global stability for the plant. In other words, the load voltage and supply current of the plant are made to track desired sinusoidal waveforms directly to handle a wide range of PQ problems concurrently, like harmonic distortions and poor power factor. Disturbances such as variations in the supply and load sides (e.g., voltage sag/swell and sudden changes in the load demand) will also be rejected.

In addition, there is feedback of the load voltage and supply current to the controller for optimization such that zero steady state error can also be guaranteed in principal, in the absence of any modeling error. This is also a coordinated control for the filters such that the coupling effect between the filters and any voltage drop in the system can be taken care of in the control design.

- 3) The development of the H_∞ controller UPQC - To handle certain modeling error that the MVR controlled UPQC is able to handle satisfactorily, the H_∞ controlled UPQC is proposed. A H_∞ feedforward/feedback controller that combines the Linear Regulator Theory and the Repetitive Control with H_∞ loop-shaping is proposed and developed to control the UPQC. The feedforward control takes advantages of the Linear Regulator Theory to guarantee zero steady-state error in principle. In the presence of any modeling errors, the H_∞ based feedback control ensures that the UPQC maintains satisfactory performance. In addition, the loop-shape of the feedback control is designed to provide an overall robust stabilization.

All in all, the H_∞ controlled UPQC has the advantages of the MVR-based UPQC while maintaining satisfactory performance in the presence of any modeling error.

- 4) A Kalman filter-based state-observer for estimating the states of the UPQC is designed and developed. This is carried out so that a state-observer on a software domain can be used in place of hardware sensors to reduce cost and maintenance. Moreover, the states obtained from the state-observer can be used effectively to

design the MVR controlled UPQC and the H_∞ controlled UPQC in this research or any other model-based controlled UPQC.

- 5) In order for the active filters of the proposed UPQC to operate without relying on external DC supplies, a Linear Quadratic Regulator (LQR)-based charging circuit is designed and developed. It will essentially be used to maintain the voltage of the DC capacitors of the active filters at the desired level (as the capacitors must be charged constantly) so that their energy will not be depleted. This eliminates the need to have DC power supply and results in lowering the cost of UPQC.

Furthermore, this proposed charging circuit can easily provide better charging characteristics, e.g., no overshoot, fast settling time, than other conventional charging methodologies, e.g., a PI-based charging circuit.

- 6) To address concerns over climate changes and energy security, this research also proposes the integration of a hybrid system, consisting of a proton exchange membrane fuel cell (PEMFC) and an ultra-capacitor (UC) with the UPQC so that the overall UPQC is able to handle a wide range of power quality (PQ) problems and perform load sharing with the grid. This not only enhances the functions of the UPQC but also ensures higher network availability, reliability and stability. Model Predictive Control (MPC), which takes into account the system dynamics, constraints and control objectives, is used to control the UPQC. The hybrid system is also generic in nature and can be used with other UPQCs to enhance their performances and capabilities.

- 7) A 1kVA power distribution system, with both linear and non-linear loads, and the UPQC hardware topology is developed. This provides a test bed for the experimental verification of the proposed and other existing UPQCs. A DSP-based programmable voltage source is also developed to simulate any forms of distorted voltage waveforms that can be experienced in industries. Dimmer loads are used to stimulate the different THD contents and load demands. The UPQC topology consists of an integration of the active series and shunt filters. Each of these filters is a half-bridge insulated gate bipolar transistor (IGBT) inverter, sharing the same DC-link. The controller is implemented on a DSP-platform, which is easily configurable for future modification and enhancement.
- 8) Various compensating capabilities are incorporated into the functionalities of the UPQC, so that the proposed UPQC in this thesis can concurrently handle a wide range of power quality problems. The capabilities of the proposed UPQC in this thesis are:
- Harmonic compensation of a distorted supply voltage;
 - Harmonic compensation of a non-linear load current drawn;
 - Compensation of voltage sags/swells at the supply side;
 - Power factor correction at the supply side; and
 - Compensation of frequency drifts at the supply side.

The proposed UPQCs in this research will be robust and adaptive to variations and disturbances in the supply side and the load demand, so that they can concurrently handle several power quality problems. The proposed controlled UPQCs are also able

to take into account the coupling effects of the active filters of the UPQCs and any voltage drop inherent in the network to optimize the performance of the UPQCs. The overall UPQC will also be cost effective and require minimal maintenance.

1.4 Organization of the Thesis

There are seven chapters in this thesis. In Chapter 1, the motivation, the objectives and the major contributions of the thesis are presented.

In Chapter 2, the history on power quality and some fundamentals on the power quality problems are discussed to provide a better understanding of power quality. The impacts of these power quality problems on the different stakeholders are also discussed. In addition, the different standards and regulations pertaining to the different power quality problems are also reviewed and discussed. Current and conventional solutions that are developed to resolve these power quality problems (so that adherence to these standards and regulations can be achieved) are also discussed. These solutions are compared in terms of their operating performances, limitations and compensating capabilities to resolve power quality problems.

In Chapter 3, the integration of the shunt and series active filters into UPQC is presented. The strengths and drawbacks of the UPQC over existing power quality solutions are also discussed to illustrate the potentials of the UPQC to handle a wide range of power quality problems. Then, the different configurations of the UPQC, i.e.,

the right shunt and left shunt UPQC, are discussed to highlight their advantages and disadvantages. The different inverter topologies and low-pass interfacing filters for the shunt and series active filters are also discussed. Existing control strategies/schemes for the UPQC are also reviewed to provide better understandings and insights into their strengths and limitations. All these factors will be used to determine the overall topology and the compensating capabilities of the UPQC, and the control approach to be adopted in this research.

In Chapter 4, the mathematical model of the proposed UPQC topology is first developed. Then, the design of a MVR controlled UPQC using the proposed mathematical model and Kalman filters is discussed and detailed. Next, the design of the LQR-based self charging circuit is discussed and incorporated in the overall controller so that the proposed UPQC can operate without relying on DC supplies. The strengths and drawbacks of the MVR-based UPQC are also discussed.

In Chapter 5, the proposed development in Chapter 4, e.g., the mathematical model and the Kalman filter, are further extended and used to design the H_∞ controlled UPQC. This H_∞ controlled UPQC has the advantages of the MVR controlled UPQC and is also able to overcome its drawbacks. This will result in a complete solution for the operation of a UPQC from the control theoretic point of view.

In Chapter 6, the design of the PEMFC/UC based MPC controlled UPQC is discussed. Firstly, the modeling of the UC and the PEMFC is detailed. Then, the design

of the MPC as a controller for the UPQC is discussed. The hybrid system of the PEMFC and UC and its different operational modes are then presented.

In Chapter 7, different test cases are first designed to evaluate the operating performances of the MVR controlled and H_∞ controlled UPQCs. Simulation studies on these test cases are then performed to verify the performances of the proposed UPQCs. Then, similar experimental studies on a DSP platform are performed to evaluate and verify the effectiveness of the proposed UPQCs in practice. The simulation and experimental results obtained are also discussed and compared. Then, comparison studies of the performance among the MVR controlled and H_∞ controlled UPQCs, and one general UPQC will be discussed. Illustrative examples of the PEMFC/UC based MPC controlled UPQC are then presented to verify its performance.

Last but not least, Chapter 8 concludes the contents of this thesis and recommends tasks for future research.

CHAPTER 2

POWER QUALITY PROBLEMS AND THEIR SOLUTIONS

2.1 Introduction

According to IEEE Standard Dictionary of Electrical and Electronics Terms, power quality is defined as “the concept of powering and grounding sensitive electronic equipment in a manner that is suitable to the operation of that equipment.” Alternatively, power quality may also be defined as “the measure, analysis, and improvement of bus voltage, usually a load bus voltage, to maintain that voltage to be a sinusoid at rated voltage and frequency.”

In short, power quality disturbances are any deviations from the ideal waveforms of the voltage and current in a network of:

- a. constant magnitude at the system nominal value;
- b. constant frequency at the system nominal value; and
- c. perfectly sinusoidal.

Power quality has never been an important concern till 1980. This is because from 1960-70, the primary concern revolved around the availability of electrical supply. However, by 1980, reliability of the electrical supply has reached 99.9999% for developed countries and the loads installed during these times were mainly linear loads

and introduced little pollutions to the network. They include:

- a. Motor loads
- b. Resistive heating loads
- c. Melting plants

Thus power quality is not a primary concern till 1980. However, from 1970-1980, there was an energy crisis [1]-[3]. This brought about a price hike in oil, which prompted increasing emphasis on the system efficiency. This led to a growth in the usage of power electronic devices or loads that were driven by power electronics [4]-[7]. Although they promise high operational efficiency, they cause distortions, or degrade the power quality in power systems. Some of these devices or loads are:

- a. Converter loads (e.g., switched-mode power supplies
- b. Light dimmers
- c. Arching loads (e.g., furnaces, smelters)

Furthermore, electrical equipment or processes are interconnected together in the network. Hence, they are exposed to any disturbances that may occur in the network. For example, failure of an equipment or process due to degradation in the power quality can have important consequences on other equipment or processes. This can cause inconvenience and/or financial losses to them. Thus, there is an increasing awareness to improve the power quality in power systems, in addition to maintaining reliable power supply.

To define precisely the compensating capabilities of the UPQC in this thesis, a

literature review of the common power quality problems is carried out. This chapter discusses about the power quality problems and their causes and effects. The solutions, i.e., commercially available products and current researches, to solve these power quality problems will be discussed. The merits and drawbacks of these solutions will also be reviewed.

2.2 Voltage Sags/Swells

2.2.1. Causes and effects of voltage sags

A voltage sag or dip is a decrease to between 0.1 to 0.9 pu in rms voltage at the power frequency for durations from 0.5 cycle to 1 min [8]. A sag of 30% of the nominal voltage occurring from $t=0.06s$, lasting for 5 cycles before the voltage is restored to its pre-sag waveform is depicted in Figure 2.1.

Figure 2.1: Waveform for supply voltage sag.

The causes for voltage sag include:-

a. Single-line-ground (SLG) fault

During a SLG fault, the magnitude of the supply voltage will drop, leading to voltage sag. The magnitude of the drop depends on the severity of the SLG fault, while the duration of the drop depends on the time between the time when the fault is initiated and the time the fault is cleared. This usually lasts about 4 to 6 cycles.

b. Energisation of large loads that draw high starting current

During the starting of motor, a large starting current is drawn from the supply, e.g., induction motor draws between 6-8 times of its full load current during starting. This will cause a large voltage drop in the line which results a voltage sag to appear at the motor side.

c. Switching off capacitor bank

The switching off large capacitor banks may result in voltage sag. As a result, certain problems will surface. Firstly, in an event of voltage sag, sensitive equipment that requires a stable voltage supply may malfunction. Voltage sag can also cause some protective devices to trip when its rms value drop below certain limit, i.e., 90% for more than one to two cycles, which may result in shutting down of certain equipment or facilities. Although this voltage sag may be transient or happen for a very short period of time, all the above can result in a halt to production lines [9]-[11], resulting in huge economical losses [12]-[13]. Other effects of voltage sag include loss of data, loss

in computer systems, premature hardware failure and erratic behavior in some equipment.

2.2.2 Causes and effects of voltage swells

A voltage swell is an increase to between 1.1 to 1.8 pu in rms voltage at the power frequency for durations from 0.5 cycles to 1 min [8]. A swell of 30% of the nominal voltage occurring from $t=0.06s$, lasting for 5 cycles before the voltage is restored to its pre-swell waveform is depicted in Figure 2.2. As with sags, swells are usually associated with system fault conditions, but not as common as voltage sags. The causes for voltage swell include:

- SLG fault: In an event of a SLG fault, there may be a temporary rise in the unfaulted phases. The swell can be more severe for ungrounded systems, i.e., 1.73 p.u. of the phase voltage, because unfaulted phase voltages appear to line voltages with respect to the faulted phase.
- Switching off of large loads.
- Switching on of capacitor banks.

Analyses and modeling of the voltage swell phenomenon have been presented in [14]. During a voltage swell, computer systems may experience memory loss, data errors, flickering lights and equipment shut-off and potentially damages the hardware. Although this voltage swell may happen for a very short period of time, its effects are serious and are further discussed in [15]-[17].

Figure 2.2: Waveform for supply voltage swell.

2.2.3 Standards on the ride-through capability of equipment during voltage sag/swell.

In view of this power quality problem, standards concerning the ride-through capability of the equipment have been developed to examine the immunity of equipment to supply voltage sags. They are IEEE standard [18] using the Computer Business Equipment Manufacturer's Association (CBEMA) curve for IT equipment, Information Technology Industry Council (ITIC) standard using ITI curve for computer and telecommunication equipment, and Specification for Semiconductor Processing Equipment Voltage Sag Immunity (SEMI) F47 standard for microprocessor, process controller and programmable logic controller. Figure 2.3(a), (b) and (c) show the CBEMA curve, the ITI curve and the SEMI F47 curve.

The CBEMA curve was originally developed by the Computer Business Equipment Manufacturers Association. In Figure 2.3(a), the different curves represent the withstand capability of computers in terms of the magnitude and duration of the voltage

disturbance, where the upper curves and the lower curves define the voltage tolerance envelope that equipment can withstand and continue to operate with respect to the fault cycles. The CBEMA curve has become the standard for industries to define the capability of various loads and devices for protection from power quality variations.

In December 1994, the CBEMA curve was changed to ITI curve. As shown in Figure 2.3(b), the ITI curve is a digitized version of CBEMA curve. It covers three regions, namely no interruption in function region, no damage region and prohibited region. Using SEMI F47, industries, i.e., semiconductor manufacturers, obtain the voltage sag immunity standard for their equipment - all equipment is required to operate in the region above the bolded line as shown in Figure 2.3(c). This standard, if adopted rightfully, is expected to eliminate more than 90% of the power quality problems for semiconductor plants.

(a)

(b)

(c)

Figure 2.3: (a) CBEMA curve, (b) ITI curve and (c) SEMI F47.

2.2.4 Solutions to voltage sag/swell.

Primarily, voltage sag occurs when there is a sudden overloading or a short circuit. Hence, past effort to solve voltage sags usually involve disconnecting some of the loads installed in order to meet the current rating of the supply. Also, on-line / stand-by uninterruptible power supply (UPS) [20]-[21], [57]-[60] can be installed to provide the additional power so that the supply voltage can be restored to its pre-sag level. However, the use of UPS can be expensive and lossy.

On the other hand, the effects of voltage swell have not been studied so closely. As noted in this chapter, a prolonged voltage swell can have disastrous effects to equipment. For example, in an event of a voltage swell, the power transformer at the load side can enter into magnetic flux saturation region, exposing them to high electromagnetic (EM) stress. Hence, there exists a need to develop solutions for swell in the supply voltage. Often, voltage sag and swell occur consecutively. Usually, in an event of voltage sag due to overloading, certain loads are automatically disconnected. After the fault is cleared, the generators and/or reactive compensators may require some time to response to control their voltage outputs. This may result in a temporary swell in the network. For example, the voltage recordings included in [61] show the occurrence of a system-wide voltage sag/swell. Hence, traditional way of disconnecting certain load automatically upon a voltage sag may not be effective enough to contain the aftermath effects of the sag. Furthermore, disconnecting certain loads results in partial load rejection, which can cause inconveniences to some users.

In recent years, other ways of mitigating the effects of a sag are being investigated. Series Compensation (SC) voltage injection strategy is one way. In this strategy, energy is supplied by an energy storage device to restore the load voltage to its pre-sag level. This is achieved by installing a compensating device i.e., the dynamic voltage restorer (DVR) [22]-[23], [62]-[77] in series with the load voltage to provide for the additional energy demanded by the load. In an event of a swell, the DVR may also be employed to absorb the additional energy in the network. Figure 2.4 shows the schematic of a DVR in a power network.

Figure 2.4: A DVR in a power network.

A DVR usually consists of a voltage source inverter (VSI), the injection transformer, and a DC link. The voltage source inverter is required to generate the required energy, in the form of an AC voltage from the DC link to compensate for the sag in the supply voltage. The injection transformer is required to inject the AC voltage waveform into the network, so that the load voltage can be restored back to its pre-sag level.

2.2.5 Limitations of DVRs.

The capabilities of DVRs are usually limited in compensating for any distortions, e.g., sag/swell or harmonics, present in the supply voltage [63]-[77]. Any distortions, i.e., harmonic distortions or undesirable characteristics, poor power factor, inherent in the current demanded by the load cannot be dealt with using the DVR. Hence, this may not be a comprehensive solution to overcome a wide range of power quality problems.

Moreover, DVRs operate with an external energy storage, which can come in the form of batteries, capacitors, or ultra-capacitors. In order to sustain the energy in the DC link, a separate charging circuit, i.e., [69], [76], will be needed to charge or maintain the voltage of the DC link. Hence, it can result in an increase in the cost and the maintenance efforts needed to install a DVR.

2.3 Harmonic Generations and Distortions

Distortion of sinusoidal voltage and current waveforms due to harmonics has been an increasing concern. Considerable efforts have been proposed and made for the management of harmonic generations and distortions in recent years. Indices to measure and standard to control harmonic distortions have been established. Furthermore, instruments to measure harmonic distortions are widely available.

In this section, the thesis discusses the causes of harmonic generations in power systems. The distortions and effects caused by harmonic generations will also be highlighted. Indices and standards developed for the management of harmonics will be reviewed. Compensating devices or ways to control harmonic distortions will be reviewed for their advantages and disadvantages.

2.3.1 Causes and effects of harmonics

Harmonics are non-sinusoidal voltages or currents having frequencies that are integer multiples of the frequency of the fundamental [8]. Harmonics have existed in the past but have insignificant effects in the power systems. Due to the increasing use of power electronics devices (brought about by the increase in the rating of the semi-conductor devices) from 1980, so that the energy efficiency can be achieved, harmonic generation has become an increasing concern. Harmonics in the supply voltage and current are generated through the increasing use of power electronics-based products, in particular, switch mode power supplies. The other sources of harmonics that are causing significant harmonic distortions in power systems include:

- Arc furnaces and other arc-discharging devices, such as fluorescent lamps
- Adjustable speed drives used in fans, pumps
- Solid state switches in light dimmers, heat-control devices
- DC-AC converters in clean energy devices, e.g., photovoltaic, wind, fuel cell

The switching actions of the power converters result in distorted supply currents. This can lead to serious repercussions throughout the supply networks [78]-[80]. One of the

problems will be the distortion of the supply voltage at the Point of Common Coupling (PCC), as shown in Figure 2.5. The supply voltage v_{pcc} at the PCC, being the difference between the source voltage v_s and the voltage across the source impedance Z_n becomes distorted when a nonlinear load $A2$ connected at the PCC injects a distorted current $i_3 + i_5 + i_7 + \dots$ into the supply network. Other linear loads $A1$ and $A3$ at the PCC will receive distorted supply voltage, which may cause overheating of power factor correction capacitors, motors, transformers and cables, and thermal tripping of protective devices, since now the linear loads are drawing distorted currents from the PCC. Further effects are discussed in [81]-[83].

Figure 2.5: Supply network with harmonic distortions.

Furthermore, if a device that requires a sinusoidal voltage waveform for the proper operation on its circuitry is installed at the PCC, it may mal-function. The other effects

of harmonics include amplification of harmonic levels during series and/or parallel resonances, reduction in the efficiency in power generation, transmission and utilization, and pre-mature aging of the insulation of electrical plant components and shortening of their useful life span. More specifically, the harmonic effects on system devices are:-

- Rotating machines

There will be increased heating due to the extra copper and iron losses.

- Transmission system

There will be extra resistive losses due to the flow of harmonic current. This can result in wastage of the transmission capacity and introduce extra dielectric stress on the insulation, shortening line/cable useful life.

- Transformer

Distorted voltages increases hysteresis and eddy current losses and insulation stress while harmonic current increases copper losses.

- Malfunction of protective devices and metering devices.

2.3.2 Harmonics indices.

To provide a measurement on the severity of harmonic distortion, indices have been developed. This sub-section discusses the indices that are used to measure harmonic distortions.

a. Total Harmonic Distortion (THD)

This indicates a ratio of the root-mean-square of the harmonic content to the root-mean-square value of the fundamental quantity, expressed as a percentage of the fundamental:-

$$THD = \frac{\sqrt{\text{Sum of the squares of all harmonic amplitudes}}}{\text{Amplitude of the fundamental}} \times 100\% \quad (2.1)$$

e.g., the harmonic contents of a typical distorted voltage waveform at a semiconductor plant given in Table 2.1.

TABLE 2.1

HARMONIC VOLTAGE SPECTRUM OF A TYPICAL DISTORTED VOLTAGE WAVEFORM

Harmonic order	Phase a		Phase b		Phase c	
	Peak value (A)	Angle (°)	Peak value (A)	Angle (°)	Peak value (A)	Angle (°)
Fundamental	230	0	230	-120	230	120
3	1.697	67	1.697	-293	1.697	427
5	20.506	-160	20.506	-760	20.506	440
7	11.314	-112	11.314	-952	11.314	728
9	1.556	-116	1.556	-1196	1.556	964
11	16.263	11	16.263	-1309	16.263	1331
13	7.354	68	7.354	-1492	7.354	1628
15	3.394	49	3.394	-1751	3.394	1849
17	8.910	179	8.910	-1861	8.910	2219
19	2.970	-123	2.970	-2403	2.970	2157
21	2.546	-133	2.546	-2653	2.546	2387
23	5.798	3	5.798	-2757	5.798	2763
25	1.556	30	1.556	-2970	1.556	3030
27	2.546	52	2.546	-3188	2.546	3292
29	3.111	172	3.111	-3308	3.111	3652

2.3.3 Harmonics standard

In view of the negative effects of harmonic currents on equipment, IEEE developed a standard on the maximum harmonic current distortion. Table 10.3 of [19] describes the current distortion limits for general distribution systems. An extract of the table is shown in Figure 2.6. As such, if these limits set in the table are closely practiced, the entire system should be able to operate with significant harmonic distortions. This would mean that the harmonic distortion caused by a single consumer will be limited to an acceptable level at any point in the system [19].

Table 10.3
Current Distortion Limits for General Distribution Systems
(120V Through 69 000V)

Maximum Harmonic Current Distortion In Percent of I_L						
Individual Harmonic Order (Odd Harmonics)						
I_{sc}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≤h	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
Even harmonics are limited to 25% of the odd harmonic limits above.						
Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.						
*All power generation equipment is limited to these values of current distortion, Regardless of actual I_{sc}/I_L .						
where						
I_{sc} = maximum short-circuit current at PCC.						
I_L = maximum demand load current (fundamental frequency component) at PCC.						

Figure 2.6: IEEE Standard 519-1992 Table 10.3.

Furthermore, IEEE also developed similar standard for voltage distortion in IEEE Standard 519-1992 Table 10.2. In this standard, the Total Harmonic Distortion (THD) of the voltage is limited to within 3% for special applications like hospitals and airports, 5% for a general system and 10% for a dedicated system which is exclusively dedicated to the converter load. An extract of Table 10.2 is shown in Figure 2.7.

Table 10.2 Low-Voltage System Classification and Distortion Limits			
	Special Applications *	General System	Dedicated System †
Notch Depth	10%	20%	50%
THD (Voltage)	3%	5%	10%
Notch Area (A_N) ‡	16 400	22 800	36 500

NOTE: The value of A_N for other than 480V systems should be multiplied by $V/480$

* Special applications include hospitals and airports.
† A dedicated system is exclusively dedicated to the converter load.
‡ In volt-microseconds at rated voltage and current.

Figure 2.7: IEEE Standard 519-1992 Table 10.2.

Typically, electrical engineers who work in various fields of electrical engineering, e.g., power systems, communications and computers, are familiar with the indices and definitions pertaining to their particular disciplines. There is also a new group of consultants who deal exclusively with power quality problems. Some industries are also developing their own standards for power quality.

2.3.4 Solutions to harmonic distortions and their limitations

There are 3 basic ideas to handle harmonic distortions. They are:

- Providing an alternative path for the harmonic currents so as to minimize the amount of currents injecting into the system.
- Shifting the harmonics to other frequencies (usually at a higher spectrum) away from resonance/problematic region.
- Correcting or modifying the distorted current waveform such that it appears sinusoidal when viewed from the system side.

In view of the above, 3 techniques are commonly employed. They are:-

- Phase multiplication
- Shunt passive filter
- Shunt and series active filters.

This section discusses the operating principle, the pros and cons of each of the methods shown above.

a. Phase multiplication

Phase multiplication deals with the arrangement of converter loads, e.g., PWM-type ASDs, DC drives, in a way such that some harmonics can cancel one another [84]-[85]. For example, two 6-pulse drives can be phase-shifted from each other by 30° , resulting in a 12-pulse system. This eliminates the 5th, 7th, 17th, 19th,..., harmonics. By connecting some drives through delta-wye transformers, and some through delta-delta transformer, the cancellation can be magnified. Figure 2.8 shows how a 12-pulse system, made up of two 6-pulse ASDs, with delta-wye transformer and delta-delta transformer, are connected. In this way, certain harmonics inherent in the currents

drawn by the ASDs are cancelled, so that the harmonic distortion in the supply current is reduced.

Figure 2.8: Phase multiplication technique for harmonic compensation in the load current.

b. Shunt passive filters

One conventional way of reducing harmonic distortion in the current is through the application of shunt passive filters [24]-[25], [86]-[87]. In principal, the shunt passive filter is made up of an inductor and capacitor connected in series. However, there will be certain resistance inherent in the elements of the shunt passive filter. A shunt passive filter prevents the load harmonic currents from injecting into the source, or other loads. This is achieved by tuning the resonant frequency f_r of the shunt passive filter to match the frequency of the harmonic component to be filtered away. In this way, the

shunt passive filter will act as very low impedance at f_r , shunting most of the harmonic component at this frequency. Moreover, the shunt passive filter exhibits low impedance characteristics at other nearby frequencies, thus absorbing these harmonic components at these nearby frequencies as well. Figure 2.9 shows how a shunt passive filter is connected in a network.

Figure 2.9: Shunt passive filter installed in a network.

In addition, the shunt passive filter is capacitive at low frequency, e.g., the system frequency. Hence, it can also be used to supply the necessary reactive power demanded by the load.

To design the shunt passive filter, the source impedance, R_s and L_s , must be known. However, the source impedance is not constant and is dependant on the network configuration directly. This implies that the filtering characteristics are strongly influenced by the source impedance. Other limitations and complications of using shunt passive filters are highlighted in [86].

It is also worthwhile to note in [86] that shunt passive filters are not adaptive to any variations in the network, once they are installed, i.e., the tuned frequency and filter size cannot be changed easily. Even with the use of genetic algorithms in [24] and [25] and non-linear optimization method in [87], the limitations described in [86] can be handled effectively. Hence, besides the limitations on its performance, shunt passive filter is not very cost-effective for harmonic compensation.

c. Shunt active filters

The concept of shunt active filters was introduced by L. Gyugyi and E. C. Strycula in 1976 [26]. This power electronics device can be used to compensate for any harmonic distortions in the non-linear load current. Presently, much development has been made in the shunt active filter [88]-[96]. It has enjoyed much success due to the fact that it is adaptive to changes in the harmonic content of the non-linear load current. Figure 2.10 depicts the operating principles of the shunt active filter.

Figure 2.10: Shunt active filter installed in a network.

Here, assume a non-linear load current is drawn from an undistorted supply voltage. Then, a reference based on the harmonic content i_h of the nonlinear load current i_L will be formed online. Next, the shunt active filter, which is a DC-AC converter, will be tasked to deliver this reference (i.e., i_h) to the load side, so that the supply current consists of only the fundamental components i_f of i_L . In this way, the supply side will be undistorted.

As the reference to be delivered by the shunt active filter is formed online based on the load demand, we can see that it is adaptive to changes in the load demand. Thus, the shunt active filter is more superior in performance than the shunt passive filter, due to the fact that it is adaptive to changes in the load demand.

d. Series active filters

A series active filter is a power electronics device that blocks the voltage harmonics in the supply voltage from the load [97]-[100]. This device operates as a dual circuit of the shunt active filter as a theoretical situation- the shunt filter to generate a harmonic current to compensate for harmonic distortions in the load current and the series filter to generate a harmonic voltage to compensate for harmonic distortions in the supply voltage. Figure 2.11 depicts the operating principles of the series active filter.

Figure 2.11: Series active filter installed in a network.

Here, assume an undistorted sinusoidal load current is drawn from a distorted supply voltage. Then, a reference based on the harmonic content v_h of the distorted supply voltage v_s will be formed online. Next, the series active filter, which is also a DC-AC converter, will be tasked to generate this reference (i.e., v_h) in series with the network, so that the load voltage consists of only the fundamental components v_f of v_s . In this way, the load voltage will be undistorted.

In reality, the series and shunt active filters are DC-AC converters with low-pass interfacing filters. Thus, it is obvious that the start-up cost of the shunt and series active filters will be more costly than that of the shunt passive filter. Furthermore, it may not be technically feasible to use a large-rating DC-AC converter as active filters with fast current response efficiently [91]. Nonetheless, the superior performance of the shunt and series active filters makes it more favorable than the use of shunt passive filter alone. Otherwise, the use of hybrid filters [101]-[104], that makes use of the advantages of the shunt passive and shunt or series active filters, is an alternative for harmonic compensation.

2.4 Supply Frequency Drifts

Supply frequency drift is the deviation of the supply system fundamental frequency from its specified nominal value, i.e., 50 Hz [7]. A frequency drift from a nominal frequency of 50Hz to 53Hz occurring from $t=0.06s$, lasting for 5 cycles before the voltage is restored to its pre-drift waveform is depicted in Figure 2.12.

The supply system frequency is directly related to the rotational speeds of the generators supplying the system. As the dynamic balance between the load and generation changes, the supply frequency may vary. The size and duration of this drift in the supply frequency depend on the load characteristics and the response of the generation control system to load changes. This shift in the supply frequency may also result from generator or small co-generation sites being loaded and unloaded, erratic operation of emergency generators or unstable frequency power sources. Frequency variation can cause erratic operation, data loss, and system crash and equipment damage. For sensitive electronic equipment, the result can be data corruption, hard drive crash, keyboard lockup and program failure. The need to be concerned with this phenomenon is highlighted in [9].

Figure 2.12: Waveform for frequency drift in supply voltage.

As such, there have been ongoing researches to detect the occurrence frequency variation and to perform frequency estimation [105]-[108]. As frequency is an important parameter in power system relaying, power-quality monitoring, and operation and distribution automation, its variations can have negative effects on voltage control by custom power devices based on constant frequency modeling. There are also some developments to employ DVR [109]-[110] to handle this power quality problem.

2.5 Poor Power Factor Loads

2.5.1 Causes and effects of harmonics poor power factor loads

Most loads are either inductive or capacitive. They will not be purely resistive. Hence, the current drawn by the load will not be in phase with the supply voltage. It will be either lagging (for inductive load) or leading (for capacitive load) the supply

voltage. Some loads are extremely inductive or capacitive, leading to a condition that the load current lags or leads the supply voltage too much such that there is a wide displacement between their phases.

To measure the displacement quantitatively, an index called the power factor is used.

Power factor is defined as the ratio of the active power to apparent power, given by:-

$$\begin{aligned} \text{Power factor} &= \frac{\text{real power}}{\text{apparent power}} \\ &= \frac{kW}{kVA} \end{aligned} \quad (2.5)$$

or

$$|\text{real power}| = |\text{apparent power}| |\cos \phi| \quad (2.6)$$

Loads that have a power factor below 0.8 are said to have a poor power factor. Some of the loads with poor power factors are:-

- 3-phase induction motor

When operated at full load, the power factor is 0.8 lagging. Hence, the power factor will be below 0.8 when it is operated at partial loading.

- Single-phase induction motor

For a single-phase induction motor, the power factor is usually around 0.6.

- Transformer

The magnetizing current of the transformer consists of pure reactive power. Hence, the power factor is zero!

Poor power factors cause problems too [111]-[114]. The reactive power is usually very high for loads with poor power factor. Due to the fact that reactive power is not the real actual power used to perform work, it becomes very inefficient to transmit this high reactive power across the transmission line. This constitute to a very high current flow across the transmission line, which causes overloading, overheating and huge energy losses on the transmission lines, as well as the equipment. In addition, the power plants, transmission lines as well as the distribution equipment will have to be oversized to handle this huge capacity. In certain regions, industrial plants with poor power factors can be subjected to additional surcharges. This will mean bigger economical losses to them, which is why power factor is sometimes known as the energy efficiency index of an electric circuit [115].

Thus, if the power factor can be improved, the economical benefits that include lower utility charges due to lower power factor surcharges and lower kVA power demand charges can be enjoyed. It can also lead to the release of the system capacity, so that better utilization of the capacity can be achieved.

2.5.2 Solutions to loads with poor power factor

To handle loads with poor power factor, power factor correction devices can be installed. In principal, these devices generate and provide reactive power locally at load side. Below is an illustrative example in Figure 2.13 to show how reactive power is generated and provided by these devices, so that the power factor at the supply side can be improved:

Consider a load with poor lagging power factor is drawing a power demand $P + Q_L$.

The compensating device is responsible to provide a reactive power Q_c so that the

supply side only need to provide a power demand $P + Q_s$ to the load side. We have:

(a)

(b)

Figure 2.13: (a) Power factor correction at the supply side via the injection of reactive power, (b) Phasor diagram depicting the real and reactive powers of the network.

where

$\cos \phi_s$ = power factor at the supply side

$\cos \phi_L$ = power factor at the load side

To compare the power factor improvement quantitatively, the power factor of the supply and load sides are calculated to be:

For the supply side, we have

$$\cos \phi_s = \frac{P}{\sqrt{P^2 + Q_s^2}} = \frac{P}{\sqrt{P^2 + (Q_L - Q_c)^2}} \quad (2.7)$$

For the load side, we have

$$\cos \phi_L = \frac{P}{\sqrt{P^2 + Q_L^2}} \quad (2.8)$$

It is obvious that the power factor at the supply side is larger than that at the load side. This leads to an improvement of the power factor at the supply side. This is achieved by having the power factor correction device providing a reactive power Q_c to the load side.

Nowadays, the compensating devices that are available and used widely include:

- Static shunt capacitors
- Synchronous condensers

Often, they are chosen according to the rating requirement. For example, the rating ranges of the static shunt capacitors are from 15kVAr to 10MVar, while the synchronous condensers are suitable to handle compensating requirement more than 10MVar. Other factors that include reliability, availability, loss management are also crucial in the installation of the devices.

2.5.3 Limitations of power factor correction devices

As seen, while there are limitations for the shunt capacitors or synchronous condensers, they can be designed to handle poor power factor at the supply side effectively. However, other compensating capabilities such as mitigating voltage sag/swell, harmonic compensation may not be incorporated into these devices.

Furthermore, if one were to install different devices to solve different power quality problems, the coupling effects among these devices can be complicated, posing serious implications on the network. Besides that, the economical cost of installing so many devices can be high!

Therefore, it will be very cost-effective to install a single device that is capable of handling a wide range of power quality problems. This approach may also eliminate any coupling effects that may be experienced if many devices are installed concurrently.

In view of these, the next chapter introduces the Unified Power Quality Conditioner, an integrated power electronic device, to handle a wide range of power quality problems in a power distribution network.

CHAPTER 3

UNIFIED POWER QUALITY CONDITIONER

3.1 Introduction

The Unified Power Quality Conditioner (UPQC) is first proposed by Akagi in 1996 [28]. The UPQC is essentially an integration of the series and shunt active filters. Figure 3.1 shows the general structure of a UPQC proposed in [28]-[29].

Figure 3.1: Simplified diagram of a UPQC.

The series active filter of the UPQC can be employed for harmonic isolation in the supply voltage and voltage regulation at the point of common coupling (PCC). The compensating component, in the form of an AC voltage waveform, is injected into the system via an injection transformer.

The shunt active filter of the UPQC can be employed for harmonic compensation in the load current, power factor correction at the supply side, and voltage regulation of the DC link of the UPQC. The compensating component, in the form of an AC current waveform, is injected into the system via an isolation transformer.

To date, many research and development works have been made on various aspects of the UPQC [28]-[41], [116]-[120]. This chapter first introduces the different physical configurations of the UPQC. Then, general control strategies of the series and shunt active filters of the UPQC are detailed.

3.2 Configuration of the UPQC

Several different topologies of the UPQC have also been proposed. The main differences among these topologies lie in the locations and inverters configurations of the series and shunt active filters [38]. This section examines two of the most common topologies of the UPQC, namely, the right-shunt and left-shunt UPQC, as well as the inverter structures of the active filters of the UPQC and the low-pass interfacing filters.

3.2.1 Right-shunt and left-shunt UPQC

In [38], a right-shunt and a left-shunt UPQC are proposed. Their single-line diagrams are shown in Figures 3.2 and 3.3 respectively.

Figure 3.2: Right-shunt UPQC topology.

Figure 3.3: Left-shunt UPQC topology.

In the above figures, the supply voltage refers to the sum of the fundamental voltage and any harmonics present, while the supply impedance refers to the source and the line impedances. v_c and i_c refer to the voltage output of the series active filter and the injected current of the shunt active filter respectively. The plant modeling using a right-shunt UPQC topology is further detailed in section 4.2.

Reference [38] compares the operating characteristics of these two UPQC topologies where:

- 1) The right-shunt UPQC can operate in a zero-power injection or absorption region; the left-shunt UPQC is not able to.
- 2) The right-shunt UPQC is capable of achieving unity power factor at the supply side, while the power factor at the supply side depends on the load for the left-shunt UPQC.
- 3) The shunt active filter of the right-shunt UPQC is capable of supplying all the reactive power requirements of the load, while the shunt active filter of the left-shunt UPQC can only supply the reactive power requirement of the load.

As such, it is apparent that the right-shunt UPQC promises better capabilities to offer better compensating characteristics. Hence, the right-shunt topology is chosen for the research work in this thesis so that the operation of the UPQC can be optimized together with appropriate control schemes to achieve optimum power quality improvement.

3.2.2 Inverter structure of the series and shunt active filters of the UPQC.

Primarily, the series and shunt active filters of the UPQC are DC-AC converters. These converters are usually voltage source inverters (VSI), which generate an AC output from a DC source. Two of the commonly adopted structures of a voltage source inverter are the half-bridge inverter (that employs two split capacitors as its DC link), which is adopted in [30], [40], [116]-[118], and the full-bridge inverter (that employs a single capacitor as its DC link), which is adopted in [31]-[35], as shown in Figure 3.4.

Figure 3.4: (a) Topology of a half-bridge inverter; and (b) full-bridge inverter.

As seen in Figure 3.4, we only need a single DC source in a full-bridge inverter, whereas two DC sources are needed for a half-bridge inverter. Furthermore, for the full-bridge inverter, an Unipolar voltage switching PWM can be adopted to effectively make the lowest harmonics to occur as sidebands of twice the switching frequency thereby relaxing the requirement of the low-pass filter. However, the half-bridge inverter has the following advantages over the full-bridge inverter:

- 1) The number of switches in a half-bridge inverter can be reduced to half of that required by a full-bridge inverter.
- 2) The half-bridge inverter can be configured to a 3-phase inverter, sharing the same DC link with ease.

Moreover, the control of two switches in a half-bridge inverter will be more desirable than the control of four switches in a full-bridge inverter. This can reduce the occurrences of shoot-through, as well as the complexity of the control algorithm needed to generate the switching signals for the inverter.

In view of the above, this research work employs the half-bridge inverter topology for study. Each of the series and shunt active filters of the UPQC is made up of a half-bridge inverter. The half-bridge inverters will also share the same DC link.

3.2.3 Low-pass interfacing filters

The AC outputs of the VSIs of the series and shunt active filters are pulses, as depicted in Figure 3.5.

Figure 3.5: VSI of an active filter.

These AC pulses cannot be injected into the system directly, as they consist of undesirable high switching frequency components inherent in the VSI outputs, explained earlier. Hence, the pulses have to be passed through an interfacing low-pass filter to eliminate the high-order switching frequency components introduced by the VSI. Most UPQCs employ 2nd order low-pass interfacing filters for the series active filter of the UPQC, while for the shunt UPQC, some researchers in [31]-[35] and [119]-[120] adopt 1st order low-pass interfacing filters, and [30], [38]-[41] adopt 2nd order low-pass interfacing filters. As such, this section discusses the strengths and drawbacks

of the 1st order and the 2nd order low-pass interfacing filters [121] and then selects the appropriate filters to be used.

a. 1st order low-pass interfacing filter

Figure 3.6 shows the topology of a 1st order low-pass filter. It comprises of only an inductor to be used to filter the harmonic content produced by the high switching frequency. Another function of the inductor is to convert the output voltage from the VSI into an injecting current to compensate for any harmonics in the load current.

Figure 3.6: VSI with a 1st order low-pass interfacing filter.

V_{in} is the switched voltage across the VSI, and the transfer function of this first order low-pass filter can be derived as follows:

$$\frac{i_{inj}}{v_{out} - v_{in}} = \frac{1}{sL} \quad (3.1)$$

the cut-off frequency $f_{c1^{st}}$ is given by

$$f_{c1^{st}} = \frac{R}{2\pi L} \quad (3.2)$$

where R refers to the output impedance.

b. 2nd order low-pass interfacing filter

2nd order Butterworth filter was selected because of its simplicity and the Butterworth approximation to an ideal low-pass filter was based on the assumption that a flat response at zero frequency was more important than the response at other frequencies. This type of design approach was of our interest because the magnitude of the output at the desired frequency should have as low attenuation as possible.

Figure 3.7 shows the topology of a 2nd order Butterworth low-pass filter. It comprises of an inductor and a capacitor. It is used to filter the harmonic content produced by the high switching frequency.

Figure 3.7: A 2nd order low-pass interfacing filter.

The transfer function is given by

$$\frac{v_{out}}{v_{in}} = \frac{1}{1 - LC\omega^2 + j\omega\frac{L}{R}} \quad (3.3)$$

the cut-off frequency $f_{c2^{nd}}$ is given by

$$f_{c2^{nd}} = \frac{1}{2\pi\sqrt{LC}} \quad (3.4)$$

The typical configuration of an n-order filter is given in Figure 3.8.

Figure 3.8: An n-order LC filter.

The transfer function and the cut-off frequency f_{cn} for an n-order LC filter are related by

$$\frac{v_{out}}{v_{in}} = \frac{1}{\prod_{k=1}^n (s - s_k) / 2\pi f_{cn}} \quad (3.5)$$

$$\text{where } k = 1, 2, 3, \dots, n, \quad s = j2\pi f, \quad s_k = 2\pi f_{cn} e^{\frac{j(2k+n-1)\pi}{2n}}$$

The normalized values for the n-order LC low-pass filter operating at the normalized 1Ω termination can be computed by the following:

$$L_k \text{ or } C_k = \frac{2 \sin(2k-1)\pi}{2n} \quad (3.6)$$

where L_k or C_k is the k^{th} component being either a series inductor or shunt capacitor.

The computed normalized values are then used to calculate the absolute values of their components using the desired cut-off frequency and output impedance as follows:

$$L_k = \frac{L_k R}{2\pi f_c} \quad (3.7)$$

$$C_k = \frac{C_k}{2\pi f_c R} \quad (3.8)$$

As observed from Figures 3.9, a filter of higher order will give better frequency responses and better roll-offs that result in better harmonics suppression. Concurrently, to achieve better harmonic suppression, the switching frequency of the VSIs in the series and shunt active filters of the UPQC can be adjusted higher. Hence, the following objectives can be achieved:

- 1) High-order harmonics present in the network can be handled.
- 2) High-order harmonics inherent due to the switching of the VSI can be eliminated so that they do not propagate into the network, and cause unwanted high frequency distortions.

Figure 3.9: Typical frequency responses of 1st, 2nd and 3rd order low-pass filters.

However, the drawbacks of implementing higher order filters will be additional cost and complexity.

In order to optimize the performance of the UPQC to handle high-order harmonics and to seek a compromise between performance and implementation cost, this research proposes the use of 2nd order low-pass interfacing filters for both the active series and shunt filters of the UPQC. While this approach can lead to increased complexity, the characteristics of the low-pass filter, i.e., their parameters values, can be incorporated

as part of a model-based control scheme to optimize the performance of the UPQC. This will be explained in Chapters 4 and 5 of this thesis.

3.3 Control of the UPQC

Further to the discussion of the UPQC configurations, this section reviews some of the control approaches of the UPQC. Generally, the control of the UPQC can be classified into two types. They are:

- a. Extraction and injection of distorted components*
- b. Model-based control*

This section discusses the development as well as the advantages and disadvantages of these two control methodologies of the UPQC.

3.3.1 Extraction and injection of distorted components

Generally, the controller for the UPQC can be depicted in Figures 3.10. Basically, the controller is made up of the extraction and the control circuit, while the control of the series and shunt active filters of the UPQC are treated differently.

Firstly, the distorted waveforms, e.g., the supply voltage and the load current, will be passed into an extraction circuit. The extraction circuit will extract the fundamental as well as the harmonic components of the distorted waveforms. Then, a reference will be formulated based on these extracted components (i.e., harmonic components). Next, the control circuit will generate the switching signals for the series and shunt active filters,

so that this reference can be injected into the system. The aim is to ensure that the load voltage or the supply current is undistorted, or have certain desirable properties, e.g., unity power factor at the supply side. Such approaches have been widely adopted in [30]-[36].

For example, in Figure 3.11, to achieve voltage harmonic compensation in the distorted supply voltage v_s , v_s is passed into an extraction circuit to extract the fundamental component v_f . v_f is then subtracted from v_s to obtain the harmonic component v_h . v_h forms the reference to be injected into the network via a controller and the series active filter. The same approach is applied independently for current harmonic compensation.

Figure 3.10: General control of a UPQC in a power distribution network.

Figure 3.11: Classical control approach for the series active filter of the UPQC.

This approach is simple and can be easily implemented. However, there is no feedback of the load voltage and supply current in these designs to show that they are undistorted or sinusoidal. From this argument, these designs are open-loop control. In addition, the controls of the series and shunt filters are independent so their coupling effect, as discussed in [37], is neglected. Moreover, the voltage drop across the line impedance and the voltage source inverters (VSIs) are also neglected. Obviously, all these will affect the performance of the UPQC.

The following sub-section discusses in detail general control schemes of the series and shunt active filters of the UPQC respectively.

3.3.1.1 A general control of the shunt active filter of the UPQC

The role of the shunt active filter of the UPQC is to eliminate any harmonic distortions in the load current through the harmonic current injection, to correct the power factor at the supply side through reactive power injection. In addition, it can also be utilized to maintain the DC link voltage of the UPQC to a desired level, so that the UPQC can operate properly and efficiently. In short, the mathematical equation

involving the supply current i_s , the load current i_L and the injected current of the shunt active filter of the UPQC i_{inj} is:-

$$i_L = i_s + i_{inj} \quad (3.9)$$

To achieve the 1st two objectives, the load current i_L will be sampled. The harmonic components, as well as its reactive current component, will be derived and extracted to form a reference i_{inj}^* . For example, i_L can be represented by a Fourier series:

$$\begin{aligned} i_L &= I_{L_f} \sin(\omega t - \theta_{L_f}) + \sum_{h=3,5,\dots}^N I_{L_h} \sin(h\omega t - \theta_{L_h}) \\ &= I_{L_f} \sin \omega t \cos \theta_{L_f} - I_{L_f} \cos \omega t \sin \theta_{L_f} + \sum_{h=3,5,\dots}^N I_{L_h} \sin(h\omega t - \theta_{L_h}) \\ &= i_{L_{f,p}} + i_{L_{f,q}} + i_{L_h} \end{aligned} \quad (3.10)$$

where $i_{L_{f,p}}$ and $i_{L_{f,q}}$ are the load instantaneous fundamental phase and quadrature currents, which are always in phase and 90° out of phase with the fundamental component of the supply voltage respectively. I_{L_f} is the amplitude of i_L and θ_{L_f} is the phase angle difference between v_{s_f} and i_{L_f} . i_{L_h} is the harmonic components of i_L , with amplitudes I_{L_h} and phase angles θ_{L_h} . In order for i_s to be distortion-free and in phase with the supply voltage, i_{inj}^* can be formulated to be:

$$\begin{aligned} i_{inj}^* &= -I_{L_f} \cos \omega t \sin \theta_{L_f} + \sum_{h=3,5,\dots}^N I_{L_h} \sin(h\omega t - \theta_{L_h}) \\ &= i_{L_{f,q}} + i_{L_h} \end{aligned} \quad (3.11)$$

As such, a general control of the shunt active filter described in [36] is depicted in Figure 3.12. It is a PI-based control scheme. Basically, it measures how well the injected compensating component i_{inj} tracks a reference i_{inj}^* , where i_{inj} is the PWM-

modulated signal generated by the controller in Figure 3.10 to control the shunt active filter.

Figure 3.12: A PI-based controller for the shunt active filter.

The performance of the UPQC will be dependent on how accurate the reference i_{inj}^* is formulated, as well as the PI-based control scheme.

To date, there have been numerous researches on the formulation of the reference. They include the synchronous frame based method [31]-[32] and [34], ANN [40], and wavelet [30]. However, while the methods may be able to formulate an accurate reference, the tracking of the reference has to be accurate as well so that the performance of the UPQC can be optimized.

Furthermore, as discussed earlier, there is no feedback of the supply current in such control approach (i.e., the approach that tracks how well the injected compensating component i_{inj} tracks a formulated reference i_{inj}^* and is largely dependent on how accurate the reference i_{inj}^* is formulated) to measure and mitigate their distortion levels directly. As such, this thesis proposes control approach that enables the supply current, as well as the load voltage, to track certain desired sinusoidal waveforms directly. This

will not only result in an optimized control of the UPQC, but also enable the UPQC to concurrently handle several PQ problems. All this will be detailed in Chapters 4 and 5.

In addition, in order for the UPQC to operate without relying on an external DC power supply, a PI-based controller, adopted in [31], [33], [35], [39] and [120], as shown in Figure 3.13, is commonly used to regulate the voltage of the DC link. The dc link voltage V_{dc} is measured and compared against a desired reference voltage V_{dc}^* . The error is then passed to a PI controller to generate the reference charging current i_{dc} to be subtracted from i_{inj}^* to be:

$$i_{inj}^* = i_{L_{f,q}} + i_{L_h} - i_{dc} \quad (3.12)$$

so that the regulation of the dc link voltage can be achieved.

Figure 3.13: A PI-based controller to regulate the DC link voltage of the UPQC.

In this thesis, a Linear Quadratic Regulator (LQR)-based controller [38] and [40], which provides better charging characteristics, e.g., no overshoot, fast settling time, than other conventional control design methods, is proposed. This will be further discussed in Chapter 4.

3.3.1.2 A general control of the series active filter of the UPQC

Likewise, the role of the series active filter of the UPQC is to eliminate any harmonic distortions in the supply voltage, as well as to be able to compensate for any voltage sag or swell in the supply voltage. To achieve that, the supply voltage v_s will be sampled. Then, it will be passed into the extraction circuit to extract its harmonic components. For example, neglecting any losses in the line impedance v_s can be represented into a Fourier series:

$$v_s = V_{s_f} \sin \omega t + \sum_{h=3,5,\dots}^N V_{s_h} \sin(h\omega t - \theta_{s_h}) = v_{s_f} + v_{s_h} \quad (3.13)$$

where v_{s_f} denotes the fundamental component of v_s with amplitude V_{s_f} , and v_{s_h} denotes the harmonic components of v_s with amplitudes V_{s_h} and phase angles θ_{s_h} , we can design an extraction circuit to extract the harmonic components v_{s_h} , i.e.,

$$v_{s_h} = \sum_{h=3,5,\dots}^N V_{s_h} \sin(h\omega t - \theta_{s_h}) \quad (3.14)$$

If harmonic compensation of the supply voltage is to be achieved, v_{s_h} will be the reference v_{inj}^* to be injected into the network. The injected component of the series active filter of the UPQC will be

$$v_{inj}^* = \sum_{h=3,5,\dots}^N V_{s_h} \sin(h\omega t - \theta_{s_h}) \quad (3.15)$$

To compensate for any voltage sag or swell in the supply voltage, the amplitude of the fundamental v_f can be fixed and memorized after certain time, i.e., after the

initialization period of the UPQC. In this way, in the event of a sag (or swell) in the supply voltage, v_s will be

$$v_s = (V_{s_f} - \Delta V_{s_f}) \sin \omega t + \sum_{h=3,5,\dots}^N (V_{s_h} - \Delta V_{s_h}) \sin(h\omega t - \theta_{s_h}) \quad (3.16)$$

where ΔV_{s_f} and ΔV_{s_h} represent a corresponding sag in the amplitudes of its fundamental and harmonic components. To compensate for the sag in the supply voltage, the reference to be formulated and injected into the network will be

$$\hat{v}_{inj} = -\Delta V_{s_f} \sin \omega t + \sum_{h=3,5,\dots}^N (V_{s_h} - \Delta V_{s_h}) \sin(h\omega t - \theta_{s_h}) \quad (3.17)$$

where the first and second terms compensate for the voltage sag in the amplitudes of its fundamental and harmonic components respectively. In this way, v_L will be fixed to the pre-sag amplitude of the supply voltage v_s , while remaining as an undistorted sinusoidal waveform of 50Hz.

In this way, the harmonic and other distorted components will be injected into the network via the series active filter of the UPQC, such that the load voltage v_L will be an undistorted sinusoidal waveform of fixed amplitude and frequency. As the operating amplitude and frequency of the supply voltage, i.e., v_s^* is generally known, v_{inj}^* can be also formulated in a simpler way, from the measured v_s , to be

$$v_{inj}^* = v_s^* - v_s \quad (3.18)$$

As such, with this voltage reference v_{inj}^* , a general control of the series active filter [36] is depicted in Figure 3.14. It is a PI-based control scheme and measures how well the injected compensating component v_{inj} tracks a reference v_{inj}^* .

Figure 3.14: A PI-based controller for the series active filter.

As discussed earlier, the controls of the series and shunt filters are independent, in which the coupling effect between the shunt and series active filters will be neglected. Furthermore, the voltage drop across the line impedance and the voltage source inverters (VSIs), i.e., the effects of the inherent resistances, are also neglected, as observed in the PI controllers of the active filters in Figures 3.12 and 3.14. These may affect the performance of the UPQC.

3.3.2 Model-based control

With regard to the mitigation of the above mentioned drawbacks, model-based control schemes are proposed [38]-[41]. A model-based coordinated control determines the switching signals for the VSIs of the series and shunt filters of the UPQC. Here, the power distribution network is modeled with the UQPC into a multi-input-multi-output state-space model. The impedances present in the different components and in the line

can be included in the model. Then, a coordinated control scheme is applied to the model. It will generate the switching sequences for the VSIs of the series and shunt filters of the UPQC. In this way, it calculates what is to be injected into the system while taking into account the coupling effect and the voltage drop across different impedances. Hence, the performance of the UPQC is optimized as far as possible.

However, one drawback of such an approach is that any modeling error can be detrimental to the performance. Also, it may require a high-speed DSP and additional sensors for the sampling of the states of the state-space model. Consequently, while the increase in hardware cost may be negligible, the complexity of the UPQC will increase.

Hence, this thesis proposes two model-based controllers for the UPQC. They facilitate periodic reference tracking and disturbance rejection as well so that it can be used to solve most of the power quality problems concurrently. The proposed model-based controlled UPQCs will be able to collectively replace some compensating devices such as the DVR and the shunt active filter discussed in Chapter 2. The proposed control schemes seeks to mitigate the drawbacks of existing control approaches, to generate accurate switching signals for the UPQC, so that its performance can be optimized. This will result in a UPQC that is robust and adaptive to variations and disturbances in the supply side and load demand. The overall UPQC may also be more cost effective and require relatively less maintenance. This will be further detailed in Chapters 4 and 5.

CHAPTER 4

MVR-BASED UPQC WITH KALMAN FILTERS

4.1 Introduction

This chapter details the development of a model-based control scheme for the UPQC. A novel Multi-variable Regulator-based (MVR) [42]-[43], [122]-[125] UPQC with Kalman filters is introduced. While the use of Kalman filters has been wide [44]-[46], [126]-[129], in this research, Kalman filters are adopted by the control design to extract the fundamental and harmonic components of the supply voltage and load current of a power distribution system, and to estimate the variables of the UPQC. Using the MVR control, the UPQC can compensate for system harmonics in the supply voltage and load current, sags/swells as well as frequency variations in the supply voltage. The power factor of the supply side will also be corrected to near to unity by the UPQC. The UPQC will operate with a self-charging circuit, without the need to rely on any external DC power supply.

All in all, the capabilities of the MVR-based UPQC include:

- i) compensation of harmonics in the supply voltage and load current;
- ii) compensation of sags, swells and/or frequency variations in the supply voltage;
- iii) correction of power factor at the supply side;
- iv) adaptive to variations in the supply and load demand; and

- v) the ability of the UPQC to operate with a self-charging circuit, without relying on any external DC power supply.

The control design employs a multi-variable regulator (MVR) [42]-[43], [122]-[125] to generate control signals for the series and shunt active filters of the UPQC. The structure of the control design incorporates:

- i) an exogenous Kalman filter to extract the fundamental and harmonic components of the supply voltage and load current;
- ii) a plant Kalman filter as a state observer for the variables of the UPQC; and
- iii) an LQR-based self-charging circuit to regulate the DC link voltage of the UPQC to a desired DC level.

The MVR ensures the global stability for the plant, as well as to facilitate periodic reference tracking and disturbance rejection. In this way, the load voltage and supply current of the plant can be made to track certain desired sinusoidal waveforms, so that harmonic compensation and power factor correction can be achieved. Disturbances such as variations at both the supply and load sides will also be rejected. While the exogenous Kalman filter is part of the control algorithm, it functions as a harmonic extractor as well [44]-[46]. The overall UPQC is highly responsive to abrupt changes in the operating conditions, i.e., voltage sags as well as changes in the load demand. The use of the plant Kalman filter as a state observer also relaxes the requirement of several state measurements. This reduces sensory circuit hardware and manufacturing and maintenance costs.

The control design is illustrated through a single-phase power distribution system here. To further apply it to a three-phase power distribution system, one would just need to duplicate three sets of the same controller, each working independently in the different phases. The various functional modules of the control circuit of the UPQC are discussed in subsequent sections of this chapter.

This chapter will first detail the modeling of the plant. Based on this model, the control design will be discussed next. After which, the injection circuit and the overall control configuration will be presented.

4.2 Modeling of the Plant

The equivalent single-phase representation of a power distribution plant with the UPQC is depicted in Figure 4.1 [38]. The distorted supply voltage v_s at the Point of Common Coupling (PCC) is represented by the sum of two voltage sources, v_{s_f} (fundamental) and v_{s_h} (harmonics). The nonlinear load is modeled by a distorted current source i_L , which consists of both the fundamental i_{L_f} and the harmonics i_{L_h} that varies with different loads. The supply current is denoted by i_s while the voltage across the nonlinear load is denoted by v_L . Ideally, v_L and i_s should be sinusoidal waves of a fixed frequency, i.e., 50Hz, without any harmonics, even though harmonics may exist in v_s and i_L . This is one of the tasks to be accomplished by the proposed UPQC. The voltage v_z is the voltage drop across the line impedance

$R_l + j\omega L_l$. The inductance of the interfacing transformer may be modeled as part of L_l .

Adopting a right shunt UPQC topology, the series active filter of the UPQC is modeled by a voltage source $u_1 \frac{V_{dc}}{2}$ with L_{se} and C_{se} as the second order low-pass interfacing filter and R_{se} to account for losses in the series voltage source inverter (VSI). Likewise, the shunt active filter of the UPQC is represented by $u_2 \frac{V_{dc}}{2}$ with L_{sh} and C_{sh} as the second order low-pass interfacing filter, R_{sh} as the losses of the shunt VSI, and $i_{C_{sh}}$ as the leakage capacitor current of the shunt low-pass interfacing filter. As explained in Chapter 3, second order low-pass interfacing filters are used, so that high frequency components generated by the VSIs can be filtered. This will result in a better performance of the UPQC.

$u_1 \frac{V_{dc}}{2}$ and $u_2 \frac{V_{dc}}{2}$ represent the switched voltages across the series and shunt VSI outputs of the UPQC respectively. v_{inj} and i_{inj} denote the injected voltage of the series active filter and the injected current of the shunt active filter respectively. Both u_1 and u_2 will be determined by the MVR, to be discussed in Subsection 4.3.3. They are supposed to take continuous values between -1 and +1, which are first chopped by a PWM generator, to be the switching signals for the VSIs. $\frac{V_{dc}}{2}$ is the desired DC voltage level of each capacitor unit for the UPQC.

Figure 4.1: Equivalent single-phase representation of a power distribution plant and the UPQC.

To derive a state-space model for Figure 4.1, Kirchhoff's voltage and current laws are applied to the three current loops in the figure.

From loop i_1 , we get

$$v_s = i_1 R_l + L_l \frac{di_1}{dt} + v_{inj} + v_L \quad (4.1)$$

From loop i_2 , we get

$$u_1 \frac{V_{dc}}{2} = R_{se} i_2 + L_{se} \frac{di_2}{dt} + v_{inj} \quad (4.2)$$

$$v_{inj} = \frac{1}{C_{se}} \int (i_1 + i_2) dt \quad (4.3)$$

From loop i_3 , we get

$$u_2 \frac{V_{dc}}{2} - i_{inj} R_{sh} - L_{sh} \frac{di_{inj}}{dt} = v_L \quad (4.4)$$

$$v_{C_{sh}} = (1/C_{sh}) \int i_{C_{sh}} dt = v_L \quad (4.5)$$

$$i_s + i_{inj} - i_{C_{sh}} = i_L \quad (4.6)$$

In addition,

$$i_1 = i_s \quad (4.7)$$

$$i_2 = i_{se} \quad (4.8)$$

$$i_3 = i_{C_{sh}} \quad (4.9)$$

where i_{se} is the current flowing through R_{se} and L_{se} .

Re-arranging (4.1)-(4.9), we have the following state-space representation for the overall plant and its state vector:

$$\dot{x} = Ax + B_1 \begin{pmatrix} v_s & i_L \end{pmatrix}^T + B_2 u \quad (4.10)$$

where

$$x = \begin{pmatrix} i_s \\ i_{se} \\ i_{inj} \\ v_{inj} \\ v_{C_{sh}} \end{pmatrix}; \quad A = \begin{pmatrix} \frac{-R_1}{L_1} & 0 & 0 & \frac{-1}{L_1} & \frac{-1}{L_1} \\ 0 & \frac{-R_{se}}{L_{se}} & 0 & \frac{-1}{L_{se}} & 0 \\ 0 & 0 & \frac{-R_{sh}}{L_{sh}} & 0 & \frac{-1}{L_{sh}} \\ \frac{1}{C_{se}} & \frac{1}{C_{se}} & 0 & 0 & 0 \\ \frac{1}{C_{sh}} & 0 & \frac{1}{C_{sh}} & 0 & 0 \end{pmatrix}; \quad u = \begin{pmatrix} u_1 & u_2 \end{pmatrix}^T;$$

$$B_1 = \begin{pmatrix} 0 & 0 & 0 & 0 & \frac{-1}{C_{sh}} \\ \frac{1}{L_1} & 0 & 0 & 0 & 0 \end{pmatrix}^T; \quad B_2 = \begin{pmatrix} 0 & 0 & \frac{V_{dc}}{2L_{sh}} & 0 & 0 \\ 0 & \frac{V_{dc}}{2L_{se}} & 0 & 0 & 0 \end{pmatrix}^T.$$

and the output equation is given by

$$y = Cx + D_1(v_s \quad i_L)^T + D_2u \quad (4.11)$$

$$\text{where } C = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 \end{pmatrix}; \quad D_1 = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}; \quad D_2 = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}.$$

In this state-space model, the supply voltage v_s and the load current i_L are considered as exogenous inputs to the plant, which act like disturbances. The outputs of the plant are the load voltage v_L and the supply current i_s , which are to be maintained as pure sine waves of 50Hz, as well as to achieve a unity power factor. The variables u_1 and u_2 are considered to be the control inputs to the plant. As such, in this way, the state-space model of the overall plant in (4.10)-(4.11) is a multi-input-multi-output system, which means that the series and shunt active filters are not treated as two separate systems. Instead, a coordinated control will be employed to operate the series and shunt active filters of the UPQC more efficiently. Moreover, since the distorted supply voltage v_s and the nonlinear load current i_L are considered as exogenous disturbances, the negative effects of their variations will be minimized by the proposed control strategy as well. Using the plant model, the next section will discuss the control design of the MVR-controller.

4.3 Control Design

The aim of the control design is to make the output of the plant $y = (v_L \quad i_s)^T$ track a reference $d = (v_L^* \quad i_s^*)^T$, under a periodic disturbance $(v_s \quad i_L)^T$. The reference signals

v_L^* and i_S^* should be pure sine waves of a fixed frequency, i.e., 50Hz, without any harmonics. (In this research, an operating frequency of 50Hz is used.)

While there are various control strategies have been proposed for UPQC with some success, such as PI/PID [33], hysteresis control [40], [33], pole-shifting [41] and LQR/LQG [33], these methods are not supposed to eliminate the steady-state error totally when the system is subjected to periodic references and disturbances. As such, this research proposes to apply the Multi-variable Regulator (MVR) theory that utilizes a model of the reference and disturbance signals in the control design. This will generate a control configuration that can result in zero steady-state error in principle. Moreover, the proposed strategy deals with the UPQC as a two-input-two-output system directly, rather than two single-input-single-output systems as in some other methods. This will provide a more effective coordination of the two control variables u_1 and u_2 .

4.3.1 Construction of the desired references

Let v_s be represented by a Fourier series:

$$v_s = V_{s_f} \sin \omega t + \sum_{h=3,5,\dots}^N V_{s_h} \sin(h\omega t - \theta_{s_h}) = v_{s_f} + v_{s_h} \quad (4.12)$$

where v_{s_f} denotes the fundamental component of v_s with amplitude V_{s_f} , and v_{s_h} denotes the harmonic components of v_s with amplitudes V_{s_h} and phase angles θ_{s_h} .

From Figure 4.1, (4.1) can be rewritten as:

$$v_s = v_{s_f} + v_{s_h} = v_z + v_{inj} + v_L \quad (4.13)$$

In our control strategy, our objective is to regulate v_L to a clean sinusoidal voltage v_{s_f} . Hence, we set v_L^* (the reference for v_L to track) to be v_{s_f} , which is simply the first part of (4.13).

$$v_L^* = V_{s_f} \sin \omega t = v_{s_f} \quad (4.14)$$

In order to achieve this objective, the injected voltage v_{inj} will be

$$v_{inj} = v_{s_h} - v_z = \sum_{h=3,5,\dots}^N V_{s_h} \sin(h\omega t - \theta_{s_h}) - v_z \quad (4.15)$$

where v_{inj} consists of v_{s_h} for harmonic compensation in the supply voltage and v_z for compensating the voltage drop across the line impedance.

After the initialization period of the UPQC, the amplitude of v_L^* will be fixed to the predetermined amplitude of v_{s_f} . In the event of a sag (or swell) in the supply voltage, v_s will become

$$v_s = (V_{s_f} - \Delta V_{s_f}) \sin \omega t + \sum_{h=3,5,\dots}^N (V_{s_h} - \Delta V_{s_h}) \sin(h\omega t - \theta_{s_h}) \quad (4.16)$$

where ΔV_{s_f} and ΔV_{s_h} represent a corresponding sag in the amplitudes of its fundamental and harmonic components. In order for v_L to track v_L^* , the injected voltage of (4.13) will become

$$v_{inj} = -\Delta V_{s_f} \sin \omega t + \sum_{h=3,5,\dots}^N (V_{s_h} - \Delta V_{s_h}) \sin(h\omega t - \theta_{s_h}) - v_z \quad (4.17)$$

In (4.17) above, the first and second terms compensate for the voltage sag in the amplitudes of its fundamental and harmonic components respectively, while the last term compensates for the voltage drop across the line impedance.

Similarly, i_L can be also represented by a Fourier series:

$$\begin{aligned}
 i_L &= I_{L_f} \sin(\omega t - \theta_{L_f}) + \sum_{h=3,5,\dots}^N I_{L_h} \sin(h\omega t - \theta_{L_h}) \\
 &= I_{L_f} \sin \omega t \cos \theta_{L_f} - I_{L_f} \cos \omega t \sin \theta_{L_f} + \sum_{h=3,5,\dots}^N I_{L_h} \sin(h\omega t - \theta_{L_h}) \\
 &= i_{L_{f,p}} + i_{L_{f,q}} + i_{L_h}
 \end{aligned} \tag{4.18}$$

where $i_{L_{f,p}}$ and $i_{L_{f,q}}$ are the load instantaneous fundamental phase and quadrature currents, which are always in phase and 90° out of phase with the supply voltage respectively. I_{L_f} represents the amplitude of i_L and θ_{L_f} represents the phase angle difference between v_{S_f} and i_{L_f} . i_{L_h} represents the harmonic components of i_L , with amplitudes I_{L_h} and phase angles θ_{L_h} .

From Figure 4.1, (4.6) can be re-written as:

$$i_s + i_{inj} = i_L + i_{C_{sh}} = i_{L_{f,p}} + i_{L_{f,q}} + i_{L_h} + i_{C_{sh}} \tag{4.19}$$

In order for the shunt active filter of the UPQC to perform harmonic compensation and power factor correction, i_s^* (the reference for i_s to track) is set to be $i_{L_{f,p}}$:

$$i_s^* = i_{L_{f,p}} = I_{L_f} \cos \theta_{L_f} \sin \omega t \tag{4.20}$$

where $\sin \omega t$ is the unit vector of the fundamental component v_{S_f} of the supply voltage v_s in (4.12). Thus, in order to achieve (4.20), the injected current i_{inj} in (4.19) will be

$$i_{inj} = i_{L_{f,q}} + i_{L_h} + i_{C_{sh}} \tag{4.21}$$

where i_{inj} consists of i_{L_h} for harmonic compensation at the load side, $i_{L_{f,q}}$ for power factor correction at the supply side and $i_{C_{sh}}$ for supplying the leakage capacitor current.

As detailed in this subsection, the fundamental and harmonic components of v_s and i_L have to be derived. The following subsection 4.3.2 discusses the modeling of v_s and i_L into their fundamental and harmonic components into state-space representations. Then, the use of Kalman filters to derive/extract these components will be discussed in subsection 4.3.4.

4.3.2 Modeling of the exogenous signals

Since all the exogenous signals v_s, i_L, v_L^*, i_s^* are periodic, they can therefore be represented by a state-space model. For example, v_s in (4.13) can be represented by

$$\begin{aligned} \dot{\xi}_{v_s} &= A_{v_s} \xi_{v_s} \\ &= \begin{bmatrix} 0 & \omega_1 & 0 & 0 & \cdots & 0 & 0 \\ -\omega_1 & 0 & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & 0 & \omega_3 & \cdots & 0 & 0 \\ 0 & 0 & -\omega_3 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & 0 & \omega_N \\ 0 & 0 & 0 & 0 & \cdots & -\omega_N & 0 \end{bmatrix} \begin{bmatrix} V_{s_f} \sin(\omega_1 t) \\ V_{s_f} \cos(\omega_1 t) \\ V_{s_3} \sin(\omega_3 t + \theta_{s_3}) \\ V_{s_3} \cos(\omega_3 t + \theta_{s_3}) \\ \vdots \\ V_{s_N} \sin(\omega_N t + \theta_{s_N}) \\ V_{s_N} \cos(\omega_N t + \theta_{s_N}) \end{bmatrix} \end{aligned} \quad (4.22)$$

$$v_s = C_{v_s} \xi_{v_s} = [1 \ 0 \ 1 \ 0 \ \cdots \ 1 \ 0] \xi_{v_s} \quad (4.23)$$

where the frequencies $\omega_h = h\omega$, $h=1,3,5,\dots,N$. The first component of the state-vector ξ_{v_s} is the fundamental component v_{s_f} of v_s , and the $3^{rd}, 5^{th}, \dots, N^{th}$

components of ξ_{v_s} are the harmonic components of v_s . Likewise, i_L, v_L^*, i_s^* can be modeled into a state-space form, although obviously the reference signals are sinusoidal and their state vectors consist of two components only and related to the fundamental components of v_s and i_L . All four state-space models can be combined into the following general form:

$$\dot{\xi} = \tilde{A}\xi \quad (4.24)$$

$$(v_s \ i_L)^T = \tilde{C}_w \xi \quad (4.25)$$

$$d = (v_L^* \ i_s^*)^T = \tilde{C}_d \xi \quad (4.26)$$

which is called the exogenous system in this thesis. It may be noted that (4.24)-(4.25) is comprehensive and large enough to model the entire harmonic spectrum of v_s and i_L . In reality, certain high frequency components and/or even harmonics may exist. As such, the exosystem state ξ consists of odd harmonics up to the 29th order in the MVR-controlled UPQC. (Note: The selection for the exosystem state to contain harmonics up to the 29th order serves to be a reference for study in the thesis only. In practice, a user may perform a THD measurement to find out where are the dominant harmonic distortions and select the order of the exosystem state accordingly. However, there is a trade-off between the sampling rate and the order of the harmonics selected, i.e., a higher order will require more computational effort and result in a lower sampling rate and a poorer performance.) The unmodelled harmonic components, i.e., harmonics above the 29th order, may be a source of modeling error and may affect the performance of the MVR-controlled UPQC. (Note that (4.26), i.e., $d = (v_L^* \ i_s^*)^T = \tilde{C}_d \xi$, is essentially the fundamental components of v_s and i_L at 50Hz, and no unmodelled components are present in d .)

The values of ξ , which will be needed by the MVR in the following subsection 4.3.3, can be obtained by passing the measurable signals v_s and i_L into a Kalman filter designed for the state-space model (4.24)-(4.26). Since estimating the state ξ is equivalent to extracting the fundamental and harmonic components of the exogenous signals v_s and i_L , the Kalman filter is in fact a replacement of the extraction circuit in conventional harmonic compensation designs.

In some previous work of harmonic estimation [44]-[46], similar approaches of Kalman filtering have been used. Subsection 4.3.4 will discuss more on the use of Kalman filters as part of the control design.

4.3.3 Multi-Variable Regulator (MVR)

Substituting the exogenous system (4.24)-(4.26) into the state-space model of the UPQC in (4.10)-(4.11), we obtain the following combined model:

$$\dot{x} = Ax + B_0\xi + B_2u \quad (4.27)$$

$$y = Cx + D_0\xi + D_2u \quad (4.28)$$

in which $B_0 = B_1\tilde{C}_w$ and $D_0 = D_1\tilde{C}_w$.

Since both the reference r and the excitation ξ for the general system (4.27)-(4.28) are periodic, for a zero steady-state error, i.e., $e_{ss} = 0$, the steady-state behaviours of u , x and y should also be periodic with the same period. Let u_{ss} and x_{ss} can be written as linear functions of ξ , given by $u_{ss} = U\xi$ and $x_{ss} = X\xi$ or $\dot{x}_{ss} = X\dot{\xi}$, where U and X are matrix gains. From (4.27) and (4.28), we can write

$$\dot{x}_{ss} = Ax_{ss} + B_0\xi + B_2u_{ss} \quad (4.29)$$

$$y_{ss} = Cx_{ss} + D_0\xi + D_2u_{ss} \quad (4.30)$$

Using $\dot{x}_{ss} = X\dot{\xi} = XA\xi$ and assuming the output y is regulated to the reference (4.26),

i.e., $d = \tilde{C}_d\xi$, they can be further written as

$$X\tilde{A}\xi = Ax_{ss} + B_0\xi + B_2u_{ss} \quad (4.31)$$

$$\tilde{C}_d\xi = Cx_{ss} + D_0\xi + D_2u_{ss} \quad (4.32)$$

For steady state condition pertaining to u_{ss} and x_{ss} , through linear algebraic manipulation, we can obtain the following conditions, known as the regulator equations:

$$X\tilde{A} = AX + B_0 + B_2U \quad (4.33)$$

$$\tilde{C}_d = CX + D_0 + D_2U \quad (4.34)$$

which are essentially a pair of linear matrix equations that can be used to derive U and X .

Then we can build a state-feedback controller to stabilize the deviation from this steady-state condition. For example, a classical state-feedback will be of the form

$$\dot{u} = F\dot{x} \quad (4.35)$$

or equivalently,

$$u - u_{ss} = F(x - x_{ss}) \quad (4.36)$$

and the MVR control law is proposed to be

$$u = u_{ss} + F(x - x_{ss}) = U\xi + F(x - X\xi) \quad (4.37)$$

Multiplying (4.33)-(4.34) by ξ , subtracting them from (4.27)-(4.28) and then applying (4.24), (4.26) and (4.29), we obtain the overall closed-loop system to be

$$\frac{d}{dt}(x - X\xi) = (A + B_2F)(x - X\xi) \quad (4.38)$$

$$e = (C + D_2F)(x - X\xi) \quad (4.39)$$

where $e = y - d$ is the tracking error. Hence, if the matrix gain F is chosen such that

$A + B_2F$ is Hurwitz (all eigenvalues are in the closed left-half plane), the closed-loop

system is (globally) stable, implying $e(t) \rightarrow 0$ in the steady state regardless of the initial conditions of x and ξ . In practice, e is satisfactorily small but nonzero due to the nonlinear effects of the PWM.

The control law (4.37) requires the values of the exogenous state ξ and the plant state x . The former can be estimated by Kalman filters, to be described in the following subsection 4.3.4, which are called the Exogenous and Reference Kalman filter in this thesis. The latter is composed of physical quantities and can possibly be measured, but the added sensors will increase the cost. Therefore, a state observer called the Plant Kalman filter is adopted in this thesis to produce an estimate $\hat{x}$ of x , which would be used in the control law (4.37). The control design is summarized in Figure 4.2.

Figure 4.2: MVR controller.

4.3.4 Kalman filters as extraction circuits and state observers

Although the control law (4.37) is effective, it is a state-feedback control law and assumes that both the exogenous state ξ and the plant state x are available. In reality, it is possible to measure the latter using sensors, since the plant is a real physical system. However, it is impossible to measure ξ directly since the exogenous system is actually a virtual system. Furthermore, even though it is possible

to measure x , it might be undesirable to install so many sensors into the system since it will increase the cost of installing a UPQC in the power distribution system. Without direct measurements of the state ξ and x , a possible way to estimate them reliably is to use Kalman filters. The state-estimates provided by the Kalman filters can then be utilized by the state-feedback control law (4.37). In addition, estimating the state of the exogenous system ξ is equivalent to extracting the fundamental and harmonic components of the exogenous signals v_s and i_L . Therefore, the Kalman filter here is in fact a replacement of the extraction circuits in conventional harmonic compensation designs.

Here, our exogenous system (4.24)-(4.26) constructed in subsection 4.3.2 can be decomposed into two subsystems, one for $(v_s \ i_L)^T$ with the state-vector ξ_w and the other for the reference signal d with the state-vector ξ_d :

$$\dot{\xi} = \frac{d}{dt} \begin{bmatrix} \xi_w \\ \xi_d \end{bmatrix} = \tilde{A} \xi = \begin{bmatrix} A_w & 0 \\ 0 & A_d \end{bmatrix} \begin{bmatrix} \xi_w \\ \xi_d \end{bmatrix} \quad (4.40)$$

and specifically, from (4.25) and (4.26), we have:

$$(v_s \ i_L)^T = \tilde{C}_w \xi + w = \begin{bmatrix} C_w & 0 \end{bmatrix} \begin{bmatrix} \xi_w \\ \xi_d \end{bmatrix} \quad (4.41)$$

$$d = (v_L^* \ i_s^*)^T = \tilde{C}_d \xi = \begin{bmatrix} 0 & C_d \end{bmatrix} \begin{bmatrix} \xi_w \\ \xi_d \end{bmatrix} \quad (4.42)$$

To obtain ξ_w , we measure $(v_s \ i_L)^T$ and apply a Kalman filter to the first subsystem:

$$\dot{\xi}_w = A_w \xi_w \quad (4.43)$$

$$(v_s \ i_L)^T = C_w \xi_w \quad (4.44)$$

so that the state ξ_w for $(v_s \ i_L)^T$ can be estimated, which actually consists of the fundamentals v_{s_f} , $i_{L_{f,p}}$ as well as the harmonics of v_s and i_L . This Kalman filter is known as the Exogenous Kalman filter in this thesis.

As discussed earlier in subsection 4.3, the value of the state, i.e., ξ_d , for the references $(v_L^* \ i_s^*)^T$ is related to the values of the components in ξ_w that are associated with the fundamentals v_{s_f} , $i_{L_{f,p}}$. Precisely, the state for v_L^* and for v_{s_f} should be the same in the initial period of operation, before any voltage sags or swells occur. Later, they will be decoupled and the magnitude of v_{s_f} will be fixed.

On the other hand, the state for i_s^* is related to those for v_{s_f} and $i_{L_{f,p}}$ by equation (4.20). Therefore, it will adapt to the variations of the supply and load. From these relationships between ξ_d and ξ_w , it can be seen that once ξ_w , the state for $(v_s \ i_L)^T$, is estimated, the state ξ_d for the reference d should be determined accordingly. However, in order to obtain a smoother estimate of (in case of sudden changes of the operating conditions in the supply or load etc.), a 2nd Kalman filter called the Reference Kalman filter can also be applied here. Note that the second subsystem of the exogenous system may be written as:

$$\dot{\xi}_d = A_d \xi_d \quad (4.45)$$

$$\xi_d = \xi_w \quad (4.46)$$

The output equation above means that the Reference Kalman filter estimates the state ξ_d by measuring the ξ_d deduced from the estimate of the state ξ_w . In other words,

the first Kalman filter, i.e., the Exogenous Kalman filter, measures $(v_s \ i_L)^T$ to estimate ξ_w based on the first subsystem (4.40)-(4.41). From this $\hat{\xi}_w$, the corresponding ξ_d is computed. Then this computed ξ_d is passed to the second Kalman filter, i.e., the Reference Kalman filter, to obtain a filtered version $\hat{\xi}_d$ based on the second subsystem (4.45)-(4.48). Combining $\hat{\xi}_w$ and $\hat{\xi}_d$, we form an estimate of the total exogenous state $\hat{\xi}$, which will be used by the state-feedback control law (4.37). These relations of the two Kalman filters, i.e., the Exogenous and the Reference Kalman filters, to obtain the total exogenous state $\hat{\xi}$, are shown in Figure 4.3.

The application of the Kalman filter to estimate the plant state x is more straightforward. In Figure 4.3, this Kalman filter simply uses the known inputs of the plant v_s, i_L, u (i.e., the exogenous input as well as the control input, both of which are known) and the outputs of the plant $y = (v_L \ i_s)^T$ to estimate the state x . This is called the “Plant” Kalman filter in this thesis. The estimate $\hat{x}$ and $\hat{\xi}$ will then be combined and passed to the state-feedback control law (4.37) to calculate the control signal u , as shown in Figure 4.4

Figure 4.3: Kalman filters as Extraction Circuits and State Observers.

In summary, by applying the exogenous and reference Kalman filters and the plant Kalman filter, only four measurements, v_s , i_s , v_L and i_L are required. Indeed, these are the four variables that one would naturally choose to measure from the power system point of view. The overall MVR controller with Kalman filters as Extraction Circuits and State Observers is shown in Figure 4.4.

Figure 4.4: MVR controller with Kalman filters as Extraction Circuits and State Observers.

4.3.5 Self-charging circuit

This research proposes that the UPQC operate without relying on an external DC supply. The supply side has to deliver additional real power through the shunt active filter to control the DC link voltage. Here, a self-charging control design is proposed in Fig. 4.5 to meet this objective.

The charging current i_{dc} takes the form of $I_{dc}(k)\sin\omega t$ where the sampling rate $k = t/50$ and the peak amplitude $I_{dc}(k)$ are updated every cycle but remain fixed within the cycle.

To regulate the DC capacitor voltage at the desired level, additional real power is to

be drawn by the shunt active filter of the UPQC from the supply side to charge the two capacitors of the DC link [90]. Let the energy E stored in each capacitor be represented by

$$E = \frac{1}{2} C \left(\frac{V_{dc}}{2} \right)^2 \quad (4.47)$$

where C is the value of each capacitor and $\frac{V_{dc}}{2}$ is the voltage of each capacitor.

When the value of the dc capacitor voltage varies from V_{dc} to V_{dc}' after the charging process, the energy E' for each capacitor will now be

$$E' = \frac{1}{2} C \left(\frac{V_{dc}'}{2} \right)^2 \quad (4.48)$$

Hence, the difference ΔE between E' and E is represented as

$$\begin{aligned} \Delta E &= E' - E \\ &= \frac{1}{2} C \left[\left(\frac{V_{dc}'}{2} \right)^2 - \left(\frac{V_{dc}}{2} \right)^2 \right] \end{aligned} \quad (4.49)$$

On the other hand, the charging energy E_{ac} delivered by the supply side to the inverter for each capacitor will be

$$\begin{aligned} E_{ac} &= Pt \\ &= (V_{rms} I_{dc,rms} \cos \phi) t \end{aligned} \quad (4.50)$$

where P is the additional real power required, t is the charging time, V_{rms} is the rms value of the instantaneous fundamental supply voltage v_{S_f} , $I_{dc,rms}$ is the rms value of the instantaneous charging current i_{dc} and ϕ is the phase difference between the supply voltage and the charging current. However, t can be defined as $\frac{T}{2}$ since the

charging process only takes place for half a cycle for each capacitor (to be explained

in Section 4.5.1), where T is the period of the supply frequency. V_{rms} and $I_{dc,rms}$ can be expressed in terms of their peak value V and I_{dc} , respectively. Assuming $\cos\phi = 1$.

Hence, substituting all these terms into (4.50), we have

$$\begin{aligned} E_{ac} &= \frac{V}{\sqrt{2}} \frac{I_{dc}}{\sqrt{2}} \frac{T}{2} \\ &= \frac{VI_{dc}T}{4} \end{aligned} \quad (4.51)$$

Neglecting the switching losses in the inverter and according to the energy conservation law, we have

$$\begin{aligned} \Delta E &= E_{ac} \\ \frac{1}{2}C \left[\left(\frac{V_{dc}'}{2} \right)^2 - \left(\frac{V_{dc}}{2} \right)^2 \right] &= \frac{VI_{dc}T}{4} \\ I_{dc} &= \frac{2C \left[\left(\frac{V_{dc}'}{2} \right)^2 - \left(\frac{V_{dc}}{2} \right)^2 \right]}{VT} \end{aligned} \quad (4.52)$$

Next, let us define

$$e_{dc}(k) = (V_{dc}^*)^2 - (V_{dc}(k))^2 \quad (4.53)$$

$$I(k+1) = I(k) + e_{dc}(k) \quad (4.54)$$

a discrete state-space model can be derived:

$$\begin{bmatrix} e_{dc}(k+1) \\ I(k+1) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} e_{dc}(k) \\ I(k) \end{bmatrix} + \begin{bmatrix} 6VT/C \\ 0 \end{bmatrix} [I_{dc}(k)] \quad (4.55)$$

based on which a control law for $I_{dc}(k)$ is proposed as follows:

$$I_{dc}(k) = K_1 e_{dc}(k) + K_2 I(k) \quad (4.56)$$

where the gains K_1 and K_2 are optimized through the Linear Quadratic Regulator (LQR) theory which can easily provide better charging characteristics, e.g., no

overshoot, fast settling time, than other conventional control design methods.

Figure 4.5: A LQR control topology for the regulation of the DC link voltage of the UPQC.

To incorporate the proposed self-charging scheme, the only modification to the control design in Section 4.3.4 is to replace i_L by $i_L + i_{dc}$. The derived i_s^* will become

$$i_s^* = (I_{L_f} \cos \theta_{L_f} + I_{dc}(k)) \sin \omega t \quad (4.57)$$

and i_{dc} , which is supplied by i_s , will be used to charge the capacitors of the DC link through the shunt active filter of the UPQC shown in Fig. 4.6. Re-arranging (4.21) with (4.57), we have

$$i_{inj} = i_L - i_s + i_{Csh} = i_{L_{f,q}} + i_{L_h} - i_{dc} + i_{Csh} \quad (4.58)$$

if i_s is made to track i_s^* in (4.57).

Despite the LQR controller to regulate the dc link voltage of the UPQC in Figure 4.5, small variations in V_{dc} (which is the sum of the desired dc voltage levels of the dc link) occur. Although V_{dc} is assumed to be fixed in our control design, $u \frac{V_{dc}}{2}$ always appears as a product term in the state-space model in (4.10), (4.11). Therefore, if the

control u is calculated based on V_{dc}^* , it suffices to ensure that the actual control signal

u_{inj} satisfies $u_{inj} \frac{V_{dc}}{2} = u \frac{V_{dc}^*}{2}$, or equivalently:

$$u_{inj} = u \frac{V_{dc}^*}{V_{dc}} \quad (4.59)$$

e.g., if u_1 calculated based on $V_{dc}^*=300\text{V}$ is 0.5, then u_{1inj} will be 1 when the actual V_{dc} drops to 150V. Hence, the control performance will remain the same even though V_{dc}^* and V_{dc} are not exactly equal. Note however that u_{inj} instead of u should be limited to ± 1 (to ensure that the active filters in the UPQC operate in linear modulation), which is equivalent to u being limited to $\pm \frac{V_{dc}}{V_{dc}^*}$. Therefore, the self-charging controller proposed in this section is still needed so that the actual dc link voltage level V_{dc} will not drop too much below the desired value V_{dc}^* .

4.4 Injection Circuit

The control signals u_{inj} , computed by the MVR controller has been detailed in the previous Section 4.3. To implement them for the series and shunt active filters of the UPQC, an injection circuit, which is made up of VSIs and interfacing low-pass filters, as shown in Figure 4.6, is needed. The injection circuit consists of i) the UPQC which includes the series and shunt active filters (with each of the individual active filter made up of half bridge inverter), ii) an injecting transformer for interfacing the output of the series active filter with the distribution system, iii) the 2nd order interfacing low-

pass filters for both the series and shunt active filters of the UPQC, and iv) sensory circuits for the sampling of the required signals described in the previous section.

The control signals generated by the control circuit will be the switching schemes for the respective active filters. Since u_{inj} takes continuous values from -1 to 1, they will be implemented in a PWM control as switching signals for the VSIs of series and shunt active filters of the UPQC. The VSI outputs will be passed through the interfacing low-pass filters to eliminate the high switching frequencies, as discussed in Chapter 3.

4.5 Overall Control Configuration

The system block diagram of a single-phase representation of the MVR-controlled UPQC, with Kalman filters, is shown in Figure 4.6. The inputs to the controller will be $v_s(k)$, $i_s(k)$, $v_L(k)$, $i_L(k)$ and $V_{dc}(k)$ that will be sampled by voltage and current sensors, while the rest of the state of the system in the state-space model in Figure 4.1 will be estimated digitally by Kalman filters. As described in the previous sections, $v_s(k)$ and $i_L(k)$ will be passed to the exogenous and the reference Kalman filter, which will extract ξ . On the other hand, $v_s(k)$, $i_s(k)$, $v_L(k)$ and $i_L(k)$ are all passed to a plant Kalman filter to extract the plant state x . The estimates of ξ and x will then be forwarded to the MVR to compute the control signals $u = (u_1 \ u_2)^T$, which

will be converted into the real control signal $u = (u_{1inj} \ u_{2inj})^T$ after taking into account the actual DC voltage level V_{dc} of the DC link.

Hence, the load voltage v_L and the supply current i_s will be regulated to become a pure sine wave at the desired frequency of 50Hz. A near unity power factor will be achieved at the supply side. Also, the UPQC operates with a self-charging circuit.

Figure 4.6: System block diagram of MVR-controlled UPQC with Kalman filters.

The MVR controller is illustrated through a single-phase power distribution system here. To apply it to a three-phase power distribution system, one would just need to duplicate three sets of the same controller, each working independently in the different phases, to generate the switching sequence for the individual active filters of the UPQC. The 12-IGBT configuration with midpoint of the two capacitors grounded (as shown in Figure 4.7) can be selected as the 3-phase UPQC configuration. This will allow the active filters of the various phases (i.e., the six IGBT branches) to operate as if they are six single-phase VSIs. The switching status of IGBT in the same branch is complementary of one another to prevent short-circuit of the branch.

4.5.1 Illustration of the operation of the UPQC

The switching sequence of the VSIs of the UPQC will be discussed next. Each IGBT in each VSI is switched on and off under two conditions, i.e., when v_s is at its positive half cycle and negative half cycle. In Figure 4.8, it is assumed that both the capacitors in the DC link have the same capacitance C and same voltage $\frac{V_{dc}}{2}$.

At $t=0$, we have $S_1 = S_2 = 1$, assuming v_s is at its positive half cycle. The upper IGBTs of the VSIs will conduct as shown in Figure 4.8(a). The bold line represents the path of the current flow of the two VSIs. From Figure 4.8(a), it can be seen that the shunt VSI is injecting $i_{L_{f,q}} + i_{L_h}$ into the supply network, $i_{C_{sh}}$ into the low-pass filter and the series VSI is injecting a positive v_{inj} . The return current paths for the shunt and series VSIs are shown by the bold dotted line in Figure 4.8(a). With the upper IGBT of the series VSI turned on, the current of the series VSI will flow in a way as shown in Figure 4.7(a) to inject a positive v_{inj} .

At this moment, the switched voltages across both VSI outputs are $\frac{V_{dc}}{2}$. However, assume now $S_1 = S_2 = 0$, implying that $\bar{S}_1 = \bar{S}_2 = 1$. The lower IGBTs of both VSIs are switched on, but they will not be in full conduction instantaneously while the upper IGBTs will not be turned off instantaneously. At this intermediate stage, the voltages across the upper IGBTs are building up and causing the upper diodes to be forward biased since V_{c1} is lower than $\frac{V_{dc}}{2}$. As shown in Figure 4.8(b), while the lower IGBT of the

shunt VSI is trying to achieve full conduction, the charging current i_{dc} flows in to charge up C_1 and $i_{C_{sh}}$ discharges through the upper diode of the shunt VSI till the voltage across the upper IGBT of the shunt VSI builds up to reverse bias it. After this intermediate stage, the lower IGBT of the shunt VSI will be in full conduction and the switched voltage across the VSI output will be $-\frac{V_{dc}}{2}$. Similarly, the voltage across the upper IGBT of the series VSI is building up and causing its upper diode to be forward biased since V_{c1} is also lower than $\frac{V_{dc}}{2}$ at the series VSI output. At this instant, C_{se} will discharge through the upper diode of the series VSI and maintain a positive v_{inj} as shown in Figure 4.7(b). After this intermediate stage, the lower IGBT of the series VSI will be in full conduction and the switched voltage across its VSI output will be $-\frac{V_{dc}}{2}$.

Now assume $S_1 = S_2 = 0$ at the moment when the supply voltage is at its negative half cycle. The lower IGBTs of both VSIs are in full conduction as shown in Figure 4.8(c). The bold solid line in Figure 4.8(c) illustrates very clearly the path of current flow $i_{L_{f,q}} + i_{L_h}$ and $i_{C_{sh}}$ of the shunt VSI and the current flow of the series VSI such that the series VSI is injecting a negative v_{inj} . The return current paths for the shunt and series VSIs are shown in bold dotted line. The switched voltages across both VSI outputs are $-\frac{V_{dc}}{2}$.

When $S_1 = S_2 = 1$, the upper IGBTs of both VSIs are turned on and the lower IGBTs off. The voltages across the lower IGBTs of both VSIs build up while the upper IGBTs

are trying to achieve full conduction. As a result, the lower diodes of both VSIs are forward biased since V_{c2} is lower than $-\frac{V_{dc}}{2}$. The conduction of the diode for the shunt VSI causes i_{dc} to flow and charge up C_2 and $i_{C_{sh}}$ to discharge till the voltage across the lower IGBT of the shunt VSI builds up to reverse bias it as shown in Figure 4.7(d). Similarly, the conduction of the lower diode for the series VSI allows C_{se} to discharge through it and maintain a negative v_{inj} in Figure 4.8(d). After this intermediate stage, the upper IGBTs of both VSIs will be in full conduction and the switched voltages across both VSI outputs will be $\frac{V_{dc}}{2}$.

(a)

(b)

(c)

(d)

Figure 4.8: Switching and self-charging sequences of the UPQC.

In this chapter, we have proposed and designed a controller for the UPQC, which is adaptive to the variations of the supply and load operating conditions of a power distribution system. An Exogenous and a Reference Kalman filters are used to extract the fundamental and harmonic components of the measured supply voltage and load current as well as to derive a reference for the load voltage and supply current to track. Estimation of the state variables of the UPQC is also carried out by the Plant Kalman filter, instead of sensory hardware, to reduce costs. Then, a closed-loop model-based MVR is used to control the UPQC, which can ensure global stability and zero steady-state error in principle. A LQR-based self-charging circuit is incorporated into the control design so that the UPQC can operate without relying on an external DC supply. The proposed circuit seeks to minimize the effect of the DC link voltage fluctuations on the performance of the UPQC.

The adaptive performance of the UPQC will be first verified through simulation studies, to be discussed in Chapter 7. Experimental studies on a DSP platform to validate its real-time implementation will also be discussed in Chapter 7. Its performance will also be further compared against the Model-Based H_∞ -controlled UPQC (to be discussed in Chapter 5) and a PI-controlled UPQC (discussed in Chapter 3) in Chapter 7.

CHAPTER 5

MODEL-BASED H_∞ CONTROL OF UNIFIED POWER QUALITY CONDITIONER

5.1 Introduction

This chapter extends the research work on the MVR controlled UPQC to propose and develop a complete solution for the operation of a UPQC from the control theoretic point of view. In short, we call it the H_∞ controlled UPQC.

The proposed approach here is a model-based feedforward/feedback control. Based on the model developed in Chapter 4, a feedforward control is applied to make the model outputs, i.e., the load voltage and the supply current, to track certain desired waveforms. It can ensure zero steady-state tracking error if there is no modeling error. Otherwise, the negative effects introduced by any modeling error can be mitigated by the feedback control simultaneously. This approach provides direct feedback to the controller and shows how well the PQ of the network outputs can be improved. The coupling effect between the series and shunt filters is also taken care of. Similarly to the MVR-based controlled UPQC in chapter 4, digital Kalman filters are implemented in place of hardware sensors to minimize manufacturing and maintenance costs. To minimize the complexity of the UPQC, the gains of the controller and the Kalman filters are calculated offline and then implemented as constant gains online. Also, the

proposed control approach ensures that the UPQC can still operate under slight frequency variations in the supply voltage.

All in all, this chapter presents a solution to the control of Unified Power Quality Conditioner (UPQC) for power quality improvement in power distribution systems. The problem formulation allows not only harmonic compensation, but also voltage sags/swells, load demand changes and power factor correction to be tackled in a unified framework.

Hence besides incorporating the functions of the MVR-based UPQC, the proposed Model-Based H_∞ controlled UPQC in this chapter combines the multivariable regulator theory with H_∞ loop-shaping, so that zero steady-state error, robustness to modeling uncertainties and insensitivity to supply frequency variations can be accomplished simultaneously. This provides a complete theoretical solution to all the abovementioned power quality problems.

In what follows, this chapter provides a complete solution for the operation of a UPQC from the control theoretic point of view, based on a multi-input-multi-output (MIMO) state-space model developed in Chapter 4. The design of the controller of the proposed Model-Based H_∞ -controlled UPQC will be detailed in the subsequent sections of this chapter.

5.2 Control Design

In this research, another model-based coordinated control is proposed for the UPQC. The aim of this control is essentially the same as the MVR-control, that is to regulate the load voltage and the supply current of the plant to track certain desired sinusoidal waveforms directly, so that they are undistorted. The coupling effect between the series and shunt filters is also accounted for in this control. It is an feedforward (FF)/feedback (FB) control, such that, in the absence of any modeling error, zero steady-state error can be achieved by the FF control in principle. Otherwise, the negative effects of any modeling errors introduced are mitigated by the FB control.

In general, the proposed control approach combines:

- An FF control that makes use of the linear regulator theory [42]-[43] to eliminate the tracking error between the model outputs and their desired references in the steady state, if there is no modeling error.
- An FB control to eliminate the effects of any modeling errors and maintain a satisfactory performance under slight frequency variations in the supply voltage. A loop-shaping approach that effectively extends the idea of repetitive control, as described in [88]-[89] and [129], to tolerate small frequency variations is adopted. To provide an overall robust stabilization, H_∞ optimization ([47]-[48], [130]) is applied to maximize the stability margin of the system.

Furthermore, the control gains can be calculated offline and implemented as constants. This control approach incorporates Kalman filters as extraction circuits to

extract the harmonic spectral of the supply voltage and load current. All these can reduce the implementation complexity and cost significantly.

Using the UPQC model discussed in the previous chapter, the proposed control law (that consists of the FF and FB controls) for the UPQC is given by

$$u = u_{ff} + u_{fb} \quad (5.1)$$

where u_{ff} refers to the FF control law and u_{fb} refers to the FB control law. Ideally, u_{ff} is the FF control law that guarantees zero tracking error between the plant outputs, i.e., $y = (v_L \ i_s)^T$, and their desired references in the steady state, if there is no modeling error and u_{fb} is a stabilizing FB control law.

Generally, the tracking error might tend to a small but nonzero value, due to the truncation of the Fourier series (to be explained below), and it might also have a large transient energy, due to voltage sags/swells or load demand changes. The former may be regarded as a modeling error and the latter a disturbance. Therefore, a task of the FB controller u_{fb} is to minimize the effects of such modeling error and disturbance on the tracking error. The following section will first discuss how to formulate the FF control law based on the linear regulator theory, and then how to formulate the FB control law based on the idea of repetitive control theory and H_∞ loop-shaping to provide overall system stabilization.

The following subsections detail the design of the FF and FB controls, followed by the discretization of the controller for experimental implementation.

5.2.1 Design of feedforward control

Likewise, the first step of our control design is to represent the periodic disturbance of the model $(v_s \ i_L)^T$ by another state-space model known as the exosystem. As discussed in the Subsection 4.3.2, the basic idea is that any periodic signal, i.e., v , that consists of a finite number of harmonics, i.e., can be represented by this state-space model (or the exosystem):

$$\dot{\xi}_v = A_v \xi_v \quad (5.2)$$

$$v = C_v \xi_v \quad (5.3)$$

As such, this same approach to model $(v_s \ i_L)^T$ into the exosystem ξ (to consist of odd harmonics up to the 29th order) is also adopted in the H_∞ -controlled UPQC. To further reduce the effects of the unmodelled harmonic components, we incorporate the unmodelled part (harmonic components >29th order) into (4.24) and rewrite (4.24)-(4.26) into (5.4)-(5.5), where the estimate of ξ can be estimated by a Kalman filter to be:

$$\dot{\hat{\xi}} = A_\xi \hat{\xi} + Lw \quad (5.4)$$

$$\hat{v} = C_\xi \hat{\xi} \quad (5.5)$$

Thus, the modeling for the $(v_s \ i_L)^T$ and the references $(v_L^* \ i_s^*)^T$ will have to be altered and is detailed below. (For clarity, different notations pertaining to certain associated matrices and parameters are used.)

In general, the observer gain L can be designed from a steady-state Kalman filter and $w = v - \hat{v}$ is called the innovation, which is essentially the difference between the

target signal $v(t)$ and the estimate $\hat{v}(t)$ (or the unmodelled part described above), generated from the Kalman filter, such that $w(t)$ should tend to zero as $t \rightarrow \infty$ provided that the model (4.10)-(4.11) is exact and the matrix $A_\xi - LC_\xi$ is stable. For example, putting $w = v - \hat{v}$ into (5.4) and using (5.5), we have

$$\begin{aligned}
 \dot{\hat{\xi}} &= A_\xi \hat{\xi} + L(v - \hat{v}) \\
 &= A_\xi \hat{\xi} + L(v - C_\xi \hat{\xi}) \\
 &= A_\xi \hat{\xi} + Lv - LC_\xi \hat{\xi} \\
 &= (A_\xi - LC_\xi) \hat{\xi} + Lv
 \end{aligned} \tag{5.6}$$

Similar to the control design in Chapter 4, we let the desired sinusoidal waveforms that v_L and i_s are to track be represented by $d = (v_L^* \ i_s^*)^T$. If harmonic compensation is the only task, we simply need to apply the above Kalman filter to v_s and i_L to extract their fundamentals v_{s_f} and i_{L_f} respectively (which are given by the first components of the states $\hat{\xi}$ of the two Kalman filters) and let v_L^* and i_s^* be equated to them respectively. Unfortunately, this simple mechanism does not extend to handle voltage sag/swell compensation and power factor correction easily. In this chapter, we propose to use two Kalman filters similar to (5.4)-(5.5) above to generate $(v_L^* \ i_s^*)^T$, an estimate of d . Of course, the associated A_ξ -matrices are only 2 by 2 since both v_L^* and i_s^* are purely sinusoidal, but the corresponding innovations w must be designed carefully, as detailed below:

- Normally, v_L^* is supposed to be v_{s_f} , the first state component of the Kalman filter for v_s . However, if any voltage sag/swell occurs in v_s , the reference v_L^* should be decoupled from v_{s_f} so that it will not be affected. In other words, the control

system is designed to maintain the magnitude of v_L^* even when the voltage sag/swell occurs. Therefore, we may let the innovation for v_L^* be

$$w = \begin{cases} v_{s_f} - v_L^* & \text{if no voltage sag / swell} \\ 0 & \text{if voltage sag / swell} \end{cases} \quad (5.7)$$

In practice, voltage sag/swell might occur anytime and v_L^* can be decoupled from v_{s_f} once it settles down after an initialization period.

- For the current, we synchronize the phase of i_s^* with that of v_{s_f} , instead of synchronizing it with that of i_{L_f} (the first state-component of the Kalman filter for i_L). This is basically the power factor correction desired. (Note: i_s^* is the reference for i_s to be regulated to). This will be achieved through the operation of the shunt active filter of the UPQC in a PWM using the control signal generated by the controller.

Hence, the innovation for i_s^* is given by

$$w = \mathcal{W}_{s_f} - i_s^* \quad (5.8)$$

with the scaling factor γ designed such that when the innovation (5.8) vanishes, the conservation of energy will be followed:

$$|v_{s_f}| |i_s^*| = |v_L^*| |i_{L_f}| \cos \phi \quad (5.9)$$

where $|\bullet|$ denotes the magnitude of a sine wave and ϕ is the phase angle between v_L^* and i_{L_f} . Note that (5.9) does not assume that the frequencies at the supply side and the load side must equal, thus remaining valid even under frequency variations at the supply side.

Hence, similar to the MVR-controlled UPQC, the four Kalman filters for v_s, i_L, v_L^* and i_s^* for H_∞ -controlled UPQC are also combined into a more compact representation:

$$\dot{\hat{\xi}} = A_\xi \hat{\xi} + L_\xi w \quad (5.10)$$

$$\begin{bmatrix} v_s \\ i_L \end{bmatrix} = C_{\xi 1} \hat{\xi} \quad (5.11)$$

$$d = C_{\xi 2} \hat{\xi} \quad (5.12)$$

where w is the vector of innovations. An FF controller can then be designed by solving a pair of matrix equations known as the regulator equations:

$$XA_\xi = AX + B_0 + B_2 U \quad (5.13)$$

$$C_{\xi 2} = CX + B_0 + D_2 U \quad (5.14)$$

for the matrices X and U , where

$$B_0 = B_1 C_{\xi 1}, \quad D_0 = D_1 C_{\xi 1}.$$

Let the control u be decomposed into

$$u = u_{ff} + u_{fb} \quad (5.15)$$

The FF control law is given by

$$u_{ff} = U \hat{\xi} \quad (5.16)$$

In effect, the regulator equations transform the original plant model (4.10)-(4.11), into the following open-loop system:

$$\frac{d}{dt}(x - X \hat{\xi}) = A(x - X \hat{\xi}) + \tilde{B}_x w + B_2(u - U \hat{\xi}) \quad (5.17)$$

$$\hat{e} = C(x - X \hat{\xi}) + \tilde{D}_1 w + D_2(u - U \hat{\xi}) \quad (5.18)$$

where

$$\tilde{B}_x = \tilde{B}_1 - XL_\xi, \quad \tilde{B}_1 = [B_1 \quad 0], \quad \tilde{D}_1 = [D_1 \quad 0]$$

and $\hat{e}$ is the estimated tracking error defined by

$$\hat{e} = y - d \quad (5.19)$$

The FF control can be represented by Figure 5.1.

Figure 5.1: FF control for the UPQC, with KF denoting the Kalman filter.

The FF control law (5.15) can guarantee zero tracking error in the steady state, provided that no modeling error is present and the innovation $w(t) \rightarrow 0$. However, in reality, there will be certain modeling errors, e.g., the variations of the various impedance values of the plant, or the truncation of the Fourier series in the formulation of the exosystem. Therefore, a complimentary FB control, which can be implemented easily, is designed to mitigate the negative effects of any modeling errors and to ensure satisfactory performance of the UPQC under slight drift of the fundamental frequency.

5.2.2 Design of feedback control

In this thesis, the FB control law is designed based on the H_∞ loop-shaping. For a given linear time-invariant MIMO plant $G(s)$, the idea of H_∞ loop-shaping [47]-[48]

and [130] is to employ a pre-compensator $W_1(s)$ and a post-compensator $W_2(s)$ to modify the open-loop gain to a desired one, and then close the loop with a stabilizing controller $K_\infty(s)$ that is computed by H_∞ optimizations to maximize the stability margin. Thus, the overall FB controller is given by $W_1(s)K_\infty(s)W_2(s)$, as shown in Figure 5.2.

Figure 5.2: Combining the pre-compensator, $W_1(s)$, the post-compensator, $W_2(s)$, and the stabilizing controller, $K_\infty(s)$, into an overall feedback controller.

Although the synthesis of the stabilizing controller $K_\infty(s)$ is pretty systematic, the design of the pre- and post-compensators $W_1(s)$ and $W_2(s)$ is problem dependent and requires some engineering skills. Several case studies of H_∞ loop-shaping in power system applications can be found in [131]-[133]. In [131], where H_∞ loop-shaping was applied to the steam generator level control in EDF nuclear power plants, the pre-compensator $W_1(s)$ was chosen as a second order low-pass filter to increase the roll-off rate at high frequencies for better noise attenuation, whereas the post-compensator $W_2(s)$ was chosen as a PI controller for zero steady-state error. On the other hand, for the power system stabilizers in [133], $W_1(s)$ was simply set to 1 whereas $W_2(s)$ was designed to increase the loop gain in the frequency range of the inter-area mode but not at other frequencies.

Our H_∞ loop-shaping approach to the UPQC is motivated by the idea that slight frequency variations can be tackled by properly designing $W_1(s)$ and $W_2(s)$, while the impedance variations in the system can be handled by the robust stabilizing controller $K_\infty(s)$. Note that the values of the line impedance and VSI impedances are not exactly known in practice. Therefore, the robustness offered by $K_\infty(s)$ is an effective means to maintain a desirable performance under such modeling uncertainties.

To design $W_1(s)$ and $W_2(s)$, it is first noted that the signals considered here are periodic. As such, for a closed-loop control system to achieve zero steady-state error for a sinusoidal reference or disturbance of frequency ω_1 , one may create an infinite open-loop gain at ω_1 using a compensator to place a pair of open-loop poles on the imaginary axis. Specifically, for a general periodic signal, poles should be placed at $\pm j\omega_1, \pm j\omega_2, \pm j\omega_3 \dots$, leading to the idea of repetitive control [129]. However, to robustly stabilize such a system when the loop is closed is complex. The proposal of this chapter is that, since an feedforward controller was already employed in Section III, we shall only focus on a few important frequencies rather than all integral multiples of ω_1 . Hence, the closed-loop system can be robustly stabilized using an approach similar to H_∞ loop-shaping [47], [48], [130], which maximizes the stability margin in a certain sense.

Another important consideration is that it is desirable to maintain the power quality even when there is a slight drift of the fundamental frequency, which has not been accounted for by the feedforward controller in Section III. To address this issue, a general form of the compensator is proposed to be:

$$W_2(s) = \prod_{i=1}^n \frac{(s + \omega_i)^2}{s^2 + 2\zeta\omega_i s + \omega_i^2} \quad (5.20)$$

with $\zeta > 0$ but very close to 0. This compensator not only creates sharp peaks at ω_i but also a high-gain region around each ω_i in the logarithmic scale of the frequency, instead of the linear scale in repetitive control. If the signal frequency deviates from the nominal value, all harmonics are deviated by the same ratio and the high loop gain thus guaranteeing that the control performance will remain satisfactory. Fig. 5.3 shows an example of $W_2(s)$ for peaks at the frequencies 50Hz, 150Hz and 250Hz, i.e., the fundamental, the third and the fifth harmonics, with the damping ratio (Note: The derivation of the damping ratio is shown in Appendix I.)

$$\zeta = \sqrt{\frac{(\omega_{co}/\omega_1)^2 + (\omega_{co}/\omega_1)^{-2} - 2}{2(\omega_{co}/\omega_1)^2 + 2(\omega_{co}/\omega_1)^{-2}}} \quad (5.21)$$

and the 3dB cut-off frequency ω_{co} chosen as $1.05 \times \omega_1$. Note also that the loop gain remains reasonably high even between integral multiplies of ω_1 , implying that not only integral harmonics but also any possible interharmonics caused by the frequency drifts will be removed effectively.

Figure 5.3: Magnitude plot of $W_2(s)$ with 3 peaks at 50Hz, 150Hz and 250Hz.

Given a linear time-invariant MIMO plant $G(s)$ as discussed earlier in the section, the idea of H_∞ loop-shaping [17], [18], [19] is to employ a pre-compensator $W_1(s)$ and a post-compensator $W_2(s)$ to modify the open-loop gain to a desired one, and then close the loop with a stabilizing controller $K_\infty(s)$ that guarantees the closed-loop system is robustly stable subject to a certain amount of normalized coprime factor uncertainties of the weighted plant $G_w(s) = W_2(s)G(s)W_1(s)$, i.e., if $M^{-1}(s)N(s)$ denotes a normalized left coprime factorization of $G_w(s)$, the controller $K_\infty(s)$ will stabilize all perturbed plants $(M(s) + \Delta_M(s))^{-1}(N(s) + \Delta_N(s))$ as long as the perturbations satisfy

$$\|[\Delta_N(s) \quad \Delta_M(s)]\|_\infty < 1/\gamma_\infty \quad (5.22)$$

where γ_∞ can be computed as the H_∞ -norm from the fictitious disturbance input δ to $[z_1 \quad z_2]^T$ in Fig. 5.4, with z_1 and z_2 being the input and output of $G_w(s)$, respectively. The set of perturbed plants $(M(s) + \Delta_M(s))^{-1}(N(s) + \Delta_N(s))$ is also intimately related to the plants within a distance of $1/\gamma_\infty$ from the nominal plant in the (nu-)gap metric [130]. Hence, maximizing the stability margin becomes equivalent to minimizing the H_∞ -norm γ_∞ .

Figure 5.4: Robust stabilization of the weighted plant in H_∞ loop-shaping.

Note that in H_∞ loop-shaping, the plant $G(s)$ is supposed to be the transfer function from the control input to the measured output. Disturbance, if any, is not modelled explicitly but to be rejected by the high loop gain. For our UPQC problem, however, the plant $G(s)$ has the state-space form (5.17)–(5.18), which includes a disturbance input w . Instead of ignoring w , we choose to proceed with some modifications on the H_∞ optimization.

On the other hand, W_1 is chosen to be

$$W_1(s) = \frac{s + 10\omega_1}{10s + \omega_1} \quad (5.23)$$

which gives a typical loop-shape of high gain at low frequencies and low gain at high frequencies, as seen in Fig. 5.3. This choice of $W_1(s)$ may also be interpreted as penalizing the high-frequency variations of u_{fb} . If this is not preferred, other choices of $W_1(s)$ should be explored.

Next, to derive the stabilizing controller K_∞ , we let A_p , $\begin{bmatrix} B_{p1} & B_{p2} \end{bmatrix}$, C_p , $\begin{bmatrix} D_{p1} & D_{p2} \end{bmatrix}$ denote the state-space data of the weighted plant $G_w(s) = W_2(s)G(s)W_1(s)$ with the B , D partitioned according to ω and u_{fb} . Consider the system

$$\dot{x} = A_p x + \tilde{B}_{p1} \tilde{\delta} + B_{p2} z_1 \quad (5.24)$$

$$\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} 0 \\ C_p \end{bmatrix} x + \begin{bmatrix} 0 \\ \tilde{D}_{p1} \end{bmatrix} \tilde{\delta} + \begin{bmatrix} I \\ D_{p2} \end{bmatrix} z_1 \quad (5.25)$$

$$\tilde{B}_{p1} = \begin{bmatrix} -LZ^{1/2} & B_{p1} \end{bmatrix}, \tilde{D}_{p1} = \begin{bmatrix} Z^{1/2} & D_{p1} \end{bmatrix}, \tilde{\delta} = \begin{bmatrix} \delta \\ \omega \end{bmatrix}$$

where the matrices Z and L are obtained from the normalized left coprime factorization of the state-space model $(A_p, B_{p2}, C_p, D_{p2})$ as shown in Appendix II.

Then, the controller

$$K_\infty = z_1 z_2^{-1} \quad (5.26)$$

can be computed to minimize γ_∞ , the H_∞ -norm from $\tilde{\delta}$ to $\begin{bmatrix} z_1 & z_2 \end{bmatrix}^T$ in (5.24)–(5.25), for the constraint $< 1/\gamma_\infty$ of the perturbation $\|[\Delta_N(s) \ \Delta_M(s)]\|_\infty$ to be sufficiently large. Finally, the overall controller for the original plant $G(s)$ is given by $u_{fb} = W_1(s)K_\infty W_2(s)e$ (5.27)

The FB control can be represented by Figure 5.5.

Figure 5.5: FB control for the UPQC, with FBC denoting the FB controller.

In other words, if there is no modeling error and $w(t) \rightarrow 0$, then $\hat{e}(t) \rightarrow 0$ and hence $u_{fb} \rightarrow 0$ as $t \rightarrow \infty$. Otherwise, the complimentary u_{fb} will seek to mitigate the negative effects of any modeling error simultaneously.

By combining the FF and FB controls, the overall FF/FB control in Figure 5.6 is proposed. As can be seen, although this control is model-based, there is no need to have additional sensors for the sampling of the states of the UPQC model (4.10)-(4.11). Only 4 sensory circuits are needed for v_s , v_L , i_s and i_L .

Figure 5.6: Overall FF/FB control for the UPQC.

One important point to note is that while the formulation of the control law (5.15), (5.16) and (5.27) may seem complex, their control gains, i.e., U and $W_1(s)K_\infty(s)W_2(s)$, are computed offline. This eliminates the requirement for real-time computation of any control gains, and thus reduces implementation complexity. However, despite the robustness of our control design, it is only meant to deal with small variations of circuit parameters or supply frequency, and performance may deteriorate significantly when such variations become significant. This limitation should be taken into account for real applications.

5.3 Overall Control Configuration

Based on the designed controller, this section discusses the overall control configuration of the proposed H_∞ -controlled UPQC. The system block diagram of a single-phase representation of the H_∞ -controlled UPQC, with Kalman filters, is shown in Figure 5.7. Similar to the MVR-controlled UPQC, the self-charging circuit is implemented into the controller, as shown in Figure 5.6, for the H_∞ -controlled UPQC to operate without relying in external DC supply. The inputs to the controller will still be the sampled signals, $v_s(k)$, $i_s(k)$, $v_L(k)$, $i_L(k)$ and $V_{dc}(k)$. The rest of the state of the system required will also be estimated digitally by Kalman filters. Similar to the previous chapter, v_s and i_L will be passed to Kalman filters to extract ξ . The estimates of ξ will then be forwarded to the Feedforward control to compute u_{ff} . The feedback control will take in v_L , i_s and the reference $d = (v_L^* \ i_s^*)^T$ extracted by the Kalman filters to compute u_{fb} . Based on u_{ff} and u_{fb} , the control signals $u = (u_1 \ u_2)^T$ will then be computed and be converted into the real control signal $u_{inj} = (u_{1inj} \ u_{2inj})^T$ after taking into account the actual dc voltage level V_{dc} of the dc link.

Hence, the load voltage v_L and the supply current i_s will be regulated to become a pure sine wave at the desired frequency of 50Hz. Power factor correction at the supply side can also be achieved.

Figure 5.7: Overall configuration of the UPQC, with KF denoting the Kalman filter and FBC denoting the feedback controller.

In this chapter, a model-based solution via H_∞ loop-shaping has been presented for the control of the UPQC as a multi-input-multi-output system, which handles the coupling effect between the series and shunt filters. The proposed solution also integrates Kalman filters to extract the harmonics of the signals, linear regulator theory to design a feedforward controller for zero steady-state error in principle, and H_∞ loop-shaping to synthesize a feedback controller that robustly stabilizes the closed-loop system. By properly choosing the innovations of the Kalman filters and the loop-shape, a wide range of power quality issues have been put into the same methodological framework and tackled simultaneously. Furthermore, the proposed loop-shape provides an effective means to maintain a good control performance when slight frequency variations occur in the supply voltage. In general, the proposed solution proposes a systematic approach to the control design of UPQC that provides an overall solution to a variety of power quality problems encountered in a power distribution system. Simulation and experimental studies are conducted in Chapter 7 to verify the robustness of the H_∞ loop-shaping design to modeling errors including the nonlinear effects introduced by the PWM and the uncertain values of the impedance in the line and VSIs.

CHAPTER 6

A PEMFC with Ultra-capacitor based Model Predictive Controlled Unified Power Quality Conditioner

6.1 Introduction

Increasing oil prices and concerns over climate changes and energy security see the rapid development of alternative energy sources. Distributed generation such as fuel cell can also provide for increased energy demand if they can be effectively distributed to the load. This will mean that costly upgrades and extension of the transmission network can be avoided. A type of the commonly used fuel cell is the proton exchange membrane fuel cell (PEMFC) [49]-[50] that chemically combines the hydrogen and oxygen to produce electrical power. Today, its deployments are mainly as transporters and uninterruptible power supplies. This is due to its technical limitations like a high capital investment, hydrogen availability and slow dynamic response. Nevertheless, fuel cell system may also be used in niche applications or critical installations like semiconductor plants or defence-related installations where system performance is much preferred over cost. Wider adoption of fuel cell technology also depends on government policies and public opinion.

To overcome the slow dynamic response of fuel cell, hybrid power systems combining the PEMFC with other energy storage devices [50]-[51] like the flywheel, batteries and ultra-capacitor (UC) are being developed. Among these devices, UC [50]-[53] promises one of the best dynamic responses and can be charged and discharged instantly and over numerous cycles. In addition, the fuel cell/ultra capacitor system may also be used as a form of storage of intermittent renewable energy sources like solar. For example, the excess solar energy captured can be used to convert water into oxygen and hydrogen as fuel for the fuel cell. This type of energy storage offers some advantages when compared to conventional batteries in terms of energy density and long-term storage.

Traditionally, the DC links of most UPQCs are being charged by the incoming grid either through the shunt active filter [41], [134] or by external DC sources, e.g., photovoltaic system [32], [135]. This would mean that in the event of power disruption, not only will the performance of the UPQC be severely affected, certain undesirable consequences, as discussed in Chapter 2, will occur, resulting in significant financial losses.

As such, even though PEMFC may be relatively costlier, there are significant advantages to use it. As such, this chapter explores the integration of a hybrid system, consisting of a proton exchange membrane fuel cell (PEMFC) and an ultra-capacitor (UC) with the UPQC. This hybrid system will enable the UPQC to concurrently achieve power quality improvement for a power distribution system and also perform load sharing with the incoming grid, whether during steady state conditions or disturbances in the network, e.g., supply voltage sags. This will result in a

comprehensive UPQC to improve the energy efficiency, power quality, availability and reliability of the network in a cleaner and greener approach.

Furthermore, this chapter also discusses the development of a controller that utilizes the Model Predictive Control (MPC) [56] theory for the UPQC. Model Predictive Control (MPC) [136]-[137] is an approach to controller design that involves online optimization. The online optimization takes into account the system dynamics, constraints and control objectives. The key motivations of using MPC for UPQC are:

- 1) It can fully utilize the state-space model developed for the UPQC presented in Subsection 6.2 below. Furthermore, this state-space model is linear, time-invariant with a low order, which is particularly suitable for the online optimization required by the MPC.
- 2) MPC is able to handle hard constraints of the process variables explicitly. In UPQC, the manipulated variable is implemented with a Pulse Width Modulation (PWM) technique, which has to be limited to ± 1 so that the active filters will operate in the linear modulation region. Conventional linear controllers need to avoid such limits, otherwise instability might occur. This results in a more conservative design, thus limiting the compensation capability of the UPQC.

In what follows, this chapter first discusses the modeling of the UC and the PEMFC. Then, the designs of the hybrid system and the MPC-based controller of the UPQC will be discussed. After that, the different modes of operation of the hybrid system with the UPQC will be presented.

6.2 Modeling of the UC

The classical model of a UC unit [52] is shown in Figure 6.1.

Figure 6.1: An ultra-capacitor model.

This model consists of a capacitance C , an equivalent series resistance R_{ES} , which models the charging and discharging behavior, and an equivalent parallel resistance R_{EP} . R_{EP} models the self-discharging losses of the UC and hence is related to the long-term storage capacity of the UC. For example, if R_{EP} is large, the self-discharging losses will be low and the UC storage capacity will be high. Conversely, if R_{EP} is small, the self-discharging losses will be high and the UC storage capacity will be low. The effect of R_{EP} will be significant if UC is not utilized. The terminal voltage of the UC V_{UC} during discharging and charging, is given by

$$V_{UC} = V_C + i_{UC} R_{ES} \quad (6.1)$$

where i_{UC} is the charging (or discharging) current and V_C refers to the energy level

E_C in the capacitor C given by

$$E_C = \frac{1}{2} C V_C^2 \quad (6.2)$$

The leakage current i_{LK} is given by

$$i_{LK} = \frac{V_C}{R_{EP}} \quad (6.3)$$

R_{EP} is usually very large compared to R_{ES} such that i_{LK} may be ignored in the simulation studies. As mentioned above, it can be used to predict the self discharge behaviour when the UC is not utilized.

The effective specific energy required for any particular load can be supplied by various UC bank configurations. In practice, the required terminal voltage level is determined by the number of capacitors connected in series to form a bank while the energy or the capacitance of UC bank is determined by the number of capacitors connected in parallel.

In our research, the UC bank is utilized to supply or absorb any sudden changes in the power required, e.g., during voltage sag/swell and restoration. This concept will be discussed in Section 6.5. Table 6.1 tabulates the parameters of the UC used in the illustrative examples in Chapter 7.

TABLE 6.1

SYSTEM PARAMETERS OF THE UC BANK

Component	C	R_{EP}	R_{ES}	V_C
Value	2F	10k Ω	0.008 Ω	200Vdc

6.3 Modelling of the PEMFC

Figure 6.2 shows a model of a PEMFC stack [49]-[50] operating at nominal conditions of temperature and pressure, with the following assumptions made and limitations.

a. Assumptions

- The gases (H_2 and O_2) are ideal;
- The stack is fed with H_2 and O_2 ;
- The PEMFC stack is equipped with a cooling system that regulates the temperature at the cathode and anode exits to the stack temperature;
- The PEMFC stack is also equipped with a water management system to regulate the humidity inside the cell at appropriate level for any load;
- The voltage drop of the individual cell is due to the reaction kinetics and charge transport (Note: Most fuel cells do not operate in the mass transport region);
- The pressure drop across flow channel is negligible; and
- The cell resistance is constant at any operational condition.

b. Limitations

- Chemical reaction dynamics caused by partial pressure changes of chemical species inside the individual cell are not considered;
- The PEMFC stack output power is limited by the fuel and air flow rates;
- The effect of temperature and humidity of the membrane on the internal resistance are not considered; and

- The flows of gases and water through the membrane are not considered.

Figure 6.2: A PEMFC model.

E_{oc} , E and i_o are the open-circuit voltage, the effective voltage and the exchange current of the PEMFC stack, which are dependent on the temperatures and partial pressures of reactants and products inside the stack. A is the Tafel slope and N refers to the number of cells in the stack. T_d indicates the response time of the PEMFC stack. V_{fc} and i_{fc} are the actual output voltage and current of the PEMFC stack, while R_{fc} represents its internal resistance. A diode is also needed to prevent any flow of negative current into the stack. As such, V_{fc} is given by (assuming the voltage drop in the diode is negligible)

$$V_{fc} = E - i_{fc} R_{fc} \quad (6.4)$$

$$E = E_{oc} - \frac{NA}{sT_d/3 + 1} \ln\left(\frac{i_{fc}}{i_o}\right) \quad (6.5)$$

$$E_{oc}, i_o = f(U_{fH_2}, U_{fO_2}) \quad (6.6)$$

where U_{fH_2} and U_{fO_2} refer to the utilizations of fuel (H_2) and oxygen (O_2) respectively. The utilizations are dependent on the flow rate, pressure and percentage of H_2 in the fuel and O_2 in the air intake by the PEMFC as well as the operating temperature. In this paper, the fuel flow rate is regulated by a flow rate regulator

based on the fuel cell output current, while the air flow rate is fixed at 40l/min to achieve an optimum fuel utilization. It is noted that fuel and oxidant flow rates for fuel cell testing and sizing the reactant Mass Flow Controllers are linearly related to the electrical current production. As such, based on Faraday's Law, the H_2 flow rate regulator can be designed as follows:

$$H_2 \text{ flow rate} = (SC_{H_2})(i_{fc})(\text{Number of Cells in Stack})(\text{Stoichiometry Ratio}) \quad (6.7)$$

where SC_{H_2} is the Gas Stoichiometry Constant of H_2 that defines the mass consumption rate of the fuel required to sustain 1 A of current at standard state conditions. The SC_{H_2} is 7 for standard state defined at 0°C and 1 atmosphere; and the Stoichiometry Ratio is the ratio of the actual mass flow rate to the mass consumption rate. To have a H_2 utilization factor of 0.9 or 90%, we can set the Stoichiometry Ratios to be $1/0.9$.

The PEMFC and operating parameters used here are tabulated in Table 6.2. The polarization and power curves of the PEMFC stack are also shown in Figure 6.3. Typically, a fuel cell produces a voltage from 0.6 V to 0.7 V at full rated load. As the current drawing from the cell increases, its voltage decreases, as depicted in Figure 6.3. This is due to several factors as described by (6.4) to (6.6). To deliver the desired amount of energy, the fuel cells can be combined in series and/or parallel configurations, known as a fuel cell stack, where in a series stack configuration, a higher stack voltage can be achieved and in a parallel stack configuration, a higher stack current can be drawn. A combination of the series and parallel stack can be configured to achieve the desired performance. In addition, a larger individual cell surface area will also result in a higher current that can be drawn from each cell.

TABLE 6.2
FUEL CELL AND OPERATING PARAMETERS

Parameter	Value	Remarks
Nominal power (W)	5998.5	These parameters are derived from the polarization curve of the fuel cell stack.
Nominal voltage (V)	45	
Nominal current (A)	133.3	
Maximum power (W)	8325	
Nernst voltage of a single cell (V)	1.1288	These parameters are obtained theoretically.
Exchange current i_o (A)	0.0160	
Number of cells N	65	This parameter is set based on the stack configuration to obtain a desired performance.
Internal resistance of the PEMFC stack R_{fc} (Ω)	0.0757	These parameters are obtained experimentally.
Response time of the PEMFC stack T_d (s)	1	
Nominal operating temperature (K)	338	These are system operating parameters.
Absolute supply pressure of fuel (atm)	1.5	
Absolute supply pressure of air (atm)	1	
Percentage of hydrogen in the fuel (%)	99.95	
Percentage of oxygen in the oxidant (%)	21

Figure 6.3: PEMFC polarization curve (top) and power curve (bottom).

6.4. Model Predictive Control

Model Predictive Control (MPC) [56], [136]-[137] has been widely used in many applications like drying towers, PVC plants and steam generators to achieve highly efficient control systems that are able to operate for long time period without much intervention. It also has the capability to deal with constraints and nonlinearities and provides flexibility in formulation. However, implementing MPC can be more complex than classical control like PID and requires higher computational efforts.

MPC is explored to fully utilize the UPQC state-space model presented in Section 4.2 to perform the online optimization and to handle hard constraints of the system, e.g., the control signal u shall be limit to between -1 and +1, as discussed in Chapter 4. This promises better system stability as the UPQC together with the hybrid system

of the PEMFC/UC (to be discussed in Section 6.5) will be able to operate in the linear modulation region.

Similar to control strategies of the MVR and H_∞ controlled UPQCs, the MPC control design here also seeks to implement a control action u to minimize any error e between the plant outputs $y = (v_L \ i_s)^T$ and their desired references $d = (v_L^* \ i_s^*)^T$, under the periodic disturbances $(v_s \ i_L)^T$. The reference signals are supposed to be pure sine waves of 50Hz without any harmonics, as discussed earlier.

As such, by defining the appropriate references for $y = (v_L \ i_s)^T$ to track, a wide range of power quality problems can be handled, while the UPQC can also perform load sharing during steady state conditions or the occurrences of disturbances in the network.

Although MPC will be used, it will not be applied to the state-space model (4.10)-(4.11) of the UPQC directly, because MPC need be applied to a discrete-time model. It might be tempting to simply apply sample-and-(zero-order)-hold to (4.10)-(4.11) to obtain a discrete-time model, but this is not an appropriate way. Even though u , the output from the MPC controller, is piecewise constant, the measurable disturbance $(v_s \ i_L)^T$ is not. A proper way to do is to first combine the UPQC (4.10)-(4.11) with the exogenous system (4.24)-(4.26) to form:

$$\dot{\xi} = \tilde{A} \xi \quad (6.8)$$

$$\dot{x} = Ax + B_1 \tilde{C}_w \xi + B_1 w + B_2 u \quad (6.9)$$

$$e = y - d = Cx + (D_1 \tilde{C}_w - \tilde{C}_d) \xi + D_1 w + D_2 u \quad (6.10)$$

and then apply sample-and-hold to this overall system. The combined A -matrix after discretization will remain in a triangular form, implying that the system can be decomposed back into a discrete-time exogenous system followed by a discrete-time UPQC model, and the MPC will be applied to the latter. The only point to note is that this discrete-time UPQC model does not take $(v_s \ i_L)^T$ as input, but the exogenous state ξ directly. Therefore the “measurable disturbance” of the discretized UPQC model will become ξ instead of $(v_s \ i_L)^T$ and the estimate of ξ provided by the Kalman filters in Section 4.3.2 will be utilized here.

The MPC scheme adopted in this paper has the following features:

- 1) The online optimization takes into account the future disturbance, which can be predicted from the current exogenous state measured and the model of the exogenous system.
- 2) The control horizon starts at the next instead of the current sampling instant. In other words, the MPC determines the next u instead of the current u . This allows one full sampling period for the MPC controller to finish the optimization.
- 3) To make it more suitable for real-time implementation, the maximum number of iterations for the quadratic programming is fixed to a small number, and the optimal solution in the previous step will be used to initialize the current step, instead of thrown away.

Overall, the proposed PEMFC/UC based MPC controlled UPQC has the following functions:

- 1) Harmonic compensations in the supply voltage and load current.
- 2) Sag/swell compensations in the supply voltage.
- 3) Power factor correction at the supply side.
- 4) Load sharing with the grid.

The first three functions are generic in our proposed and most UPQCs. In order that a UPQC to perform the 4th function, we incorporate the hybrid system with the UPQC to provide the DC link voltage (Note that now we do not need a self-charging circuit (as proposed in Section 4.3.5) for the UPQC). We will also modify our control strategy for i_s^* to track (4.20) with a gain k , instead of (4.46), i.e.,

$$i_s^* = k i_{L_{f,p}} = k I_{L_f} \cos \theta_{L_f} \sin \omega t \quad (6.11)$$

where $0 \leq k \leq 1$. For example,

Case $k = 0$,

The UPQC accounts for 100% of the loading and performs the first 3 functions concurrently;

Case $0 < k < 1$,

The UPQC shares the loading with the grid, while it concurrently performs the first 3 functions;

Case $k = 1$,

The grid accounts for 100% of the loading, while the UPQC only performs the first 3 functions.

Furthermore, during disturbances in the supply and load, e.g., any supply voltage sag/swell, i_s will rise/fall accordingly to provide/reduce the power required to mitigate the sag/swell. In this paper, we deliberately synchronizes i_s^* with the load instantaneous fundamental phase current. This will mean that the supply only provides the real power required by the load side, but not any additional/reduced power required to mitigate the sag/swell. This will reduce the reliance on the grid during disturbances to maintain the DC link voltage of the UPQC, especially if the sag/swell is due to certain system faults, e.g., line-to-ground fault. Instead, any additional/reduced power will be provided/absorbed by the hybrid system of PEMFC/UC, to be discussed in the next section.

As such, the following section discusses the hybrid system of PEMFC/UC and the different modes of operation with the UPQC to effectively handle a wide range of power quality problems as well as to perform load sharing with the grid.

6.5 Hybrid system of the PEMFC/UC and its Modes of Operation

A hybrid system consisting of the PEMFC stack and the UC as shown in Figure 6.4 is proposed. The PEMFC stack is regulated to a fixed V_{dc} by a DC-DC converter, and is used to provide the necessary energy needed for the UPQC to perform its various functions. A fuel flow regulator (with the design as discussed in section 6.3) based on the stack current i_{ST} is used to control the H_2 flow rate into the PEMFC, so that an

optimum utilization of the fuel can be achieved. In this thesis, the H_2 utilization factor is set at 0.9 or 90%.

Figure 6.4: The hybrid system of PEMFC/UC.

The UC is connected parallel to the DC bus through an inductor L_{UC} to limit the rate of current flowing through the UC, and the coupling diodes and a generic switching device S_1 (e.g., a MOSFET switch) to facilitate charging and discharging during the operations of the UPQC. S_1 is coupled in series with a diode to ensure current flow into UC to charge it. However, this diode is not necessary if S_1 is a directional switch. Conversely, current flows out of UC through the other diode to provide energy to mitigate the effect of a voltage sag in the supply. Different modes of operations will be discussed in detail in the subsequent sections. This system is then coupled as the DC link to the full bridge voltage source inverters (VSIs) of the active filters of the UPQC.

For this UPQC, full-bridge inverters are used for the active filters of the UPQC. This effectively reduces the DC-link voltage level requirement of the UPQC, as

compared to the use of half-bridge inverter. As such, given the same fuel cell stack, a higher efficiency can be achieved during the boosting operation of the DC-DC converter. In addition, the unwanted harmonic components generated by the full-bridge inverters are also shifted further away from the desired components, as compared to the use of half-bridge inverters. This eases the sizing of the low-pass interfacing filters of the UPQC.

The different modes of operation of the hybrid system as a DC link to the UPQC are discussed in the following sub-sections. The system is also simplified for brevity in illustrations.

6.5.1 Mode 1: Steady state condition

During this mode, the plant is in steady state condition, with the UPQC performing harmonic compensation in v_s and i_L as well as power factor correction at the supply side. As can be seen in Figure 6.5, the PEMFC is delivering the required energy/power P_{FC} to regulate the DC link voltage. P'_{FC} refers to the actual power delivered to the DC link after the DC-DC converter. S_1 is opened under this steady state condition. The 2nd diode will not be operational if P_{FC} is sufficient for this steady state condition.

If V_{UC} falls below a preset value (e.g., 190Vdc), S_1 will also be closed for the power flow from PEMFC to charge the UC via the interfacing diode. This is indicated

by the dotted path. This shall happen if the energy in UC is discharged through R_{EP} in Figure 6.1, when the UC is left idle for a long time.

Figure 6.5: Mode 1 operation of the hybrid system.

6.5.2 Mode 2: Sudden dip in V_{dc}

Due to the synchronization of i_s^* with the load instantaneous fundamental phase current discussed earlier, the supply will only deliver real power required by the load. Hence, in the events of (a) a sag in the supply voltage, (b) a restoration after a swell in the supply voltage or (c) a sudden increase in the load demand, the energy in V_{dc} can be depleted quickly.

In order to maintain the DC link voltage for a proper operation of the UPQC, the hybrid system will have to deliver the necessary power, as shown in Figure 6.6. (In this situation, S_1 will remain open.) As such, due to the slow response of the PEMFC to react, the UC is first utilized to deliver the instantaneous energy/power P_{UC} through the 2nd diode as soon as V_{dc} drops below V_{UC} (assuming the voltage drop across the diode is negligible). Meanwhile, the PEMFC will also react to replenish the energy

depleted and will fully account for the steady-state energy depletion of the DC link if the dip in V_{dc} continues, transiting into Mode 1.

Figure 6.6: Mode 2 operation of the hybrid system.

6.5.3 Mode 3: Sudden surge in V_{dc}

Similarly, if there is a sudden surge in V_{dc} , i.e., due to (a) a swell in the supply voltage, (b) a restoration after a sag in the supply voltage, or (c) when there is a sudden drop in the load demand, there will be excess energy in the DC link. This will mean a rise in the DC link voltage.

When this happens (e.g., $V_{dc} > 210V$), S_1 will be closed so that the excess energy can be absorbed by the UC, indicated by the energy/power flow $P_{V_{dc}}$, as seen in Figure 6.7. This will result in a fast regulation to maintain the DC link voltage as well as to ‘recycle’ any excess energy which would otherwise be wasted.

Likewise, due to the PEMFC’s slow dynamic response to react to the lower power requirement, there will be excess energy P_{FC} generated. This energy will also be

absorbed by the UC. In this way, the UC also helps to maintain the overall energy balance.

However, it may be noted that the UC can be overcharged if there is too much excess energy in either the PEMFC or the DC link. This can be mitigated by simply having a higher rated UC, additional energy storage or the incorporation of a control circuit to prevent overcharging.

Figure 6.7: Mode 3 operation of the hybrid system.

6.6 Overall Control Configuration

The system block diagram of a single-phase representation of the PEMFC/UC based MPC-controlled UPQC, with Kalman filters, is shown in Figure 6.8. The inputs to the controller are $v_s(k)$, $i_s(k)$, $v_L(k)$, $i_L(k)$ which will be sampled by voltage and current sensors. $v_s(k)$ and $i_L(k)$ will be passed to an exogenous Kalman filter, which will extract ξ_w , the state vector representing their fundamental and harmonic components. This ξ_w will then be passed to the reference Kalman filter to obtain an

estimate of ξ_d , the state vector representing the references for the plant outputs, v_L and i_s , to track. These two combine to form a complete estimate of the state vector ξ . Then ξ and the error e , which is formed by subtracting the desired reference d in (11) from the measured $v_L(k)$ and $i_s(k)$, will be input to the MPC. The MPC will compute the control signal u to regulate v_L and i_s to pure sine waves at the desired frequency of 50Hz, while correcting the power factor at the supply side, and perform load sharing with the grid when required.

Figure 6.8 : System block diagram of MPC-controlled UPQC with dc link supported by the hybrid system of PEMFC/UC.

In this chapter, we have discussed the development of a PEMFC/UC based MPC-controlled UPQC for power quality improvement and load sharing in a power distribution system in a cleaner and greener way. A hybrid system making up of the PEMFC and the UC is proposed. The different operational modes of this system, utilizing the characteristics of the PEMFC and the UC to concurrently handle a wide range of PQ problems as well as to perform load sharing, under steady state conditions or during the occurrences of disturbances in the network has been discussed. By formulating the desired references to be tracked by the plant outputs into the MPC controller, the hybrid system can be effectively utilized to ensure a stable and enhanced operation of the UPQC. In addition, the proposed hybrid system is generic in nature and can be explored with other UPQCs to enhance their performances and capabilities. The performance of the proposed UPQC will be verified through illustrative examples in Chapter 7.

CHAPTER 7

SIMULATION AND EXPERIMENTAL STUDIES

7.1 Introduction

In the previous Chapters 4, 5 and 6, we have discussed the different designs of the MVR controlled, H_∞ controlled and PEMFC/UC based MPC controlled UPQCs. In this chapter, we verify their operating performances through simulation and experimental studies. Different test cases are designed to verify their performances. After which a comparison study between them, a LQR, and the PI-controlled UPQC (discussed in Chapter 3) will be performed. The last section of this chapter also presents illustrative examples of the PEMFC/UC based MPC controlled UPQC to demonstrate its performance.

In addition, it is noted that detailed simulations and experiments were performed to validate and evaluate in practice the performance of the proposed UPQC respectively and detailed comparison of the simulation and experimental results was not performed as the intent is to show that the UPQC has indeed resulted in improved network performance.

7.1.1 Setup for simulation studies

In the simulation setup, the MVR, the exogenous and plant Kalman filters, the self-charging and injection circuits described in Chapter 4 are connected together and their performances are verified through simulation studies using Matlab. The following settings (that closely replicate the experimental setting) in the Matlab environment is used.

In the simulation studies, a single-phase distribution system of 1kVA, 100Vrms, 50Hz with non-linear loads including a single-phase dimmer load and a fluorescent lamp supplied by a distorted supply voltage typically found in a semiconductor plant is used for investigation. The dc link voltage of the UPQC is 300V.

Furthermore, the capacity of the UPQC will depend on the functionalities of the UPQC. For example, the functionalities of the MVR controlled and H^∞ controlled UPQCs are compensating capabilities in harmonics (in the supply voltage and load current), disturbances and slight and unknown frequency variations in the supply voltage and power factor correction at the supply side. As such, the typical kVA capacity of the MVR controlled and H^∞ controlled UPQCs is 0.2kVA or 20% of the system capacity. Besides these functionalities, the PEMFC/UC based MPC controlled UPQC is able to perform load sharing with the grid and thus the kVA capacity of PEMFC/UC based MPC controlled UPQCs can be set higher, i.e., 100% of the average load demand of the system.

As described in Chapter 4, the exogenous state vector ξ in (4.24)-(4.26) consists of odd harmonics up to 29th order. The decoupling of $\hat{d}_{v_L}$ from $\hat{v}_f$ as described in Chapter 4, Subsection 4.3, is done after 10 cycles (0.2s) upon the installation of the UPQC.

Another point to note is that the control u is converted into the switching signals for the VSIs by means of PWM. The switching frequency must be high enough for the harmonics to be tackled (up to the 29th order here), and is chosen as 7 kHz in the experiment.

The values of the various system parameters in Figure 4.1 are given in Table 7.1. The control design also requires the values of the line impedance and VSI impedances, which are coarsely estimated and listed in Table 7.2. Since the latter values are not precisely known in practice, they become a source of modeling uncertainties for the controller to handle.

TABLE 7.1
VALUES OF THE COMPONENTS OF THE UPQC

Component	V_{dc}	L_{se}	C_{se}	L_{sh}	C_{sh}
Value	300Vdc	3.8mH	10 μ F	1.8mH	10 μ F

TABLE 7.2
LINE IMPEDANCE AND VSI IMPEDANCES OF THE UPQC

Component	R_l	L_l	R_{se}	R_{sh}
Value	0.01 Ω	1.0mH	0.01 Ω	0.01 Ω

7.1.2 Setup for experimental studies

In the experimental setup, the control circuit described in the Chapter 4 is implemented with the dSPACE 1103 controller for fast prototyping in a single-phase power distribution system, as shown in Figure 7.1. Likewise, a single-phase distribution system of 1kVA, 100Vrms, 50Hz is used as a platform to conduct the experimental studies. A programmable source, which is made up of another DSP-controlled VSI, is used to generate the distorted voltage source for the various test cases. The non-linear loads are light dimmers, where the THD of the load current can be varied by adjusting their light intensity. The values of the system components used are taken from those in Tables 7.1 and 7.2 and the switching frequency remains at 7 kHz.

Figure 7.1 (a): A single-phase power distribution system with UPQC installed.

Figure 7.1 (b): A hardware development of a single-phase power distribution system with UPQC installed.

The UPQC also consists of the different modules: IGBTs for the active filters and the drivers circuits

1. Low-pass interfacing filters for the active filters
2. Sensory circuits

7.2 MVR controlled UPQC with Kalman filters

7.2.1 Simulation studies

For the simulation studies, four test cases are conducted out to verify the actual performance of the UPQC under different supply and load conditions. They are:

- a. Harmonic compensation in the supply voltage and load current with power factor correction at the supply side;
- b. Disturbances in the supply voltage;
- c. Variations in the load demand; and
- d. Slight and unknown frequency variations in the supply voltage

Before the compensating capabilities of the UPQC are tested, the capacitors in the dc link have to be charged up using the LQR-based charging circuit described in Chapter 4. Thus, the first cycle will be used by the controller to charge V_{dc} to the desired level in Figure 7.2. Then harmonic compensation is performed.

Figure 7.2: Charging of the dc link voltage.

7.2.1.1 Simulation Test Case 1: Harmonic compensation in the supply voltage and load current with power factor correction at the supply side

This test is performed to verify the steady-state performance of the UPQC in active harmonic compensation and power factor correction, i.e., to compensate for harmonics in the supply voltage v_s and load current i_L , and to achieve a near unity power factor at the supply side. The voltage and current waveforms under this condition are shown in Figure 7.3. The dimmer load is supplied by a distorted supply voltage v_s in Figure 7.3 with a THD value of 18.4%. The waveform of the non-linear load current i_L in Figure 7.3 is also highly distorted and consists of harmonics up to 29th order, with a lagging power factor. The THD value of i_L is 41.5%. However, with the installation of the UPQC, the waveforms of v_L and i_s , as shown in Figure 7.2 are almost sinusoidal with THD values of around 2.0% and 2.2% respectively.

Furthermore, the waveform of i_s appears in phase with v_s , where there is a phase difference between v_L and i_L . Specifically, the measured reactive power delivered by the supply side and that consumed by the load side is close to zero and around 254VAr respectively, where the latter is provided by the UPQC for the reactive power compensation. As such, the performance of the MVR controlled UPQC to perform active harmonics compensation and power factor correction is verified through this simulation test case.

Figure 7.3: Simulation Test Case 1: Voltage waveforms under a distorted supply voltage with a non-linear load under steady state condition.

Figure 7.4 verifies the function of the Kalman filter (described in Chapters 4 and 5) as a harmonic extractor by comparing the harmonic spectral of v_s and i_L extracted by the Fourier Transform and the harmonic spectral extracted by the Kalman filter. As seen in the figure, they are almost identical. Of course, the Kalman filter in our control method does not only serve as a harmonic extractor, but also part of the control algorithm to optimize the performance of the UPQC to handle a wide range of power quality problems besides the harmonic compensation.

Figure 7.4: Simulation Test Case 1: Actual harmonic spectral of the supply voltage and load current (shaded bars) and the harmonic spectral extracted by the exogenous Kalman filter (non-shaded bars).

7.2.1.2 Simulation Test Case 2: Disturbances in the supply voltage

The 2nd test case demonstrates the ability of the control design to respond to disturbances in v_s quickly. Figure 7.5(a) shows the voltage and current waveforms under different operating conditions of v_s in the system. For $0.1 \leq t < 0.2s$, active harmonic compensation is performed. For $0.2 \leq t < 0.3s$, v_s is experiencing a sag of 25%. This sag is cleared for the next 5 cycles. Then, for $0.4 \leq t < 0.5s$, there is a swell of 20% in v_s . Finally for $0.5 \leq t < 0.6s$, the swell is cleared. With the compensation of the UPQC, the waveform of v_L remains sinusoidal, after being regulated to v_L^* in (4.14), with a fast response time less than 1 cycle, despite the disturbances in v_s . It can be seen that besides harmonic compensation, the controller

compensates for the sag/swell in v_s , ensuring that the amplitude of v_L remains unchanged. The THD value of v_L is below 1.5% throughout the test period. It can also be observed that throughout this test period, the waveform of i_s remains quite sinusoidal and is regulated to i_s^* in (4.58), with a THD value of less than 4%, and in phase with the supply.

However, when there is a sag (swell), i_s increases (decreases). This rise in i_s , absorbed (injected) by the shunt active filter of the UPQC, is needed to provide for the additional real power injection by the series active filter of the UPQC. As such, while v_L is able to be regulated to v_L^* in less than 1 cycle, the controller needs around 2 cycles to regulate i_s to a sinusoidal waveform around 2 cycles upon the occurrences of any disturbances to v_s . The waveforms of the injected voltage and current of the respective active filters (captured after from the respective low pass filters) are also shown in Fig. 7.5(b). Also, the measured reactive power delivered by the supply and that consumed by the load side are close to zero and around 240VAr respectively, in which the latter is provided by the UPQC for the reactive power compensation. All in all, this verifies the performance of the UPQC to concurrently perform harmonic compensation and power factor correction, despite the disturbances in the amplitude of v_s .

Figure 7.5(a): Simulation Test Case 2: Voltage and current waveforms under sag and swell conditions.

Figure 7.5(b): Simulation Test Case 2: Injected voltage and current waveforms under sag and swell conditions.

7.2.1.3 Simulation Test Case 3: Variations in the load demand

This test case demonstrates the ability of the control design to adapt to variations in the load demand quickly. In this test case, the load is made to vary during the steady-state operation of the UPQC. Figure 7.6 (a) shows the voltage and current waveforms under different load demands. For $0.1 \leq t < 0.2\text{s}$, a dimmer load is installed; for $0.2 \leq t < 0.3\text{s}$, a fluorescent lamp is installed; and for $0.3 \leq t < 0.4\text{s}$, both the dimmer and the fluorescent lamp are installed. The loadings and the harmonic contents of the load current are different during these time intervals. The corresponding THD values of i_L are 41.5%, 26.3% and 23.8%. Once there are variations in the load demand, the UPQC takes about 2 cycles to regulate the supply current i_s to the appropriate i_s^* in (4.58). The steady-state THD value of i_s throughout this test case is below 2.5%. In addition, v_L remains sinusoidal with a THD value of below 3% through this test period, despite a distorted v_s . The injected voltage and current by the respective active filters are also shown in Fig. 7.6 (b). This verifies the performance of the MVR controlled UPQC to concurrently compensate for harmonics in the v_s and i_L and is adaptive to the variations in the load demand as well.

Figure 7.6 (a): Simulation Test Case 3: Voltage and current waveforms under variations in the load demand.

Figure 7.6 (b): Simulation Test Case 3: Injected voltage and current waveforms under variations in the load demand.

7.2.1.4 Simulation Test Case 4: Slight and unknown frequency variations in the supply voltage

This test case explores the capabilities of the MVR-controlled UPQC to maintain

the power quality under slight frequency variations in the supply voltage. This, in fact, may be regarded as a modeling error in the exosystem, mentioned in (4.42)-(4.43). The voltage and current waveforms under this test case are shown in Figure 7.7. For this test period, v_s first experiences 3 cycles with operating frequency of 50Hz followed by 3 cycles of v_s at 53Hz followed by 3 cycles of v_s at 47Hz. Without the UPQC, these variations in the frequency of the supply side would be propagated to the load side, such that v_L would not only be distorted but also operate at a deviated frequency. However, the MVR-controlled UQC regulates v_L to the fixed reference v_L^* of fixed amplitude and frequency in less than 1 cycle. In addition, the THD value of v_L remains below 3% throughout the test period. However, the distortion level is high for i_s , with a THD value of more than 50%. Furthermore, i_s appears out of phase with v_s , which may result in poor power factor at the supply side.

Figures 7.8 and 7.9 shows the harmonic spectral of the voltages and currents from the 2nd harmonic up to the 29th harmonic, relative to the fundamental, measured when v_s is at the 3rd cycle of 47Hz and the 3rd cycle of 53Hz respectively. As seen, the harmonic components in v_L are satisfactory low, while those of i_s remain high. This is probably be explained by the fact that the variation in the supply frequency becomes a source of modeling error in the model, according to in (4.42)-(4.43). As such, the MVR controlled UPQC is not robust to this modeling error, and hence is unable to be optimized to handle this variation. Furthermore, certain undesirable effects occur due to the injection of harmonics into the systems, i.e., the 5th harmonic

component is higher in i_s than i_L . These negative effects of frequency variation in the supply voltage will be further investigated in the experimental study.

Figure 7.7: Simulation Test Case 4: Voltage and Current waveforms under frequency variations in the Supply Voltage.

Figure 7.8: Simulation Test Case 4: Harmonic Spectral of voltages and currents

when v_s is at 47Hz.

Figure 7.9: Simulation Test Case 4: Harmonics Spectrum of voltages & currents

when v_s is at 53Hz.

7.2.2 Experimental Studies

The 4 similar test cases are conducted to verify the actual performance of the UPQC under different supply and load conditions. Online data acquisitions of the voltage and current waveforms are performed with Tektronix TPS2024 and the results are then plotted using Matlab.

7.2.2.1 Experimental Test Case 1: Harmonic compensation in the supply voltage and load current with power factor correction at the supply side

In this test case, v_s is distorted and a dimmer is used as the non-linear load. The waveforms of the distorted v_s and i_L as well as the compensated v_L and i_s are shown in Figure 7.10. The THD values of v_s and i_L are 10.0% and 65.0% respectively, while those of the compensated v_L and i_s are 2.91% and 3.6% respectively, upon the installation of the UPQC. In addition, i_s appears to be in phase with v_L , which is regulated to the fundamental component of v_s , as shown in Figure 7.10. Also, it can also be observed that the waveform of i_s is in phase with that of v_s , despite the fact that the waveform of i_L lags that of v_L . Quantitatively, the measured reactive power delivered by the supply side and that consumed by the load side is around 5VAr and around 188VAr. The regulation of the dc link voltage to a fixed amplitude of 300Vdc under steady state condition is shown in Figure 7.11. As seen, there is a slight voltage fluctuation around the 300Vdc level. This fluctuation will be taken into account by the controller according to (4.57), so that the performance of the MVR controlled UPQC can be optimized as well. As such,

the ability of the MVR controlled UPQC to perform harmonic compensation and power factor correction in the supply side in practice is verified here.

Figure 7.10: Experimental Test Case 1: Voltage waveforms under a distorted supply voltage with non-linear load under steady state condition.

Figure 7.11: Experimental Test Case 1: DC link voltage.

Similar to the simulation studies, the actual harmonic spectral of v_s and i_L (computed directly using Fourier Transform) and those extracted by the exogenous Kalman filter are compared in Figure 7.12. (Note that the bar labeled as the 31st order of the actual harmonic spectrum in fact means the sum of all unmodelled harmonic components (with order $> 29^{\text{th}}$)). As seen in Figure 7.12, the function of the exogenous Kalman filter as a harmonic extractor is also verified in these experimental studies.

Figure 7.12: Experimental Test Case 1: Actual harmonic spectral of the supply voltage and load current (shaded bars) and the harmonic spectral extracted by the exogenous Kalman filter (non-shaded bars).

7.2.2.2 Experimental Test Case 2: Disturbances in the supply voltage

This test case demonstrates experimentally the ability of the control design to respond to disturbances in v_s quickly. The same disturbances occurring in v_s are

also seen here. Figure 7.13 shows the voltage and current waveforms under different operating conditions of v_s in the system. Likewise, with the compensation of the UPQC, the waveform of v_L remains sinusoidal, after being regulated to v_L^* in (4.14), with a fast response time less than 1 cycle. i_s also settles down a sinusoidal waveform in around 2 cycles. All in all, the steady state THD values of v_L and i_s are less than 3.5% and 4.5% respectively.

The same behavior in the voltages and currents as described in the simulation study is also observed in Figure 7.13. The reactive power delivered by the supply and that consumed by the load are measured to be around 4VAr and 240VAr respectively. All in all, this verifies the performance of the UPQC to concurrently perform harmonic compensation and power factor correction, despite the disturbances in the amplitude of v_s .

Figure 7.13: Experimental Test Case 2: Voltage waveforms under sag and swell conditions.

7.2.2.3 Experimental Test Case 3: Variations in the load demand

In this test case, the load demands and harmonic contents of the dimmer are varied, by adjusting the brightness of the dimmer. Three load conditions are considered, and the waveforms of i_L and i_S are shown in Figure 7.14. The peak amplitudes of i_S^* in (4.46), i.e., $(I_{L_f} \cos \theta_{L_f} + I_{dc}(k))$, are around 5.0, 3.8, 1.8A for Figures 7.14(I) – (III) respectively. As can be seen, the regulation of i_S to i_S^* in (4.58) is achieved for various load conditions. The controller is able to respond quickly to compensate for the variations in the load demands and harmonic contents. This is accomplished without alteration to any parameters in the hardware or software circuitry. Generally, for the different load currents in this test case, the controller is able to optimize the UPQC to keep the THD values of i_S below 5%.

Figure 7.14: Experimental Test Case 3: Load current (top) and supply current (bottom) waveforms for various load demands.

7.2.2.4 Experimental Test Case 4: Slight and unknown frequency variations in the supply voltage

Similar to the simulation test case 4, the same frequency variations at v_s occurs. The voltage and current waveforms under this test case are shown in Figure 7.15. Similar to the simulation results, while the MVR-controlled UQC is able to regulate v_L to the fixed reference v_L^* of fixed amplitude and frequency in less than 1 cycle, with a THD of around 5%, the distortion level of i_s is relatively high, with a THD value of more than 60%. Likewise, i_s appears out of phase with v_s , which results in poor power factor at the supply side.

Figures 7.16 and 7.17 show the equivalent harmonic spectral of the voltages and currents of 47Hz and 53Hz respectively. Similar observations to the simulation study can be seen here. As such, we confirmed that the MVR controlled UPQC is not robust and adaptive to this modeling error, and hence is incapable to handle the negative effects of this variation.

Figure 7.15: Experimental Test Case 4: Voltage and current waveforms under frequency variations in the supply voltage.

Figure 7.16: Experimental Test Case 4: Harmonic spectral of voltages and currents when v_s is at 47Hz.

Figure 7.17: Experimental Test Case 4: Harmonic spectral of voltages and currents

when v_s is at 53Hz.

As such, the H_∞ controlled UPQC was proposed and designed as a more adaptive approach, as well as to be more robust to modeling errors. The next section will discuss the simulation and experimental studies of the H_∞ controlled UPQC.

7.3 H_∞ controlled UPQC

7.3.1 Simulation studies

Likewise, the same simulation configuration, as explained in the previous section, is set up for the H_∞ controlled UPQC. The exogenous state vector ξ in (5.9)-(5.11) consists of odd harmonics up to 29th order. The 4 test cases described in the previous

section are also used to verify the performance of the proposed UPQC through simulation studies here.

7.3.1.1 Simulation Test Case 1: Harmonic compensation in the supply voltage and load current with power factor correction at the supply side

Similar to the simulation test case for the MVR-controlled, the capacitors in the dc link have to be charged up using the LQR-based charging circuit described in Chapter 4, and the response is the same as shown in Figure 7.1. The voltage and current waveforms under this condition are shown in Figure 7.18. The THD values of v_s and i_L are 18.4% and 41.5% respectively, while the THD values of v_L and i_s are 1.8% and 2.0% respectively. Furthermore, the waveform of i_s appears in phase with v_s , thereby despite the phase difference between v_L and i_L . The measured reactive power delivered by the supply side and that consumed by the load side is close to zero and around 254VAr. As such, the performance of the H_∞ controlled UPQC to perform active harmonic compensation and power factor correction is also verified through this simulation test case.

Figure 7.18: Simulation Test Case 1: Voltage waveforms under a distorted supply voltage with a nonlinear load under steady state condition.

7.3.1.2 Simulation Test Case 2: Disturbances in the supply voltage

This test case as discussed earlier will be used to verify the ability of the H_∞ controlled UPQC to respond to disturbances in v_s quickly. Figure 7.19 (a) shows the voltage and current waveforms under different operating conditions of v_s in the system. Similarly, with the compensation of the UPQC, the waveform of v_L remains sinusoidal, after being regulated to v_L^* in (4.14), with a fast response time less than 1 cycle, despite the disturbances in v_s . The same rise (fall) in i_s due to the sag (swell) in v_s is also observed here. However, i_s is being regulated to a sinusoidal waveform in less than 1 cycle, with a steady state THD value of around 3%. Related waveforms of the injected voltage and current of the respective active filters are also shown in Fig. 7.19(b). Also, the measured reactive power delivered by the supply and that

consumed by the load side are also close to zero and around 240VAr. As such, the ability of the UPQC to concurrently compensate for any sag and swell in v_s , perform harmonic compensation and power factor correction is verified through simulation studies.

Figure 7.19 (a): Simulation Test Case 2: Voltage and current waveforms under sag and swell conditions.

Figure 7.19 (b): Simulation Test Case 2: Injected voltage and current waveforms under sag and swell conditions.

7.3.1.3 Simulation Test Case 3: Variations in the load demand

The same variations in load demand in the equivalent test case for the MVR controlled UPQC is also simulated here. The voltage and current waveforms are shown in Figure 7.20 (a). Here, the H_∞ controlled UPQC takes about 1 cycle to regulate the supply current i_s to the appropriate i_s^* in (4.46). The steady-state THD value of i_s throughout this test case is below 2.3%. In addition, v_L remains sinusoidal with a THD value of below 2.8% through this test period, despite a distorted v_s . The injected voltage and current by the respective active filters are also shown in Fig. 7.20(b). This verifies the performance of the H_∞ controlled UPQC to also concurrently compensate for harmonics in the v_s and i_L and is adaptive to the variations in the load demand as well.

Figure 7.20 (a): Simulation Test Case 3: Voltage and current waveforms under variations in the load demand.

Figure 7.20 (b): Simulation Test Case 3: Injected voltage and current waveforms under variations in the load demand.

7.3.1.4 Simulation Test Case 4: Slight and unknown frequency variations in the supply voltage

This fourth test case will also explore the capabilities of the H_∞ controlled UPQC to maintain the power quality under slight frequency variations in the supply voltage, which may be regarded as a modeling error in the exosystem. The same occurrences in the equivalent simulation test case 4 of the MVR controlled UPQC is observed here. The voltage and current waveforms are shown in Figure 7.21. Note that the UPQC would attempt to maintain v_L at 50Hz (The reference $\hat{d}_{v_L}$ has been decoupled from $\hat{v}_f$ since $t = 0.2s$). On the other hand, even though it does not know the drift of the supply frequency explicitly, the UPQC automatically tries to match the frequency of i_s to the changing frequency of v_s based on the innovation (5.7), as demonstrated in the waveforms in Figure 7.21. Therefore, the task of maintaining a

clean i_s is much more challenging than that of maintaining a clean v_L . As a result, the distortion of v_L is very mild, but the distortion of i_s is more noticeable in Figure 7.21.

It is important to examine the effectiveness of the H_∞ loop-shaping approach in dealing with the unknown frequency variations. Figures 7.22 and 7.23 also shows the contents of the signals from the 2nd harmonic up to the 29th harmonic, relative to the fundamental, measured when v_s is at the 3rd cycle of 47Hz and 53Hz respectively. As our $W_2(s)$ in (5.20) contains peaks at 50Hz, 150Hz and 250Hz, the corresponding 3rd and 5th harmonics in v_L and i_s should be low, which are confirmed by the Figures 7.22 and 7.23. The residual harmonics in i_s are mainly due to the 13th and 17th harmonics of v_s (Note that the 13th /17th harmonics of i_L actually has a different frequency from the 13th /17th harmonics of i_s). On the other hand, the strong 3rd and 5th harmonics of v_s and i_L are mostly suppressed in v_L and i_s . This confirms that the H_∞ loop-shaping approach is effective in handling unknown frequency variations, a source of modeling error in the exosystem, at the supply side.

Figure 7.21: Simulation Test Case 4: Voltage and current waveforms under frequency variations in the supply voltage.

Figure 7.22: Simulation Test Case 4: Harmonics Spectrum of voltages & currents when v_s is at 47Hz.

Figure 7.23: Simulation Test Case 4: Harmonic spectral of voltages and currents

when v_s is at 53Hz.

7.3.2 Experimental studies

Similar to the MVR controlled UPQC, the control circuit of the H_∞ controlled UPQC described in the Chapter 5 is implemented with the dSPACE 1103 controller for fast prototyping. Using the same single-phase power distribution system in the experimental studies for the MVR controlled UPQC, the 4 test cases are again carried out to verify the actual performance of the H_∞ controlled UPQC in practice. The robustness of the control design to the abovementioned impedance uncertainties and PWM nonlinearities will also be examined in the experiment.

7.3.2.1 Experimental Test Case 1: Harmonics compensation in the supply voltage and load current with power factor correction at the supply side

The distorted waveforms of v_s and i_L , and the compensated waveforms of v_L and i_s are summarized in Figure 7.24. The THD values of v_s and i_L are 10.0% and 65.0% respectively, while the THD values of v_L and i_s are only 2.9% and 3.4% respectively. The measured reactive power delivered by the supply side and that consumed by the load side is around 4VAr and 188VAr.

Figure 7.24: Experimental Test Case 1: Voltage waveforms under a distorted supply voltage with non-linear load under steady state condition.

7.3.2.2 Experimental Test Case 2: Disturbances in the supply voltage

In this test case, the programmable source simulates the occurrence of sag and swell in the supply voltage, while the load demand is kept constant throughout the

entire interval. The voltage and current waveforms are shown in Figure 7.25. The transient performance is close to that of the simulation, despite the different harmonic contents in v_s and i_L , as well as the uncertainties in the source and VSI impedance. As such, the H_∞ controlled UPQC is able to concurrently compensate for any sag and swell in v_s , and perform harmonic compensation and power factor correction in the supply side quite effectively in practice.

Figure 7.25: Experimental Test Case 2: Voltage waveforms under sag and swell conditions.

7.3.2.3 Experimental Test Case 3: Variations in the load demand

In this test case, the load current and its harmonic contents are varied by adjusting the intensity of the dimmer. Similar waveforms of the distorted i_L in the previous experimental test case 3 for the MVR controlled UPQC are used, as shown in Figure 7.26. As seen, the THD values of i_L vary from 19.5% to 81.2%, while that of i_s ,

after compensation, are below 4%. This verifies the responsiveness of the H_∞ controlled UPQC to load demand variations.

Figure 7.26: Experimental Test Case 3: Load current (top) and supply current (bottom) waveforms for various load demands.

7.3.2.4 Experimental Test Case 4: Slight and unknown frequency variations in the supply voltage

In this last test case, the programmable source simulates the occurrence of frequency variations in v_s . Similarly to the experimental test case 4 in the MVR controlled UPQC, 3 cycles of v_s at 50Hz are followed by 3 cycles of v_s at 53Hz then 3 cycles of v_s at 47Hz, while v_L remains at 50Hz throughout the entire interval. The voltage and current waveforms and the harmonic spectral under this test case are shown in Figures 7.27-7.29. Once again it is confirmed that i_s has suffered more than v_L from the frequency variations in v_s but their distorted

waveforms have negligible 3rd and 5th harmonics, which are consistent with our H_∞ loop-shaping design.

Figure 7.27: Experimental Test Case 4: Voltage and current waveforms under frequency variations in the supply voltage.

Figure 7.28: Experimental Test Case 4: Harmonic spectral of voltages and currents when v_s is at 47Hz.

Figure 7.29: Experimental Test Case 4: Harmonic spectral of voltages and currents

when v_s is at 53Hz.

7.4 Comparison Studies

Based on the different test cases, this section compares the performance among the MVR controlled UPQC, the H_∞ controlled UPQC, and the PI controlled UPQC (described in chapter 3). The steady state performance and the performance under modeling errors will be investigated and discussed here.

7.4.1 Steady state performance

The steady state performance of the MVR controlled UPQC and the H_∞ controlled UPQC can be observed in the simulation and experimental Test Cases 1. The PI controlled UPQC was also subjected to similar test studies to obtain the steady state

performance in harmonic compensation. The THD values for v_L and i_s of the different UPQCs are summarized in Table 7.3.

As discussed earlier, while all the UPQCs are able to achieve satisfactory performances in the harmonic compensation, the H_∞ controlled and the MVR controlled UPQC are able to provide much lower THD values for both the load voltage v_L and supply current i_s than the PI controlled UPQC. This may be attributed to the optimization of the UPQC via the model based MVR and the H_∞ based feedback/feedforward control schemes that are adopted in this research. Essentially, model-based control schemes are able to taking into account the system parameters as well as to provide a coordinated control of the UPQC so that the overall performance can be optimized.

Furthermore, we also note that the UPQC topology in Chapter 3 consists of only a 1st order low-pass interfacing filter for the shunt active filter of the UPQC, while the proposed UPQCs in this thesis consist of 2nd order low-pass interfacing filter. As discussed earlier in this chapter, the employment of higher order low-pass interfacing filter can further aid to suppress the inherent and undesirable harmonic components generated by the VSIs of the active filters, hence producing better harmonic compensation.

TABLE 7.3
STEADY STATE PERFORMANCE IN HARMONIC COMPENSATION FOR THE DIFFERENT
UPQCs

		MVR (THD %)	H_∞ (THD %)	PI (THD %)
Simulation (for THD values of v_s =18.4% and $i_L = 41.5\%$)	v_L	1.8	2.0	~5
	i_s	2.0	2.2	~5
Experiment (for THD values of v_s =10.0% and $i_L = 65.0\%$)	v_L	2.9	2.9	~6
	i_s	3.4	3.6	~6

Specifically, with regard to the performance of the 2 proposed model-based UPQCs, we first note that for the simulation studies, the UPQC model was accurately represented, i.e., no modeling error was known and the system parameters in Tables 7.1 and 7.2 were accurate. As such, the model-based controllers, i.e., the MVR and the H_∞ controllers are able to optimize the performance of the UPQC to provide better results than the PI controller. As for the experimental studies, although the system parameters were chosen to closely match the values in Tables 7.1 and 7.2, variations do occur in all of these parameters. As such, the H_∞ controlled UPQC seems to be more robust to modeling errors than the MVR controlled UPQC to perform harmonic compensation. This can be explained by the ability of the H_∞ based feedback control in the former to suppress the harmonics more significantly.

The effects of the modeling errors will be further examined in the following subsection.

7.4.2 Performance under the presence of modeling errors

As discussed in the steady-state performance, the robustness of the UPQCs to modeling errors is further investigated here. The modeling uncertainties due to the variations of the impedances of the UPQC with respect to the coarsely estimated values in Tables 7.1 and 7.2 will be further examined here. Furthermore, we note that the non-linear effects of the PWM switching which is unaccounted for in the modeling present another source of modeling error for the UPQCs.

For the MVR controlled and H_∞ controlled UPQCs, their system parameters in Tables 7.1 and 7.2 are varied by at least certain percentages, i.e., 2%, 5% and 10%. The inductors and capacitors values of the PI controlled UPQC are also varied by the same percentages. However, the designed control parameters for the 3 UPQCs based on the original system parameters remain unchanged. Simulation studies are then carried out to investigate the steady-state performance of the 3 UPQCs. The steady-state THD values of v_L and i_s under this study are tabulated in Table 7.4.

TABLE 7.4

STEADY-STATE PERFORMANCE IN HARMONIC COMPENSATION FOR THE DIFFERENT UPQCs UNDER PRESENCE OF MODELLING ERRORS

	Error (%)	MVR (THD %)	H_∞ (THD %)	PI (THD %)
v_L	2%	~3.0	~2.0	~6
i_s		~3.5	~3.0	~6
v_L	5%	~4.0	~3.0	~10
i_s		~7.0	~4.0	~12
v_L	10%	~6.0	~5.0	>15
i_s		~10.0	~6.0	>20

As seen in Table 7.4, such modeling error has certain negative effects on the performance on model-based control schemes, i.e., MVR and H_∞ controls, as well as non-modeled based control scheme, i.e., PI control. In Table 7.4, it is observed that the effects of these variations in the system parameters have more negative impact on the harmonic compensation capabilities of the PI controlled UPQC, such that the THD values of v_L and i_s deteriorate more drastically. However, modeling errors may be inevitable, e.g., the passive components, such as the resistors, inductors and capacitors, in the system may vary due to ageing and temperature. As a result, proper controllers, regardless of whether they are model-based or non-model based controllers, have to be designed to handle these variations, at least to certain extent. As such, this research proposes two model-based control schemes for the UPQCs

that are capable of handling these variations quite satisfactory, while also provides coordinated controls for the series and shunt active filters of the UPQC.

It is also observed from measurements that the actual system parameters for the experimental setup vary from those in Tables 7.1 and 7.2. As a matter of fact, the variations for the actual system parameters with respect to those in Tables 7.1 and 7.2 are given in Tables 7.5 and 7.6.

TABLE 7.5
ACTUAL VALUES OF THE COMPONENTS OF THE UPQC

Component	V_{dc}	L_{se}	C_{se}	L_{sh}	C_{sh}
Value	300±8Vdc	3.8+0.2mH	10+0.5μF	1.8+0.15mH	10+0.4μF

TABLE 7.6
ACTUAL LINE IMPEDANCE AND VSI IMPEDANCES OF THE UPQC

Component	R_l	L_l	R_{se}	R_{sh}
Value	0.01+0.01Ω	1.0+1.0mH	0.01+0.01Ω	0.01+0.01Ω

From Tables 7.5 and 7.6, while there are variations in the values of the actual system parameters, both the MVR controlled and the H_∞ controlled UPQCs are able to produce satisfactory results when implemented experimentally, even though the H_∞ controlled UPQC proves to be more robustness and adaptive than the MVR controlled UPQC, in terms of system parameter variations as well as the non-linear effects of the PWM switching of the VSIs that are not modeled or represented in the UPQC model. The robustness and adaptiveness of the H_∞ controlled UPQC to modeling errors can also be observed in Test Case 4: *Slight and Unknown Frequency*

Variations in the Supply Voltage, where the H_∞ controlled UPQC is able to perform harmonic compensations more effectively than the MVR controlled UPQC under such modeling errors.

As such, we also investigate how another type of modeling error, i.e., slight and unknown frequency variations in the supply voltage, affects the PI controlled UPQC. Table 7.7 summarizes the advantages of using the proposed H_∞ controller over the PI-controlled UPQC. The PI parameters have been properly tuned to optimize the performance at 50Hz. However, during the 6 cycles of frequency variations at 53/47Hz (as in Test Case 4 discussed earlier), the power quality fluctuates significantly, with a serious dip in v_L and a big drop in the power factor. The control signal u_2 also saturates at ± 1 , which partly accounts for the performance degradation. On the other hand, as observed in Figure 7.27, the H_∞ controlled UPQC can maintain the power quality more steadily over the 6 cycles of frequency variations and it is observed that saturations occur only when the frequency variations last 10 cycles or longer. As such, once again, the model-based H_∞ control scheme proves to be more robust and adaptive to modeling errors.

TABLE 7.7
POWER QUALITY FLUCTUATIONS DURING FREQUENCY VARIATIONS

		H_{∞}	PI
v_L	RMS	99.5-102V	82.4-104V
	THD	<4.4%	<18.5%
i_s	RMS	3.8-4.2A	4.4-5.7A
	THD	<31.4%	<68.9%
Power factor		>0.95	>0.89

However, for this comparison test case, a model-based state feedback LQR controller without the Kalman filter stage [38] (The formulation of this controller is given in Appendix III) is also studied and compared against the H_{∞} controller. Generally, the LQR controller has resulted in a better performance for the frequency change case in terms of harmonic compensation of the distorted supply voltage and load current, i.e., the load voltage and supply current are less distorted with lower THD values of <4% and <20% respectively. This is largely due to the capability of the LQR controller, being a model-based control, to take into account the system parameters to generate control signals to provide a coordinated control of the UPQC while being independent of the Kalman filter stage. Whereas, the H_{∞} and the MVR controllers require the frequency-dependent Kalman filter stage as a state observer and harmonic extraction circuits and hence are less robust to any shift in fundamental frequency. Although the H_{∞} controller adopts a feedback control using a H_{∞} loop shaping to create peaks with high-gain regions around them to ensure better performance over the MVR controller during frequency change case, only 3

peaks are created (due to computational constraints) which may not be sufficient to handle frequency change case better than the LQR controller without the Kalman filter stage.

7.5 PEMFC/UC based MPC controlled UPQC

This section presents illustrative examples to verify the performance of the PEMFC/UC based UPQC in Chapter 6. The MPC, the various Kalman filters, the hybrid system of PEMFC/UC and the UPQC are connected and implemented using Matlab/Simulink. In the illustrative examples, similar to the simulation studies performed earlier, a 100Vrms single-phase distribution system with non-linear loads which include a single-phase dimmer load and a fluorescent lamp supplied by the typical distorted supply voltage at the semiconductor plant is used for investigation. The DC-link voltage of the UPQC is 200V. The different modes of operation of the hybrid system with the UPQC to perform the various functions will be investigated next.

7.5.1 Test case 1 (Mode 1): Harmonic compensation in supply voltage and load current with power factor correction at the supply side, and load sharing with the supply.

In this test case, the 1st, 3rd and the last functions of the UPQC will be illustrated. The hybrid system will be operating at Mode 1 (as illustrated in Section 6.5.1) for

most of the period, where the PEMFC will be delivering power to maintain the DC link voltage and/or to share the load demand with the supply.

Figure 7.30 shows the waveforms of v_s , v_L , i_s and i_L for this test case. The initialization of the controller occurs during the first 3 cycles, where for $0 \leq t < 0.16$ s, the UPQC performs harmonic compensation in v_s and i_L with power factor correction at the supply side. The hybrid system is only tasked to deliver power to maintain the DC link voltage. For $0.16 \leq t < 0.32$ s and $0.32 \leq t < 0.48$ s, the hybrid system is concurrently tasked to take over 50% and 100% of the load demand respectively. As seen in Figure 7.30, i_s varies accordingly to the operations of the UPQC.

Figure 7.30: Simulation Test Case 1: Voltage and current waveforms.

The real power flows of the supply, load and PEMFC are shown in Figure 7.31. As can be seen, during $0 \leq t < 0.16\text{s}$, P_{FC} of around 200W is only delivered to regulate the DC link voltage. Then for $0.16 \leq t < 0.32\text{s}$ and $0.32 \leq t < 0.48\text{s}$, P_{FC} is increased accordingly to perform load sharing of 50% and 100% respectively with the supply as well. It is also observed in Figure 7.32 that UC also supplies (during a dip in the DC link voltage) or absorbs (during a rise in the DC link voltage) transient power P_{UC} during the first 3 cycles of initialization, at $t=0.16\text{s}$ and $t=0.32\text{s}$ when there is a variation in the delivery of the supply. This helps to supplement the slow dynamic response of the PEMFC so that the DC link voltage can be maintained to a satisfactory level, as shown in Figure 7.33. A point to note is that the fuel cell is operating at an efficiency of around 60% during the load sharing where P_{FC} is observed to be more than P_L for $0.32 \leq t < 0.48\text{s}$.

Figure 7.31: Simulation Test Case 1: Real power waveforms.

Figure 7.32: Simulation Test Case 1: Ultra-capacitor power waveform.

Figure 7.33: Simulation Test Case 1: DC link voltage.

The waveforms of the compensated harmonic v_L and i_s are observed to be sinusoidal, with THD values below 4% throughout the test period. The measured steady state reactive power delivered by the supply is nearly zero, while that drawn by the load is around 2500VAR, showing a significant power factor correction at the supply side by the UPQC.

As such, it is shown that with the incorporation of the hybrid system with the UPQC, the overall UPQC is able to perform load sharing with the supply to ensure better network availability and reliability, besides handling PQ problems.

7.5.2 Test Case 2 (Modes 2 and 3): Sag in the supply voltage.

In this test case, the 2nd function of the UPQC will be tested. The hybrid system will be operating at Mode 2 (as illustrated in Section 6.5.2) during the occurrence of the sag, and Mode 3 (as illustrated in Section 6.5.3) when the sag clears. In order to verify the performance of the UPQC with/without the hybrid system, 3 types of UPQC configurations in Table 7.8 are simulated.

TABLE 7.8

DIFFERENT CONTROL CONFIGURATIONS OF UPQC

Type	Description
1	The UC is decoupled from the hybrid system and i_s^* is not regulated to the load instantaneous fundamental phase current.
2	The UC is decoupled from the hybrid system and i_s^* is regulated to the load instantaneous fundamental phase current.
3	The UC is coupled with the PEMFC to form the hybrid system and i_s^* is regulated to the load instantaneous fundamental phase current.

In this test case, for $0 \leq t < 0.16\text{s}$, the UPQC performs harmonic compensation in v_s and i_L with power factor correction at the supply side. The hybrid system delivers power to maintain the DC link voltage. For $0.16 \leq t < 0.30\text{s}$, a sag of 55% in v_s occurs. At $t=0.30\text{s}$, the sag is cleared. For $0.3 \leq t < 0.5\text{s}$, a total of 10 cycles are shown to illustrate the steady behavior of the 3 types of UPQC configurations. Likewise, the controller requires 3 cycles for initialization.

Figure 7.34 shows the waveforms of v_s and i_L that are used for this test case. Figure 7.35 shows the waveforms of v_L . As can be seen during the sag, v_L exhibits more voltage variations in amplitudes for Types 1 and 2 than Type 3. When the sag is cleared at $t=0.3\text{s}$, the amplitudes of v_L even swell to around 200V for Types 1 and 2. This is due to the absence of the UC in Types 1 and 2 to absorb the excess energy upon the clearance of the sag. Moreover, for Types 1 and 2, v_L takes a longer period (3 more cycles) than for Type 3 to return to the pre-sag level.

Next, we will discuss the behaviors of i_s during this test case for the 3 types of control configurations, where their waveforms are shown in Figure 7.36. For Type 1, i_s is not regulated to the load instantaneous fundamental phase current. Hence, the supply is tasked to deliver power through the shunt active filter to provide the additional power required by the DC link to mitigate the sag, i.e., during a sag, i_s will rise to provide additional energy needed by the DC link to mitigate the sag (also observed in the earlier similar test cases in sub-sections 7.2.1.2, 7.2.2.2, 7.3.1.2 and 7.3.2.2). However, if this sag is caused by an increase in the load demand or even a

short-circuit fault at the load side, drawing additional power from the supply can have counter-productive effects on the network. As such, we seek to regulate i_s to the load instantaneous fundamental phase current for Types 2 and 3. Type 3 further utilizes the hybrid system to provide this additional power to reduce the reliance on the supply such that the waveform of i_s is observed to have less fluctuations for Type 3 than Type 2. For further investigation, the DC link voltages are also plotted in Figure 7.37.

As can be seen in Figure 7.37, similarly, the fluctuations of the DC link voltage for Type 3 is significantly lower than those for Types 1 and 2, especially during the sag period. Furthermore, the DC link voltages for Types 1 and 2 even swell to around 300V and 275V respectively when the sag is cleared at $t=0.3s$.

In addition, the power P_{FC} delivered by the PEMFC for the 3 types of control configurations is shown in Figure 7.38. As seen in Types 1 and 2, during the first 3 cycles of initialization, without the support of the UC, the PEMFC is delivering power of more than 8kW and then drops to near zero. This is due to the slow response of the PEMFC to react quickly to provide the appropriate level of power required. As such, even though the capacitor of the DC-DC converter for the PEMFC in Figure 7.37 is pre-charged to 200V, the DC link voltages for Types 1 and 2 sag to below 150V and then swell to more than 230V during the initialization, as observed in Figure 7.37.

Likewise, at $t=0.16s$, when the sag first occurs, there are surges in the PEMFC powers for Types 1 and 2. These surges cause the DC link voltage to build up to more than 230V in Figure 7.37 and then fluctuate around 200V. Moreover, for Type 2, as the PEMFC is tasked to deliver additional power needed by the series active filter of the UPQC to regulate the DC link voltage and mitigate the sag, fluctuations in the PEMFC power are more significant than those for Type 1. Generally, constant fluctuations can shorten the life cycle of a PEMFC. A point to note is that during steady-state condition, i.e., $0 \leq t < 0.16s$, the hybrid system is only required to deliver a nominal power of around 200W to regulate the DC link voltage as also observed in Figure 7.31.

However, for Type 3, as seen in Figure 7.39, the UC is able to respond quickly to the sag at $t=0.16s$, to provide the necessary (higher) power needed to regulate the DC link voltage. This ensures that its fluctuation, as seen in Figure 7.37, is minimal. As can be seen in Figure 7.38, the PEMFC responds in a stable manner when the sag continues to provide for the additional power needed to mitigate the sag. Similarly, when the sag clears at $t=0.3s$, the excess energy generated by the PEMFC (due to its slow response to react to the lower power requirement) is absorbed by the UC as shown in Figure 7.39. This will not only result in a stable regulation of its DC link voltage in Figure 7.37, but also help to harness the excess energy, which would otherwise be wasted.

It is also observed in Figure 7.39 that the UC power can rise (to deliver power for discharging) or dip (to absorb power for charging) quite significantly to more than 2-

3 times the nominal operating power levels. Although this is equivalent to a current level as high as 100A in this test case, it can result in a better regulation of the DC link voltage and more efficient harnessing of the excess energy. In addition, normal storage devices like batteries may not have the capability to absorb this high current quickly. One option is to size the inductor L_{UC} of the hybrid system in Figure 6.4 accordingly, i.e., to increase the value of the inductor so as to control the desired rate of current flow in the UC. In this paper, the use of UC (which can be charged and discharged quickly with high currents) with the PEMFC has proven to be a more effective and efficient option.

Figure 7.34: Simulation Test Case 2: Supply voltage and load current waveforms.

Figure 7.35: Simulation Test Case 2: Load voltage waveforms.

Figure 7.36: Simulation Test Case 2: Supply current waveforms.

Figure 7.37: Simulation Test Case 2: DC link voltage waveforms.

Figure 7.38: Simulation Test Case 2: PEMFC power waveforms.

Figure 7.39: Simulation Test Case 2: UC power waveform.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

This chapter concludes with a summary of research work done so far and recommends tasks for further research.

8.1 Conclusions

The increasing use of the advanced power electronics as well as non-linear loads to achieve better energy efficiency has led to power quality problems like the generation of harmonic currents, poor power factor at the supply side as well as distortion and instability in the supply voltage. As such, these power quality problems can propagate throughout the network and cause several negative consequences. Some of these consequences include overheating of power factor correction capacitors, motors, transformers and cables, thermal tripping of protective devices, memory or data corruption and loss, and mal-functioning of devices, which can lead to substantial financial losses as well. Thus, standards pertaining to the control and mitigation of these power quality problems have been developed as guidelines for electrical power suppliers as well as consumers to adhere to. Compensating devices that can help to mitigate these power quality problems are also being researched and developed.

Uninterruptible power supplies and the dynamic voltage restorers which can be used to compensate for voltage instability and distortions, the passive and the active filters which can be used to compensate harmonic distortions in the supply voltage and load current, and capacitors banks which can be used to improve the power factor at the supply side, are some of such compensating devices. However, their capabilities are usually limited as they can only solve one or two of the power quality problems. It is also not cost-efficient and effective to install each of these devices to handle each of these power quality problems separately, while neglecting the inherent coupling effects among all these devices when installed together.

The UPQC has shown promising developments as a comprehensive device to handle power quality problems simultaneously. The series active filter of the UPQC can be employed to compensate for any distortions in the supply voltage, while the shunt active filter of the UPQC can be employed to compensate for current harmonics in the load current, as well as to correct the power factor of the supply side near to unity.

Today, several control approaches have been proposed and developed. A simple and most common approach focuses on extracting and injecting distorted components, e.g., harmonics, (from sampled supply voltage and load current) into the network. While this approach is simple and is relatively more easier to be implemented, it can be considered as an open loop control approach and thus has certain drawbacks that can limit the performance and robustness of the UPQC. Some of these drawbacks include the inability to ensure zero steady-state error totally in principle when the system is subjected to periodic references and disturbances and the failure to account for the

coupling effect between the series and shunt active filters of the UPQC and the various voltage drops in the network.

One alternative approach is the model-based control, where the UPQC is modeled, taking into account the coupling effect mentioned above and the various voltage drops in the network. Then, a coordinated control is applied to control the UPQC as a single MIMO system. However, the cost and complexity of the UPQC is relatively higher than the above mentioned approach because of the additional sensors or high-speed DSP needed. Furthermore, any modeling error can be detrimental to its performance.

In view of the various issues above, this research proposed and developed two model-based controllers for the UPQC, namely, the MVR controlled and the H_∞ controlled UPQCs. As such, this research first focuses to develop a theoretical model of the UPQC incorporating appropriate topologies like the employment of the right shunt UPQC, the 2nd order low-pass filters for both the active filters and the split capacitor dc link configuration.

Then, the MVR controlled UPQC is developed. For this UPQC, Kalman filters are employed to extract the fundamental and harmonic components of the measured supply voltage and load current and to perform states estimations of the UPQC as well. By using Kalman filters, instead of hardware sensory circuits, to perform these tasks will help to reduce implementation cost. Then, a closed-loop model-based MVR controller is developed to control the UPQC. This controller ensures global stability and zero steady-state error in principle. A LQR-based self-charging circuit is also developed and

incorporated into the controller so that the UPQC can operate without relying on an external dc supply. The proposed controller also seeks to minimize the effect of the dc link voltage fluctuations on the performance of the UPQC. The robust and adaptive performance of the MVR controlled UPQC has been verified through simulation studies. Experimental studies on a DSP platform are then carried out to validate its real-time implementation. The compensating capabilities of the UPQC for harmonics in the load voltage and supply current, voltage sags and swells as well as power factor correction at the supply side are achieved. It has been demonstrated that the MVR concept with Kalman filters as harmonic extractors and state observer can be implemented as an effective control scheme for the UPQC. The proposed control design is not only fast and adaptive but also cost effective for practical implementation and usage. However, while the MVR controlled UPQC is robust and adaptive against modeling error, it is also noted that certain modeling error, for example, unknown frequency drift, can affect the performance of the MVR controlled UPQC.

As such, this research extends the strengths of the MVR controlled UPQC to develop the H_∞ controlled UPQC. Likewise, this proposed solution integrates Kalman filters to extract the harmonics of the signals and to perform states estimations. Then, it employs the linear regulator theory to design a feedforward controller for zero steady-state error in principle and the H_∞ loop-shaping to synthesize a feedback controller that robustly stabilizes the closed-loop system. By properly choosing the innovations of the Kalman filters and the loop-shape, a wide range of power quality issues have been put into the same methodological framework and tackled simultaneously. Simulation and experimental studies have confirmed that the H_∞ controlled UPQC is robust to

modeling errors including the nonlinear effects introduced by the PWM and the uncertain values of the impedance in the line and VSIs. Furthermore, the proposed loop-shape is an effective means to maintain a good control performance when slight frequency drifts occur in the supply voltage. Comparison studies among the proposed MVR and H_∞ controlled (with Kalman filters) UPQC and the LQR and PI-controlled UPQC are also performed to discuss the strengths and drawbacks of these UPQCs.

All in all, it is shown that the MVR controlled and the H_∞ controlled UPQC are highly effective, adaptive and robust. Nevertheless, there is still room for improvements on the proposed design concepts and on the research of UPQCs, especially in frequency change cases.

A PEMFC/UC based MPC-controlled UPQC has also been designed for power quality improvement and load sharing in a power distribution system. A hybrid system making up of the PEMFC and the UC is proposed. The different operational modes of this system, utilizing the characteristics of the PEMFC and the UC to concurrently handle a wide range of PQ problems as well as to perform load sharing, under steady state conditions or during the occurrences of disturbances in the network have been discussed. By formulating the desired references to be tracked by the plant outputs into the MPC controller, this hybrid system can be effectively utilized to ensure a stable and enhanced operation of the UPQC. Desirable characteristics in the different voltages and currents of the plant can be observed. The performance of the proposed UPQC has been verified through illustrative examples. It is concluded that the proposed UPQC can be an effective method to handle PQ problems as well as to act as a power source in a

cleaner and greener way. Furthermore, the proposed hybrid system is generic in nature and can be explored with other UPQCs to enhance their performances and capabilities.

8.2 Recommendations for Further Research

In the author's opinion, the following recommendations remain open for further research:

a. Development of multi-level inverters topology for the active filters of the UPQC

As more and more facilities/operations are operating at high (e.g., 6.6kV) or even higher distribution voltage levels, there may be a need to install higher rated UPQC to mitigate the harmonic distortions that may arise at such levels. The use of high power rated power electronics, for example, 6.5kV high voltage-IGBT (HVIGBT), to construct the VSIs of the active filters can be a viable option.

Alternatively, one can adopt a modular VSI/multi-level inverters topology [138]-[140] using several IGBTs of lower voltage level. This method will facilitate scalable implementation and necessary replacement more easily. Further research could also be done to evaluate the performance of model-based control schemes for such high rated power UPQCs.

b. Investigation of the MVR and H_∞ controlled UPQCs in a 3-phase network

In Figure 4.7 of Chapter 4, the 12-IGBT configuration with midpoint of the two capacitors grounded is proposed for the 3-phase UPQC topology. This will only require the duplication of three sets of the same controller, each working independently in the different phases, to generate the switching sequence for the individual active filters of the UPQC. Whereas in [39], two sets of 3 single-phase H-bridge inverters are proposed as the 3-phase UPQC topology to handle the unbalanced supply voltages and load currents. Regardless of the topology, coupling effects between the line impedances and series and shunt active filters in the different phases exist. For example, in the event of a sag in one of the phases, the DC link voltage may drop and affect the operations of the other active filters in the un-faulted phases. As such, further studies are recommended to investigate the performances of the proposed controllers and how they can handle or mitigate any coupling effects. A 3-phase plant model could also be developed to further refine the control designs for implementation in a 3-phase network.

c. Investigation of other PEMFC models and experimental verification of the PEMFC/UC based MPC controlled UPQC

This research proposes the PEMFC/UC based MPC controlled UPQC to concurrently handle most PQ problems and perform load sharing with the grid. To better understand the characteristics and evaluate the performance of the PEMFC to optimize the proposed PEMFC/UC based MPC controlled UPQC, it is recommended to investigate other various PEMFC models [141]-[145] to conduct comprehensive studies. Further

works may also be conducted to explore how the PEMFC can be utilized more efficiently on top of the current proposed approach. For example, the PEMFC may be used for steady state operations while the UC is used to mitigate transient disturbances in the supply voltage. Experimental verifications of the proposed system may also be conducted to verify its performance. This will involve adopting efficient and computationally intensive platforms to facilitate the implementation of the MPC at appropriate sampling frequency. Further research into PEMFC and UC as a hybrid system for other applications are also recommended.

d. Enhancement of the H_∞ loop shape of the H_∞ controlled UPQC

For the H_∞ controlled UPQC in this thesis, $w_2(s)$ only consists of 3 peaks at the frequencies 50Hz, 150Hz and 250Hz, i.e., the fundamental, the third and the fifth harmonics in (5.23). As such, this UPQC is able to suppress harmonic distortion near these frequencies quite effectively under the presence of modeling errors as verified in Chapter 7. By widening this loop shape to introduce more peaks will enhance the ability of the UPQC to handle higher order harmonics. As such, further investigation on how to incorporate more peaks into the loop shape can be carried out, so that the UPQC will be even more robust against modeling error.

e. Investigation of other state estimator techniques

In this research, Kalman filters are used to extract the harmonic contents of the supply voltage and load current, as well as to perform states estimations of the UPQC model.

This has been proven to be a rather effective way as compared to the Fourier Transform and to replace sensory hardware circuits. This method can also be used in other model-based control approaches in [38]-[41].

However, it is worthwhile to investigate if other state estimation techniques in [146]-[147] are more effective to perform the above tasks. Some of the parameters that can be investigated include their accuracies and responsiveness, especially during transients in the supply and load demand. This can help to further optimize the performance of the UPQC.

f. Modeling of a variable frequency as part of the control algorithm

In this research, the frequency used in the Kalman filters to extract the harmonic components of the supply voltage and load current is fixed at 50Hz. However, as discussed in Chapter 2, unknown frequency drift can occur. In such events, the performance of the UPQC can suffer. While the H_∞ controlled UPQC is able to mitigate the negative effects of this frequency drift quite satisfactorily, its performance can be further optimized if the Kalman filter is modeled with a variable frequency such that frequency estimation is part of the overall control algorithm [143]. As such, this thesis recommends further research in this area.

Of course, there are definitely other further improvements and research works that can be done for the UPQCs other than the recommendations mentioned in this chapter. We hope that the above recommendations can be considered for further research in the future.

BIOGRAPHY

K. H. Kwan received the B.Eng. degree with first class honors in Electrical and Electronic Engineering from Nanyang Technological University, Singapore in 2004. He won the IEEE Singapore Power Engineering Chapter Gold Medal cum Book Prize Awards and the Singapore Power Ltd Book Prize Award during his undergraduate studies.

He was a lecturer in Temasek Polytechnic where he drove the Singapore Fuel Cell Community (a Singapore Government Initiative to develop a fuel cell industry) and the Clean Energy Testbedding Community with the Singapore Business Federation. He was also involved in several clean energy projects in fuel cell and solar.

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LIST OF PUBLICATIONS

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- K. H. Kwan, Y. C. Chu and P. L. So, “Model-based H_∞ control of a unified power quality conditioner,” *IEEE Transactions on Industrial Electronics*, vol. 56, no. 7, pp. 2493-2504, Jul. 2009.
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Appendix I

For the transfer function $W_2(s) = \prod_{i=1}^n \frac{(s + \omega_i)^2}{s^2 + 2\zeta\omega_i s + \omega_i^2}$, by letting $a = \omega / \omega_1$ for $n = 1$,

we have

$$W_2 = \frac{(1 + ja)^2}{1 + 2j\zeta a - a^2} = \frac{1 - a^2 + 2ja^2}{1 - a^2 + 2j\zeta a} \quad (\text{AI-1})$$

If $a^2 = 1$, the magnitude of the transfer function is symmetric about $a = 1$, such that the peak occurs at $\omega = \omega_1$ and the peak value is $1/\zeta$. As such, the magnitude at ω_{co} (the cut-off frequency at -3db attenuation) will be $1/\zeta / \sqrt{2}$, i.e.,

$$|w_2| = \sqrt{\frac{(1 - a^2)^2 + 4a^2}{(1 - a^2)^2 + 4a^2\zeta^2}} = 1/\zeta / \sqrt{2} \quad (\text{AI-2})$$

By manipulation, the damping ratio is

$$\zeta = \sqrt{\frac{a^2 + 1/a^2 - 2}{2a^2 + 2/a^2}} \quad (\text{AI-3})$$

or

$$\zeta = \sqrt{\frac{(\omega_{co} / \omega_1)^2 + (\omega_{co} / \omega_1)^{-2} - 2}{2(\omega_{co} / \omega_1)^2 + 2(\omega_{co} / \omega_1)^{-2}}} \quad (\text{AI-4})$$

Appendix II

The matrices Z and L in (38)-(39) can be obtained from the normalized left coprime factorization of $(A_p, B_{p2}, C_p, D_{p2})$. In the continuous-time case, let matrix Y be the solution to the Riccati equation:

$$H_{11}^T Y + Y H_{11} + Y H_{12} Y - H_{21} = 0 \quad (\text{AII-1})$$

where

$$H_{11} = (A_p - B_{p2} D_{p2}^T R_{p2}^{-1} C_p)^T$$

$$H_{12} = -C_p^T R_{p2}^{-1} C_p$$

$$H_{21} = -B_{p2} (I + D_{p2}^T D_{p2})^{-1} B_{p2}^T$$

$$R_{p2} = I + D_{p2} D_{p2}^T$$

Then the matrices Z and L are given by:

$$Z = R_{p2} \quad (\text{AII-2})$$

$$L = -(B_{p2} D_{p2}^T + Y C_p^T) Z^{-1} \quad (\text{AII-3})$$

Appendix III

The LQR controller for the UPQC is based on [38], where the Q and R matrices are:

$$Q = \begin{bmatrix} 20 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 10 \end{bmatrix}$$

$$R = \begin{bmatrix} 0.05 & 0 & 0 \\ 0 & 0.05 & 0 \\ 0 & 0 & 0.05 \end{bmatrix}$$

Based on the UPQC's parameters, the control gain K is:

$$K = \begin{bmatrix} 8.2747 & 6.1871 & 4.5704 & -7.0153 & -0.0026 & -0.0009 \\ 0.1355 & -0.0010 & -0.0047 & 0.1344 & 8.4074 & 14.1371 \end{bmatrix}$$

Hence, the control signal u_{LQR} is

$$u_{LQR} = K(z - z_{ref})$$

where z and z_{ref} are the transformed plant state vector and its respective reference.