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Dynamic Control Modes of the Unified Power Flow Controller (UPFC)

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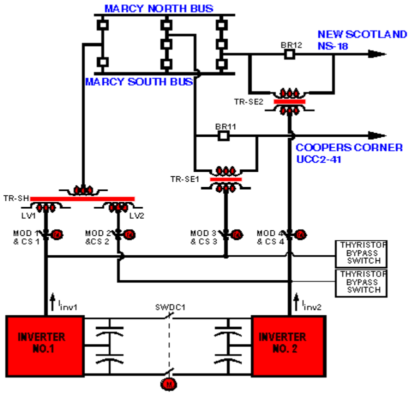
Topics

I. Introduction: NYPA’s Convertible Static Conpensator (CSC)
II. Control schemes of the UPFC and positive-sequence time-domain simulation
III. Small-signal linearized models
IV. Complete modal-decomposition technique for damping contribution analysis
V. Damping controller design
VI. Conclusions

I. Introduction: Convertible Static Compensator (CSC)



CSC Schematic Structure

11 Operating Configurations

Circuit Configuration = 0

Config.	Type	Inverter Connection			Allowable Transitions
		Inv #1 to:	Inv #2 to:	SWDC1	
0	OFF	not used	not used	Open	ALL
1	STATCOM100-1	TR-SH(LV1)	not used	Open	0,3,7
2	STATCOM100-2	not used	TR-SH(LV2)	Open	0,3,8
3	STATCOM200	TR-SH(LV1)	TR-SH(LV2)	Open	0,1,2
4	SSSC100-UCC	TR-SE1	not used	Open	0,6,8
5	SSSC100-UNS	not used	TR-SE2	Open	0,6,7
6	SSSC100-UCC SSSC100-UNS	TR-SE1	TR-SE2	Open	0,4,5
7	STATCOM100-1 SSSC100-UNS	TR-SH(LV1)	TR-SE2	Open	0,1,5
8	SSSC100-UCC STATCOM100-2	TR-SE1	TR-SH(LV2)	Open	0,2,4
9	UPFC100/100-UNS	TR-SH(LV1)	TR-SE2	Closed	0
10	UPFC100/100-UCC	TR-SE1	TR-SH(LV2)	Closed	0
11	IPFC100-UCC/100-UNS	TR-SE1	TR-SE2	Closed	0

– Shunt

(Sh1) Voltage control mode
(Sh2) Var setpoint control mode

– Series Standalone

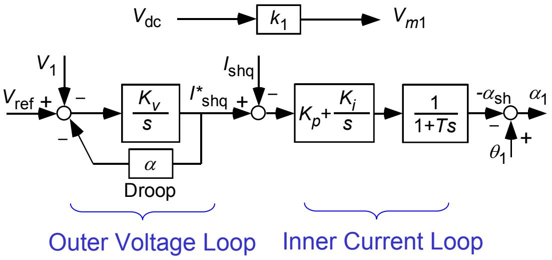
(Se1) Line P setpoint mode
(Se2) Fixed injected voltage magnitude mode

– Series Coupled

(SeC1) Line P,Q setpoints mode
(SeC2) Fixed injected voltage (V_d,V_q)

II. Control Schemes – Shunt VSC

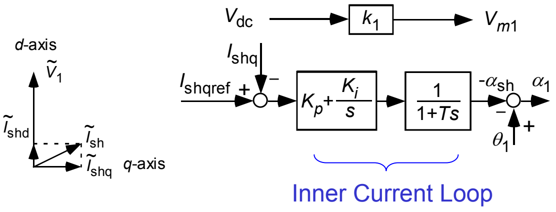
Voltage Control Mode:



V_{ref} ↑, I^*_{shq} ↑, α_{sh}>0, P_c>0, charging: V_{dc}↑, V_{m1}↑, I_{shq} ↑, V_1 ↑

- k_1 is set to a constant
- In steady state, α_{sh} is a constant
- Transient deviations of α_{sh} cause nonzero active power to go through the DC capacitor and thus result in a change of V_{dc}

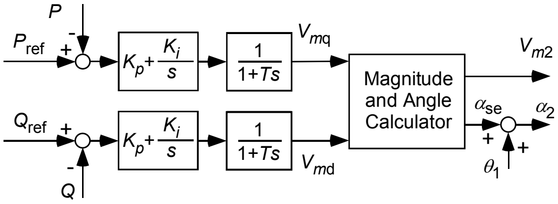
Var Control Mode:

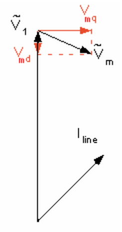


Control Schemes – UPFC Series VSC

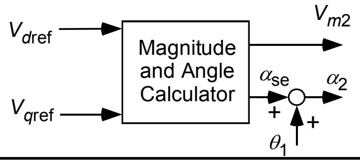
- UPFC shunt VSC control structure is same with the STATCOM:
  - But α_{sh} can be a nonzero value in steady state
- UPFC series VSC:

Line *P*,*Q* Control Mode





Inverter Voltage Control Mode



- Both the DC-to-AC ratio of the inverter and the phase angle of the inverter output voltage are controlled

Positive-Sequence Time-Domain Simulation

Overall System Equations

- Generators, exciters, governers, and other power system controllers such as power system stabilizers (PSS)

$$\dot{x} = f(x, x_{VSC}, V)$$

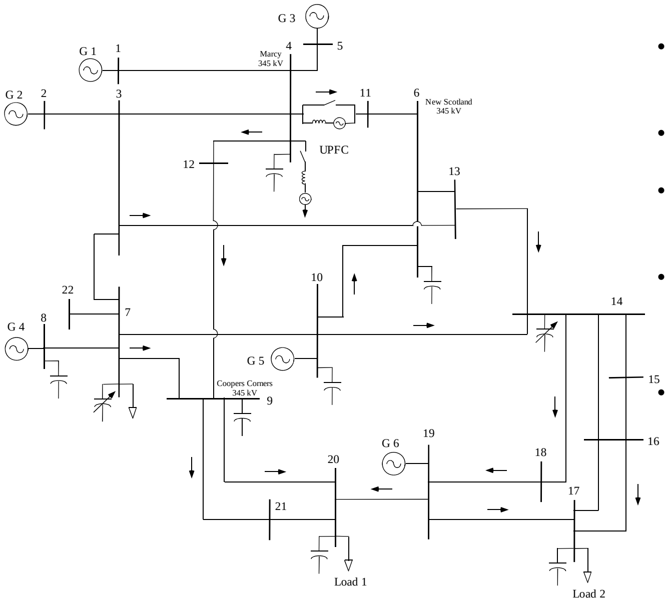
- DC link capacitor dynamics and the VSC controls

$$\dot{x}_{VSC} = f_{VSC}(x, x_{VSC}, V)$$

- Power system network, loads

$$I(x, x_{VSC}, V) = YV$$

22-Bus Test System



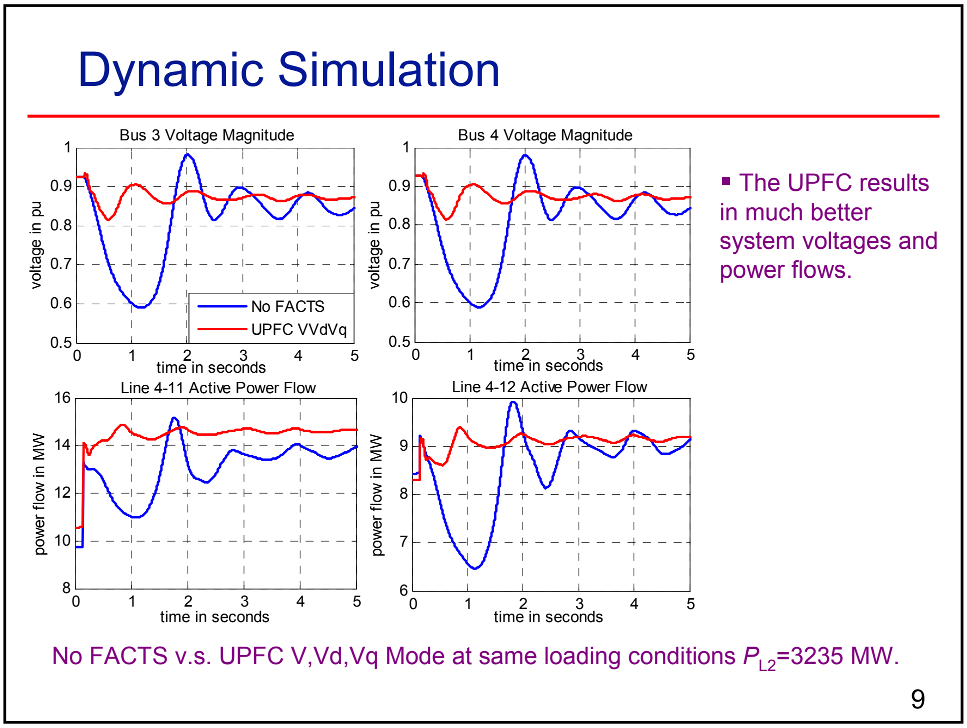
- 6 generators (northwest) and 3 loads (southeast).
- UPFC Bus 4, Line 4-11
- Base load on Bus 17: 2500 MW
- Gradually Increase P_{load} on Load 2, and P_{gen} on G1, G2, and G3.
- Single-phase line-to-ground fault on Bus 3 at t = 0.1 s and trip Line 3-13 after 4 cycles

22-Bus Test System

Fault: A single-phase LG fault at Bus 3 at time t = 0.1 s and trip Line 3-13 after 4 cycles

Configuration	Setpoints	Maximum Load on Bus 17 (MW)	Line Power Transfer (MW)	
			Line 4-11	Line 4-12
No FACTS	-	3235	1390	904
UPFC Var,Vd,Vq	(sh) I_{shqref} = 1.0 pu (se) V_{dref} = 0 pu, V_{qref} = -0.055 pu	3343	1469	904
UPFC V,Vd,Vq	(sh) V_{ref} = 0.91 pu (se) V_{dref} = 0 pu, V_{qref} = -0.055 pu	3340	1473	905

Dynamic Simulation



- The UPFC results in much better system voltages and power flows.

No FACTS v.s. UPFC V,Vd,Vq Mode at same loading conditions P_{L2}=3235 MW.

III. Small-Signal Linearized Models

Overall System Equations

$$\dot{x} = f(x)$$

$$I = YV$$

$$\Downarrow$$

$$\dot{x} = Ax + Bu$$

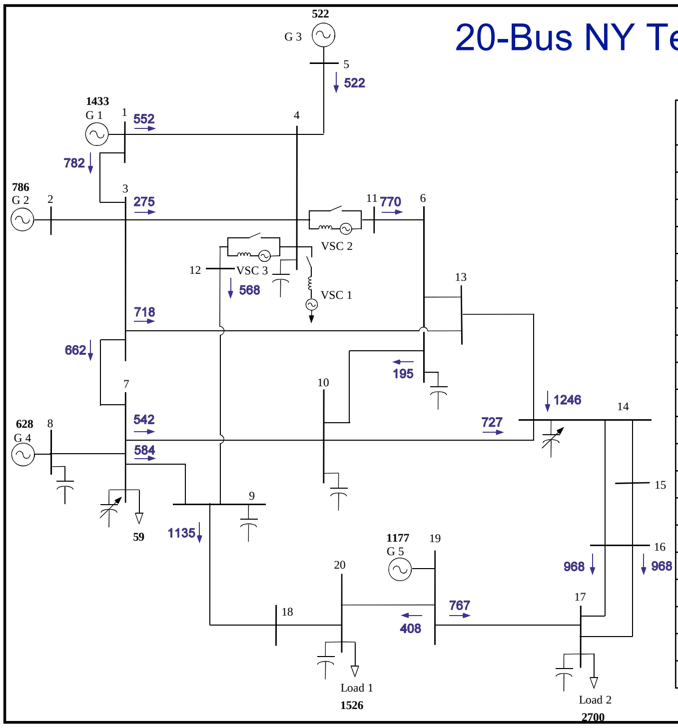
$$y = Cx + Du$$

State Matrix Building

The integration part in the nonlinear simulation is replaced by a sequential perturbation of the state and input variables.

Share a common set of codes with dynamic models for FACTS controllers, generators, and exciters.

20-Bus NY Test System



Bus #	Volt Mag. (pu)	Volt Angle (degree)
1 (G1)	1.0646	-3.3
2 (G2)	1.0728	6.4
3	1.0309	-20.6
4	1.0312	-20.7
5 (G3)	1.035	-16.0
6	1.0450	-36.9
7	1.0336	-33.3
8 (G4)	1.0429	38.3
9	1.0375	-41.6
10	1.0452	-38.66
11	1.0312	-20.7
12	1.0312	-20.8
13	1.0451	-37.0
14	1.0377	-45.8
15	1.0367	-46.1
16	1.0294	-56.6
17	1.0355	-59.5
18	1.0186	-51.6
19	1.0448	-58
20 (G5)	1.0351	-62.0

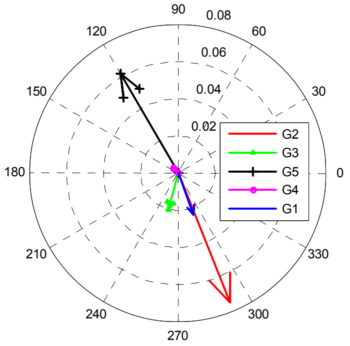
Eigenvalues of the Linearized Model

Total 40 states: 6 generator states and 2 exciter states for each machine

Mode	Eigenvalues	Dmp Ratio	Freq (Hz)	Dominant States
6,7	$-0.29 \pm j1.79$	0.160	0.284	$\Delta\omega$ and $\Delta\delta$ of G4
10,11	$-0.22 \pm j5.81$	0.038	0.925	$\Delta\omega$ and $\Delta\delta$ of G5 and G1,2,3
12,13	$-0.35 \pm j6.72$	0.051	1.070	$\Delta\omega$ and $\Delta\delta$ of G2 and G1
16,17	$-0.471 \pm j9.32$	0.050	1.483	$\Delta\omega$ and $\Delta\delta$ of G3

Swing Mode10,11

- Inter-area mode of interest



IV. Complete Modal Decomposition

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

$$\Rightarrow$$

$$\begin{bmatrix} \Delta\dot{\delta}_{mi} \\ \Delta\dot{\omega}_{mi} \\ \dot{z}_r \end{bmatrix} = \begin{bmatrix} \sigma_i & \omega_i & 0 \\ -\omega_i & \sigma_i & 0 \\ 0 & 0 & A_r \end{bmatrix} \begin{bmatrix} \Delta\delta_{mi} \\ \Delta\omega_{mi} \\ z_r \end{bmatrix} + \begin{bmatrix} b_{mi1} \\ b_{mi2} \\ B_r \end{bmatrix} u$$

$$y = \begin{bmatrix} c_{mi1} & c_{mi2} & C_r \end{bmatrix} \begin{bmatrix} \Delta\delta_{mi} \\ \Delta\omega_{mi} \\ z_r \end{bmatrix} + D_m u$$

State Transformation

$x_m = Tx$

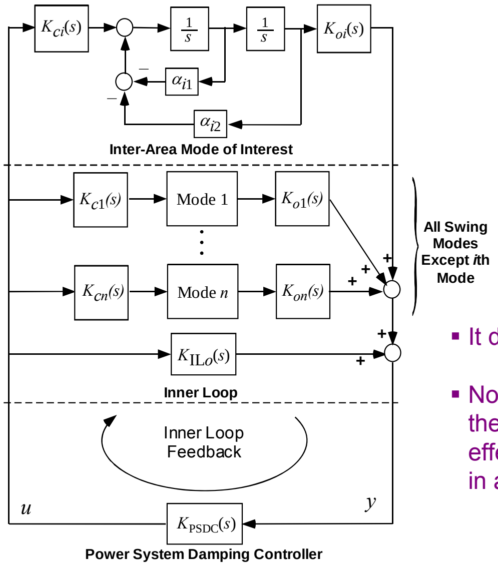
Limitation: the transformation requires that *A* be diagonalizable. A sufficient condition for diagonalizability is that *A* has no repeated eigenvalues.

$$T_{mi} = [c_{m1}\ c_{m2}] \begin{bmatrix} s-\sigma_i & -\omega_i \\ \omega_i & s-\sigma_i \end{bmatrix}^{-1} \begin{bmatrix} b_{m1} \\ b_{m2} \end{bmatrix} = \frac{\beta_{i1}s + \beta_{i2}}{s^2 + \alpha_{i1}s + \alpha_{i2}}$$

$$K_{ci}(s)K_{oi}(s) = \beta_{i1}s + \beta_{i2}$$

where $\lambda_i = \sigma_i + j\omega_i$ is the mode of interest.

Complete Modal Decomposition



- $K_{ci}(s)$: controllability transfer functions for the inter-area mode *i*
- $K_{oi}(s)$: observability transfer functions for the inter-area mode *i*
- $K_{PSDC}(s)$: the transfer function of damping controller
- $K_{IL}(s)$: the inner-loop transfer function from *u* to *y*

- It decouples all system modes

- Note that for a specific mode of interest, the inner-loop sensitivity contains the effect of other swing modes to this mode, in addition to network effect

Effective Control Action

Effective Control Action for Mode *i*:

$$K_{ei}(s) = K_{ci}(s)\frac{K_{PSDC}(s)}{1-K_{IL}(s)K_{PSDC}(s)}K_{oi}(s)$$

Assume $|K_{\mathrm{PSDC}}(\omega)| >> 1$, we obtain:

$$|K_{ei}(\omega)| = \left|\frac{K_{ci}(\omega)K_{oi}(\omega)}{K_{\mathrm{IL}}(\omega)}\right|$$

Maximum Damping Influence (MDI) Index

Assume $|K_{\mathrm{PSDC}}(\omega)K_{\mathrm{IL}}(\omega)| << 1$. For $K_{\mathrm{PSDC}}(\omega) = kG_c(\omega)$, we obtain:

$$\left|\frac{dK_{ei}(\omega)}{dk}\right| = \underbrace{\left|K_{ci}(\omega)K_{oi}(\omega)\right|}\cdot\left|G_c(\omega)\right|$$

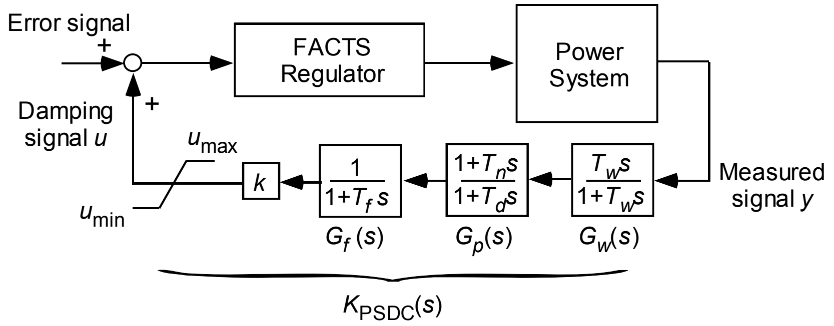
Index $|K_{ci}(\omega)K_{oi}(\omega)|$

V. Damping Controller Design

- Damping input signal selection based on effective control action
  - local and remote signals
    - local signals: bus frequencies, bus voltages, and line currents and power flows
    - remote signals: remote bus angles, can be measured using phasor measurement units (PMU), or synthesized from local signals using bus voltages and line reactances
  - Two indices for selecting a feedback variable *y*
    - MDI Index: indicates the effectiveness of measurements having high observability gain and low inner-loop gain
    - Index $|K_{ci}(\omega)K_{oi}(\omega)|$: indicates that as *k* increases from zero, the larger this index is, the faster the control effect changes
- Damping controller components
- UPFC damping controller design example

Damping Controller Components

Damping controller: consists of a washout loop $G_w(s)$, a phase compensator $G_p(s)$, a lowpass (LP) filter $G_f(s)$, a constant gain k, and saturation limits $[u_{\min}, u_{\max}]$.



MDI Index for the UPFC

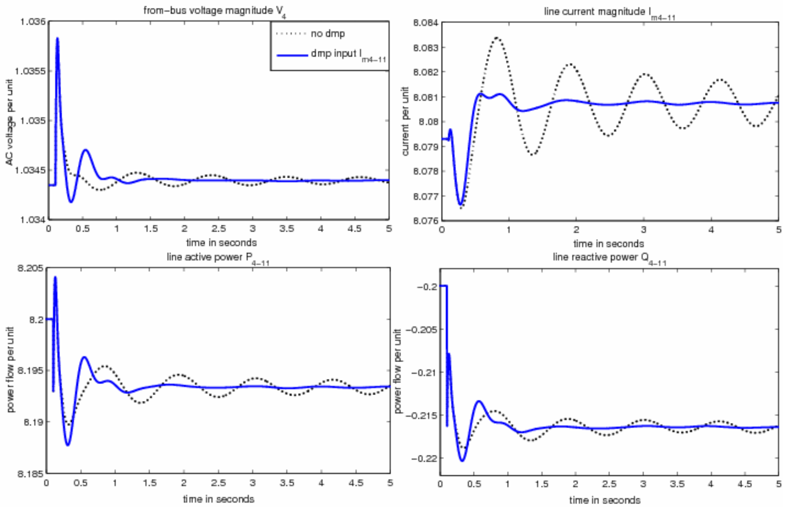
UPFC on Bus 4, Line 4-11

MDI Index

Local Signals	STATCOM		UPFC Series Vd,Vq Mode		UPFC Series P,Q Mode	
	V Mode	Var Mode	Shunt V Mode	Shunt Var Mode	Shunt V Mode	Shunt Var Mode
V4	4.92	5.75	4.82	5.58	3.37	4.10
P4-11	26.10	25.09	22.81	21.08	16.82	15.43
Im4-11	**67.95**	**58.43**	**60.17**	**58.54**	16.34	14.84

I_{m4-11} as the damping input signal to the shunt regulator has the highest MDI indices for the STATCOM and for the UPFC in the Vd,Vq mode.

UPFC Damping Controller Simulation



VI. Conclusions

- UPFC, when appropriately controlled, can substantially improve the transient power transfer capability of transmission system during a system disturbance.
- The fixed injected voltage control is advantageous when compared with the line flow control mode for damping control