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Stochastic Distribution Controls for Minimizing Uncertainties Impact for Complex Systems

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Outlines

- ORNL – A Brief Introduction
- Stochastic Distribution Controls - Addressing Challenges
- Two Case Studies on Stochastic Optimization via Probability Density Function Shaping (Power Dispatch) and Frequency Distribution Control for Power Grid

ORNL’s mission

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employees

$750M
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research guests annually

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Forefront scientific computing facilities

World's most intense neutron source

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journal articles published in CY17

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258
invention disclosures in FY18

60
patents issued in FY18

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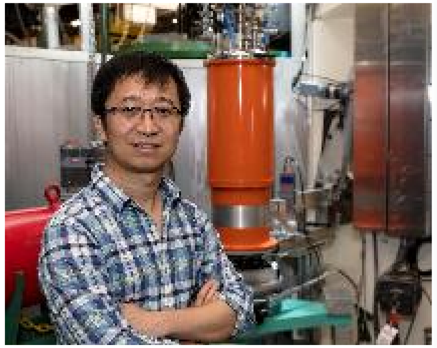
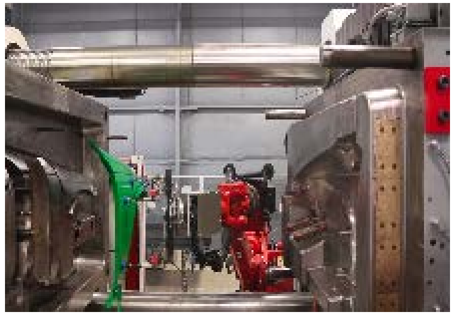
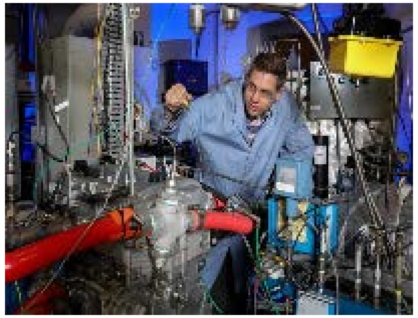


- Building Technologies Research and Integration Center
- Carbon Fiber Technology Facility
- Center for Nanophase Materials Sciences
- High Flux Isotope Reactor
- Manufacturing Demonstration Facility
- National Transportation Research Center
- Spallation Neutron Source
- Oak Ridge Leadership Computing Facility

Energy and Transportation Science Division (FY18 Highlight)

1) Rapid 3D Printing of Molds for Precast Concrete Industry
2) GROVER – Ground-based Robotic Omnidirectional Vehicle for Electric-mobility Research
3) Window Air Conditioning Unit Cools with Propane
4) Additive Manufacturing Crack Free, Subscale Turbine Blades
5) Co-developed Large-scale Thermoset Printer
6) Smart Neighborhood Developed with ORNL Technology
7) New Fuels Developed with New Combustion Strategies
8) Major Growth in Natural Gas Portfolio
9) Lightweight, aluminum-based (ACMZ) alloy developed





Challenges for Complex Systems Operation

- **CHALLENGES:**

  Minimizing uncertainties impact on system operation

- **FACT:**

  Narrowly distributed random variables

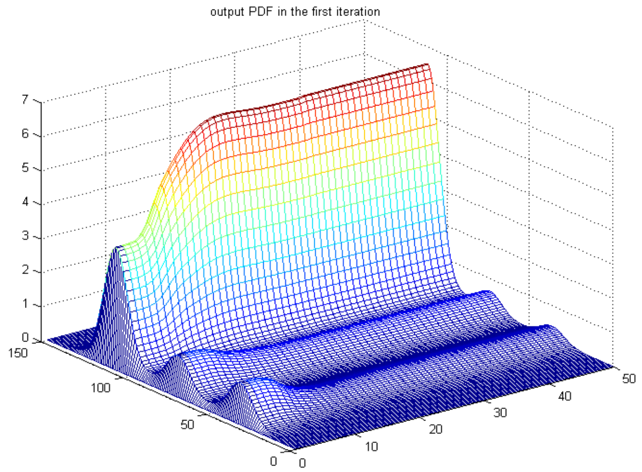
  → **minimum uncertainty**

Objectives of Stochastic Distribution Control

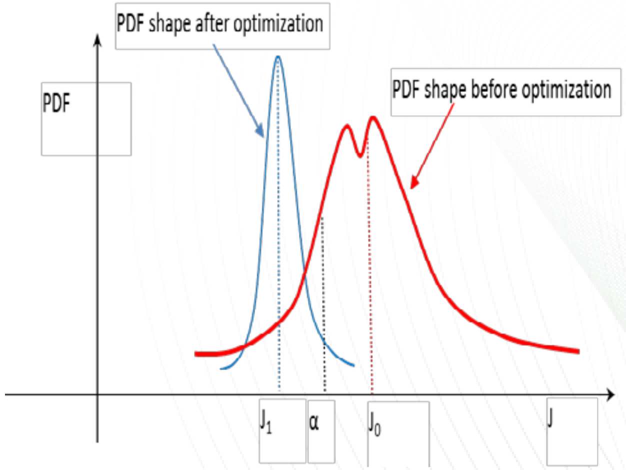
Objective: Minimizing uncertainties for complex systems seen in power grid, industrial processes and transportation, etc

Solution: Feedback control and optimization design that shapes the output probability density functions (PDFs) for non-Gaussian dynamic stochastic variables in complex systems

Reason: PDF Shaping has been a long standing issues



PDF Controls



Optimization via PDF Shaping

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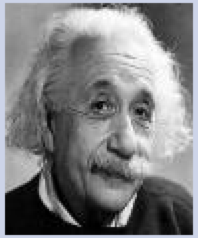
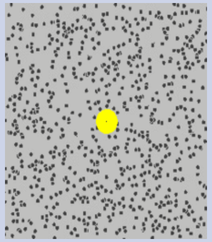
Comparing with Traditional Stochastic Control

Traditional	Stochastic Distribution Control (1996 -)
• Stochastic differential equations - Gaussian Driven Systems (Einstein, Langevin, Stratonovich, Ito, *et, al* , 1904, 1944, 1950) = Solving PDEs    • Mean and Variance Control • Largely Linear Systems • Example: Minimum Variance Control (1970), Kalman Filter and LQG Control (1965),Neural Nets Modelling, etc	• Non-Gaussian Dynamic Systems - Some PDFs measurable for a lot of PDF shaping required processes! • Total probabilistic control (controlling PDF means controlling all the aspects of a random variable) • Wide applications: 1. Modelling, 2. Filtering and state estimation, 3. Data miming, 4. Stochastic optimization, etc

History

1996 (Karny): design control PDF to shape closed loop PDF (Automatica, 1996)

Problem: cannot be implemented in real-time;

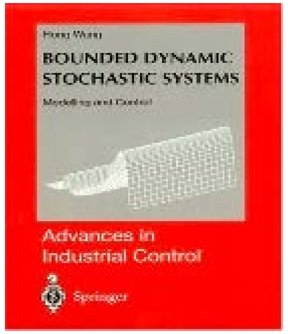
1996: motivated by applications, my group (Univ. Manchester, UK) started to investigate how a crispy control signal can be designed to shape the output PDF.

Publication since 1998,

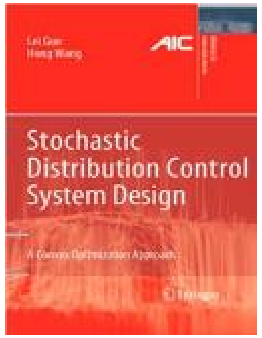
Books	3 (1 in 2 languages)
Invited Conference Talks/Keynotes	21
Journals and Conference	96
International Prizes	2

Impact

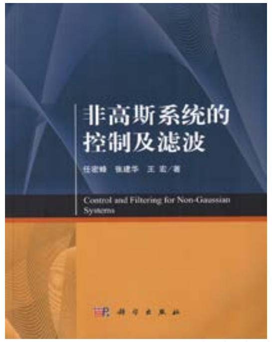
- Citation >7000
- H-index = 45



Springer2000



Springer 2010



ChinaScience2016

Prize 2006

Prize 2014

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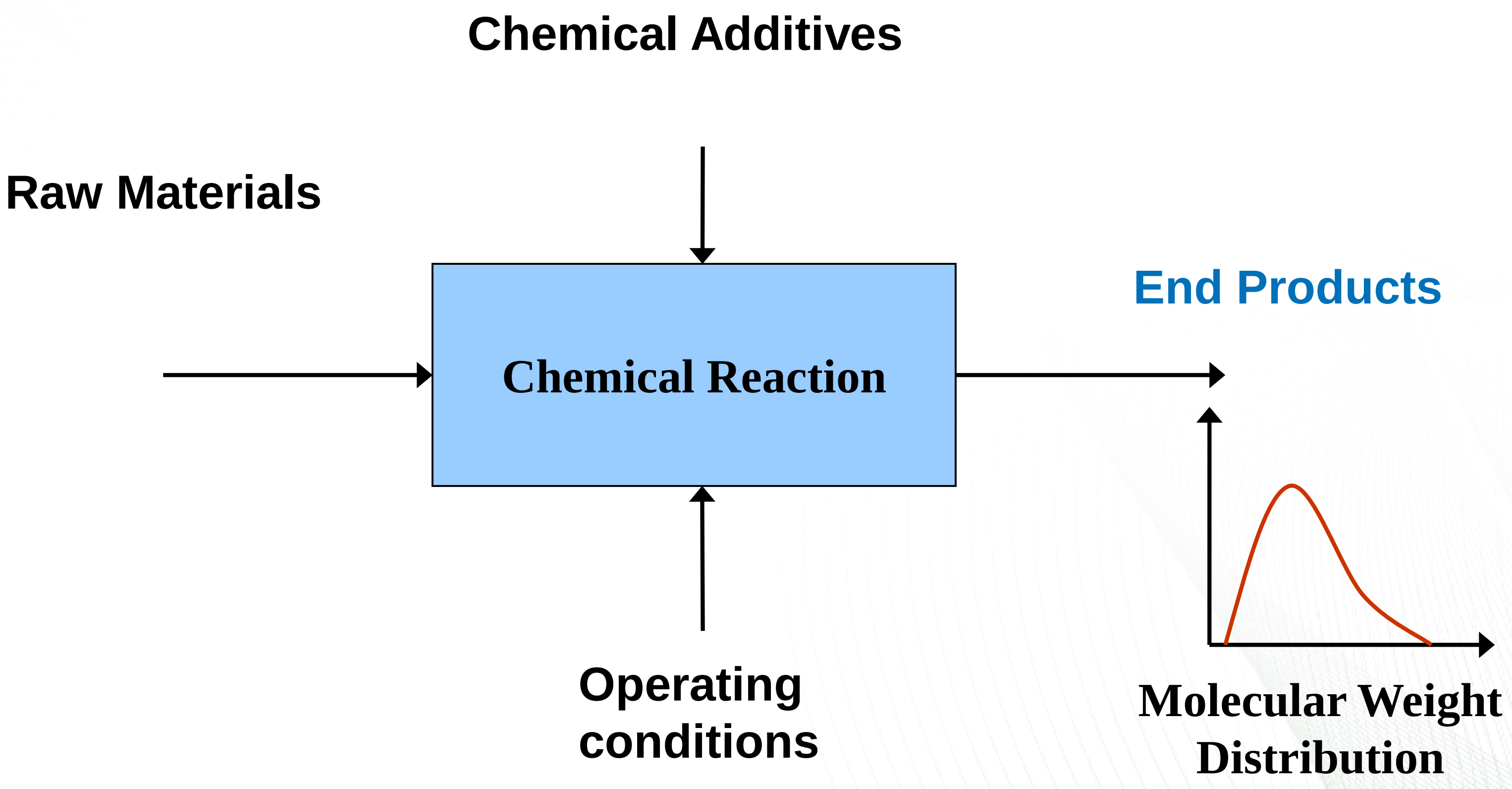
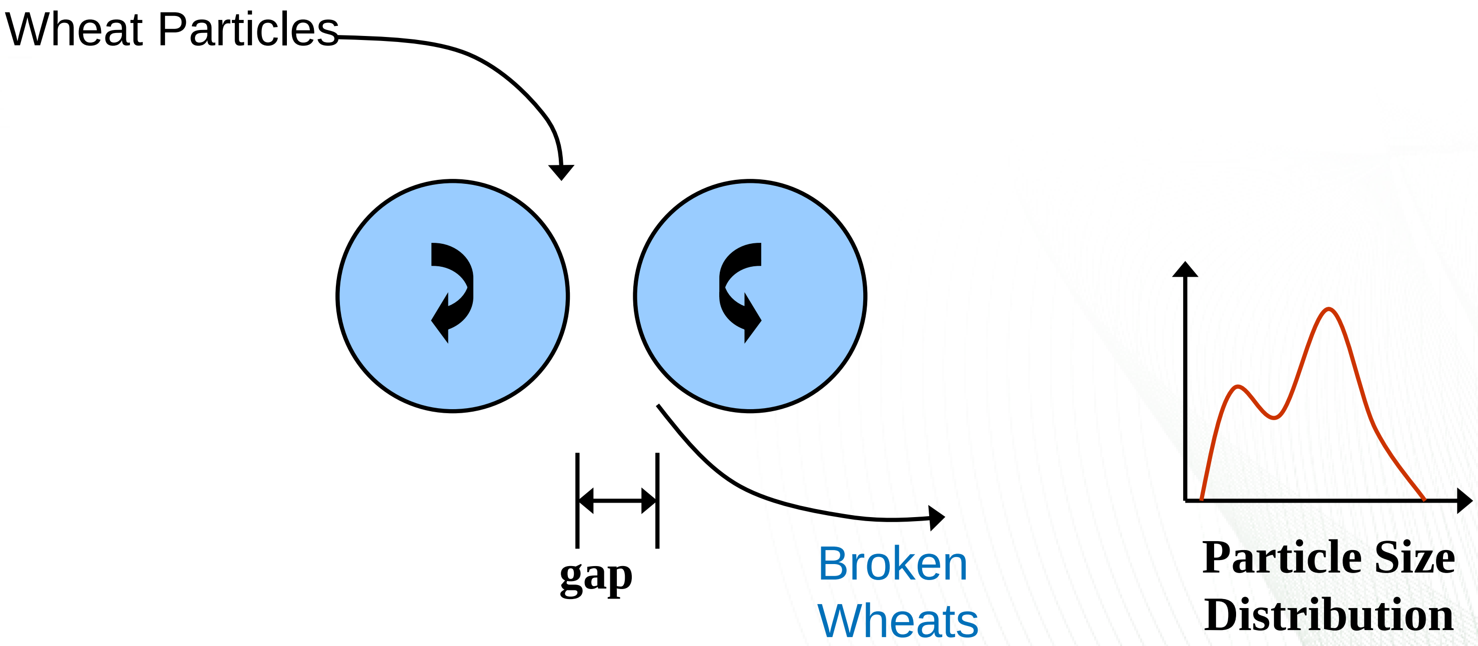
Industrial Application I

(MWD Control)

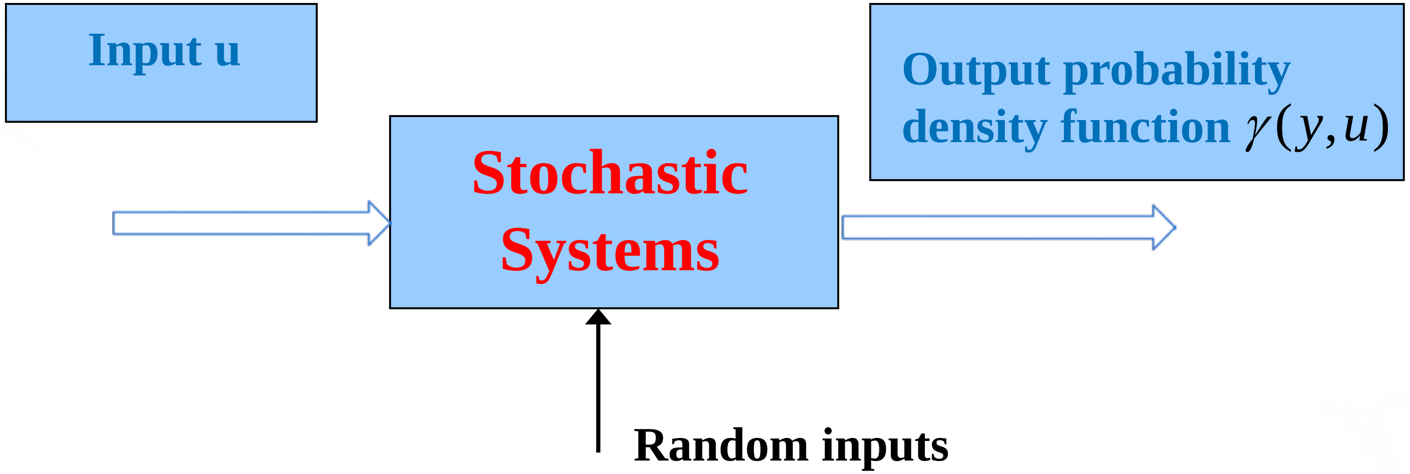


Industrial Application II

(Particle Size Distribution Control)



System Representations and PDF Control Purpose

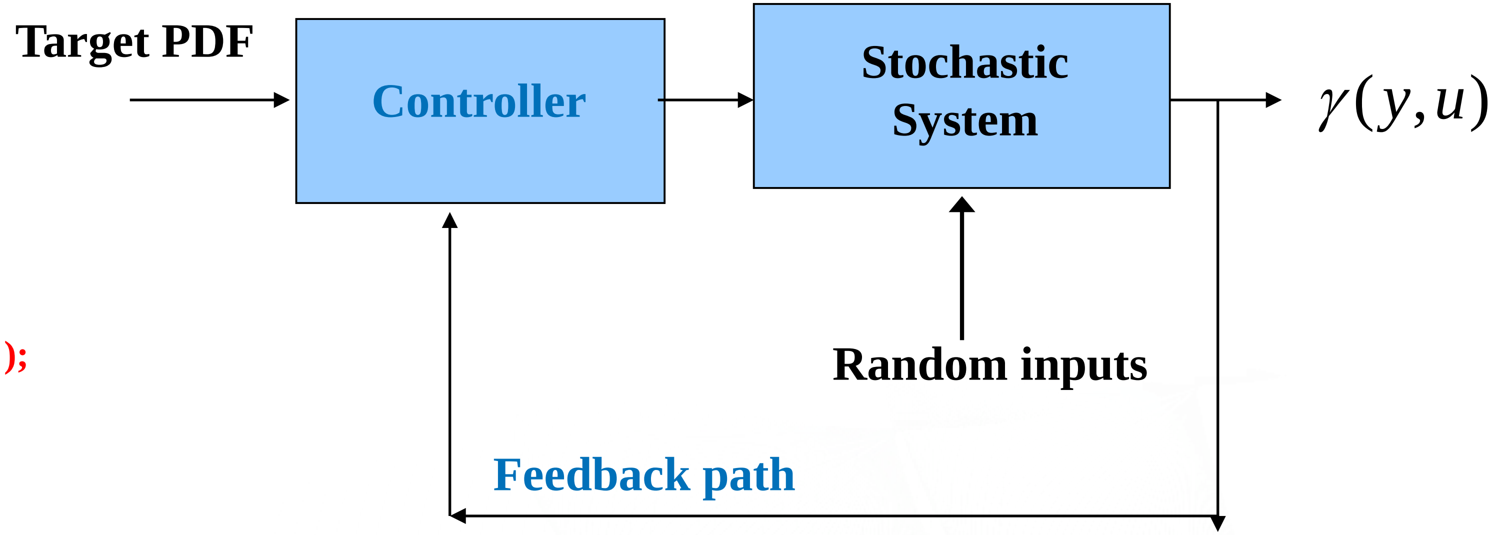


- Model the dynamics between the input variables and the output probability density functions

- Develop a new set of control and optimization algorithms which can be used to control the shape of the output PDFs for general nonlinear Gaussian stochastic systems

FEEDBACK = Closed Loop Structure Control

Probability Density Function Control Theory [1]



a) B-spline ANN model based approaches (1996 -);

b) Input-output model based algorithms (1999 -);

c) ARMAX system with random parameters (2000 -);

d) Minimum entropy control (2002 -);

e) Iterative learning B-splines (2007 -);

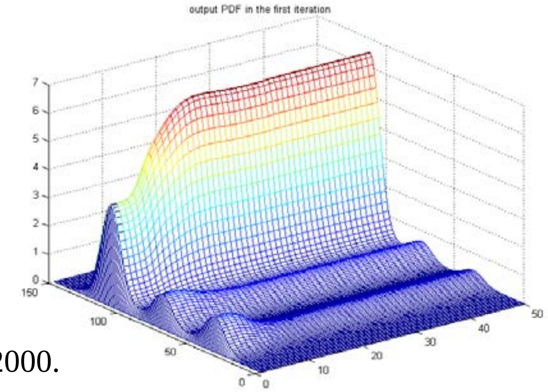
f) Estimation of PDFs of unknown parameters systems and output PDF control (2003 -);

g) Stochastic decoupling concept using PDFs shaping (2014 -);

h) Stochastic optimization via PDF shaping applied to power grid (2016 -).

i) Applications to combustion, and particle distribution systems and product quality

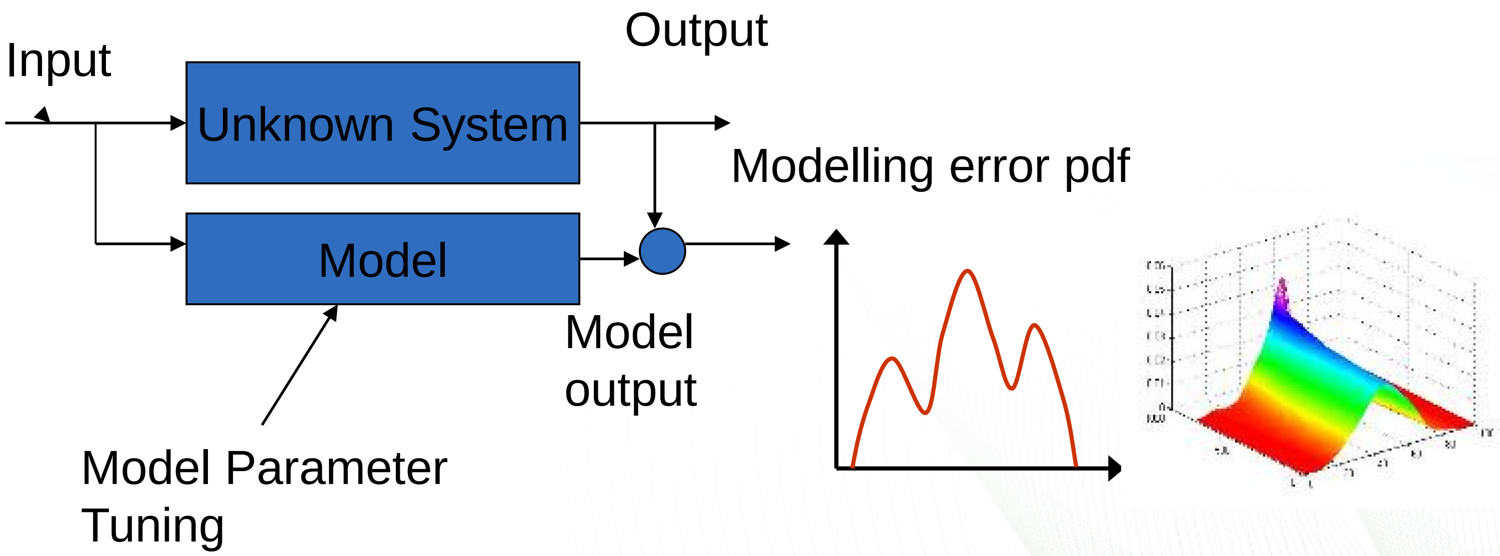
profile have been made



[1] H. Wang, Bounded Dynamic Stochastic Distributions Modelling and Control, Springer-Verlag (London) Ltd, March, 2000. (ISBN 1-85233-187-9, total page number: 176).

Probability density function control is everywhere

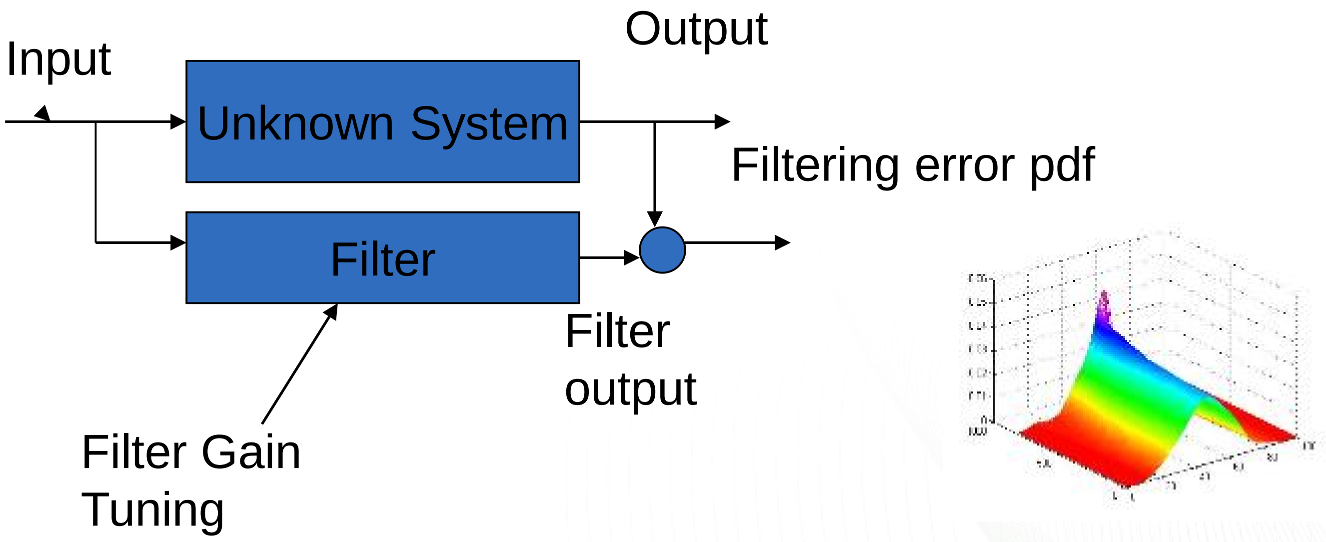
- Modelling [2]: Selection model parameters so that the modelling error pdf is made as close as possible to a narrowly distributed Gaussian or minimum entropy （IEEE Transactions on Neural Networks, 2011, Ding, Chai and Wang)



[2] J. Ding, T Y Chai and H Wang, Off-line modelling for product quality prediction of mineral processing using modelling error PDF shaping and entropy minimization, ***IEEE Transactions on Neural Networks***, Vol. 22, pp. 408 - 419, 2011.

Probability density function control is everywhere

- Filtering ([3] – [4]): Select filtering gain so that the filtering error signal is made as close as possible to a narrowly distributed Gaussian or minimum entropy （IEEE Transactions on Automatic Control and Automatica, 2006)



[3] Zhou, J., H. Yue and H. Wang, Minimum entropy control of B-spline PDF systems with mean constraint, ***Automatica***, Vol. 42, pp. 989 – 994, 2006.

[4] L. Guo and H. Wang, Minimum entropy filtering for multivariate stochastic systems with non-Gaussian noises, ***IEEE Transactions on Automatic Control***, Vol 51, pp. 695-670, 2006.

Probability density function control is everywhere

- Data mining (PCAs): Select principal components so that the recovery error is made as close as possible to a narrowly distributed Gaussian or minimum entropy （ACC2004)

- General Closed Loop Control: Select a good control so that the tracking error is made as close as possible to a narrowly distributed Gaussian or minimum entropy （IEEE Transactions on Automatic Control 2009, IEEE Transactions on Neural Networks 2009)

Probability density function shaping based optimization

Taking into account the uncertainties in human operator's decision making, the following stochastic optimization needs to be solved

$$\min_x J(x,w)$$
$$s.t.\ f(x,v)=0$$

where

- $J(x)$ *is the performance function (e.g., energy consumption),*
- x *is the decision variable,*
- $f(x,v)=0$ *is the constraints*
- *{w,* v*} groups the uncertainties of decision making phase.*

Existing theory has solved the above problem in the mean-valued sense with minimized variance for Gaussian uncertainties (see chanced constraint optimization (1953 -), optimal stochastic control, etc, 1965 -).

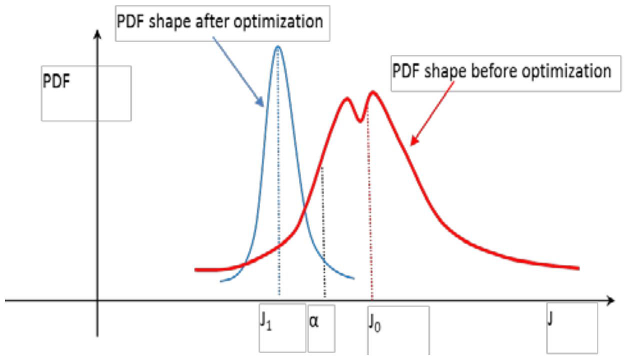
Dealing with uncertainties in optimization – probability density shaping

Novelty: we developed a novel approach that solves the above problem by shaping the probability density functions (pdf) of $J(x)$ and $f(x, v)$ ([9]-[11])

Key Idea:

1) Select the decision variable $\boldsymbol{x}$ so that the probability density function of $\boldsymbol{J(x)}$ is made as left and as narrow as possible;

2) Select the decision variable $\boldsymbol{x}$ so that the probability density function of $\boldsymbol{f(x, v)}$ can converge to a δ -distribution - functional distance concept;



In theory, we have shown that all the existing stochastic optimization becomes a special case of our solution

Our Publications on PDF Shaping Based Optimization:

[5] A Wang and H Wang, Performance Analysis for Operational Optimal Control for Complex Industrial Processes – the Square Impact Principle, ***Control Engineering***, Vol. 20, pp. 1 – 5, 2013.

[6] H. Wang, et, al, "Minimizing uncertainties impact in decision making with an applicability study for economic power dispatch," Technical report, Sept. 2016 (http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-26084.pdf).

[7] S. Wang, H. Wang, R. Fan and Z. F. Zhang, Objective PDF-Shaping-Based Economic Dispatch for Power Systems with Intermittent Generation Sources via Simultaneous Mean and Variance Minimization*, IEEE Conference and Control and Automation, Alaska, 2018. DOI: 10.1109/ICCA.2018.8444293.

Our proposed solution - functional distance

Denote the pdf of J as $\gamma_J(x,\tau)$, $\tau \in [a,b]$,

$$\pi(x) = \int_a^b [\delta(\tau - a) - \gamma_J(x,\tau)]^2 d\tau = min$$

Denote the pdf of *f(x, v)* as $\gamma_f(x,\varphi)$, $\varphi \in [c,d]$

$$\varepsilon(x) = \int_c^d [\delta(\varphi) - \gamma_f(x,\varphi)]^2 d\varphi$$

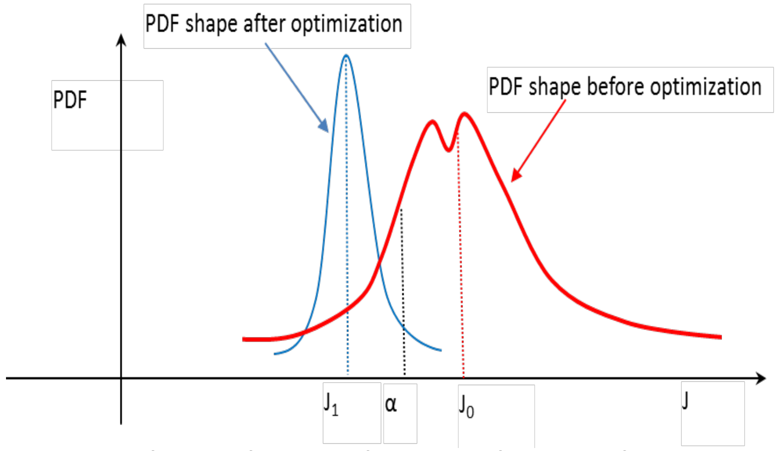


Figure 1. PDFs of the performance function before and after the optimization

We just need to select x_k so that the following is minimized.

$$J_\sigma = \pi(x_k) + \sum_{j=1}^{k} \varepsilon(x_j)\,, \quad k = 1, 2, 3, \dots$$

Minimizing $J_\sigma(x)$ for k that goes to infinite, the constraint *f(x, v) = 0* can be strictly guaranteed,

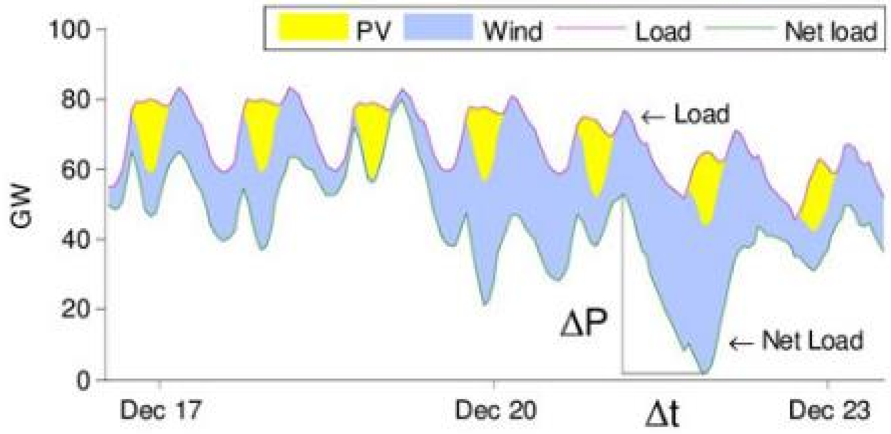
$$\sum_{j=1}^{+\infty} \varepsilon(x_j) < +\infty \quad \Longrightarrow \quad \lim_{k\to+\infty} \int_c^d \left[\delta(\varphi) - \gamma_f(x_k,\varphi)\right]^2 d\varphi = 0$$

$$\lim_{k\to+\infty} \gamma_f(x_k,\varphi) = \delta(\varphi) \quad \to \quad \lim_{k\to+\infty} f(x_k, v) = 0$$

Applying PDF shaping to power grid operation

- Uncertainties in power grid (Wind, solar, etc.)

- Need to optimize probabilistic Power Flow

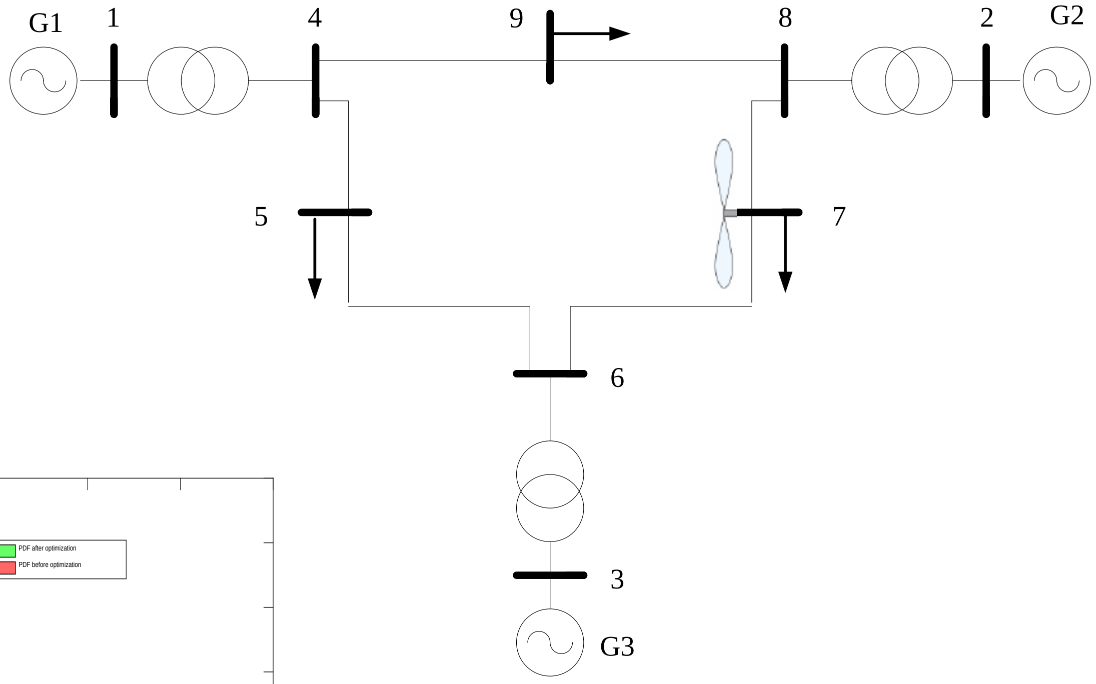


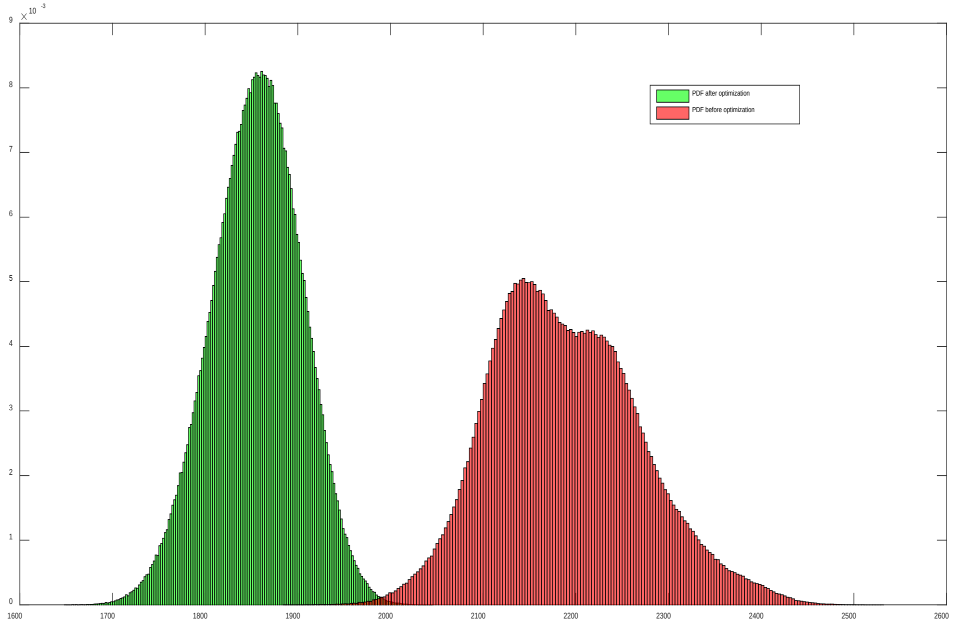
Economic dispatch for power systems with intermittent generation with normal distribution

Cost function and constrains

$$F_c = \sum_{t=1}^{24} \sum_{i=1}^{3} f_{it}(P_{it})$$

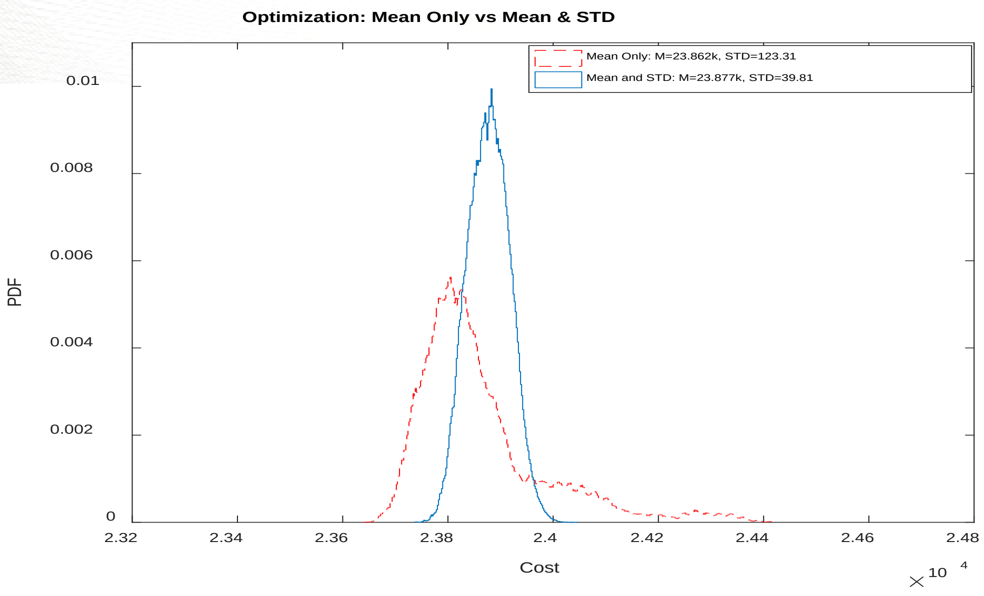
$$\sum_{i=1}^{3} P_{it} + P_t^W - P_{Dt} = 0$$

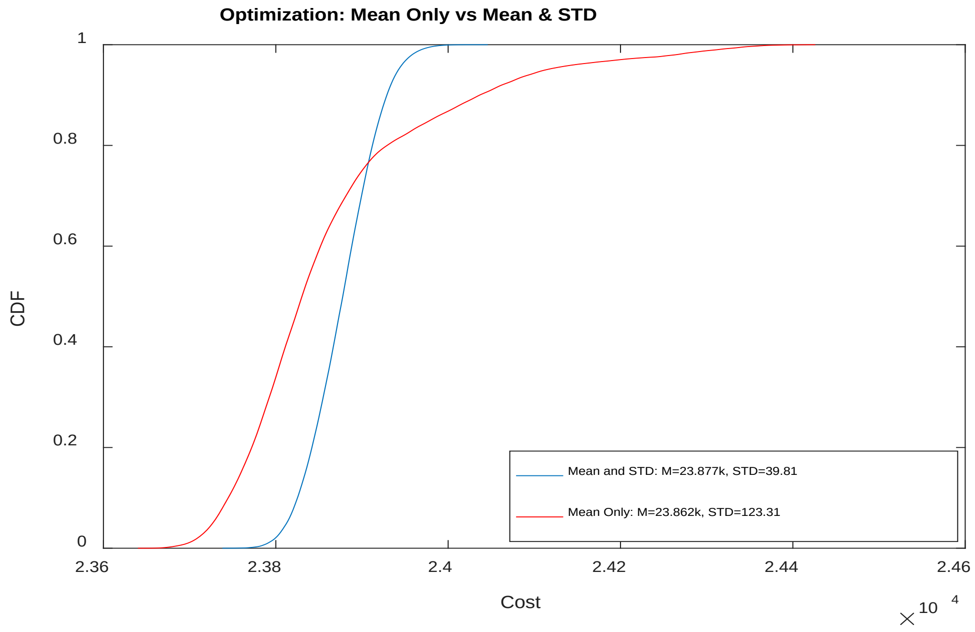




P_t^W and P_{Dt} are stochastic variables, representing the output of wind farm and load demand in the system. F is a nonlinear function of P_{it}

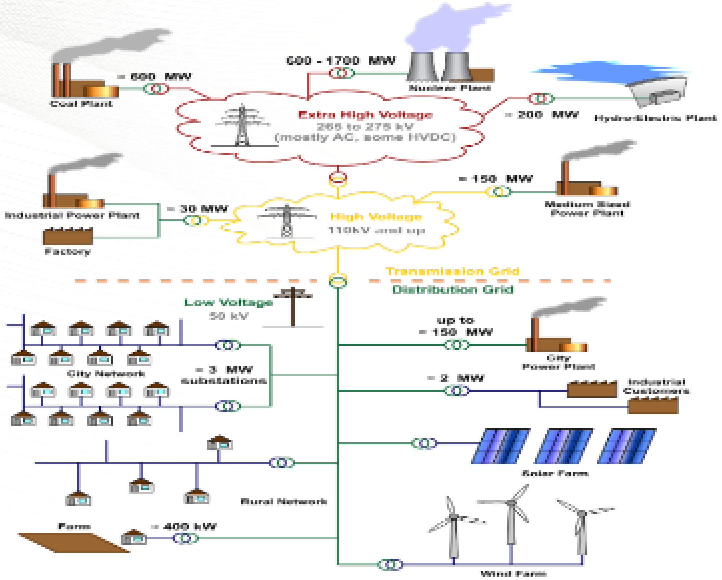
Results with Weibull distribution





- *The preliminary study has produced a new angle to look into the uncertainty minimization which will lead to a wide spectrum of applications in power grid, manufacturing and transportation*
- *The proposed solution is generic and we will look into funding opportunities with DoE for example ASCAR and EERE programs, etc*
- *Further dissemination will be planned which will form the first step to take our findings to relevant industry sectors*

Narrowing Frequency Probability Density Function for Achieving Minimized Uncertainties in Power Systems Operation – a Stochastic Distribution Control Perspective



- ❑ Any random variable can be characterized by its probability density function (PDF) shape
- ❑ Narrowly distributed PDF = small uncertainty and randomness [1]
- ❑ Reduce randomness means to control the PDF to make it as narrow as possible

FACTS :

- ❑ Distributed energy resources (DERs) such as solar power, wind energy and storage increases
- ❑ Randomness degree increases that affect grid operation performance

Objective of operational control – randomness minimization approach with increased DERs

- ❑ Control active power injections to minimize frequency uncertainty and randomness - PDF shaping
- ❑ Control reactive power injection to minimize voltage uncertainty and randomness – PDF shaping

[8] H. Wang, and Z H Qu, Narrowing Frequency Probability Density Function for Achieving Minimized Uncertainties in Power Systems Operation – a Stochastic Distribution Control Perspective, IEEE Conference on Control Applications and Technology, Copenhagen, Denmark, August, 2018.

Stochastic Swing Equation – Solution in PDF Sense

Denote the following two vectors for the power and the load respectively,

$$P = [P_1, \quad P_2, \dots , \quad P_n]^T \in R^n \qquad (2)$$

$$L = [L_1, \quad L_2, \dots , \quad L_m]^T \in R^m \qquad (3)$$

Then the swing equation can be represented as an *Ito* differential equation given as ([12], [32])

$$d\omega = f(P, L)dt + \sigma(P, L)dv \qquad (4)$$

where

- $f(P, L)$ and $\sigma(P, L)$ are two functions that show how the power and load are related to the frequency,
- and dv is the increment of a Brownian motion.

For example in line with equation (1), we can have

$$f(P, L) = \sum_{i=1}^{n} P_i - \sum_{j=1}^{m} L_j$$

Stochastic Swing Equation – Solution in PDF Sense

- The solution of the stochastic frequency response is the dynamic evolution of its PDF denoted as (y, P, L) .

- Since the power and the load are time-varying function, such a PDF can be further denoted as $\gamma(y, P(t), L(t))$ where $y \in [a, b]$ is the definition variable for the frequency PDF, and the interval $[a, b]$ defines the allowable range of the variation of the frequency.

- Form the stochastic systems theory, it can be seen that such a PDF of the frequency can be solved using the following well-known Fokker Planck and Kolmogorov (FPK) equations ([11]) for $\forall y \in [a, b]$

$$\frac{\partial}{\partial t}\gamma(y, P, L) = -\frac{\partial}{\partial y}[f(P, L)\gamma(y, P. L)] + \frac{1}{2}\frac{\partial^2}{\partial y^2}[\sigma^2(P, L)\gamma(y, P, L)] \qquad (5)$$

- This equation reflects how the power and load can affect the dynamic evolution of the shape of the frequency PDF denoted as $\gamma(y, P, L)$.

- Solution to such a partial differential equation can require heavy computation load and is generally difficult to obtain online.

Optimization and Solution using PDF Shaping Approach

Objective: The purpose of frequency variation control is to

manipulate the only controllable part of the power and the load at different time scales so that the shape of $\gamma(y, P(t), L(t))$ can be made as narrow as possible centered at its targeted mean value (say 60Hz)

Optimization:

Use the controllable power and load to minimize the following performance function

$$J_1 = \int_a^b [\gamma(y, P, L) - g(y)]^2 \, dy \rightarrow \min_{\{P,L\}} J_1 \qquad (6)$$

where $g(y)$ is the desired PDF of the frequency.

Target PDF Selection - delta function

For the minimization problem in equation (6), one can always select an impulse function as

$$g(y) = \begin{cases} +\infty & when\ y = 60Hz \\ 0 & otherwise \end{cases} \qquad (7)$$

In practice, value $+\infty$ means a biggest possible number

The following performance function should be used instead of the one given in equation (8).

$$\min_{\{P,L\}} \int_{T_1}^{T_2} \int_a^b [\gamma(y,P,L) - g(y)]^2 dydt + \rho \frac{d}{dt} ||P|| + \mu \frac{d}{dt} ||L|| \qquad (10)$$

where $\rho,\ \mu > 0$ are two pre-specified weights.

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Illustrative Simulation Results – Frequency PDF 3D respnses

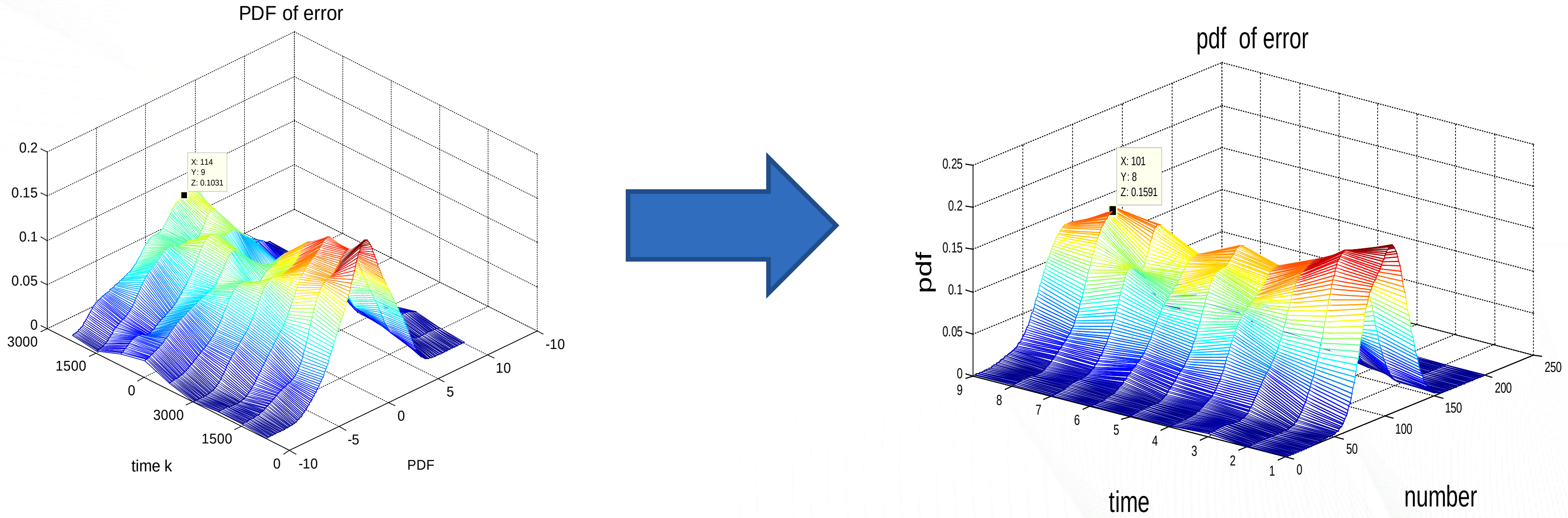

Figure 2. A possible PDF response of the frequency error before and after the optimization.

Conclusions

- Stochastic distribution control is a new area that looks into shaping output probability density functions,
- Generic solutions have been obtained – suited for non-Gaussian systems
- It has potential applications to many areas in industrial processes – modelling, control, filtering, data mining, optimizations and transportation systems
- A necessary condition on pdf shaping based stochastic optimization has been derived
- Encouraging results have been obtained for the economic power dispatch

Current Situation + Future

- There are 30 research centers worldwide following our work on stochastic distribution control;
- Special issues and invited sessions are seen in control journals and conferences since 2002;