Development of a Probabilistic Power Flow Model to Study PEV Grid Interactions

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How can PEVs best contribute to the overall energy system?

- Interactions with the Grid
  - –Charging infrastructure
    - G2V, V2G, V2H
    - PEV consumer behavior
    - Incentives & disincentives
  - –Renewables integration
    - PEVs as virtual distributed storage?
  - –Transmission/distribution effects
  - –Cost or revenue implications
  - –Total GHG inventory
    - Make the right systemic decisions

We need a tool to study these questions

- Probabilistic modeling methodology
  - Electrical grid power flows
    - Power injections & demands
    - Probabilistic load flow (PLF)
  - PEV & renewable energy integration
  - Not just mean or worst-case analyses
    - Statistical metrics
      - E.g. 6-sigma design
  - Computationally efficient
    - Large system models
    - Long simulated period

We are planning an extensible and robust methodology

- Modeling tool objectives
  - Linear (DC) and non-linear (AC) formulations
  - Scale flexibility
    - Evaluate linked scalable grid networks
      - E.g. Trans-national, town, city and province wide
  - Finite element (FE) approach
    - Nodal & element properties
      - Object-oriented approach
    - Accommodate future technology additions
      - E.g. PEV consumer models, wind turbines
    - Sub-structuring
    - Iterative non-linear solution techniques
    - System optimization

Monte Carlo simulation can yield stochastic solutions

- Advantages
  - Re-use existing code
  - Relatively easy to program
  - Fully non-linear
- Disadvantages
  - Computationally costly
    - 10,000's of runs
  - Difficulty capturing the tails of the distribution
    - Extreme events
- Use to validate statistical methods
- Previous MC PHEV study at IESVic
  - 3 sample BC Hydro distribution networks

A direct statistical approach has a number of advantages

- Single pass solution
  - Computationally efficient
    - Allows for rapid model modifications & re-runs
    - Facilitates 'what-if' design, analysis and planning process
  - Represent state vectors and line flows as PDFs
    - Linearization is required
      - DC (and AC) load-flow problem solution
      - Multi-linearization about operating points
    - Statistical independence assumption
      - Could in general be dependent
    - Obtain output PDFs by convolution

PDF: probability density (or distribution) function – describes the probability of a random variable having a given value.

Numerically there are a number of options to handle the convolution process

- Numerical convolution
  - –Laplace transforms, FFT
- Cumulant-based methods
  - –Linearized system
    - Simple addition of variable's cumulants
    - Zhang & Lee
      - – Gram-Charlier series reconstruction
      - – Based on Hermites (polynomial derivatives of normal distribution)
    - Alternate expansions
      - – Edgeworth types
      - – Cornish-Fisher

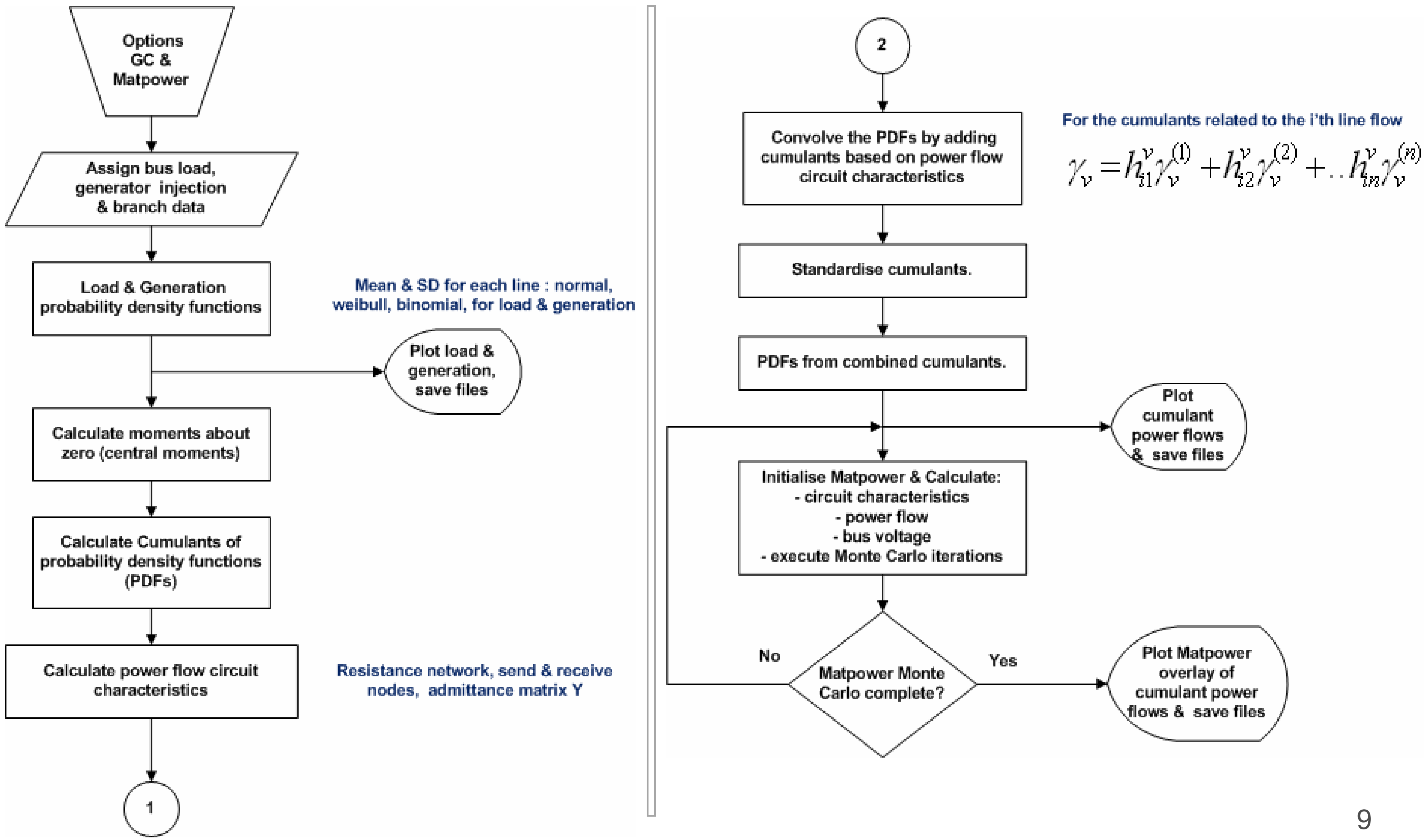
Zhang, P. and Lee, S. Probabilistic load flow computation using the method of combined cumulants and Gram-Charlier expansion," IEEE transactions on power systems, Vol. 19, No. 1, 2004, pp. 676.

We have so far validated the results for simple standard IEEE DC networks

- GC_Code
  - Cumulant/Gram-Charlier method
- MATPOWER Monte Carlo (MMC)
  - Deterministic DC & AC power flow simulation
  - Monte Carlo iterations for validation of GC_Code
- Development status
  - Standalone GC verification
    - Normal, weibull & binomial
  - Proof of concept GC_Code in Matlab
  - Future C++ code development

MATPOWER: Zimmerman, Murillo-Sanchez, G., \MATPOWER - A Matlab Power System Simulation Package. www.pserc.cornell.edu/matpower, Vol. 3.2, 2007.

GC_Code flowchart, including Monte Carlo MATPOWER validation



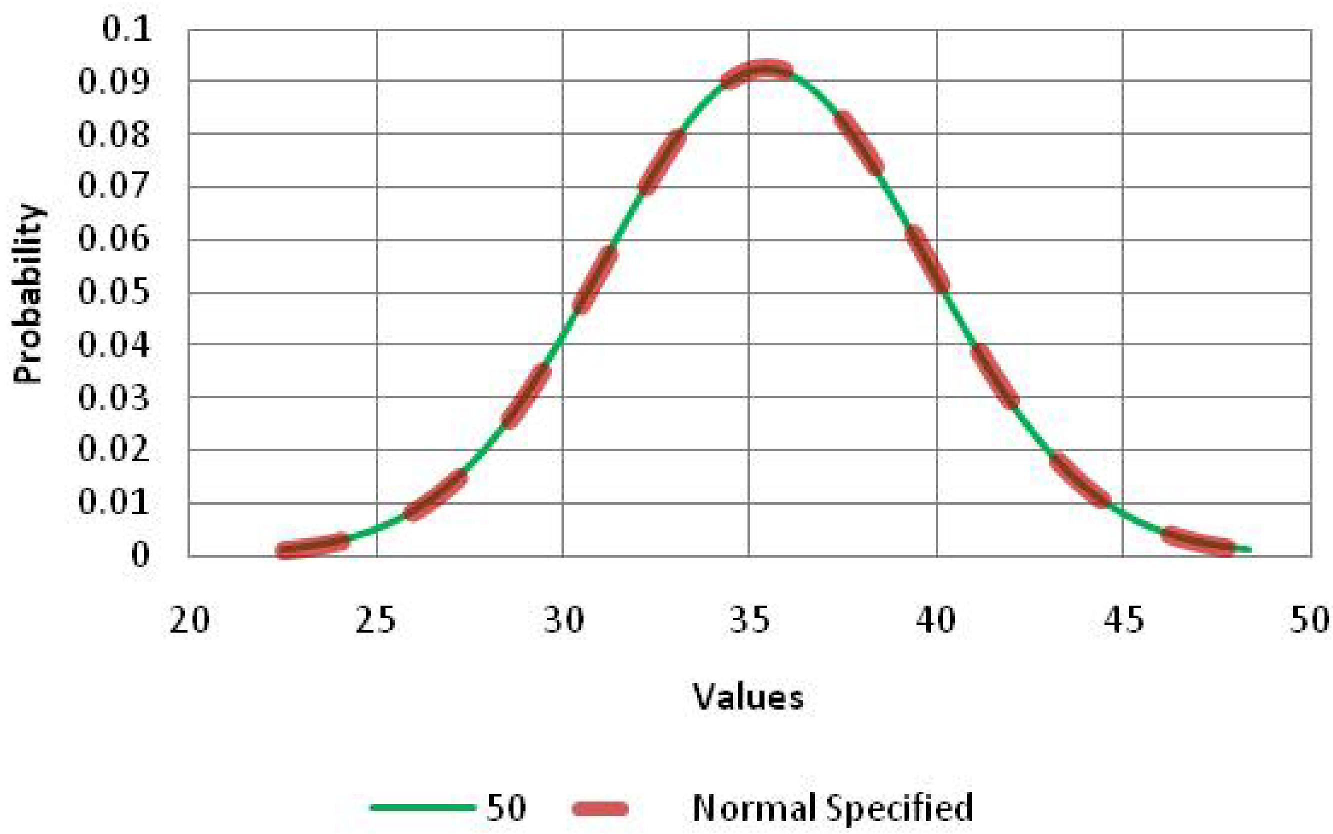
Standalone GC verification

Three standard distributions have been tested

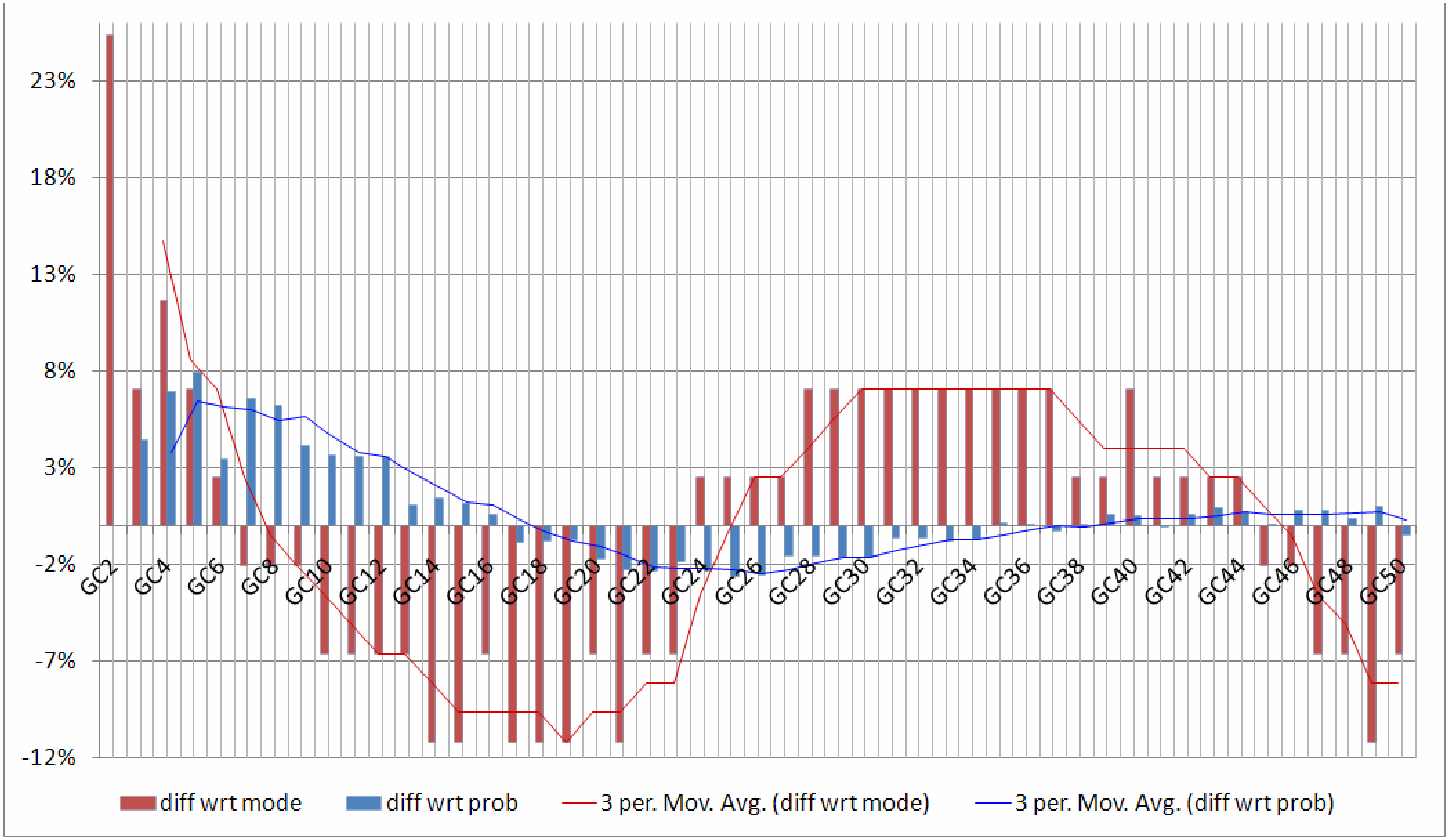
- Normal distribution (standard assumption)
  - Exact replication
  - Independent of GC order (2 to 50)
- Weibull distribution (e.g. wind power)
  - Increasing GC coefficients improves results
    - GC=8, 6% over prediction
  - Mean value varies
    - GC=8, -2% under prediction
- Binomial (PEV presence/not)
  - Discrete distribution
    - Still in final development testing

For normal, distributions & means are independent of GC order

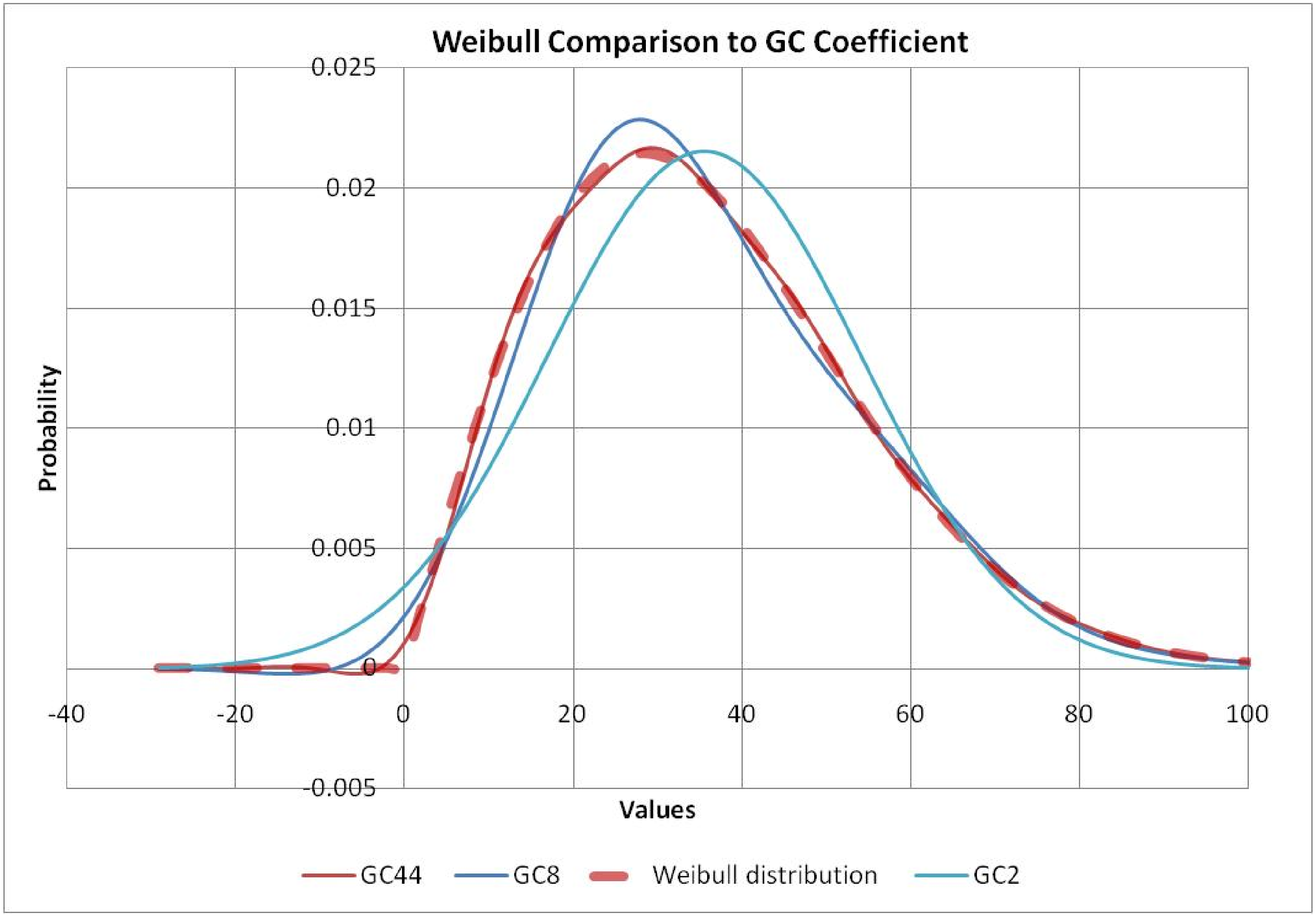
- Normal distribution
  - Exact replication of normal distribution by GC_Code cumulant process



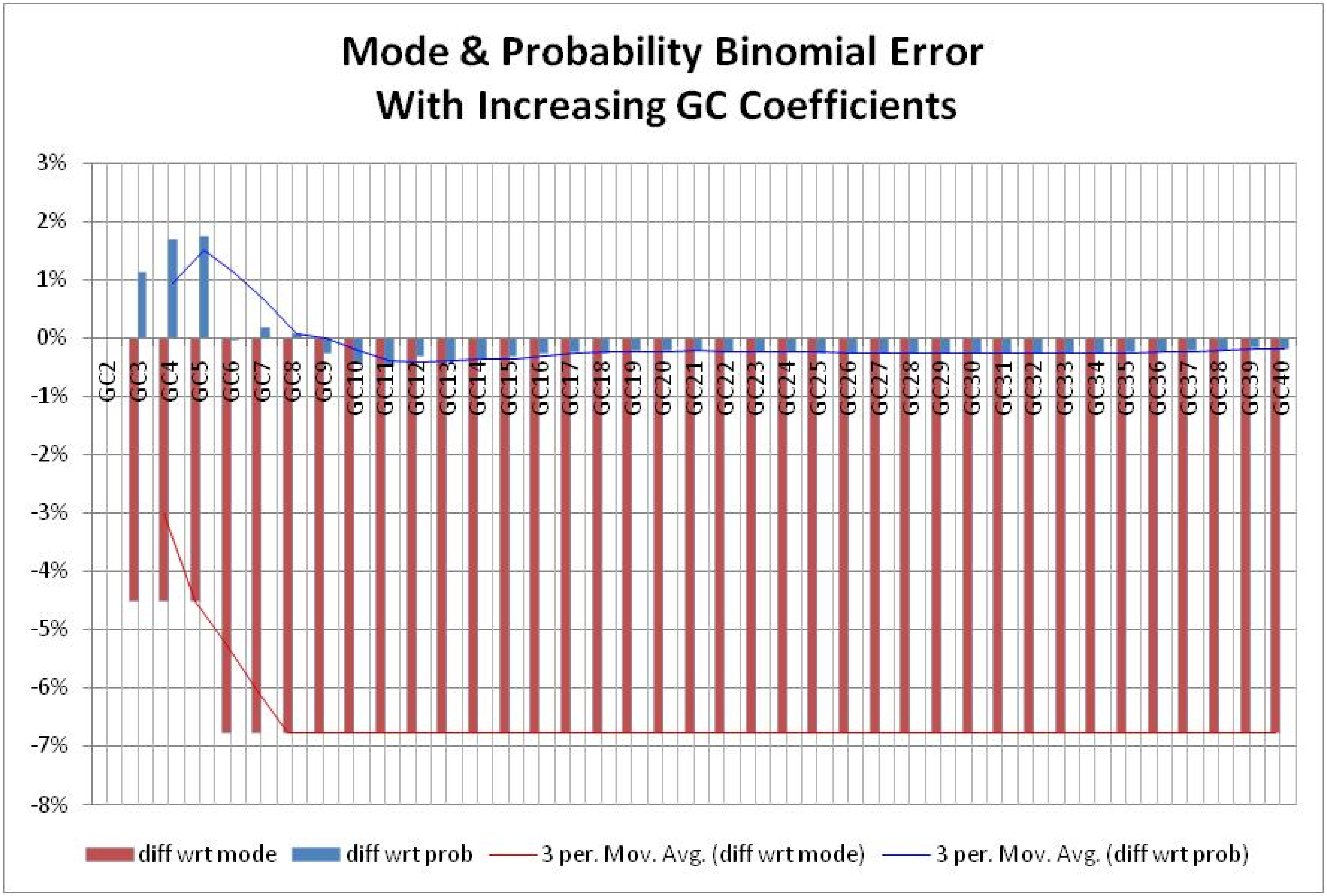
For Weibull, increasing GC order improves probability prediction, mode variable



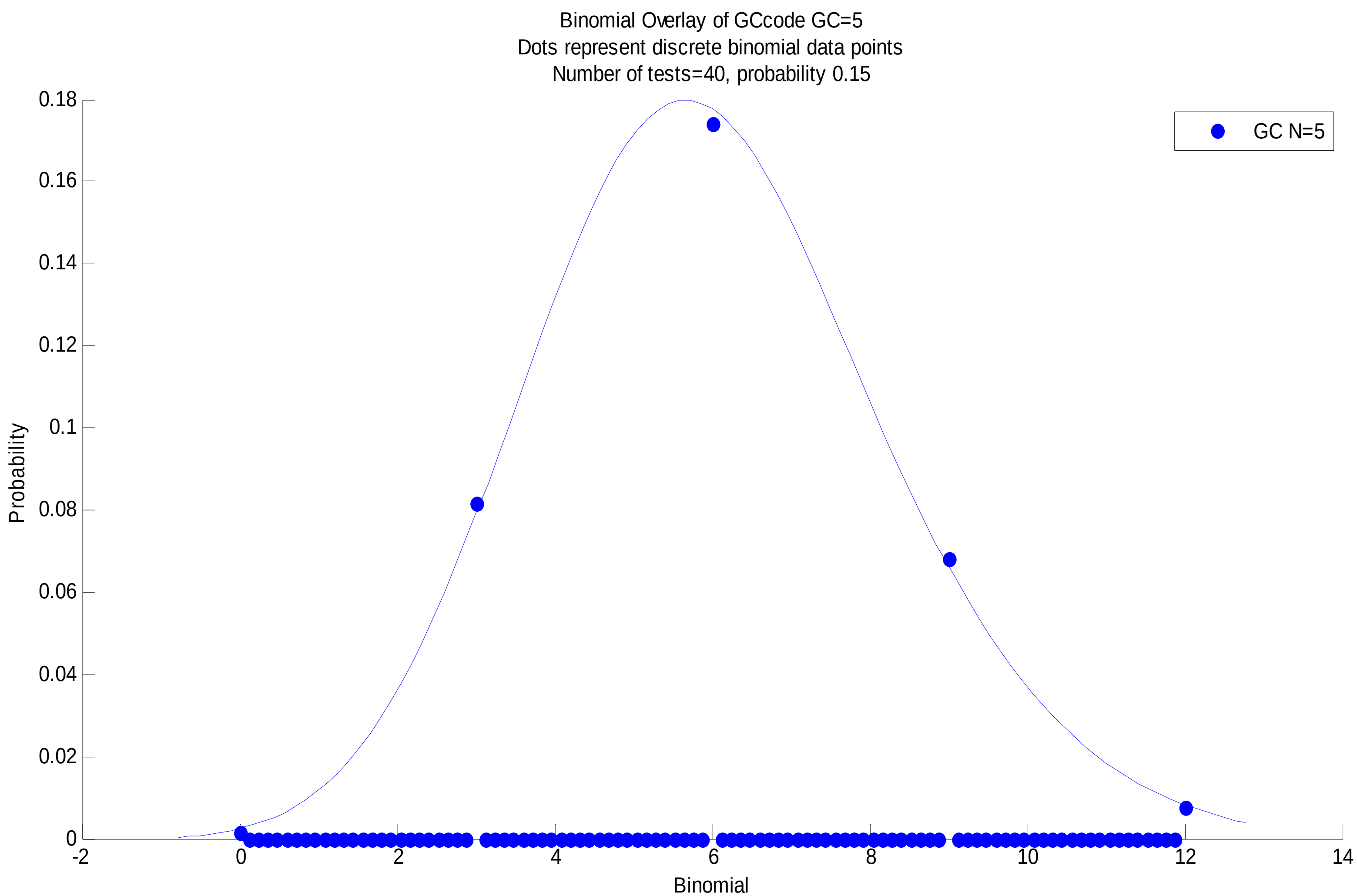
Weibull distribution results



Preliminary Binomial distribution results show mode is a poor metric to compare



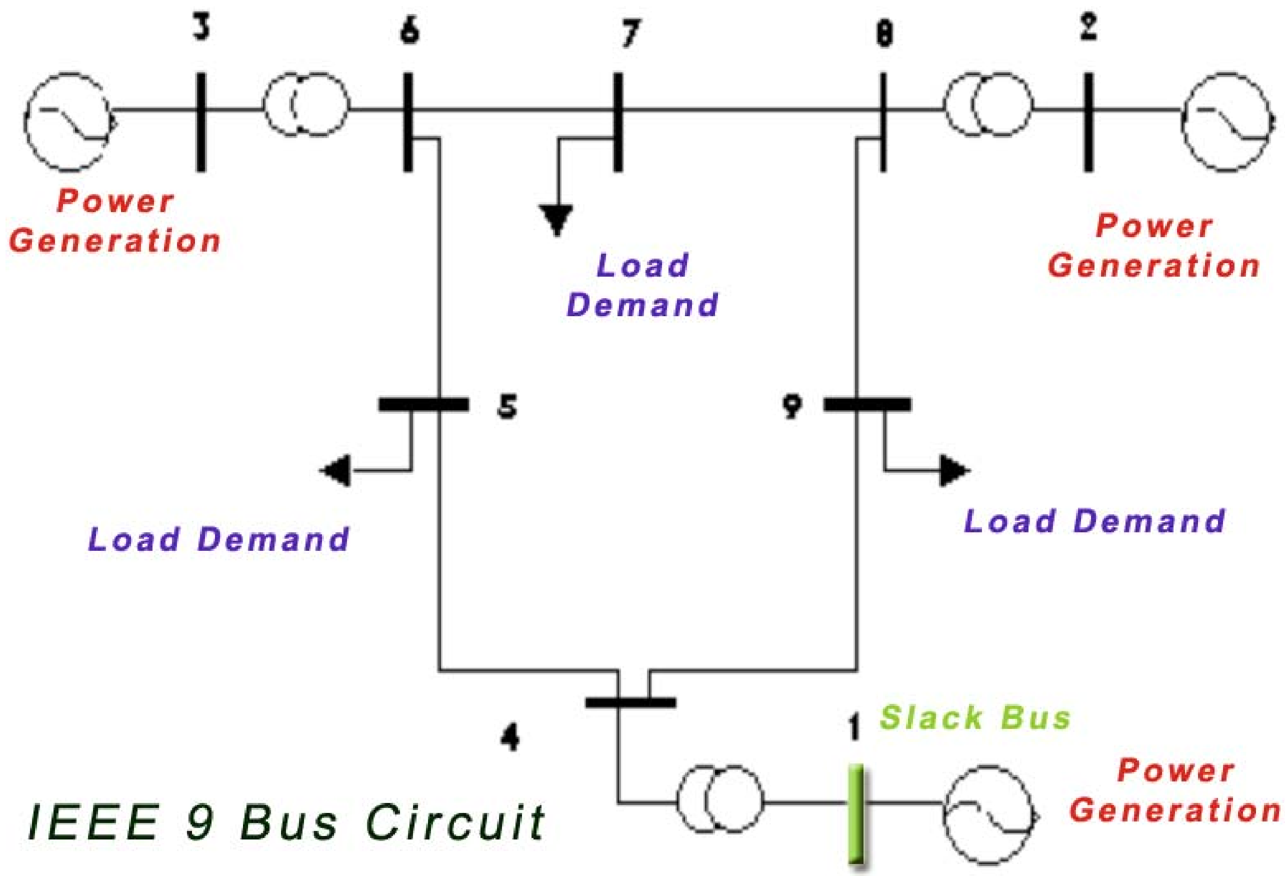
Good correspondence with discrete Binomial values



Probabilistic load flow (PLF) simulations

Case 9 IEEE Power Flow Circuit used as simple test case

- 2 generation injection & 3 load demand buses
- 1 slack bus



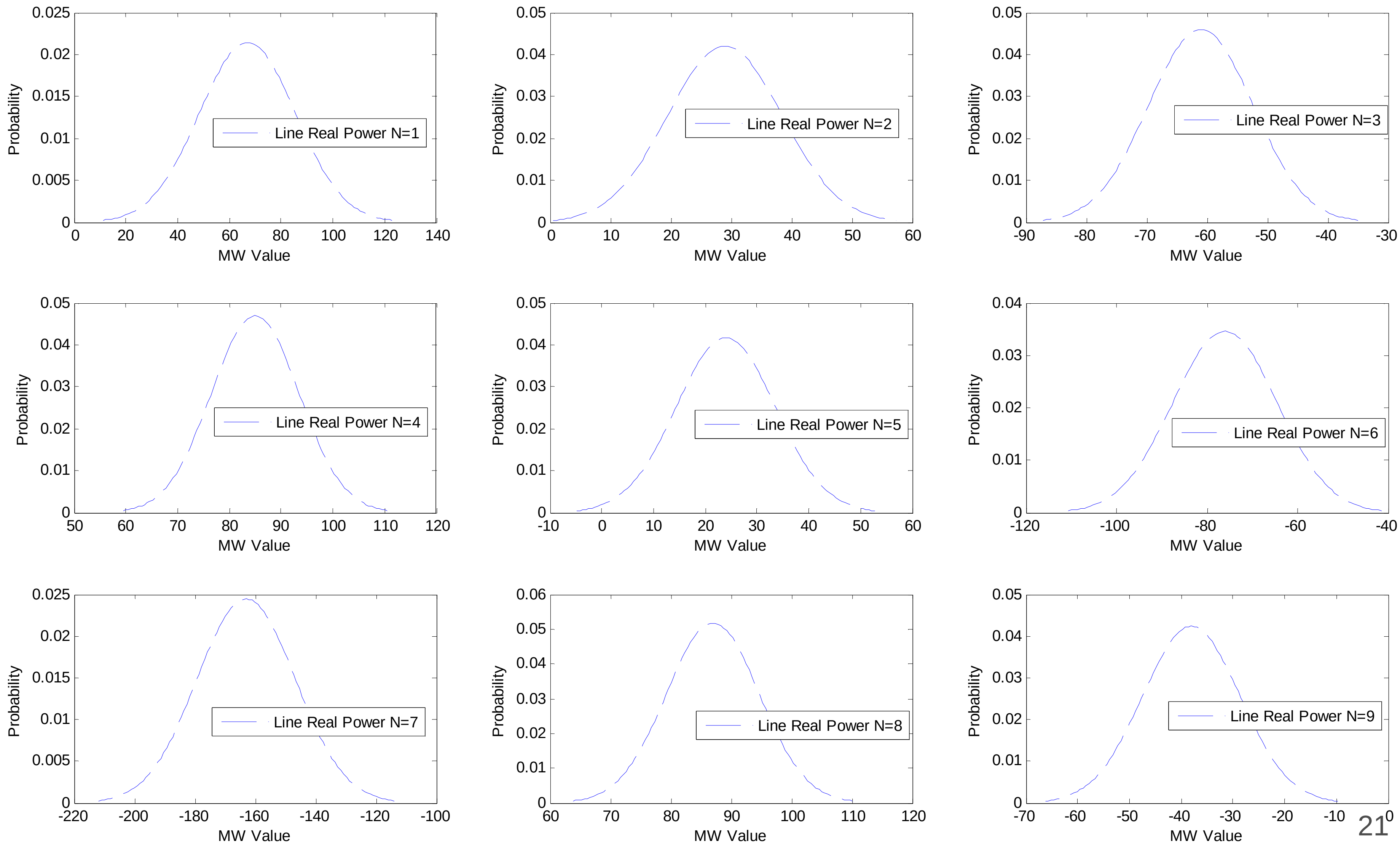
Case 9 IEEE Power Flow Circuit data (Matpower & additional probabilistic)

Power Demand									
Matpower	**Power Demand**		**Standard**		Shadowed areas are additional probability data				
bus_i	**Pd - Real**	**Qd - Reactive**	**Pdsgma - Real**	**Qdsgma - Reactive**	**Type**	**alpha**	**beta - real**	**no. of tests - real**	**probability - real**
1	0	0	0	0	1	0	0	0	0
2	0	0	0	0	1	0	0	0	0
3	0	0	0	0	1	0	0	0	0
4	0	0	0	0	1	0	0	0	0
5	90	30	4.5	1.5	1	2	101.6	180	0.5
6	0	0	0	0	1	2	0	0	0
7	100	35	25	5.25	1	2	112.8	200	0.5
8	0	0	0	0	1	2	0	0	0
9	125	50	6.25	2.5	1	2	135.4	250	0.5
Power Generation (Injection)									
Matpower	**Power**		**Standard**		Shadowed areas are additional probability data				
bus	**Pg - Real**	**Qg - Reactive**	**Pgsgma - Real**	**Qgsgma - Reactive**	**Type**	**alpha**	**beta- real**	**no. of tests - real**	**probability -real**
1	0	0	0	0	1	2	0	0	0
2	163	0	16.3	0	2	2	183.9	326	0.5
3	85	0	8.5	0	1	2	95.9	170	0.5

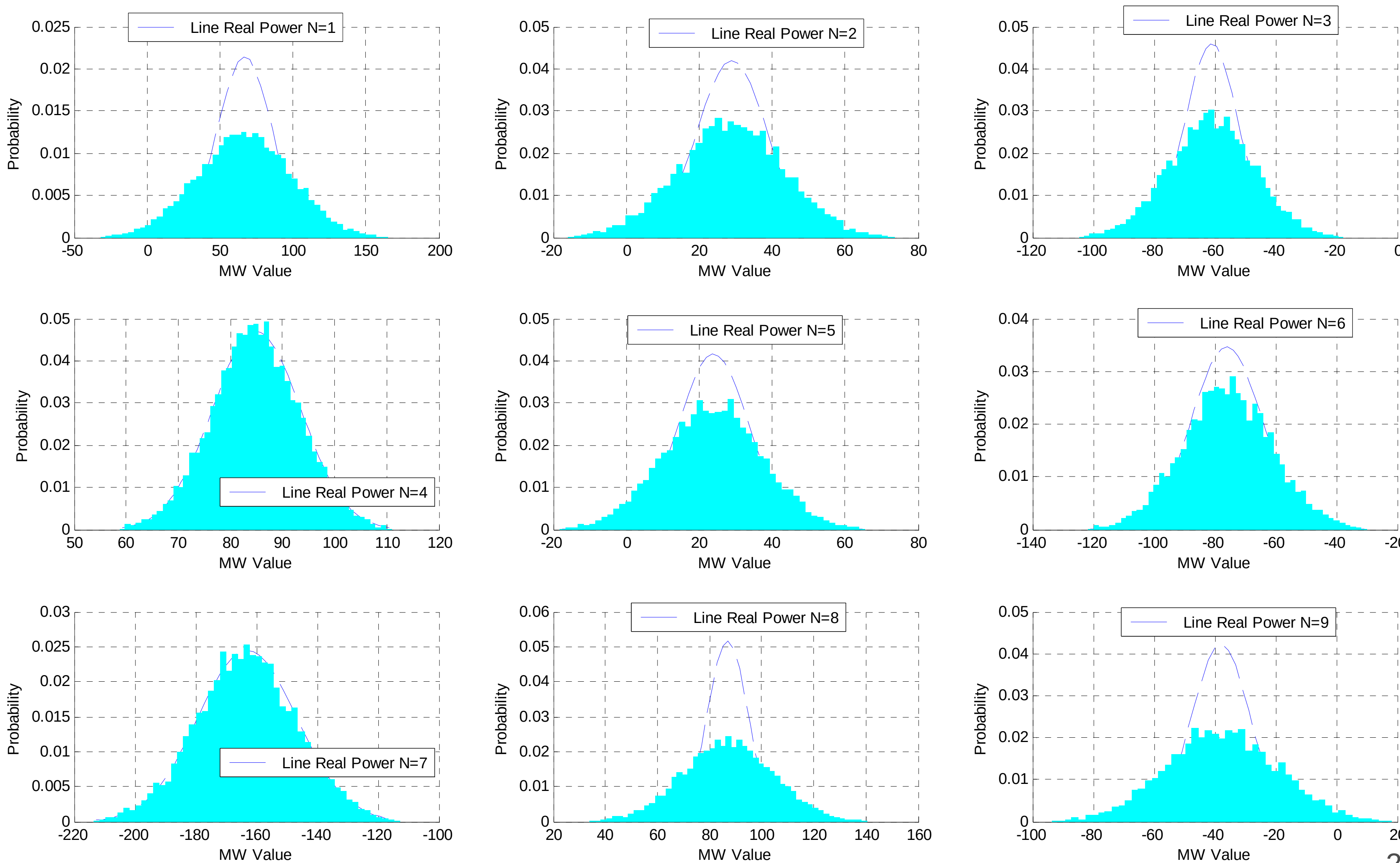
- All probabilistic variables have identical means
- Mean line flows computed exactly with deterministic code

PLF results for normal distributions

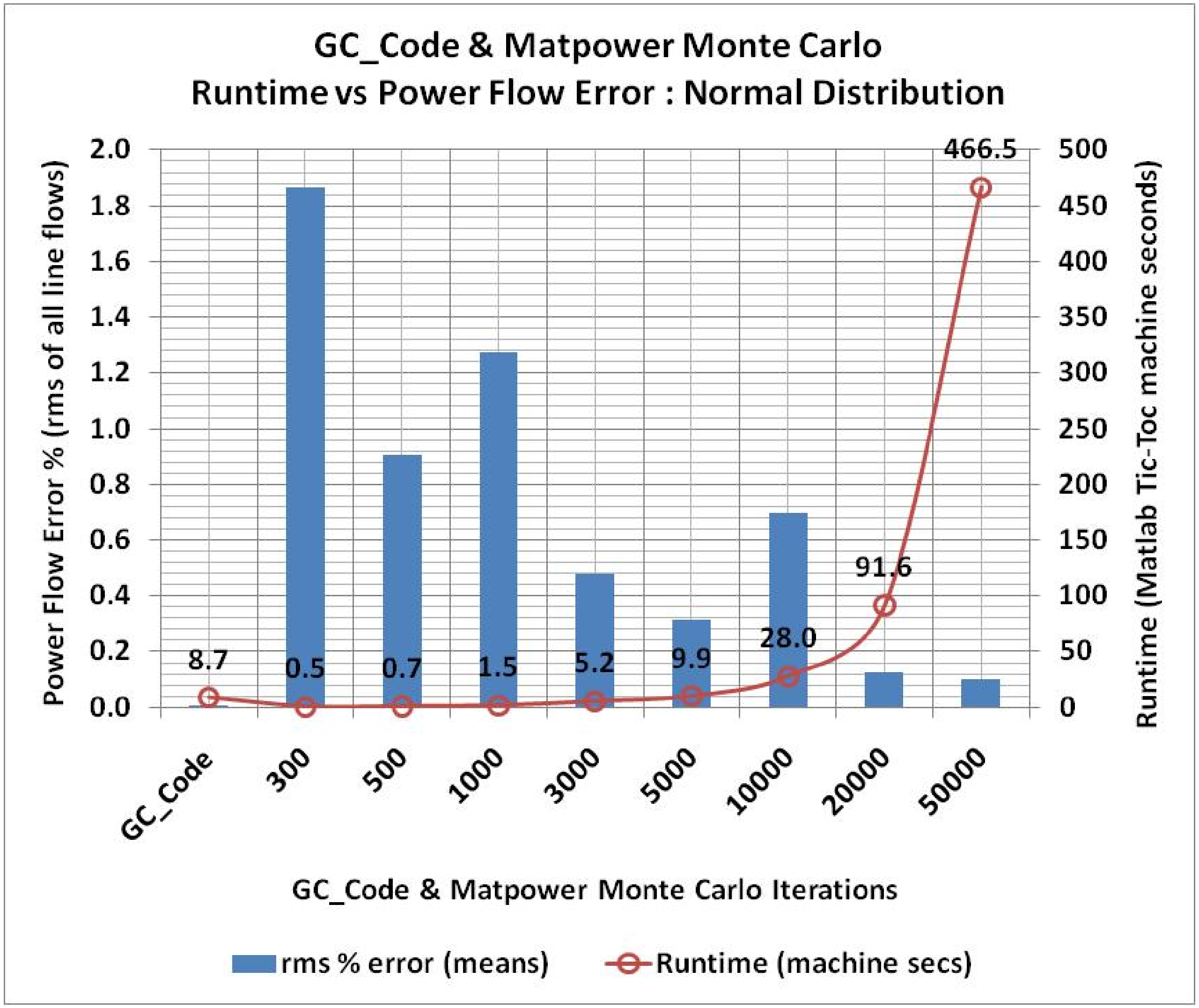
Normal distribution line flows, GC=8; means exact



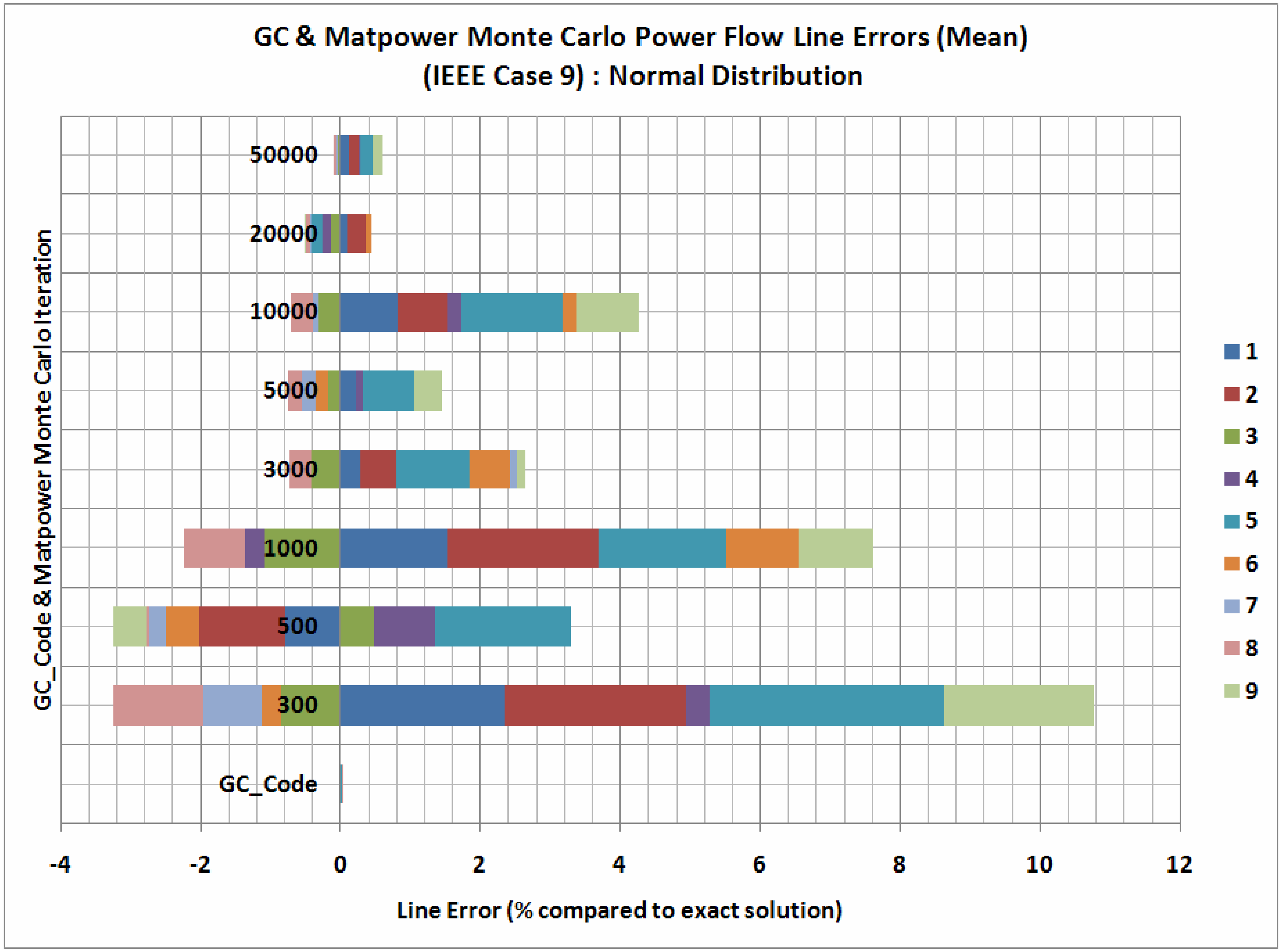
Normal distribution line flows, GC=8, overlaid with MMC, 10k iterations



Power flow error (line flow rms of mean values) vs. runtime



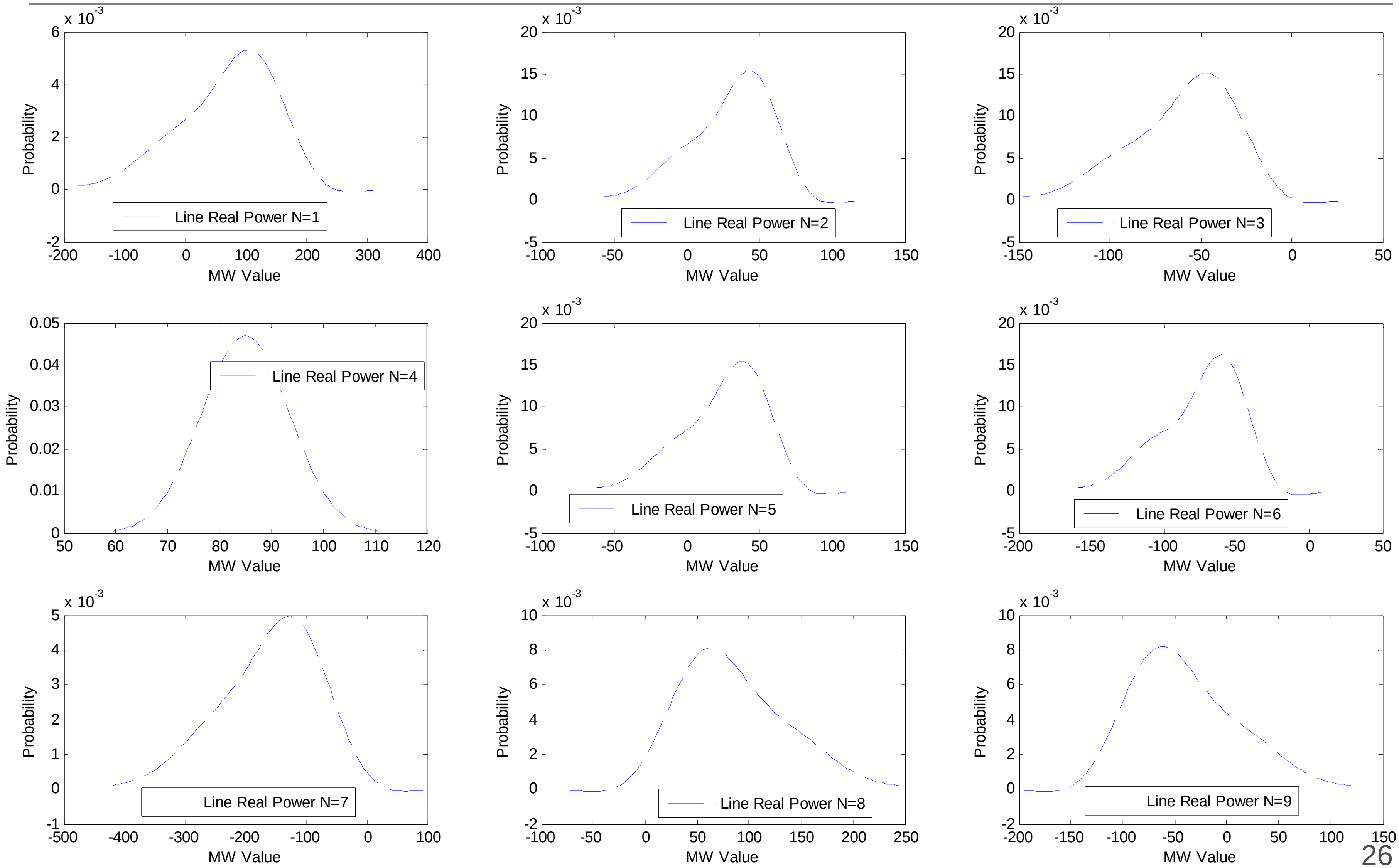
GC_Code matches deterministic result while MMC requires many iterations



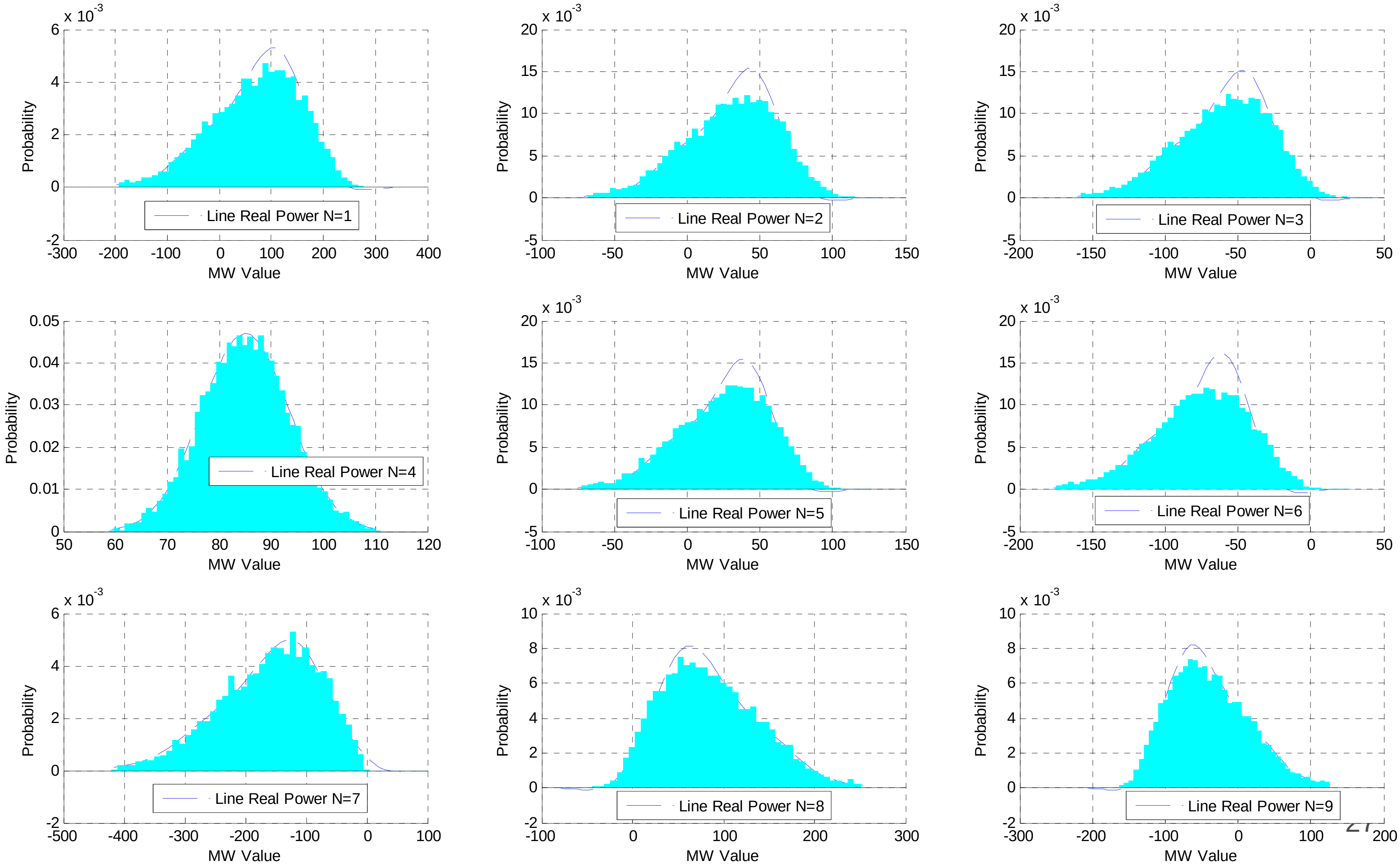
PLF results for Weibull distribution on bus 2

- Weibull shape parameter = 2
  - Wind energy

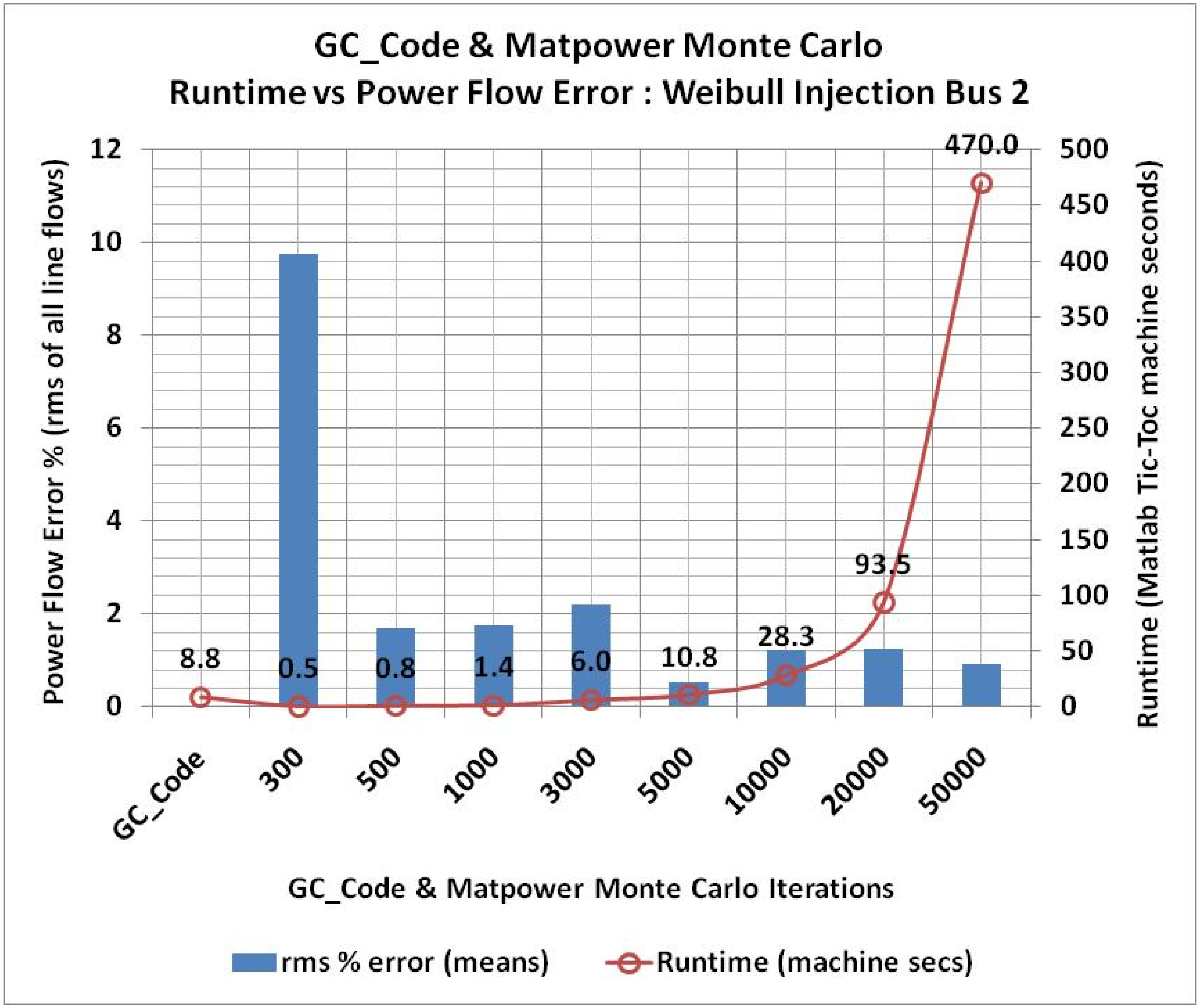
Weibull injection at bus 2, GC=8; means exact



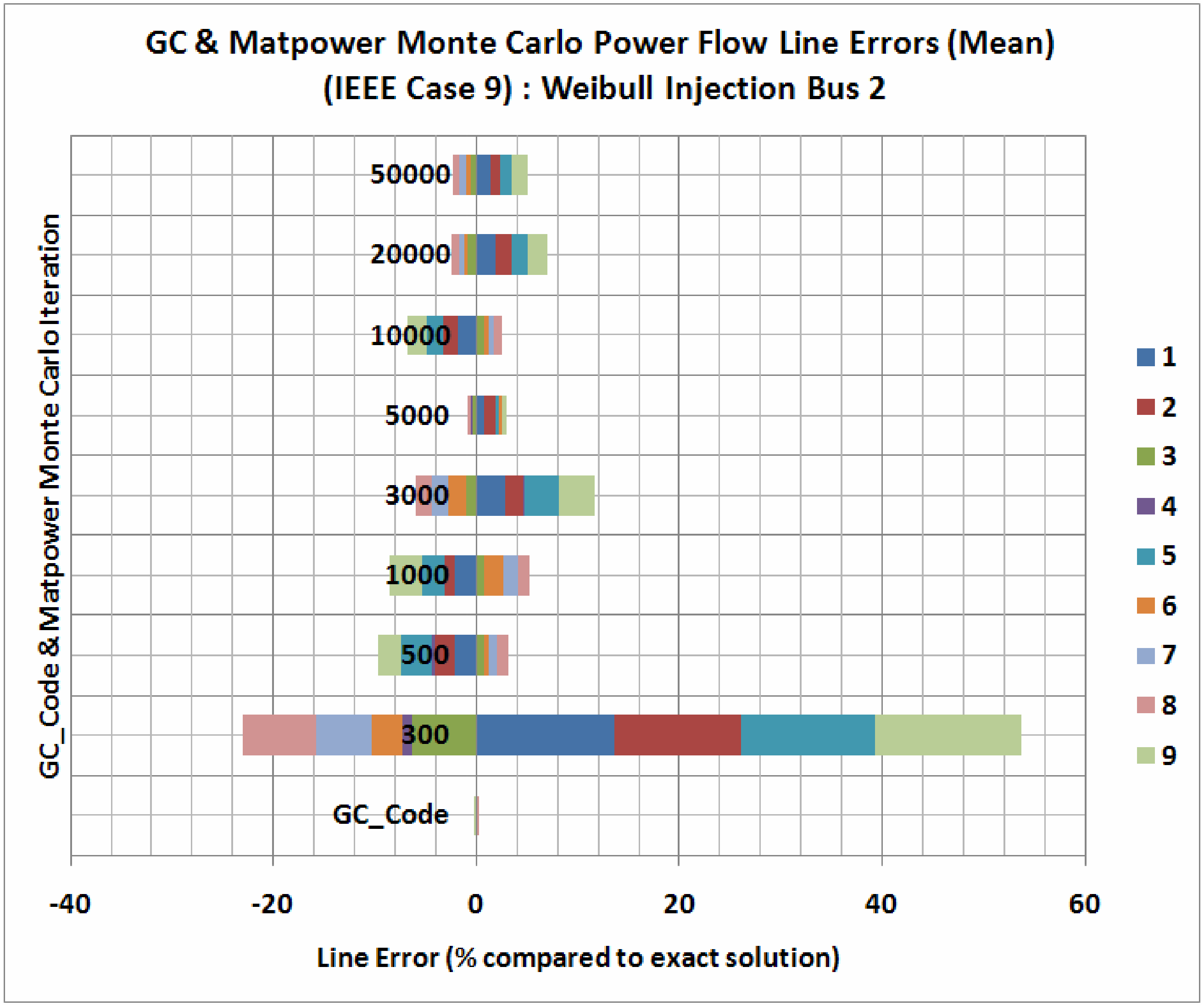
Weibull injection at bus 2, GC=8, overlaid with MMC, 10k iterations



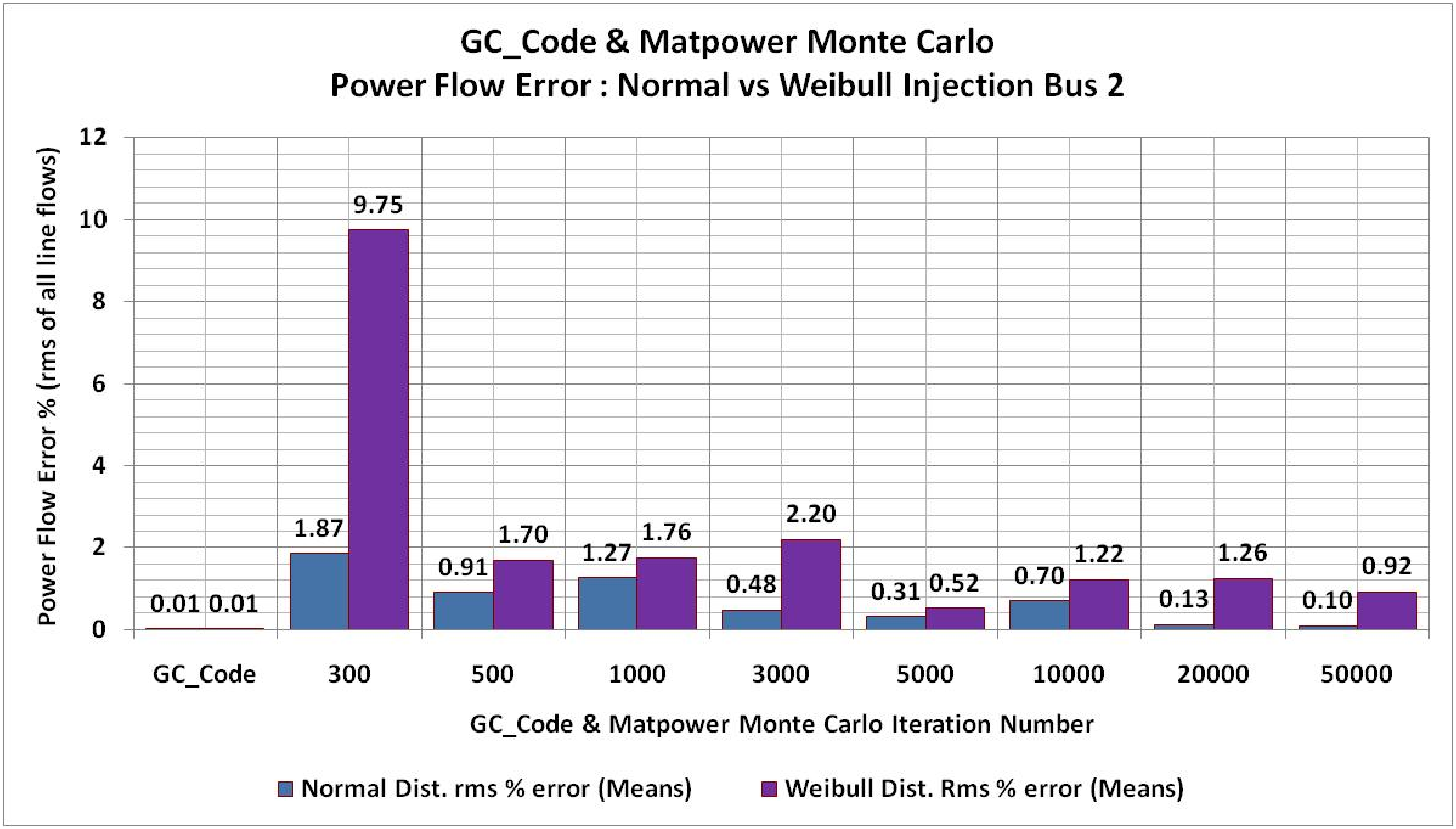
Power flow error (line flow rms of mean values) vs. runtime



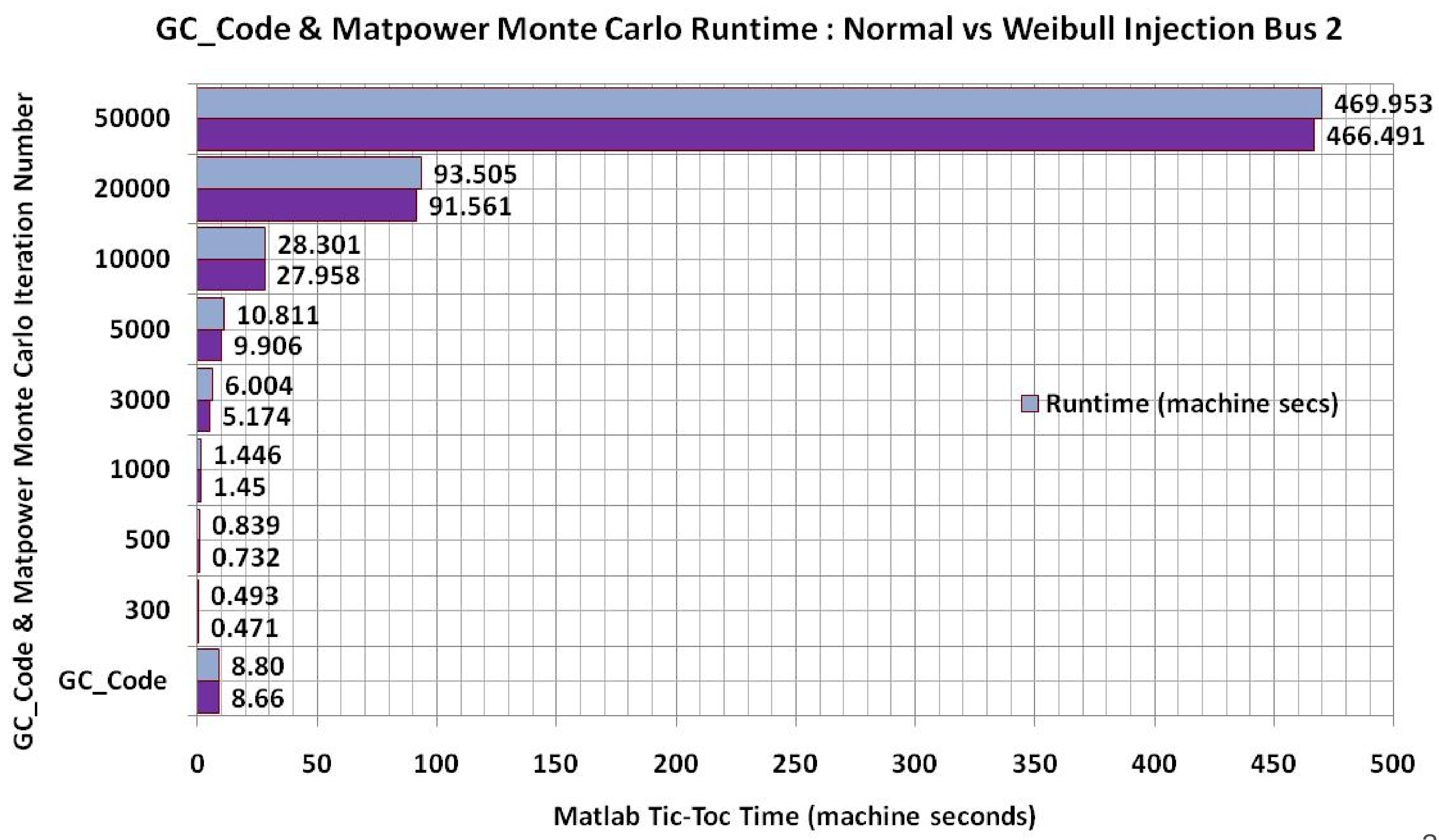
Line flow errors again decrease with increased MMC iterations



Line flow errors are generally higher with Weibull injections for MMC



There was no difference in runtime with normal or Weibull distributions



Still lots of work to do

- Short-term
  - AC code implementation of GC approach
- Medium-term
  - FE approach to model construction
  - Investigate other reconstructions besides GC
  - Renewables/PEV distributions
  - Apply to real grid topologies
- Long-term
  - Intra time step statistics
- Questions?