TU Delft

IEPG Intelligent Electrical Power Grids

SIAM-SC Workshop Day 2020

Optimization Problems in Operation and Planning of Electrical Power Systems

Dr.ir. José Rueda
Associate Professor Power System Stability, Control, and Optimization

8st August 2020

LEARNING OBJECTIVES (LOS)

At the end of the lecture the students will be able to:

- **LO1:** Describe the rationale behind power flow and optimal power flow (OPF) calculations.
- **LO2:** Describe the rationale behind probabilistic power flow (PPF) calculation.
- **LO3:** Evaluate power system steady-state performance based OPF and PPF.

OUTLINE

1. Power flow calculation
Related to LO1 & LO3

2. Optimal power flow calculation
Related to LO1 & LO3

3. Probabilistic power flow calculation
Related to LO2 & LO3

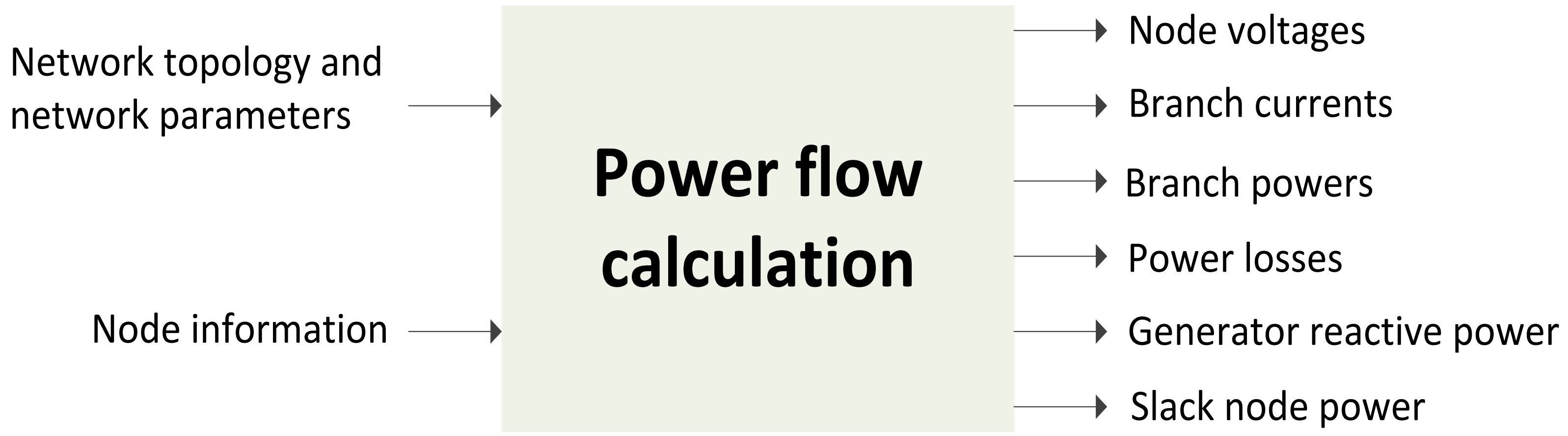
4. Conclusions

1. Power flow calculation

1.1 WHAT IS POWER FLOW CALCULATION?

Power flow calculation is an iterative procedure for determination of the power flows (active and reactive) throughout the entire network, using information available about

- Nodal power injections (P,Q)
- Voltages (magnitude U, angle δ)
- System topology (interconnection of components), including parameters (e.g. reactances)



Note: The terms power flow and load flow both stand for the same analysis technique, however it is recommended to use the name power flow. P. Kundur: **"Load does not flow, but power flows."**

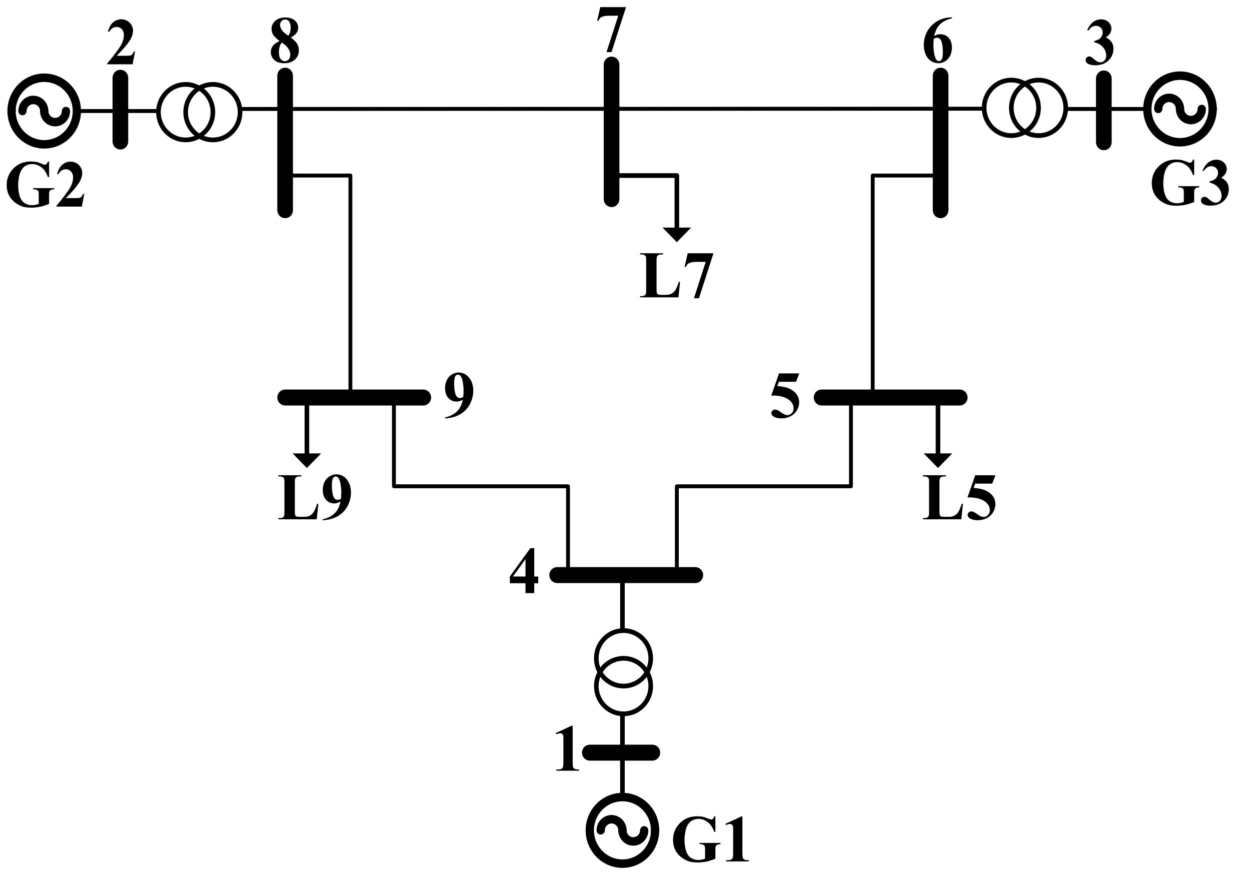
1.2 NEWTON–RAPHSON METHOD

1. Build the network admittance matrix $\mathbf{Y}_{\mathbf{bus}}$
2. Make an initial estimation: $k = 0,\ \mathbf{x}^k = \begin{bmatrix} \boldsymbol{\delta}^k & \mathbf{U}^k \end{bmatrix}^T$
3. Calculate the mismatches: $\mathbf{h}(\mathbf{x}^k) = \begin{bmatrix} \Delta\mathbf{P}_i\left(\mathbf{x}^k\right) & \Delta\mathbf{Q}_i\left(\mathbf{x}^k\right) \end{bmatrix}^T$
4. Perform the stop test: $\begin{cases} \max(|\mathbf{h}(\mathbf{x}^k)|) < \varepsilon ? \Rightarrow stop. \\ \max(|\mathbf{h}(\mathbf{x}^k)|) > \varepsilon ? \Rightarrow go\ to\ 5. \end{cases}$
5. Construct the Jacobian Matrix: $\mathbf{J}^k = \mathbf{J}(\mathbf{x}^k)$
6. Calculate the corrections from: $\Delta\mathbf{x}^k = \begin{bmatrix} \Delta\boldsymbol{\delta}^k & \Delta\mathbf{U}^k \end{bmatrix}^T = \mathbf{J}(\mathbf{x}^k)^{-1} \cdot \mathbf{h}(\mathbf{x}^k)$
7. Add the corrections to the initial estimation:

$$\text{New iteration } k+1: \ \mathbf{x}^{k+1} = \mathbf{x}^k + \Delta\mathbf{x}^k \Rightarrow \begin{cases} \boldsymbol{\delta}^{k+1} = \boldsymbol{\delta}^k + \Delta\boldsymbol{\delta}^k \\ \mathbf{U}^{k+1} = \mathbf{U}^k + \Delta\mathbf{U}^k \end{cases}$$

ε is a pre-specified tolerance $\left(\text{e.g. } 0.0001\right)$

1.3 EXAMPLE WITH IEEE 9-BUS TEST SYSTEM



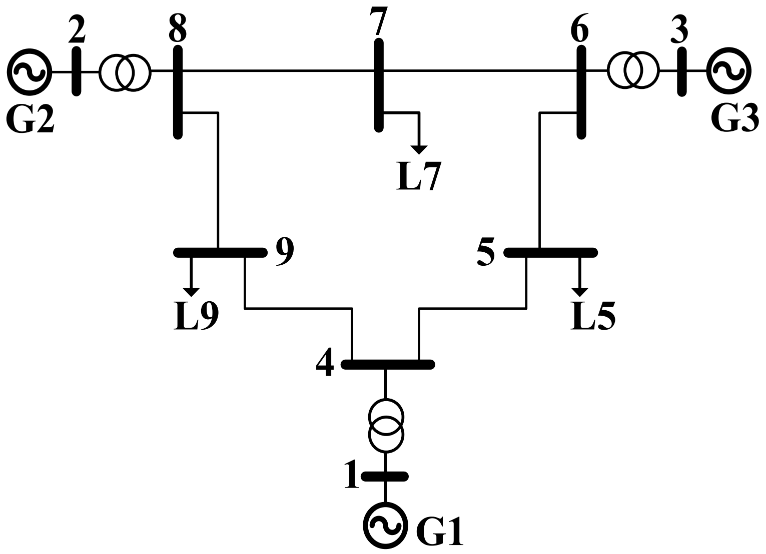
Bus	Type	Known variables	Unknown variables
1	Slack	U_{G1} = 1.04 p.u. δ_{G1} = 0°	P_{G1} Q_{G1}
2	PV	P_{G2} = 163 MW U_{G2} = 1.025 p.u.	δ_{G2} Q_{G2}
3	PV	P_{G3} = 85 MW U_{G3} = 1.025 p.u.	δ_{G3} Q_{G3}
5	PQ	P_{L5} = 90 MW Q_{L5} = 30 MVar	U_{G5} δ_{G5}
7	PQ	P_{L7} = 100 MW Q_{L7} = 35 Mvar	U_{G7} δ_{G7}
9	PQ	P_{L9} = 125 MW Q_{L9} = 50 Mvar	U_{G9} δ_{G9}

Source of the model: Joe H. Chow (Editor), "Time-Scale Modeling of Dynamic Networks with Applications to Power Systems", Springer, Berlin, Heidelberg, 1982, Chapter 4, page 70.

1.3 EXAMPLE WITH IEEE 9-BUS TEST SYSTEM

Results – Summary in Matlab command window

```
================================================================================
|     Bus Data                                                                 |
================================================================================
 Bus      Voltage          Generation             Load
  #   Mag(pu) Ang(deg)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
----- ------- --------  --------  --------  --------  --------
    1  1.040    0.000*    71.64     27.05       -         -
    2  1.025    9.280    163.00      6.65       -         -
    3  1.025    4.665     85.00    -10.86       -         -
    4  1.026   -2.217       -         -         -         -
    5  1.013   -3.687       -         -       90.00     30.00
    6  1.032    1.967       -         -         -         -
    7  1.016    0.728       -         -      100.00     35.00
    8  1.026    3.720       -         -         -         -
    9  0.996   -3.989       -         -      125.00     50.00
                        --------  --------  --------  --------
               Total:    319.64     22.84    315.00    115.00
```

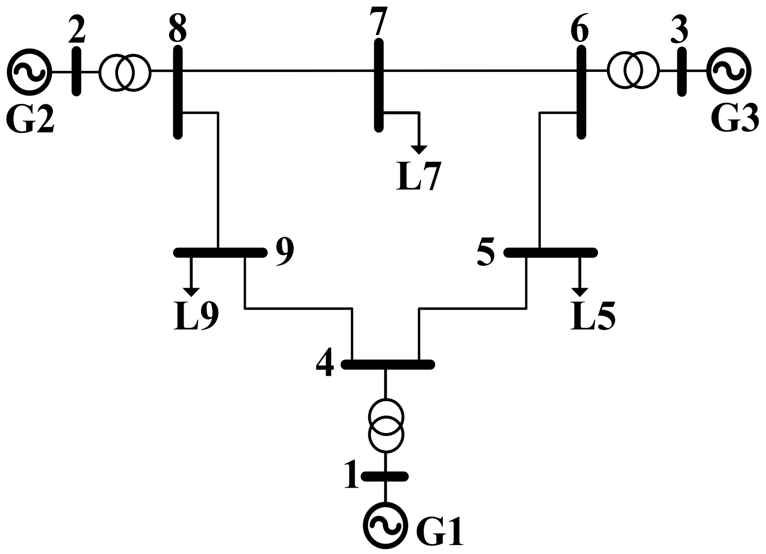


1.3 EXAMPLE WITH IEEE 9-BUS TEST SYSTEM

Results – Summary in Matlab command window

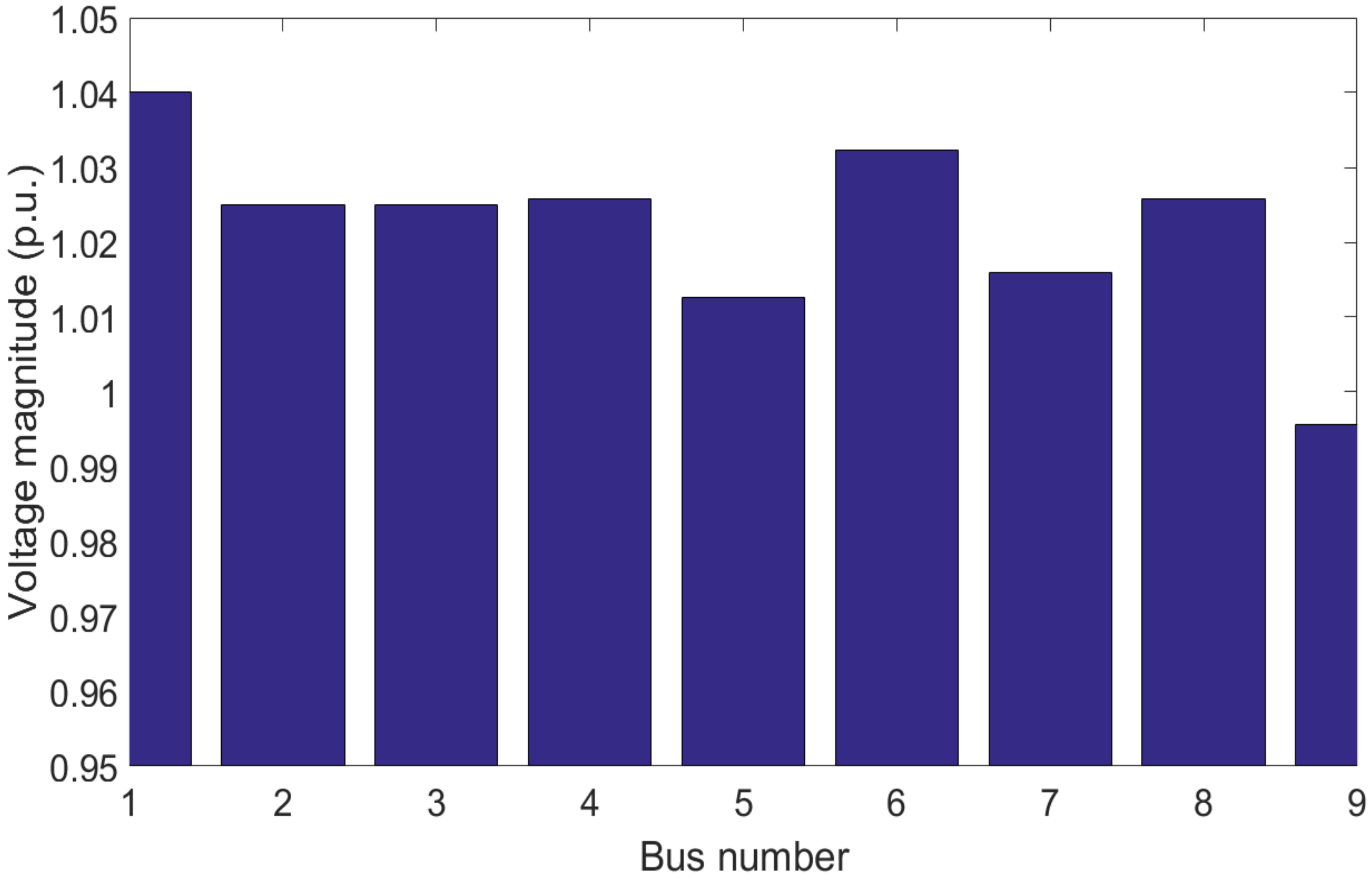
Branch Data

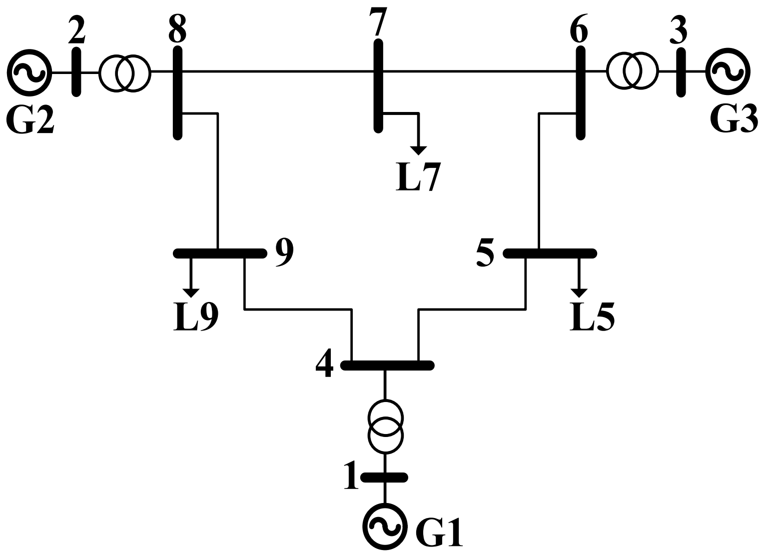
Brnch #	From Bus	To Bus	From Bus Injection P (MW)	From Bus Injection Q (MVAr)	To Bus Injection P (MW)	To Bus Injection Q (MVAr)	Loss (I^2 * Z) P (MW)	Loss (I^2 * Z) Q (MVAr)
1	1	4	71.64	27.05	-71.64	-23.92	0.000	3.12
2	4	5	30.70	1.03	-30.54	-16.54	0.166	0.90
3	5	6	-59.46	-13.46	60.82	-18.07	1.354	5.90
4	3	6	85.00	-10.86	-85.00	14.96	0.000	4.10
5	6	7	24.18	3.12	-24.10	-24.30	0.088	0.75
6	7	8	-75.90	-10.70	76.38	-0.80	0.475	4.03
7	8	2	-163.00	9.18	163.00	6.65	0.000	15.83
8	8	9	86.62	-8.38	-84.32	-11.31	2.300	11.57
9	9	4	-40.68	-38.69	40.94	22.89	0.258	2.19
						Total:	4.641	48.38



1.4 EXAMPLE WITH IEEE 9-BUS TEST SYSTEM

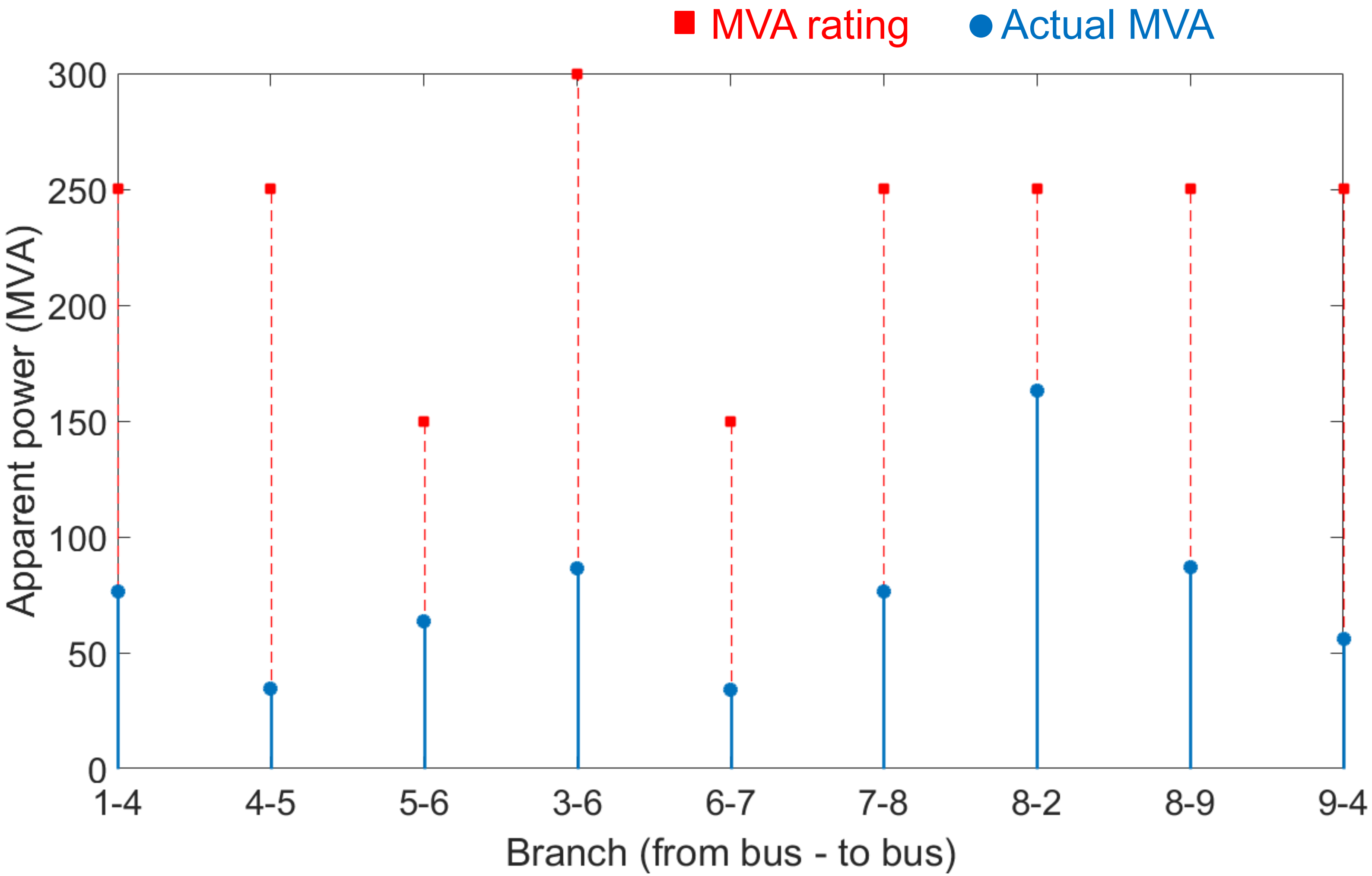
Results – Bus voltage magnitude

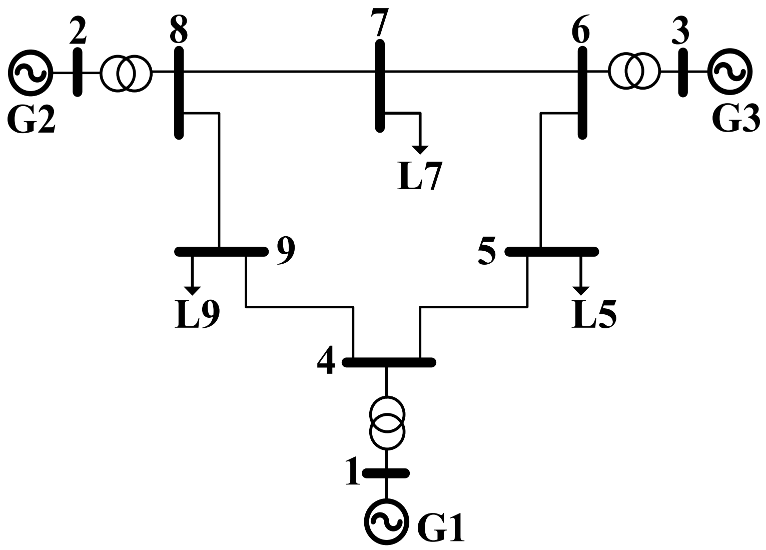




1.3 EXAMPLE WITH IEEE 9-BUS TEST SYSTEM

Results – Branch loading





2. Optimal power flow calculation

2.1 OPTIMAL POWER FLOW (OPF)

- Power flow calculation is based on known inputs
  - Active power of generators (except slack) and demand
  - Reactive power of demand
  - Set-point of voltage magnitude for generators (except slack)
  - Voltage magnitude and angle of slack generator

- Optimal power flow calculation finds the optimal values of certain (decision) variables to achieve a desired operational target (e.g. minimum operating cost)
  - Applications: long-term/day-ahead/intra-day/ operational planning
  - Computational expensive problem
  - Format:
    - Usually based on steady-sate (power flow) equations
    - Non-linear equations describing dynamic performance
    - Consideration of single/multiple scenarios
    - Consideration of probabilities

2.2 FORMAT OF AN OPTIMIZATION PROBLEM

Minimize/maximize

Objective function $\left\{ OF = \sum_{r=1}^{p} w_r \cdot f_r(\mathbf{x}) \right.$

subject to

Constraints $\left\{ \begin{array}{ll} g_i(\mathbf{x}) \leq 0, & i = 1,\ldots,m \\ h_j(\mathbf{x}) = 0, & j = m+1,\ldots,n \end{array} \right.$

considering the search space given by

Bounds $\left\{ x_k^{\min} \leq x_k \leq x_k^{\max}, \quad k = 1,\ldots,\mathrm{D} \right.$

Solution vector $\left\{ \mathbf{x} = [x_1, x_2, \ldots, x_{\mathrm{D}}] \right.$

2.2 FORMAT OF AN OPTIMIZATION PROBLEM – COMPLEXITIES

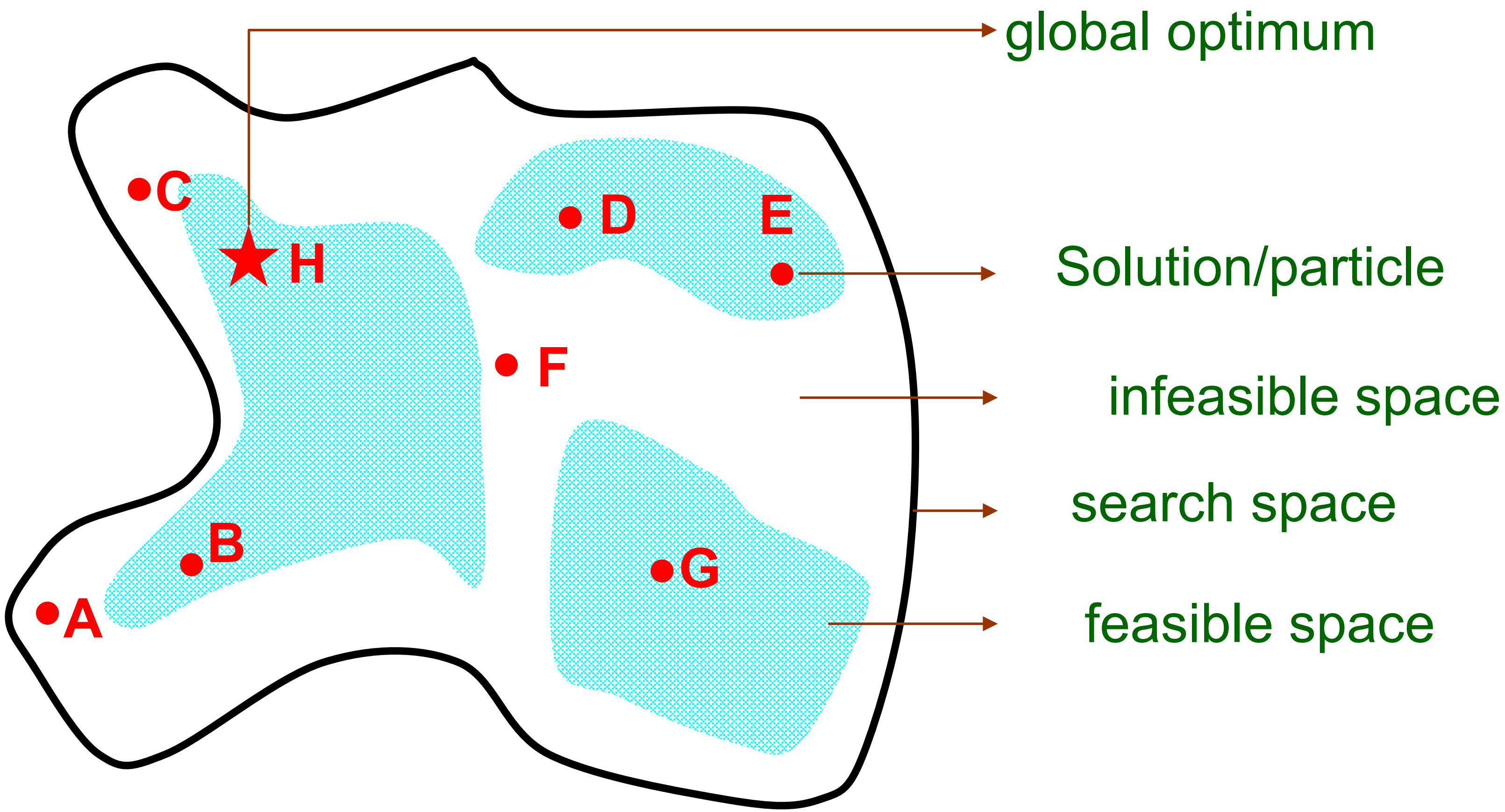
Problem type

- Single objective/multi-objective
- Constrained/unconstrained
- Continuous (real numbers).
- Combinatorial (countable items - integer numbers).
- Mixed-integer.

Problem Complexities

- High dimensional search space
- Non-convex, discontinuous search landscape
- Multimodality
- High numerical accuracy, high nonlinearity.
- Lack of analytical expressions
- High computational burden

2.2 FORMAT OF AN OPTIMIZATION PROBLEM – SEARCH SPACE



2.3 ECONOMIC DISPATCH

Minimize

$$OF = \sum_{i=1}^{\mathrm{N_g}} f_P^i\left(P_g^i\right) \quad \Big\} \text{ Dispatch cost}$$

subject to

$$\left.\begin{aligned} \mathbf{p}(\mathbf{v},\boldsymbol{\theta}) - \mathbf{p}_{\mathrm{g}} + \mathbf{p}_{\mathrm{d}} = \mathbf{0} \\ \mathbf{q}(\mathbf{v},\boldsymbol{\theta}) - \mathbf{q}_{\mathrm{g}} + \mathbf{q}_{\mathrm{d}} = \mathbf{0} \end{aligned}\right\} \text{ Nodal power balance}$$

$$\mathbf{s} \le \mathbf{s}_{\mathrm{max}} \quad \Big\} \text{ Branch flow limit}$$

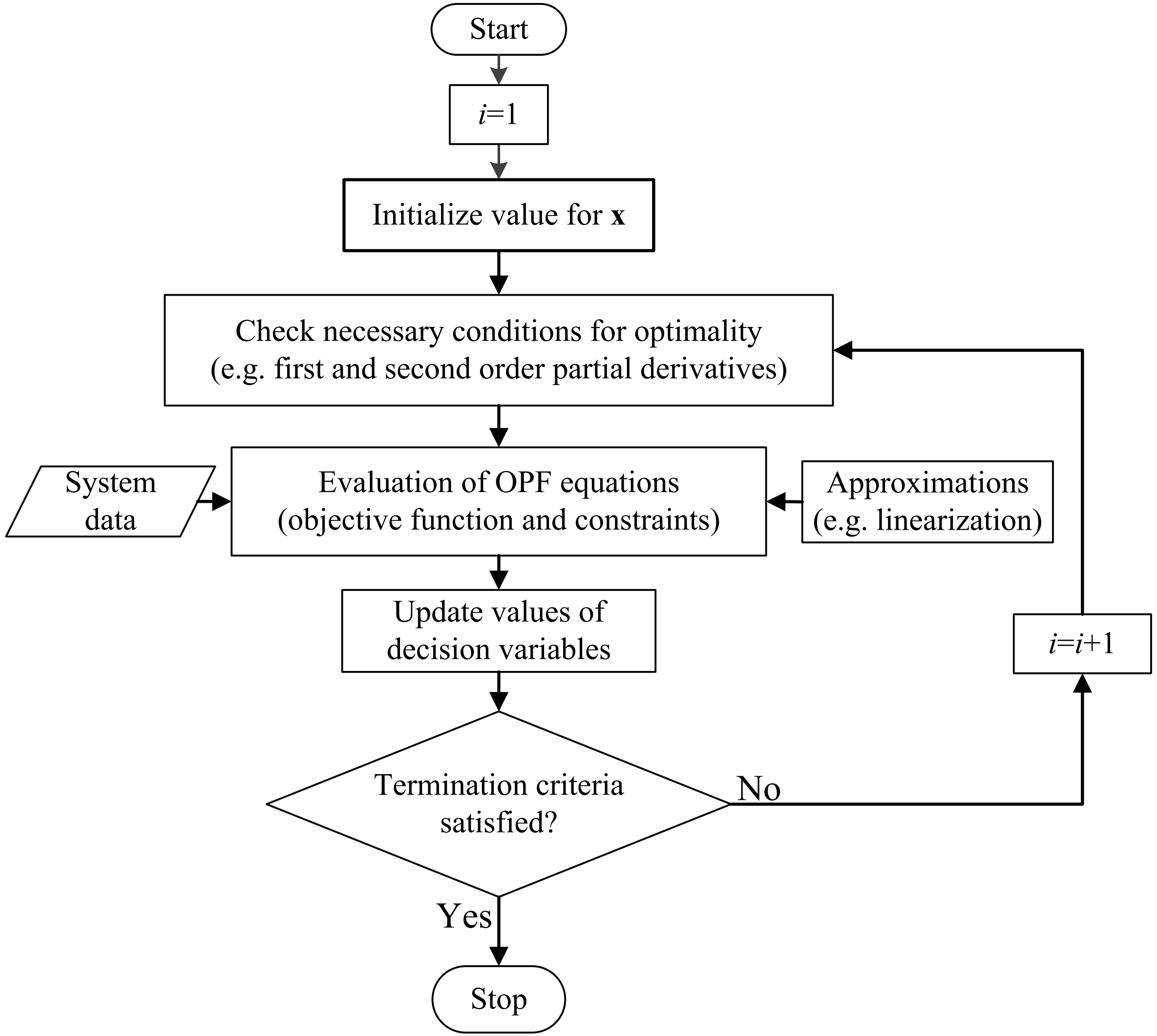
within the search space defined by

$$\mathbf{x}_{\mathrm{min}} \le \mathbf{x} \le \mathbf{x}_{\mathrm{max}}$$

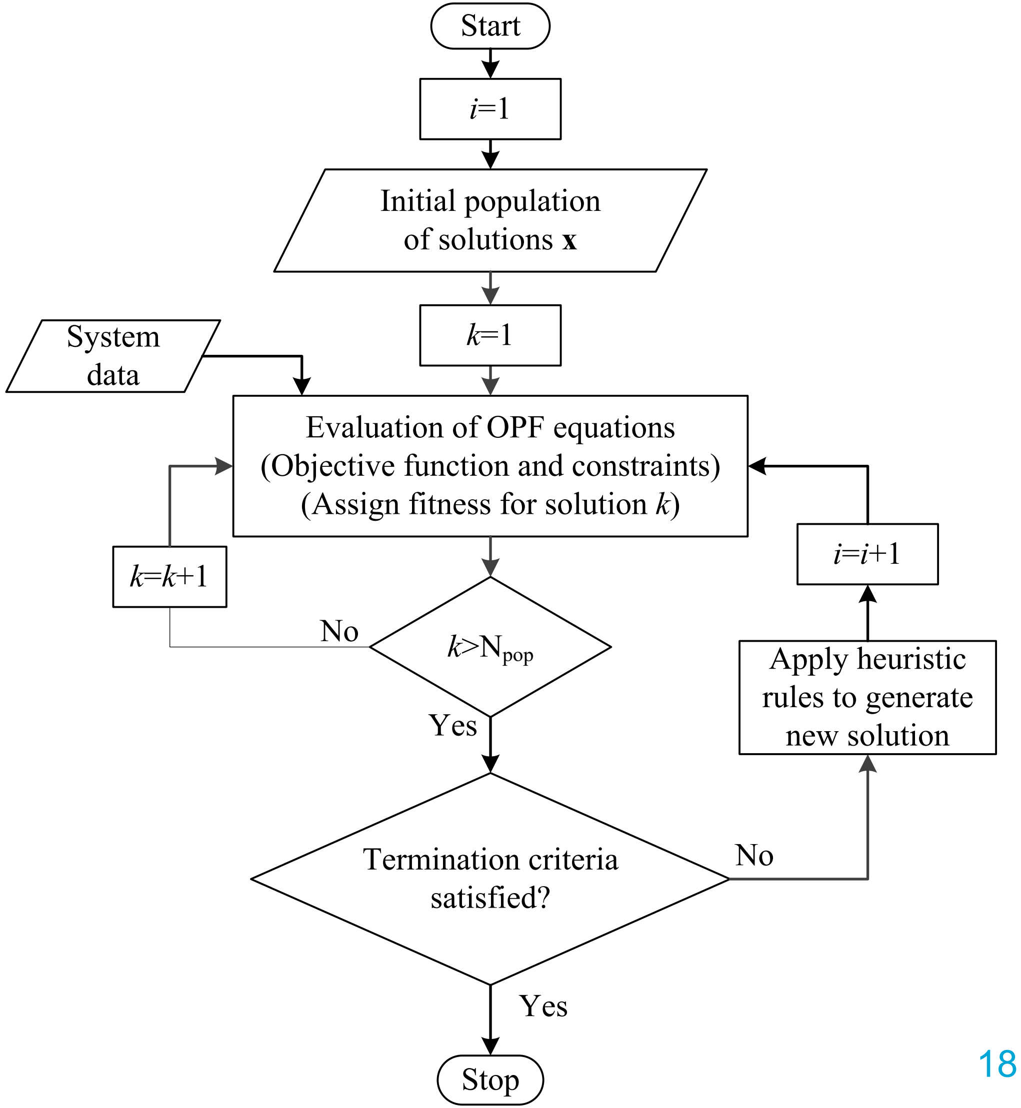
$$\mathbf{x} = \left[\theta_1,\ldots,\theta_{\mathrm{N_b}}, V_{\mathrm{m1}},\ldots,V_{\mathrm{mN_b}}, P_{g1},\ldots,P_{\mathrm{gN_g}}, Q_{g1},\ldots,Q_{\mathrm{gN_g}}\right] \quad \Big\} \text{ Bus voltages and generator output powers}$$

2.4 SOLUTION APPROACHES

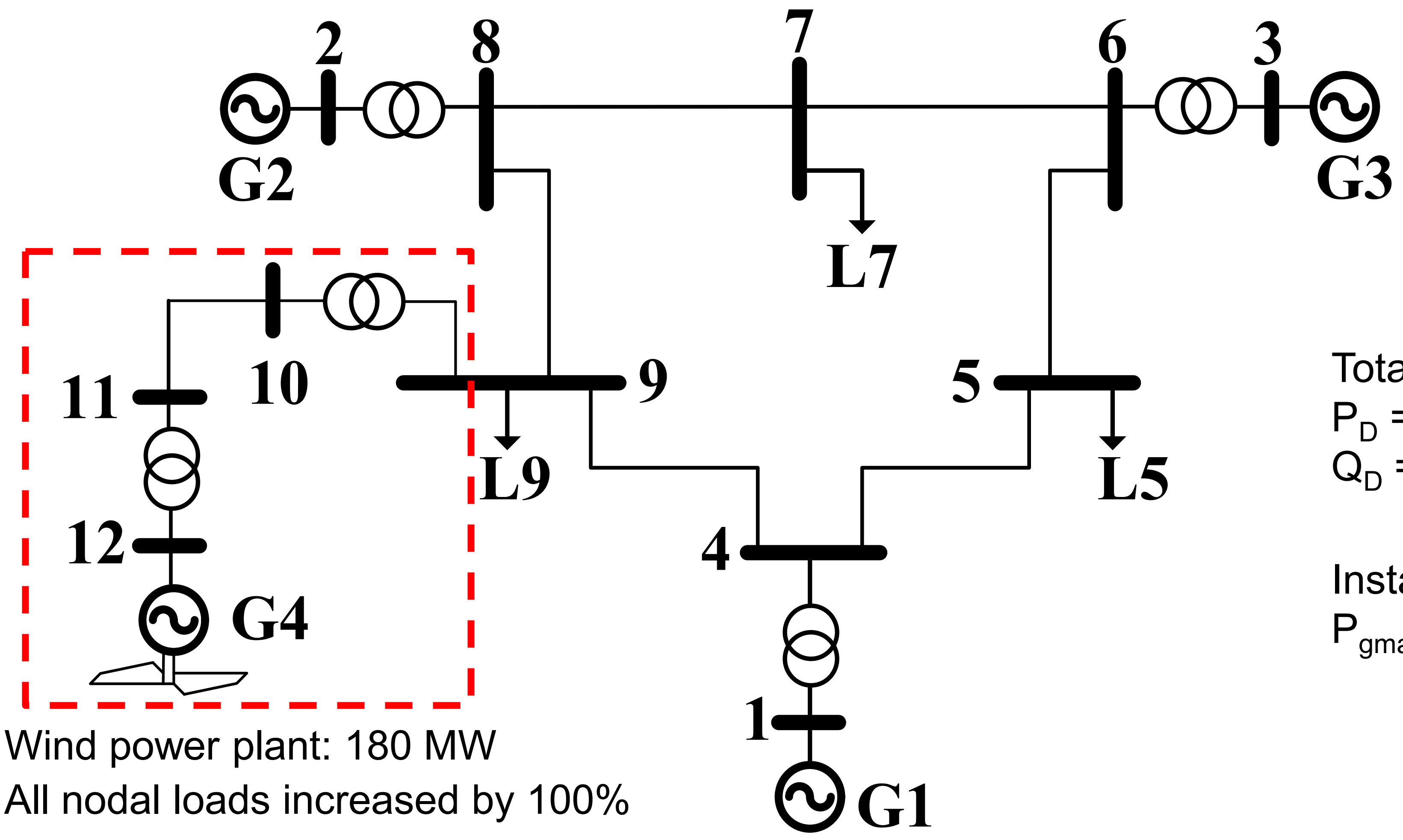
Conventional solvers



Heuristic solvers



2.5 MODIFIED IEEE 9-BUS TEST SYSTEM



Wind power plant: 180 MW
All nodal loads increased by 100%

Total demand:
P_D = 630 MW
Q_D = 230 MVar

Installed capacity:
P_{gmax} = 1000 MW

2.5 MODIFIED IEEE 9-BUS TEST SYSTEM

Results – Summary in Matlab command window

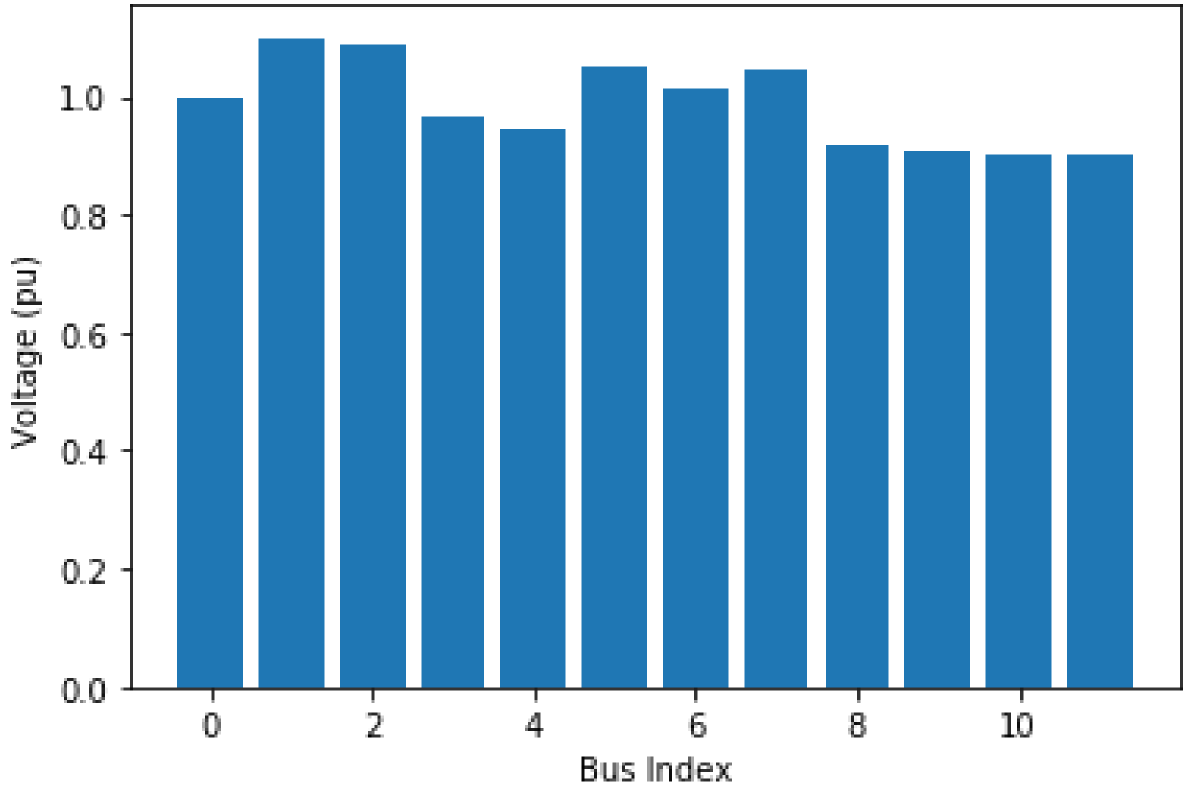
```
MATPOWER Version 6.0, 16-Dec-2016 -- AC Optimal Power Flow
MATPOWER Interior Point Solver -- MIPS, Version 1.2.2, 16-Dec-2016
 (using built-in linear solver)
 it    objective   step size   feascond     gradcond     compcond     costcond
----  ------------ --------- ------------ ------------ ------------ ------------
  0      8363.125               0.249617      4.83151      61.2245            0
  1     9271.0818    0.61134   0.0273033      7.91587       15.459    0.0494446
  2     9471.7038     1.1027   0.0159182      4.12957      7.29601    0.0104105
  3     9693.5985    0.53029  0.00197725     0.760058      1.91089    0.0113958
  4     9629.1017   0.089031 4.00425e-05    0.0852819     0.207201   0.00327501
  5     9502.3814    0.26994 0.000316454    0.0524247    0.0229664   0.00645574
  6     9491.3976    0.10042 4.33479e-05   0.00640794   0.00324347  0.000563203
  7     9481.8253   0.086481 0.000188667   0.00139129  0.000885627  0.000491102
  8     9480.1239   0.025114 1.44476e-05  6.89418e-05  9.44475e-05  8.73315e-05
  9     9480.0702 0.00063236 1.03412e-08   4.5557e-07  9.39902e-06  2.75748e-06
 10     9480.0605 0.00012647 2.83336e-10  1.16428e-08  9.39981e-07   4.9752e-07
Converged!
```

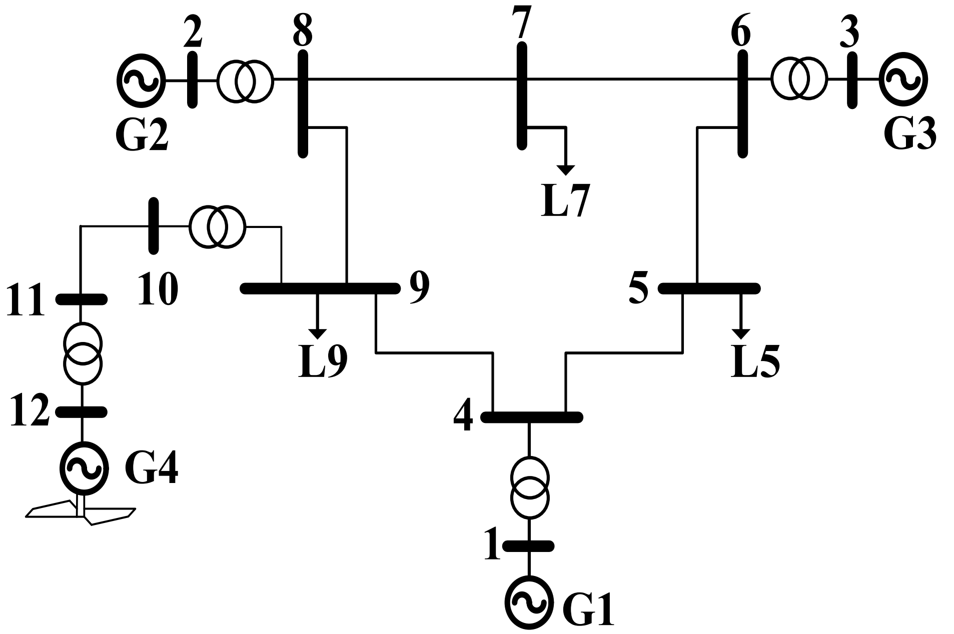
Minimum cost ($/h) & constraints fullfilled

$$OF = \sum_{i=1}^{N_g} f_P^i\left(P_g^i\right) \qquad f_P^i\left(P_g^i\right) = C_2\left(P_g^i\right)^2 + C_1 P_g^i + C_0$$

2.5 MODIFIED IEEE 9-BUS TEST SYSTEM

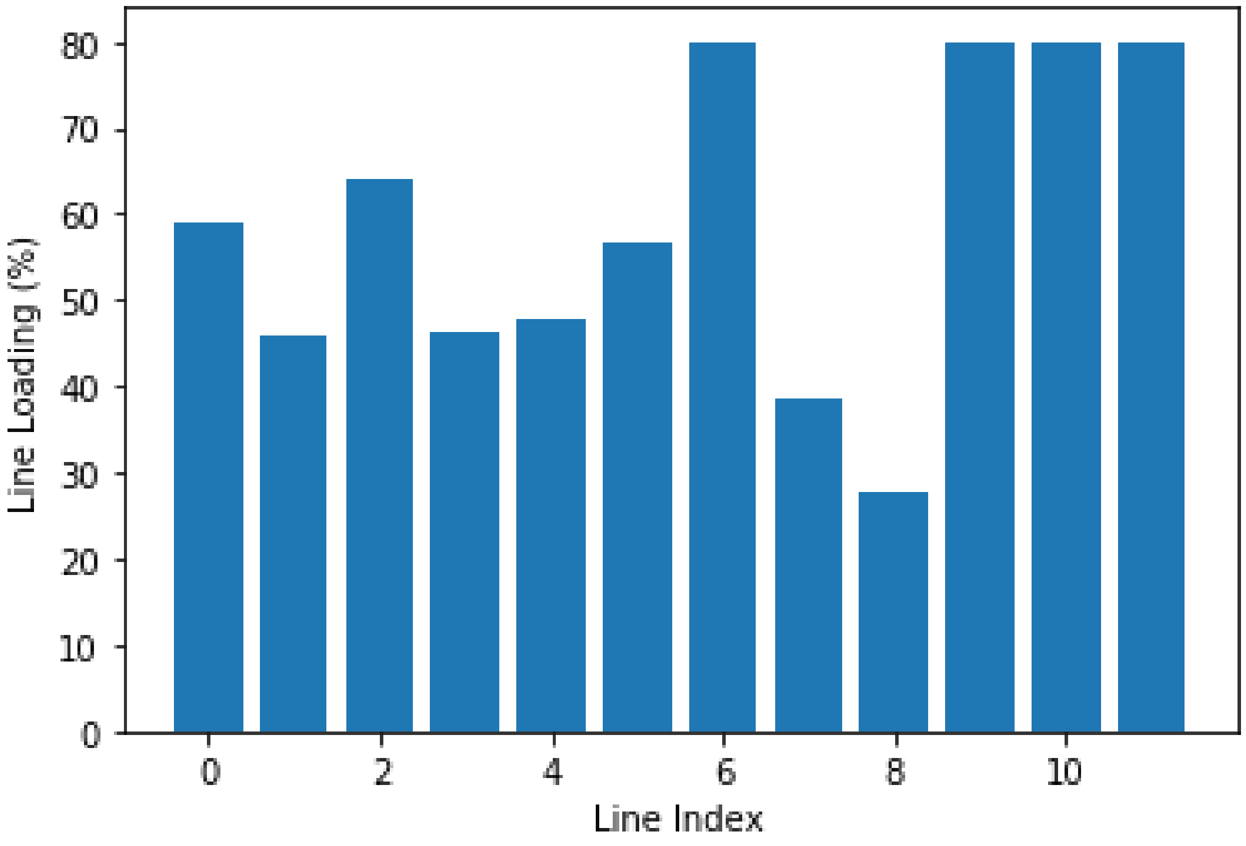
Results – Bus voltage magnitude

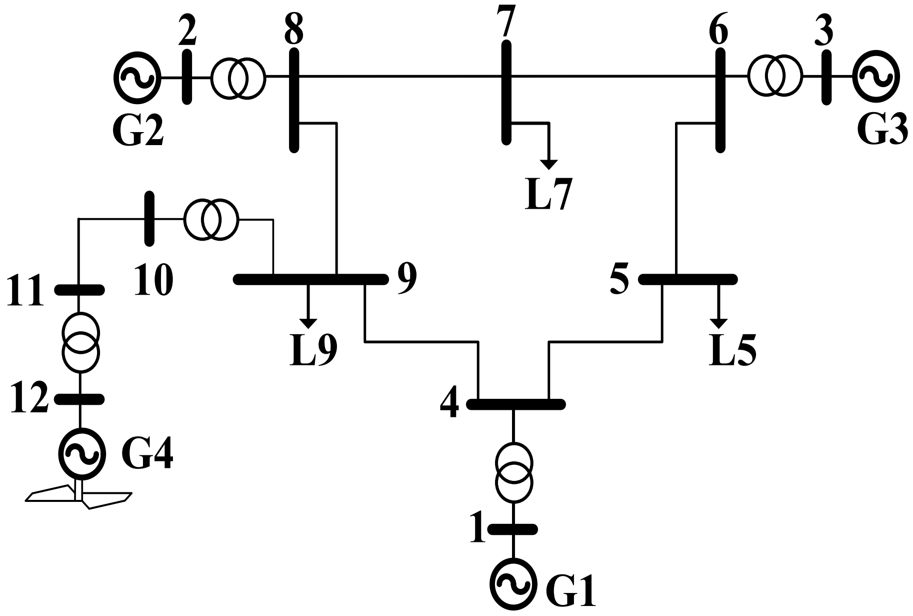




2.5 MODIFIED IEEE 9-BUS TEST SYSTEM

Results – Branch loading



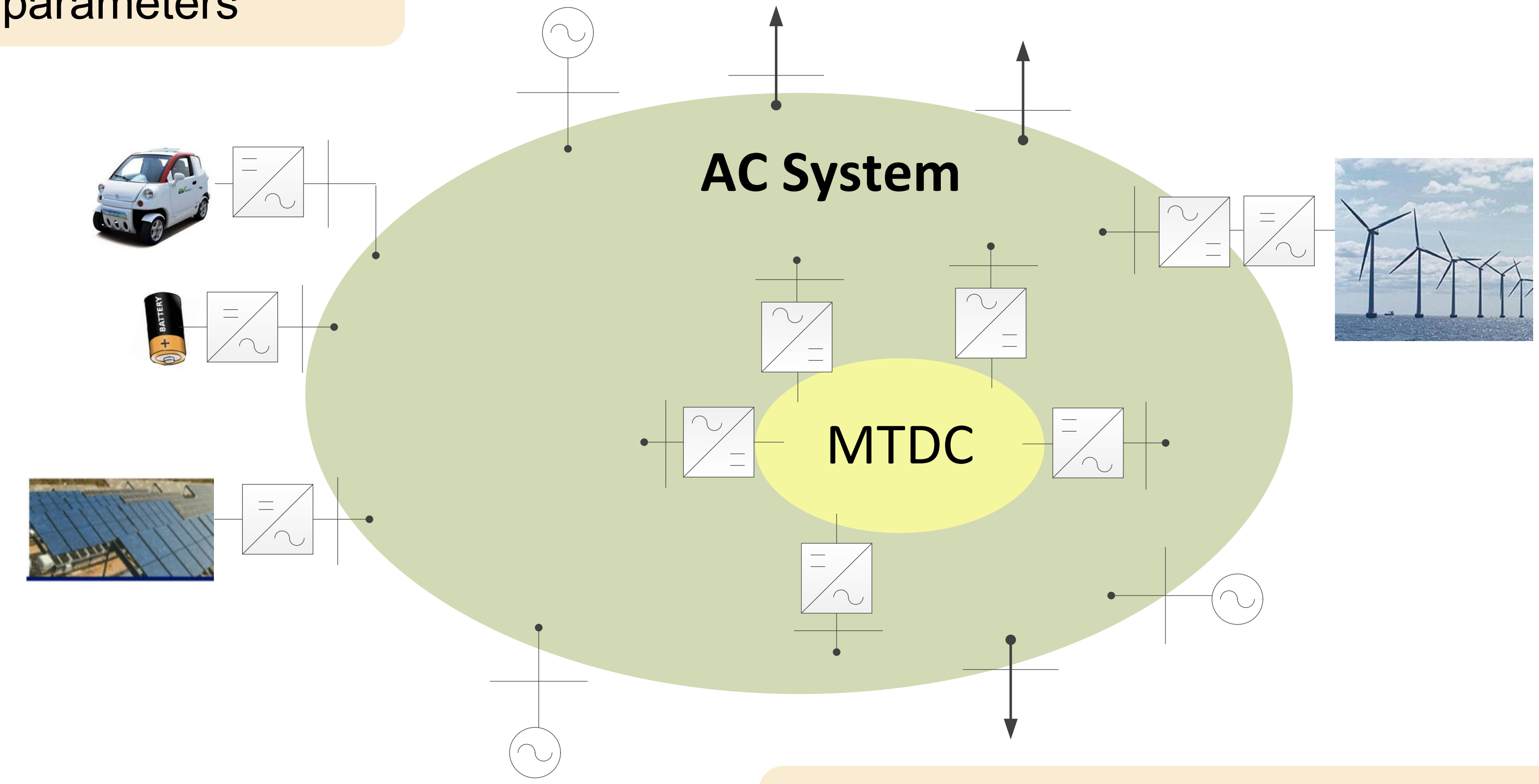


3. Probabilistic power flow calculation

3.1 SOURCES OF UNCERTAINTY

Load, Generation, Storage

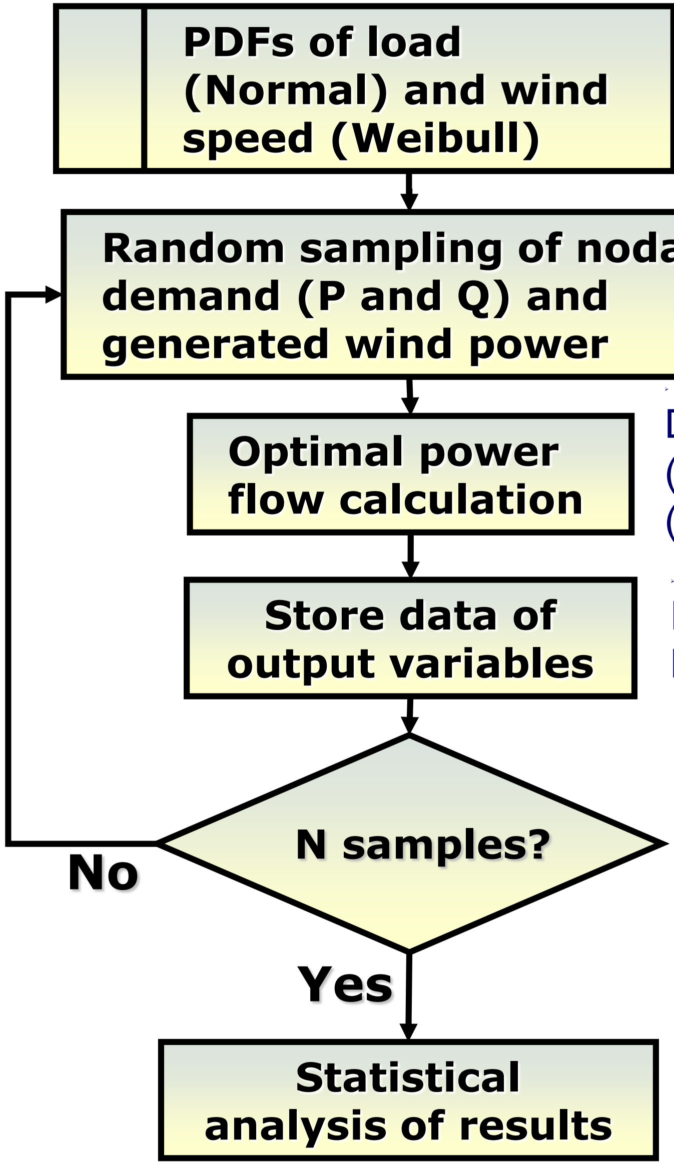
Time and spatial variation, composition, parameters



Network

Topology, parameters & settings (e.g., tap settings, temperature dependent line ratings)

3.2 PROBABILISTIC EVALUATION OF POWER FLOW



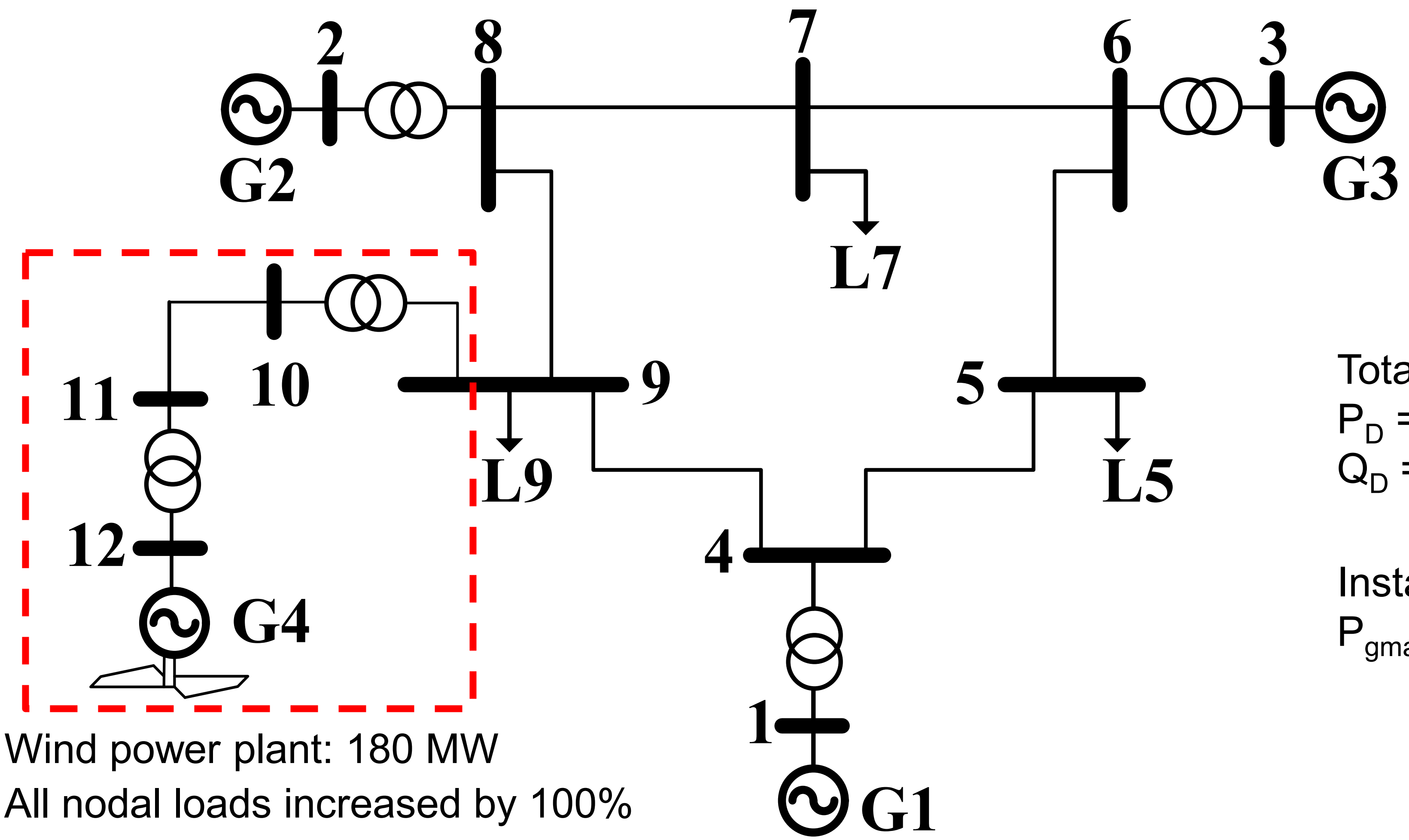
Models built based on collected historical data

Sampling technique (e.g. Latin Hypercube Sampling)

Determine the economic dispatch (minimum cost) of conventional (thermal) power plants.

Bus voltage magnitude and angle, branch power flows, losses, etc.

3.3 EXAMPLE WITH MODIFIED IEEE 9-BUS TEST SYSTEM



Wind power plant: 180 MW
All nodal loads increased by 100%

Total demand:
P_D = 630 MW
Q_D = 230 MVar

Installed capacity:
P_{gmax} = 1000 MW

3.3 MODIFIED IEEE 9-BUS TEST SYSTEM

PDF of demand active power:

$$f\left(x|\mu,\sigma\right)=\frac{1}{\sigma\sqrt{2\pi}}e^{\frac{-(x-\mu)^2}{2\sigma^2}}$$

μ: mean value

σ: standard deviation

x : active power

PDF of wind speed:

$$f\left(x|a,b\right)=\frac{b}{a}\left(\frac{x}{a}\right)^{b-1}e^{-\left(\frac{x}{a}\right)^b}$$

a: scale parameter

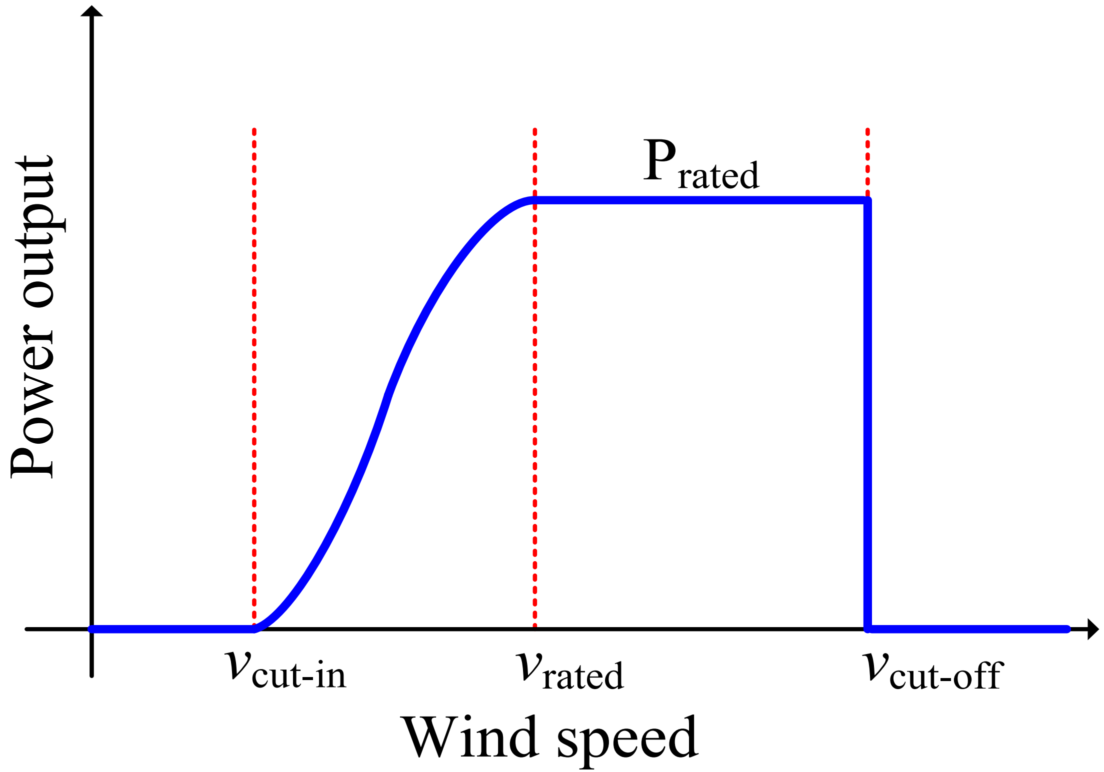
b: shape parameter

Quadratic cost function of thermal generators:

$$f_P\left(P_g\right)=C_2P_g^2+C_1P_g+C_0$$

3.3 MODIFIED IEEE 9-BUS TEST SYSTEM

Power curve of a pitch regulated wind generation system



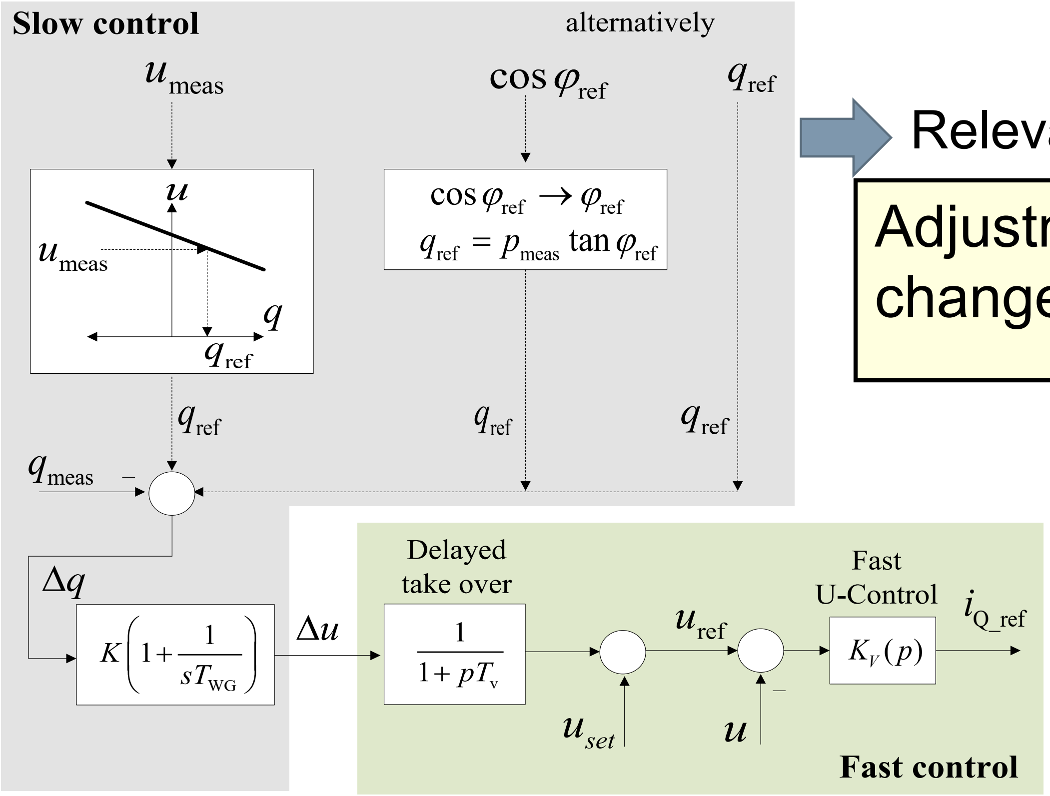
Power output

$$
\begin{cases}
0 & v \leq v_{cut\text{-}in} \\
\dfrac{P_{rated}\left(v^3 - v_{rated}^3\right)}{\left(v_{rated}^3 - v_{cut\text{-}in}^3\right)} & v_{cut\text{-}in} < v < v_{rated} \\
P_{rated} & v_{rated} \leq v < v_{cut\text{-}off} \\
0 & v \geq v_{cut\text{-}off}
\end{cases}
$$

Further reading: Vaishali Sohoni, S. C. Gupta, and R. K. Nema, “A Critical Review on Wind Turbine Power Curve Modelling Techniques and Their Applications in Wind Based Energy Systems", Journal of Energy, vol. 2016, Article ID 8519785, pp. 1-19, June 2016.

3.3 MODIFIED IEEE 9-BUS TEST SYSTEM

Hierarchical Var control scheme of wind generation systems



Relevant for power flow, OPF, and PPF calculations

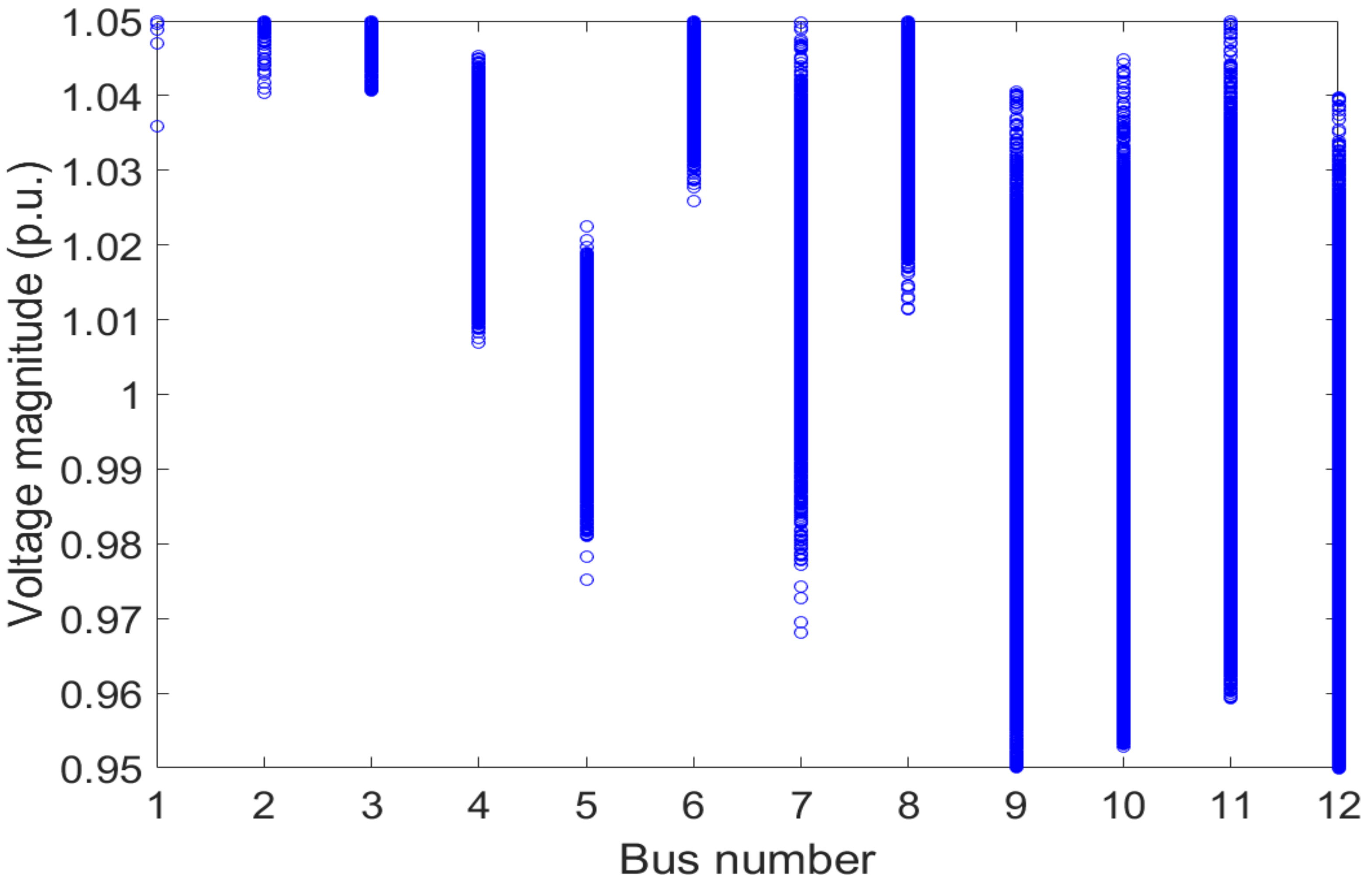
Adjustment of the slow response to small operational changes (i.e. time frame of 10 s to few minutes)

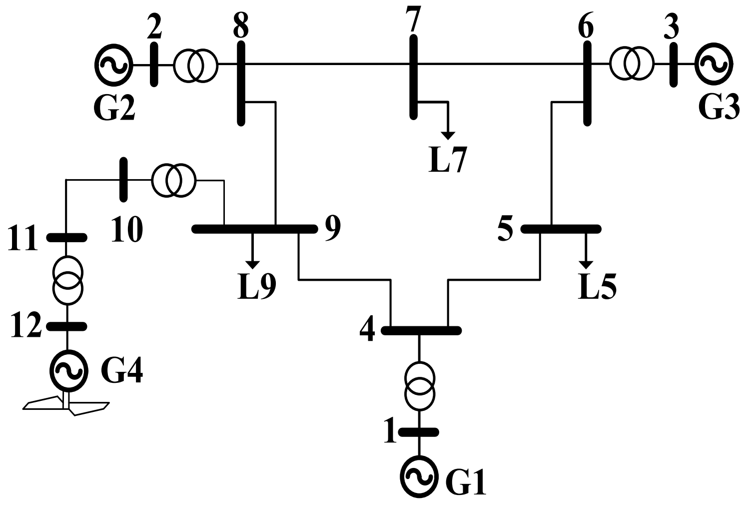
Relevant for RMS and EMT simulations

Fast response of controllers to large operational changes (i.e. time frame of few µs to few seconds)

3.4 MODIFIED IEEE 9-BUS TEST SYSTEM – EXAMPLE RESULTS

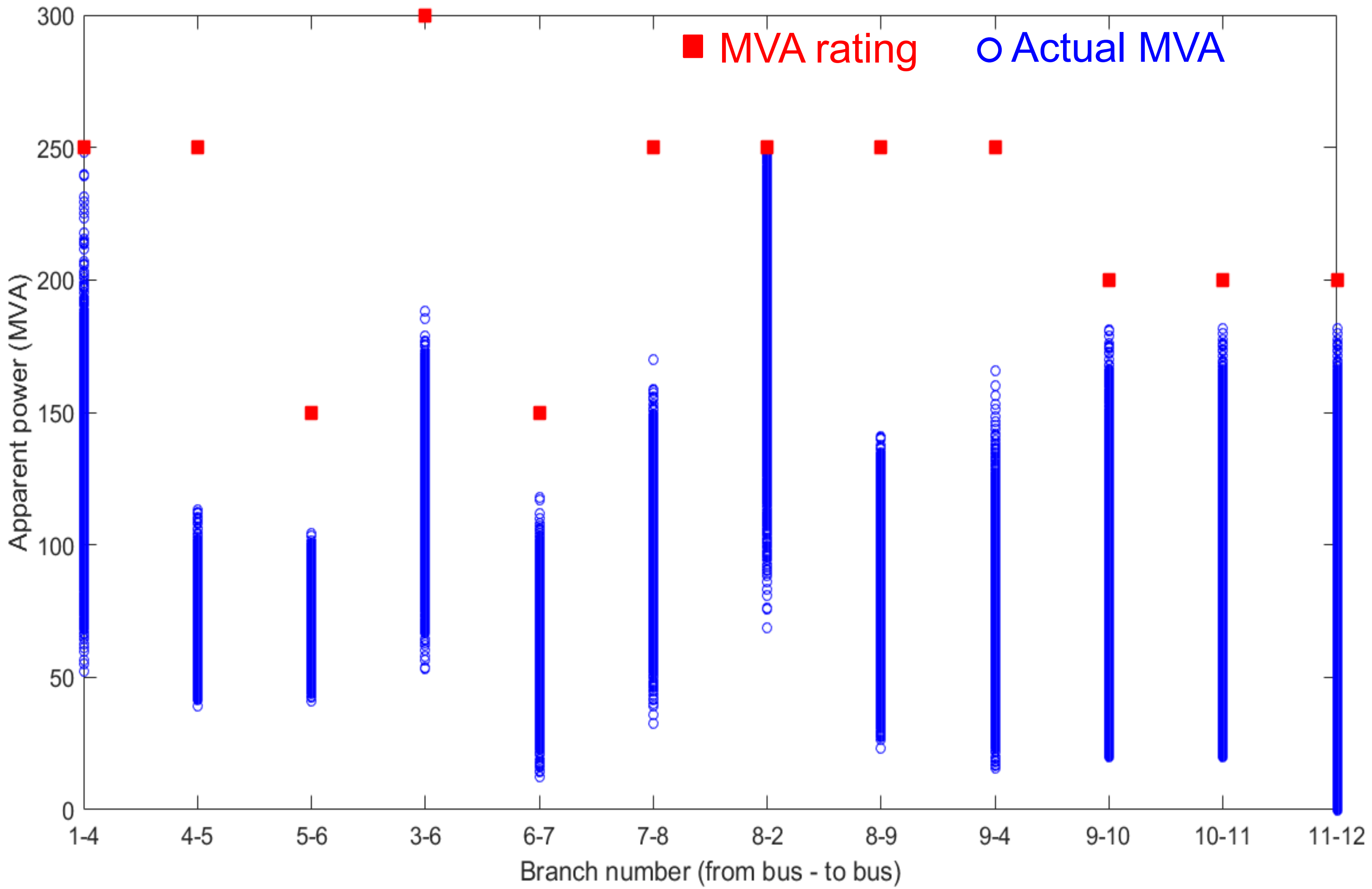
Bus voltage magnitudes (Wind power plant with unit power factor)

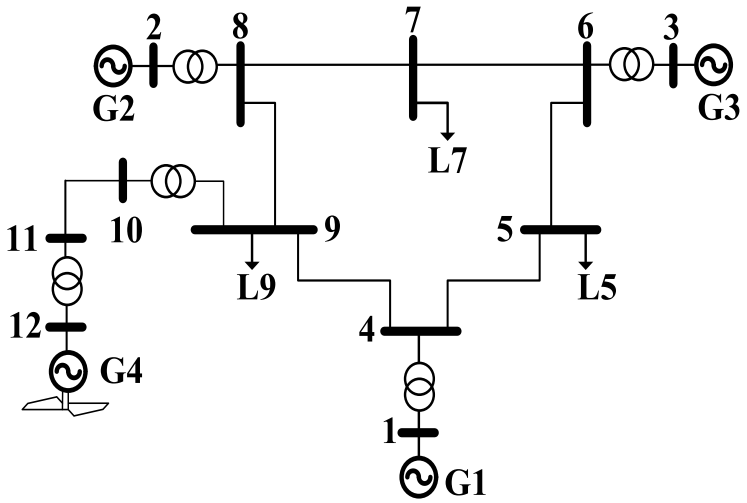




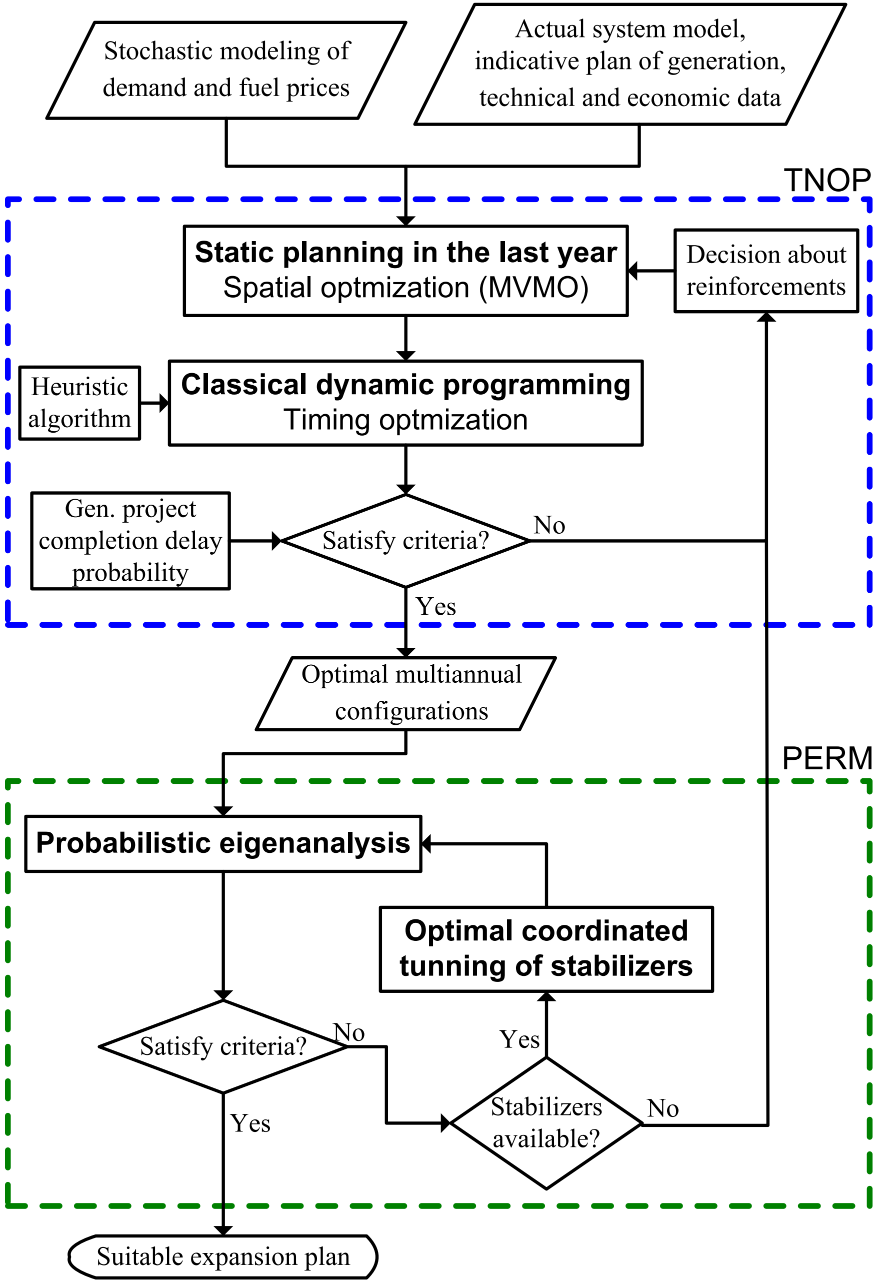
3.4 MODIFIED IEEE 9-BUS TEST SYSTEM – EXAMPLE RESULTS

Branch loading (Wind power plant with unit power factor)

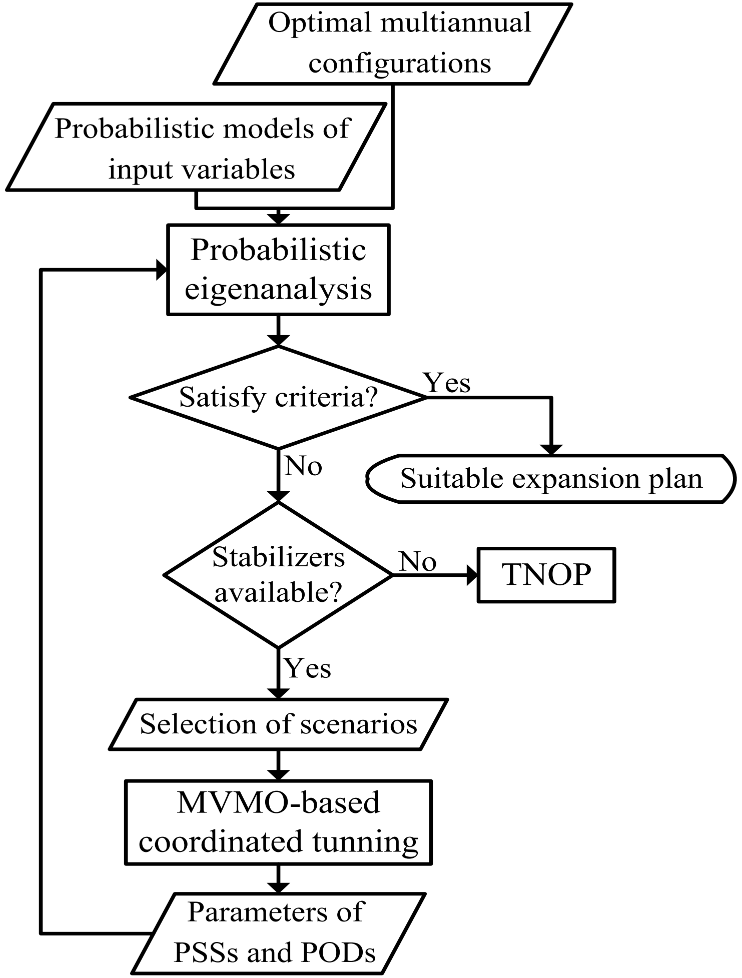




3.5 OPERATIONAL PLANNING WITH SECURITY CONSIDERATIONS



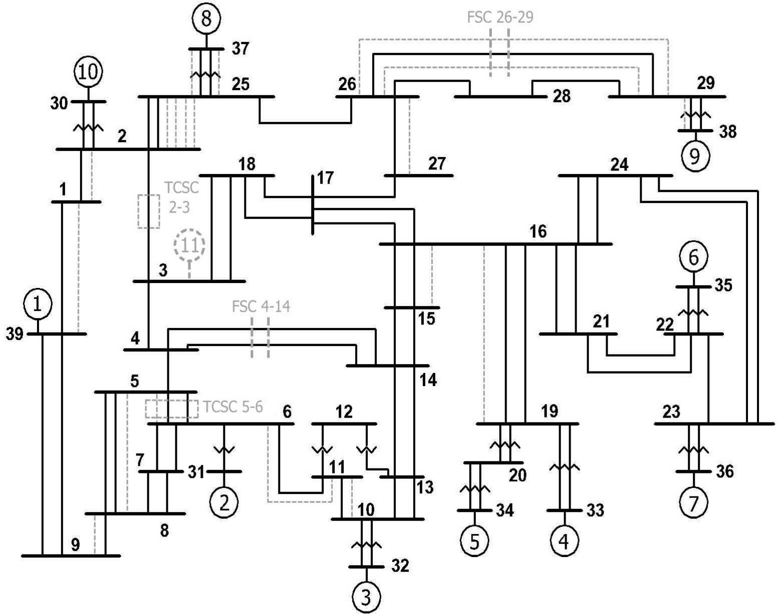
Probabilistic assessment of system stability



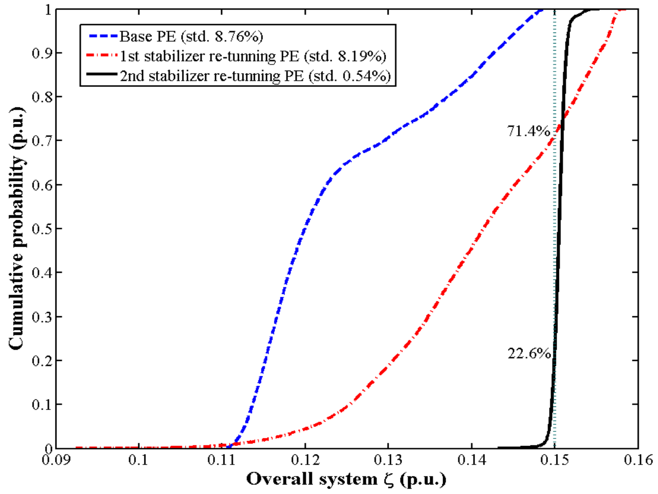
TNOP: Transmission network operational planning
PERM: Probabilistic eigenanalysis-based recursive method

3.5 OPERATIONAL PLANNING WITH SECURITY CONSIDERATIONS

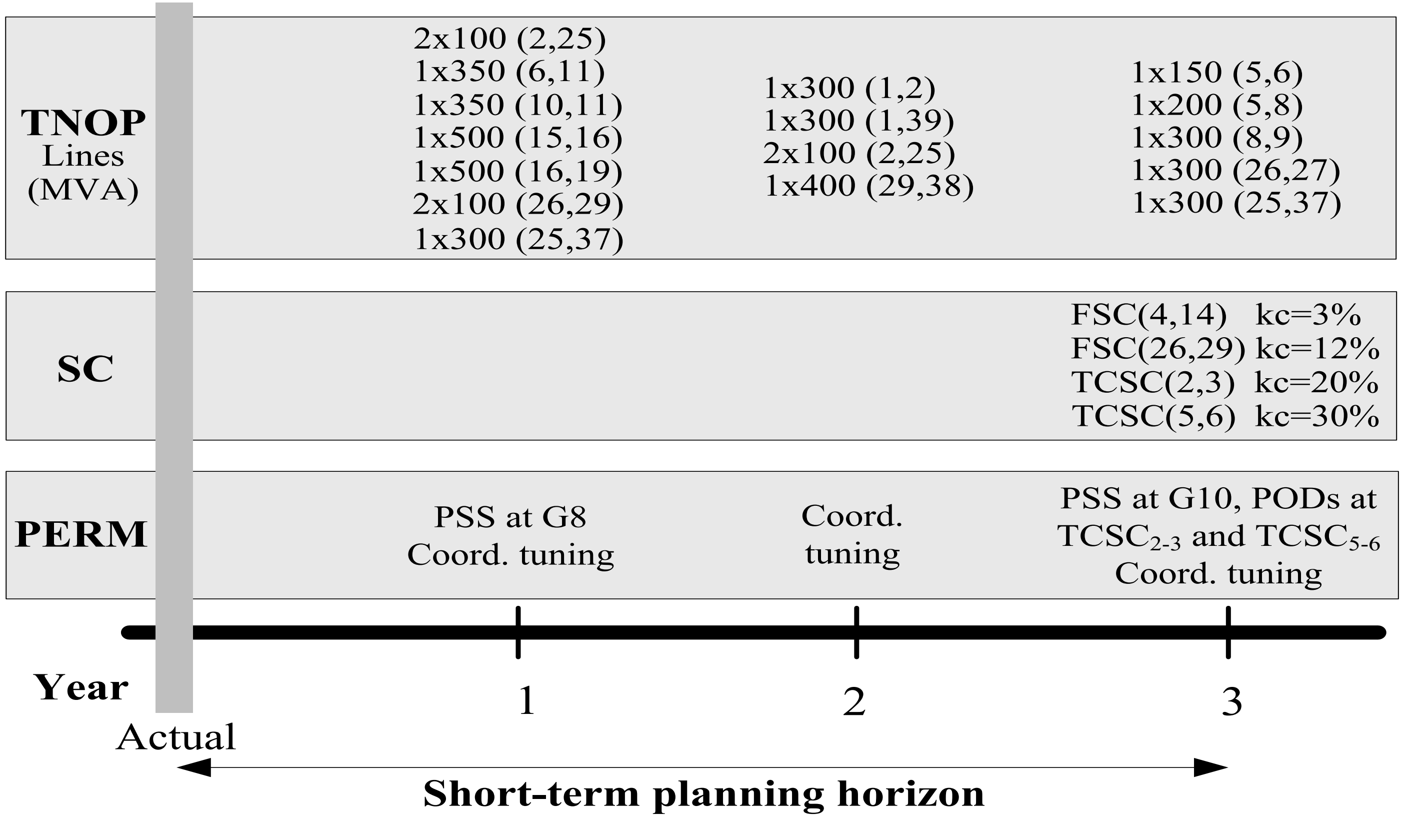
IEEE New England 39 Bus test system



Reduction of Instability risk



Optimal investment sequence



TNOP: Transmission network operational planning
SC: Series compensation
PERM: Probabilistic eigenanalysis-based recursive method
(i,j): transmission route between bus i and bus j
kc: compensation percentage
FSC: Fixed-series capacitor
TCSC: Thyristor-Controlled Series Capacitor
PSS: Power System Stabilizer
POD: Power Oscillation Damper

4. Conclusions

4.1 OPTIMIZATION IN POWER SYSTEM OPERATION & PLANNING

Features

- Consideration of static and dynamic aspects
- Many variables and restrictions (high nonlinearity)
- Different types of uncertainties
- Interplay between different decision making in different time horizons

Systems with high RES

Challenges:

- **Extracting relevant information (mining) of large volumes and diverse types of uncertainties**
- **Harmonizing multiple and different objectives**
- **Highly complex, high dimensional, and computationally expensive optimization problems**

4.2 MODERN HEURISTIC OPTIMIZATION TEST BEDS

Join and contribute to the IEEE PES Working Group on Modern Heuristic Optimization and the Task Force on Modern Heuristic Optimization Test Beds

Web: http://sites.ieee.org/psace-mho/

Contribute to

- Development of new tests beds (operation and planning)
- Optimization by considering steady-state/dynamic performance
- Application of statistical tests for performance assessment
- Joint publications and task force report.

Contact: Dr. José Rueda. Delft University of Technology, Netherlands

Email: j.l.ruedatorres@tudelft.nl

4.2 MODERN HEURISTIC OPTIMIZATION TEST BEDS

Developed test beds

- Optimal power flow problems (2014)
- Stochastic OPF & Optimal scheduling of distributed energy resources (2017)
- Stochastic OPF & Dynamic OPF - Systems with RES, EVs, and DSR (2018)
- Optimal transmission expansion planning – Deterministic (2019)
- Optimal transmission expansion planning – Probabilistic (2020) OPEN COMPETITION

Web: http://sites.ieee.org/psace-mho/

Contact: Dr. José Rueda. Delft University of Technology, Netherlands

Email: j.l.ruedatorres@tudelft.nl

Thanks for your attention!