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Impact of Increased Penetration of DFIG based Wind Turbine Generators on Transient and Small Signal Stability of Power Systems

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Project team - Investigators

- V. Vittal - ASU
- J.D. McCalley - ISU
- V. Ajjarapu - ISU
- V. Shanbhag – UIUC

Project team – Industry advisors

- Ali Chowdhury – CAISO
- Terry Harbour – MidAmerican Energy
- Nicholas Miller – GE
- Mark Sanford – GE
- Jinan Huang – IREQ
- Dale Osborn – MISO
- LaMonte Reynolds – ITC
- David Schooley - Exelon

Main topics investigated

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Impact of increased penetration of DFIGs on:

- Transient stability and small signal stability – V. Vittal, ASU
- Frequency stability – J. McCalley, ISU
- Voltage stability – V. Ajjarapu, ISU
- Market impacts and market mechanisms – V. Shanbhag, UIUC

Students who worked on this project

- Durga Gautam – ASU
- Shuyang Zhang – ISU
- Pradip Vijayan – ISU
- Ryan Kopinski – ISU
- Eknath Vittal – ISU
- Subhadarshi Sarkar - ISU
- DeeAnne Zhang – UIUC
- Aswin Kannan – UIUC
- Siddhartha Khaitan (post-doc) - ISU

DFIG wind turbines

- DFIGs are variable speed wind turbines
- Hence they provide a constant frequency electrical output for varying wind speeds
- This is accomplished by power electronics

DFIG wind turbine

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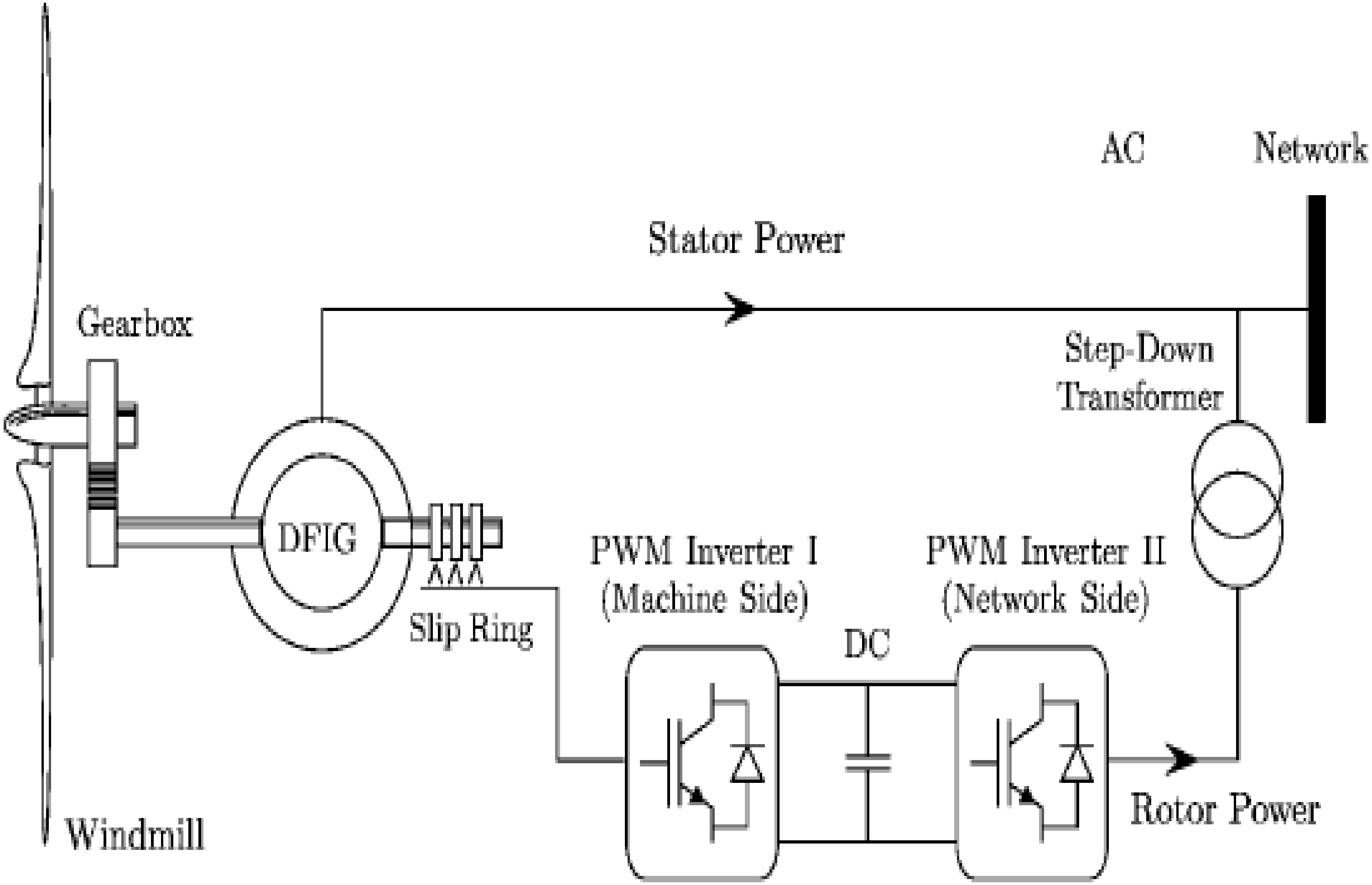


DFIG wind turbine

- The system, shown on the previous slide, consists of a wind turbine with doubly-fed induction generator
- This means that the stator is directly connected to the grid while the rotor winding is connected via slip rings to a converter
- The power electronic converter only has to handle a fraction (20–30%) of the total power

DFIG wind turbine

- For variable-speed systems with limited variable-speed range, e.g.   30% of synchronous speed, the DFIG can be an effective solution
- The power electronic converter only has to handle a fraction(20–30%) of the total power
- The losses in the power electronic converter can be reduced in comparison to a case where it has to handle the total power
- This also reduces the cost of the converter

DFIG wind turbine

- The back-to-back converter consists of two converters, i.e., machine-side converter and grid-side converter, that are connected “back-to-back”
- Between the two converters a dc-link capacitor is placed, as energy storage, in order to keep the voltage variations (or ripple) in the dc-link voltage small
- With the machine-side converter it is possible to control the torque or the speed of the DFIG and also the power factor at the stator terminals, while the main objective for the grid-side converter is to keep the dc-link voltage constant

Basic premise

- Since DFIG based wind turbine generators (WTGs) are asynchronous machines they have four mechanisms by which they can affect the electromechanical modes 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**

Basic premise

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

Objective

- Given this basic premise our goal is to develop a **<u>systematic approach</u>** to quantify how the penetration of DFIG WTGs will impact small signal stability and transient stability of power systems
- To analyze this we have considered a large portion of the Midwestern US where there is very heavy increase in wind penetration

Basis of the study – Small signal stability

- The basis of this study lies on the premise that with the penetration of DFIG based wind farms the effective inertia of the system will be reduced, coupled with additional power injection into the system
- In this regard, a first step proposed towards studying the system behavior with increased DFIG penetration is to identify how the small signal stability behavior changes with the change in inertia

Basis of the study – Small signal stability

- The approach is thus intended to evaluate eigenvalue sensitivity with respect to generator inertia
- The eigenvalue sensitivity with respect to inertia can be expressed as

$$\frac{d\lambda_i}{dH_j} = \frac{w_i \dfrac{\partial A}{\partial H_j} v_i^T}{w_i^T v_i}$$

where,

H_j is the inertia of j^{th} generator

$\underline{\lambda_i}$ is the i^{th} eigenvalue

w_i and v_i is the left and right eigenvector corresponding to i^{th} eigenvalue respectively

Basis of the study – Small signal stability

- The key to the proposed analysis is to examine the **sensitivity with respect to inertia** and identify which modes are affected in a detrimental fashion and which modes are benefitted by the increased DFIG penetration

- The inertia sensitivity is **only conducted** for the cases where **all machines are synchronous machines**

Key steps

- Replace all the DFIGs with conventional synchronous generators of the **same MVA rating** which will represent the base case operating scenario for the assessment
- Perform eigenvalue analysis in the frequency range: 0.1 to 2 Hz and damping ratio below 2.5%
- 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

Study system

- A total of 14 wind farms with total installed capacity of 1460MW are modeled as DFIGs which constitutes the wind farms within and very close to the identified area
- The standard DFIG model used for present work has following ratings :
  - The steady-state power output is 1.5 MW
  - MVA rating of each unit is 1.67 MVA
  - The reactive power capability of each unit is +0.95/-0.90 pf
  - This corresponds to $Q_{max} = 0.49$ MVAr and $Q_{min} = -0.73$ MVAr

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 for CASE A

- The analysis is carried out for **Case A**, for all modes in a range of frequencies from 0.1Hz to 2Hz
- As the stability of a mode is determined by the real part of eigenvalue, the sensitivity of the real part is examined and the mode which has the **largest real part sensitivity to change in inertia** is identified

Analysis for 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

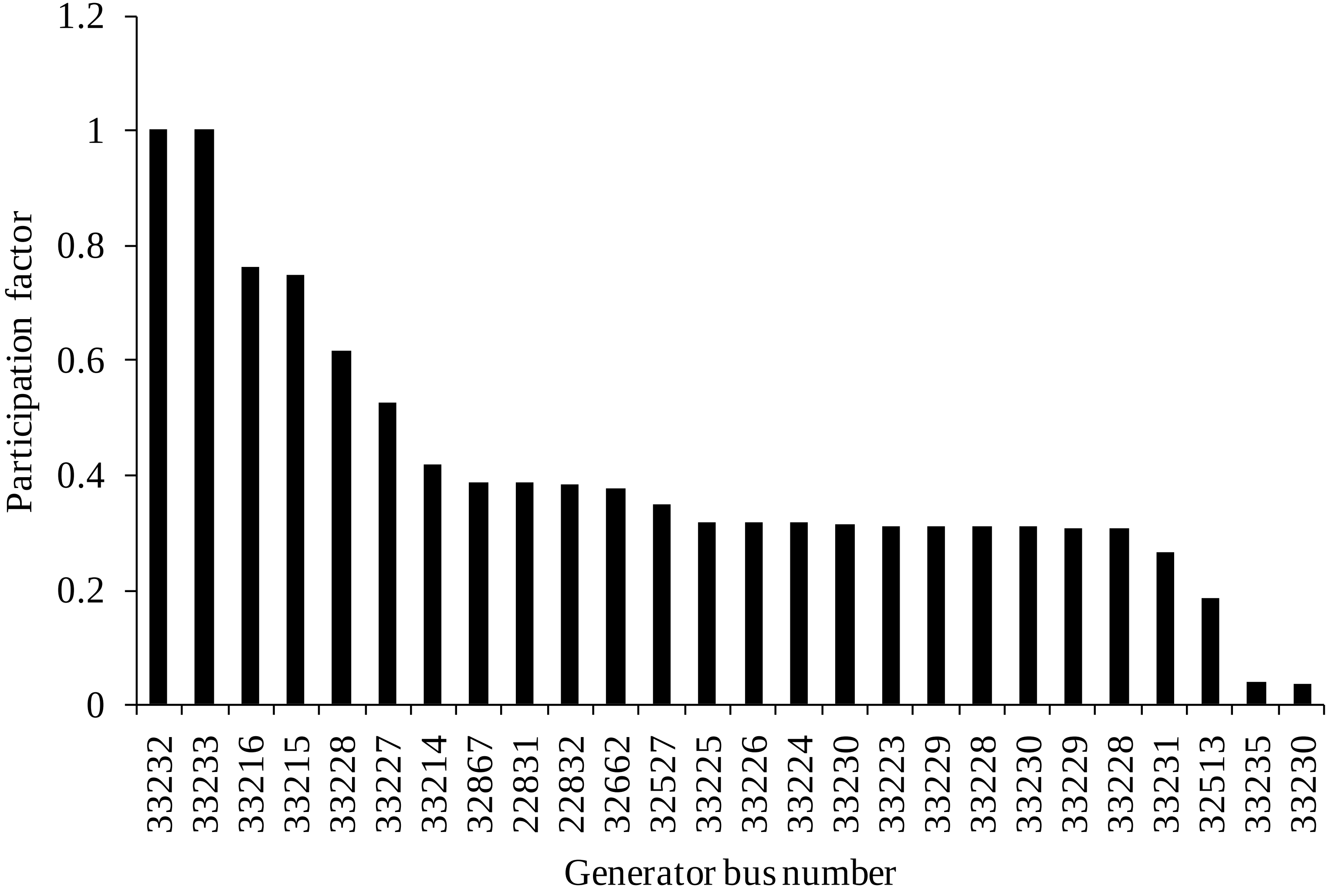
Real Part (1/s)	Imaginary Part (rad/s)	Frequency (Hz)	Damping Ratio (%)
-0.0643	3.5177	0.5599	1.83

Analysis for 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 for CASE A



Participation factor corresponding to the generator speed state for the dominant mode with detrimental effect on damping

Analysis for 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

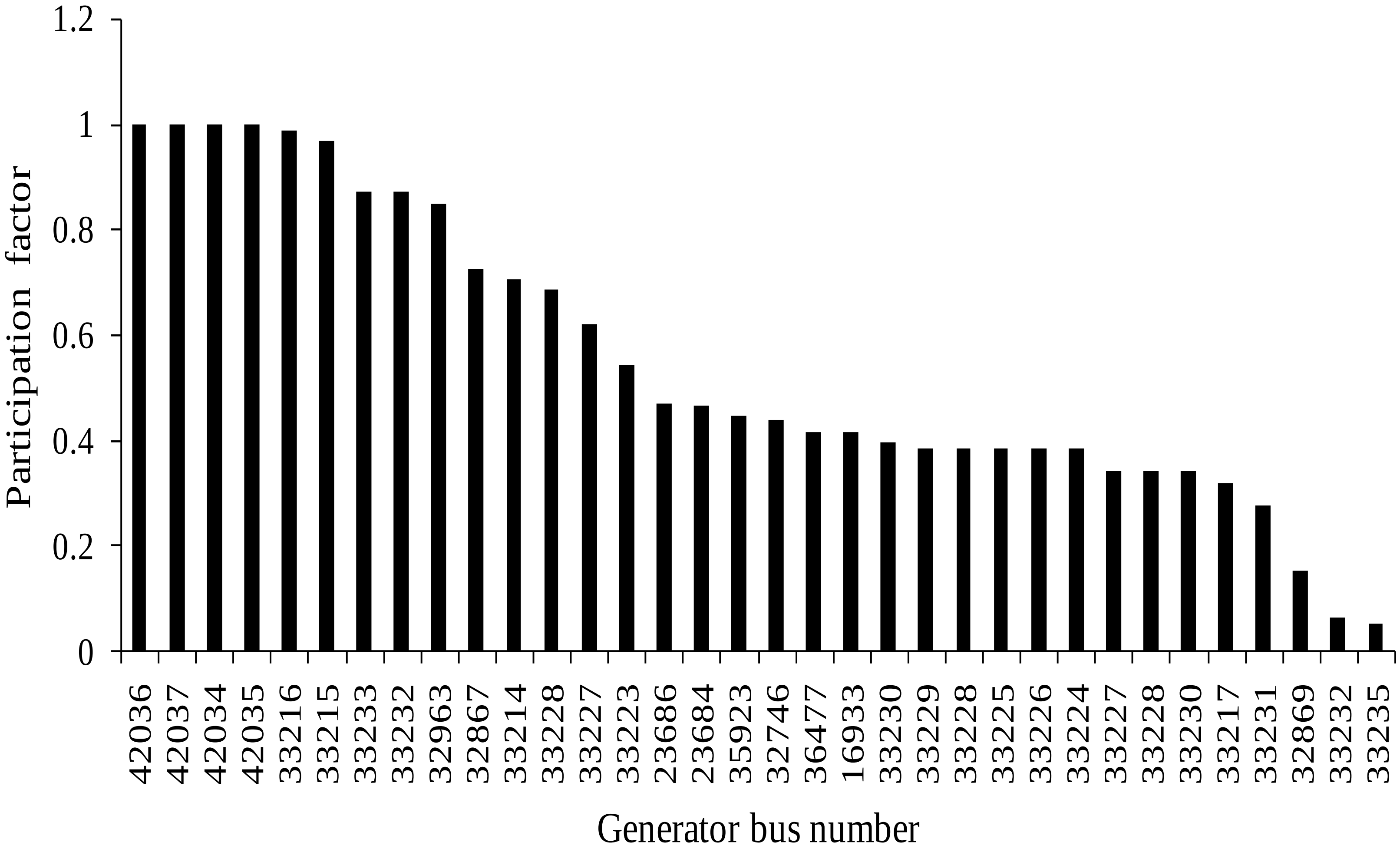
Real Part (1/s)	Imaginary Part (rad/s)	Frequency (Hz)	Damping Ratio (%)
-0.0651	2.8291	0.4503	2.3

Analysis for 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

Analysis for CASE A



Participation factor corresponding to the generator speed state for the dominant mode with beneficial effect on damping

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

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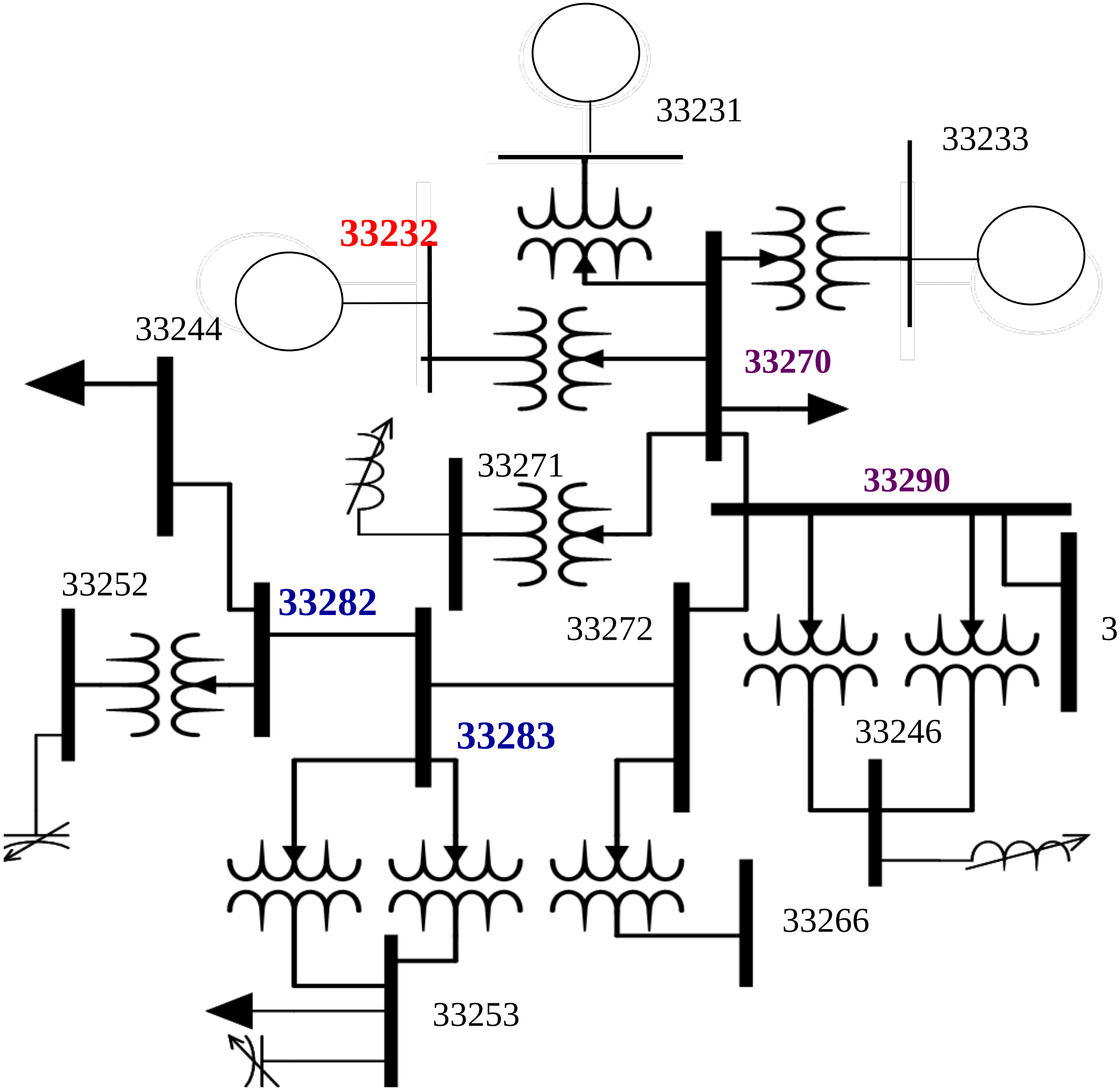
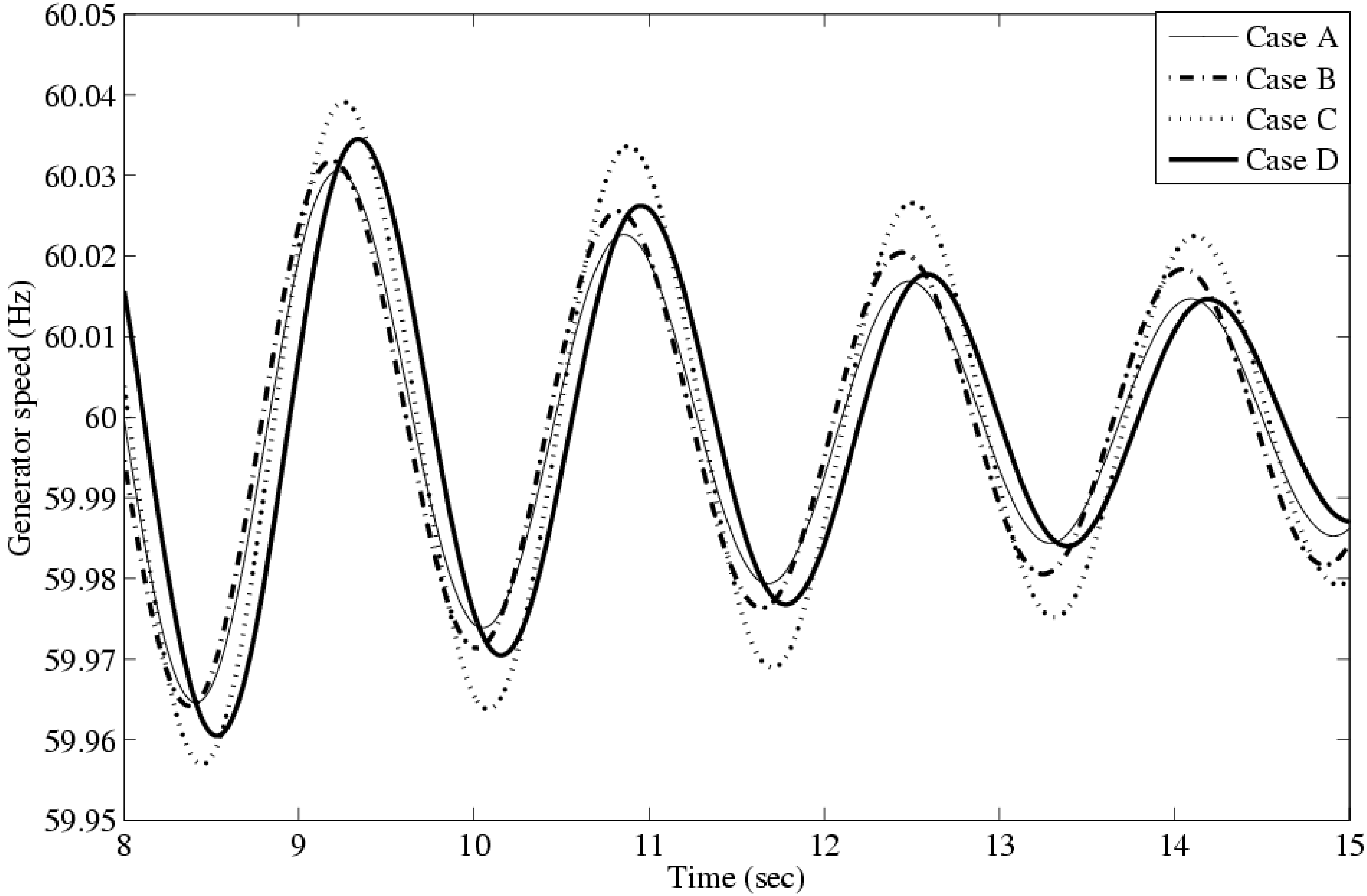
RESULT SUMMARY FOR CASES A, B, C AND D FOR THE DOMINANT MODE WITH BENEFICIAL EFFECT ON DAMPING

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

Exciting the modes via disturbances – detrimental effect



Time domain comparison – Detrimental effect



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

Time domain comparison – Beneficial effect

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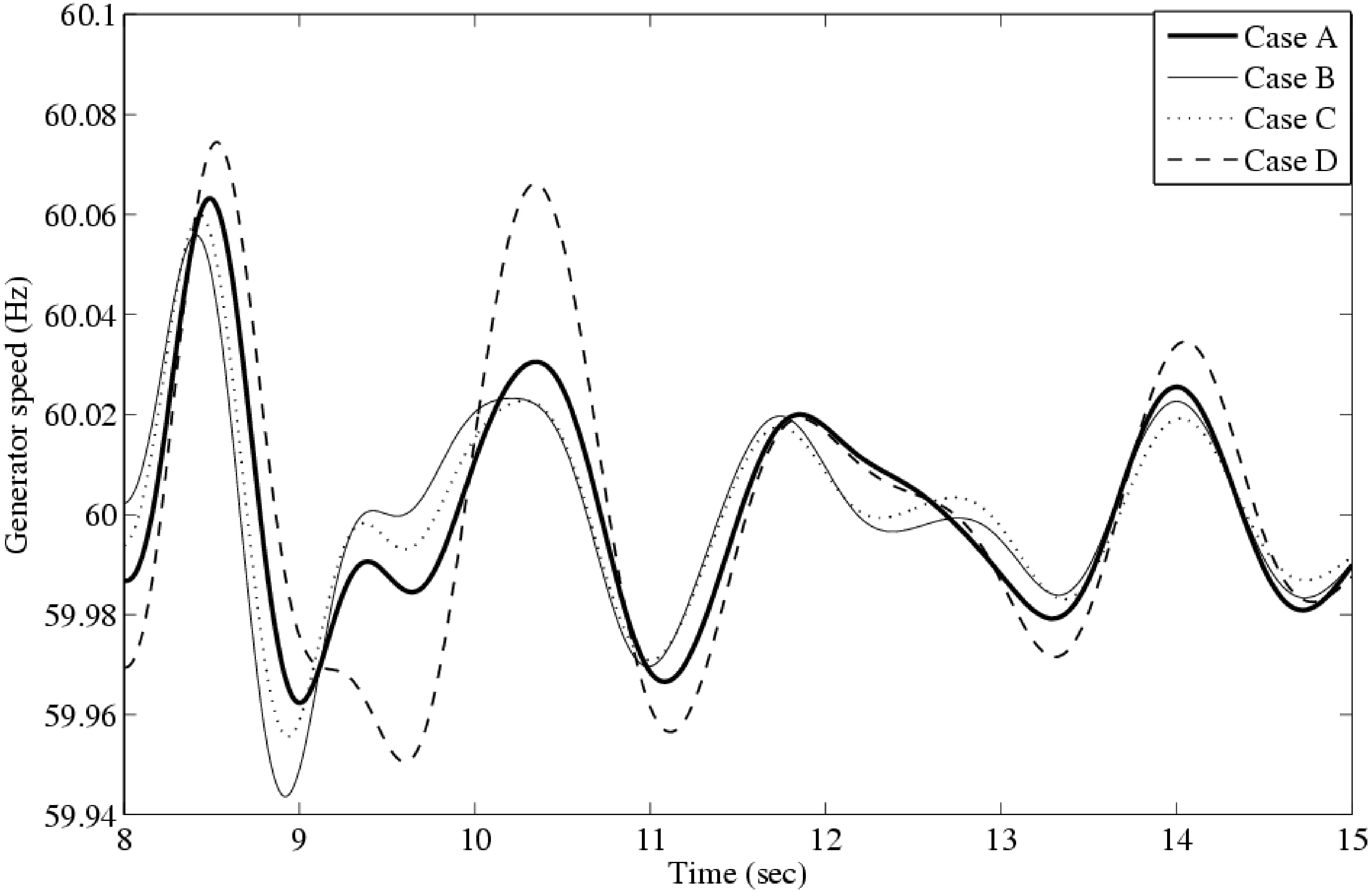

Generator speed for bus 33216 for the Cases A, B, C and D

Conclusions

- The approach developed can pin-point both the detrimental impact and beneficial impact of increased penetration of DFIGs in the system
- The combination of small-signal stability analysis coupled with the large disturbance analysis of exciting the mode identified provides a detailed picture of the impact on the system
- The next step is to determine appropriate control techniques to mitigate the impact of the detrimental effects due to increased DFIG penetration

Work since the project finished

- We leveraged the PSERC work to develop an NSF proposal which was funded
- We have been working on supplementary controls that mimic the effect of inertia in DFIGs
- We have tested our ideas on the same system
- Significant improvement in damping of the critical modes and in improved system performance is observed

Thank you.

Any questions?