Reactive Power Support for Large-Scale Wind Generation

Ian A. Hiskens

Vennema Professor of Engineering

Electrical Engineering and Computer Science

Acknowledgements: Sina Baghsorkhi, Jon Martin, Daniel Opila.

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Motivation (1)

- Utility-scale wind generation should be capable of:
  - Voltage regulation.
  - Dynamic reactive support.
- Provision of these services should be consistent with traditional generation.
- Wind-farms are composed of many distributed wind turbine generators (WTGs).
  - Behavior is vastly different to a single large generator.

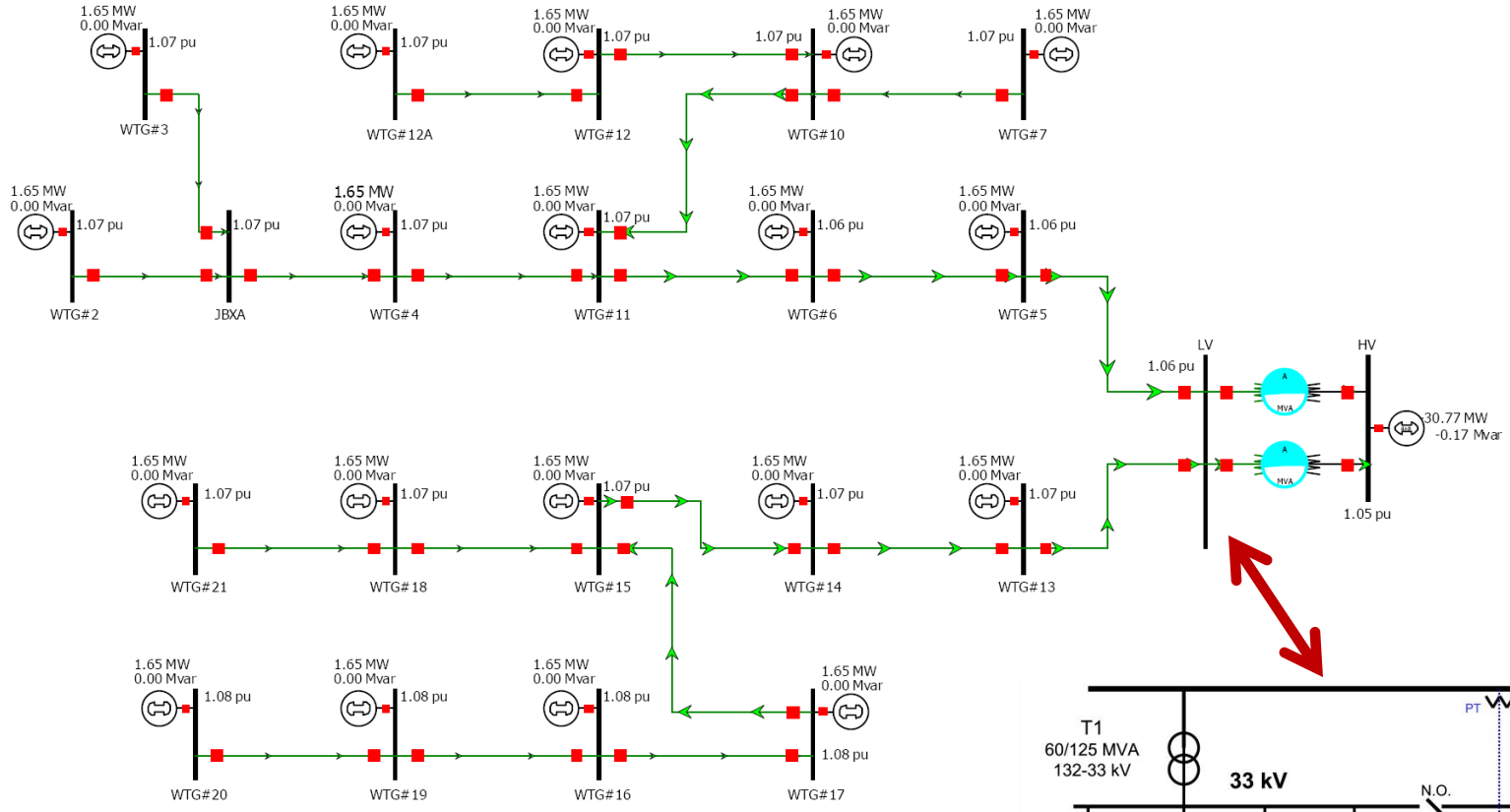
Motivation (2)

- A number of issues have been observed in practice:
  - Many wind-farms are located at lower (sub-transmission) voltage levels.
  - Actual reactive power available from wind-farms is less than predicted.
  - *Ad hoc* schemes are used to coordinate capacitor/reactor switching with Statcom/SVC controls.
    - Excessive switching, resulting in high circuit-breaker maintenance.
    - Reduced dynamic (fast acting) reactive reserve.

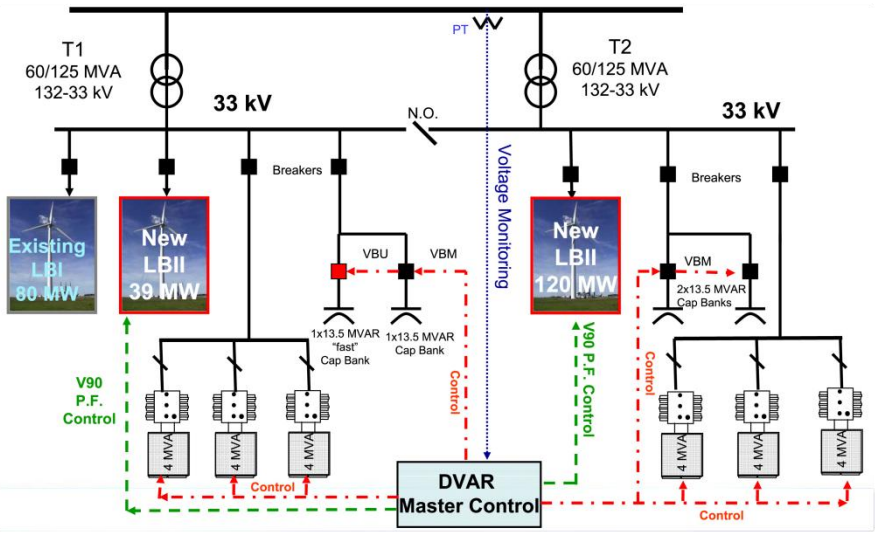
Outline

- Wind-farms on sub-transmission networks.
- Reactive power from the collector system.
- Coordination of wind-farm reactive sources.

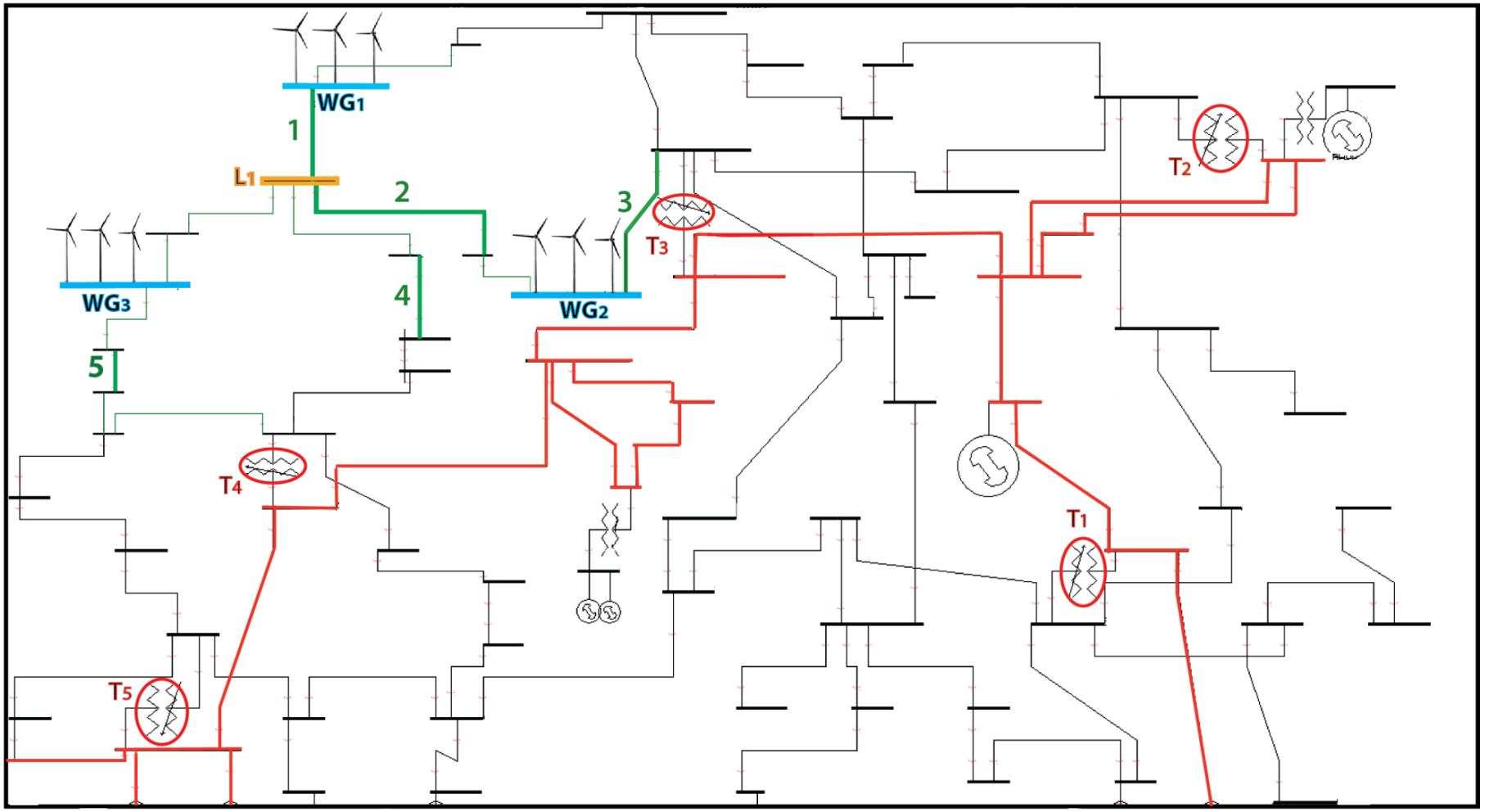
Wind-farm overview



Collector network



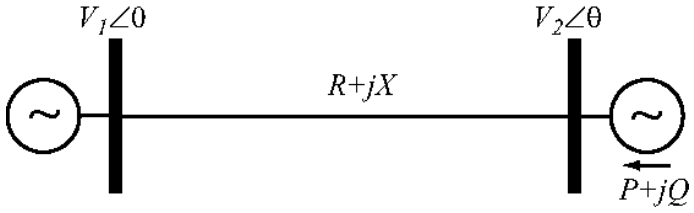
Wind-farms at sub-transmission



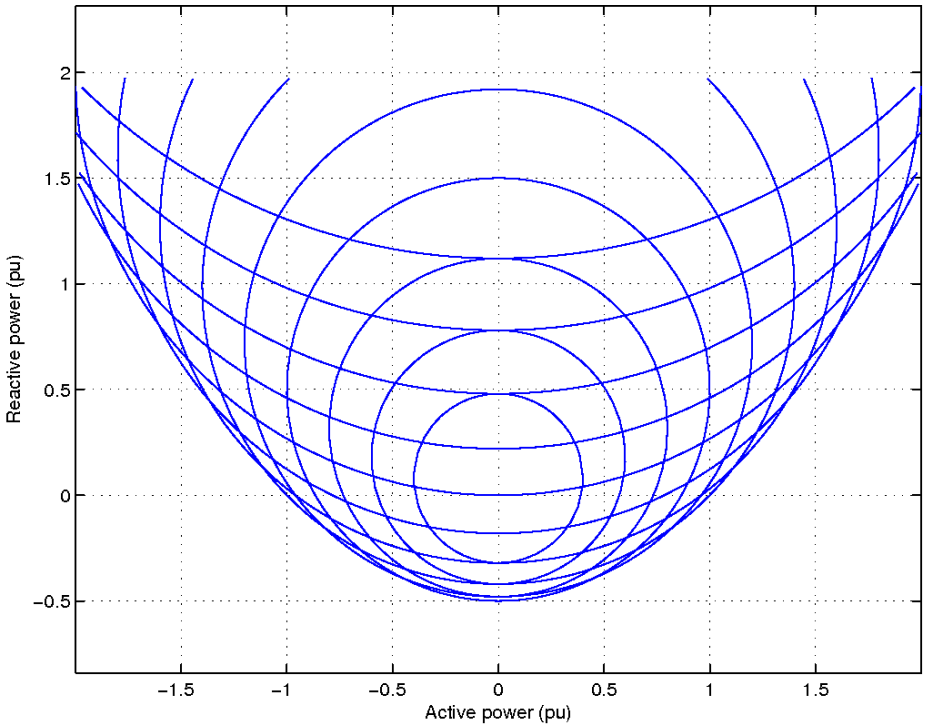
Effect of resistance

- Voltage contours for a two-node network:

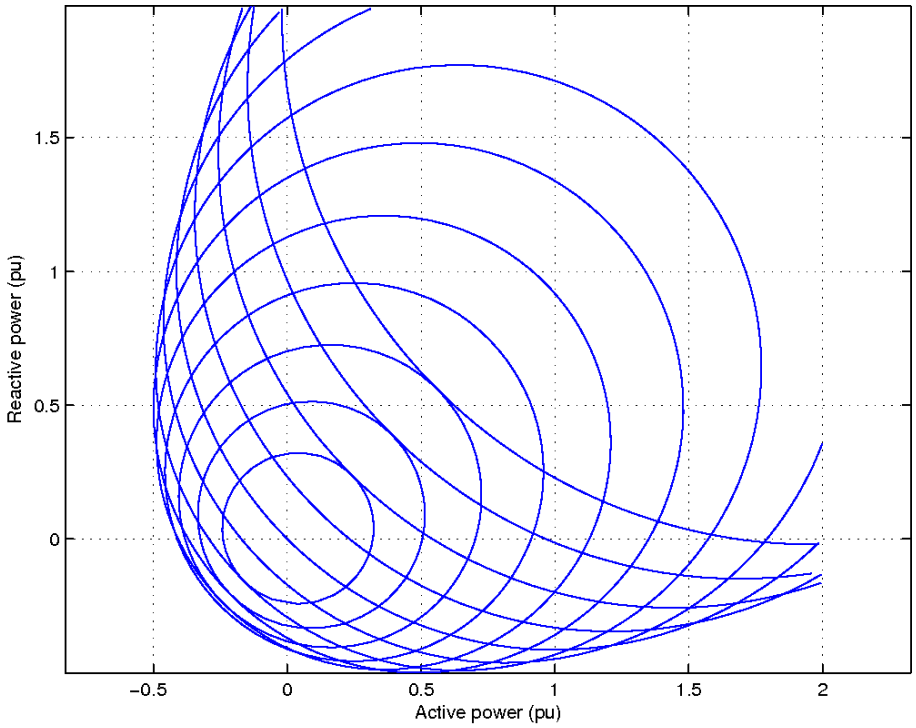
$$\left(\frac{V_2^2 R}{R^2+X^2}-P\right)^2+\left(\frac{V_2^2 X}{R^2+X^2}-Q\right)^2=\frac{V_1^2 V_2^2}{R^2+X^2}$$

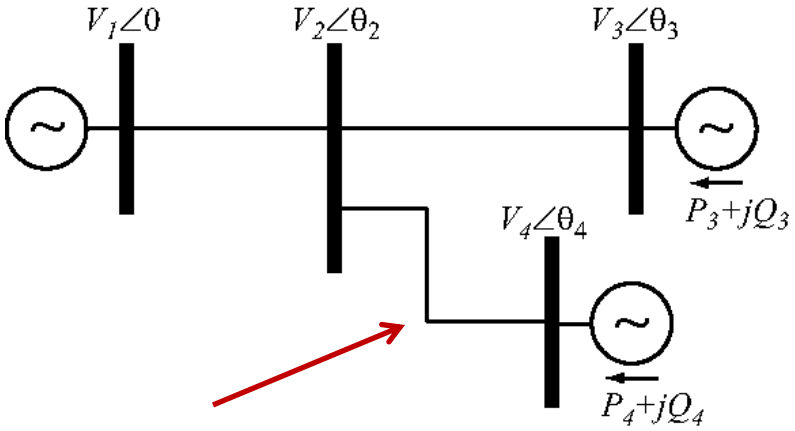


R=0.0pu, X=0.5pu



R=0.5pu, X=0.5pu

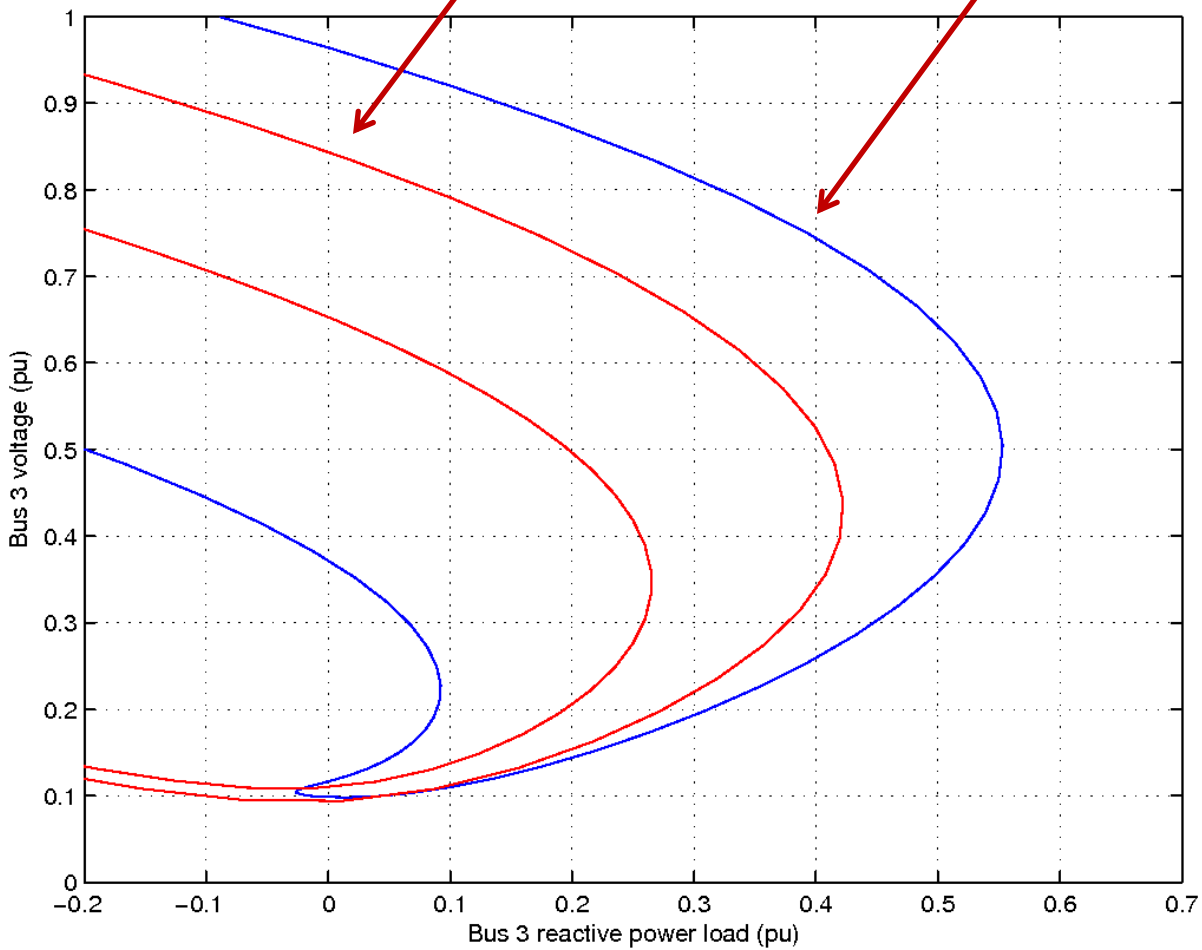




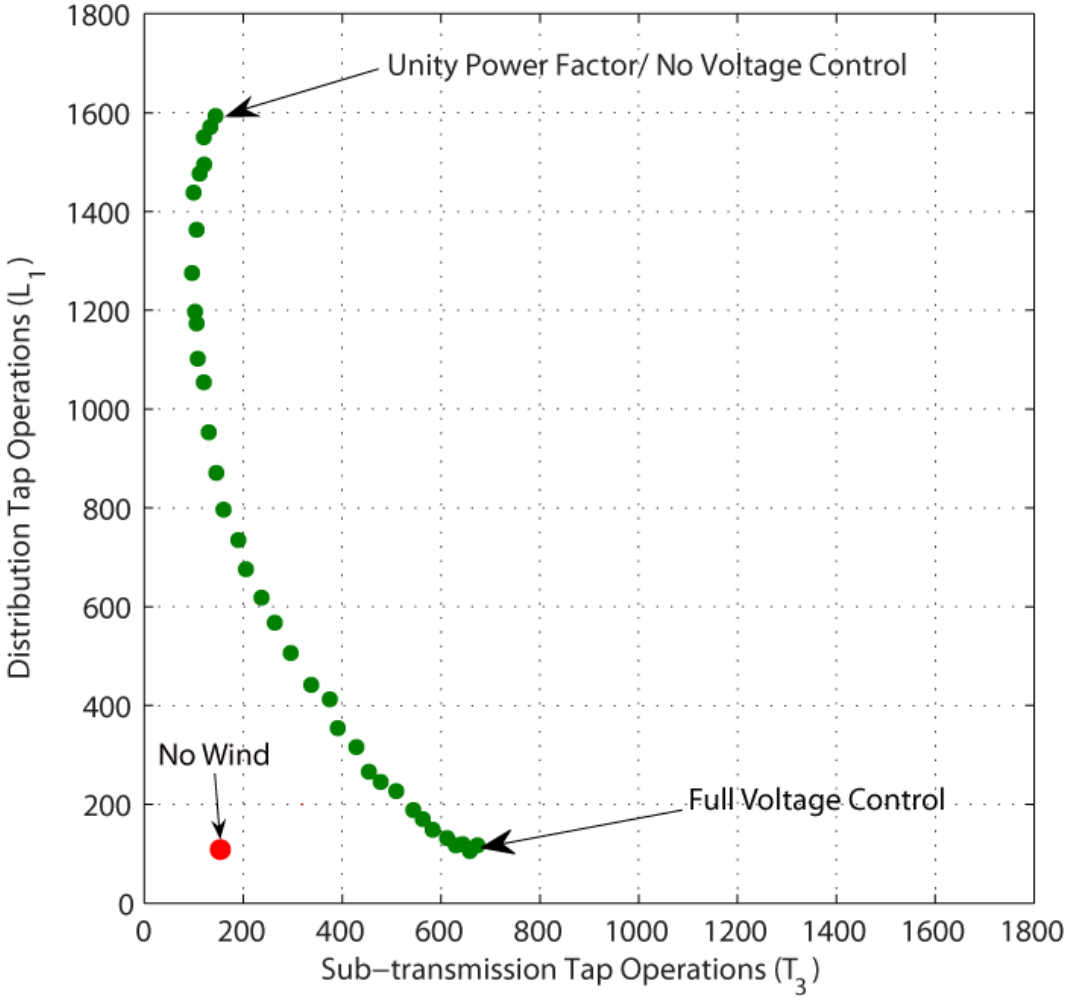
Resistive line

With resistance

No resistance



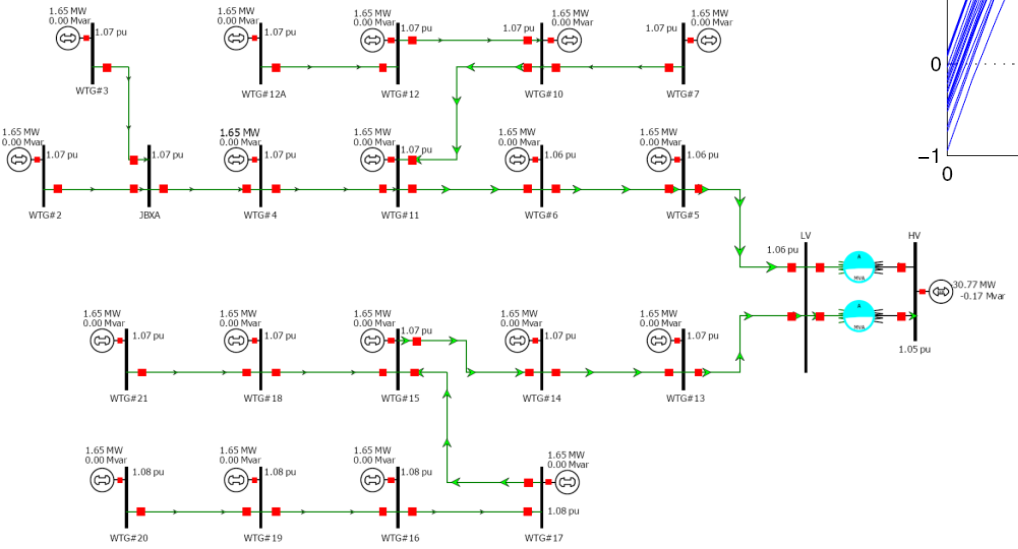
Wind-farm voltage control

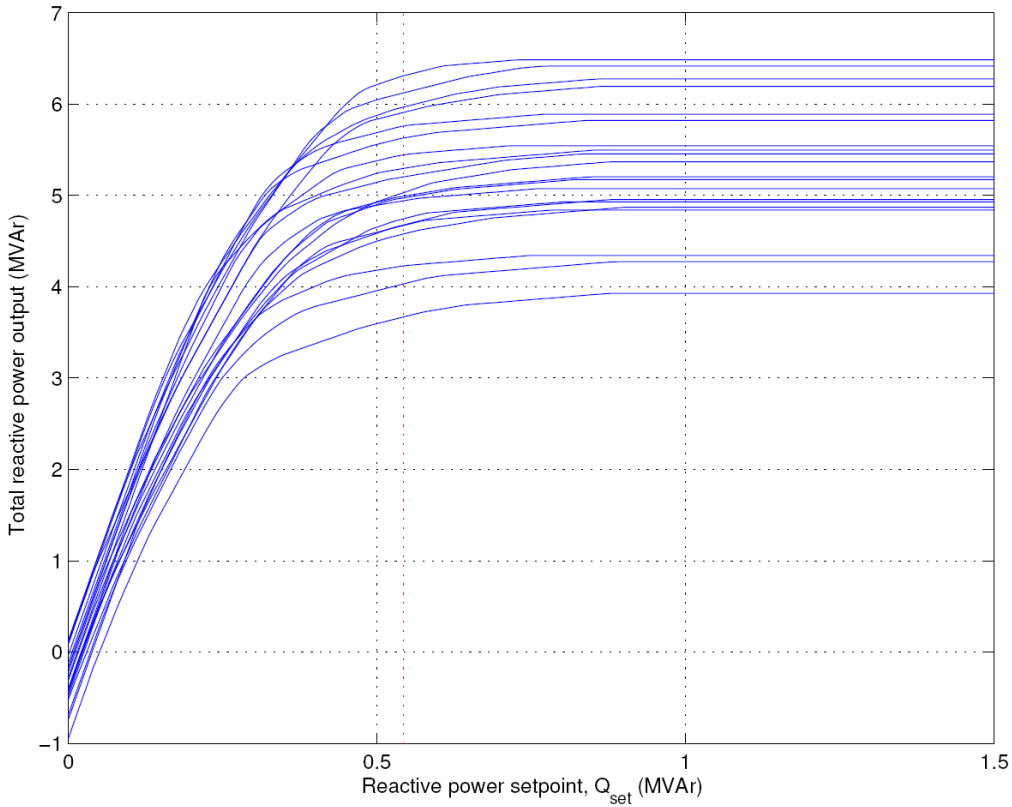


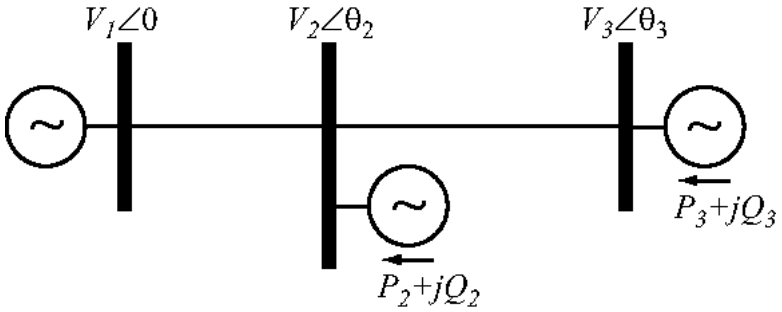
- Constant power factor/ limited voltage control:
  - Increased tap operations at distribution OLTCs.
  - Reduced tap operations at sub-transmission OLTCs.
- Full voltage control:
  - Reduced tap operations at distribution OLTCs.
  - Increased tap operations at sub-transmission OLTCs.

Reactive power availability

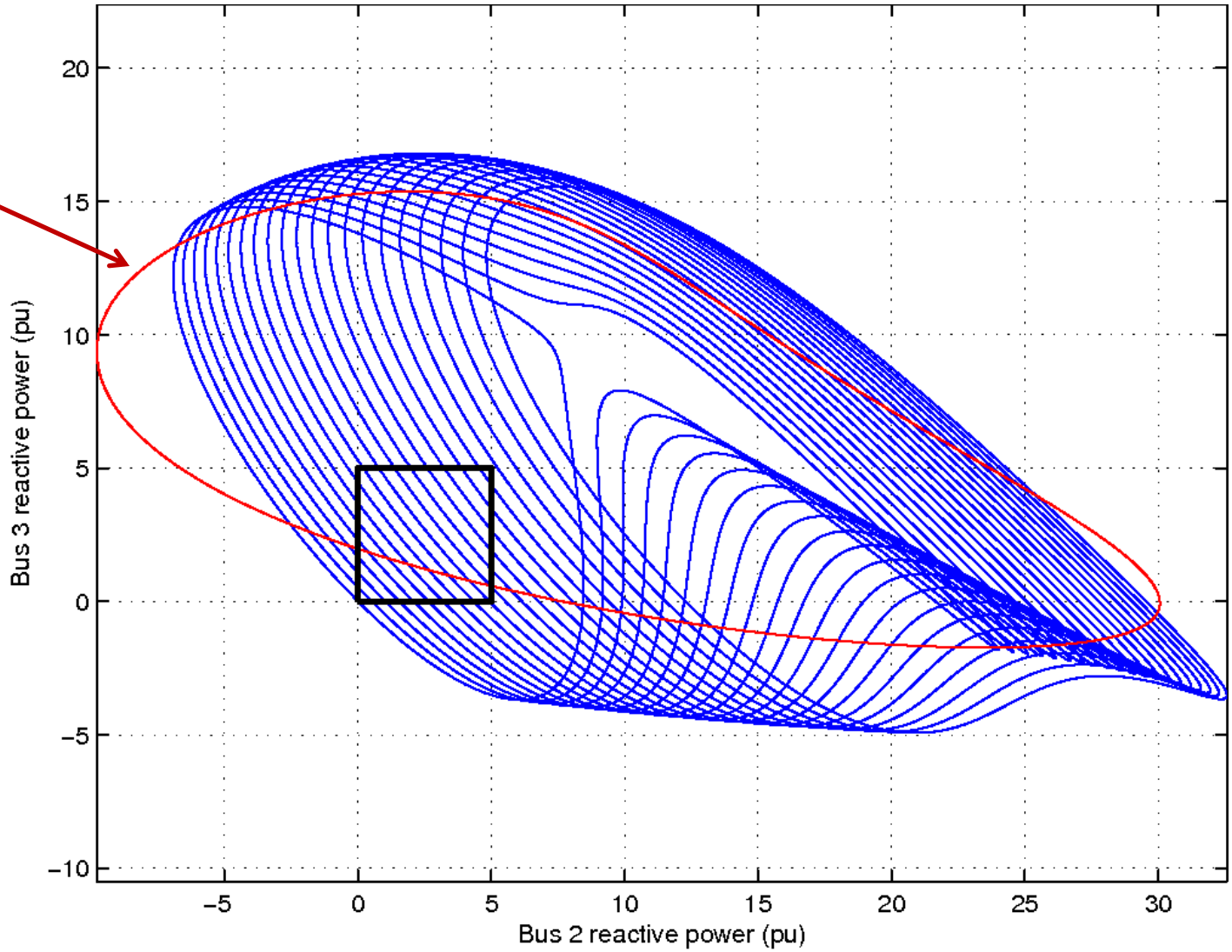
- Generator voltage limits restrict maximum available reactive power.



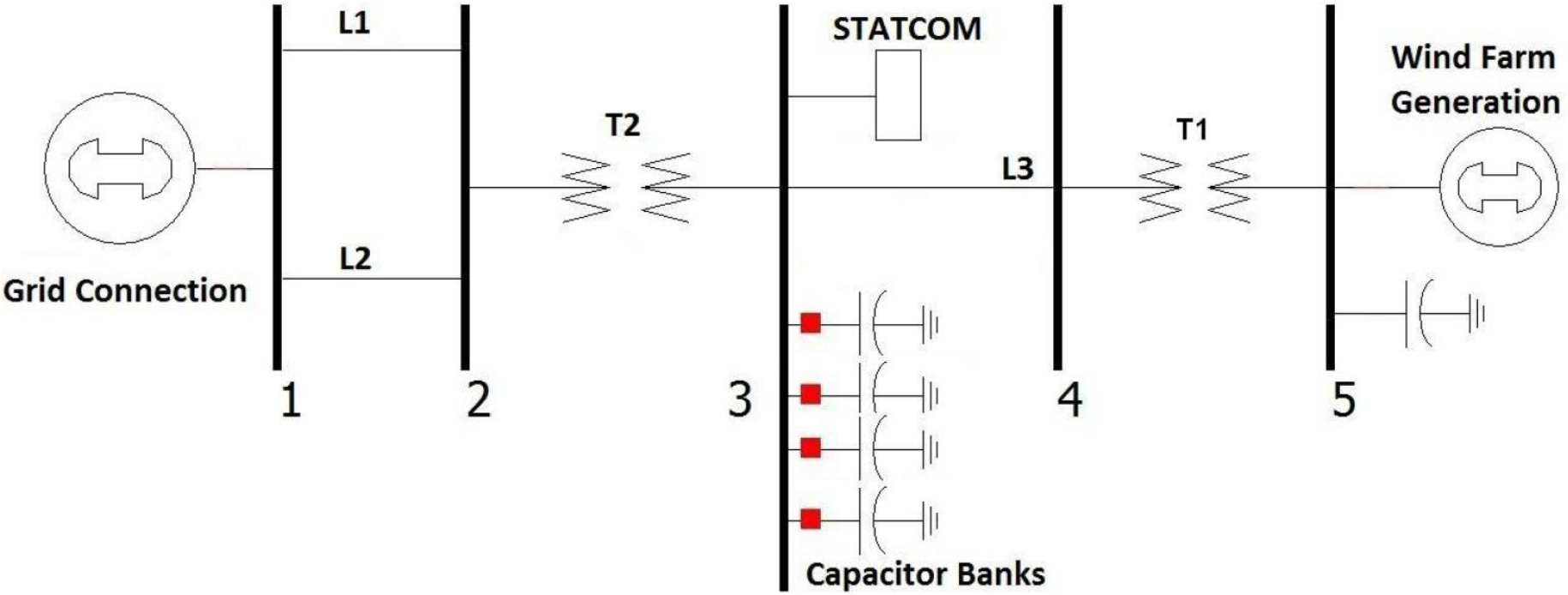



$V_1\angle 0$
$V_2\angle\theta_2$
$V_3\angle\theta_3$
P_3+jQ_3
P_2+jQ_2

$V_3 = 1.1$ pu


Bus 3 reactive power (pu)
Bus 2 reactive power (pu)
20
15
10
5
0
−5
−10
−5
0
5
10
15
20
25
30

Farm-level system optimization



$$\min \sum_0^T c_k(x,u)$$

$$\text{such that}$$

$$g_k(x_k,u_k) \leq 0 \ \ \forall\, k$$

Information classes

1) **Exact Future Knowledge** - Exact knowledge of the future for the full time horizon.
2) **Stationary Stochastic Knowledge-** Stationary stochastic predictions about the future, no explicit forecasting.
3) **No Explicit Future Knowledge-** Both optimization- and rule-based methods.

Controllers with future knowledge

Number of Capacitor Switches

STATCOM Usage

$$c_k(x_k, u_k) = \alpha N_{CS} + abs(\bar{S})$$

	Given Data	Objective
1) Exact future knowledge: Deterministic Dynamic Programming (DDP)	P(t)	$\min \sum_0^T c_k(x,u)$ such that $g_k(x_k, u_k) \leq 0 \ \forall k$
2) Stochastic knowledge: Stochastic Dynamic Programming (SDP)	$P(P_{k+1} \mid P_k)$	$\min \ E_w \sum_0^\infty \gamma^k c(x,u)$ such that $g(x,u) \leq 0 \ \forall k.$

Controllers ***without*** future knowledge

$$c_k(x_k, u_k) = \alpha N_{CS} + abs(\bar{S})$$

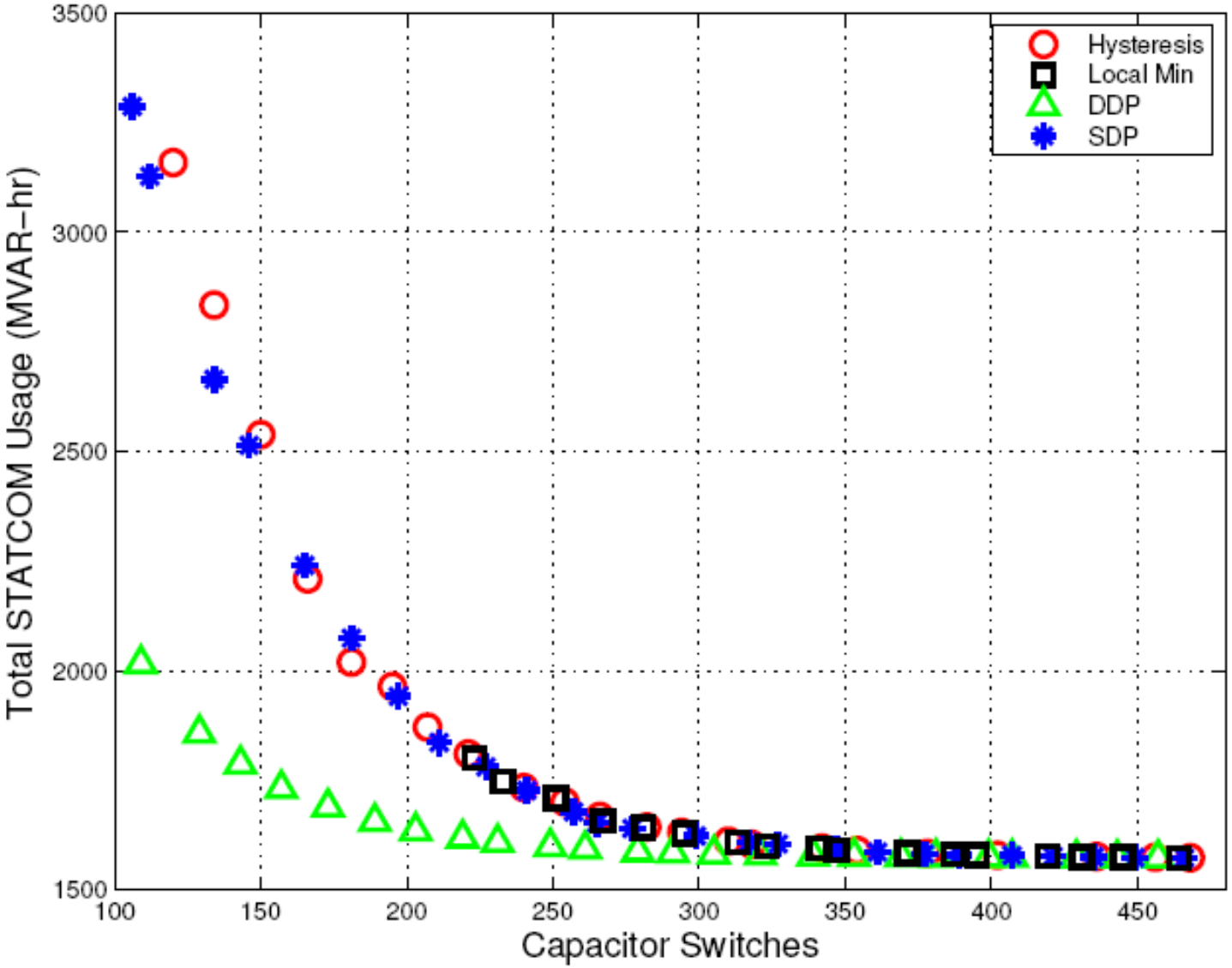
	Given Data	Control Law
3a) No future knowledge: Instantaneous optimization	None	$u^*(x) = \underset{u \in U}{\operatorname{argmin}}\, c(x, u)$
3b) No future knowledge: Rule-based hysteresis	None	$NC_{k+1} = \begin{cases} NC_k + 1 & \text{if } \bar{S} > \beta \\ NC_k - 1 & \text{if } \bar{S} < -\beta \\ NC_k & \text{otherwise.} \end{cases}$

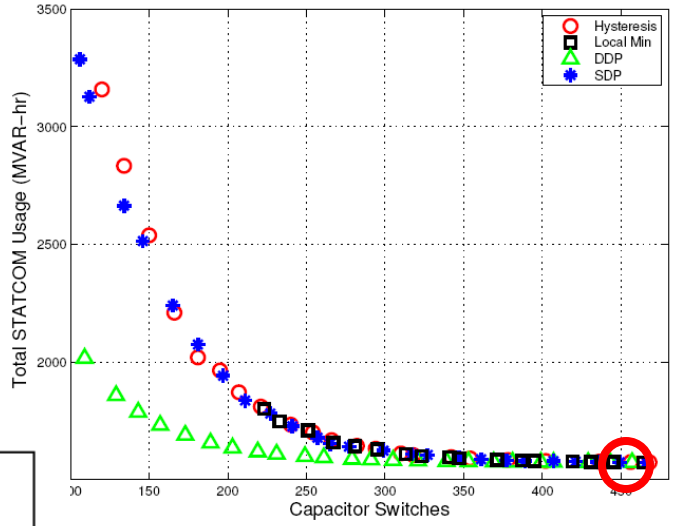
Threshold

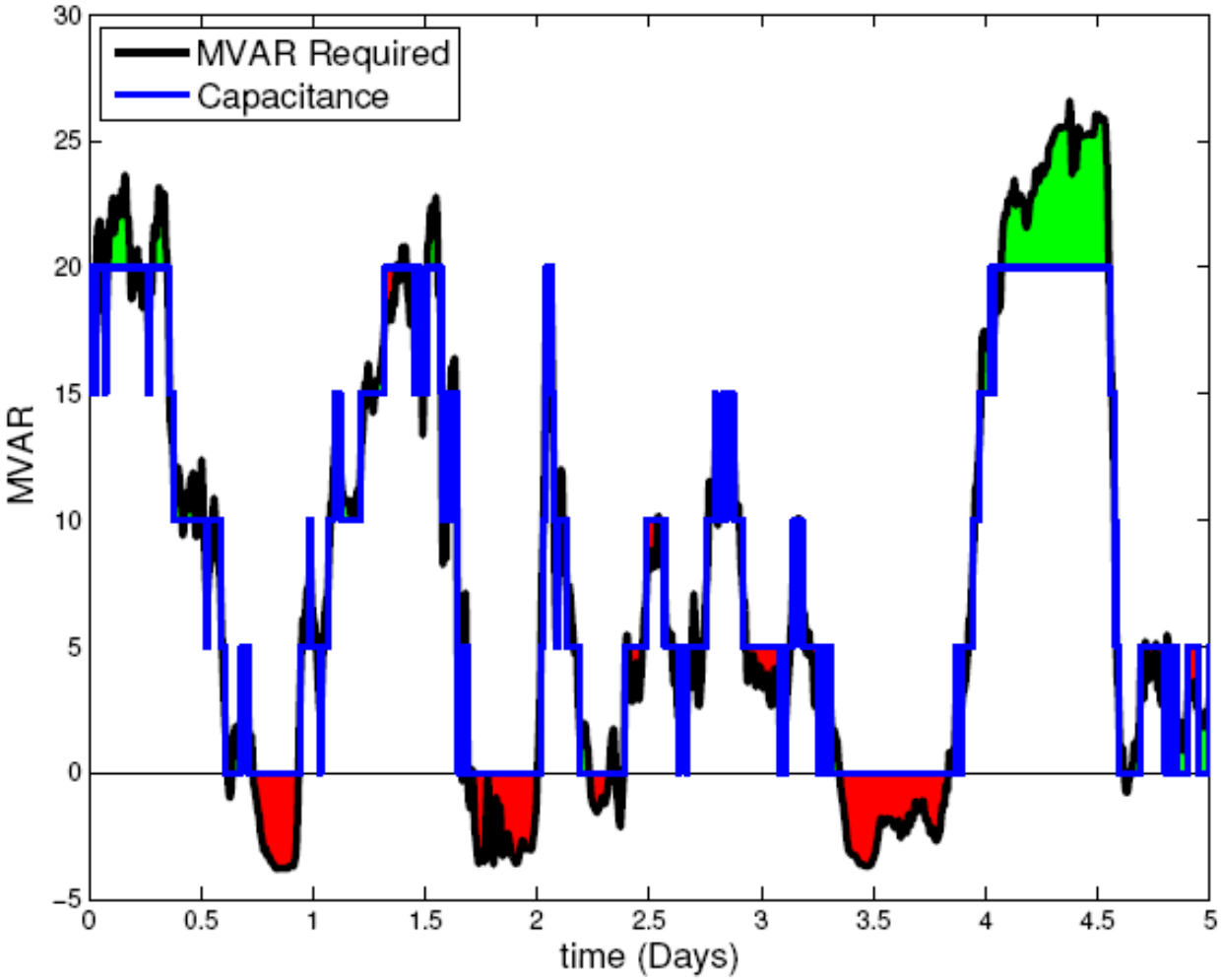
STATCOM Usage

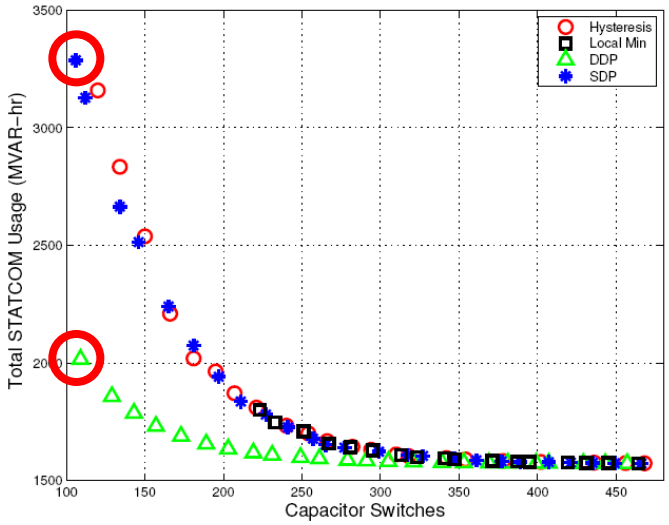
Number of Capacitors

Capacitor switching versus Statcom

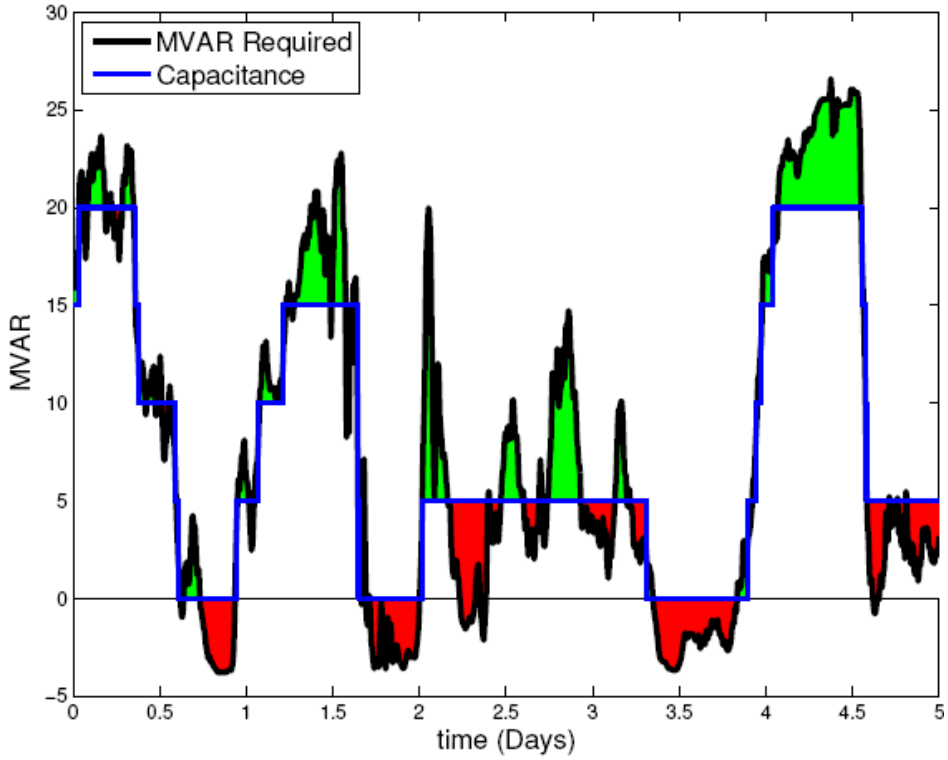



Hysteresis
Local Min
DDP
SDP
Total STATCOM Usage (MVAR-hr)
Capacitor Switches
3500
3000
2500
2000
150
200
250
300
350
400

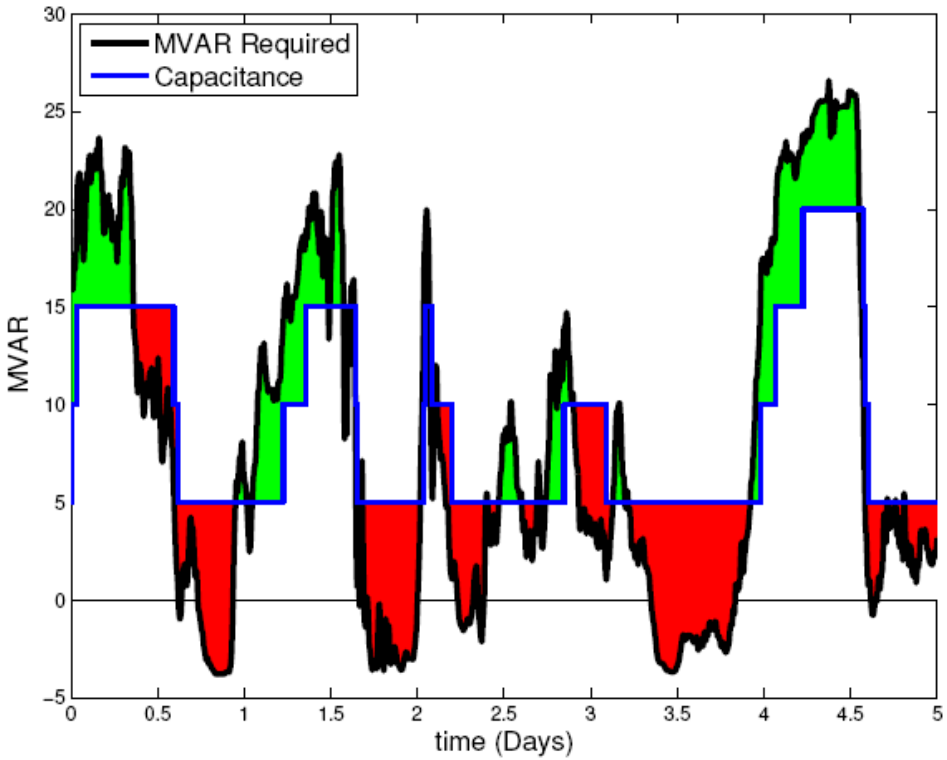

MVAR Required
Capacitance
MVAR
time (Days)
30
25
20
15
10
5
0
−5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5



Exact future knowledge



Stochastic future knowledge



Conclusions

- Resistance can have an important, but non-intuitive, effect for wind-farms connected at the sub-transmission level.
- Total reactive power available from WTGs may be much less than expected.
- System-level control of substation equipment can improve performance, but future information is important.