Technical and environmental impact of integrating distributed generation with electric grid and microgrid

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Outline

- Introduction to EECS@WSU
- Future Power Grid
- Distributed Generation and Microgrid
  - Introduction
  - Modeling and Simulation of DG and Microgrid
  - Real Time Simulation
  - Optimal Siting and Sizing of DG
  - System Stability Analysis with DG
  - Economic and Environmental analysis
- Summary
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Introduction to EECS@WSU

- @WSU: Total enrollment of 25,996 students (September, 2010)
- @EECS: A total of 39 faculty members, 157 graduate students and 665 undergraduates (September, 2010)
- @EECS: Prioritized focus area includes
  - ECE: Electric power/energy, Microelectronics, Systems and controls
  - CS: AI/Smart environments, Distributed and networked systems, Bioinformatics
- @Power: 8 current power engineering (direct or applied research) faculty with close to 30 graduate students
Introduction to Power Engineering @WSU

• Anjan Bose, Regents Professor, Power Engineering
• Robert Olsen, Professor & Assoc Dean, High Voltage and Transmission
• Mani Venkatasubramanian, Professor, Power Engineering
• Luis Perez, Associate Professor, Power Engineering
• Dave Bakken, Associate Professor, Distributed Computing
• Carl Hauser, Associate Professor, Communication
• Sandip Roy, Associate Professor, Control
• Anurag Srivastava, Assistant Professor, Power Engineering

Two vacancies
Introduction to Power Engineering @WSU

Research Projects:

• Gridstat Project, communication for smart grid and TCIPG project with UIUC (DoE: $18M)
• Real Time Smart Grid Simulation ($2M, DoE)
• Smart Grid Investment Grant (with Avista, Snohomish PUD, WECC, PG&E and Entergy)
• Smart Grid Demonstration (with Avista)
• Smart Grid Planning (with WECC/ASU/CSM)
• Smart Grid Training Grant ($2.5M with several utilities)
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Future Power Grid

Employ technologies to make present grid more reliable, secure, efficient and economical.
Future Power Grid

SMART GRID
A vision for the future — a network of integrated microgrids that can monitor and heal itself.

- Smart appliances: Can shut off in response to frequency fluctuations.
- Demand management: Use can be shifted to off-peak times to save money.
- Storage: Energy generated at off-peak times could be stored in batteries for later use.
- Generators: Energy from small generators and solar panels can reduce overall demand on the grid.
- Sensors: Detect fluctuations and disturbances, and can signal for areas to be isolated.
- Processors: Execute special protection schemes in microseconds.
**Energy Independence and Security Act of 2007**

Characteristics of a Smart Grid as described by Title XIII of the Energy Independence and Security Act of 2007:

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased use of digital information and control</td>
<td>Dynamic optimization of grid operations and resources</td>
</tr>
<tr>
<td>Deployment and integration of distributed resources and generation</td>
<td>Cyber-security;</td>
</tr>
<tr>
<td>Deployment of “smart” real-time, automated, interactive technologies</td>
<td>Development and incorporation of demand response,</td>
</tr>
<tr>
<td></td>
<td>Energy efficiency resources;</td>
</tr>
<tr>
<td></td>
<td>Deployment and integration of advanced electricity storage</td>
</tr>
<tr>
<td></td>
<td>Peak-shaving technologies, including plug-in electric and hybrid electric vehicles,</td>
</tr>
</tbody>
</table>
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DG and Microgrids

Distributed Generation

• Decentralizing small generating units generally near load centre.
• Most commonly used technologies include wind turbines, photovoltaic, fuel cell and biomass powered generators.
• Usually ranges from 10kW to 50MW.

Microgrid

• Interconnection of distributed generation integrated with storage devices
• Providing energy to local loads in low voltage distribution systems
• Interconnection to main feeder or as island.
Renewable Distributed Generation

Energy from different renewable sources

Ref: Department of Energy: http://www.energy.gov/
R. Lasseter et al., “Integration of distributed energy resources: The CERTS microgrid concept.”
Microgrid Control

DMS: Distribution Management System
MGCC: MicroGrid System Central Controller
MC: Micro Source Controller
LC: Load Controller

Hierarchical Control of Microgrid
Tools for Modeling

- MATLAB
- Simulink
- LINGO optimization toolbox
- HOMER
- Real Time Digital Simulator
About HOMER

Hybrid Optimization Model for Electric Renewables (HOMER) is a freely available software developed by U.S National Renewable Energy Laboratory (NREL).

Assists the user to design the power systems and compare technologies across a wide range of applications.

It can solve the optimal solutions for all the possible combinations from the given options in one simulation.

HOMER ranks different architectures based on Net Present Cost (NPC).

Front GUI of HOMER
MSU’s RTDS system consists of cubicle with 2 processor racks.

Processors:
- 3PC: Triple Processor Cards (8)
- GPC: Giga Processor Cards (2)

Components:
- WIF: Workstation Interface Card
- IRC: Inter-rack Communications Card
- DOPTO: Digital Optical Isolation System (board and connector cards)
- DDAC: Digital Analog Converter Card
- OADC: Optical Analog Digital Converter
- GTDI: Digital Input
- GTNET
- Digital panel I/O
- High Voltage Panel

Software: RSCAD 2.010.3 with C-Builder

Real Time Digital Simulators (RTDS®) performs fully digital Electromagnetic Transient Power System Simulation in real time.
Hardware in the Loop

- HIL test helps in building a testing platform for devices in various fields such as power system, automotive, controls etc.
- By HIL test, behavior of a new device or control algorithm under different operating conditions can be studied.
Microgrid Model
Simulation Results

Voltage at bus MG

Current flowing through bus MG

Current flowing through bus MT-MG

Current flowing through bus WT-MG

Current flowing through bus PV-MG

Time (s)
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DG size is defined as the penetration of the DG with respect to total load of the system:

\[ \%DG = \frac{P_{DG}}{P_{Load}} \]

Over sizing and improper location of the DG leads to undesired voltage profiles in the system.

Several works have been reported to find the optimal size and location of DG for connecting to the grid.
APPROACH

• In this work optimal size and location is found based on voltage support and stability.

• DG is placed on the test case considered and power flow is run by varying size of DG to see the impacts of DG on grid.

• A suitable stability index is selected to find the stability of a system for distribution networks.

• Objective function and constraints for finding the optimal location and size is formulated in LINGO
TEST CASE & TOOLS USED

• IEEE 13 node test case

Features:
- Short and highly loaded feeder with 3.466MW. DG at 632 & 671.
- Spot loads, distributed loads, single and 3 phase unbalanced loads, wye and delta connected.
- Three phase, two phase and single phase lines with different spacing.
- It has shunt capacitor banks.

Tools used:
- Three phase unbalanced power software developed at MSU. This software can handle multiple DG’s modeled either as PV or PQ node.
- LINGO is used to find the optimal size and location which is a commercial optimization tool that solves linear and non linear problems precisely.
IEEE 37 Bus Test Case

DG at 703 and 734
STABILITY INDEX

The mathematical formulation for the stability index is derived from the two line diagram.

\[ P_i, Q_i, V_i \angle \theta_i \] \hspace{1cm} \[ P_j, Q_j, V_j \angle \theta_j \] 

\( P_i, Q_i \) are real and reactive powers injected in bus i. 
\( V_i \angle \theta_i \) is voltage and voltage angle at bus i. 
\( P_{Li}, Q_{Li} \) are real and reactive power components of load i. 
\( P_j, Q_j \) are real and reactive powers injected in bus j. 
\( V_j \angle \theta_j \) is the voltage and voltage angle at bus j. 
\( P_{Lj}, Q_{Lj} \) Are real and reactive power components of load j.

The derived index is

\[
L(i) = 4 \left[ V_i V_j \cos(\theta_j - \theta_i) - V_j^2 \cos(\theta_i - \theta_j)^2 \right] / V_j^2
\]

L(i) is the value of stability index at node I.
- if L(i) < 1, the system is stable
- L(i) > 1, the system is unstable.

This concept can be extended to larger systems and stability index at all nodes can be found using above mathematical formulation.
The stability index is used to optimize the size and location and the objective is to minimize the stability index.

Stability indices at all the nodes for a particular case of DG size are

<table>
<thead>
<tr>
<th>Node no</th>
<th>Phase A</th>
<th>Phase B</th>
<th>Phase C</th>
</tr>
</thead>
<tbody>
<tr>
<td>650</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>632</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>633</td>
<td>0.0216</td>
<td>0.0124</td>
<td>0.0108</td>
</tr>
<tr>
<td>634</td>
<td>0.7730</td>
<td>0.4372</td>
<td>0.494</td>
</tr>
<tr>
<td>645</td>
<td>-</td>
<td>0.177</td>
<td>0.4194</td>
</tr>
<tr>
<td>646</td>
<td>-</td>
<td>0.0164</td>
<td>0.0131</td>
</tr>
<tr>
<td>7</td>
<td>0.55061</td>
<td>0.0184</td>
<td>0.2366</td>
</tr>
<tr>
<td>671</td>
<td>G</td>
<td>G</td>
<td>G</td>
</tr>
<tr>
<td>692</td>
<td>0.0003</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>675</td>
<td>0.147</td>
<td>0.0092</td>
<td>0.0082</td>
</tr>
<tr>
<td>684</td>
<td>0.088</td>
<td>-</td>
<td>0.028</td>
</tr>
<tr>
<td>611</td>
<td>-</td>
<td>-</td>
<td>0.05</td>
</tr>
<tr>
<td>652</td>
<td>0.035</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>680</td>
<td>0.00015</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

$P_{DG} = 1.866$MW

G – Generator
- index doesn’t exist

Similarly stability indices for all the cases can be found and the DG size and location that gives best values can be considered as best size and location.
FORMULATION IN LINGO

• In order to automate the process of finding optimal size and location a formulation is developed in LINGO.
• The objective function and the constraints of the formulation are

Objective:

$$\text{Min}(4\left[ V_i V_j \cos(\theta_i - \theta_j) - V_j^2 \cos(\theta_i - \theta_j)^2 \right]/V_j^2)$$

Subject to:

Equality Constraints

$$V_j^p = \left( V_i^p - \sum_{m=a}^{z} Z_{ij}^p I_j^p \right)$$

$$\sum_N I_j^p - \sum_O I_j^p - IL_j^p = 0$$

Power flow equations

Inequality Constraints

$$P_{DG}^{\min} \leq P_{DG} \leq P_{DG}^{\max}$$

$$V_i^{\min} \leq V_i \leq V_i^{\max}$$

$$IL_i^p \leq IL_i^{\max}$$

Source limits Voltage limits Load limits

The above equations are implemented in the format required by LINGO and has to be simulated to get the desired results.
## Simulation Results

<table>
<thead>
<tr>
<th>Feeder type</th>
<th>Optimal size</th>
<th>Minimized stability index value</th>
<th>Optimal location</th>
<th>Minimized stability index value</th>
<th>Optimal size and location</th>
<th>Minimized stability index value</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE 13 node feeder</td>
<td>60%DG at node 671</td>
<td>0.6461</td>
<td>671 with 60% DG</td>
<td>0.6461</td>
<td>60% DG at node 671</td>
<td>0.6461</td>
</tr>
<tr>
<td>IEEE 37 node feeder</td>
<td>50% DG at node 703</td>
<td>0.7191</td>
<td>709 with 50% DG</td>
<td>0.7730</td>
<td>60% DG at node 709</td>
<td>0.6931</td>
</tr>
</tbody>
</table>
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Comprehensive modeling of the biomass generation is required to assess techno-economic and environmental impact on electric grid.

Technical analysis and sensitivity analysis will help independent owners to choose among different options.

Comprehensive model will provide opportunities to better understand and perform integrated technical analysis of efficiency, interdependencies and economics.
Biomass energy can be extracted through various ways like Solid Fuel Combustion, Gasification, Digestion, and Fermentation.
Gas Turbine Model in Simulink

Temperature control

Turbine dynamics (Exhaust temperature calculation)

Speed control

Acceleration control

Turbine dynamics (Mechanical torque calculation)

Gas turbine model in MATLAB/Simulink
Distribution test case system

Simulink model of four bus test case system
Transient Stability and stability indicators

Stability:

*Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.*

Transient Stability:

The ability of the power system to maintain synchronism when subjected to a severe disturbance.

Stability indicators:

Maximum rotor speed deviation, oscillation duration, rotor angle, mechanical power, and terminal voltages are taken as the indicators.
Stability Indicators

Rotor speed deviation and Oscillation duration:

![Graph showing rotor speed deviation and oscillation duration]

Maximum rotor speed deviation and oscillation duration

Rotor angle:

- The rotor angle increases when a disturbance happens and returns back to normal once the disturbance clears.

Terminal Voltage:

- When a disturbance happens in the system, the terminal voltage changes and when the fault clears, it returns back to normal.

Mechanical Power:

- Changes in mechanical power due to the fault.
Sensitivity Analysis Approach

Parameters varied:

The gas turbine parameters- offset, coefficients of $F_1$ as well as $F_2$.

offset: minimum fuel flow

$F_1$: Torque calculation

$F_1 = A_1(1 - W_f) + B_1(1 - N)$

$F_2$: Exhaust temperature calculation

$F_2 = T_r - A_2(1 - W_f) + B_2(1 - N)$

Indicators observed:

Mechanical power, rotor speed deviation, rotor angle, terminal voltage
Results with Three phase fault

- A three phase fault is applied at 4 seconds and released after six cycles.
### Variation of $F_1$ coefficients for 3phase fault

$$F_1 = A_1(1-W_f) + B_1(1-N)$$

Stability indicators with different values $A_1$

<table>
<thead>
<tr>
<th>$A_1$</th>
<th>$P_{mech}$</th>
<th>Rotor angle increment (deg)</th>
<th>Max rotor speed deviation (pu)*$10^{-3}$</th>
<th>Oscillation duration (sec)</th>
<th>Terminal voltage oscillation duration (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.52</td>
<td>0.321</td>
<td>96.8</td>
<td>3.77</td>
<td>6.4</td>
<td>5.4</td>
</tr>
<tr>
<td>0.78</td>
<td>0.48</td>
<td>97.0</td>
<td>6.07</td>
<td>6.5</td>
<td>5.4</td>
</tr>
<tr>
<td>1.04</td>
<td>0.641</td>
<td>96.5</td>
<td>8.45</td>
<td>6.8</td>
<td>5.5</td>
</tr>
<tr>
<td>1.3</td>
<td>0.8</td>
<td>97</td>
<td>11.3</td>
<td>7.5</td>
<td>5.5</td>
</tr>
<tr>
<td>1.56</td>
<td>0.961</td>
<td>96.3</td>
<td>14.18</td>
<td>7.8</td>
<td>5.5</td>
</tr>
<tr>
<td>1.82</td>
<td>1.12</td>
<td>96.5</td>
<td>17.38</td>
<td>8.2</td>
<td>5.5</td>
</tr>
<tr>
<td>2.08</td>
<td>1.28</td>
<td>96.6</td>
<td>21.2</td>
<td>9.5</td>
<td>5.8</td>
</tr>
</tbody>
</table>

$A_1$ has been increased in steps of 20% and the change in $A_1$ led to the change in mechanical power, maximum rotor speed deviation and oscillation duration.
Variation of $F_1$ coefficients for 3phase fault

Mechanical power

$P_{mech}$

$F_1$ varying from .52 to 2.08

Rotor speed deviation

$F_1$ varying from .52 to 2.08
Results with $F_1$ variation

Not much change in rotor angle and terminal voltage with the change in $A_1$. 

(rotor angle and terminal voltage graphs)
Results with $F_2$ variation

(Offset and $A_2$)

\[ F_2 = T_r - A_2(1-W_f) + B_2(1-N) \]

• Offset has been varied from 0 to 1. The increase in offset increases the mechanical power and maximum rotor speed deviation.

• $A_2$ has been increased in steps of 20% and the change in $A_2$ led to the only change in exhaust temperature, but not in other parameters because of active speed control.
Test case system: 6 bus

- Ideal source
- Gas turbine
- Asynchronous generator
- Synchronous generator
- RL loads
## Results of 6 bus system

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Synchronous machine</th>
<th>Induction machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terminal voltage reduction (pu)</td>
<td>0.33</td>
<td>0.05</td>
</tr>
<tr>
<td>Terminal voltage peak (pu)</td>
<td>1.15</td>
<td>1.02</td>
</tr>
<tr>
<td>Maximum speed (pu)</td>
<td>1.007</td>
<td>1.022</td>
</tr>
<tr>
<td>Settling time (sec)</td>
<td>8</td>
<td>7</td>
</tr>
</tbody>
</table>

The terminal voltage of the IG and the speed of the SG are more effected due to the fault.
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Environmental and Economic analysis will help to decide overall impact of the system with technical analysis.

- HOMER can be used to do environmental and economical analysis.
- Comprehensive model will provide opportunities to better understand and perform analysis based on input data taken.
Modeled power system

Available equipments in library

Output window

Snapshot of HOMER
Modeling of the Power system

Considered generator size (kW) | Considered grid size (kW)
---|---
500, 1100, 1209, 1300 | 0 and 700

Considered generator and grid sizes

Power System in HOMER

Daily load profile
## Inputs to the system

<table>
<thead>
<tr>
<th>Type of cost</th>
<th>$/kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital cost</td>
<td>1000</td>
</tr>
<tr>
<td>Replacement cost</td>
<td>800</td>
</tr>
<tr>
<td>Op and maintenance cost</td>
<td>0.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resource</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural residues</td>
<td>30-45 $/ton</td>
</tr>
<tr>
<td>Energy crops</td>
<td>60-70 $/ton</td>
</tr>
<tr>
<td>Forest products</td>
<td>30-36 $/ton</td>
</tr>
<tr>
<td>Animal waste</td>
<td>46-50 $/ton</td>
</tr>
<tr>
<td>Diesel</td>
<td>0.6-0.8 $/lt</td>
</tr>
</tbody>
</table>
Some Definitions in HOMER

Net Present Cost (NPC):

Discounted value of all the cash flows needed to operate and purchase the hybrid system over its lifetime. NPC is calculated by using the below formula.

\[
C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})}
\]

\[
CRF(i, N) = \frac{i(1 + i)^N}{(1 + i)^N - 1}
\]

where

- \(i\) - interest rate
- \(N\) - number of years
- \(R_{proj}\) - project life time (years)
Results Summary

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Fuel cost ($/ton or $/lt)</th>
<th>Net present cost (NPC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural residues</td>
<td>30 – 45</td>
<td>$ 7,244,118 – $ 7,857,481</td>
</tr>
<tr>
<td>Energy crops</td>
<td>60 – 70</td>
<td>$ 8,309,066 – $ 8,610,123</td>
</tr>
<tr>
<td>Forest products</td>
<td>30 – 36</td>
<td>$ 7,244,118 – $ 7,586,529</td>
</tr>
<tr>
<td>Animal waste</td>
<td>46 – 50</td>
<td>$ 7,887,586 – $ 8,008,009</td>
</tr>
<tr>
<td>Diesel</td>
<td>0.6 – 0.8</td>
<td>$ 7,022,551 – $ 7,566,217</td>
</tr>
</tbody>
</table>

Economic Analysis results summary

- The cost of the biomass resources is high compared to the diesel.
- Forest products are comparatively cheap among other biomass resources for the considered inputs.
The carbon dioxide emissions from biomass resources are less compared to the diesel.
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- Introduction to Distributed Generation and Microgrid modeling and simulation have been discussed.
- A formulation for optimal sizing and siting of DG have been developed.
- A biomass generation model has been developed in MATLAB/Simulink and stability of the power system with the integration of gas turbine has been carried out.
- Cost analysis and environmental impact of various biomass resources has been carried out.
- Comparison of economical and environmental impacts of biomass fuels and diesel has been discussed.
- Impact of DG is system dependent and can not be generalized.
Acknowledgements

- Thanks to the Department of Energy, Pacific Gas and Electric (PG&E), Department of Homeland Security, Department of Defense/ Office of Naval Research for financial support

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