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Reactive Security Study of a Large Power System

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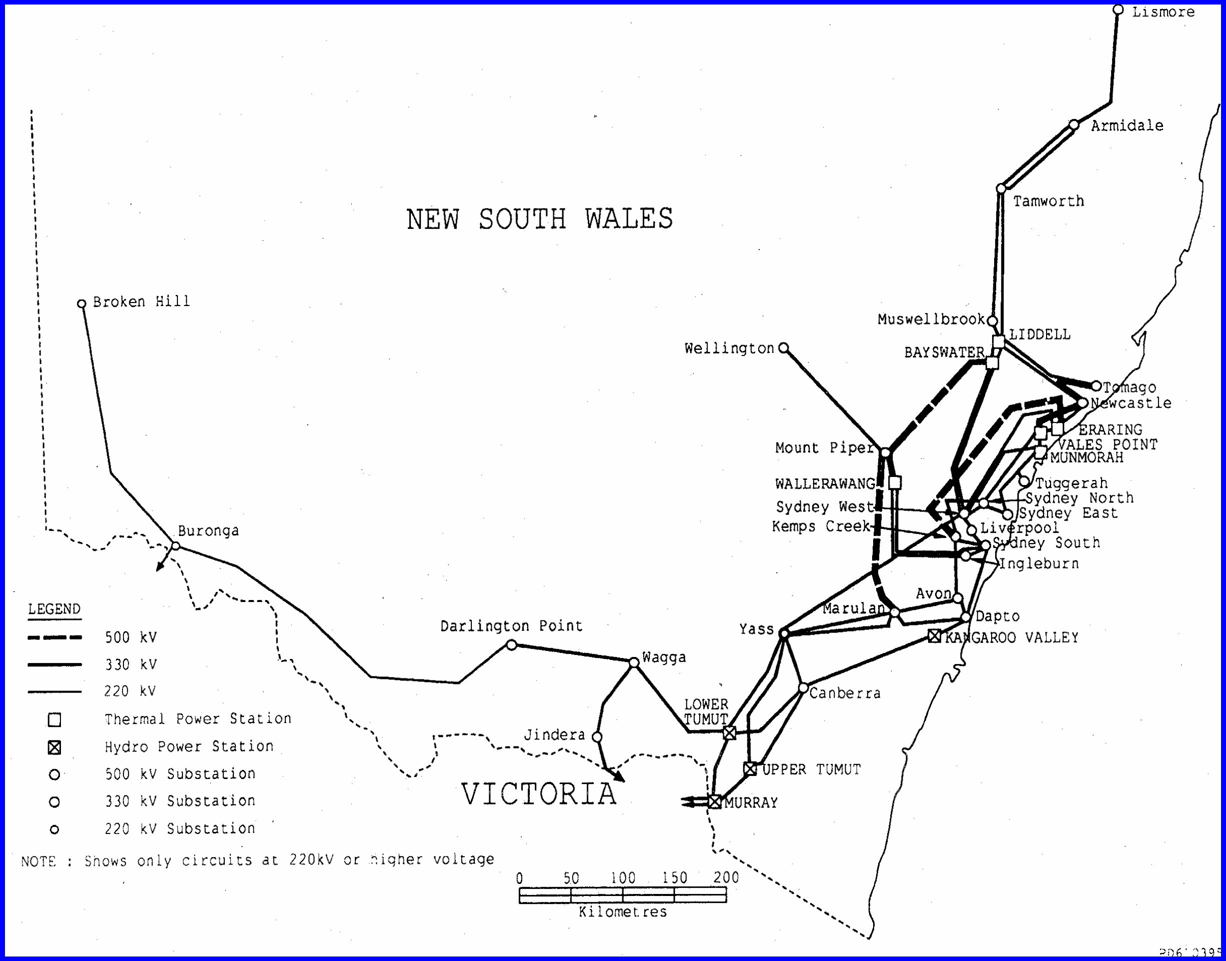
Outline *(Bologna)*

- Introduction
- System and Modelling
- Computation of the Security Boundary
- Application to NSW Main Grid
- Impact of Load Modelling
- Coordinated Control Schemes
- Conclusions

Introduction

- TransGrid is transmission company (TNSP) in National Electricity Market
- Voltage collapse determines limits (ATC)
- Contributing factors:
  - higher flows in NEM
  - load modelling
  - restriction on physical expansion
- Need stability margins more accurately

◆NSW System



Key load centres

Bus 74 (Newc 330)

Bus 76 (Tomago330)

Bus 3229 (Newc 132)

Bus 3207 (SydW 132)

Bus 3283 (Syd E 132)

Bus 3286 (Syd S 132)

Bus 3172 (Dapto 132)

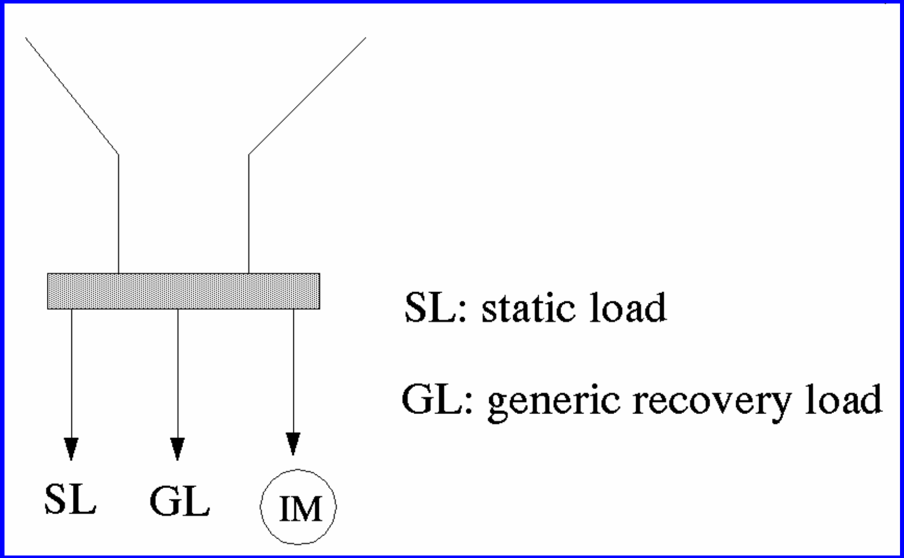
Bus 3101 (Canb 132)

Composite Load Model

- Traditional PQ load model
- Generic dynamic model
- Aggregate induction motor model

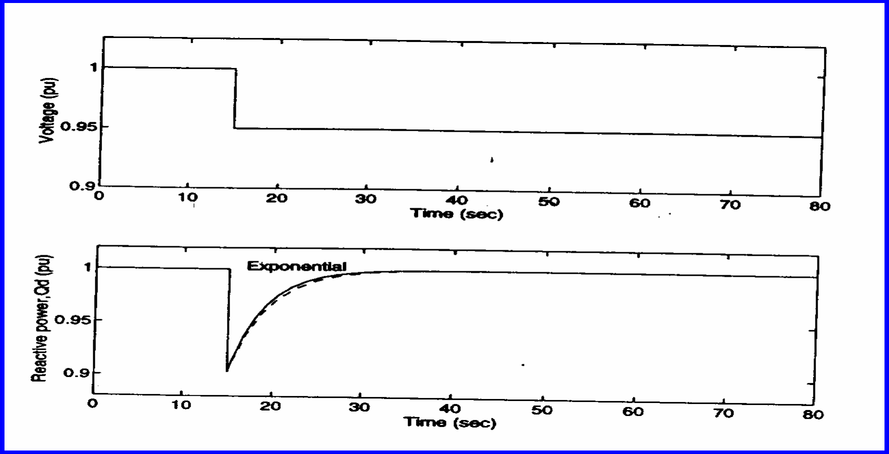
Load = $w_1 SL + w_2 GL + w_3 IM$

$w_1 + w_2 + w_3 = 1$



◆Generic recovery load model

- represent all down-stream OLTC and themo-controlled loads



Step response of the load model

$$\dot{x}_p = P_s(V) - P_d$$

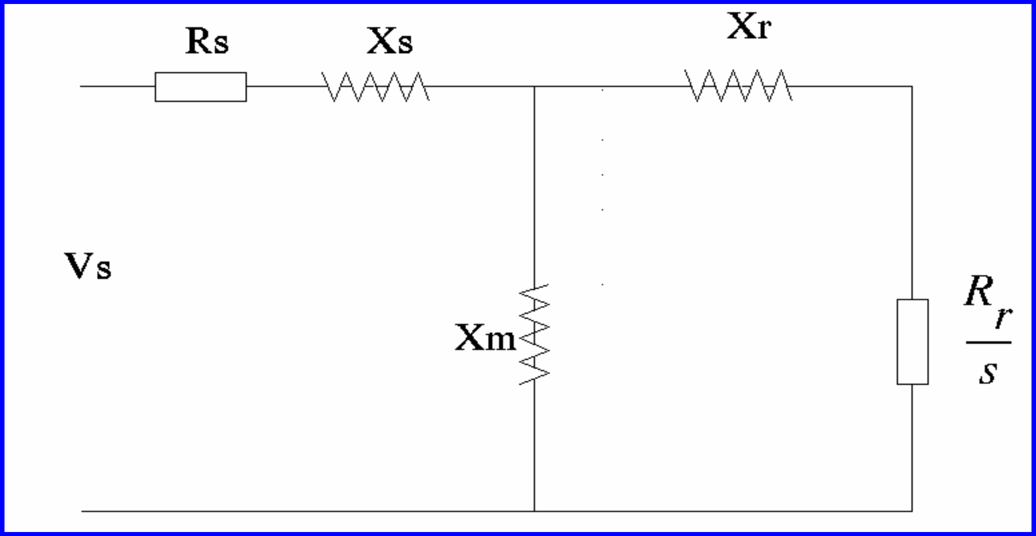
$$P_d = \frac{1}{T_p} x_p + P_t(V)$$

$$\dot{x}_q = Q_s(V) - Q_d$$

$$Q_d = \frac{1}{T_q} x_q + Q_t(V)$$

◆Aggregate induction motor and static load

- □static load $P_d = P_0(\frac{V}{V_0})^{\alpha}, Q_d = Q_0(\frac{V}{V_0})^{\beta}$
- □ IM -- represent all down-stream compressor and other rotating load



$$\dot{s} = \frac{1}{2H}(T_m(s) - T_e(s,V))$$

Power System Model

$$\dot{x} = f(x, y, p)$$
$$o = g(x, y, p)$$

◆Dynamic variables	x_p , x_q , s	24
◆Algebraic variables	P_d , Q_d	16
	V , ☆	216
◆Parameters		

Computation of Security Boundary

- Steady-state critical points in a loading direction (SNB, Hopf, …)
- Security boundary
- Closest boundary points
- Security proximity index -- minimum distance

◆System descriptions

$$\left.\begin{aligned} \dot{x} &= f(x, y, p) \\ 0 &= g(x, y, p) \end{aligned}\right\} = F_G(x, y, p)$$

◆Linearization

$$\Delta\dot{x} = J_s \cdot \Delta x$$

◆Ray in parameter space

$$p = p_0 + \tau \cdot \gamma$$

$$\gamma = \sum_{i \ni R^m} \beta_i e_i$$

$$\lambda = \alpha + jw$$

◆General method for steady-state stability study

Minimize/maximize α^2

subject to:

$$
\begin{aligned}
F_G(x,y,+\tau\gamma) &= 0 \\
J_s^T l' - a l' + w l'' &= 0 \\
J_s^T l'' - a l'' - w l' &= 0 \\
l^T l - 1 &= 0
\end{aligned}
$$

- Different characteristic points found by choice of stability constraints

α	ω	$\frac{d\alpha}{d\tau}$	Category
$\neq 0$	$\neq 0$	$= 0$	minimum or maximum damping pt
$= 0$	$\neq 0$	$\neq 0$	Hopf bifurcation point
$= 0$	$= 0$	≈ 0	SN bifurcation point

◆Stability boundary

$$SNB, \quad \sum_s$$
$$HB, \quad \sum_h$$

◆Closest bifurcation points

Minimize

$$\|\eta(p - p_0)\|$$

subject to

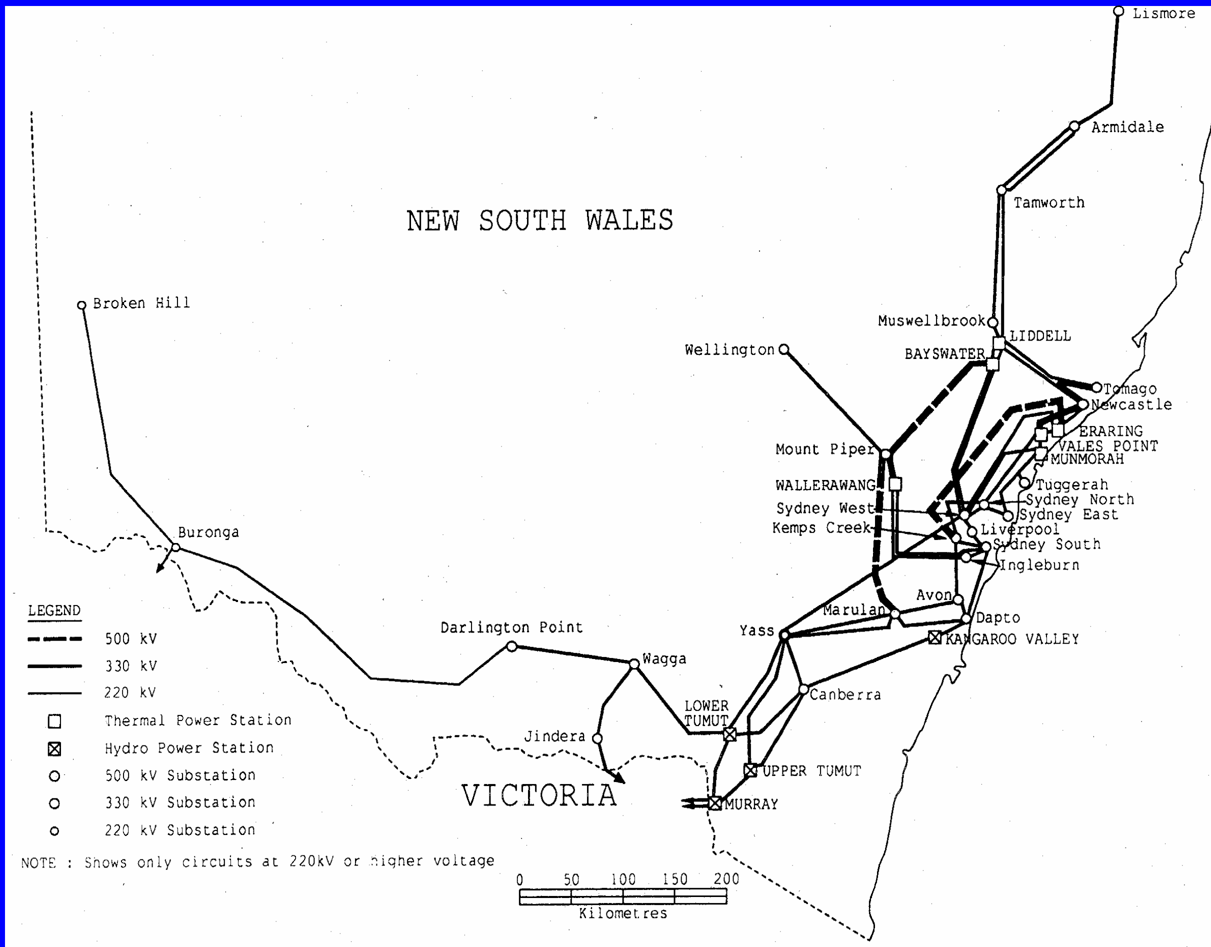
$$F(x, y, p) = 0$$
$$J_s^{\mathrm{T}}\, l - \mathrm{j}wl = 0$$
$$l^T l - 1 = 0$$

Application to NSW Grid

- Security boundary and closest point

- Cases
  - All lines in service
  - Lines tripped out

◆NSW System



Key load centres

Bus 74 (Newc 330)

Bus 76 (Tomago330)

Bus 3229 (Newc 132)

Bus 3207 (SydW 132)

Bus 3283 (Syd E 132)

Bus 3286 (Syd S 132)

Bus 3172 (Dapto 132)

Bus 3101 (Canb 132)

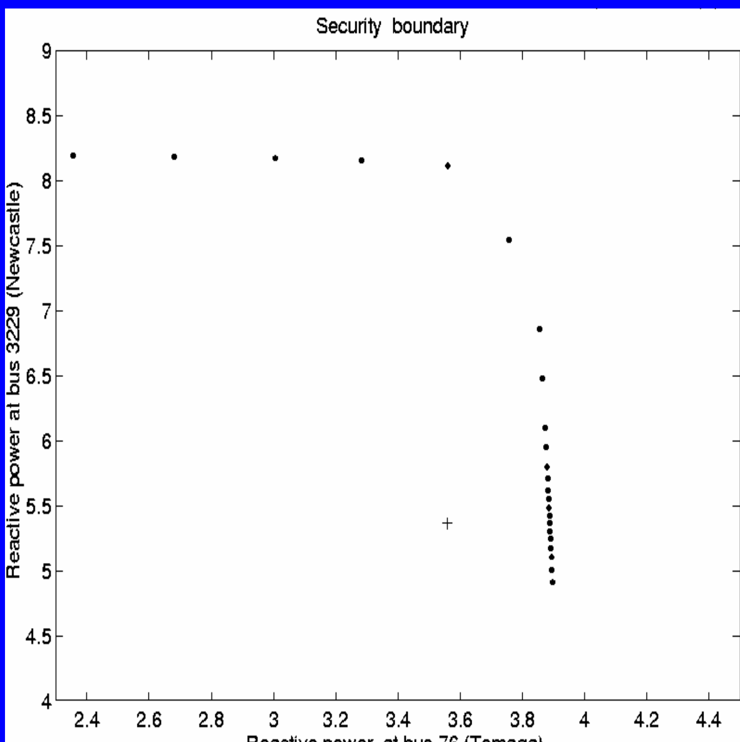
TABLE II Dynamic load parameters

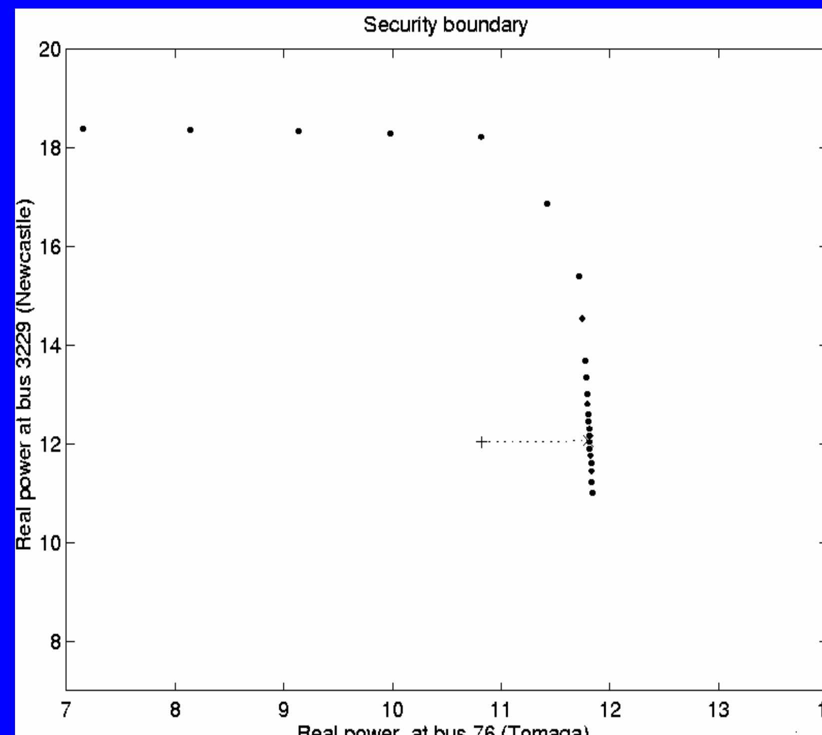
A-Tomago, B-Newcastle, C-Sydney West, D-Sydney east, E-Sydney South, F-Dapto, G-Canberra, H - Mbrk

Bus	Composition	w_1,	w_2	w_3	α	β	IM set
A	Indus, Resi	35%	15%	50%	1	3	II
B	Indus, Resi	25%	15%	60%	1	3	II
C	Resi, Indus	30%	15%	55%	1	3	I
D	Resi, Com	60%	20%	20%	1	3	I
E	Resi, Com	85%	15%	0%	1	3	–
F	Resi	90%	10%	0%	1	3	–
G	Resi	85%	15%	0%	1	3	–
H	Indus, Resi	20%	10%	70 %	1	3	II

◆Security boundary & closest point

☐Case 2 (a): after line 76-74 (Tomago-NewC) outage





Reactive power load, Q

Real power load, P

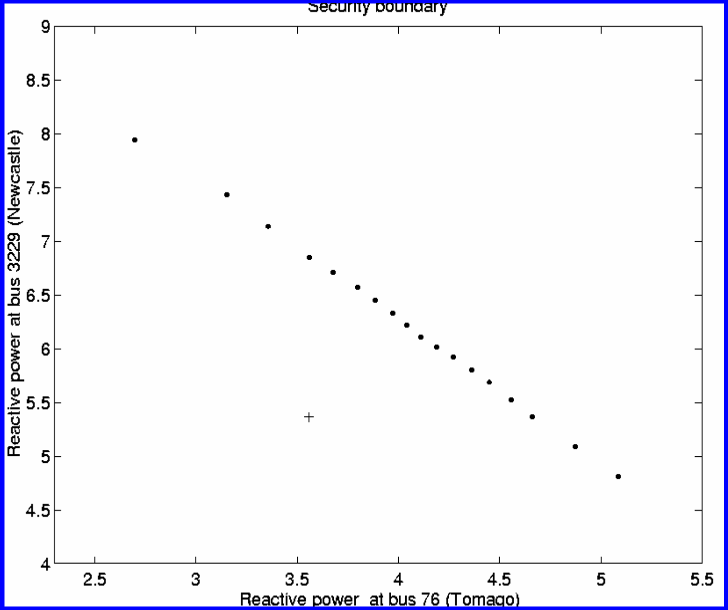
Closest point (1179.68Mw, 1206.17Mw)

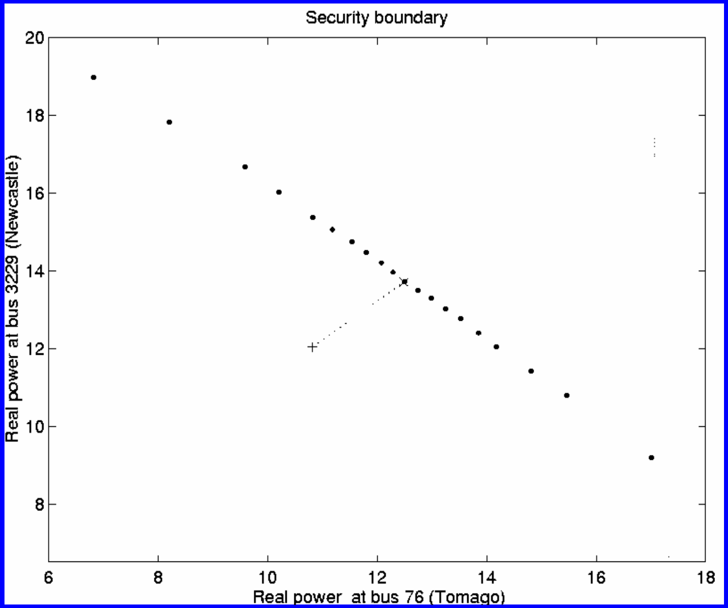
TABLE IV Case 2 Line76-74 Outage

Loading direction	Load Margin	Percentage Percentage
L_{76}	$113.6MW + j37.4Mvar$	10.5%
L_{8229}	$621.5MW + j276.9Mvar$	51.6%
both	$204.8MW + j79.9Mvar$	9.0%

◆Security boundary & closest point

□Case 5 (b): after generation reduced at bus 201 (Liddell power station)





Reactive power load, Q

Real power load, P

Closest point (1249.24Mw, 1370.96Mw)

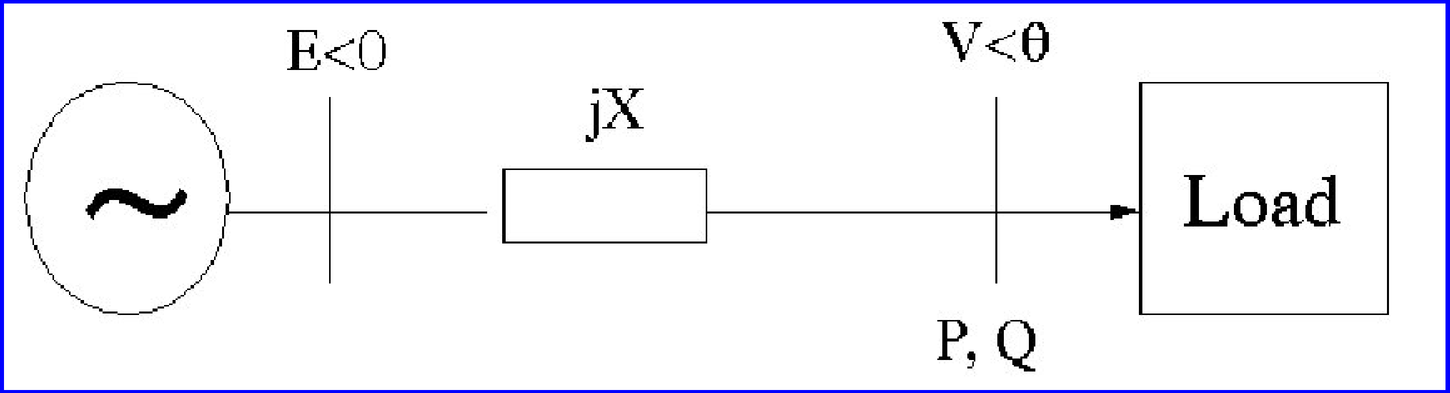
TABLE V Case 3-5, Load margins

	Load margin at buses 76 and 3229	percentage %
Case 3: line 86-76 out	841.5MW $+j$328.5Mvar	36.8%
Case 4: line 70-74 out	1275.7MW $+j$498.1Mvar	55.8%
Case 5: trip off gen 201	308.6MW $+j$120.5Mvar	13.5%

Impact of Load Modelling

- Stability Margins
  - Different load models
  - Weighting factors
  - Q_{limit} and tap regulation
- Dynamic Responses

Two Bus System



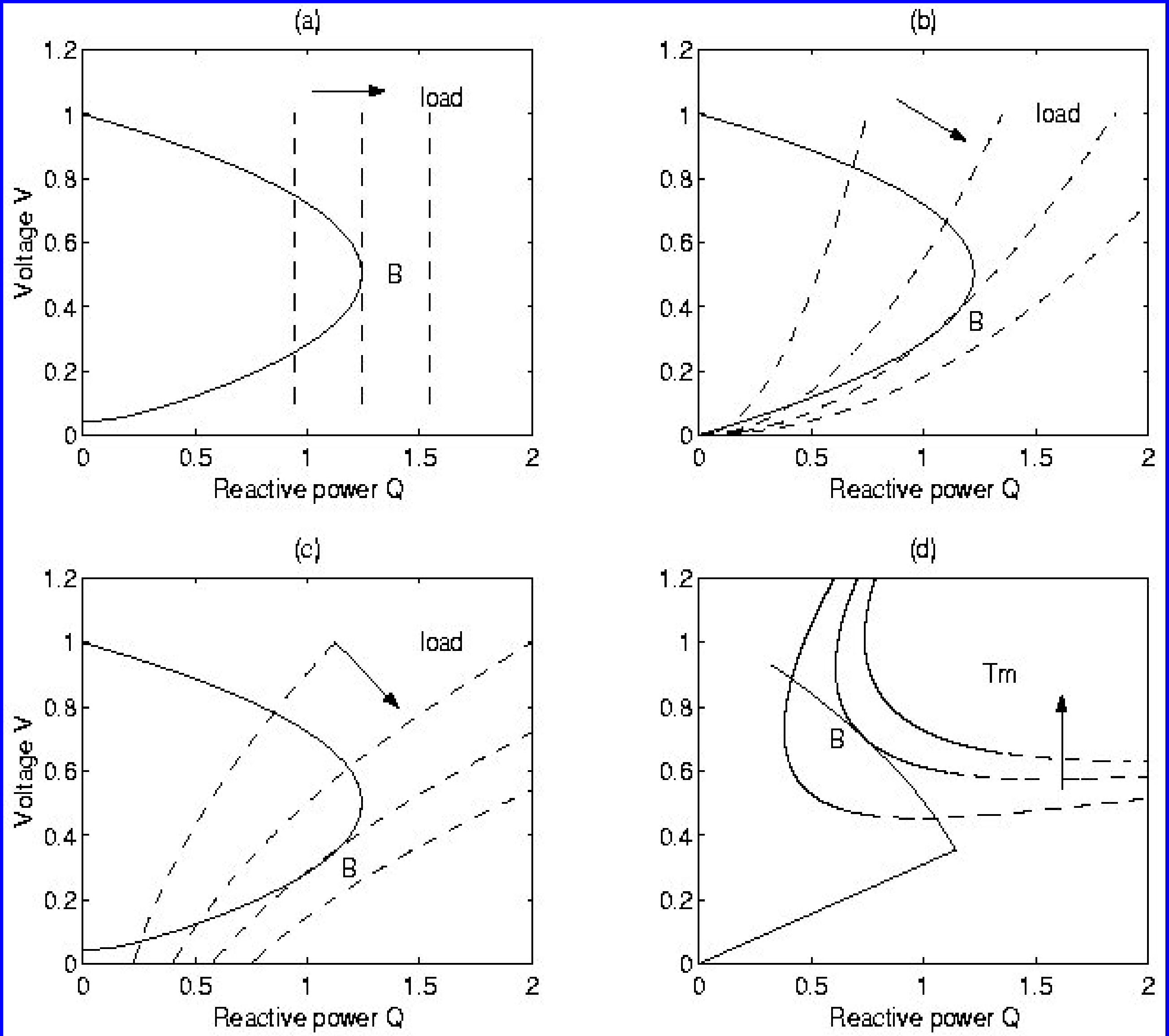

(a)
(b)
(c)
(d)
load
load
load
Tm
B
B
B
B
Voltage V
Voltage V
Reactive power Q
Reactive power Q
Reactive power Q
Reactive power Q
0
0.2
0.4
0.6
0.8
1
1.2
0.5
1.5
2

TABLE VI Margins with different load models

power	constant power load	exponential load ($\alpha, \beta = 0.5$)	composite dynamic load (Table II)
V_{cr} p.u.	0.7091	0.5377	0.7155
ΔL_{76}	$70.9MW + 23.3Mvar$	$255.9MW + 84.2Mvar$	$113.6MW + 37.4Mvar$
%	6.5%	23.6%	10.5%

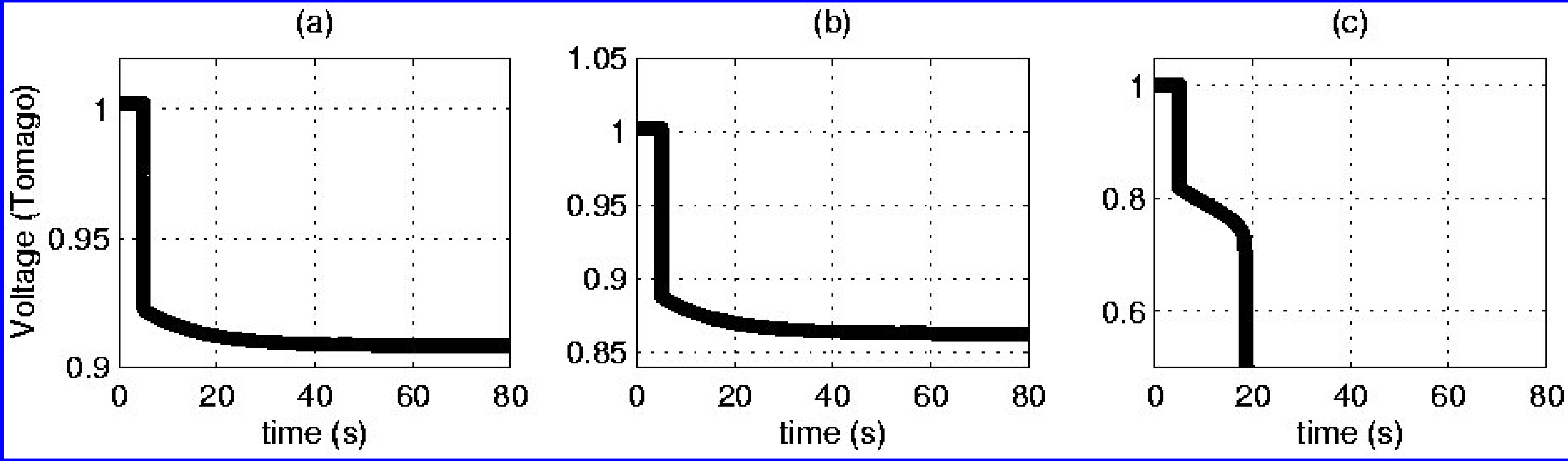
TABLE VII Margins with different load parameters and weighting factors

	V_{cr}	margin at bus 76 MVA	percentage
$w_s = 0.7$	0.8241	$4.5 + j1.5$	0.4%
$w_s = 0.5$	0.7155	$113.6 + j37.4$	10.5%
$w_s = 0.1$	0.4212	$783.4 + j257.74$	72.4%
$\alpha_s = 0.8$ $\beta_s = 2$	0.5701	$232.4 + j76.47$	21.5%

TABLE VIII Margins with/without Q_{limit} and tap regulation

	with	without
V_{cr} (pu)	0.7428	0.6905
ΔQ_{76}	$60.46 MVAR$	$76.42 MVAR$

Dynamic Response: Voltage at Tomago a) Line fault; b)with 5% load increase after tripping; c)with 15% load increase



Coordinated control scheme

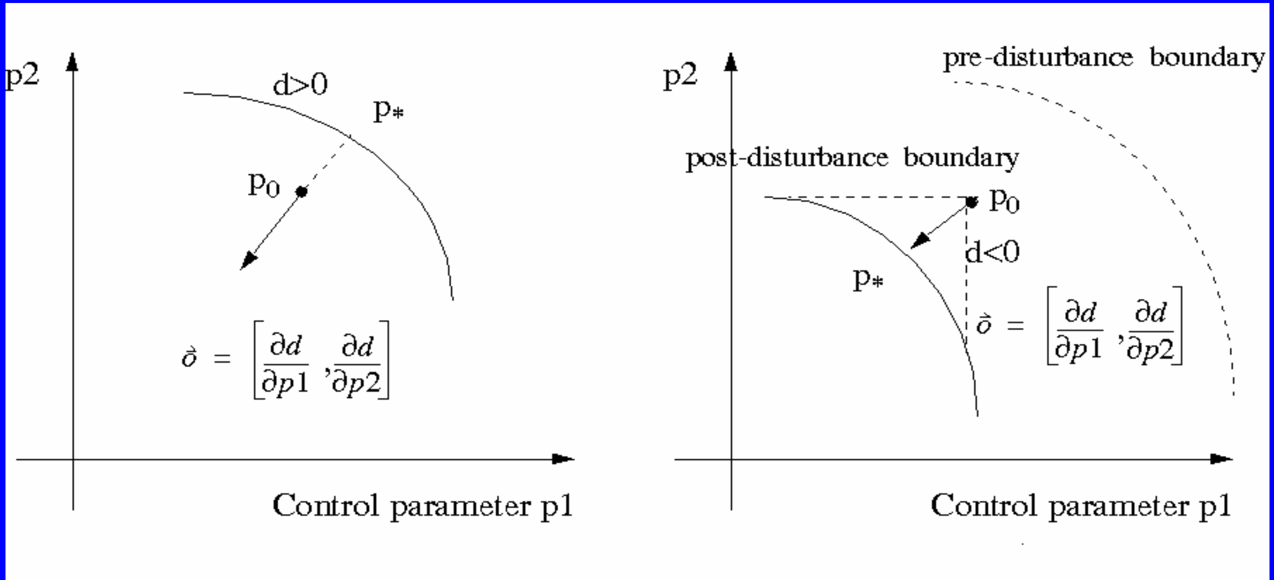
- Provide security enhancement
- Control actions
  - reactive power compensation, tap regulation, load control, FACTs, SVC, UPFC …
- Traditionally, done one by one, trial and error

- Why coordination
  - minimum overall effort / cost
  - maximum control effect
  - better voltage profile, hence better quality of supply
- Difficulty
  - Combination of dissimilar controls

◆ Optimal direction to increase security margin

- sensitivity of minimum distance w.r.t. controls

$$\frac{\partial d}{\partial p} = \frac{-\omega f_p}{(\omega f_p)(\frac{p_* - p_0}{|p_* - p_o|})}$$



(a) inside the boundary (b) outside the post-boundary

◆ Illustrative example

□ Control parameters

--- Load (constant power factor) and capacitor at

Bus 76 (Tomago330)
Bus 3229 (Newc 330)
Bus 3207 (SydW 132)
Bus 3283 (Syd E 132)
Bus 3286 (Syd S 132)

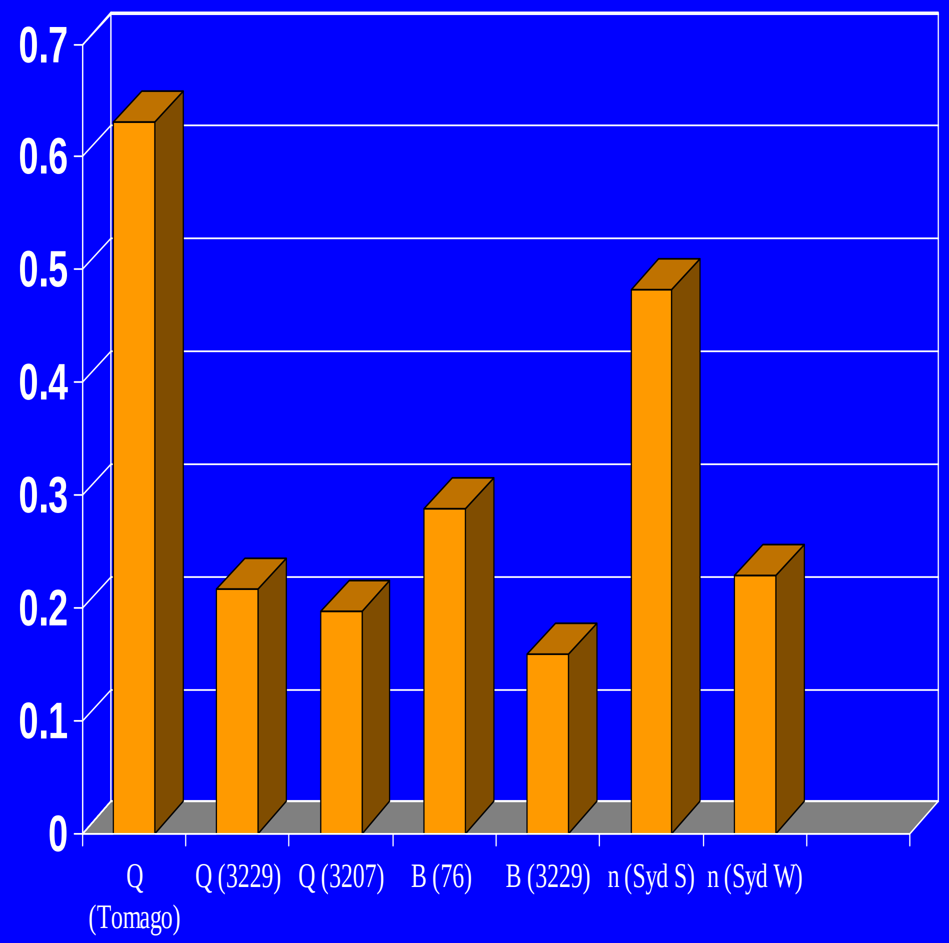
--- taps at line

Bus 74 (Tomago330) to bus 3229 (Newc 330)
Bus 3207 (Syd W 132) to Bus 37 (Syd W 330)
Bus 42 (Syd E 330) to Bus 3283 (Syd E 132)
Bus 3286 (Syd S 132) to Bus 31 (Syd S 330)
Bus 89 (Mbrk 330) to Bus 3271 (Mbrk 132)

□ minimum d = +0.1530 (with line 76-74 out of service and variation of all parameters)

Sensitivity of d w.r.t. controls

Controls	Sensitivity $\frac{\partial d}{\partial p}$
load 76 (Tomago)	-0.6306
load 3229 (Newcastle)	-0.2163
load 3207 (Sydney W)	-0.1969
load 3283 (Sydney E)	-0.1808
load 3286 (Sydney S)	-0.1335
capacitor 76 (Tomago)	0.2872
capacitor 3229 (Newcastle)	0.1580
capacitor 3207 (Sydney W)	0.1450
capacitor 3283 (Sydney E)	0.1335
capacitor 3286 (Sydney S)	0.1073
tap (74-3229)	0.0589
tap (3207-37)	0.1206
tap (42- 3283)	0.2285
tap (3286-31)	-0.4826
tap (89-3271)	-0.0451



Optimal scheduling of control actions

- Actual control sequence accounts for
  - combination of dissimilar controls
  - different response speeds
  - different dynamic characteristics
  - priority
- Optimal scheduling by
  - economic cost
  - availability of controls
- When, how to take actions at each step?

□Problem formulation

$$\min \quad J(p) := \sum_{t=1}^{N} C(x_t, p_t), \qquad p_t \in R^m, x_t \in R^m$$

subject to:

(i) controls capability constraints

$$p_t^{low} \le p_t \le p_t^{upper}, \qquad t = 1,2\ldots N$$

(ii) stability constraints

$$S_{margin}(p_t) - S_{margin}(p_{t-1}) > \varepsilon$$

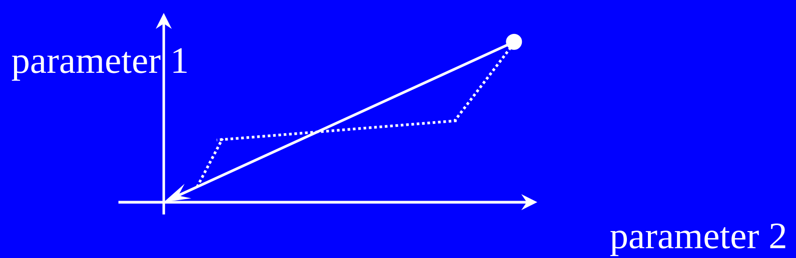
- Dynamic programming (DP)
  - stage-wise method
  - backward recursive relationship
  - disadvantage: curse of dimensionality
- Differential dynamic programming (DDP)
  - successive approximation
  - computationally effective

□Numerical example

□composite cost functions

-- economic cost, $_load > $ cap > $ tap

--minimum angle criterion

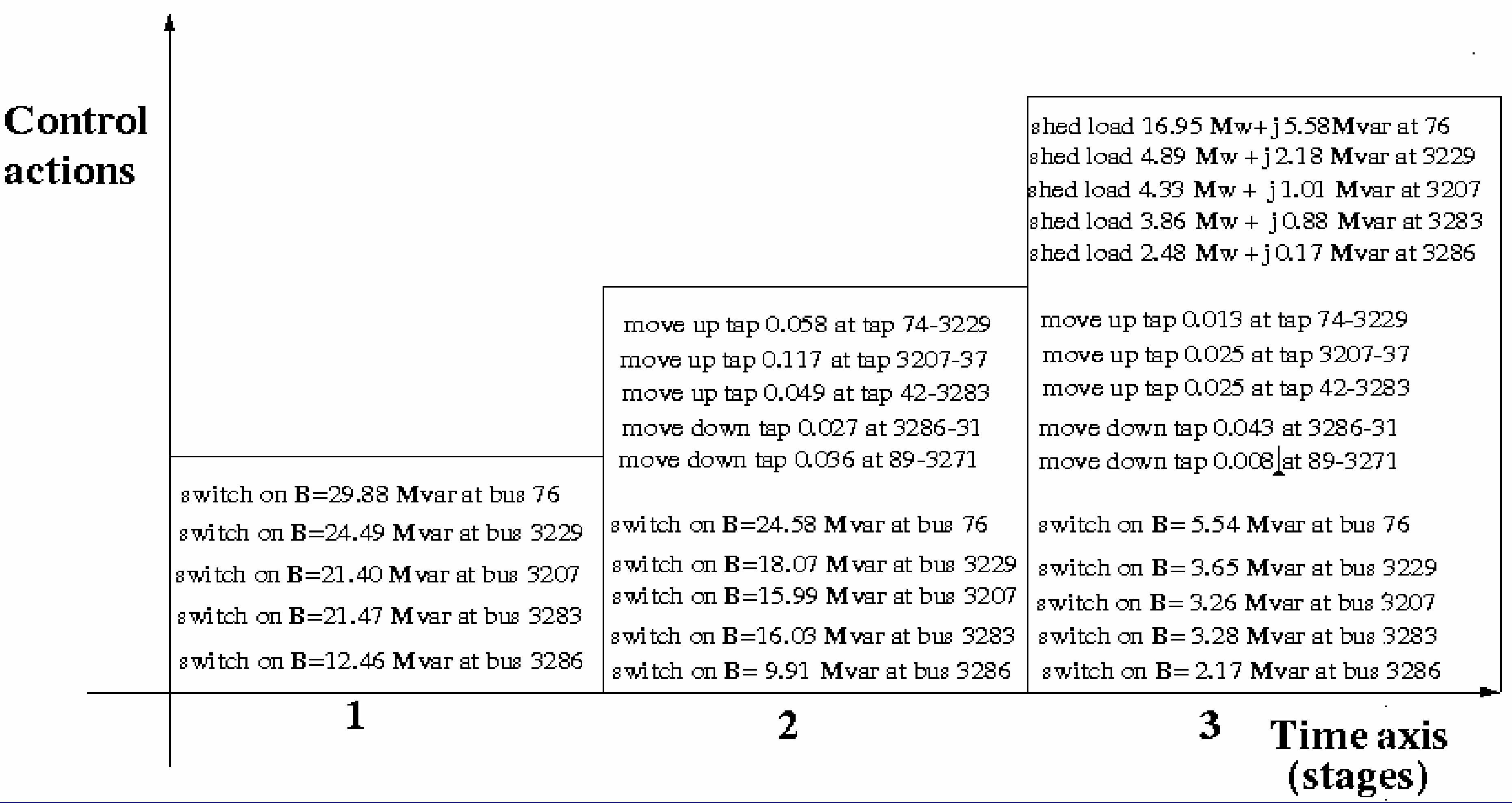


□stages and system limits

Stages	Controls available
1	**all capacitors**
2	all capacitors, **all taps**
3	all capacitors,all taps, **all loads**

Controls	minimum	maximum
tap (74-3229)	0.857	1.048
tap (3207-37)	0.945	1.155
tap (42- 3283)	0.857	1.048
tap (3286-31)	0.945	1.155
tap (89-3271)	0.857	1.048
capacitor 76 (Tomago)	0	190 Mvar
capacitor 3229 (Newcastle)	0	380 Mvar
capacitor 3207 (Sydney W)	0	500 Mvar
capacitor 3283 (Sydney E)	0	130 Mvar
capacitor 3286 (Sydney S)	0	300 Mvar
all loads	maximum shedding 50 Mw	

□Optimal Scheduling (ε=0.2)



Conclusions *(Bologna)*

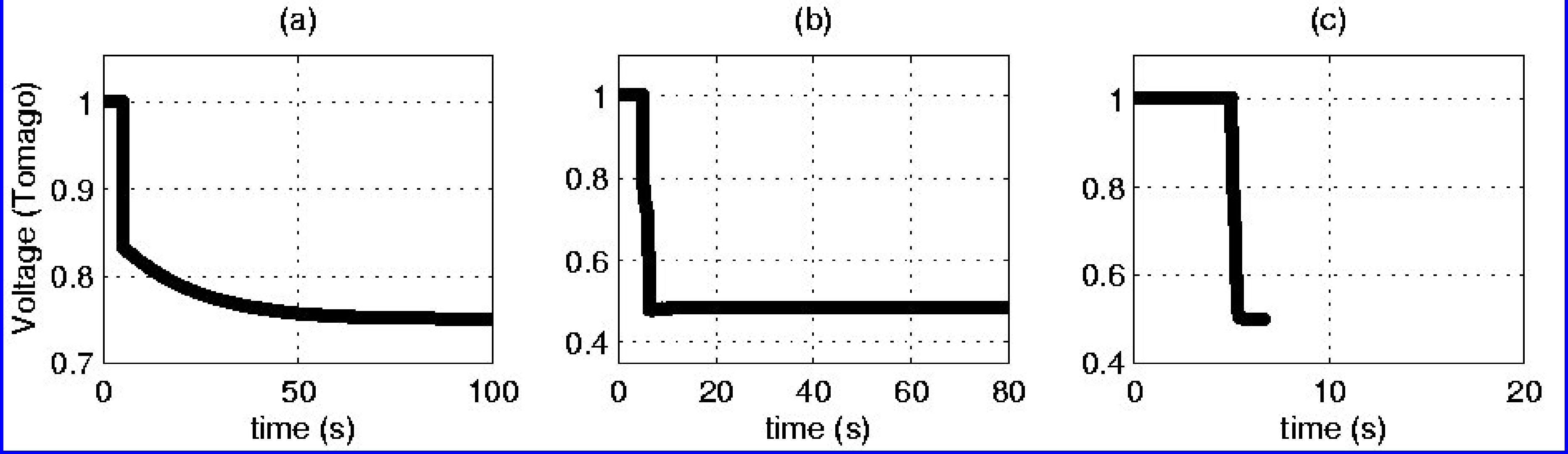
- Quantify voltage stability margin
- Use composite load model
- General method for steady state voltage stability analysis
- Impact of load modelling
- Importance of accurate load representation
- Optimal control directions
- Co-ordination of dissimilar controls

◆Future Work

- More control devices (SVC, FACTS,UPFC…)
- Other objective functions (control times..)
- New search algorithm (Evolutionary algorithm…)
- Several disturbances
- Interrelationship of market structures with physical and practical implemented control
- Global control ideas

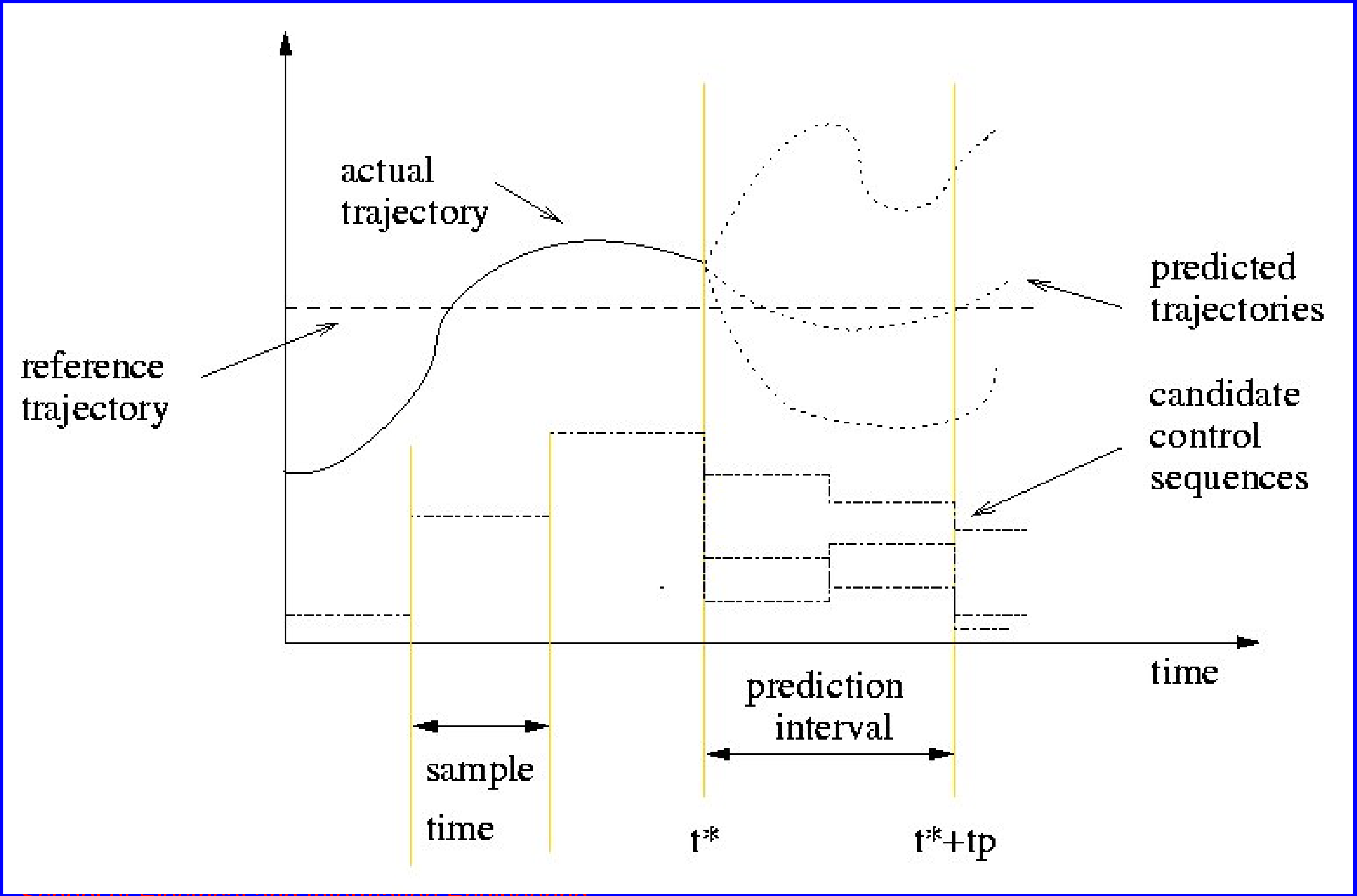
Extra Slides

Dynamic Response: Voltage at Tomago after line fault and 10% load increase; a) α_t=4,β_t=6; b) α_t=1.5,β_t=1.5; c) %IM (w_3) increased 50% to 60%



Model Predictive Control Approach

- Widespread in process control
- Multivariable case comes naturally
- Constraint handling
- Future behaviour predicted for many candidate input sequences
- Optimal input sequence selected by (constrained) optimization


actual
trajectory
predicted
trajectories
reference
trajectory
candidate
control
sequences
time
prediction
interval
sample
time
t*
t*+tp

Optimization by Search

- All controls are switching actions
- Combinatorial optimization problem
- Organize control state space in tree structure
- Search tree for optimum
- Comninatorial explosion
- Search heuristics
- Similar problem as solved in chess computers!

Simulation Example