Integration of FACTS and Battery Energy Storage

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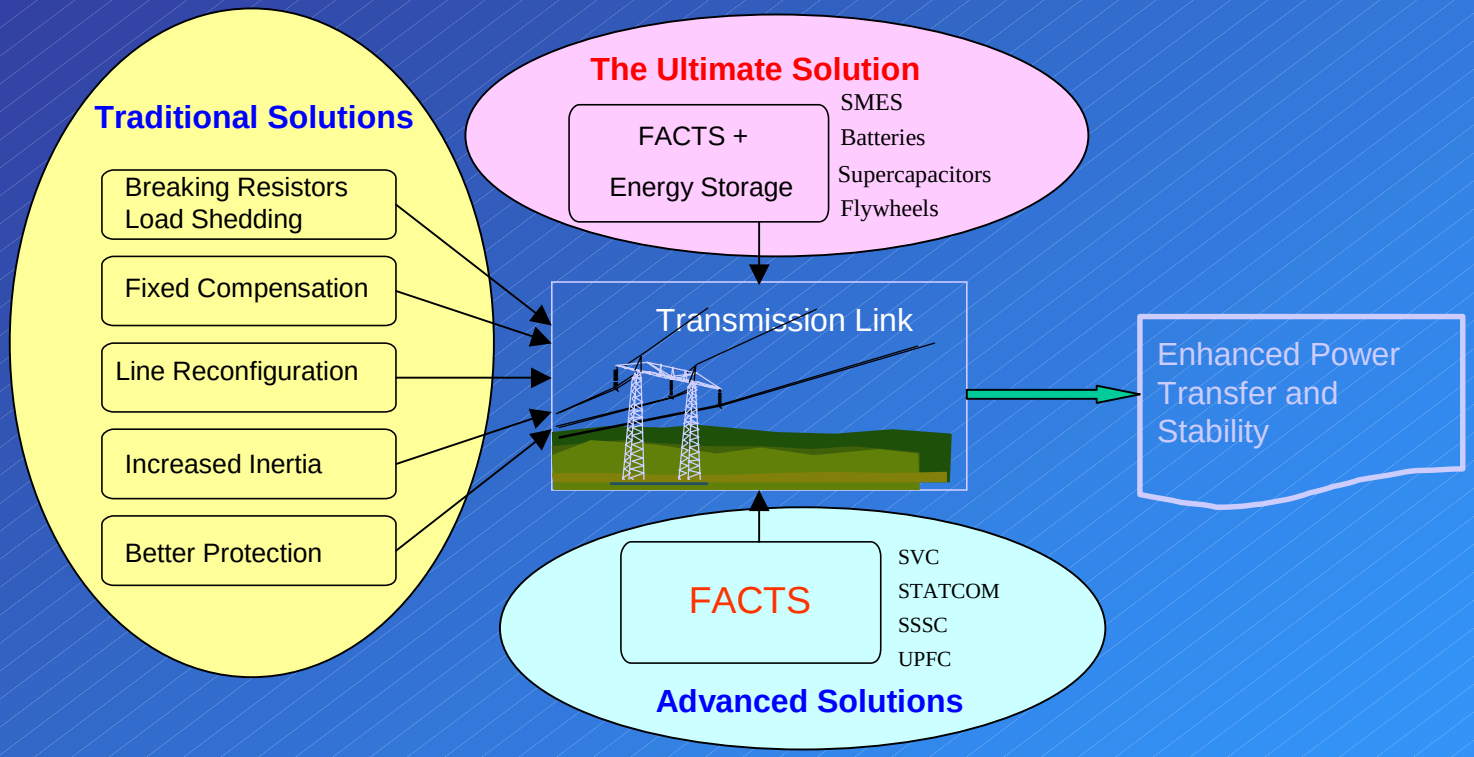
Objectives

Enhance power transmission system operation by integrating battery energy storage systems into FACTS devices

Motivation

- Deregulation has led to the increased need for embedded controllers in the transmission system
- FACTS is an emerging technology that is being implemented in a number of facilities nation-wide and internationally
- The integration of FACTS and energy storage provides increased control flexibility for a wide range of power system dynamics


Traditional Solutions
Breaking Resistors
Load Shedding
Fixed Compensation
Line Reconfiguration
Increased Inertia
Better Protection
The Ultimate Solution
FACTS +
Energy Storage
SMES
Batteries
Supercapacitors
Flywheels
Transmission Link
Enhanced Power Transfer and Stability
FACTS
SVC
STATCOM
SSSC
UPFC
Advanced Solutions

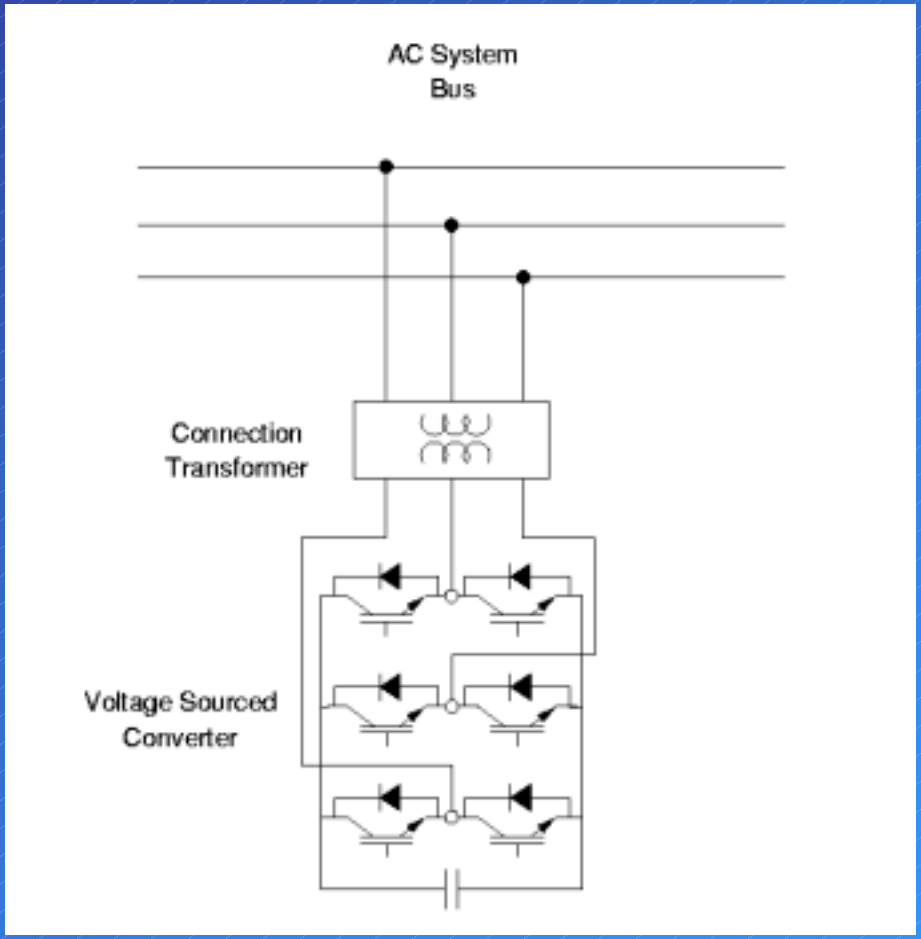
StatCom

- Voltage Support
- Reactive Power Support
- Limited impact on transient stability
- Limited impact on oscillation damping

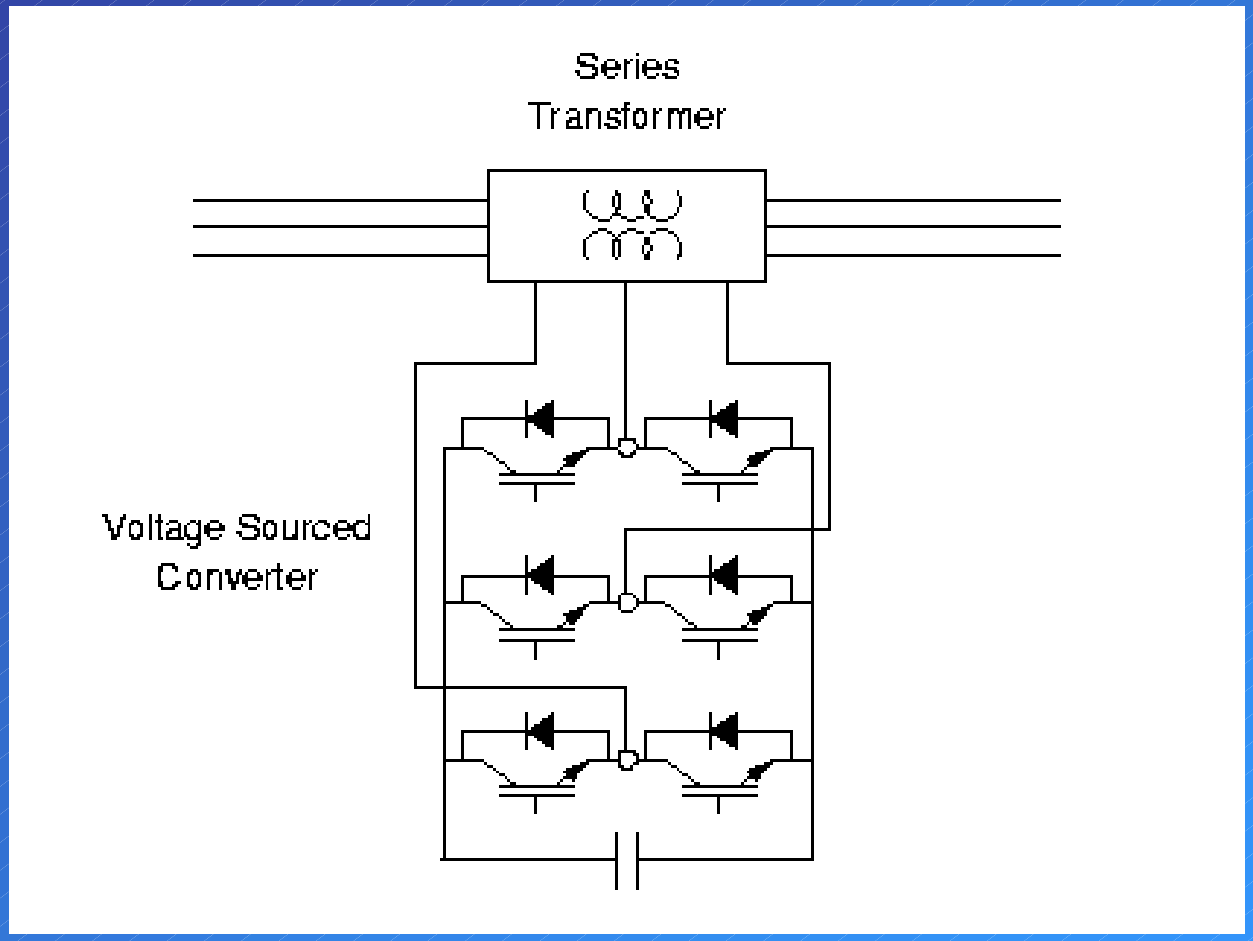
StatCom with ESS

- Voltage Support
- Reactive Power Support
- Active Power Support
- Oscillation damping and transient stability improvement

StatCom


AC System
Bus
Connection
Transformer
Voltage Sourced
Converter

SSSC



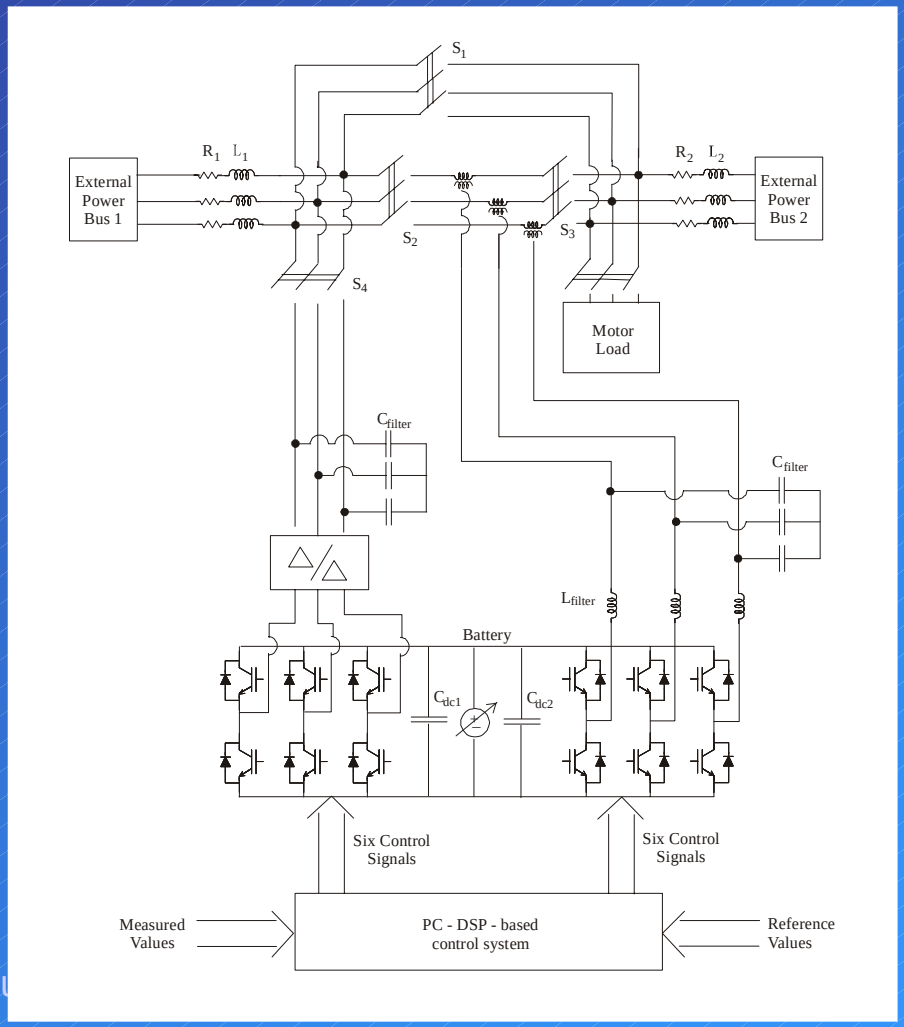
SSSC

- Active Power Control
- Limited Voltage Support
- Good impact on transient stability
- Good impact on oscillation damping
- Limited impact on voltage stability

SSSC with ESS

- Active Power Control
- Improved Voltage Support
- Good impact on transient stability
- Good impact on oscillation damping
- Voltage stability improvement

Experimental FACTS/BESS and its Test System



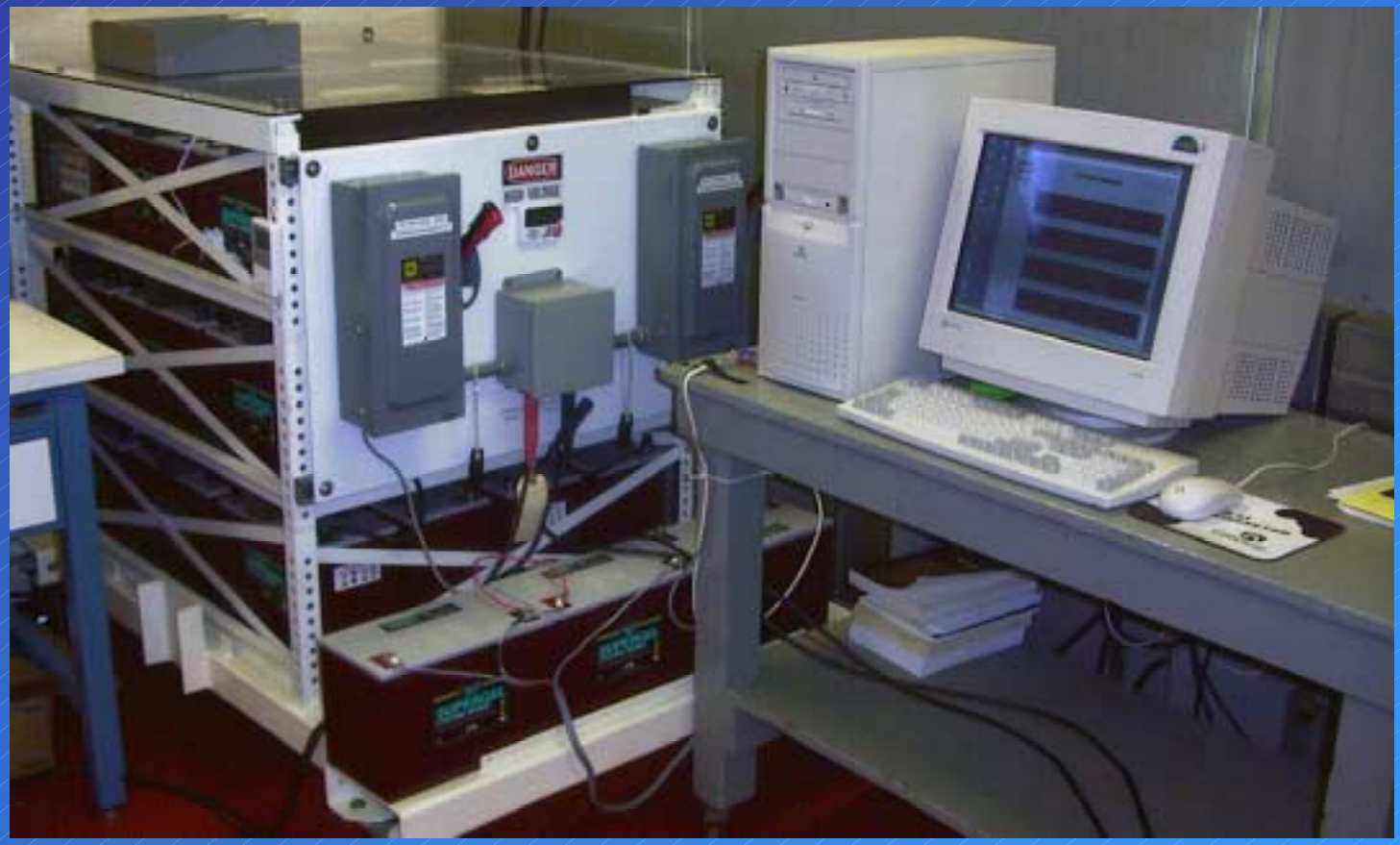
StatCom

StatCom Front Panel

Sensor Rack

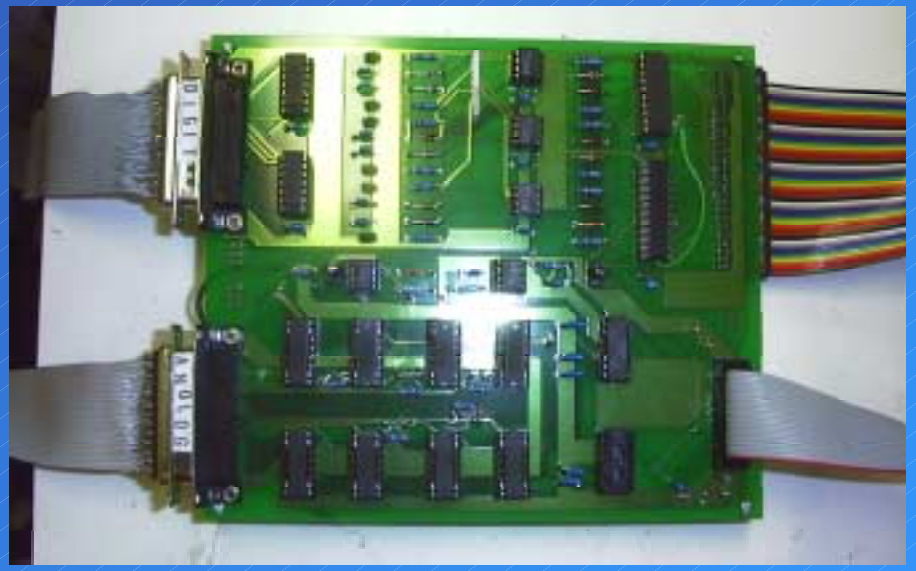
Converter Rack

BESS



Electronics

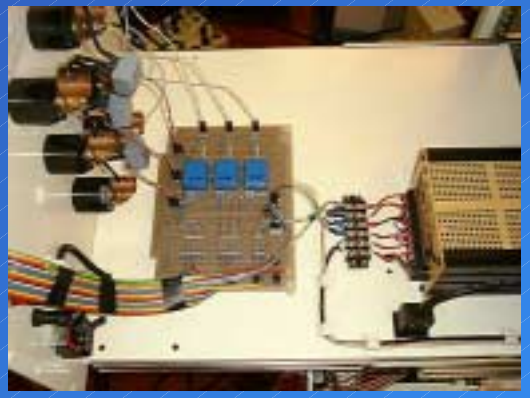
Monitoring and control system



Signal interface board

SSSC

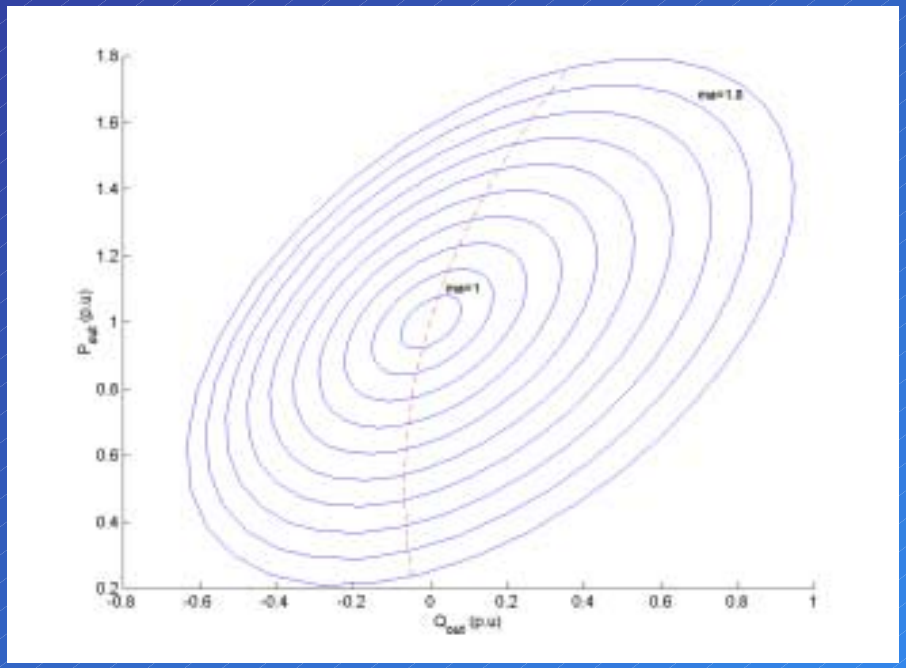
SSSC Front Panel



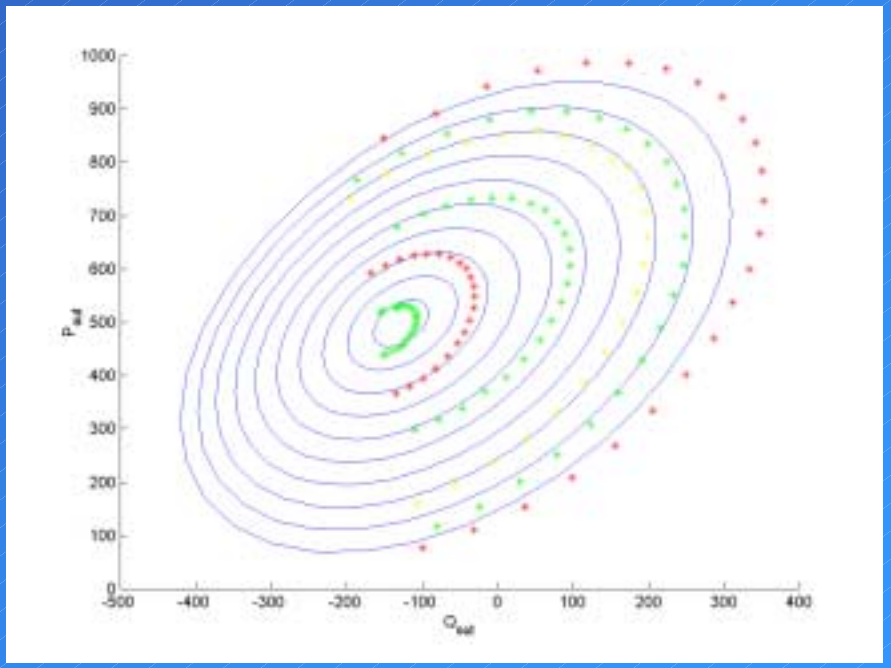
Sensor Rack

Inverter Rack

Output Power of SSSC and SSSC/BESS

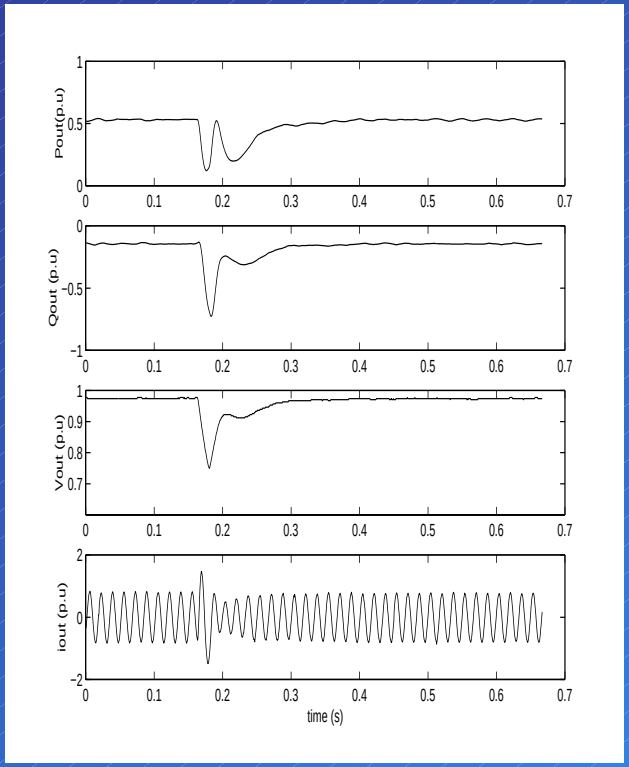


PQ relationship

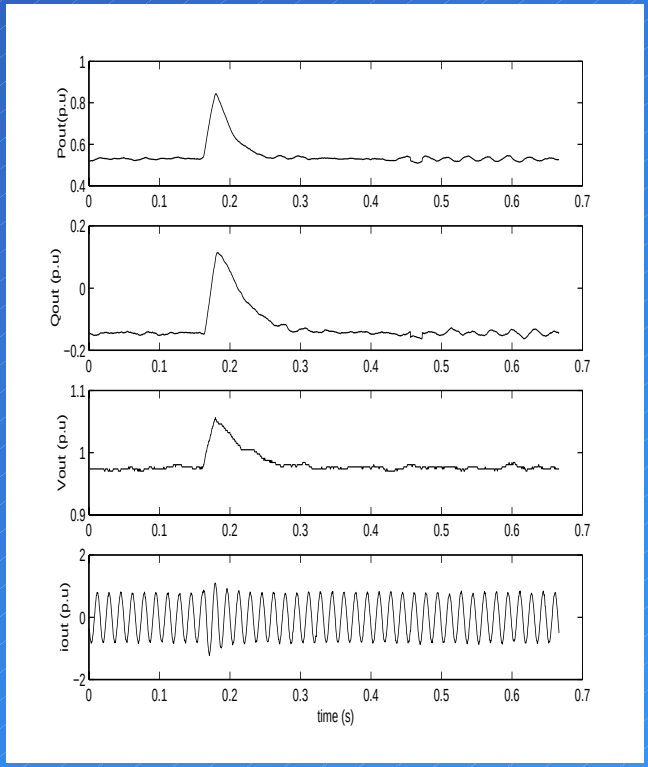


Experimental Comparison

Disturbance Rejection



Induction Machine On

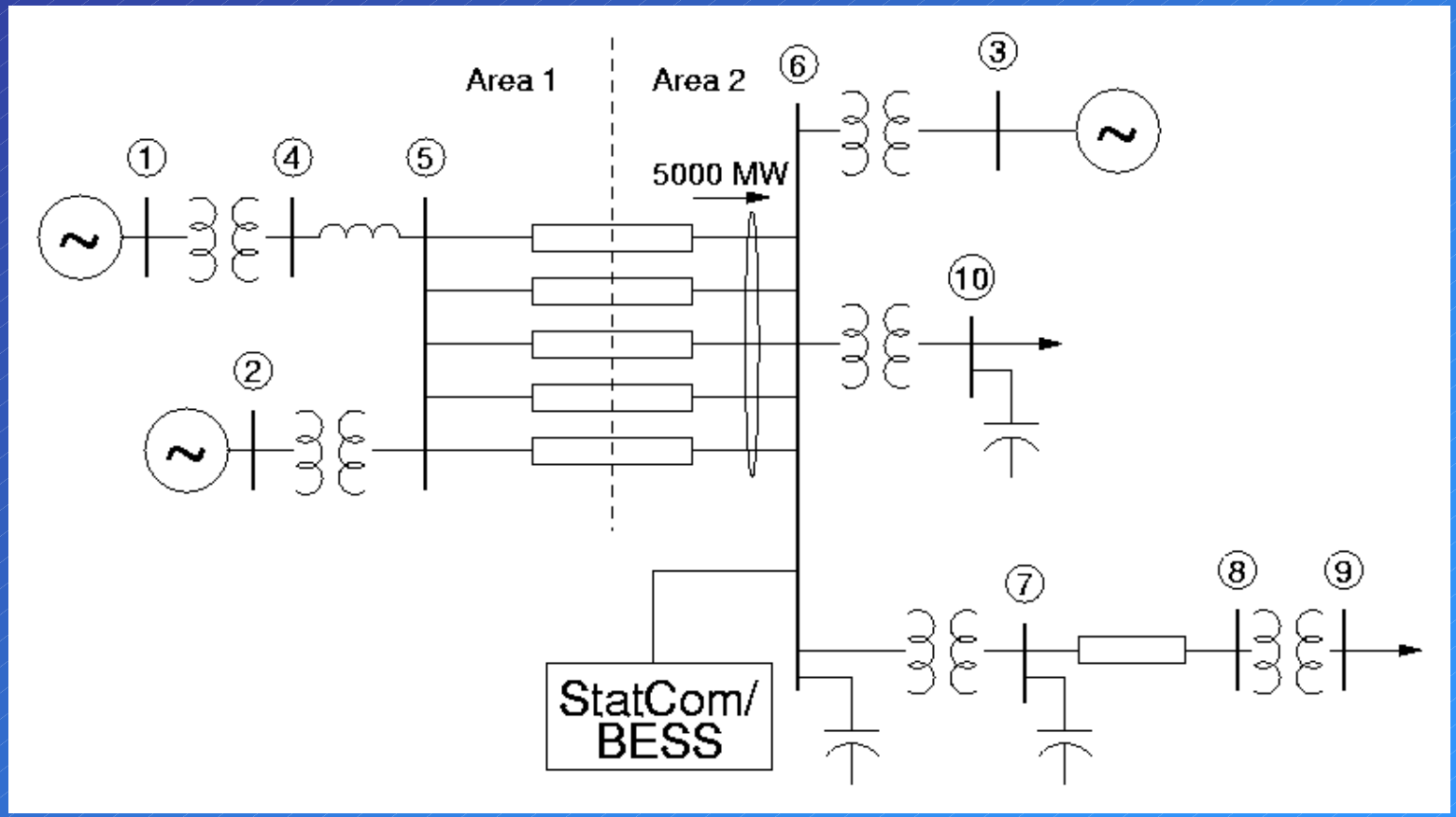


Induction Machine Off

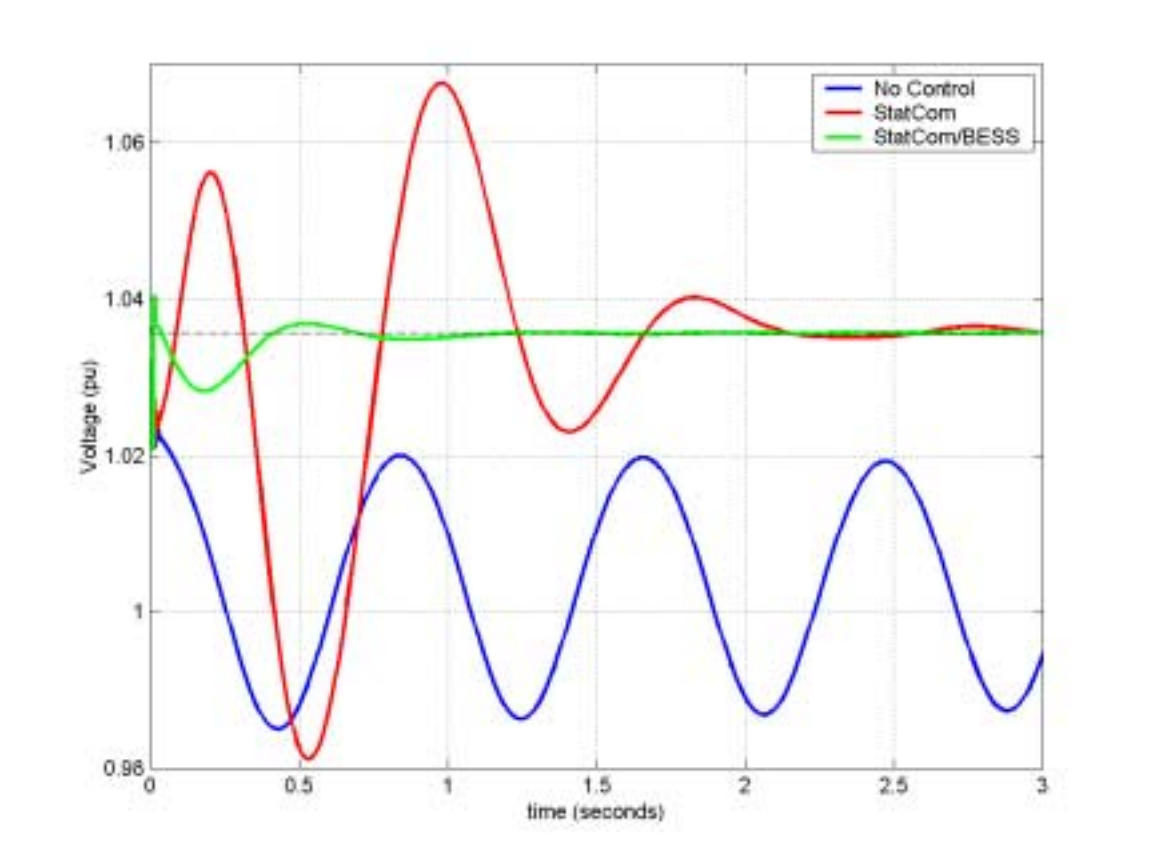
Performance Comparisons

StatCom vs StatCom/BESS

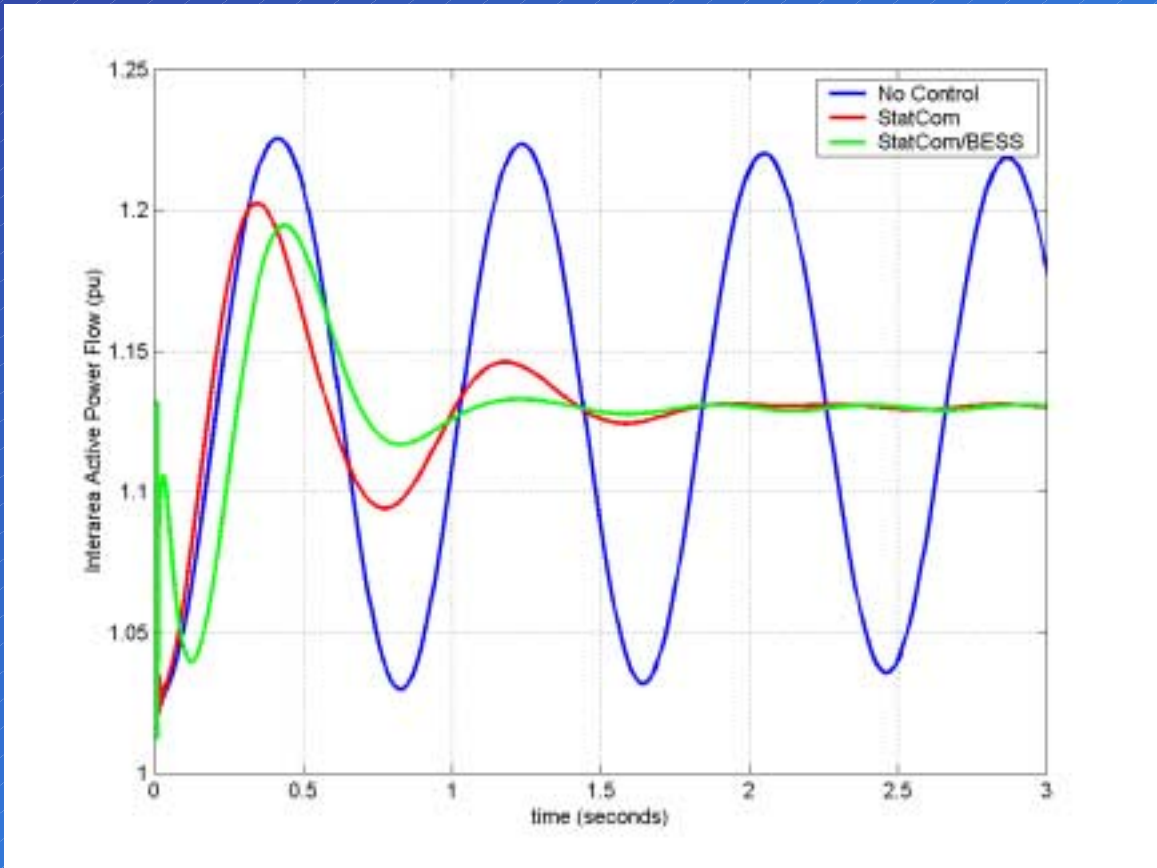
Multi-Machine Test System



Voltages


No Control
StatCom
StatCom/BESS
1.06
1.04
1.02
1
0.96
Voltage (pu)
0
0.5
1
1.5
2
2.5
3
time (seconds)

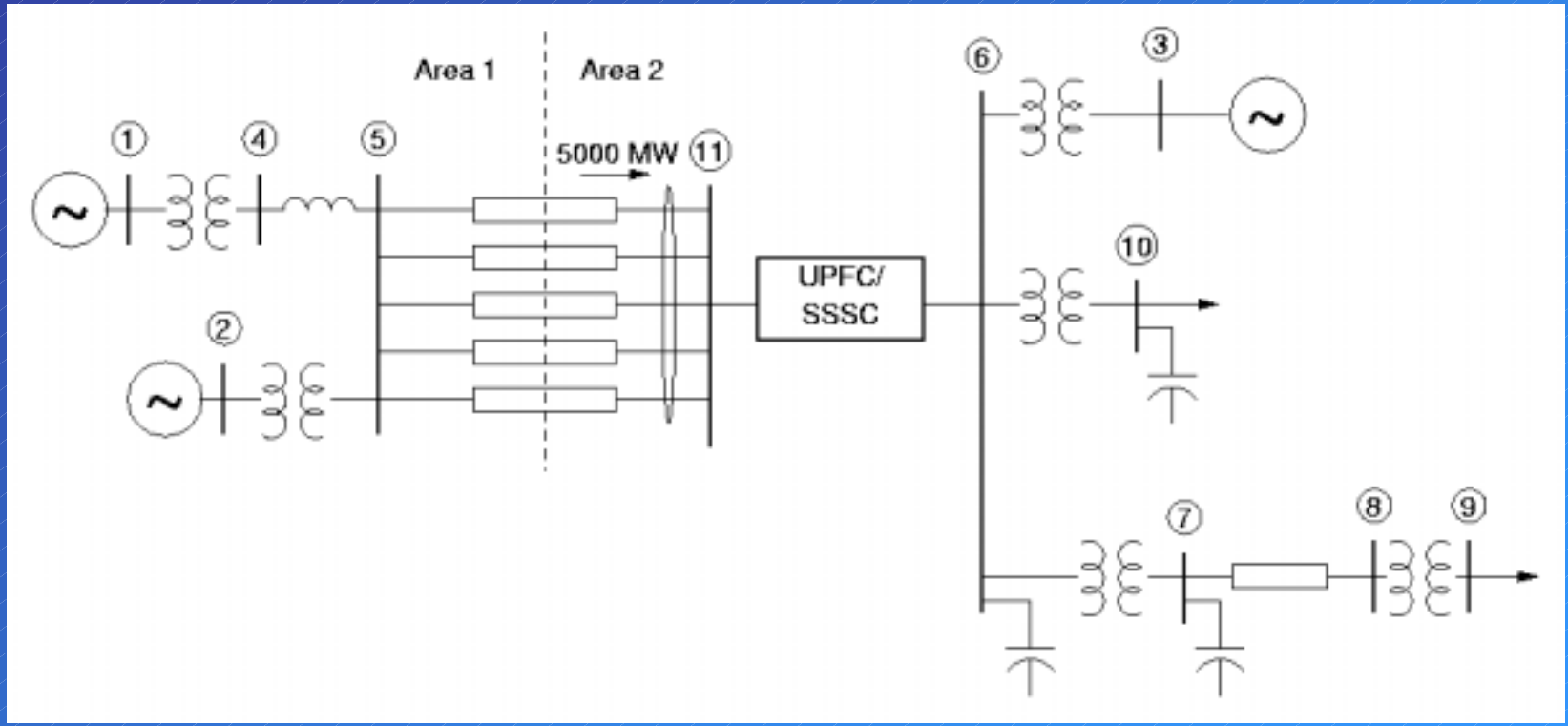
Active Power



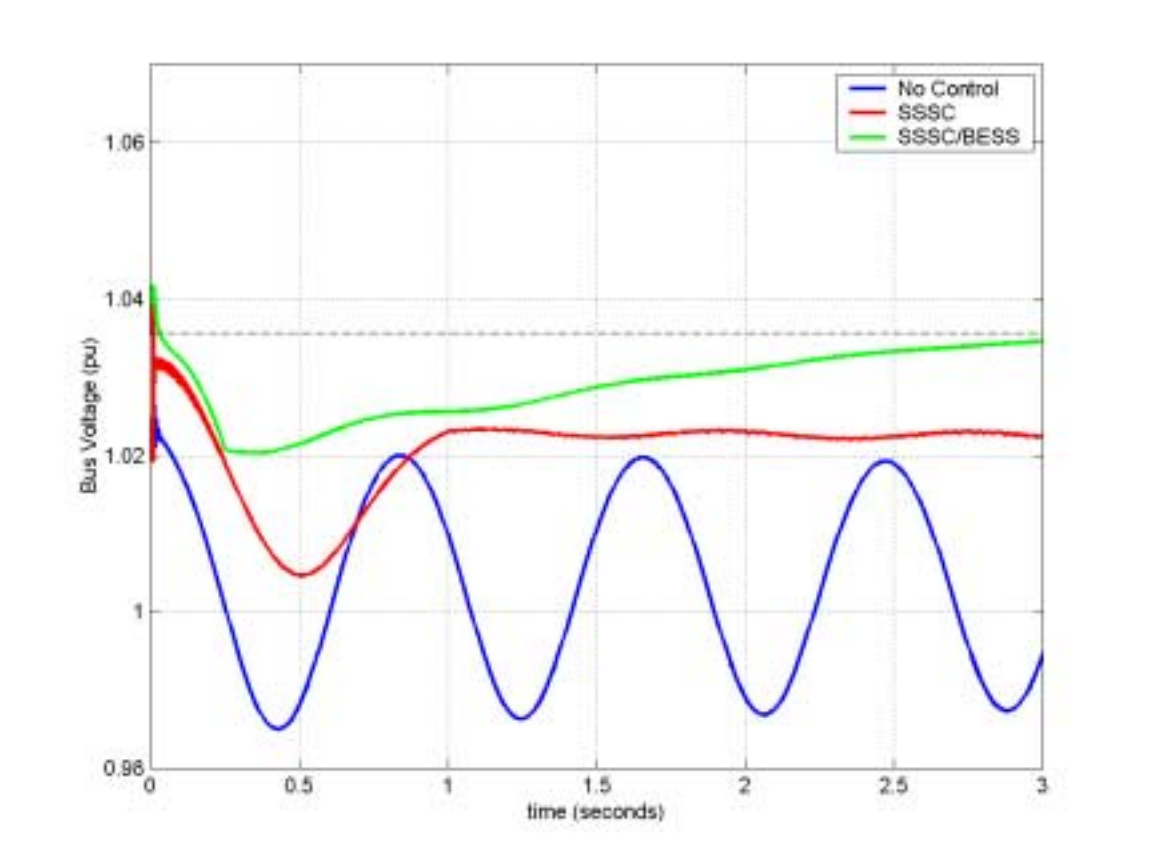
Performance Comparisons

SSSC vs SSSC/BESS

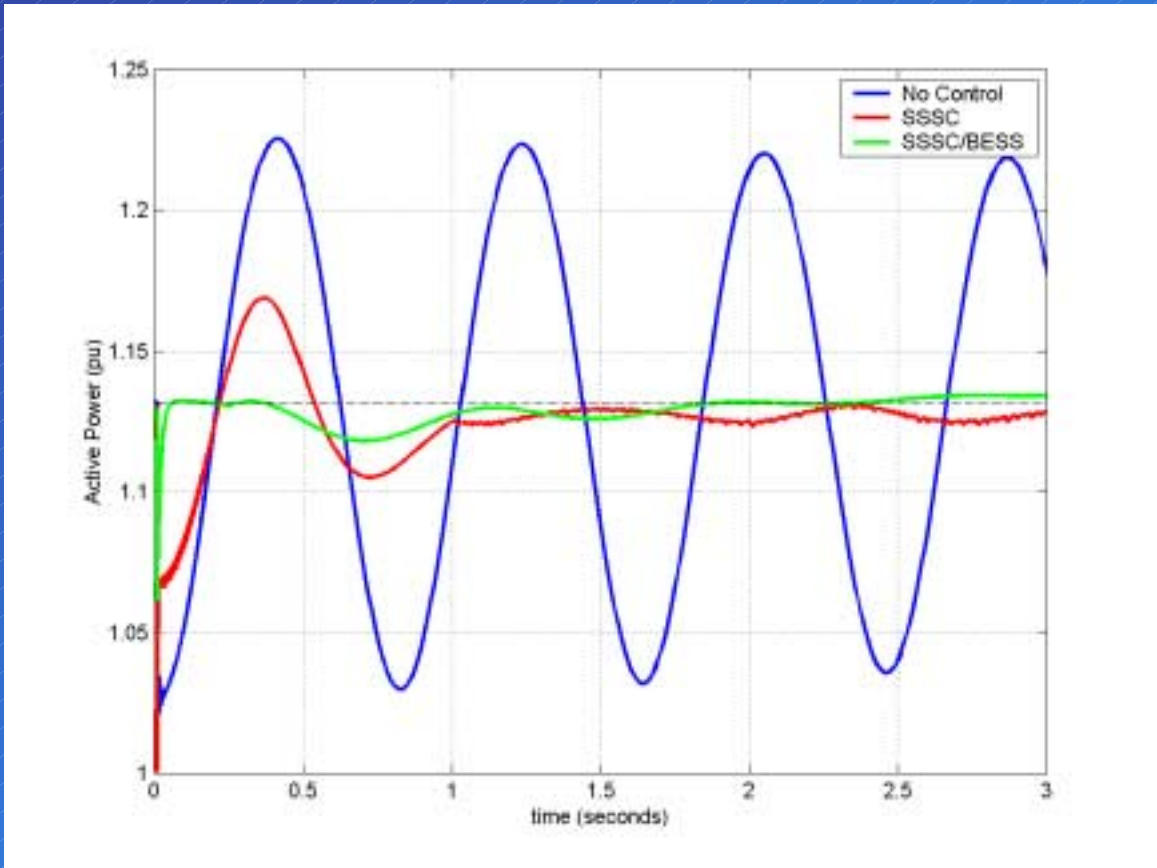
SSSC and UPFC



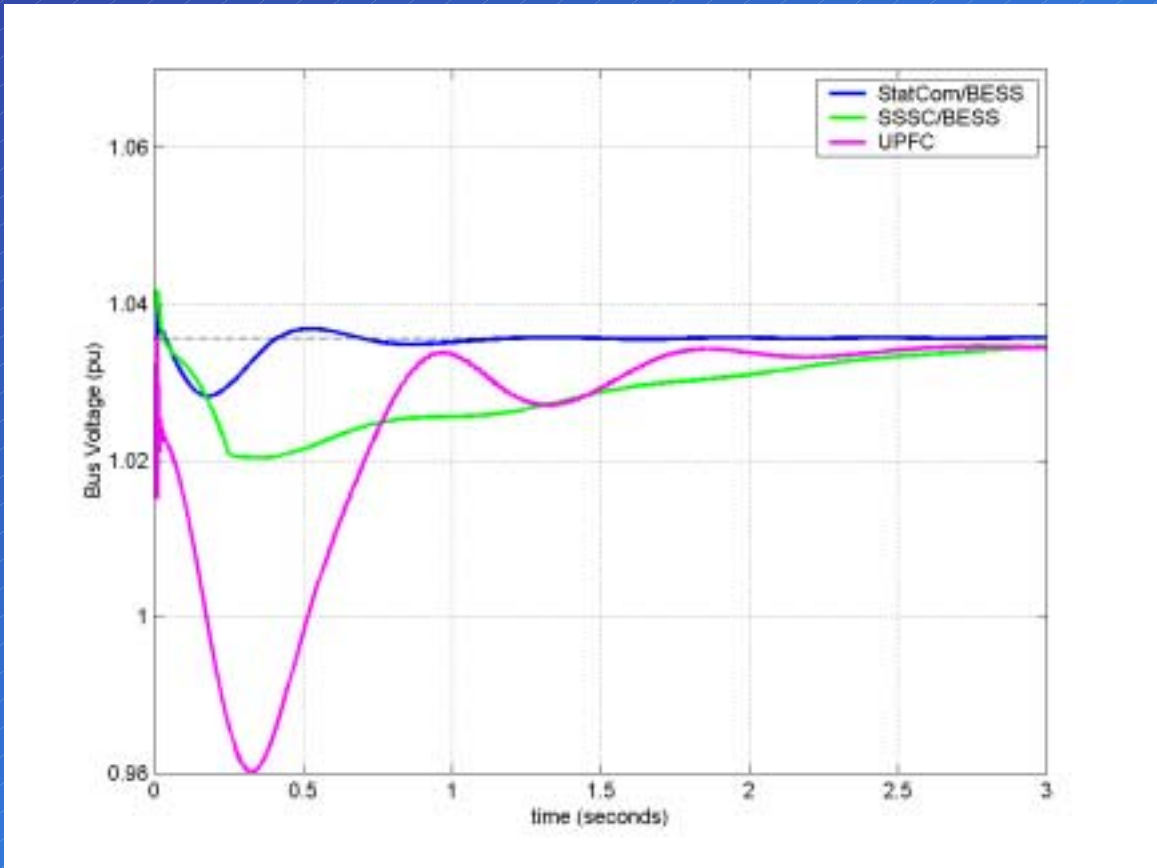
Voltages


No Control
SSSC
SSSC/BESS
1.06
1.04
1.02
1
0.96
Bus Voltage (pu)
0
0.5
1
1.5
2
2.5
3
time (seconds)

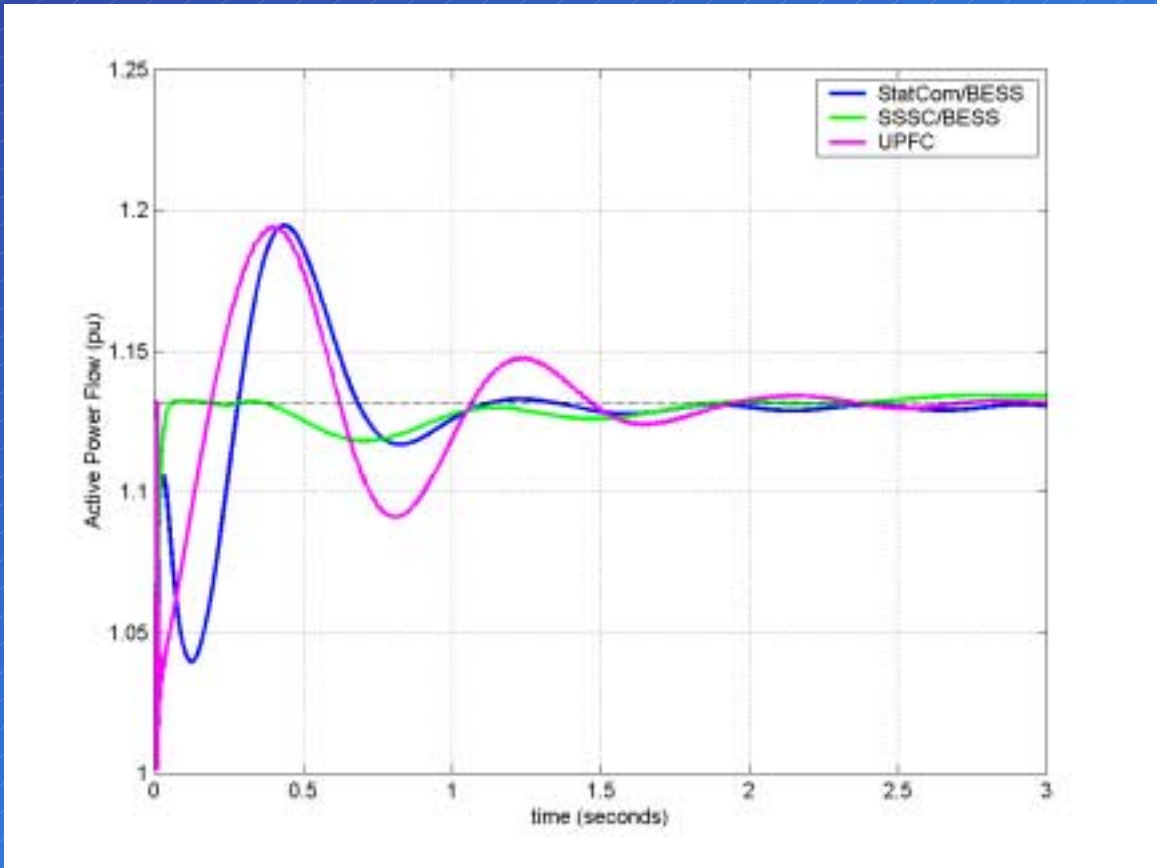
Active Power



Summary Voltages



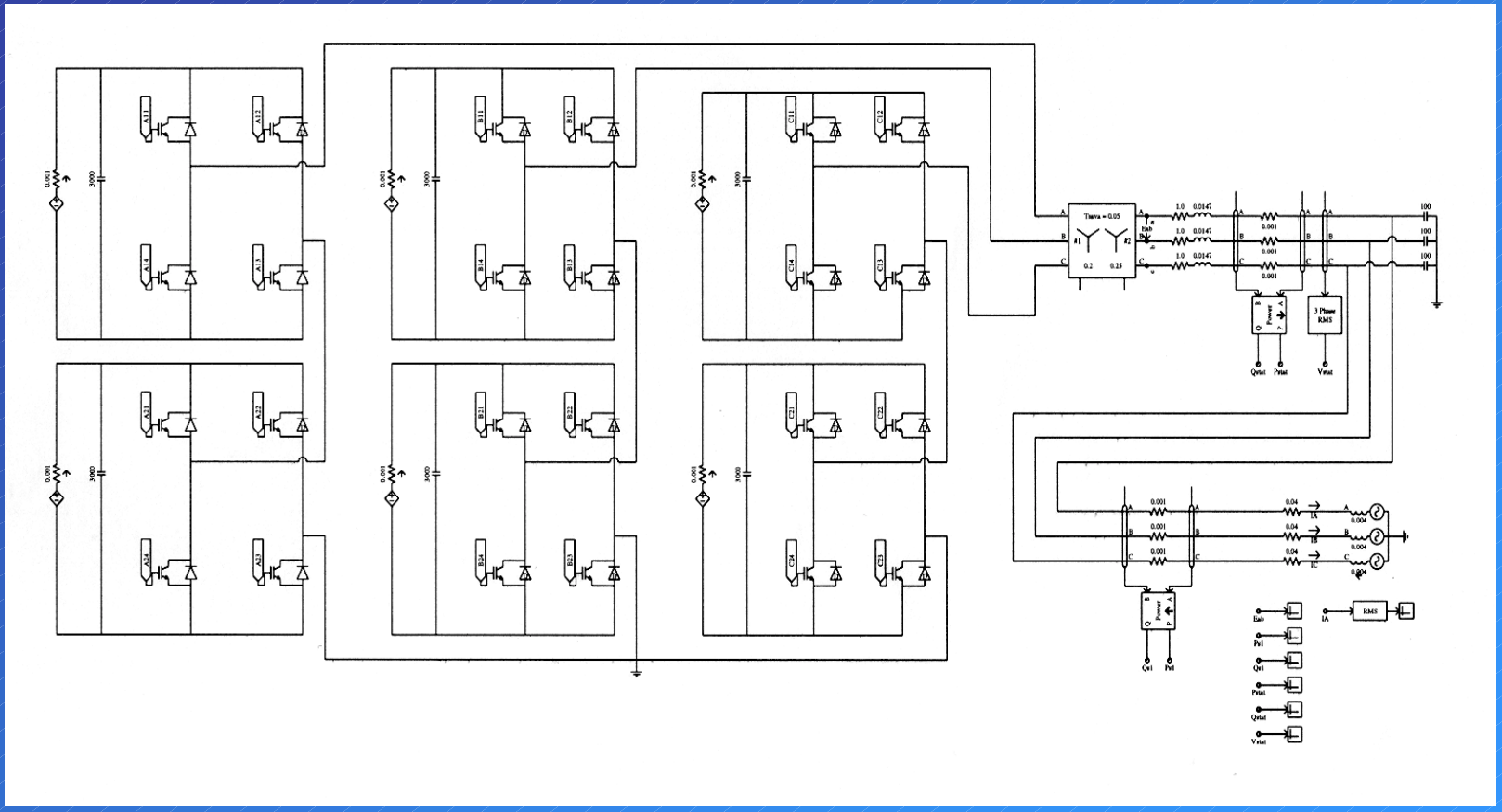
Summary Active Powers



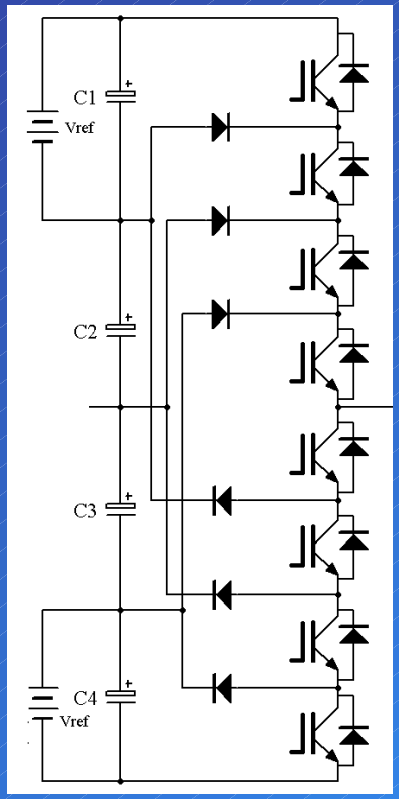
Current Work

- Develop Multi-level converter topologies to reduce BESS size
- Multilevel topologies offer
  - improved voltage quality,
  - decreased switching frequencies, and
  - decreased voltage stress and power losses on the individual devices.

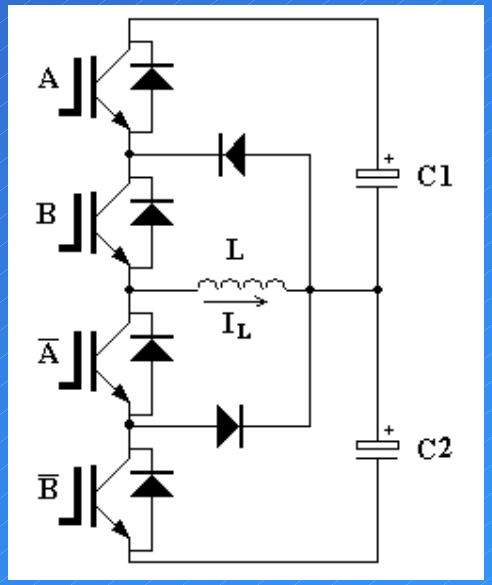
Topology of a 5-level cascaded converter



(a) 5-level diode-clamped multilevel inverter with (b) balancing circuit

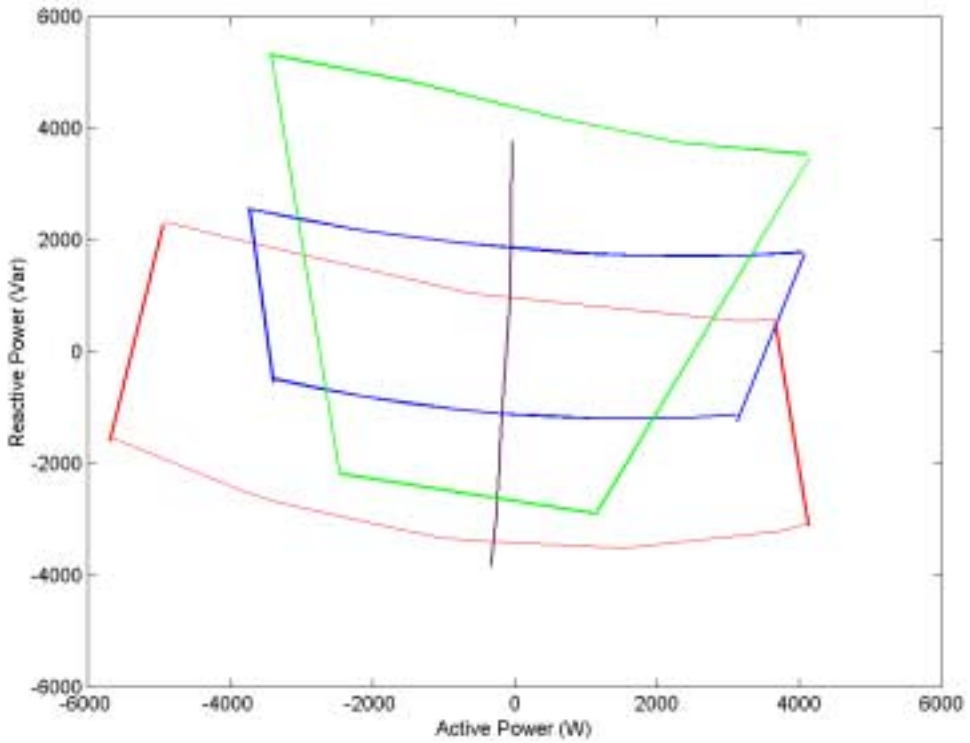


(a)



(b)

Comparison of Operating Regions of Different Topologies



Traditional StatCom

Cascaded 5-level StatCom/BESS

Diode-Clamped 5-level StatCom/BESS

Traditional StatCom/BESS

Traditional StatCom Ratings

		500 W/500 Var	500 W/-500 Var	-500 W/-500 Var	-500 W/500 Var
No. of Batteries		34	34	34	34
Battery voltage		204 V /phase leg	204 V /phase leg	204 V /phase leg	204 V /phase leg
Battery max current		30 A 15 A /string	30 A 15 A /string	30 A 15 A /string	30 A 15 A /string
I_{RMS}		11.6 A	16.1 A	15.8 A	12.3 A
V_{RMS}		144 V	144 V	144 V	144 V
Switches per cycle and average freq.	T1	11 / 660 Hz	11 / 660 Hz	10 / 600 Hz	11 / 660 Hz
	T2	7 / 420 Hz	7 / 420 Hz	7 / 420 Hz	7 / 420 Hz
	T3	6 / 360 Hz	6 / 360 Hz	6 / 360 Hz	6 / 360 Hz
Switching Current Peak/RMS		20 A / 6 A	25.5 A / 8 A	25.2 A / 7 A	21.6 A / 5.8 A
Peak Battery Current		20.3 A	25 A	26 A	22.3 A

5-level Cascaded StatCom

		500 W/500 Var	500 W/ -500 Var	-500 W/ -500 Var	-500 W/ 500 Var
No. of Batteries		36	36	36	36
Battery voltage		72 V / phase leg	72 V / phase leg	72 V / phase leg	72 V / phase leg
Battery max current		15 A	15 A	15 A	15 A
I_{RMS}		3 A	7 A	6 A	2.5 A
V_{RMS}		227 V	209 V	209 V	226.5 V
Switches per cycle and average freq.	a_{11}	12 / 720 Hz	9 / 540 Hz	8 / 480 Hz	8 / 480 Hz
	a_{12}	8 / 480 Hz	9 / 540 Hz	7 / 420 Hz	7 / 420 Hz
	a_{21}	14 / 840 Hz	14 / 840 Hz	13 / 780 Hz	13 / 780 Hz
	a_{22}	13 / 780 Hz	13 / 780 Hz	13 / 780 Hz	13 / 780 Hz
Switching Current Peak/RMS	a_{11}	14 A / 4.5 A	14 A / 6 A	7 A / 2 A	6 A / 4 A
	a_{12}	13 A / 5 A	13 A / 7 A	7 A / 2 A	9 A / 1 A
	a_{21}	10 A / 2 A	12 A / 2.5 A	5 A / 1.5 A	6 A / 1 A
	a_{22}	8 A / 2 A	14 A / 3 A	5 A / 1.5 A	6 A / 2 A
Peak Battery Current	lower	14 A	13 A	5 A	6 A
	upper	14 A	14 A	7 A	9 A

5-level Diode-Clamped StatCom

		500 W/ 500 Var	500 W/ -500 Var	-500 W/ -500 Var	-500 W/ 500 Var
No. of Batteries		36	36	36	36
Battery voltage		108 V / phase leg	108 V / phase leg	108 V / phase leg	108 V / phase leg
Battery max current		2.75 A	4.17 A	3.62 A	2.45 A
I_{RMS}		3.95 A	6.19 A	6.18 A	3.92 A
V_{RMS}		125 V	111 V	109 V	124 V
Switches per cycle and average freq.	g_{11}	12 / 720 Hz	9 / 540 Hz	8 / 480 Hz	11 / 660 Hz
	g_{12}	9 / 540 Hz	12 / 720 Hz	11 / 660 Hz	11 / 660 Hz
	g_{13}	11 / 660 Hz	12 / 720 Hz	13 / 780 Hz	10 / 600 Hz
	g_{14}	12 / 720 Hz	10 / 600 Hz	8 / 480 Hz	11 / 660 Hz
Switching Current Peak/RMS	g_{11}	4.57 / 0.85 A	6.70 / 0.79 A	3.67 / 0.21 A	3.33 / 0.14 A
	g_{12}	5.14 / 1.89 A	8.59 / 2.80 A	8.11 / 1.71 A	4.28 / 0.8 A
	g_{13}	5.14 / 2.34 A	8.47 / 3.80 A	8.77 / 3.28 A	4.85 / 1.6 A
	g_{14}	5.10 / 2.41 A	8.47 / 4.02 A	8.74 / 4.18 A	5.02 / 2.25 A
Peak Battery Current	outer	4.52 A	7.2 A	5.75 A	4.38 A
	inner	5.10 A	8.2 A	8.1 A	4.98 A

Conclusions

- FACTS/BESS controllers offer improved performance over FACTS-only controllers
- Multi-level topologies offer comparable performance with decreased electronics and BESS size

Future Work

- Laboratory verification of multi-level topologies in system studies (StatCom in progress, SSSC still in development)
- Development of system-level controls for coordinated FACTS/BESS systems
- Placement studies (in progress)