Impact of increased penetration of wind and PV solar resources on the bulk power system

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Motivation

- This talk examines the impact of increased penetration of wind and solar resources on the bulk energy system (BES)
- The BES includes the generation system and all components of the transmission system 69 kV and above (the new definition by FERC/NERC says 100 kV and above but allows for the 69 kV system in portions of the interconnection)
- In most large scale system studies the transmission system at 69 kV and above is included

Wind and PV solar grid interface

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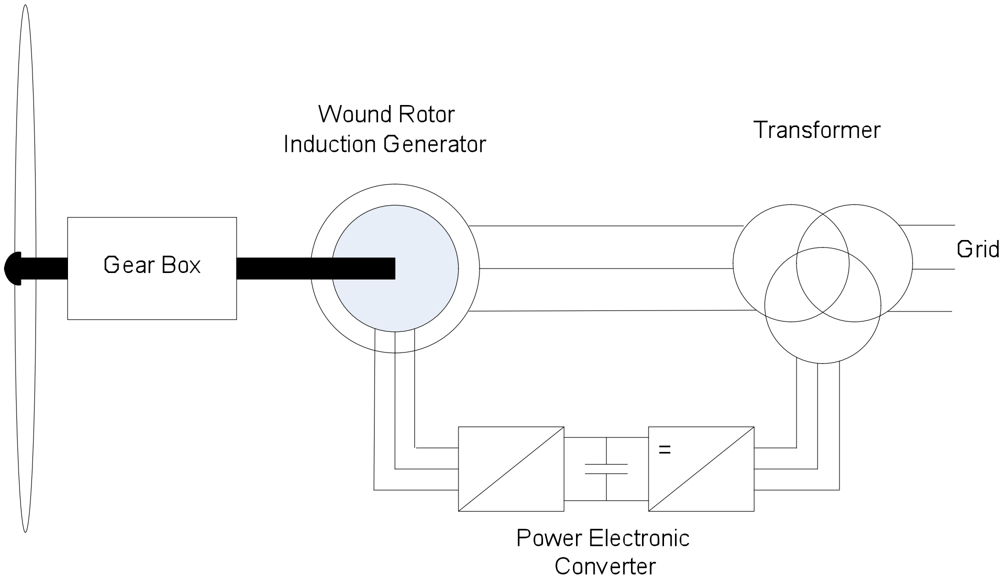
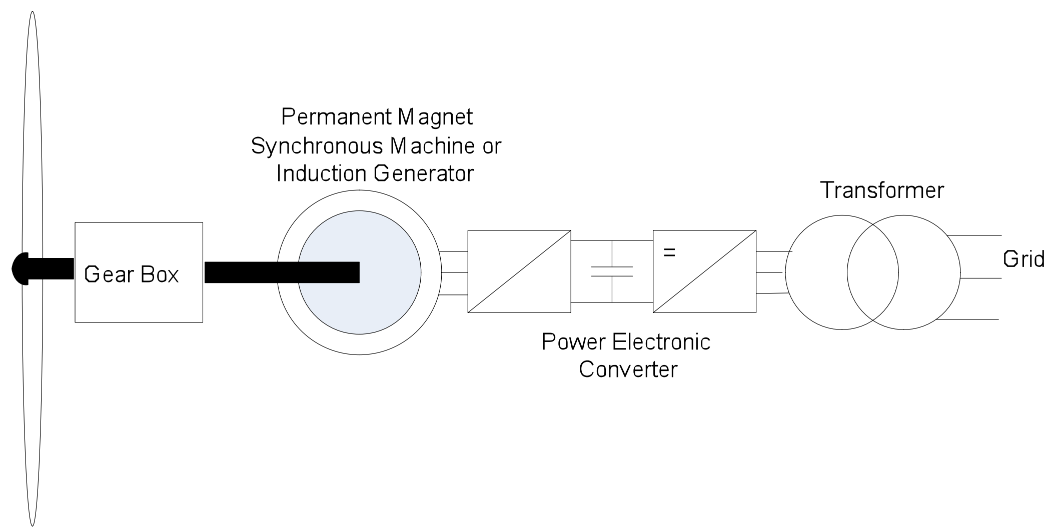
- Modern wind turbine generators are typically rated between 1.5 MW to 5 MW
- They are either doubly fed induction generator based (WTG3) or full converter permanent magnet synchronous machine (WTG4) based units
- Both types of machines are interfaced with the BES through a power electronic converter

Wind and PV solar grid interface



Schematic of Type 3 wind turbine generator

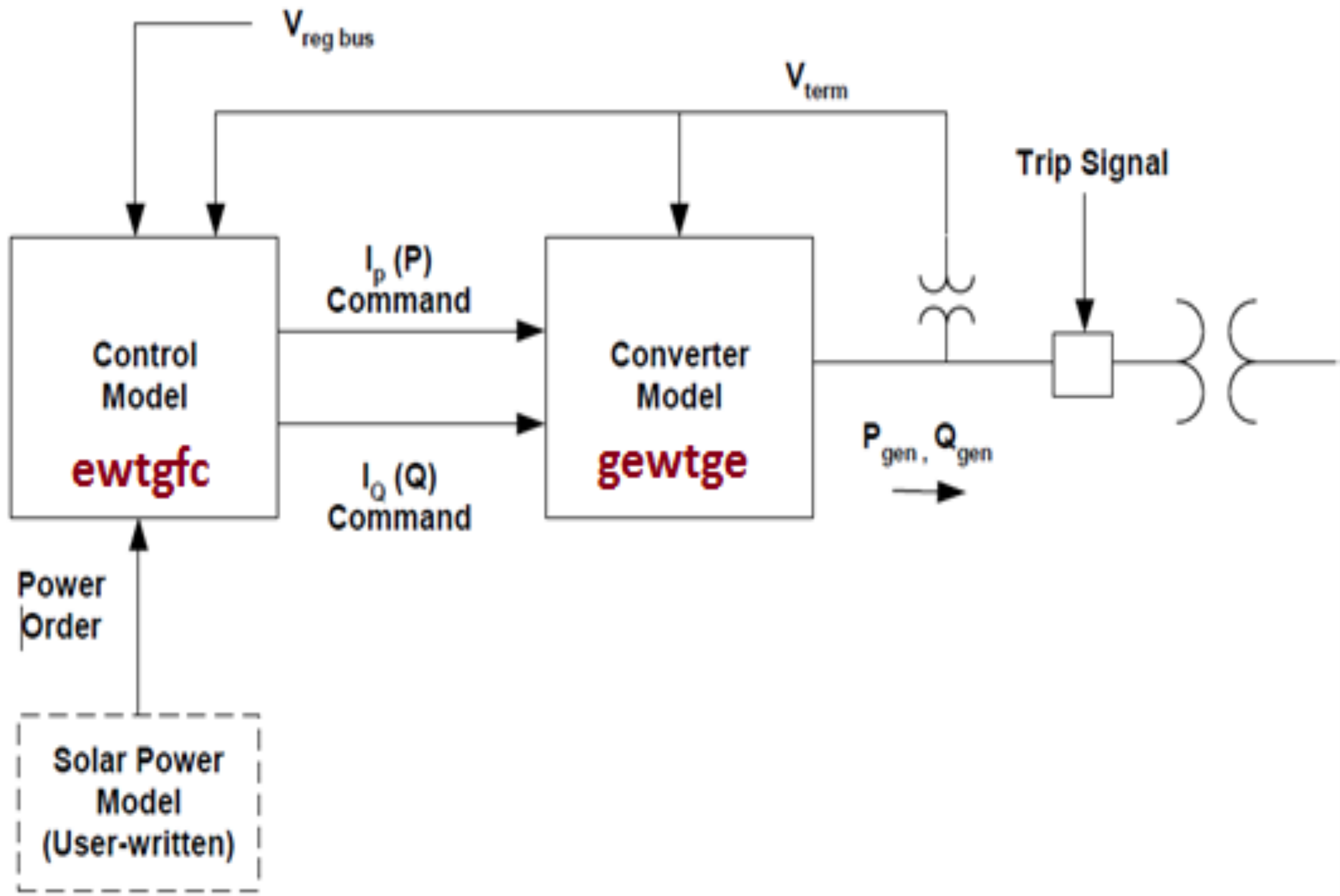


Schematic of Type 4 wind turbine generator

Wind and PV solar grid interface

- Large scale PV solar farms starting at the tens of kW level to the MW level are primarily interconnected to the BES through a power electronic inverter
- Residential roof top PV solar also has an inverter which is capable of control however, present standards force them to operate at unity power factor and do not allow them to control voltage

Wind and PV solar grid interface

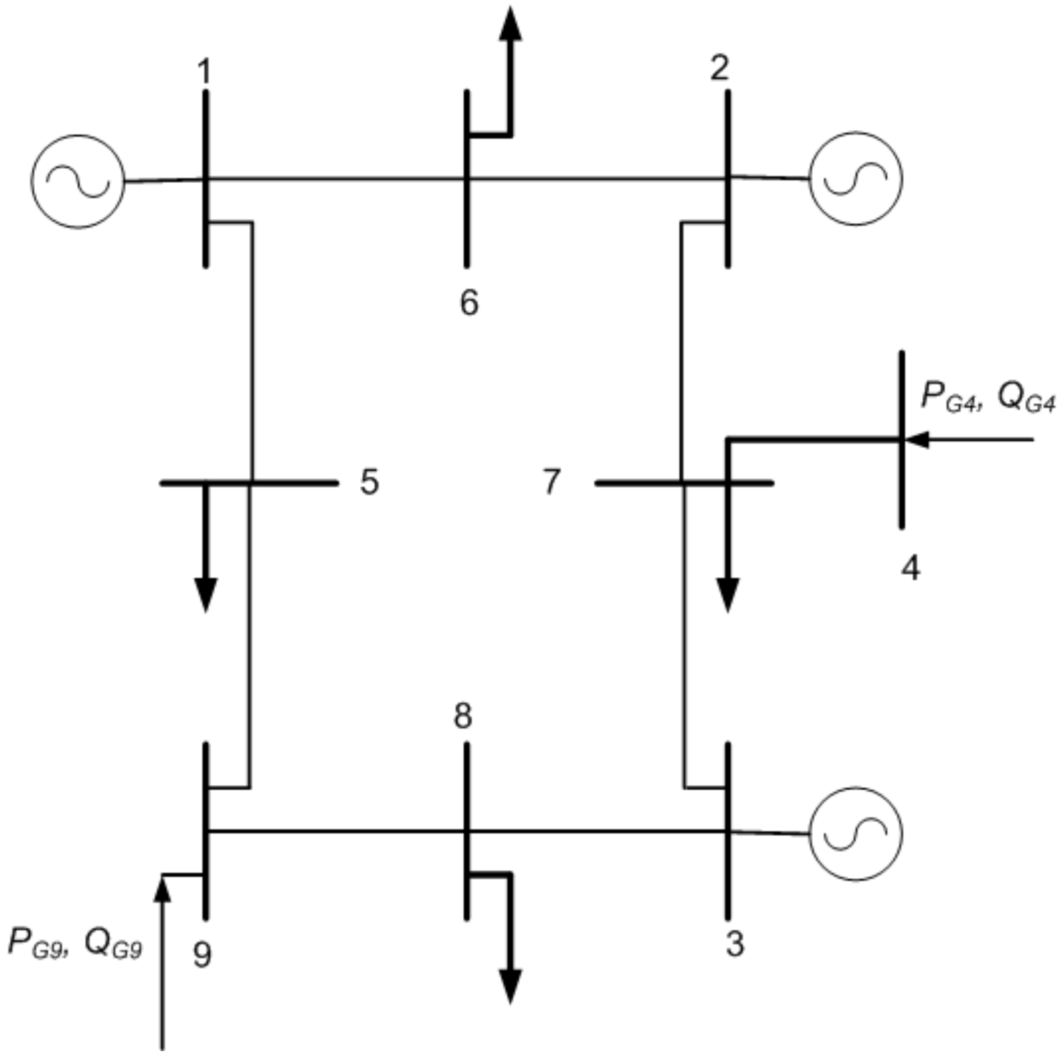


Salient features of wind and PV solar impacts on system dynamic performance

- Since wind turbine generators (WTGs) and PV solar are asynchronous sources they have four mechanisms by which they can affect the electromechanical modes of the **remaining synchronous machines** in a large interconnected power system

  1. **Displacing synchronous machines thereby affecting the modes**
  2. **Impacting major transmission path flows**
  3. **Displacing synchronous machines that have power system stabilizers**
  4. **Interaction with other synchronous machines**

Schematic of asynchronous injection into the grid



Nature of grid injections –steady state

- In the case of wind or PV solar, the injection source (Buses # 4 and 9) would be an asynchronous source and the real and reactive power injection would be controlled by the power electronic inverter
- The **remaining synchronous generators** at steady state would adjust their initial angular positions to account for the injection at Buses #4 and #9.
- The **relative rotor angle difference** between some generators **will increase** and some of them **will decrease**
- The **synchronizing capability** between those generators whose rotor angle difference increases will decrease and will increase for those whose rotor angle difference reduces

Synchronizing capability

- The synchronizing capability between the remaining synchronous machines is a function of the **rotor angles differences**, the **voltages at the terminals of the machines**, the **electrical impedance** between the nodes of the machines, and the **inertia** of the machines

- The asynchronous injections primarily affect the rotor angles differences and to a lesser extent the voltages at the terminal of the machines

Nature of grid interactions – dynamic state

- If the system is now subjected to a disturbance, the disturbance will affect the synchronous generators based on the location of the disturbance and its severity
- If the disturbance is close to generators whose synchronizing capability has reduced due to the two injections then these generators will be affected detrimentally.
- If the disturbance is located close to generators whose synchronizing capability has increased then these generators will not be affected to the same extent

Nature of grid interactions – dynamic state

- Hence depending on the size and location of the injection due to the renewable resources, and the location and severity of the disturbance **certain generators** in the system will be **detrimentally affected** and some generators will be **beneficially affected**

- **Key question** – Is there a systematic approach to determining how the remaining machines are affected?

Approach to identify impact of increased wind penetration

- The electromechanical modes of oscillation in a power systems are largely determined by the **inertia in the system** and the **synchronizing capability**
- With the penetration of DFIGs **no inertia** is provided but a **significant amount of power** is injected in the system which **affects the synchronizing power capability** of the remaining synchronous machines

Approach to identify impact of increased wind penetration

- Replace all the wind turbine with conventional round rotor synchronous generators of the **same MVA rating** which will represent the base case operating scenario for the assessment
- Evaluate the sensitivity of the eigenvalues with respect to inertia (H_j) which is aimed at observing the effect of generator inertia on dynamic performance
- Perform eigenvalue analysis for the case after introducing the existing as well as planned DFIG wind farms in the system

Study system

- The study is carried out in a system with following components
  - Buses = 22050
  - Generators = 3104
  - Lines = 24125
  - Total Generation = 580,611MW
  - Wind Generation = 3359 MW (65 wind farms)
- The increased wind penetration is incorporated in the identified area which has a total installed capacity of 4730.91MW

Scenario description

- **Case A** constitutes the case wherein all the existing DFIGs in the study area are replaced by conventional round rotor synchronous machines (GENROU) of equivalent MVA rating
- The original base case provided with existing DFIGs in the system is referred to as **Case B**
- **Case C** constitutes the case wherein the penetration of DFIG based WTGs in the study area is increased by 915 MW. The load in the study area is increased by 2% (predicted load growth) and rest of the generation increase is exported to a designated nearby area
- **Case D** constitutes the case wherein the DFIG wind farms with the increased wind penetration are replaced by GENROU of corresponding MVA rating. Thus, in Case D the GENROU machines representing the WTGs are of higher MVA rating than in Case A

Analysis of Case A

- Among the several modes of oscillation analyzed, the result of sensitivity analysis associated with the mode having significant detrimental real part sensitivity, in comparison to the real part of the eigenvalue is shown below

DOMINANT MODE WITH DETRIMENTAL EFFECT ON DAMPING

Real Part (1/s)	Imaginary Part (rad/s)	Frequency (Hz)	Damping Ratio (%)
-0.0643	3.5177	0.5599	1.83

Analysis of Case A

EIGEN VALUE SENSITIVITY CORRESPONDING TO THE DOMINANT MODE WITH DETRIMENTAL EFFECT ON DAMPING

No.	Generator Bus #	Base Value of Inertia (s)	Sensitivity of Real Part ($1/s^2$)
1	32672	2.627	-0.0777
2	32644	5.7334	-0.0355
3	32702	3	-0.0679
4	32723	5.548	-0.0367
5	49045	5.2	-0.0383
6	49050	4.6	-0.0444
7	49075	4.2	-0.0475
8	52001	5.2039	-0.0389
9	55612	3.46	-0.0581
10	55678	4.3	-0.0467
11	55881	4	-0.0506
12	55891	4.418	-0.0466
13	55890	5.43	-0.037
14	55889	5.43	-0.0374

Analysis of Case A

- Among the several modes of oscillation analyzed, the result of sensitivity analysis associated with the mode having significant beneficial real part sensitivity, in comparison to the real part of the eigenvalue is shown below

DOMINANT MODE WITH BENEFICIAL EFFECT ON DAMPING

Real Part (1/s)	Imaginary Part (rad/s)	Frequency (Hz)	Damping Ratio (%)
-0.0651	2.8291	0.4503	2.3

Analysis of Case A

EIGEN VALUE SENSITIVITY CORRESPONDING TO THE DOMINANT MODE WITH BENEFICIAL EFFECT ON DAMPING

No.	Generator Bus #	Base Value of Inertia(s)	Sensitivity of Real Part ($1/s^2$)
1	32672	2.627	0.0169
2	32644	5.7334	0.0078
3	32702	3	0.015
4	32723	5.548	0.008
5	49045	5.2	0.0075
6	49050	4.6	0.0092
7	49075	4.2	0.0104
8	52001	5.2039	0.0079
9	55612	3.46	0.0125
10	55678	4.3	0.0098
11	55881	4	0.0107
12	55891	4.418	0.0095
13	55890	5.43	0.0082
14	55889	5.43	0.008

Eigenvalue analysis

RESULT SUMMARY FOR CASES A, B, C AND D FOR DOMINANT MODE WITH DETRIMENTAL EFFECT ON DAMPING

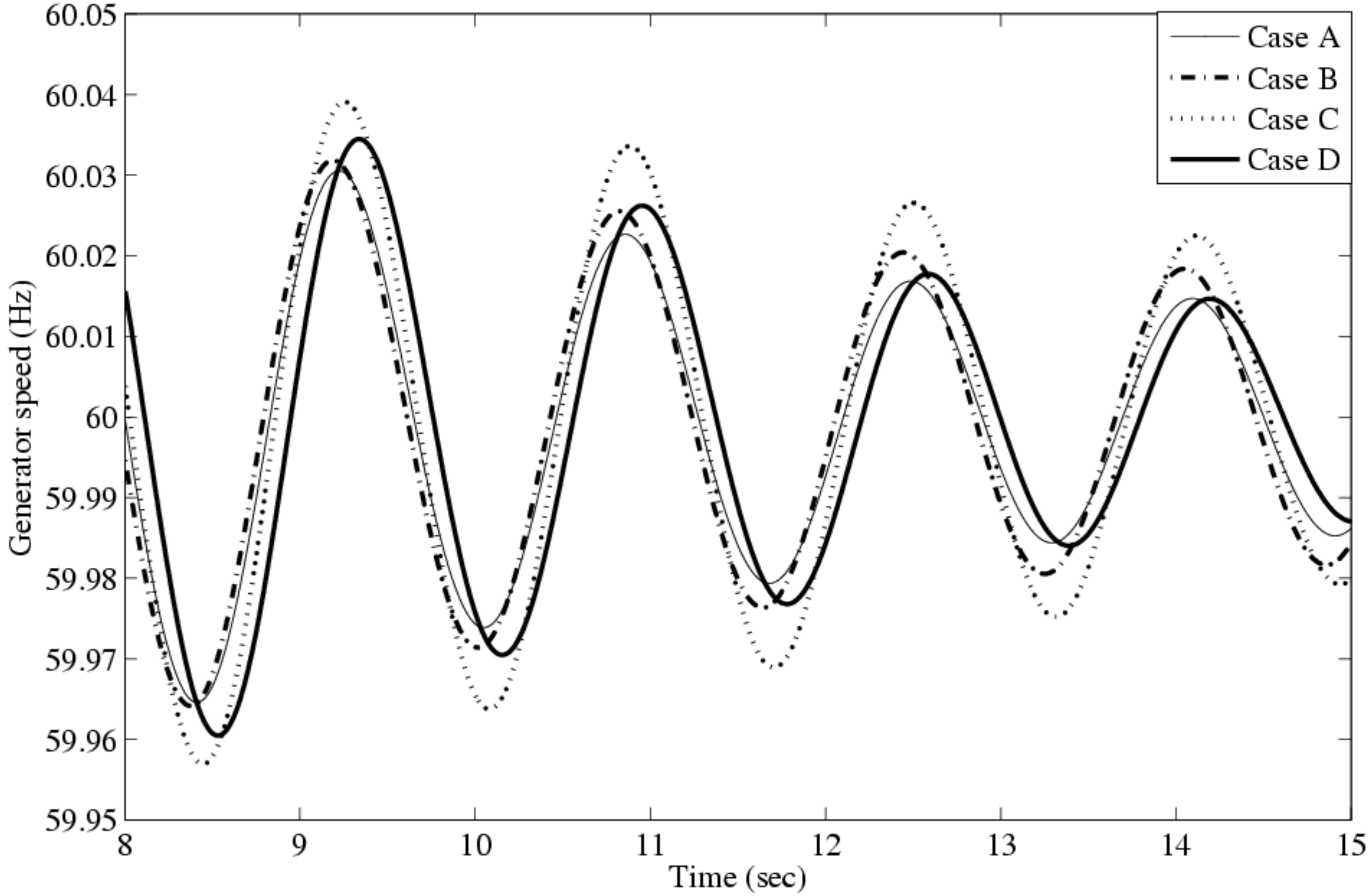
Case	Real	Imaginary	Frequency (Hz)	Damping Ratio (%)	Dominant Machine
A	-0.0643	3.5177	0.5599	1.83	33232
B	-0.0412	3.5516	0.5653	1.16	33232
C	-0.0239	3.5238	0.5608	0.68	33232
D	-0.0427	3.4948	0.5562	1.22	33232

Eigenvalue analysis

RESULT SUMMARY FOR CASES A, B, C AND D FOR THE DOMINANT MODE WITH BENEFICIAL EFFECT ON DAMPING

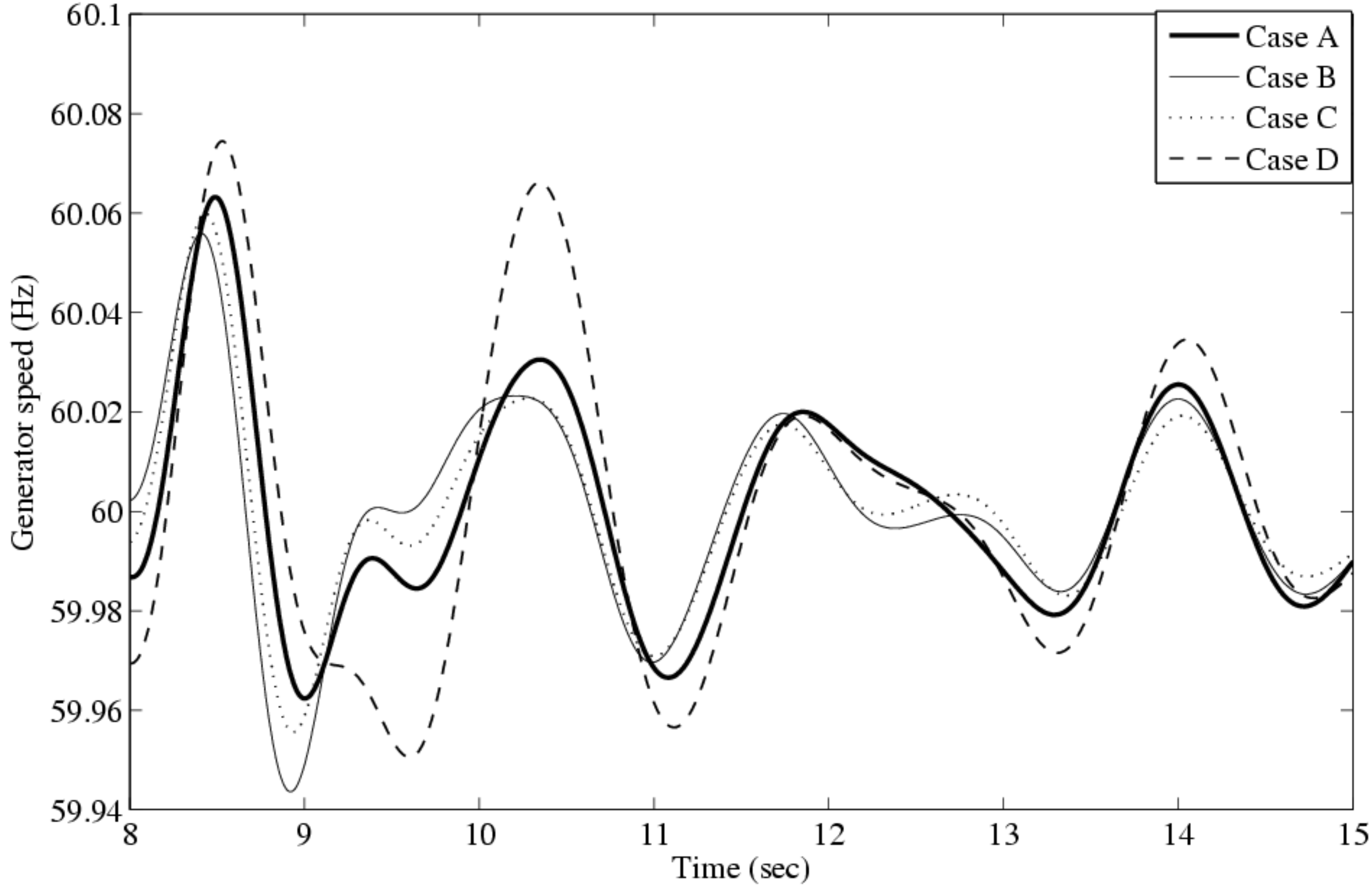
Case	Real	Imaginary	frequency (Hz)	Damping Ratio (%)	Dominant Machine
A	-0.0651	2.8291	0.4503	2.3	42037
B	-0.0725	2.8399	0.452	2.55	33216
C	-0.0756	2.8189	0.4486	2.68	42037
D	-0.0566	2.805	0.4464	2.02	42037

Nonlinear time domain analysis – detrimental effect



Generator speed for bus 32527 for the Cases A, B, C and D

Nonlinear time domain analysis – beneficial effect



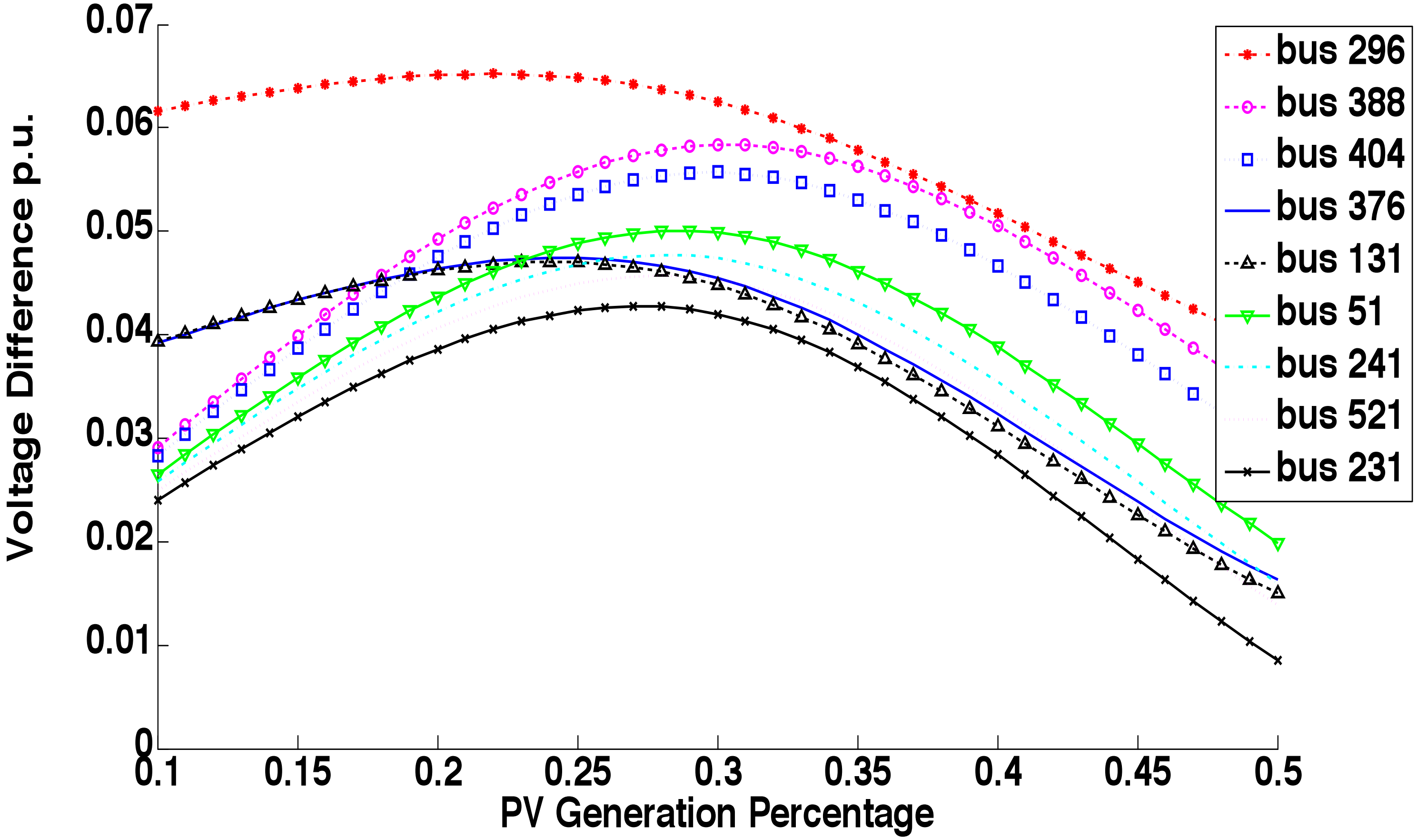
Generator speed for bus 33216 for the Cases A, B, C and D

Impact of increased PV solar presentation

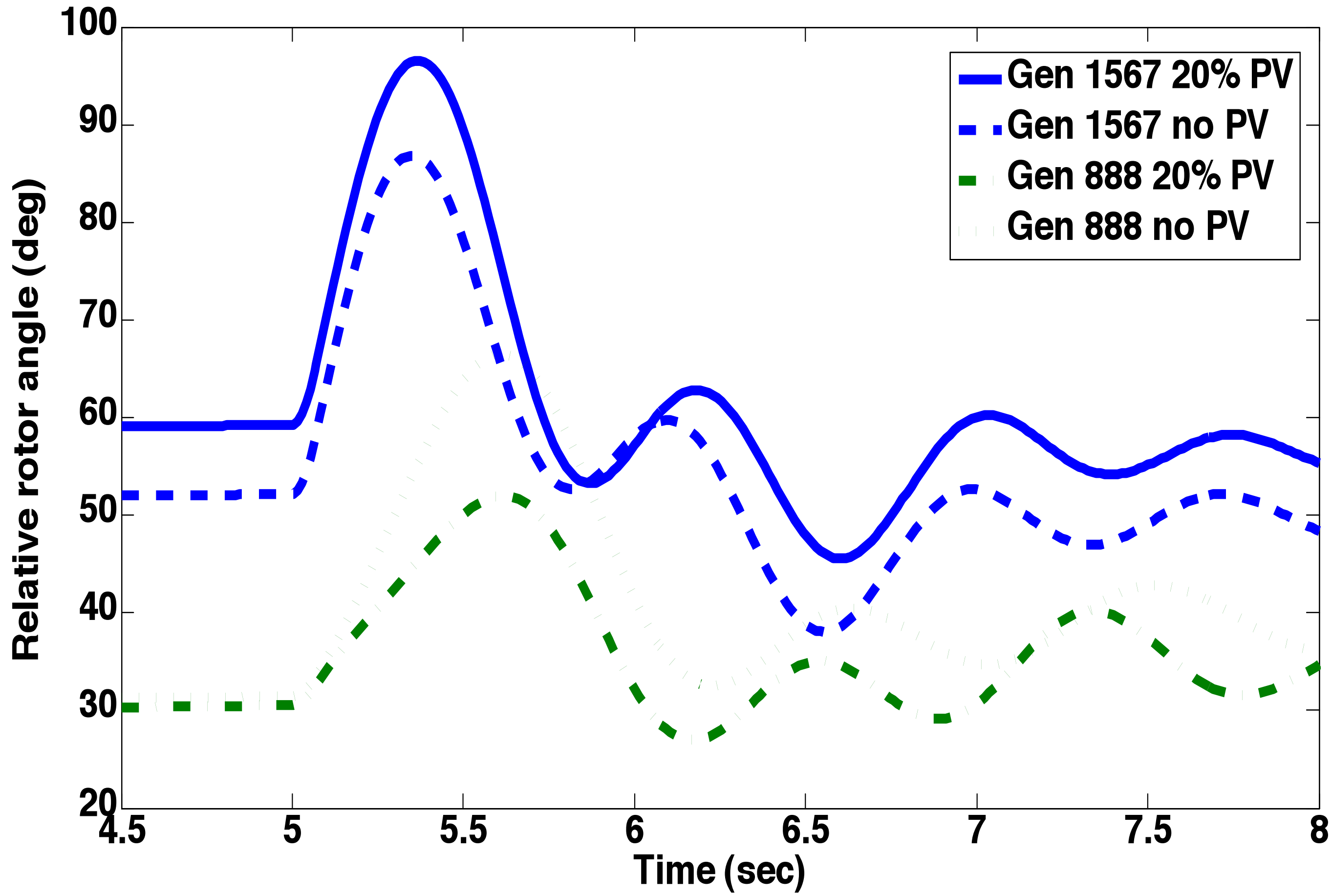
Summary of the Studied Area

Total Load	**MW**	**13276.82**
	MVAr	**2187.90**
Total Generation	**MW**	**21571.03**
	MVAr	**2238.72**
Total Export	**MW**	**7650.83**
	MVAr	**63.4**
Total Losses	**MW**	**607.82**
Total Number of Gen.		**226**
Total Number of Buses		**2419**
Total Number of Lines		**1861**

Steady state voltage impact

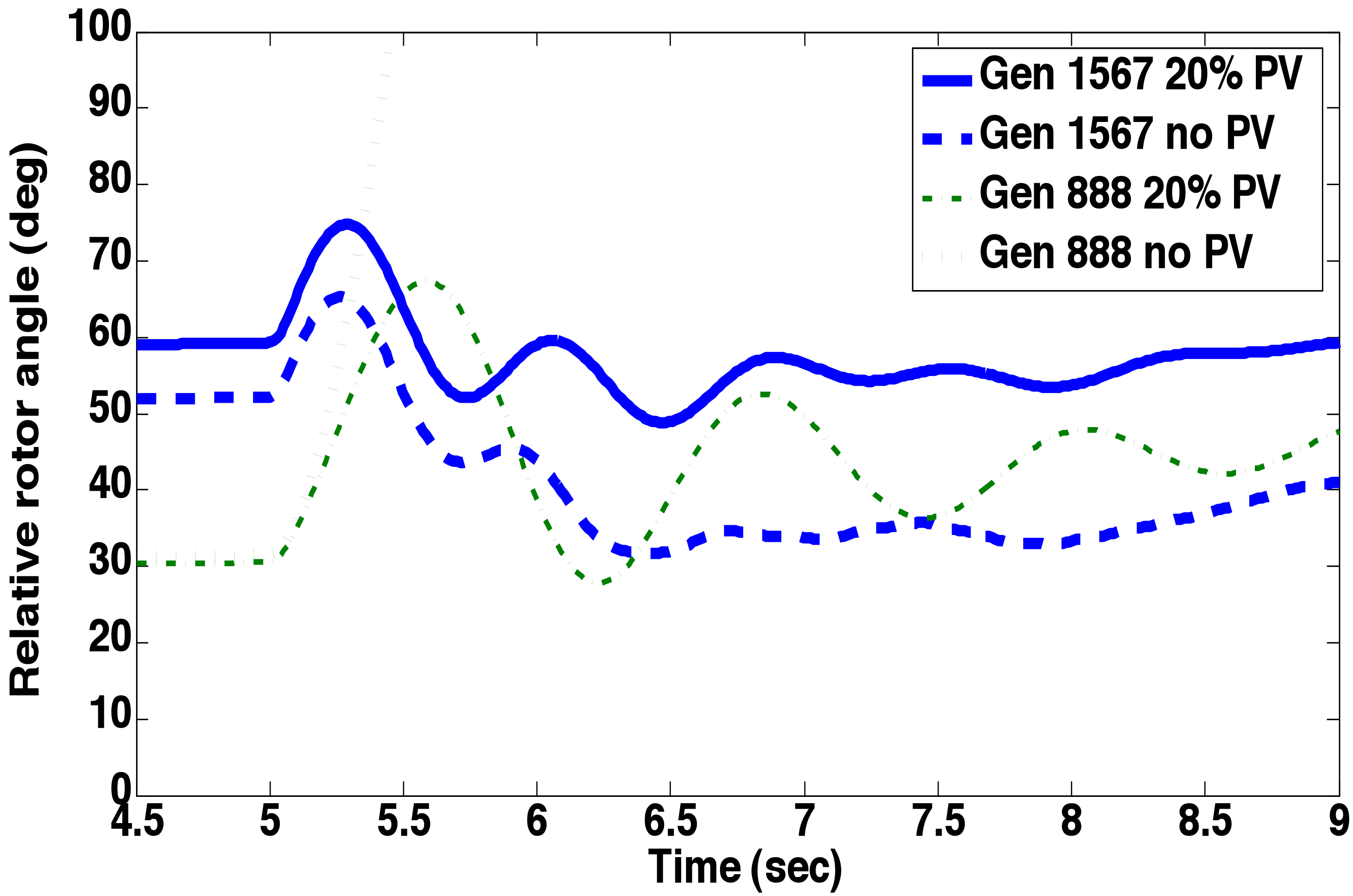


Transient rotor angle stability



Relative rotor angles of the generators 1567 and 888 following the fault at bus 1001

Transient rotor angle stability



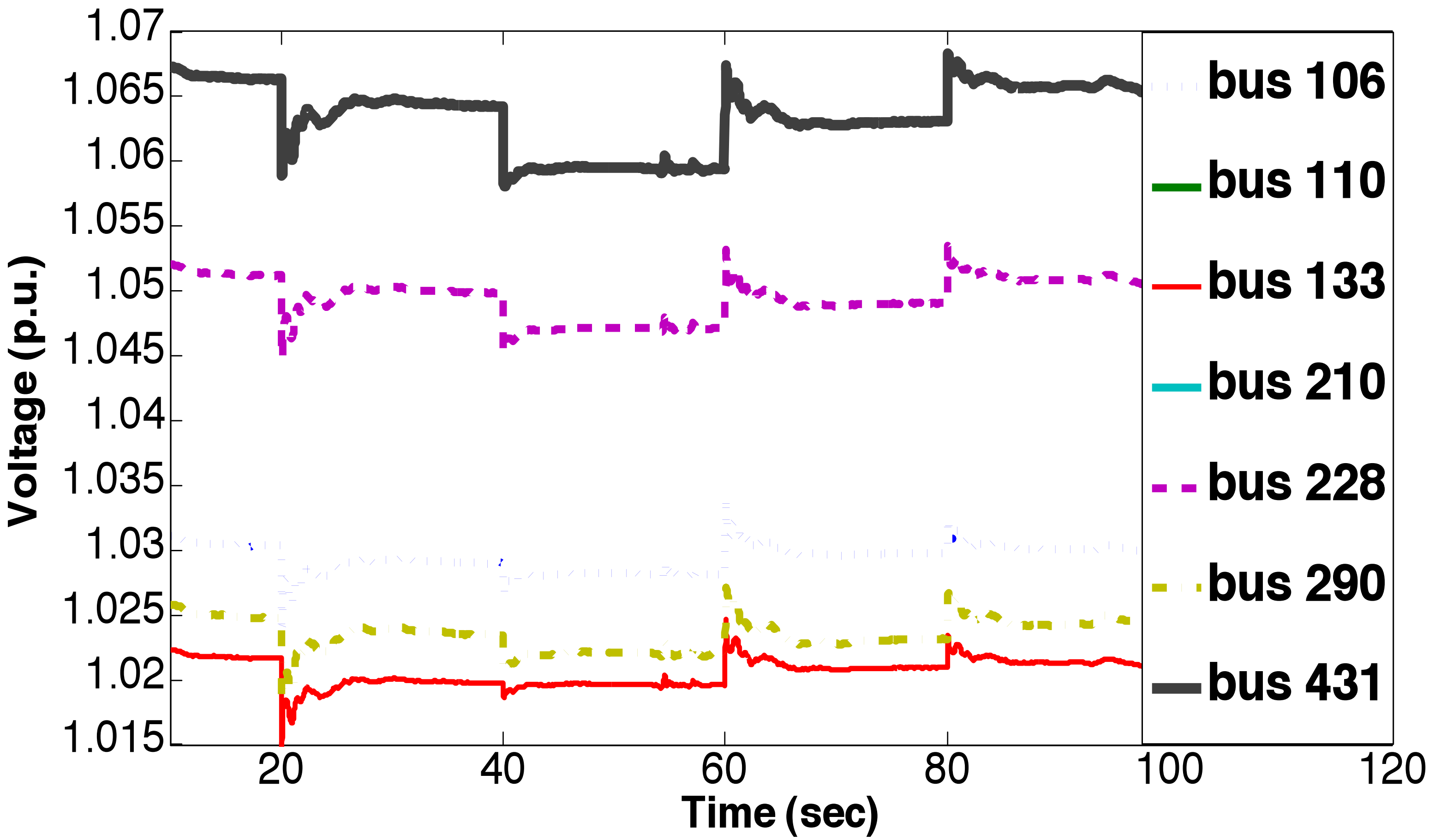
Relative rotor angles of the generators 1567 and 888 following the fault at bus 1164

Disturbance due to cloud cover

Moving cloud across the valley:

- Residential roof top PVs are dropped due to the cloud cover
- Output of the PVs are reduced to 50% of the nominal values
- A case with 20% PV generation is simulated in DSATools

Disturbance due to cloud cover



Voltages of the 69 kV buses due to cloud cover

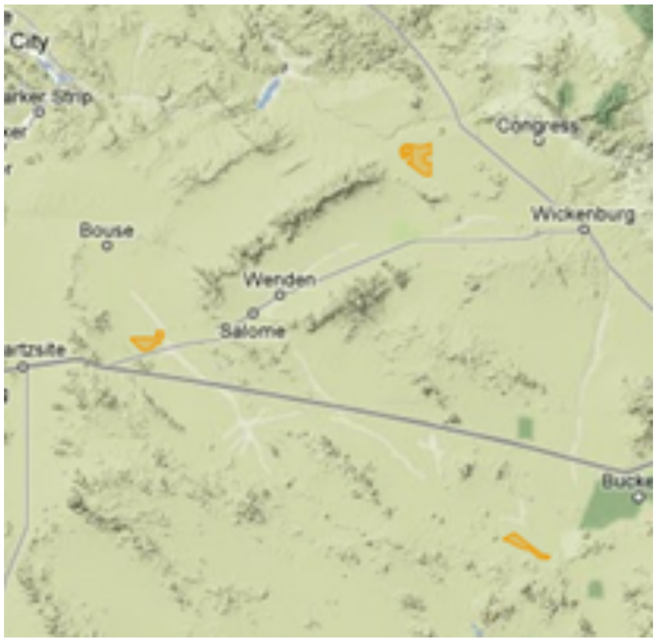
Impact on frequency

- In the case of frequency response due to loss of generation or load the lack of inertia due to increased penetration of wind or solar generation could have an impact because these sources have no inertia
- Inertia can be emulated in power electronic inverters. However, the inertia support provided by these features is limited
- It is important to note that with increased penetration of wind and solar the reliability requirements also require a certain amount of active spinning reserve which are typically conventional synchronous machines and as a result they pick up the loss of generation and control frequency

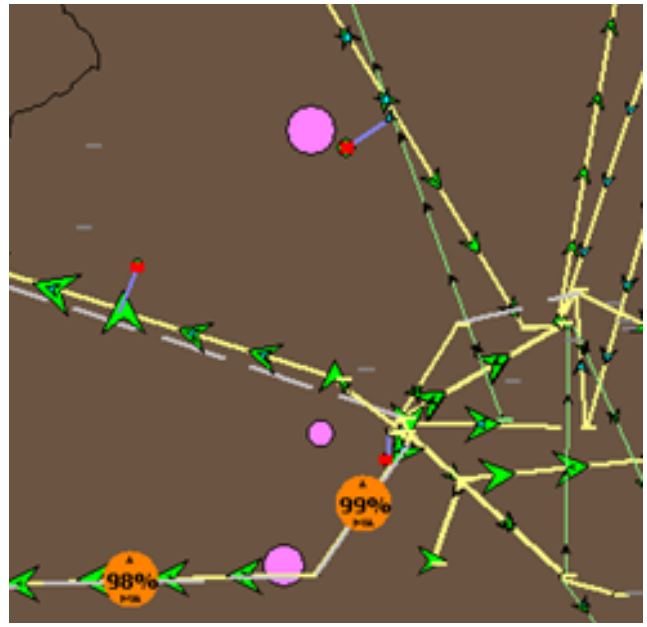
Other activities at ASU

- Project funded by the Science Foundation of Arizona
- Looking at siting of solar resources and evaluating economic feasibility
- Use of several GIS databases and the PowerWorld tool to conduct initial feasibility of siting
- Also implementing a stochastic power flow to account for variability of solar generation and load
- Co-Investigators – G.T. Heydt and R. Ayyanar

Other activities at ASU



The GIS screen



The PowerWorld screen. (The three plants in red are solar plants)

Other activities at ASU

- Long term transmission planning with increased penetration of wind and solar in the WECC – DOE FOA68
- Team consists of ASU, WSU, CSM and the WECC
- Co-Investigators, G.T. Heydt, R. Gorur, A. Bose, R. Olsen, S. Suryanarayanan
- Examining new transmission expansion planning tools and also conducting detailed studies of plans
- New transmission line designs to improve capability and viability of HVDC

Other activities at ASU

- NSF Cyber Physical Systems initiative award
- Examining impact of variable renewable resources on power system performance
- Considered historical wind data from an actual wind farm in Colorado
- Developed a spatio-temporal finite stae Markov Chain model for wind forecast
- Have developed a stochastic optimization based short term scheduling algorithm with demand side management
- Co-Investigator Junshan Zhang

Other activities at ASU

PSERC

- Modeling and analysis of a 12 kV feeder in Flagstaff, Arizona with commercial PV and significant amount of roof top PV
- At low loads PV represents 40% of the injection in the feeder
- Joint effort with APS and GE sponsored by DOE
- Co-Investigators R. Ayyanar and G.T. Heydt

Conclusions

- Increased penetration of wind and PV solar resources affect dynamic performance of the system depending on where these resources are connected to the system and the amount of power they inject into the system
- Some conventional generators in the system will be detrimentally affected and some will be beneficially affected
- This impact can be systematically determined and pin pointed
- Since these resources are interfaced using power electronic components they have the ability to provide fast control
- If these resources do not have the same rating as a conventional unit their ability to respond to disturbances could be limited