Policy and Technical Challenges in Integrating Distributed Generators

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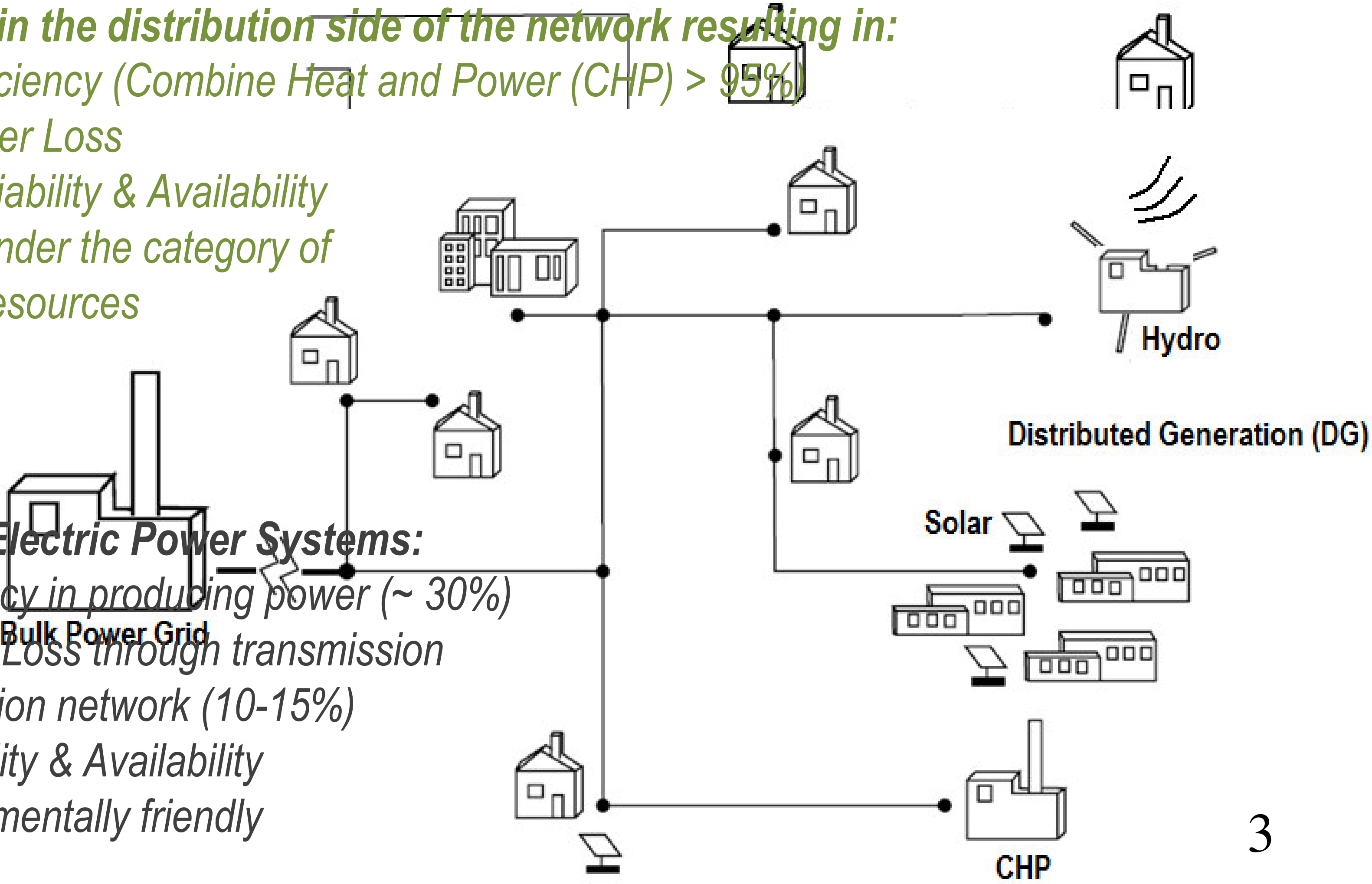
Talk outline

- Background
- Motivation for Our Work (Questions)
- Approaches & Methods
- Technical Results
- Policy Implications

The historical Structure of Distribution System vs. The Future Structure of Energy Systems with multiple DGs

In Future Electric Energy systems, Distributed Generators (DG) with different technologies will be located in the distribution side of the network resulting in:

- *Increasing Efficiency (Combine Heat and Power (CHP) > 95%)*
- *Reducing Power Loss*
- *Increasing Reliability & Availability*
- *Some falling under the category of Renewable Resources*



Traditional Electric Power Systems:

- *Low Efficiency in producing power (~ 30%)*
- *High Power Loss through transmission and distribution network (10-15%)*
- *Low Reliability & Availability*
- *Not environmentally friendly*

Federal Government Goals for DGs

- Deployment of renewable power (often sub-set of DG) is being widely encouraged through various state policies such as renewable portfolio standards (RPS)
  - Proposals for a national standard to require up to 30 % of electricity from renewable sources by 2025
- High incentives for increasing energy efficiency and conservation
  - Distributed Generators (DG) potentially improve efficiency (power loss reduction & high efficiency)

Potential Frequency Instability Problems in Distribution Networks due to DGs

- If penetration of DGs is low (1-2%)
  - DGs may get damaged without adequate protection (blades breaking)
  - Protection of DGs may disconnect them automatically
- If penetration of DGs is high (10-15%) [Donnelly, Lopes, Cardell]
  - Only local (distribution) system may be affected
- If penetration of DGs is very high (> 20%) [Guttromoson]
  - Both local and backbone (EHV,HV) transmission systems may be affected
- To our knowledge, there is no precise explanation and systematic solution for the problem

Research Questions (Motivation)

- Answering the following questions:

1. What are the basic causes of frequency problems in local (distribution) networks with larger DGs sending power into the grid?
2. What are the possible solutions for avoiding frequency problems?
3. How to design policies to support deploying DGs without causing technical problems?

Approaches & Methods
Section 1: Static Analysis

- Optimum Power Flow (OPF):
  - Optimal DG locations with respect to network power loss minimization
  - Optimal voltage setting for DGs

Given $\{P_L\} = \{P_{L_1}, \cdots, P_{L_n}\}$,

$$\{P_G^*\} = \min_{P_G} \sum_{i=1}^{N_G} c_i\left(\tilde{P}_{G_i}\right)$$

subject to loadflow equations:

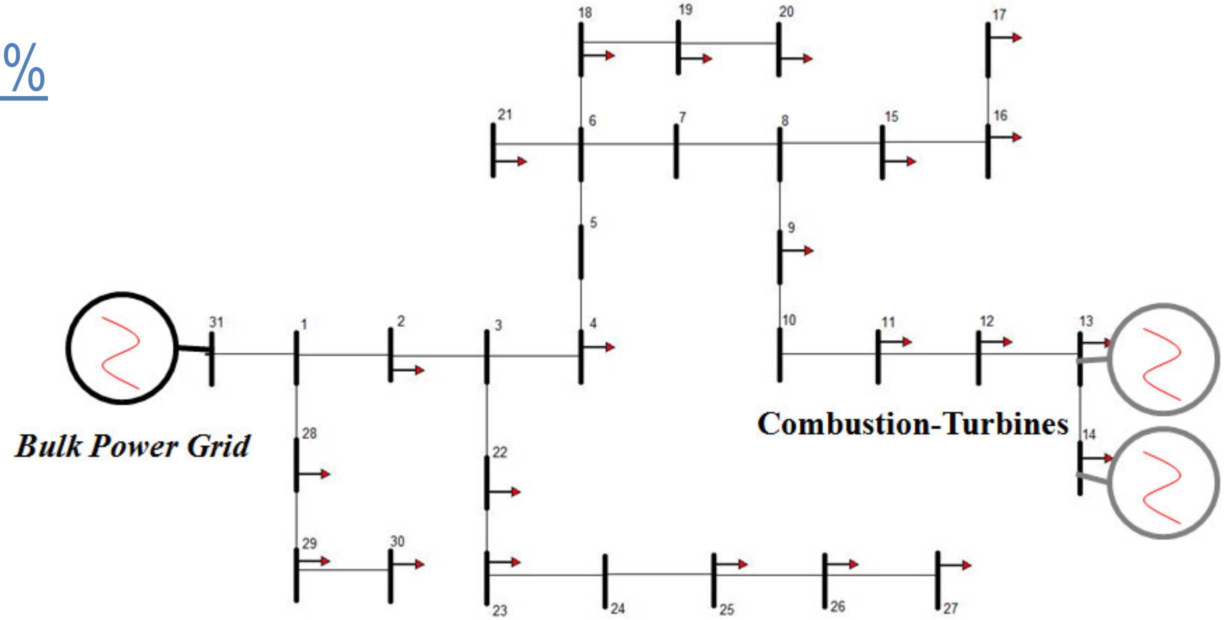
$$P_{ij} = G_{ij}\left(V_i^2 - V_i V_j \cos\delta_{ij}\right) + B_{ij} V_i V_j \sin\delta_{ij}$$
$$Q_{ij} = B_{ij}\left(V_i^2 - V_i V_j \cos\delta_{ij}\right) - G_{ij} V_i V_j \sin\delta_{ij}$$
$$P_i = \sum P_{ij}$$
$$Q_i = \sum Q_{ij} + V_i^2 B_{ii}$$

and other security operation constraints such as:

$$\left|P_{ij}\right| \le P_{ij}^{\max}$$
$$P_i^{\min} \le P_i \le P_i^{\max}$$
$$V_i^{\min} \le V_i \le V_i^{\max}$$
$$Q_i^{\min} \le Q_i \le Q_i^{\max} \quad i \in \text{all buses}, i \ne j$$

Optimum Locating DGs with respect to Loss Minimization

- Using IEEE-30-bus distribution network test system
- Two combustion turbines (C-T) with the same capacity of 750 KW providing 10% of total demand (15 MW)
- Power loss reduction by optimum placement and utilization is (0.7 MW) 50%



Section 2: Small-Signal-Stability (Dynamic) Analysis

- State space model (first order differential equations)

$$\frac{d}{dt}X = AX + BU, \quad X(0)$$

$$X = [\omega_G \;\; V_{CE} \;\; W_F \;\; W_{F\,\mathrm{dot}} \;\; P_G]$$

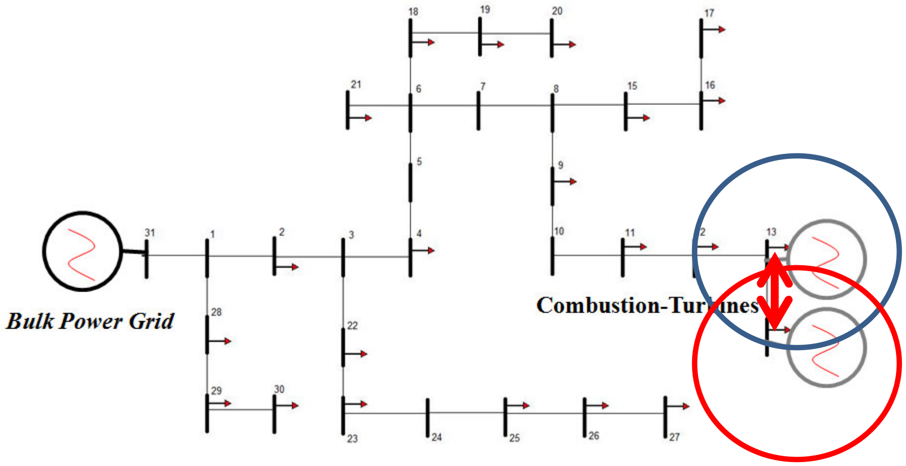
  - State—frequency, fuel control, fuel flow, derivative of fuel flow, active power
  - Typical DG parameters: Inertia, Governor Control (G-C), Electrical Distance
- Properties of A determine stability of the system (Eigenvalue Analysis)
- Sensitivity analysis of the system dynamics

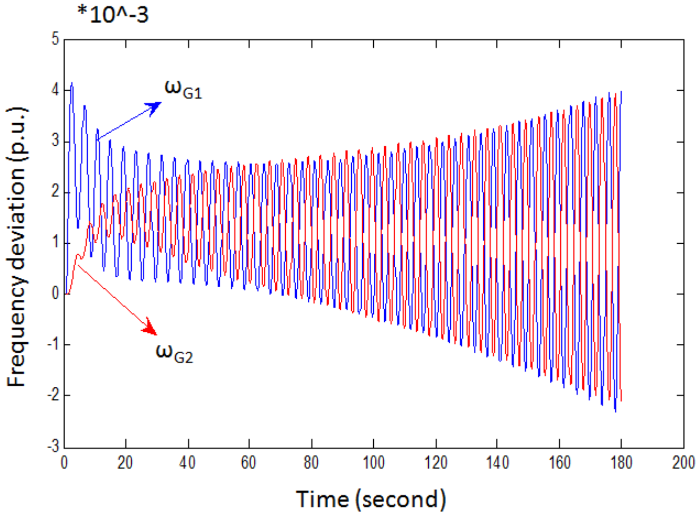
Dynamic Analysis of Optimum Locations

- Two C-Ts at optimum locations are small signal unstable
  - Due to short electrical distance (impedance) between DGs, Governor-Controls of DGs are strongly coupled and acting against each other

$$\frac{d}{dt}X = AX + BU, \quad X(0)$$

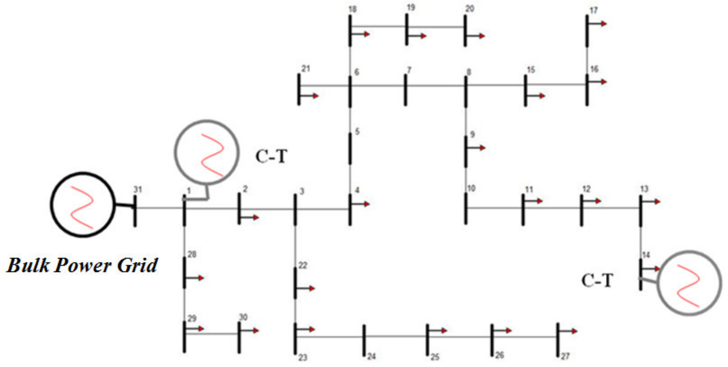
$$X = [\omega_G \ \ V_{CE} \ \ W_F \ \ W_{F\mathrm{dot}} \ \ P_G]$$

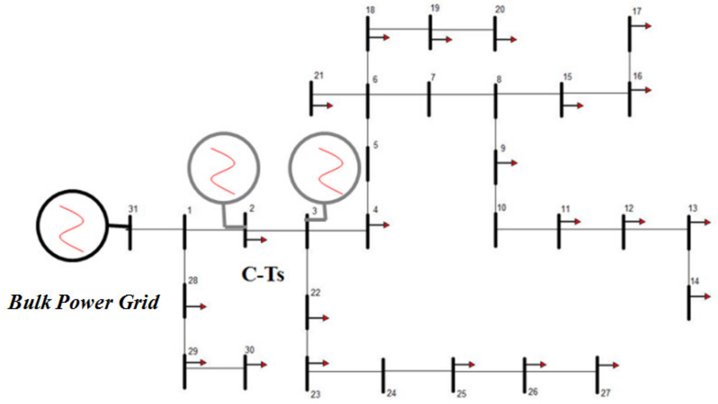




Exhaustive Small Signal Study of Different Combinations of Locating C-Ts

- Out of 900 possible combinations of locating two C-Ts, 192 cases have unstable frequency
- Instability depends on:
  - Impedance between DGs (Electrical Distance); in other words; Location of DGs (in contrast with Cardell results);
  - Inertia of DGs;
  - Governor-Control system; and,
  - Dynamic model of DGs



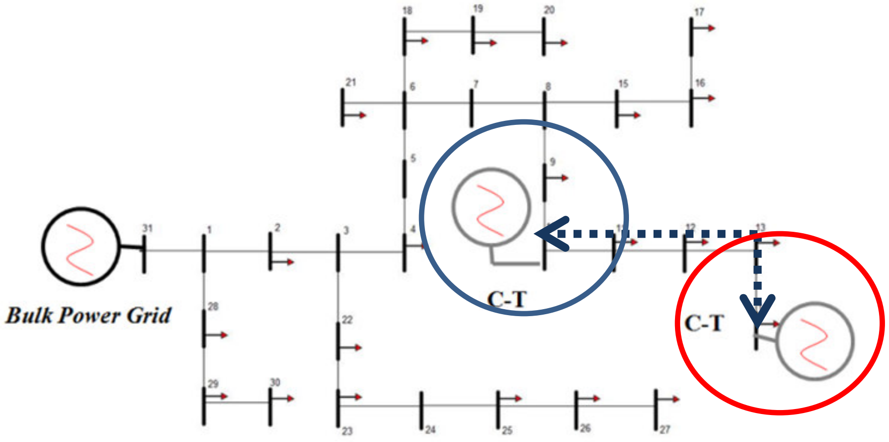


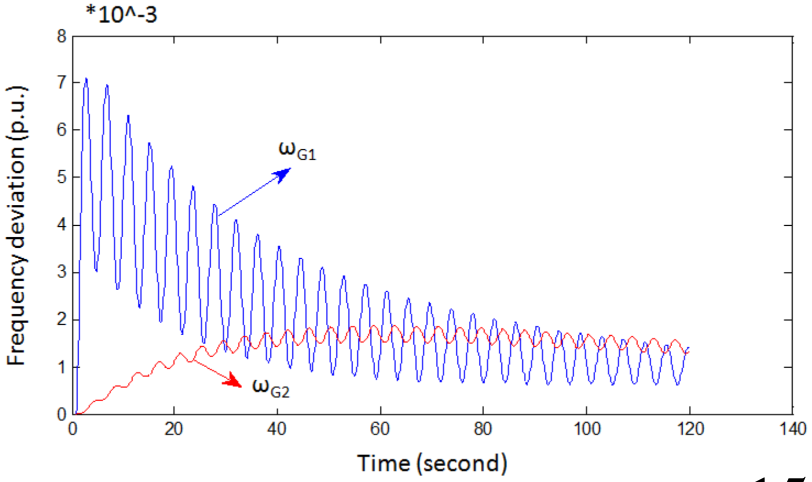
Section 3: Potential Robustness Enhancement Methods

Changing the locations of DGs (changing the planning of the system by locating DGs on initially stable locations)

Cons:

- Not being able to minimize power loss
- Slow dynamic response

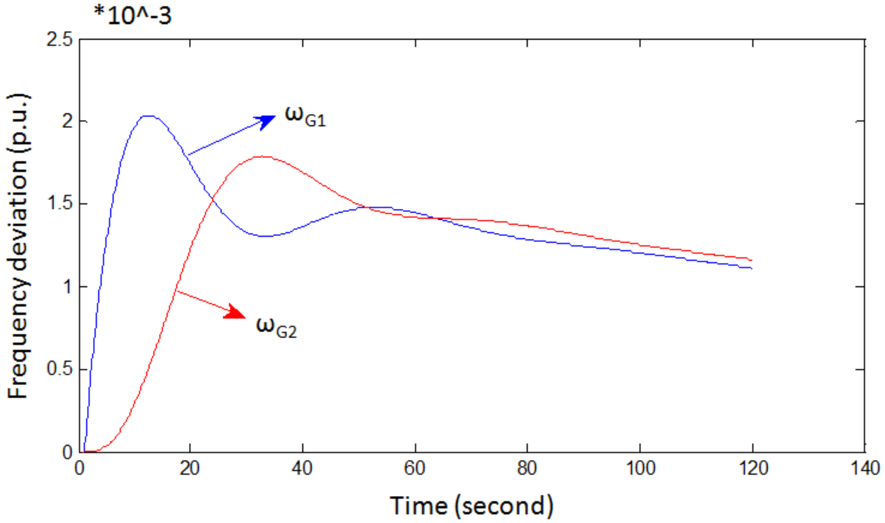




Potential Robustness Enhancement Methods

Increasing inertia of C-Ts: By increasing inertia tenfold all unstable cases becomes stable

Cons: Increasing inertia means using storage which is usually expensive, also dynamic response of storage systems is inherently slow



The Most Effective Robustness Enhancement Method

High Communication and Observation or Advanced Control Systems (work in progress)

- The whole system is fully controllable, also all DGs are locally controllable, thus, the system is stabilizable either by centralized control systems or decentralized control systems

- Cons: cost of designing and implementing control systems

Conclusions

- Distributed Generators can significantly improve efficiency by reducing power loss
- Today's electric systems may not accommodate large number of larger DGs sending power into the grid due to frequency problem
- Possible solutions:
  - Changing planning design of distribution networks
  - Introducing new standards (beyond IEEE 1547)
  - Designing new control strategies
- There is no single solution to fit all the criteria
- Future work: designing advanced control systems and reframing current standards

Acknowledgements

- Dr. Jovan Ilić with using the power flow program in Graphic Interactive Power System Simulator (GIPSYS) under development at Carnegie Mellon University
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- The financial support under the Portugal-Carnegie Mellon joint program

Thank You for Your Attention

Back-up Slides

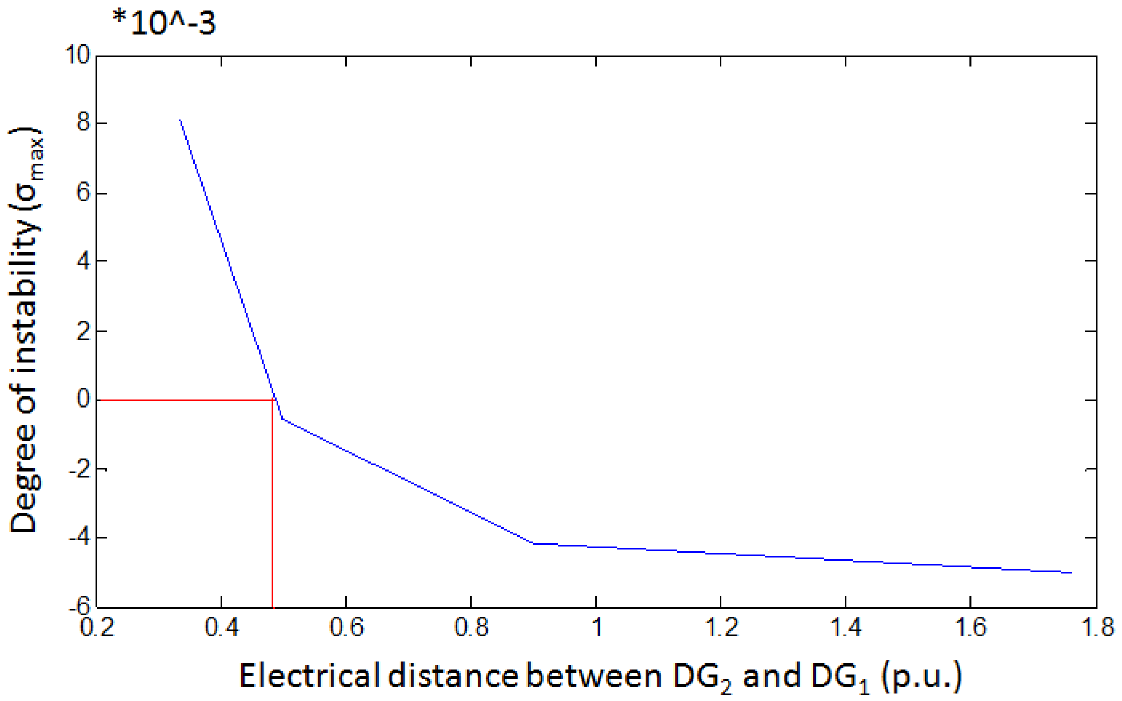
- Dynamic models
  - Combustion-Turbines with G-C

$$\frac{d}{dt}\begin{bmatrix}\omega_G\\ V_{CE}\\ W_{F1}\\ W_{F2}\end{bmatrix}=\begin{bmatrix}\frac{-D}{M} & 0 & \frac{c}{M} & 0\\ \frac{-K_D}{b} & \frac{-1}{b} & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 1 & \frac{-\delta}{\alpha} & \frac{-\beta}{\alpha}\end{bmatrix}\begin{bmatrix}\omega_G\\ V_{CE}\\ W_{F1}\\ W_{F2}\end{bmatrix}+\begin{bmatrix}\frac{-1}{M}\\ 0\\ 0\\ 0\end{bmatrix}P_G+\begin{bmatrix}0\\ \frac{K_D}{b}\\ 0\\ 0\end{bmatrix}\omega^{ref}$$

  - Interconnected state variable

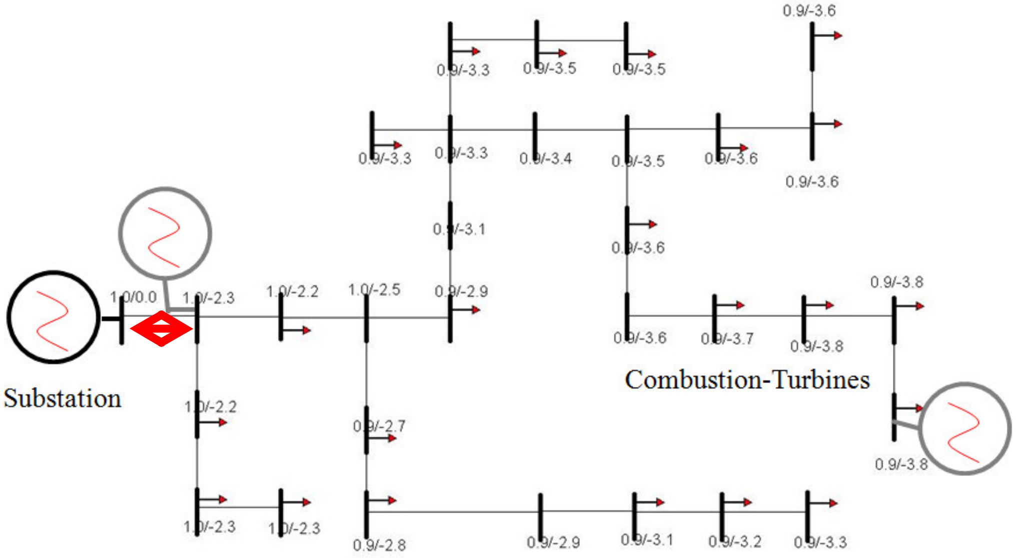
$$\frac{d}{dt}P_G=\mathbf{K}_P\omega_G+\mathbf{D}_P\frac{d}{dt}P_L$$

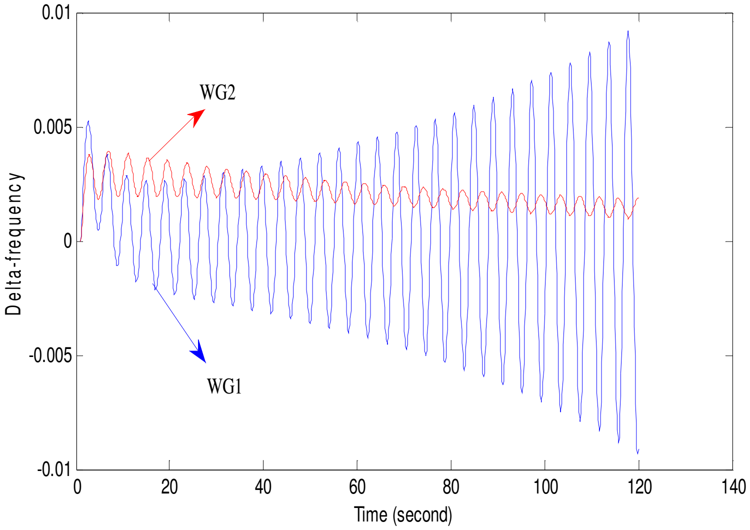
Illustration of the degree of instability as a function of electrical distance between DGs (Case A). Also, it illustrates that by increasing electrical distance between DGs, instability decreases and after certain point (critical electrical distance) system becomes stable.



Case B of instability

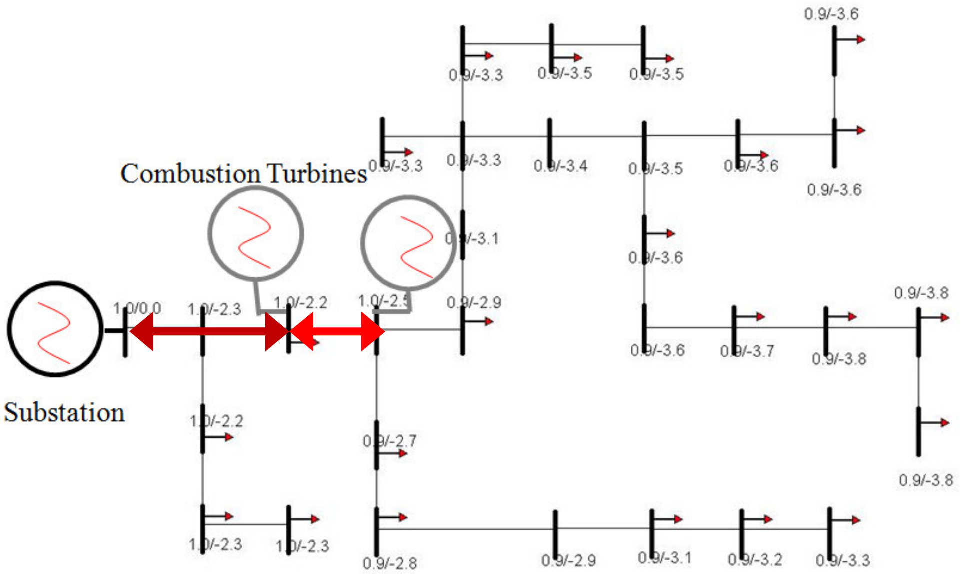
- Short electrical distance between DG close to sub-station and sub-station causes strong coupling and makes the DG unstable

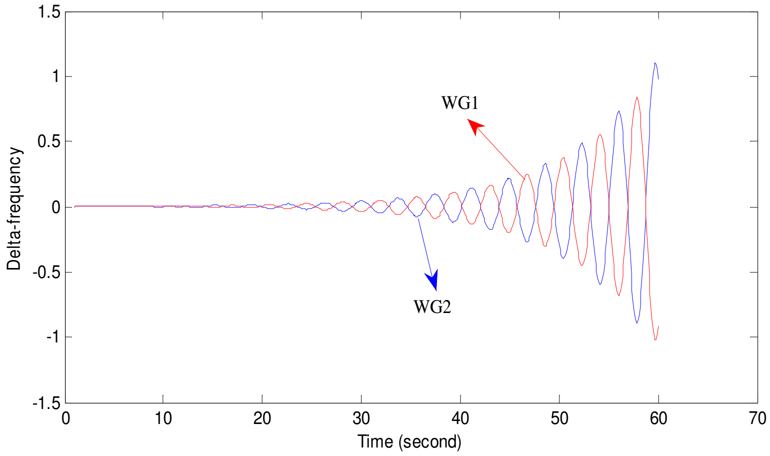




Case C of instability

- Strongly coupling between two DGs and DGs and Sub-station
- Instability is aggregated



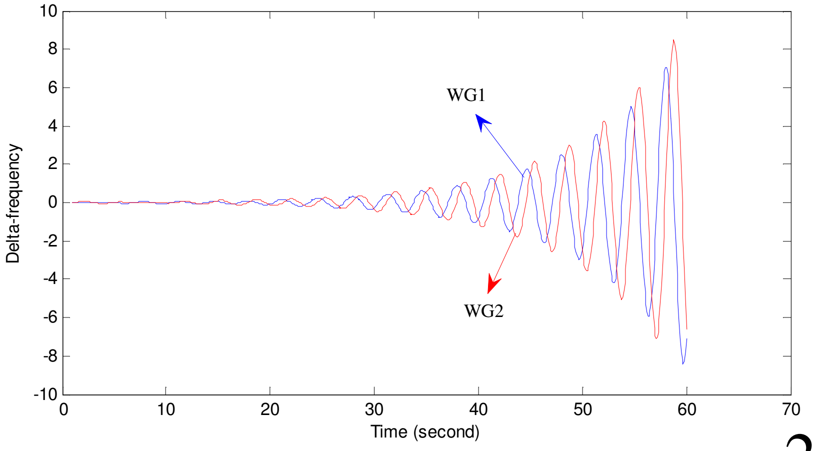


Frequency Stability of Hydro Plants

- H-Ps are potentially unstable because of the non-minimum phase properties
- Out of 900 cases 866 cases are unstable
- Fig. dynamic response at optimum locations

$$\frac{d}{dt}\begin{bmatrix}\omega_G\\ q\\ v\\ a\end{bmatrix}=\begin{bmatrix}\frac{-(e_H+D)}{M} & \frac{k_q}{M} & 0 & \frac{-k_w}{M}\\ \frac{1}{T_f} & \frac{-1}{T_q} & 0 & \frac{1}{T_w}\\ 0 & 0 & \frac{-1}{T_e} & \frac{a}{T_e}\\ \frac{-1}{T_s} & 0 & \frac{1}{T_s} & \frac{-(r_h+r')}{T_s}\end{bmatrix}\begin{bmatrix}\omega_G\\ q\\ v\\ a\end{bmatrix}+\begin{bmatrix}\frac{-1}{M}\\ 0\\ 0\\ 0\end{bmatrix}P_G+\begin{bmatrix}0\\ 0\\ 0\\ \frac{1}{T_s}\end{bmatrix}\omega^{ref}$$

ω_G is the frequency of the generator, *q* is the penstock flow, *v* is the governor droop and *a* is the gate position



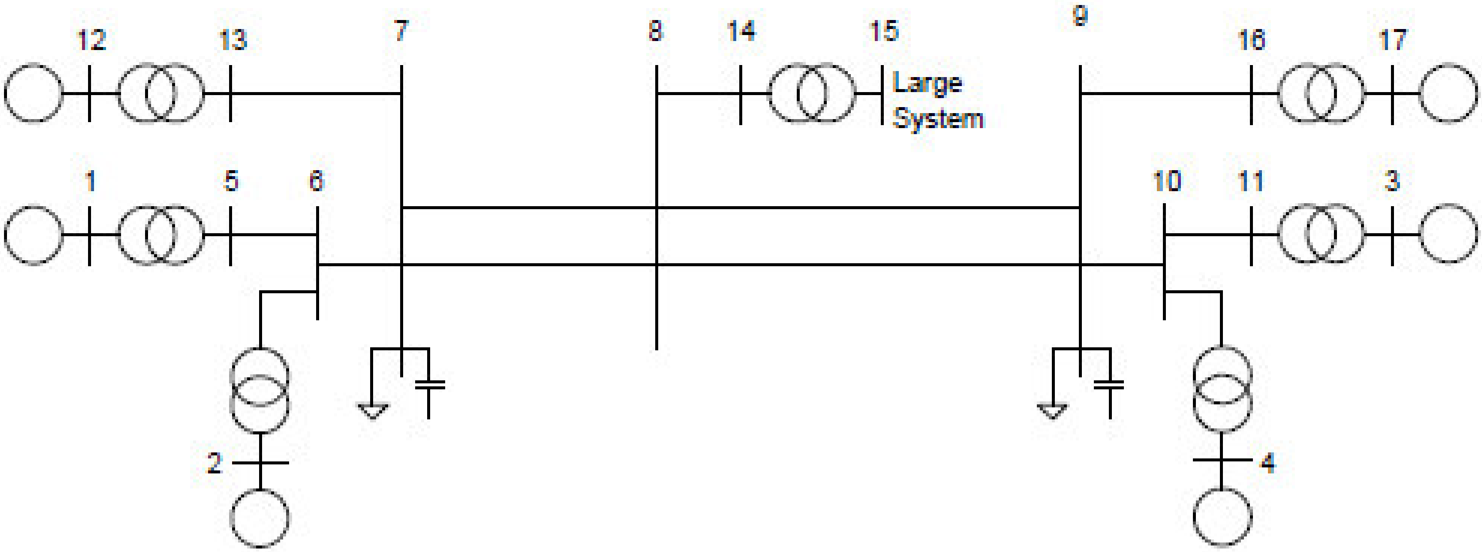
Droop Characteristic

- A droop constant represents the sensitivity of the steady-state frequency to the real-power output of a generator when the frequency setting is kept constant.

$$Droop = -\left.\frac{\partial \omega_G[K]}{\partial P_G[K]}\right|_{\omega_G^{ref}[K]=0}$$

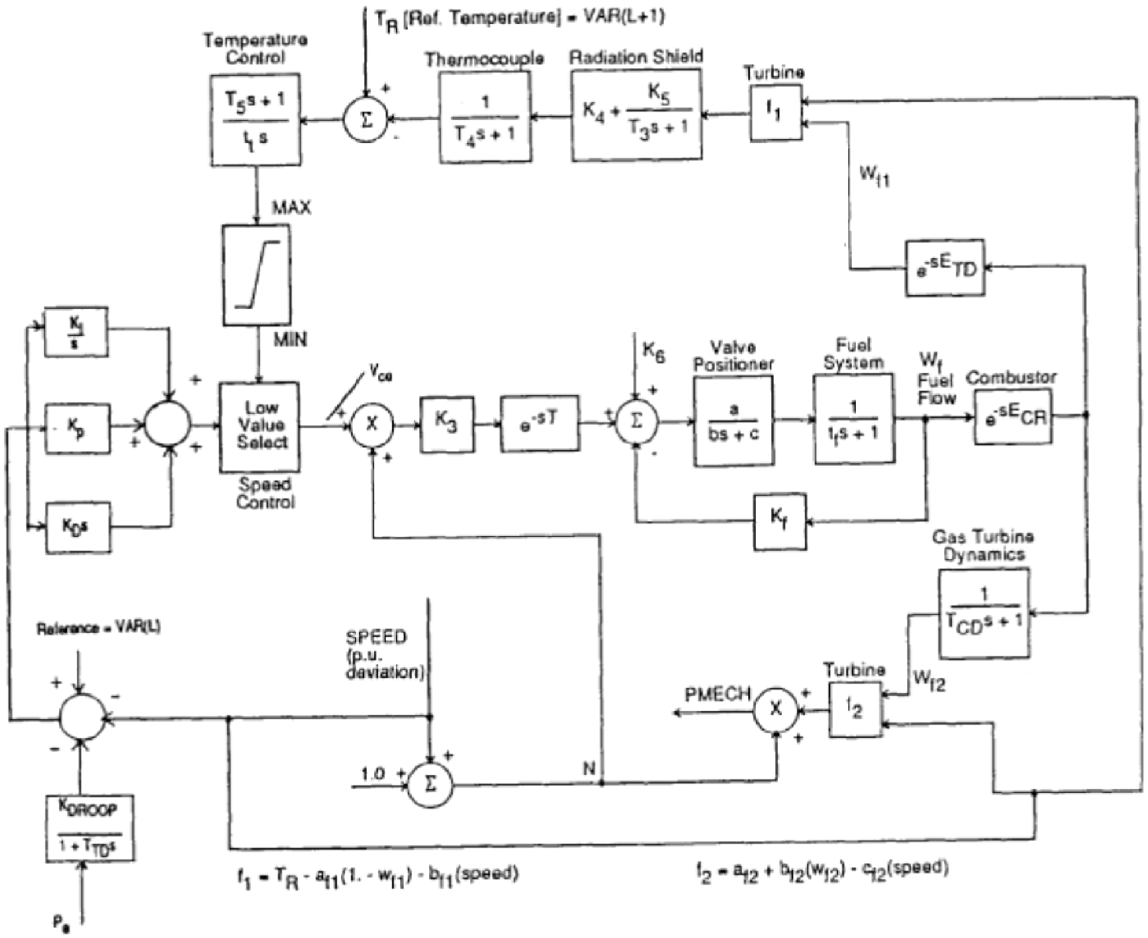
- Droop constant of C-Ts with G-C is 0.075 and without G-C is 0.5
- Droop constant of hydro plants with G-C is 0.040 and without G-C is 0.428

Real world example form Portugal distribution network



- Each area has synchronous machines (DGs)
- There is an electromechanical mode of oscillatory between two areas
- To resolve the problem Power System stabilizer (PSS) is implemented
- Effectiveness of PSS depends on observability and controllability of the system

Block diagram for Governor-turbine system of combustion turbine



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Eigenvalues of 30 Bus System when DGs are placed in different locations

DGs at buses 13 and 14 (case A)	*DGs at buses 1 and 14 (case B)*	*DGs at buses 2 and 3 (case C)*	*DGs at buses 10 and 14 (stable case)*
-19.9943	-19.9943	-19.9943	-19.9943
-19.9943	-19.9943	-19.9943	-19.9943
0.0081 + 1.5217i	0.0134 + 1.5270i	0.1091 + 1.6931i	-0.0130 + 1.5029i
0.0081 - 1.5217i	0.0134 - 1.5270i	0.1091 - 1.6931i	-0.0130 - 1.5029i
-0.0186 + 1.4984i	-0.0182 + 1.4987i	-0.0143 + 1.5018i	-0.0184 + 1.4985i
-0.0186 - 1.4984i	-0.0182 - 1.4987i	-0.0143 - 1.5018i	-0.0184 - 1.4985i
-1.1387	-0.9628	-1.1190	-1.1378
-0.9989	-1.1366	-0.6989 + 0.6914i	-1.1130
-0.1969	-0.2437	-0.6989 - 0.6914i	-0.0050
-0.0037	-0.0066	-0.0321	-0.0407