Impact of Increased Penetration of DFIG based Wind Turbine Generators on Voltage Response and Stability

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PSerc Seminar

Outline

- Wind Farm Grid Code Requirements for Reactive Power

  The fault ride-through capability: Ensures that the wind turbine is able to remain grid-connected during grid faults

  - US: FERC Order 661A
  - Other Countries
- Reactive Power Capability of DFIG
  - Impact on System losses and Voltage Stability Margin
    - Demonstration Through a Sample Test System
- Wind Variability on Voltage Stability
    - Demonstration Through a Sample Test System
- Demonstration on - offshore wind Park
- Conclusions and Discussion

FERC Order 661A

- ZVRT

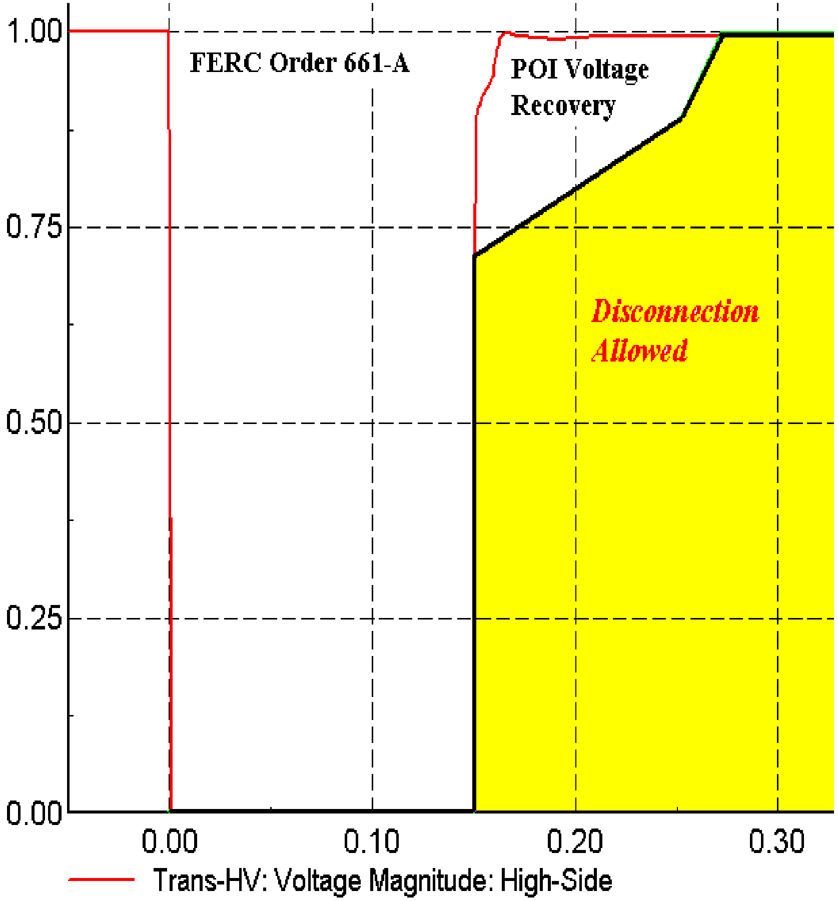
  (Zero Voltage Ride Through)

  - 2008 - present
    - 3φ short of 0 V at POI for 0.15s (9 cycles)

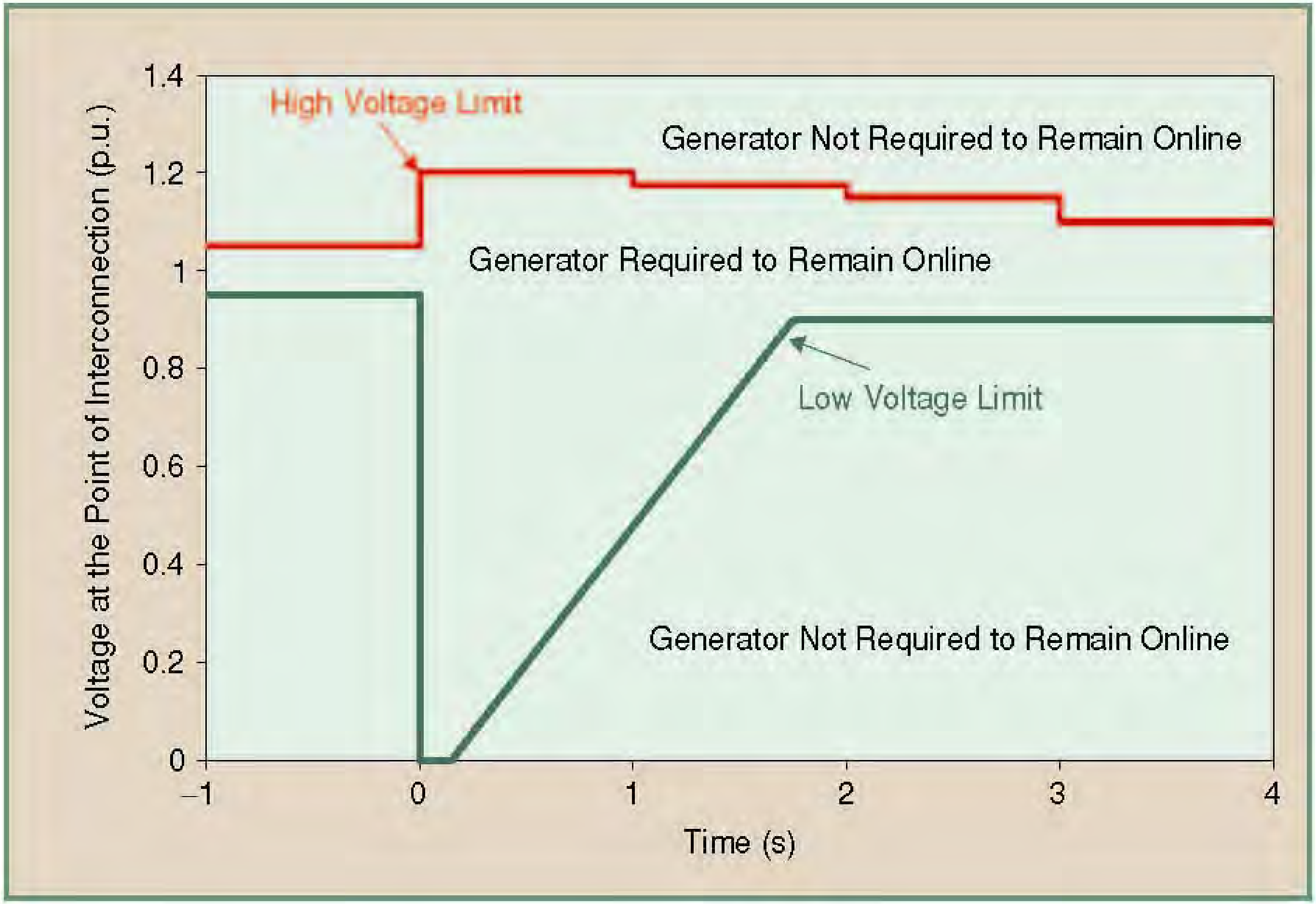
  (Wind farms installed prior to Dec. 31, 2007 are allowed to trip off line in the case of a fault depressing the voltage at the POI to below 0.15 p.u., or 15 percent of nominal voltage)

- PF
    - ± 0.95

(including dynamic voltage support, if needed for safety and reliability)



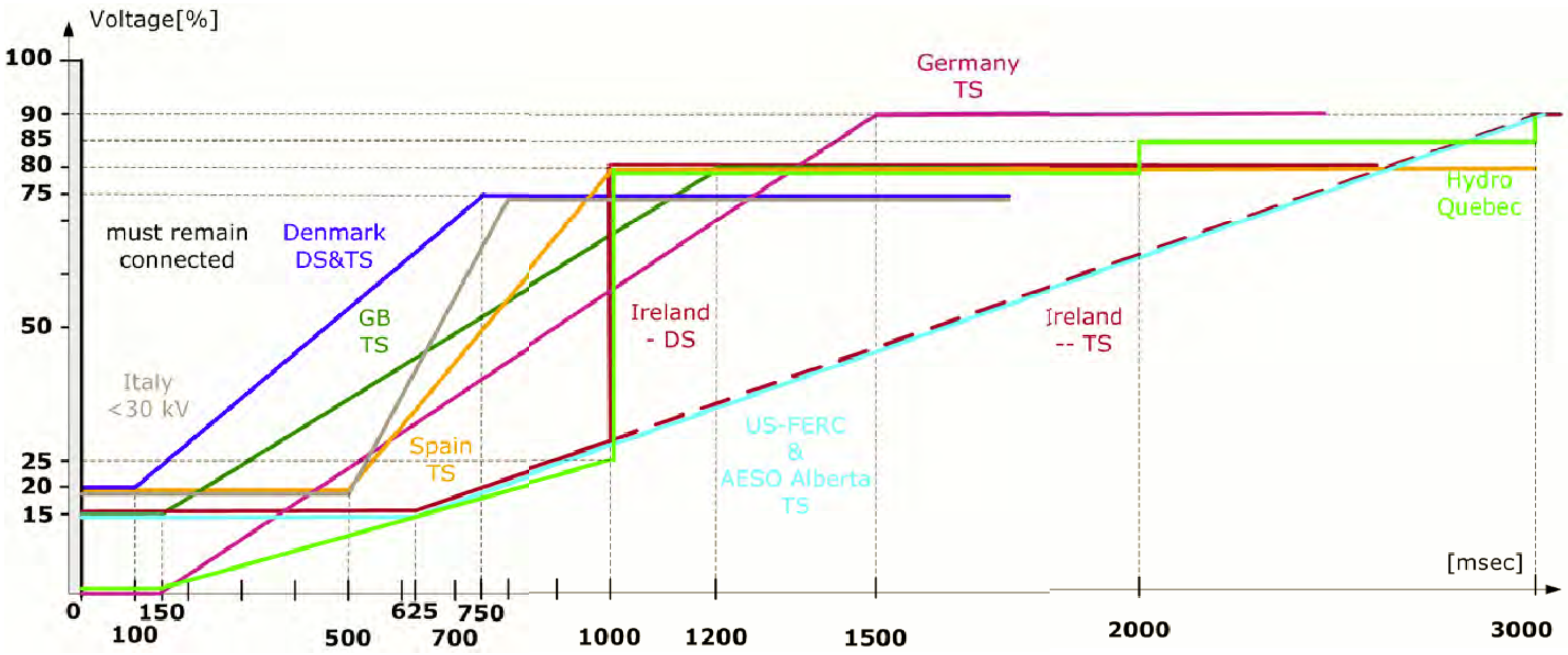
Proposed WECC Low Voltage Ride-Through (LVRT) requirements for all generators[1]



Most grid codes now require that wind power plants assist the grid in maintaining or regulating the system voltage

[1] SOURCE: R. Zavadil, N. Miller, E. Mujadi, E. Cammand B. Kirby, “Queuing Up: Interconnecting Wind Generation into The Power System” November/December 2007, IEEE Power and Energy Magazine

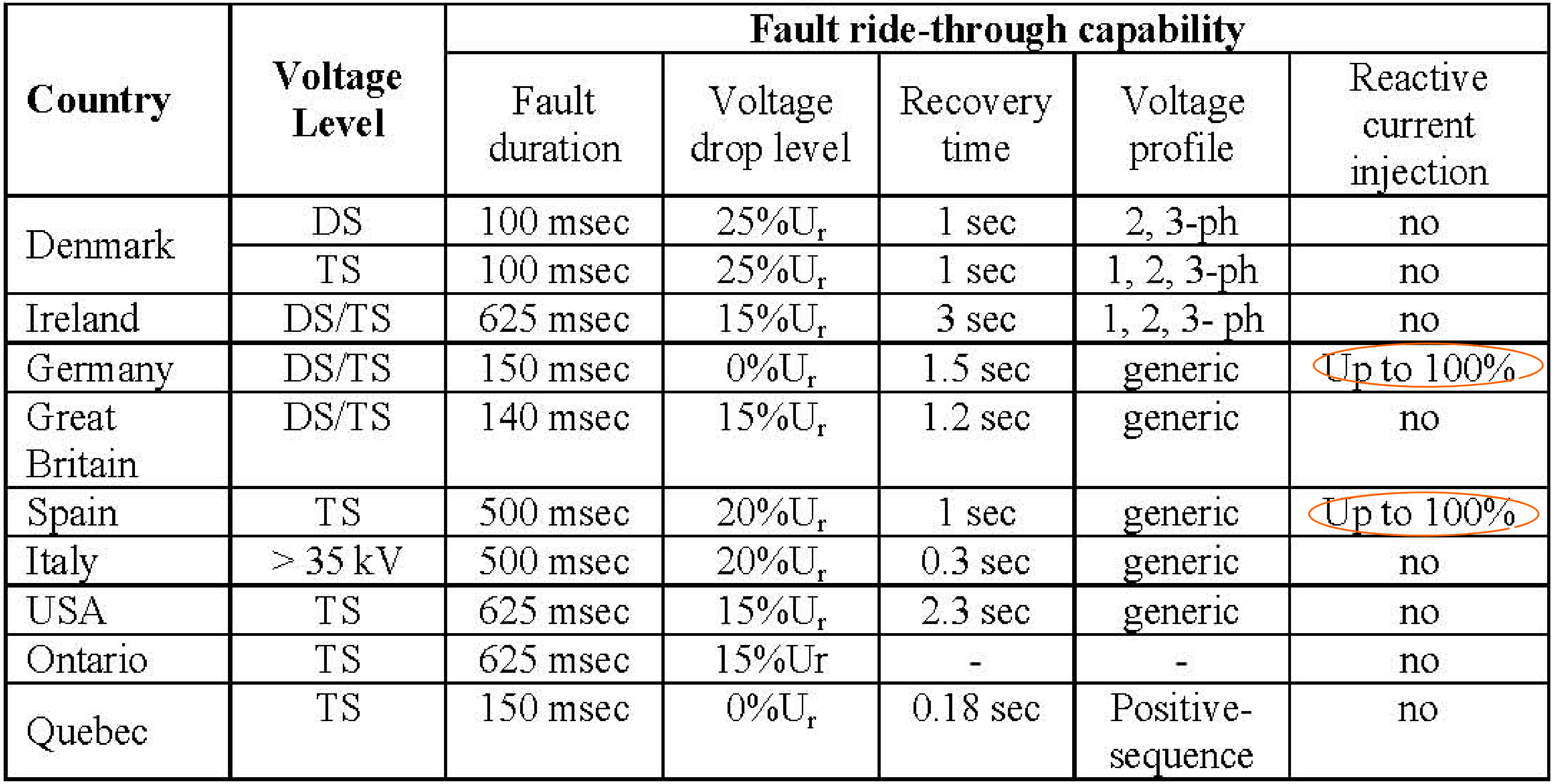
LVRT requirements of various National Grid Codes[2]



DS: Distribution TS: Transmission

2. SOURCE: Florin Iov, Anca Daniela Hansen, Poul Sørensen, Nicolaos Antonio Cutululis ,"Mapping of grid faults and grid codes" Risø-R-1617(EN), July 2007

Summary of ride-through capability for wind turbines[2]



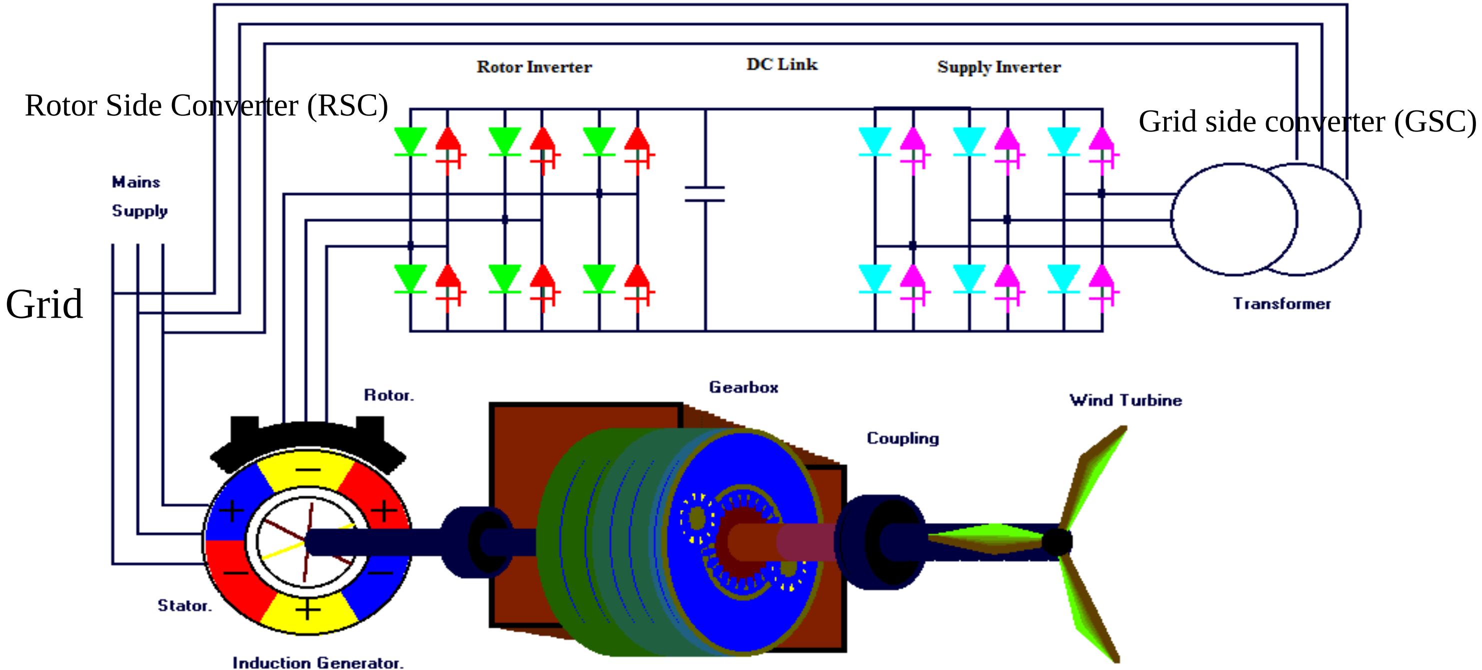
Country	Voltage Level	Fault ride-through capability				
		Fault duration	Voltage drop level	Recovery time	Voltage profile	Reactive current injection
Denmark	DS	100 msec	$25\%U_r$	1 sec	2, 3-ph	no
	TS	100 msec	$25\%U_r$	1 sec	1, 2, 3-ph	no
Ireland	DS/TS	625 msec	$15\%U_r$	3 sec	1, 2, 3- ph	no
Germany	DS/TS	150 msec	$0\%U_r$	1.5 sec	generic	Up to 100%
Great Britain	DS/TS	140 msec	$15\%U_r$	1.2 sec	generic	no
Spain	TS	500 msec	$20\%U_r$	1 sec	generic	Up to 100%
Italy	> 35 kV	500 msec	$20\%U_r$	0.3 sec	generic	no
USA	TS	625 msec	$15\%U_r$	2.3 sec	generic	no
Ontario	TS	625 msec	15%Ur	-	-	no
Quebec	TS	150 msec	$0\%U_r$	0.18 sec	Positive-sequence	no

2. SOURCE: Florin Iov, Anca Daniela Hansen, Poul Sørensen, Nicolaos Antonio Cutululis ,"Mapping of grid faults and grid codes" Risø-R-1617(EN), July 2007

In general all generators which are coupled to the network either with inverters or with synchronous generators are capable of providing reactive power

In DFIG real and reactive power can be controlled independently

Requires Power Electronic Devices of about 30% rating compared to Synchronous generator with full converter



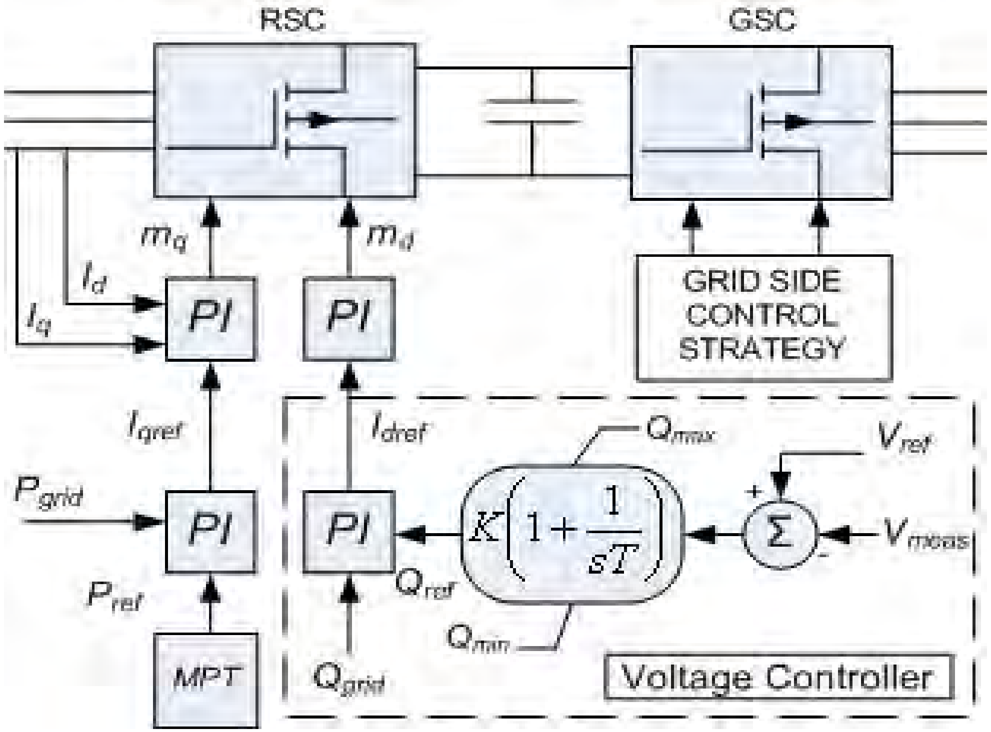
SOURCE:
http://www.windsimulators.co.uk/DFIG.htm

Voltage Controller

A voltage controller placed at the Point of Interconnect (POI) measures utility line voltage, compares it to the desired level, and computes the amount of reactive power needed to bring the line voltage back to the specified range .

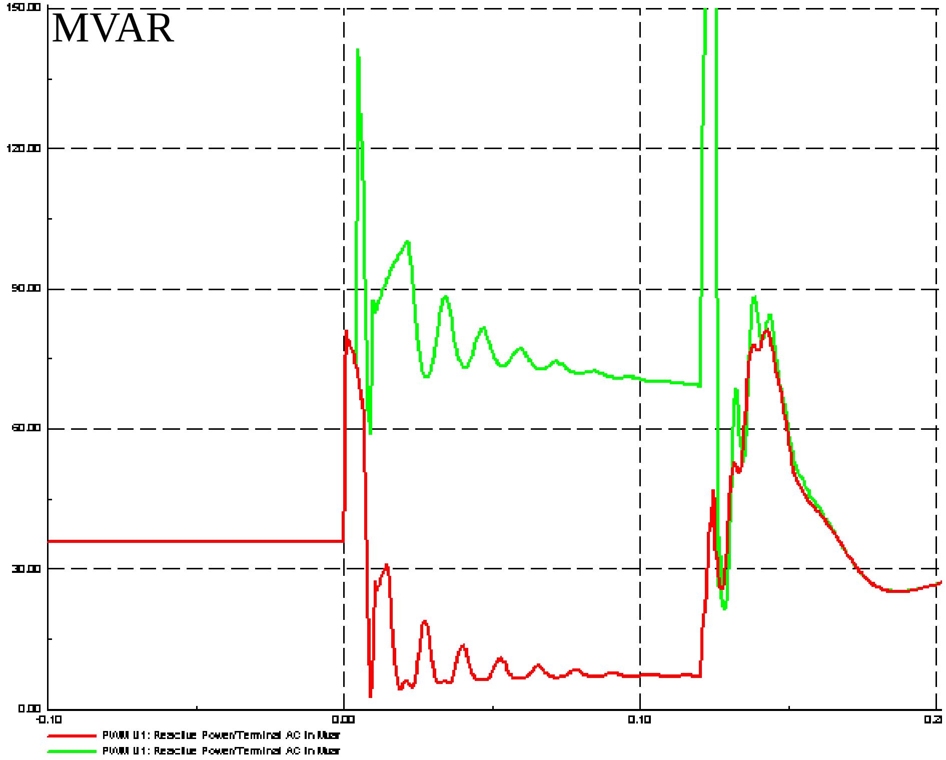
- Monitors POI or remote bus
- PI control adjusts stator Q_{ref} signal from V_{error}
- $Q_{mx/n}$
  - CC (capability curve)
  - FERC

$$|Q_{max}| = P_{output} \tan(\cos^{-1}(0.95))$$

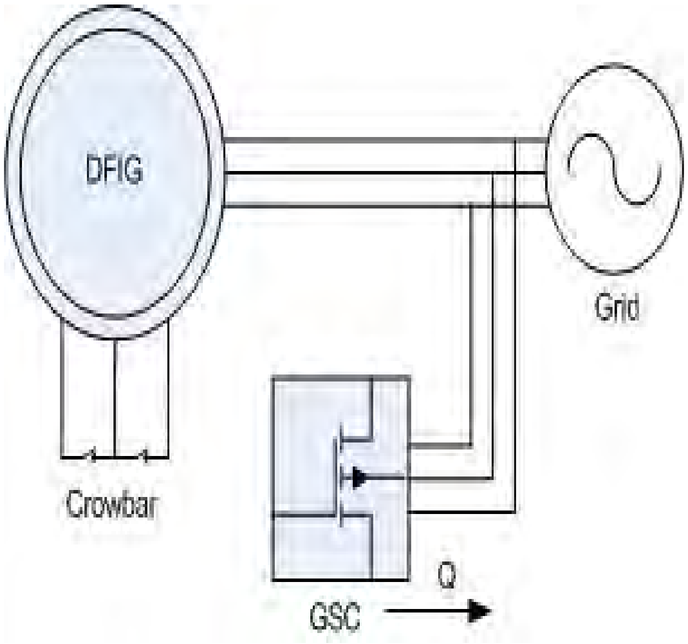


Grid Side Reactive Power Boosting

By default the grid voltage is controlled by the rotor-side converter as long as this is not blocked by the protection device (i.e. crowbar), otherwise the grid side converter takes over the control of the voltage

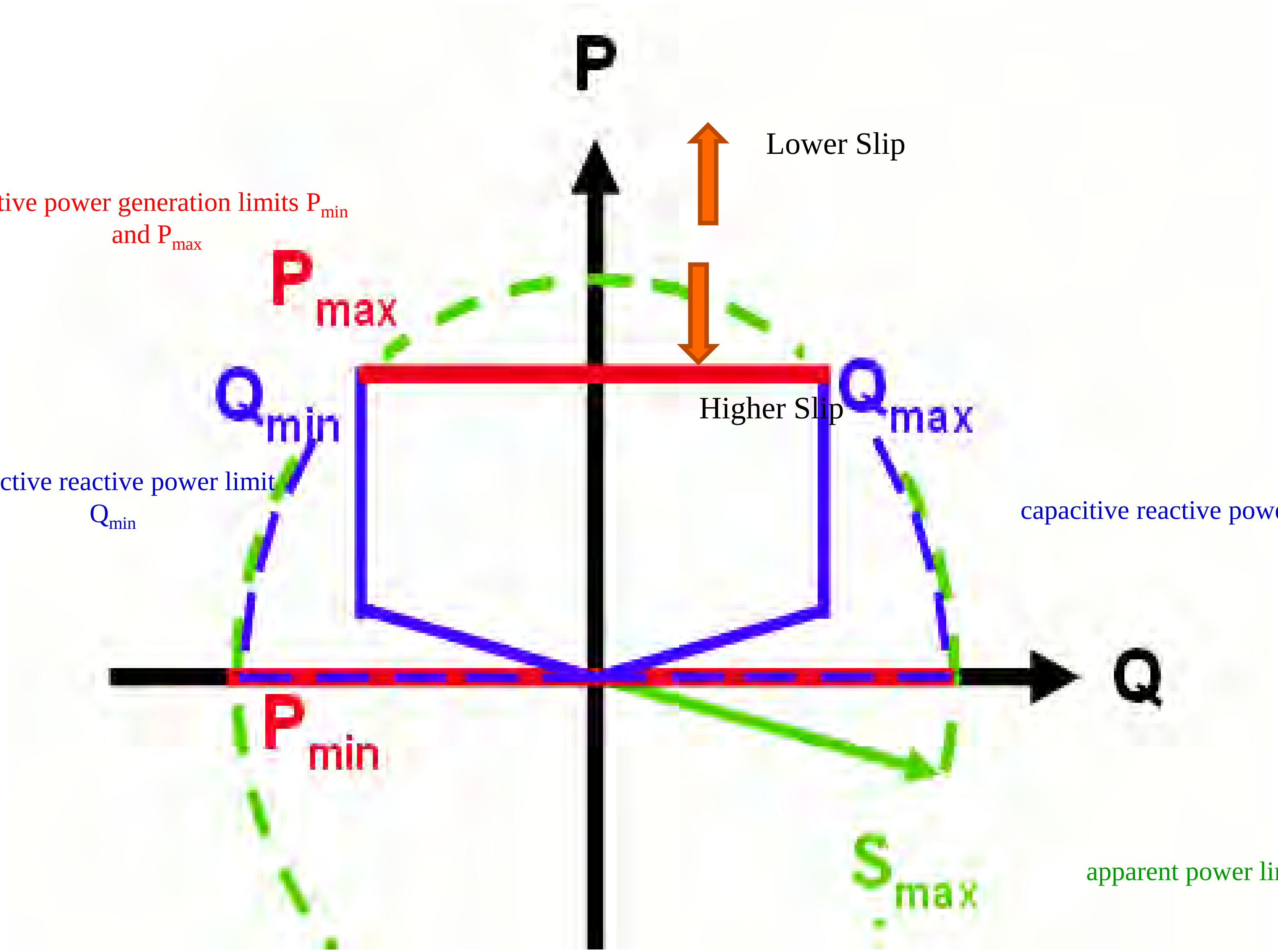


Impact of Grid Side Reactive Boosting with (green) and without (*red*) Control



Capability Curve of a DFIG Machine

- Capability Curve :
  - Variation in reactive power limits vs real power output.
  - Useful to estimate reactive power reserves in a system
  - Essential in accurately studying voltage stability



Lower Slip

Higher Slip

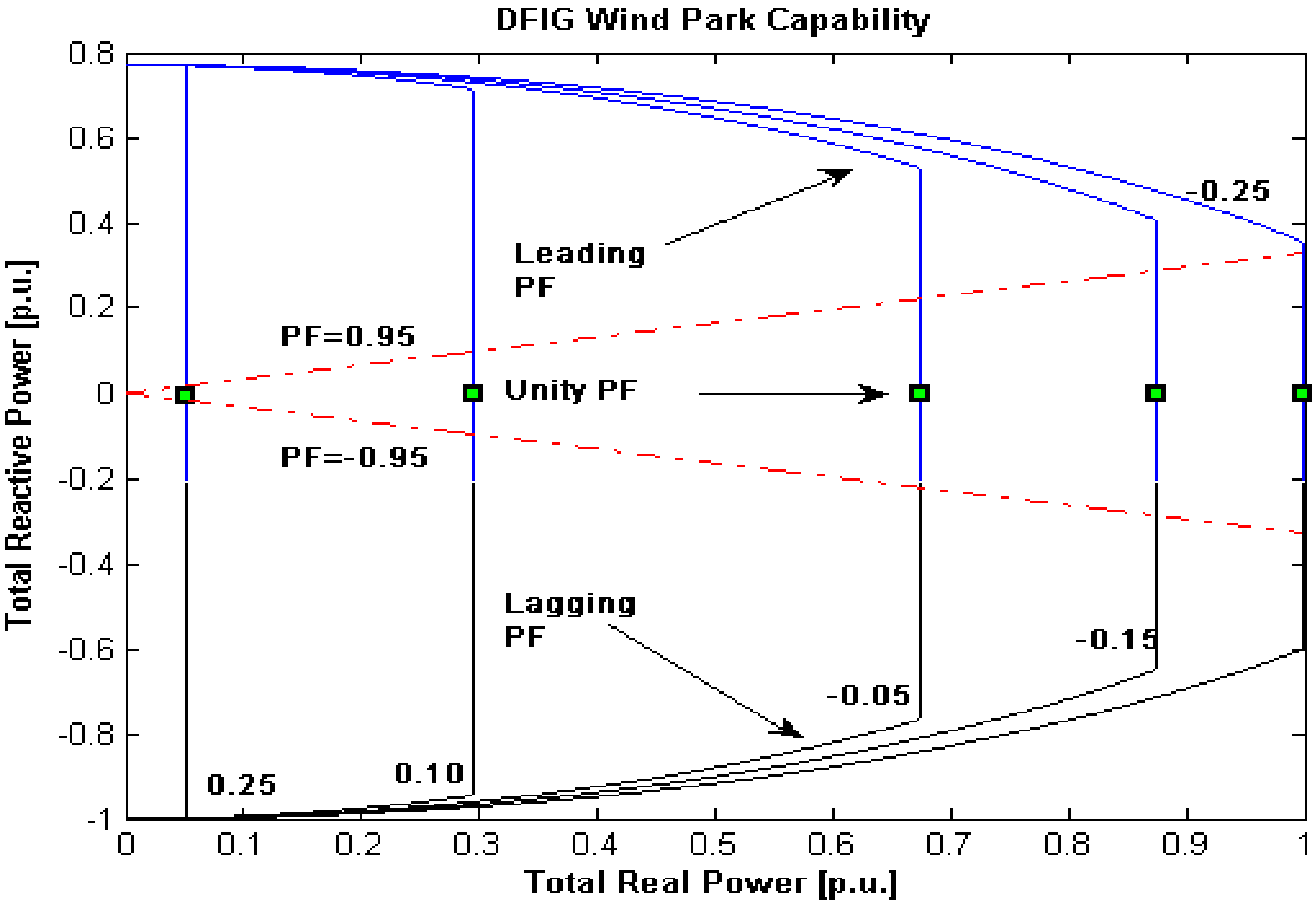
Active power generation limits P_{min} and P_{max}

Inductive reactive power limit Q_{min}

capacitive reactive power limit Q_{max}

apparent power limit S_{max}

Capability curve of a 1.5 MW machine

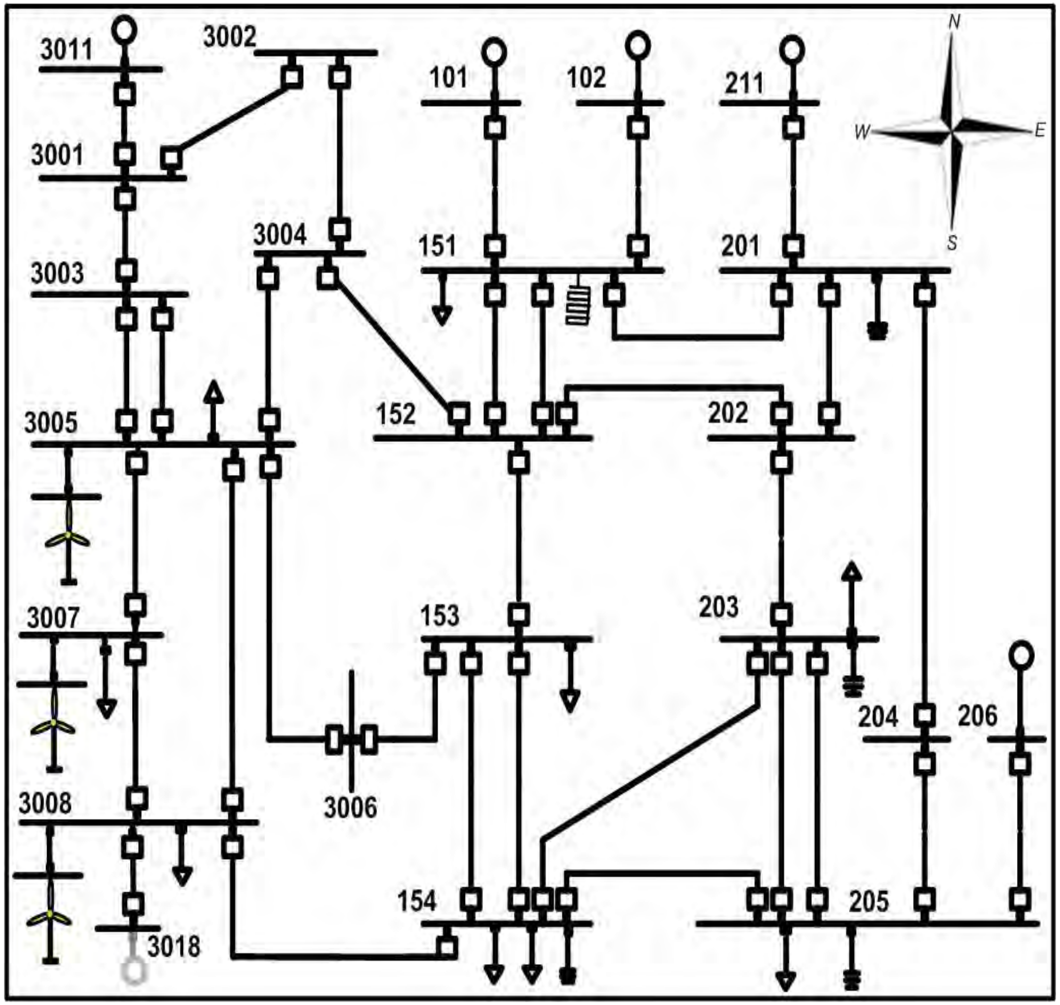


Rated electrical power	1.5 MW
Rated generator power	1.3 MW
Rated stator voltage	575 V
Rotor to stator turns ratio	3
Machine inertia	30 kgm^2
Rotor inertia	610000 kgm^2
Inductance: mutual, stator, rotor	4.7351, 0.1107, 0.1193 p.u.
Resistance: stator, rotor	0.0059, 0.0066 p.u.
Number of poles	3
Grid frequency	60 Hz
Gearbox ratio	1:72
Nominal rotor speed	16.67 rpm
Rotor radius	42 m
Maximum slip range	+/- 30%

Impact of Capability Curve:

a) On System Loss b) On Voltage Stability Margin

A Sample Simulation Study

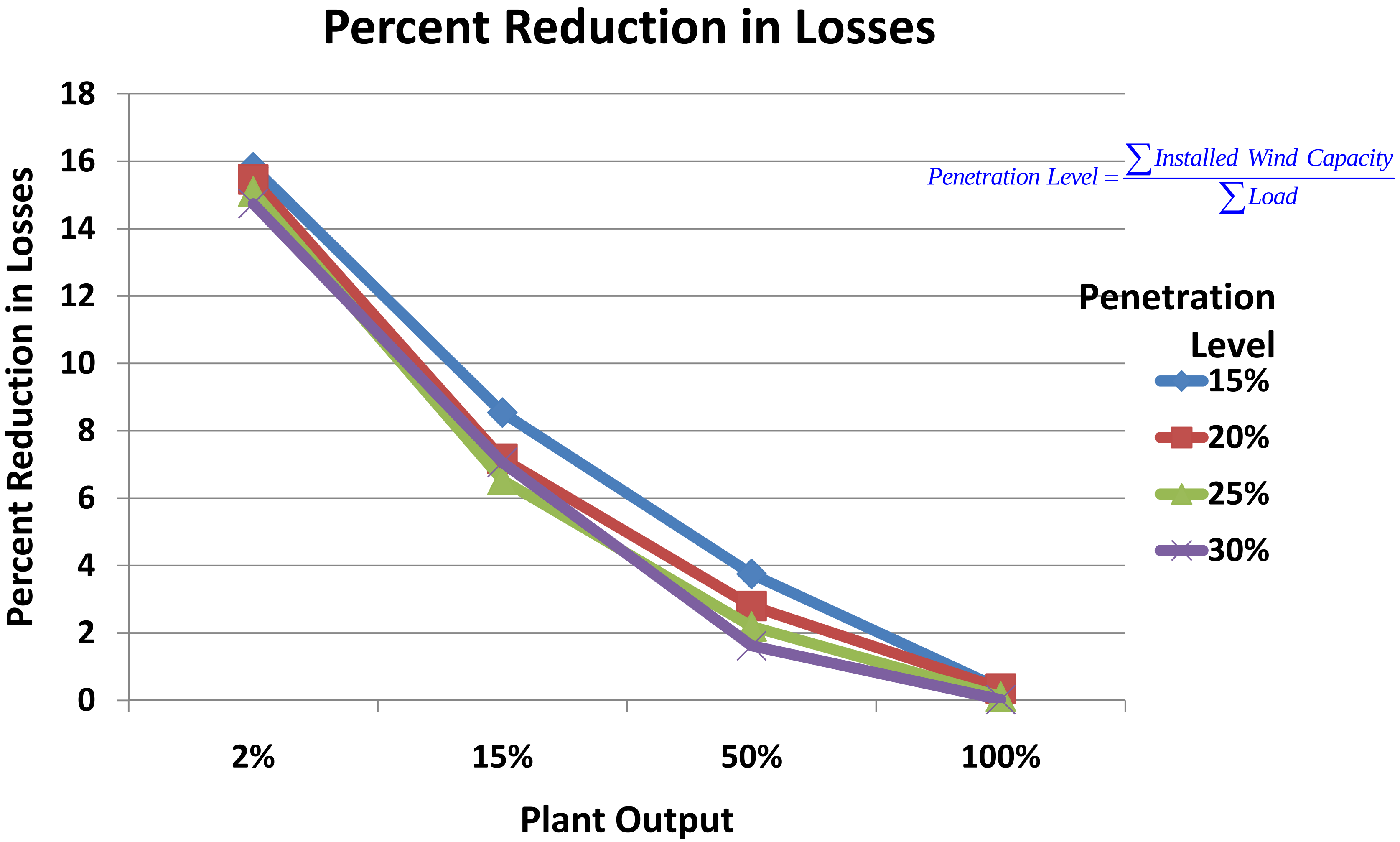


$$\text{Penetration Level} = \frac{\sum \text{Installed Wind Capacity}}{\sum \text{Load}}$$

Various Wind Penetration Levels at 15, 20, 25 & 30% are simulated

At each penetration level, total wind generation is simulated at 2, 15, 50 & 100% output

a) Impact of Capability Curve on System Losses



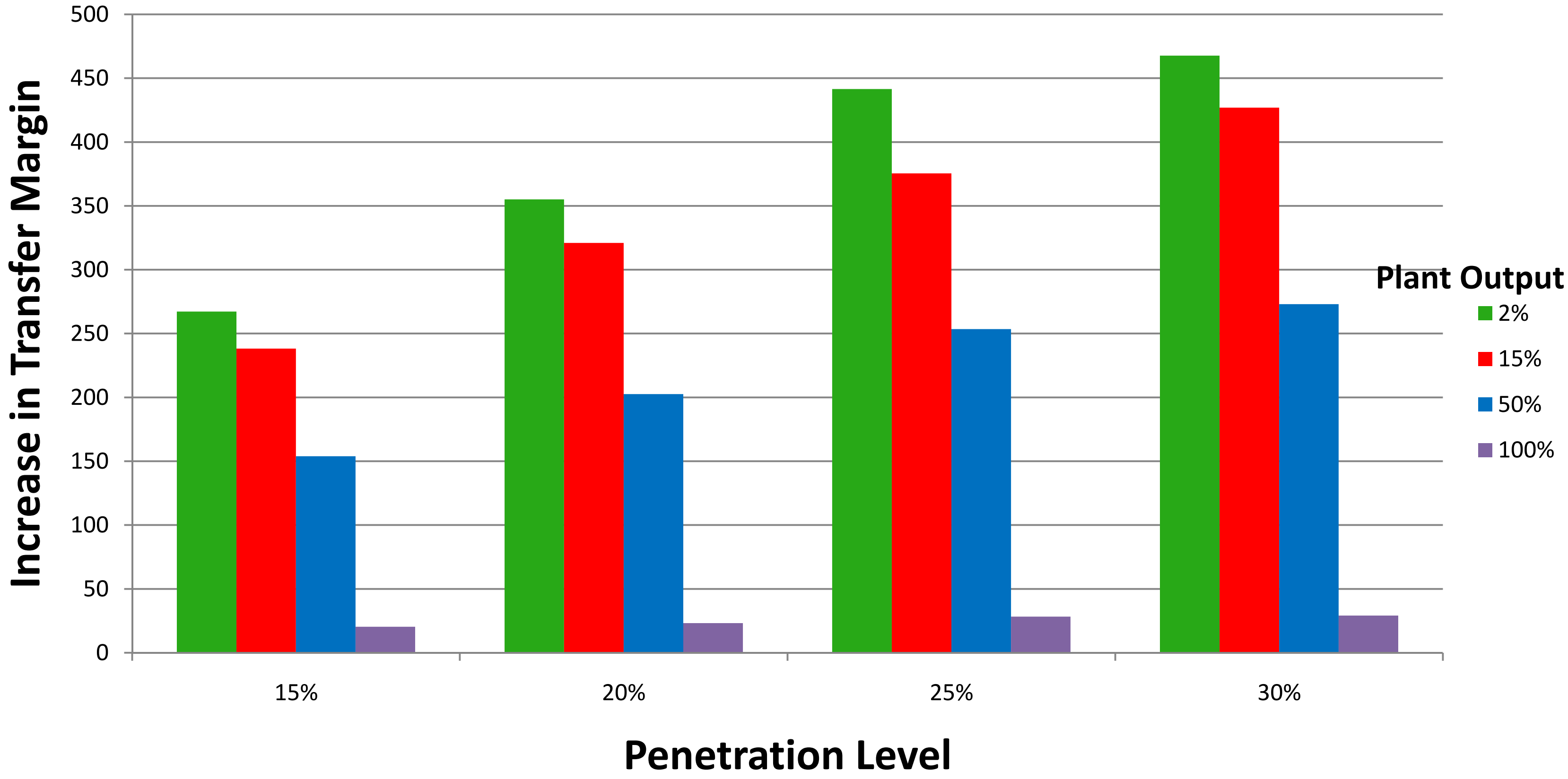
$$\text{Penetration Level} = \frac{\sum \text{Installed Wind Capacity}}{\sum \text{Load}}$$

Transfer Margin Assessment

- Develop peak load base case matrix:
  - % Penetration of peak load (x)
  - % Park output (y)
- Critical contingencies for case list
  - n-1 outages
- Perform appropriate static analysis (PV)
  - Identify weak buses
    - Voltage criteria limit
      - 0.90 – 1.05 V p.u.
      - Max load is 5% below collapse point for cat. B (n-1)
      - Add shunt compensation
    - Transfer Margin Limit
- Repeat for all % output (y) and % penetration (x) levels
- Perform dynamic analysis

b) Impact of Capability Curve on Voltage Stability Margin

Increase in Transfer Margin (in MW) Using Capability Curve



Dynamic Performance Validation

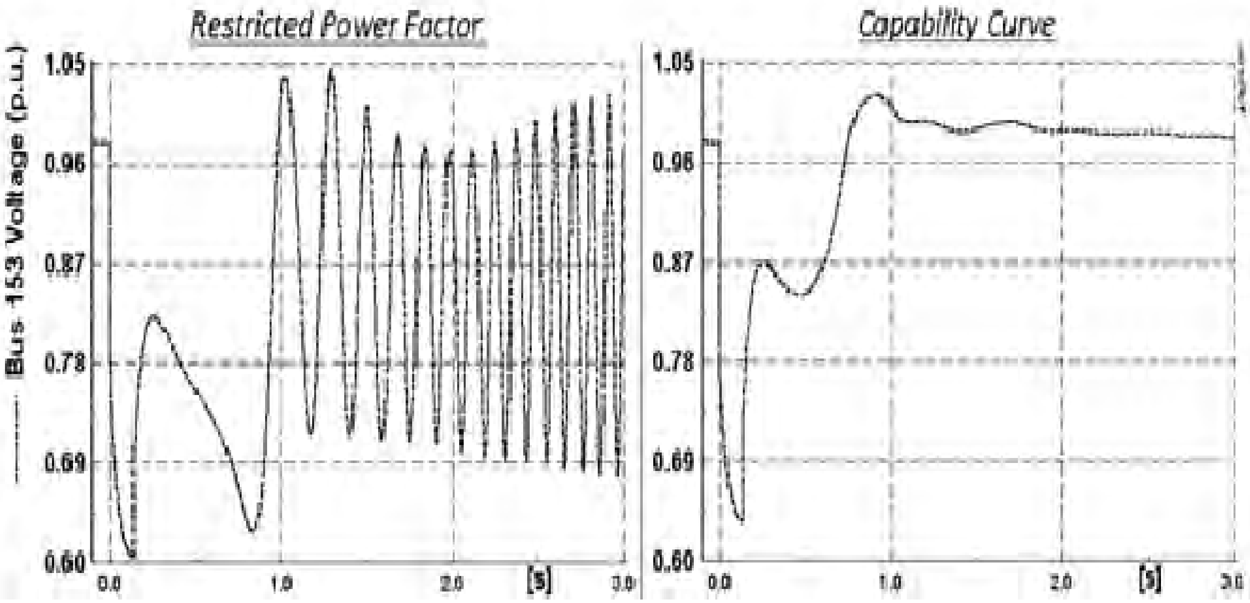
- ❑3φ short Circuit at Bus 3001 , CCT 140 ms
- ❑ Operation Comparison
  - FERC +/- 0.95
  - CC

20% penetration at cut-in speed

20% penetration at 15% output

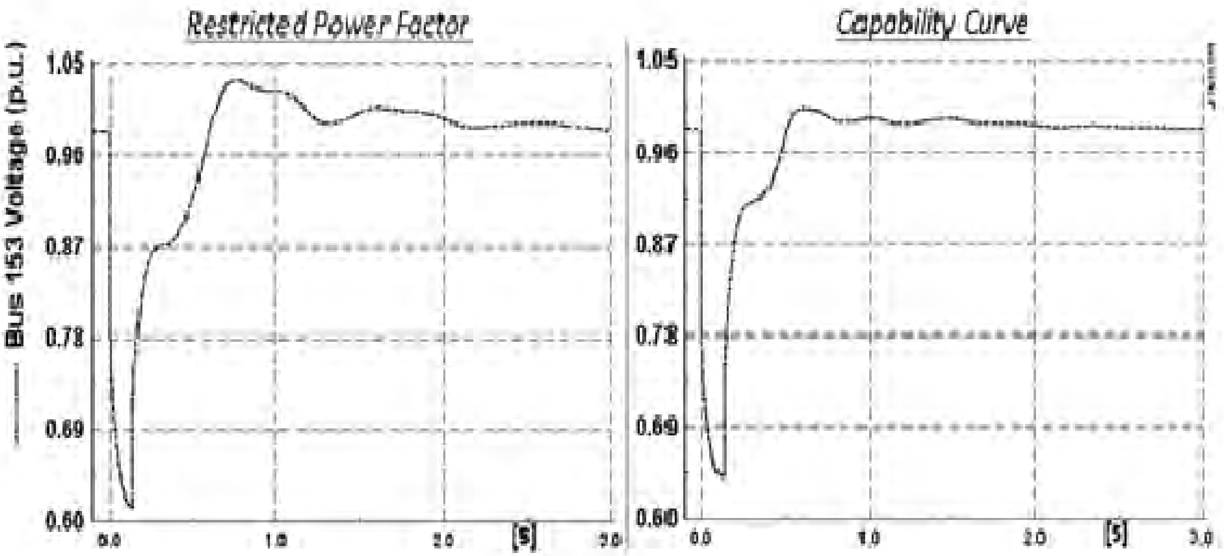
20% penetration at 100% output

20% penetration at cut-in speed



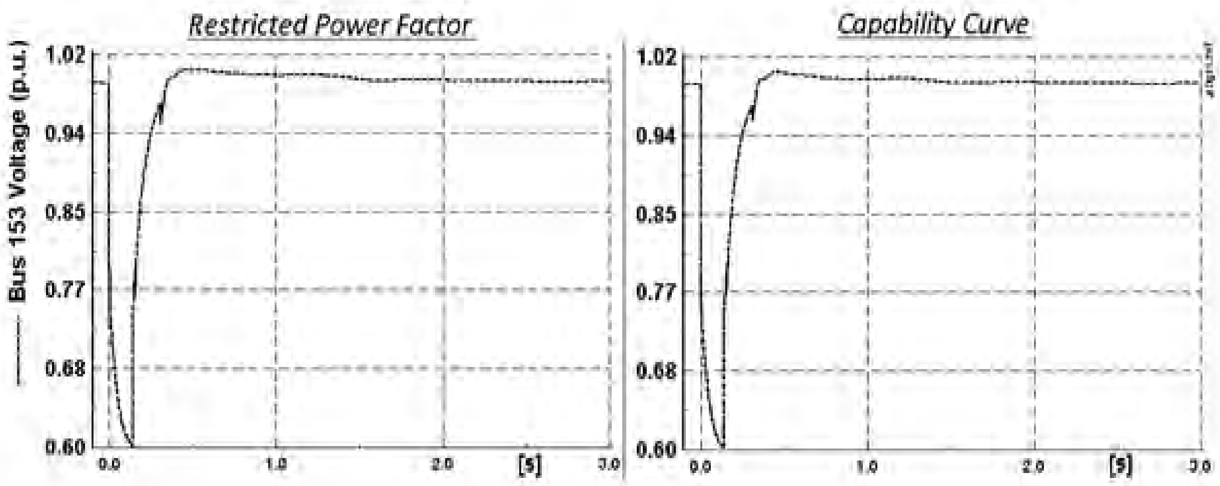
- 153 voltage
- RPF control
  - unable to recover post fault
- Extended reactive capability stabilizes system

20% penetration at 15% output



- CC control provides enhanced post fault voltage response
    - Reduced V overshoot / ripple

20% penetration at 100% output



- Near identical reactive injections
  - voltage recovery at bus 153

Voltage Stability Assessment Incorporating Wind Variability

Electricity generated from wind power can be highly variable with several different timescales –

- hourly, daily, and seasonal periods

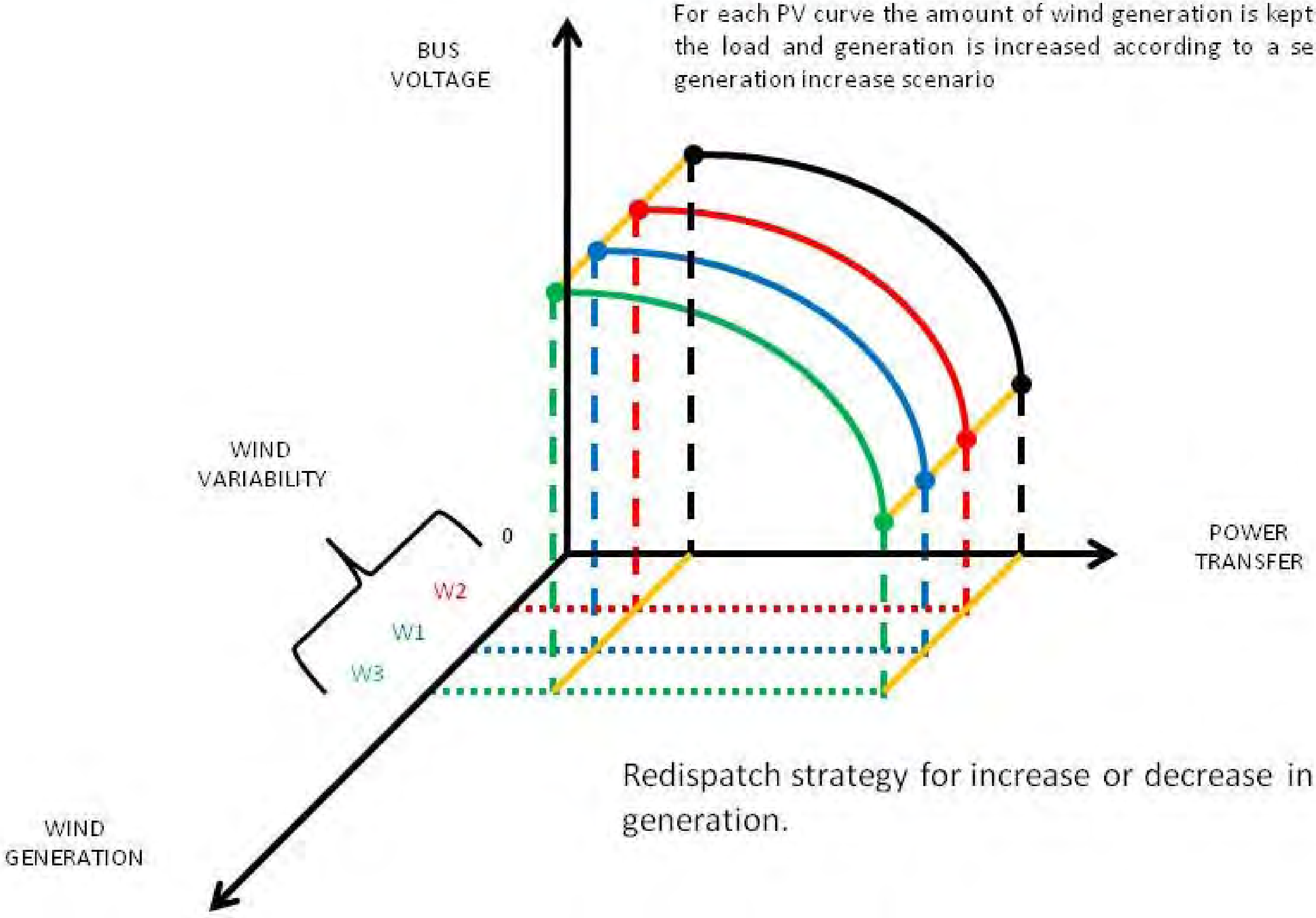
Increased regulation costs and operating reserves.

Wind variations in the small time frame (~seconds) is very small (~0.1%) for a large wind park. [1]

Static tools can be used to assess impact of wind variation

[1] SOURCE: Design and operation of power systems with large amounts of wind power , Report available Online : http://www.vtt.fi/inf/pdf/workingpapers/2007/W82.pdf

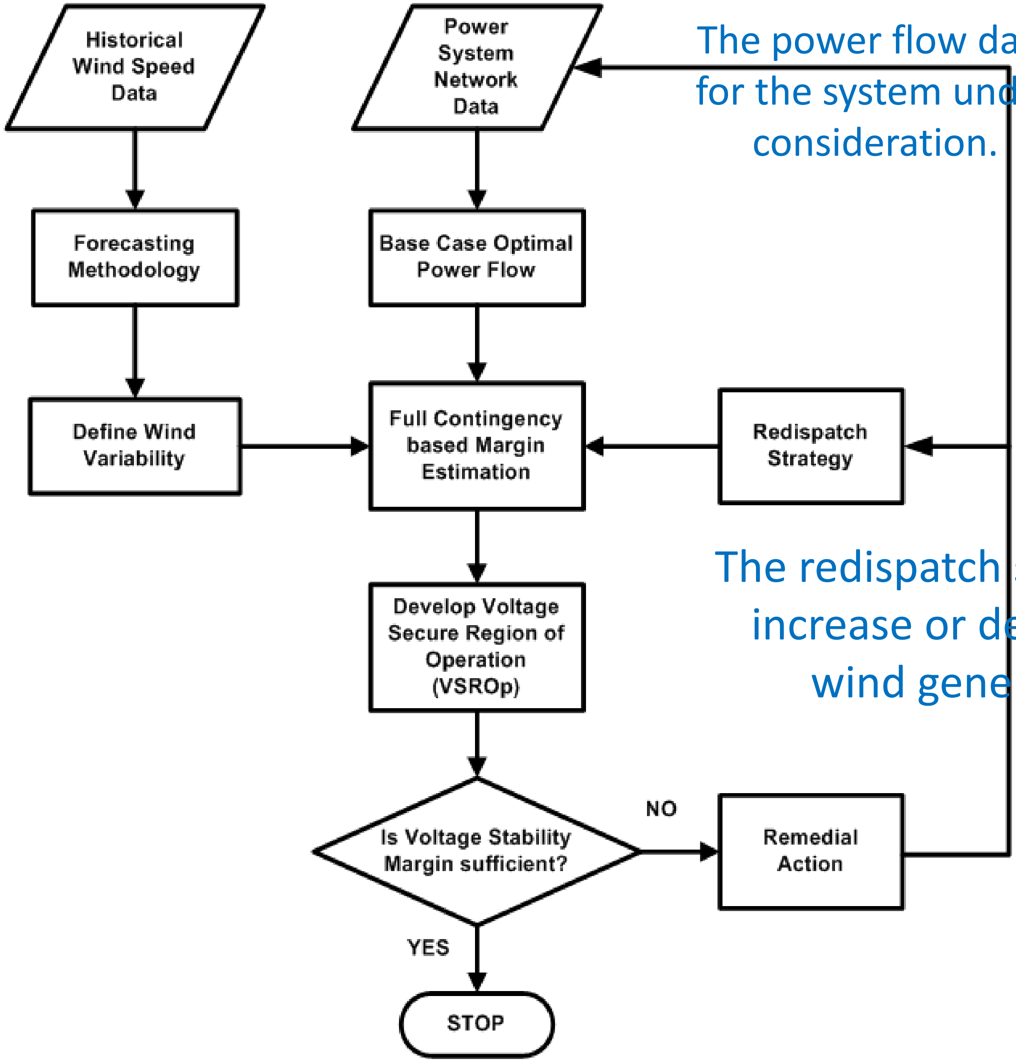
Voltage Secure Region of Operation (VSROp)



For each PV curve the amount of wind generation is kept constant and the load and generation is increased according to a set loading and generation increase scenario

Redispatch strategy for increase or decrease in wind generation.

Methodology



Historical Wind Speed Data

Forecasting Methodology

Define Wind Variability

Power System Network Data

Base Case Optimal Power Flow

Full Contingency based Margin Estimation

Redispatch Strategy

Develop Voltage Secure Region of Operation (VSROp)

Is Voltage Stability Margin sufficient?

NO

Remedial Action

YES

STOP

The power flow data for the system under consideration.

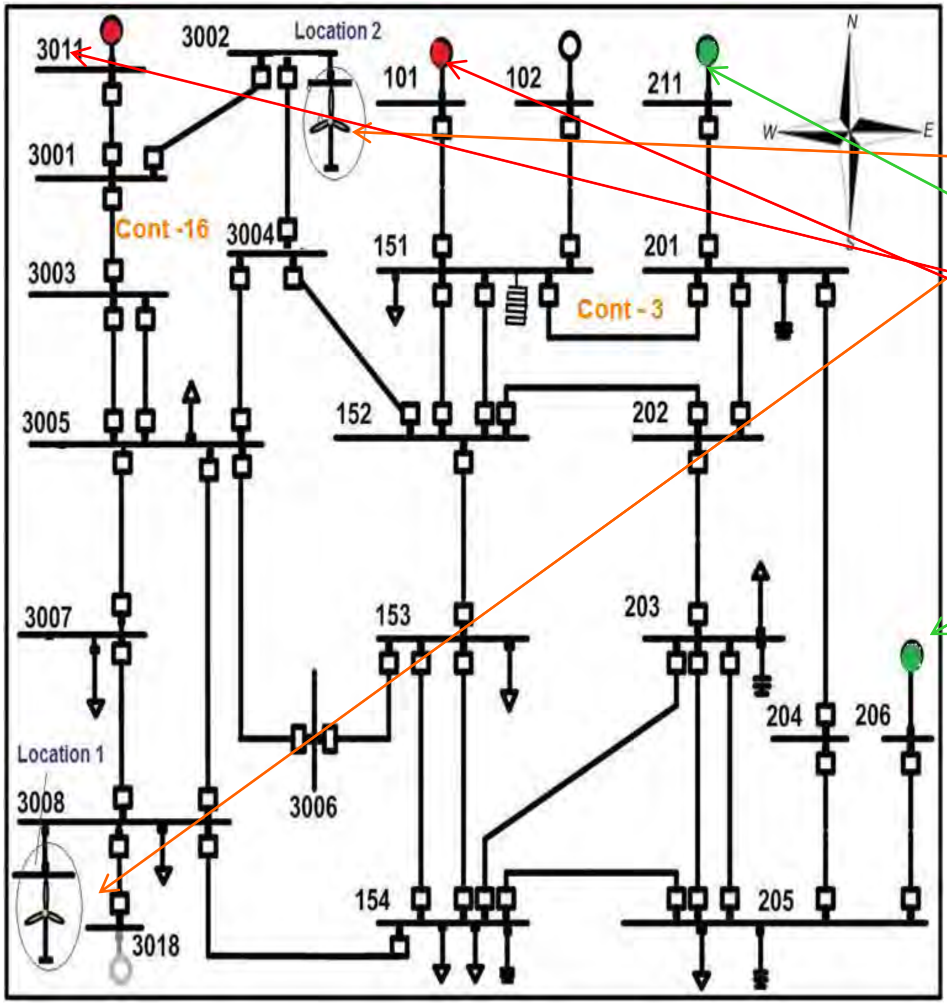
The assumed level of wind generation in the base case and wind variability that is to be studied.

The redispatch strategy for increase or decrease in wind generation.

Test System

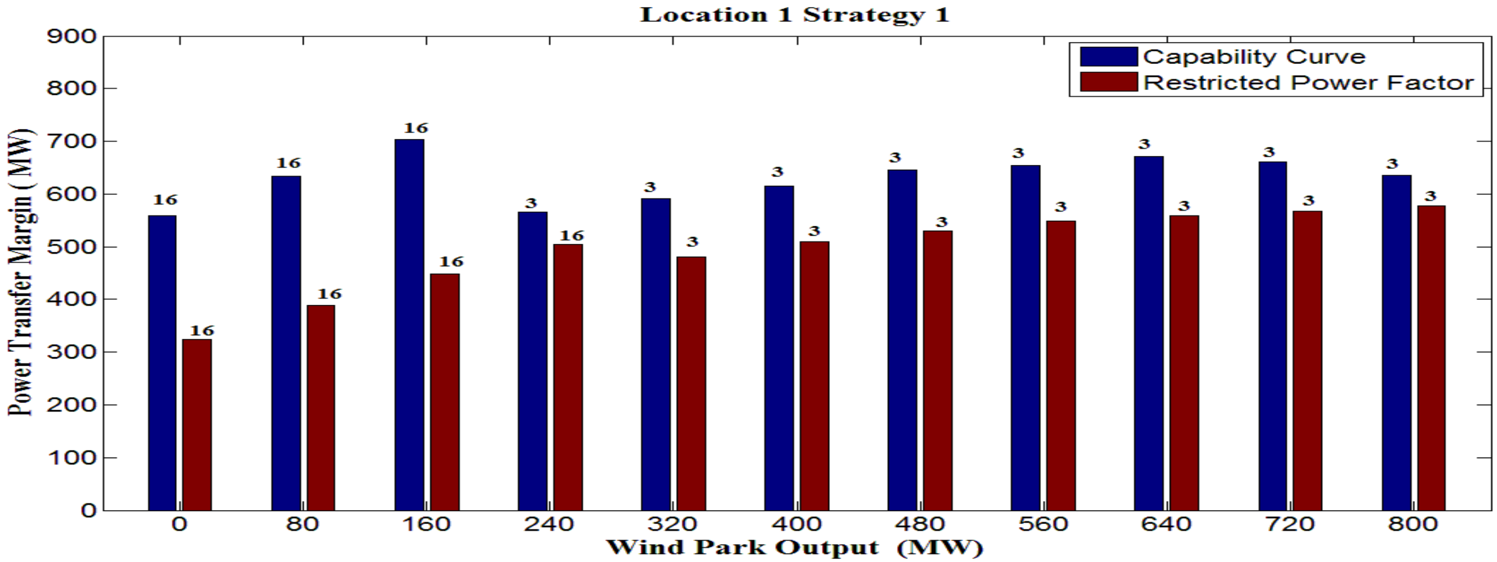
- The test system used for the previous analysis is again used to develop the VSROP
- In the previous study all the generators pick up for the wind, which results in the optimal redispatch of all generators.
- But this is not a practical assumption, and for a more realistic scenario, only a few generators are available to pick up for wind ramp events
- The units selected for the redispatch are units with fast ramping capability
- With this more realistic scenario, the effect of Capability Curve over restricted power factor mode is analyzed.

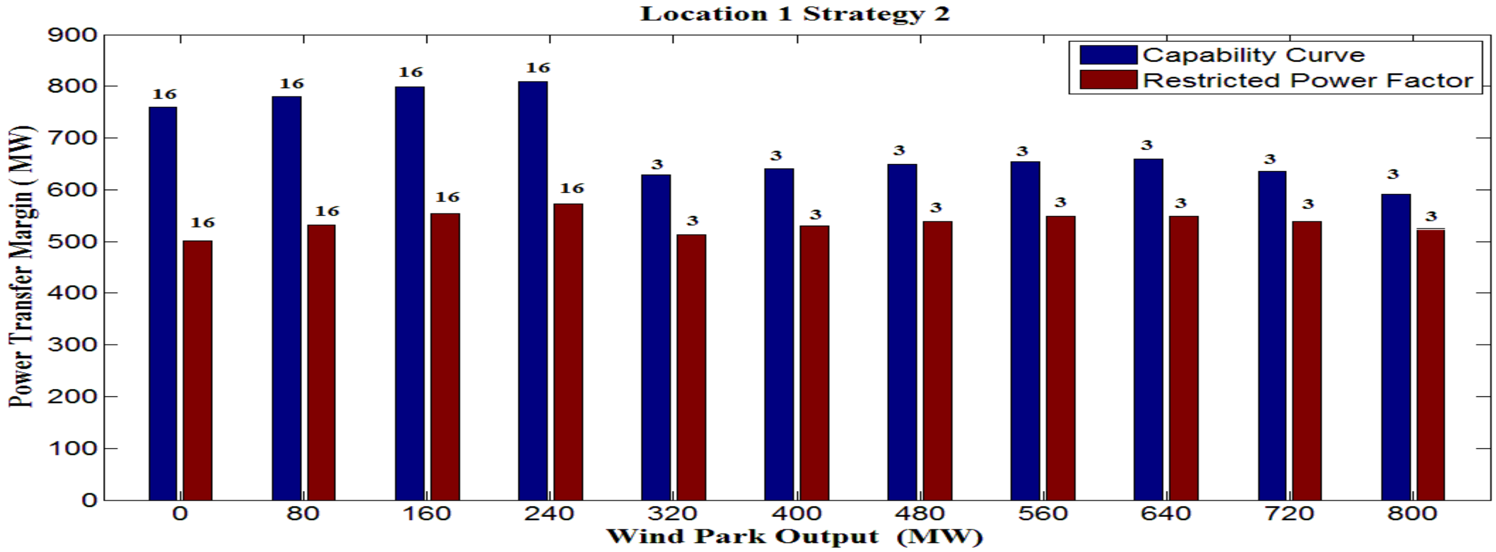
Sample Test System



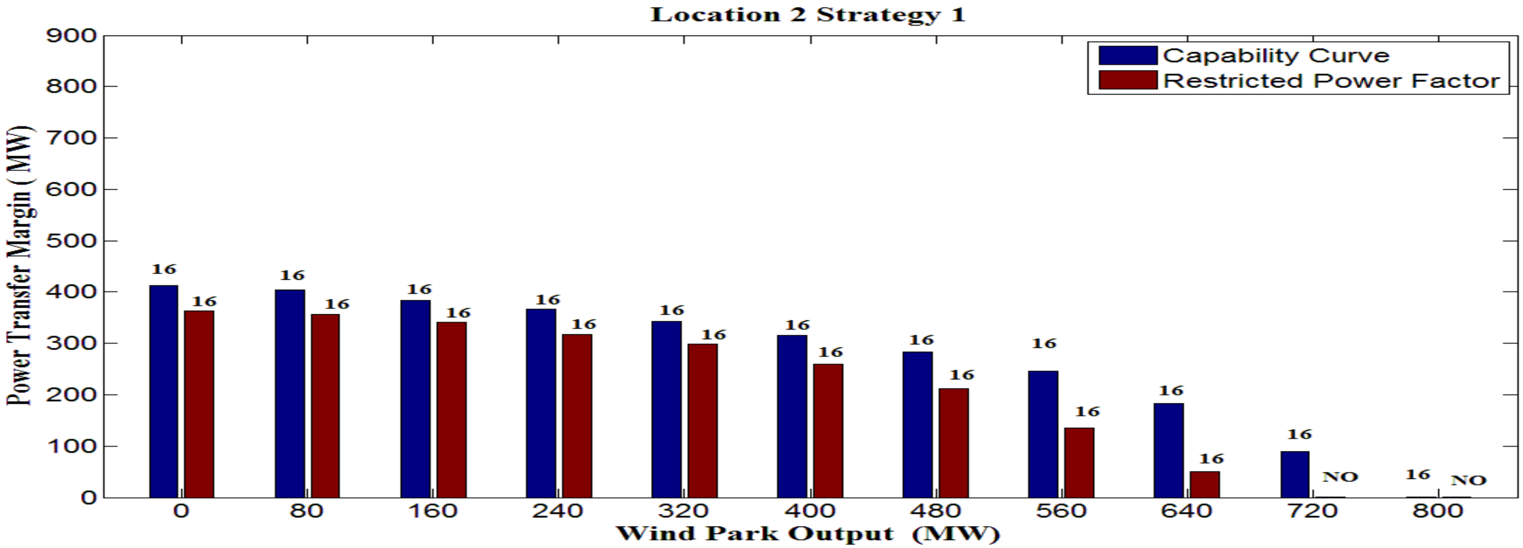
- Two locations are chosen for adding wind generation.
- Each wind unit is of size 800 MW.
- Two redispatch strategies are chosen
  - Gen 101 and Gen 3011 [remote to load] (RED)
  - Gen 206 and Gen 211 [close to load] (GREEN)
- Base case wind output is 560 MW. Any change in wind power is compensated by redispatch units
- Determine – minimum margin and most restrictive contingency.

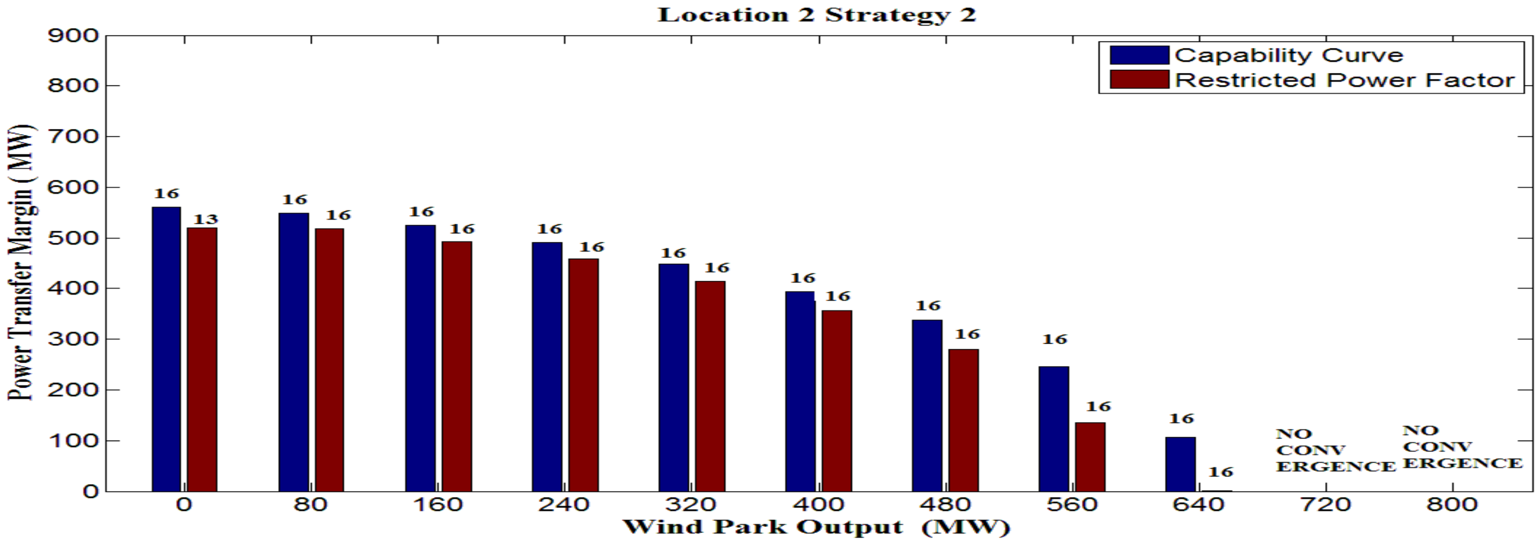
Results: Comparison of Re-dispatch Strategies at Location 1





Results: Comparison of Re-dispatch Strategies at Location 2





Observations

- A larger power transfer margin available over the entire range of variability with Capability Curve
  - Leads to higher penetration levels

- This tool helps determine the wind level at which minimum power transfer margin is obtained.

- This power level need not be at minimum wind or maximum wind.

- The tool also provides the most restrictive contingency at each wind level.

Extension of Work to the Eastern Interconnection System

- The previous sections have established that by employing the capability curve improved voltage performance can be obtained
- From a practical implementation point of view, it is important to test how in the actual power system, with known wind locations and load centers, the voltage performance is affected by the capability curve.
- Case Study: Eastern Costal Area off shore wind farm

Case study
(Off Shore)

- Contribution of any reactive power source is directly proportional to its proximity to the load
- Coastal areas are densely populated and are hence high load centers
- High population density and the various environmental regulations, makes it very difficult to site generation close to these coastal load centers.

Modeling of Offshore Wind Farm

- The study region is restricted to an eastern coastal region of the system.
- The 22,000 bus Eastern Interconnection system is used to obtain static and dynamic data for the region being considered.
- The region of study is restricted to 648 buses with a total load of 7100 MW. The study area has 57 units.
- The coastal load pocket with 600 MW base case load is the region chosen for the interconnecting offshore wind park.

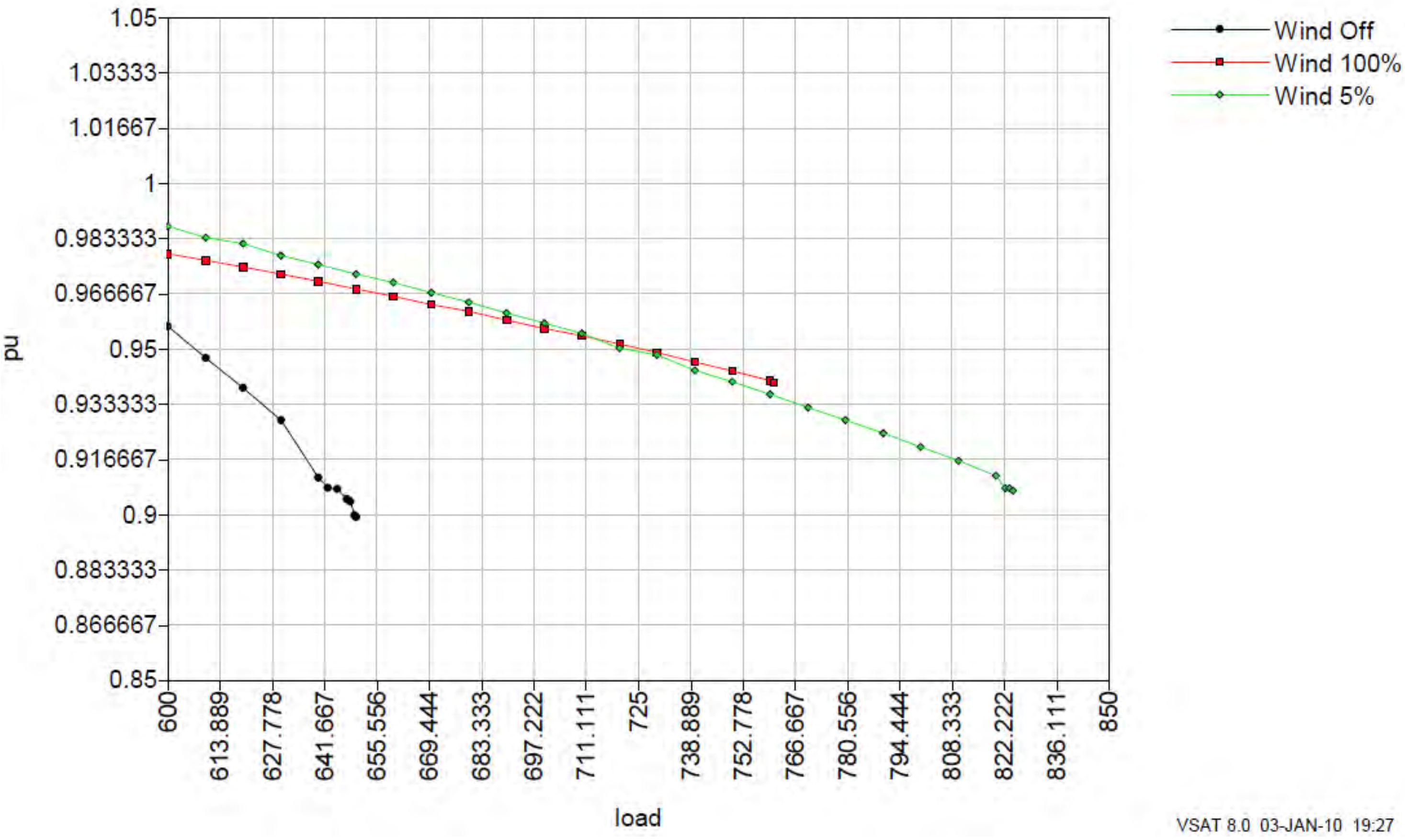
Scenarios Analyzed

- No Wind Park
- Wind Park at 100% Output
- Wind Park at 5% Output.
- All loss of line contingencies in the load pocket are considered – 30 line out contingencies

Scenario Set Up

- The initial load level in the load zone is maintained at 600 MW
- Generation outside the load zone is used to import power into the load zone
- The load is increased while maintaining a constant power factor
- The voltage criteria used for the system is that all pre contingency voltage should be above 0.95 p.u and below 1.05 p.u. on all buses over 115kV
- For post contingency scenarios, the minimum voltage is extended to 0.9 p.u. and the maximum voltage is increased to 1.1 p.u.
- The 5 most critical contingencies are the loss of any of the import lines
- Three buses are monitored for Voltage violations
- PV curves are developed for each of the three scenarios considered

Post-contingency Voltage Variation at WF1 Bus



Dynamic Analysis

- The purpose of this analysis is to verify the results obtained in the steady state analysis.
- Additional impact of tap changing transformers – long term voltage stability.
- GE 1.5 MW machine model is used. The reactive limits are modified to incorporate the capability curve.
- The disturbance on the system is the loss of a line with no fault.

System State with Increasing Load Levels

Load Level	625	775	825
Wind Park 100%	Secure	Insecure	Insecure
Wind Park Off	Insecure	Insecure	Insecure
Wind Park – Cut In speed	Secure	Secure	Insecure

Summary of Results

- This section demonstrates the benefit of utilizing the capability curve of an off shore wind park to reliably serve load during low wind periods.

- The accessibility of wind farms as a reactive power source will lead to higher import capabilities into the coastal load pockets from remote generation.

Conclusions

- **As levels of wind penetration continue to increase the responsibility of wind units to adequately substitute conventional machines becomes a critical issue**
    - Recent advancement in wind turbine generator technology provides control of reactive power even when the turbine is not turning. This can provide continuous voltage regulation. A performance benefit , not possible with the conventional machines
    - Wind generators can become distributed reactive sources. Coordination of this reactive power is a challenging task
- Proper coordination of DIFG wind parks can reduce losses , improve voltage performance
- **The FERC order 661-A, gives general guidelines for interconnecting wind parks, but for specific parks employing DFIG units the restriction on power factor may be lifted**

Publications

- P. Vijayan, S. Sarkar, V. Ajjarapu, ”Novel Voltage Stability Assessment Tool to Incorporate Wind Variability”, *presented at* IEEE Power and Energy Society General Meeting 2009, Calgary, July 26-30,2009
- R. J. Konopinski, P. Vijayan, V. Ajjarapu, “Extended Reactive Capability of DFIG Wind Parks for Enhanced System Performance”, IEEE Transactions on Power Systems, August 2009