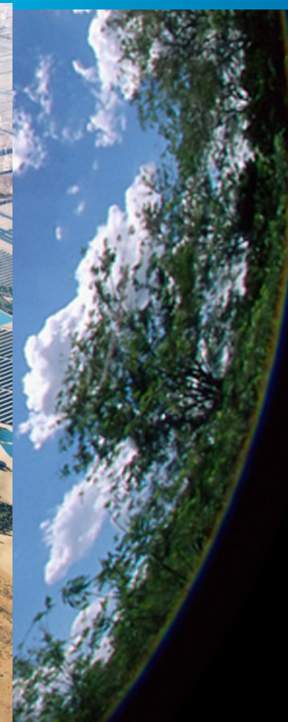
Variable Energy Resource Induced Power System Imbalances



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Presentation Outline

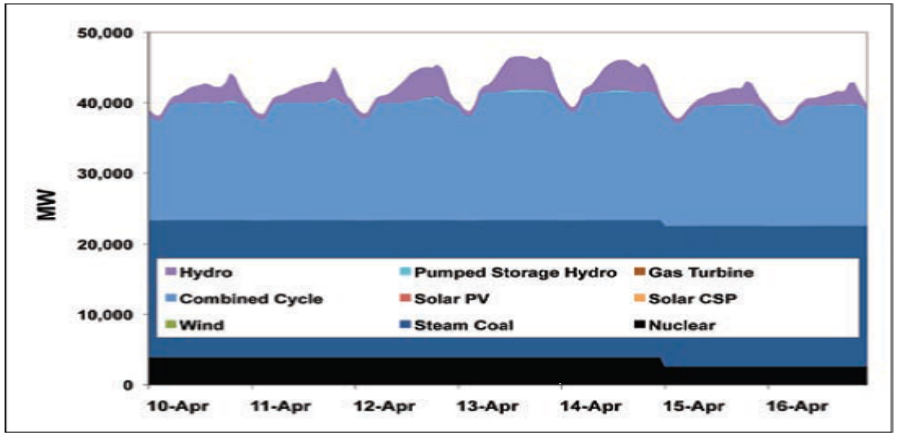
Goal: to demonstrate the value of enterprise control assessment techniques in the integration of variable energy resources

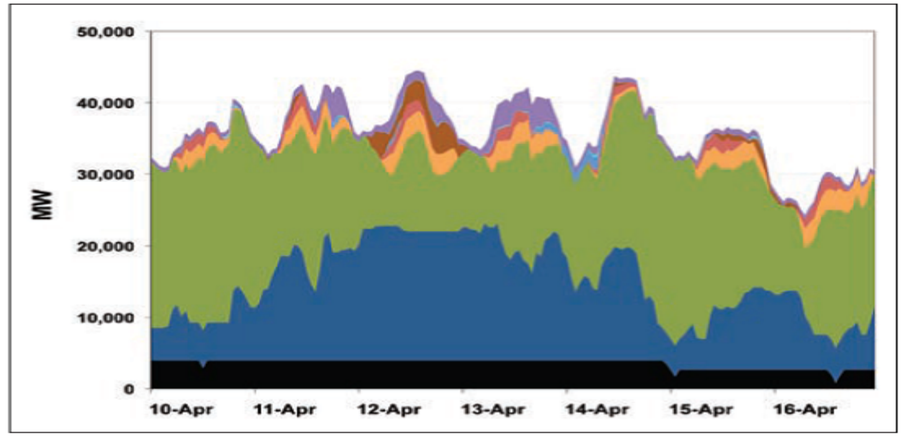
- **Introduction**: More challenging balancing with VERs
- **Motivation**:
- **Methodology**
- **Results**
- **Conclusion**

Introduction: More Challenging Balancing w/ VERs

- The main role of the Balancing Authority (BA) is to maintain generation and consumption balance in the power system.
- Integration of variable energy resource (VER) into the power system brings new level of variability and uncertainty.
- Traditional requirements and standards are no longer guarantee for safe operations.

Introduction: More Challenging Balancing w/ VERs





- Variable energy resources can exacerbate the load following requirement for thermal generation units!
- Greater burden on thermal unit control & ramping capability!
- Thermal unit capacity utilization & economic rationale will naturally deteriorate!

∴ VERs create a more dynamic environment for grid balance!

Motivation: Grappling with the Complexity

- A large set of power system and VER parameters can affect the balancing performance of the system.
- Three is no explicit connection between specific parameters and the magnitude of imbalances.
- A holistic modeling approach is required to capture the interconnections of different procedures.

Wind Short-Term Forecast Error

Wind Day-Ahead Forecast Error

Resource Scheduling Time Resolution

Wind Penetration Level

Generator Ramping Rates

Real-Time Market Frequency

Wind Variability

Load Day-Ahead Forecast Error

Load Short-Term Forecast Error

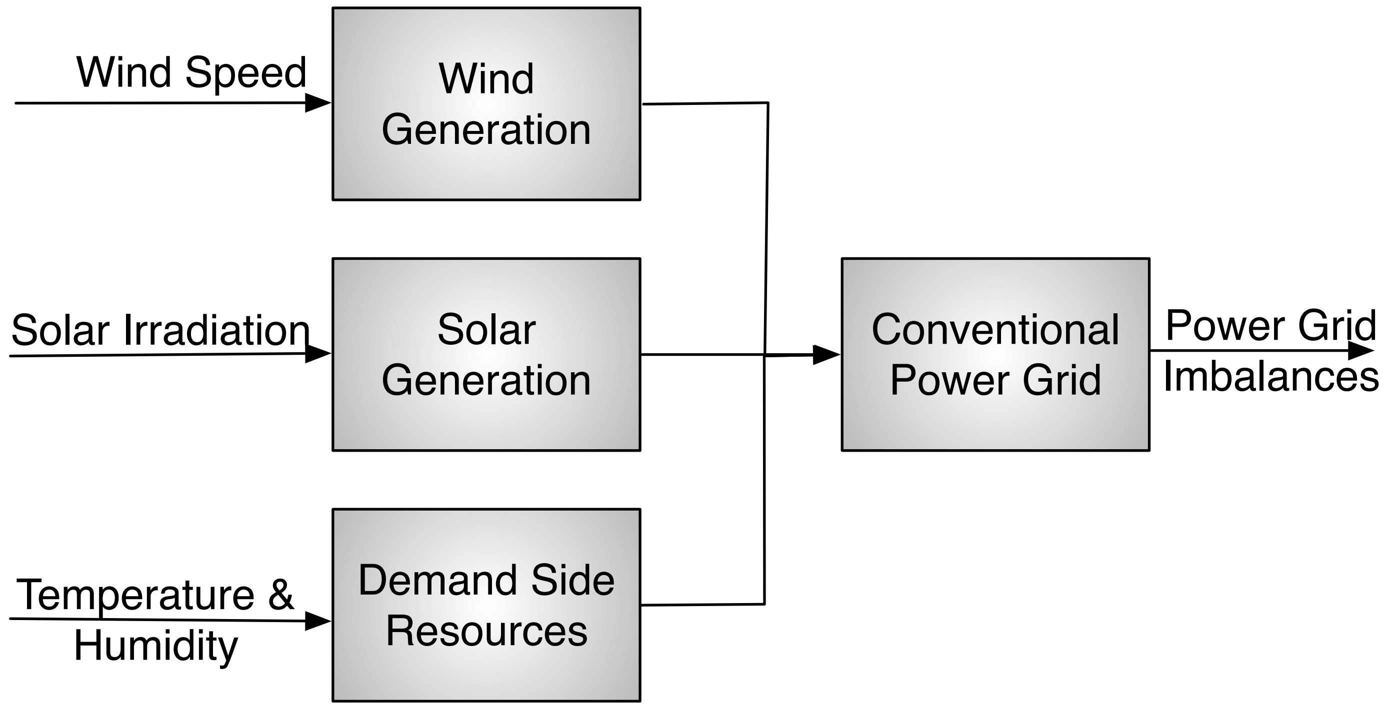
Load Variability

Adequacy of Existing VER Integration Study Methods

- **Assumption 1**. *Invariant Probability Density Function of Imbalances*: The probability density function of the power system imbalances measured over the previous period will be of the same functional shape in the next period. Normally, it is assumed that the imbalances have a normal distribution.
- **Assumption 2**. *Equivalence of Standard Deviations*: The standard deviation of power system imbalances is equivalently determined by either the net load variability or the forecast error. Some works use variability, while others use the forecast error.
- **Assumption 3**. *Invariant Standard Deviation*: The standard deviation in the next period will be of the same magnitude as in the current period.
- **Assumption 4**. *Non-dependence on Power System Operator Decisions & Control*: The standard deviation of power system imbalances does not depend on the endogenous characteristics of the power system operator decisions and control. According to the Assumption 2, it depends only on variability and forecast error, which can be viewed as exogenous disturbances to the power system operation and control.

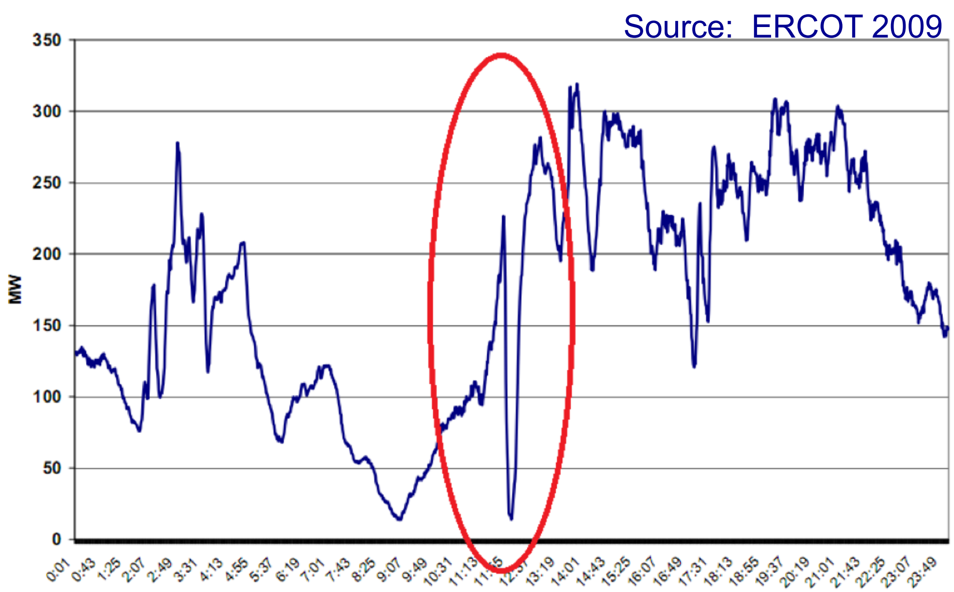
∴ **No consensus on methods for RE integration on flimsy assumptions**

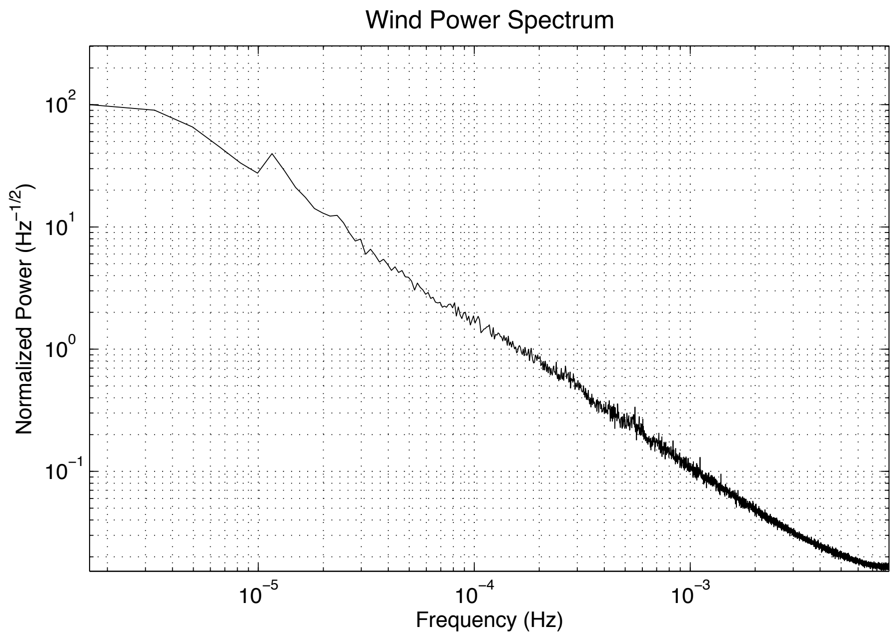
A High Level Systems/Enterprise View



∴ **Can a systems-oriented (enterprise control) view be taken to understand how power system disturbances are systematically rejected?**

Variability & Uncertainty in Wind Power Generation



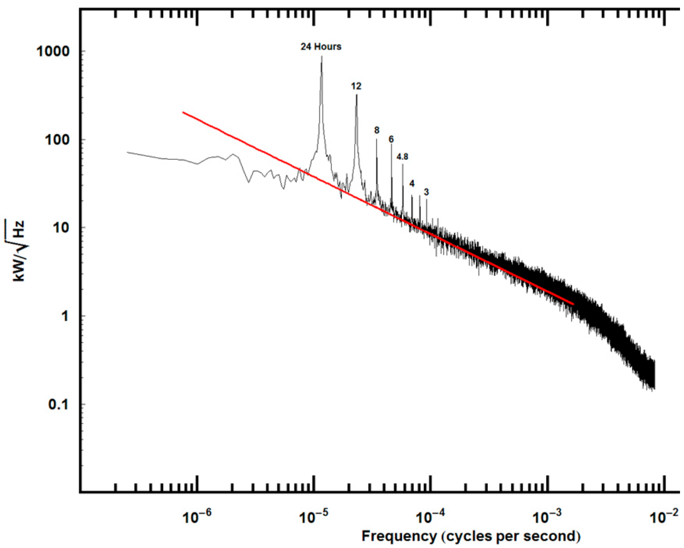


∴ **Enhanced control is required to avert potential grid instability**

∴ **Wind integration introduces dynamics over many time scales**

Variability & Uncertainty in Solar Power Generation

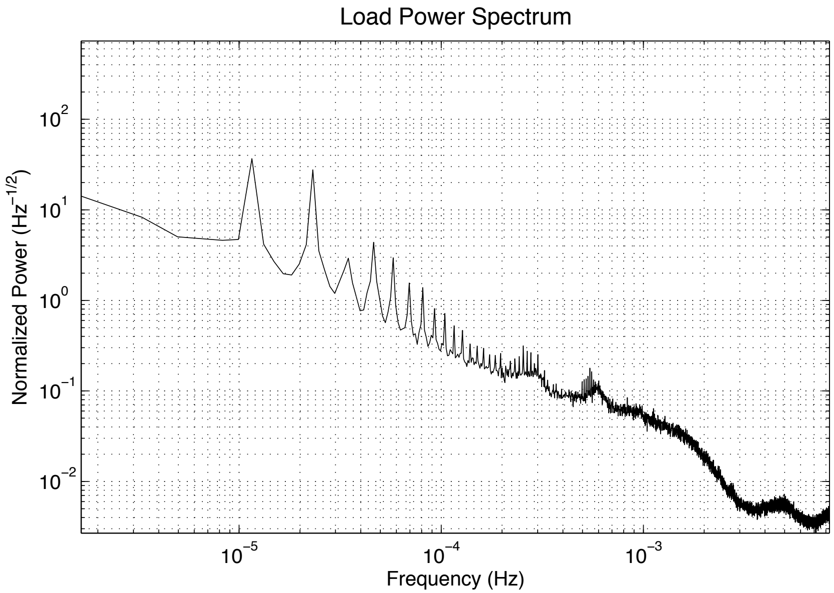
Source: NERC 2009

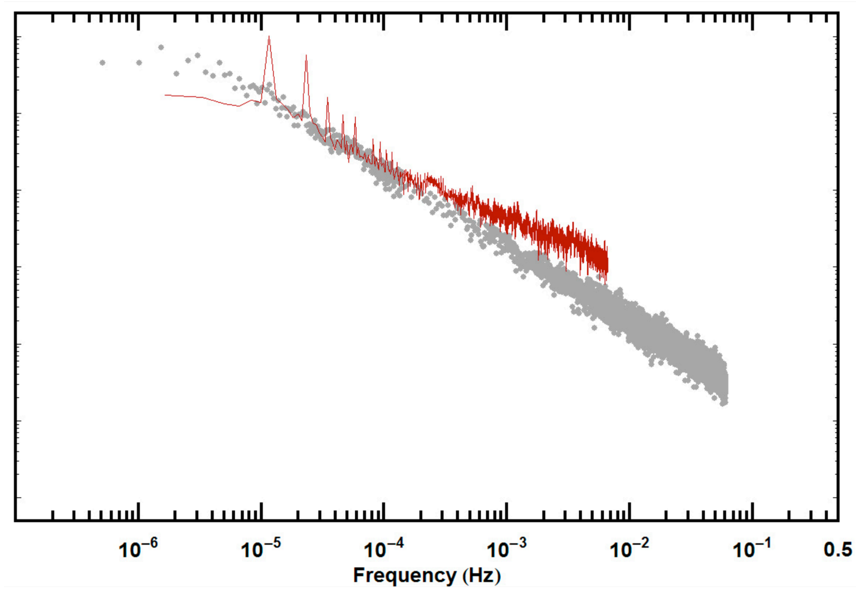


∴ **Enhanced control is required to avert potential grid instability**

∴ **Solar PV integration introduces dynamics over many time scales**

VER vs. Load Power Spectra

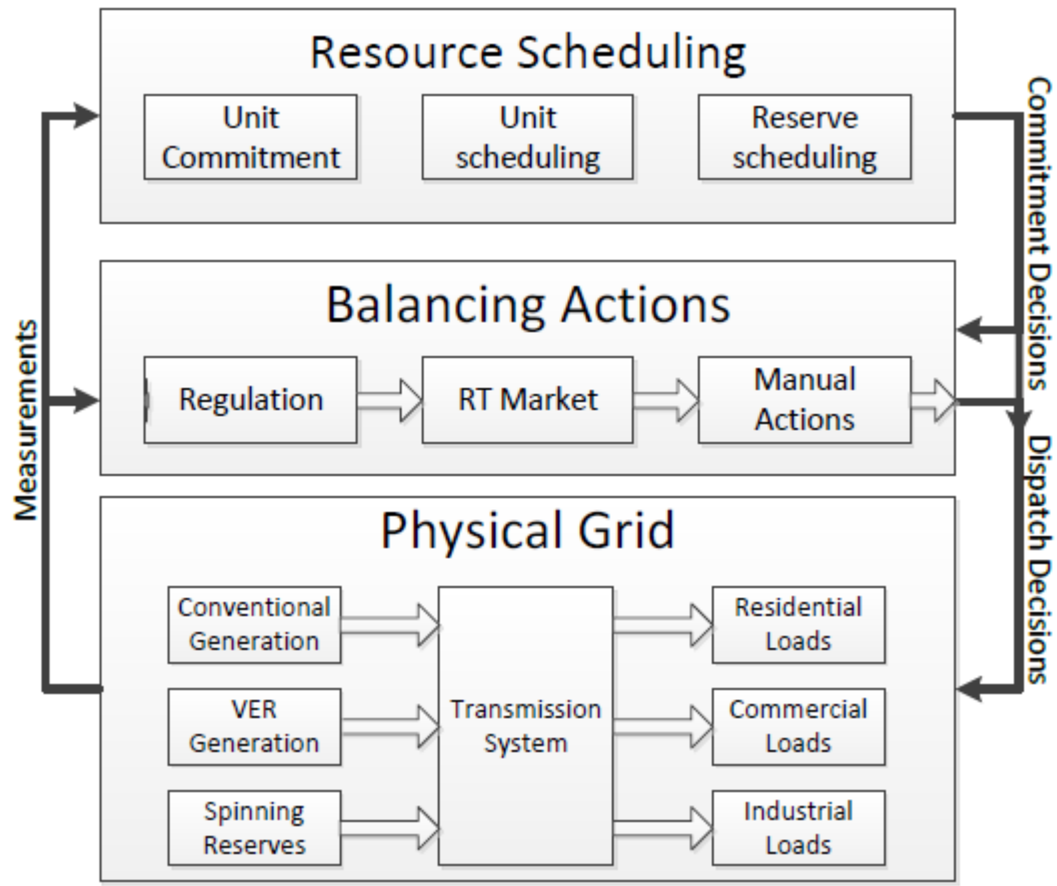




- The sum of the stochastic power spectra must be matched by the dispatchable grid resource for reliable operation
- VER & load power spectra are generally dissimilar
- Power grid operation has many assumptions based upon ***only*** the statistical history of the load power spectra … (Can this continue?)

∴ Reliable VER integration is not immediately assured with existing power system operation techniques

The Conceptual Model of Power System Operations



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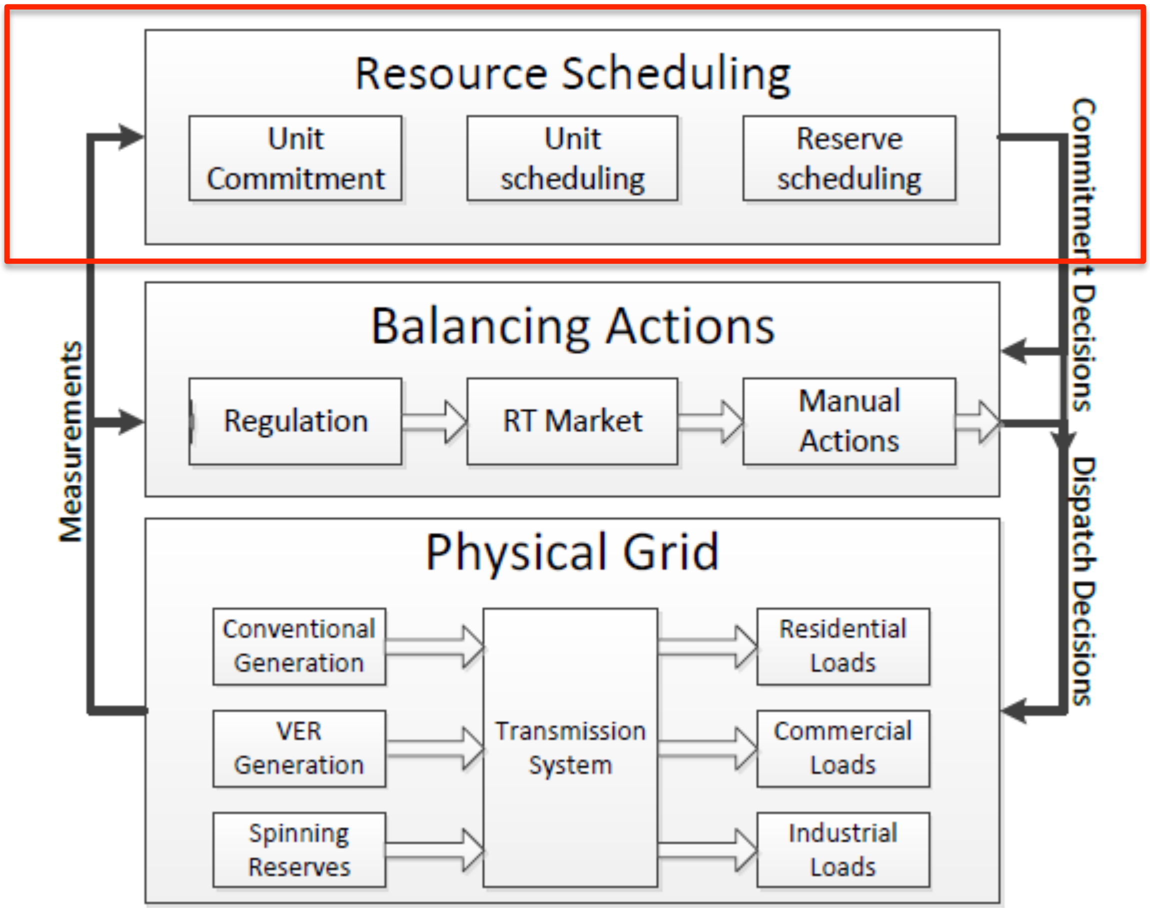
The Conceptual Model of Power System Operations



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Security-Constrained Unit Commitment (SCUC)

$$\min \quad \sum_{t=1}^{24}\sum_{i=1}^{N_G}(w_{i,t}C_i^F + C_i^G P_{i,t}^G + w_{i,t}^u C_i^U + w_{i,t}^d C_i^D)$$

$$\text{s.t.} \quad \sum_{i=1}^{N_G} P_{i,t}^G = P_t^D$$

$$-R_i^{G,max}\Delta T \le P_{i,t}^G - P_{i,t-1}^G \le R_i^{G,max}\Delta T$$

$$w_{i,t}P_i^{G,min} \le P_{i,t}^G \le w_{i,t}P_i^{G,max}$$

$$w_{i,t} = w_{i,t-1} + w_{i,t}^u - w_{i,t}^d$$

$$\sum_{i=1}^{N_G} w_{i,t}(P_i^{G,max} - P_{i,t}^G) \ge P^{res}$$

$C_i^F, C_i^G, C_i^U, C_i^D$	fixed, generation (fuel), startup and shutdown costs of generator i
$P_{i,t}^G$	power output of generator i at time t
P_t^D	total demand at time t
$P_i^{G,max}, P_i^{G,min}$	max/min power limits of generator i
$R_i^{G,max}$	maximum ramping rate of generator i
ΔT	scheduling time step, normally, 1 hour
N_G	number of generators
$w_{i,t}$	ON/OFF state of the generator i
$w_{i,t}^u, w_{i,t}^d$	startup/shutdown indicators of generator i
P^{res}	system reserve requirements

Reserve Scheduling

There are two types of assumptions usually made about power systems, which are also reflected in the formulation of the SCUC problem:

- The reserve scheduling constraint ensures availability of extra generation capacity so that generation units are able to increase their outputs. However, it is usually assumed that the generation units can reduce their output to the necessary value, and no additional constraint is required to ensure that ability. While this assumption may be true for specific power systems, it is not necessarily true in general.
- Similar to the generation scheduling, ramping rates are scheduled based on the day-ahead demand forecast. However, it is usually assumed that the ramping capabilities guaranteed by ramping constraints are sufficient for normal operations of the power system. Again, while this assumption may be true for specific power systems, it is not necessarily true in general.

Reserve Scheduling

To avoid the assumptions stated above and increase the generalization capabilities of the proposed method, additional reserve scheduling constraints are included into the SCUC model.

$$\sum_{i=1}^{N_G} w_{i,t}\left(P_i^{G,max} - P_{i,t}^G\right) \geq P_{res}$$

$$\sum_{i=1}^{N_G} w_{i,t}\left(P_i^{G,max} - P_{i,t}^G\right) \geq P_{res}$$ Up generation reserve

$$\sum_{i=1}^{N_G} w_{i,t}\left(P_{i,t}^G - P_i^{G,min}\right) \geq P_{res}$$ Down generation reserve

$$\sum_{i=1}^{N_G} w_{i,t}\left(R_i^{G,max} - R_{i,t}^G\right) \geq R_{res}$$ Up ramping reserve

$$\sum_{i=1}^{N_G} w_{i,t}\left(R_i^{G,max} + R_{i,t}^G\right) \geq R_{res}$$ Down ramping reserve

Reserve Requirements and Scheduled Reserves

According to the reserve scheduling constraints, actually scheduled reserves always exceed reserve requirements.

Actually scheduled reserves — Reserve requirements

$$\boxed{\sum_{i=1}^{N_G} w_{i,t}\left(P_i^{G,max} - P_{i,t}^{G}\right)} \geq \boxed{P_{res}}$$

The difference between this two values depends on the system generation base. In the "worst case" scenario, the scheduled generation will exactly match the reserve requirements, while in some other case the same reserve requirement will result in scheduling of much higher reserves.

This situation creates discrepancies in the interpretation of simulation results, since depending on the power system, the same reserve requirements may result in both perfectly balanced system and a system with severe imbalances.

Reserve Requirements and Scheduled Reserves

To avoid the discrepancies described above, it is assumed that the power system always operates in the "worst case" scenario, i.e., actually scheduled reserves and the requirements always match. To achieve this, the scaling factors are defined as the ratio of the reserve requirements and scheduled reserves:

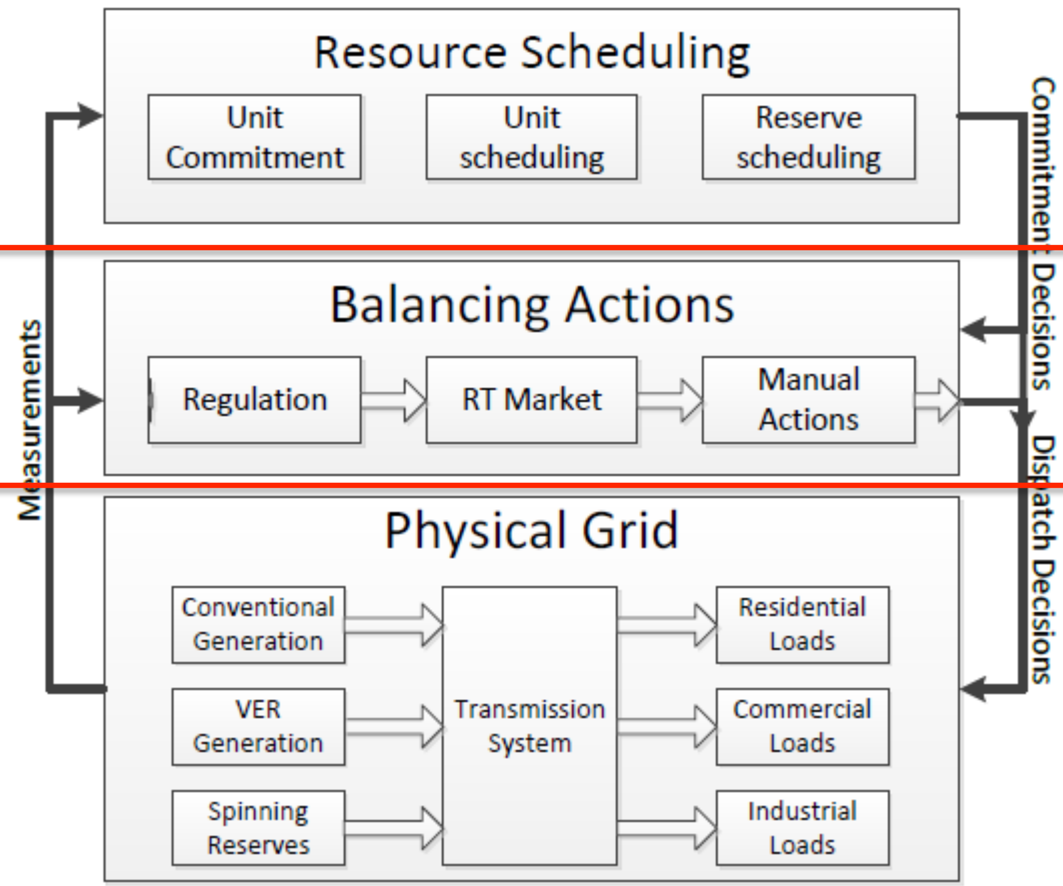
$$\alpha_t^P = \frac{P_{res}}{\sum_{i=1}^{N_G} w_{i,t} \left(P_i^{G,max} - P_{i,t}^G\right)} \qquad \alpha_t^R = \frac{R_{res}}{\sum_{i=1}^{N_G} w_{i,t} \left(R_i^{G,max} - R_{i,t}^G\right)}$$

Maximum generation and ramping capabilities of committed units are re-scaled as follows:

$$P_{i,t}^{G,max} = P_{i,t}^G + \alpha_t^P \cdot \left(P_i^{G,max} - P_{i,t}^G\right) \qquad R_{i,t}^{G,max} = R_{i,t}^G + \alpha_t^R \cdot \left(R_i^{G,max} - R_{i,t}^G\right)$$

This transformation results in a perfect match of reserve requirements and the scheduled reserves for any simulation scenario and makes the simulations more case-independent.

Balancing Actions



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Security-Constrained Economic Dispatch (SCED)

The real-time market is implemented in a form of linear security-constrained economic dispatch to avoid problems with convergence.

$$\min \quad \sum_{i=1}^{N_G} (b_i \Delta P_{i,t}^G + 2c_i P_{i,t}^G \Delta P_{i,t}^G)$$

$$\text{s.t.} \quad \sum_{i=1}^{N_B} (1-\gamma_{i,t})(\Delta P_{i,t}^G - \Delta P_{i,t}^L) = 0$$

$$\sum_{i=1}^{N_B} a_{l,i,t}(\Delta P_{i,t}^G - \Delta P_{i,t}^L) \leq F_l^{max} - F_{l,t}$$

$$-R_i^G \Delta t \leq \Delta P_{i,t}^G \leq R_i^G \Delta t$$

$$P_{i,t}^G - P_i^{G,min} \leq \Delta P_{i,t}^G \leq P_i^{G,max} - P_{i,t}^G$$

b_i, c_i	generator i offer curve linear and quadratic coefficients
$\Delta P_{i,t}^G, \Delta P_{i,t}^L$	bus i incremental generation and load
$F_{l,t}, F_l^{max}$	line l power flow level and flow limit
N_B	number of buses
$\gamma_{i,t}$	bus i incremental transmission loss factor
$a_{l,i,t}$	bus i generation shift distribution factor to line l
Δt	real-time market time step, normally, 5 minutes.

Regulation Service and Operator Manual Actions

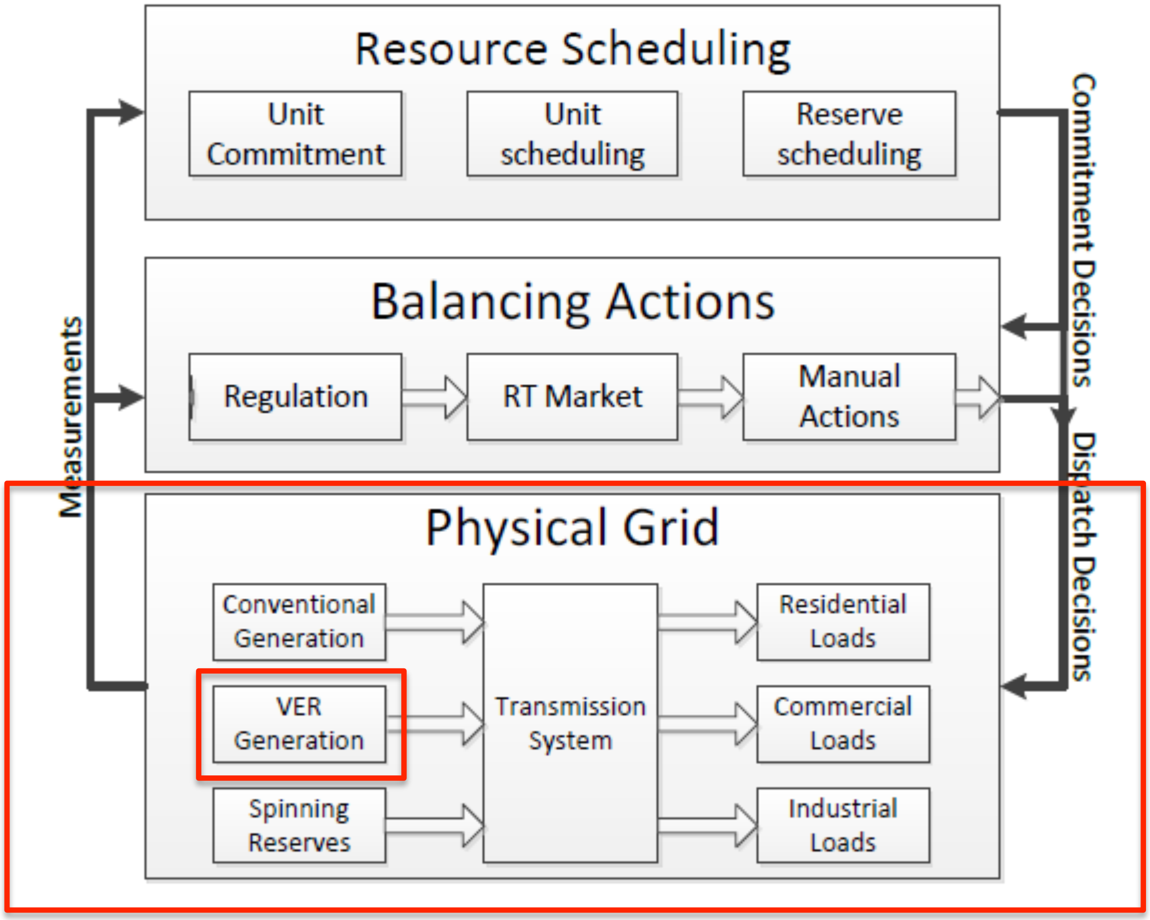
Steady-state regulation model:

- At each simulation step, the regulation service responds to the imbalances by moving its output to the opposite direction. The regulation output changes until imbalance mitigation or regulation service saturation.

Power system operator model:

- The trigger of operator manual actions works, when the actual imbalances exceed 80% of the largest generation unit. The operator actions include bringing new generation units online to suppress imbalances.

Physical Grid and VER Integration



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VER Incorporation into the System

The VER penetration level is defined as the ratio of the installed VER capacity and the peakload:

$$PEN = P_{VER}^{max} / P_{L}^{peak}$$

Using this definition of VER penetration level, the output of VER can be presented as follows:

$$P_{VER}(t) = \frac{P_{VER}(t)}{P_{VER}^{max}} \cdot \frac{P_{VER}^{max}}{P_{L}^{peak}} \cdot P_{L}^{peak} = \\ = \overline{P_{VER}}(t) \cdot PEN \cdot P_{L}^{peak}$$

$\overline{P_{VER}}(t)$ is VER output normalized by the installed VER capacity.

VER Incorporation into the System

Several different definitions of VER forecast error are commonly used in the literature. In this study VER forecast error is defined as the standard deviation of the forecasting error normalized by the installed VER capacity*:

$$ERR = \frac{\sigma\left(e(t)\right)}{P_{VER}^{max}}$$

Using this definition of VER forecast error, the forecasting error profile can be presented as follows:

$$e(t) = \frac{e(t)}{\sigma\left(e(t)\right)} \cdot \frac{\sigma\left(e(t)\right)}{P_{VER}^{max}} \cdot \frac{P_{VER}^{max}}{P_L^{peak}} \cdot P_L^{peak} =$$
$$= \overline{e}(t) \cdot ERR \cdot PEN \cdot P_L^{peak}$$

$\overline{e}(t)$ is error profile normalized to unit standard deviation.

*The same definition applies for both day-ahead and short term forecast errors.

VER Incorporation into the System

Since variability should indicate how fast VER output changes, this study defines variability as the standard deviation of VER output change rate normalized by the installed VER capacity. Thus, if VER output changes with the following rate:

$$R_{VER}(t) = \frac{dP_{VER}(t)}{dt}$$

The definition of variability can be written as:

$$VAR = \frac{\sigma\left(R_{VER}(t)\right)}{P_{VER}^{max}}$$

According to the definition, VER variability can be manipulated by scaling the time axis. Thus, using a normalized VER profile $\overline{P_{VER}}(t)$ with variability VAR_0, VER output can be written as:

$$P_{VER}(t) = \overline{P_{VER}}(\alpha t) \cdot PEN \cdot P_L^{peak}$$
$$e(t) = \overline{e}(\alpha t) \cdot ERR \cdot PEN \cdot P_L^{peak}$$

$$\alpha = \frac{VAR}{VAR_0}$$

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Test System

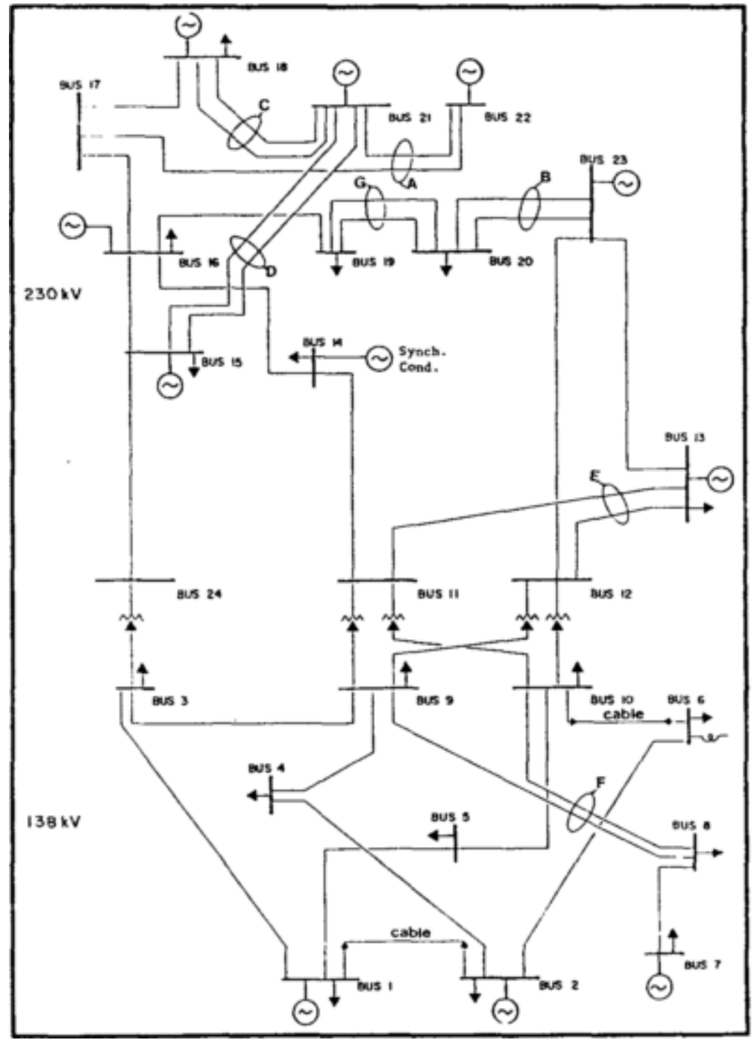
The IEEE Reliability Test System – 1996

- 3 nearly identical interconnected areas
- Buses 73
- Generators 99
- Annual peak load 8550 MW
- Total generation available 10215 MW

Wind and load data from Bonneville Power Administration (BPA) is used.

- Wind penetration level 20%
- Day-ahead forecast error 10%
- Short-Term forecast error 5%

NERC defined Control Performance Standard (CPS) is used to assess the balancing performance of the system.

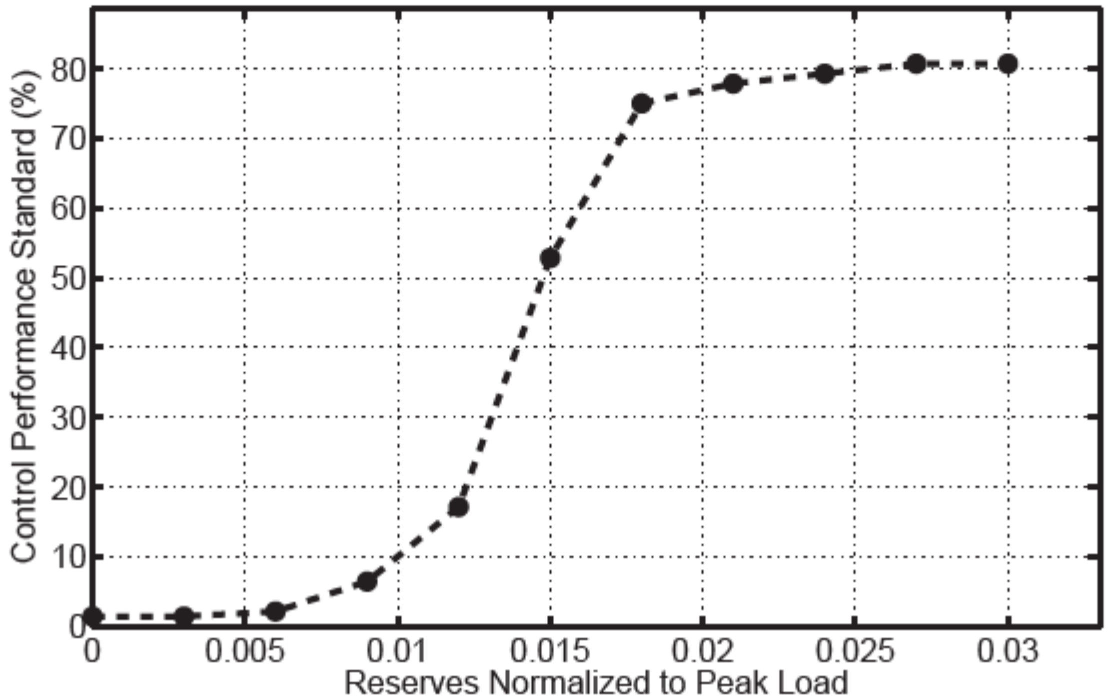


Simulation Scenarios

- **Case Study 1: VER impact on power system imbalances**
  - Scenario 0: Balancing of the traditional power system.
  - Scenario 1: The impact of wind penetration level *ceteris paribus*.
  - Scenario 2: The impact of wind variability *ceteris paribus*.
  - Scenario 3: The impact of wind day-ahead forecast error *ceteris paribus*.
  - Scenario 4: The impact of wind short-time forecast error *ceteris paribus*.
- **Case Study 2: Imbalance mitigation by increased reserve requirements**
  - Scenario 0: Balancing of the traditional power system.
  - Scenario 1: Imbalance mitigation by increasing generation reserves *ceteris paribus*.
  - Scenario 2: Imbalance mitigation by increasing ramping reserves *ceteris paribus*.
  - Scenario 3: Imbalance mitigation by increasing regulation reserves *ceteris paribus*.

Scenario 0: Traditional power system reserve requirement estimation

Muzhikyan, A., Farid, A. M. & Youcef-Toumi, K. Variable Energy Resource Induced Power System Imbalances: Mitigation by Increased System Flexibility, Spinning Reserves and Regulation. in *IEEE Conf. Technol. Sustain.* 1–7 (2013)



Scenario 0: Traditional power system regulation requirement estimation

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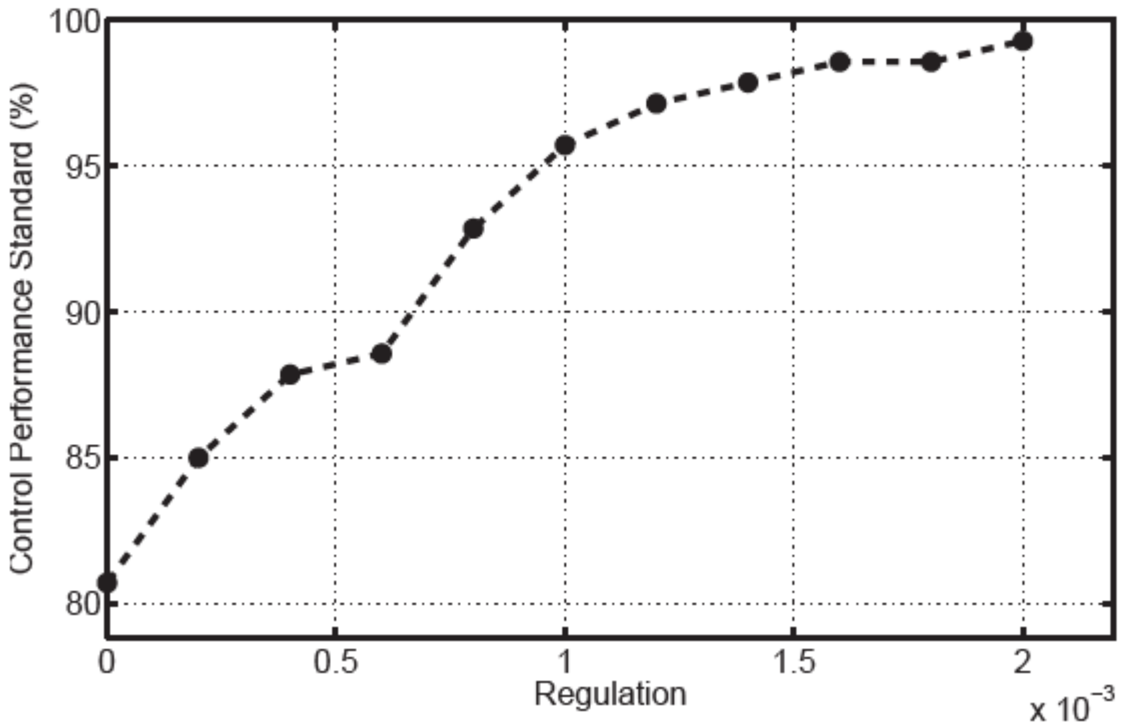

Case Study 1: VER Impact on Power System Imbalances

Scenario 1: The impact of wind penetration level *ceteris paribus*

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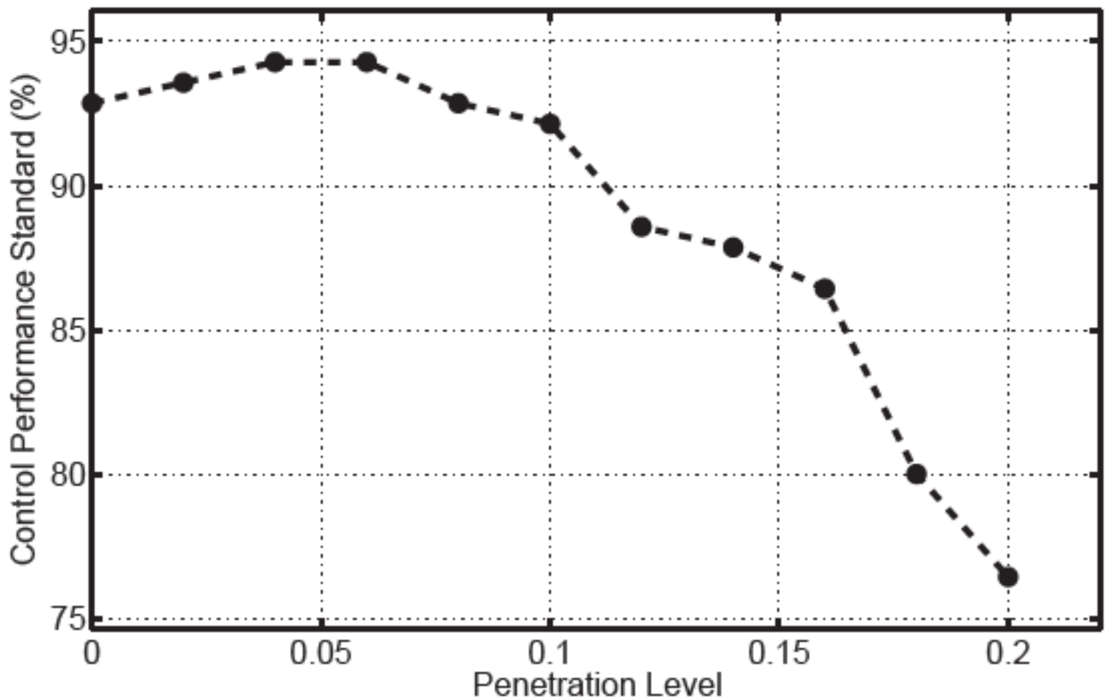

Case Study 1: VER Impact on Power System Imbalances

Scenario 2: The impact of wind variability *ceteris paribus*

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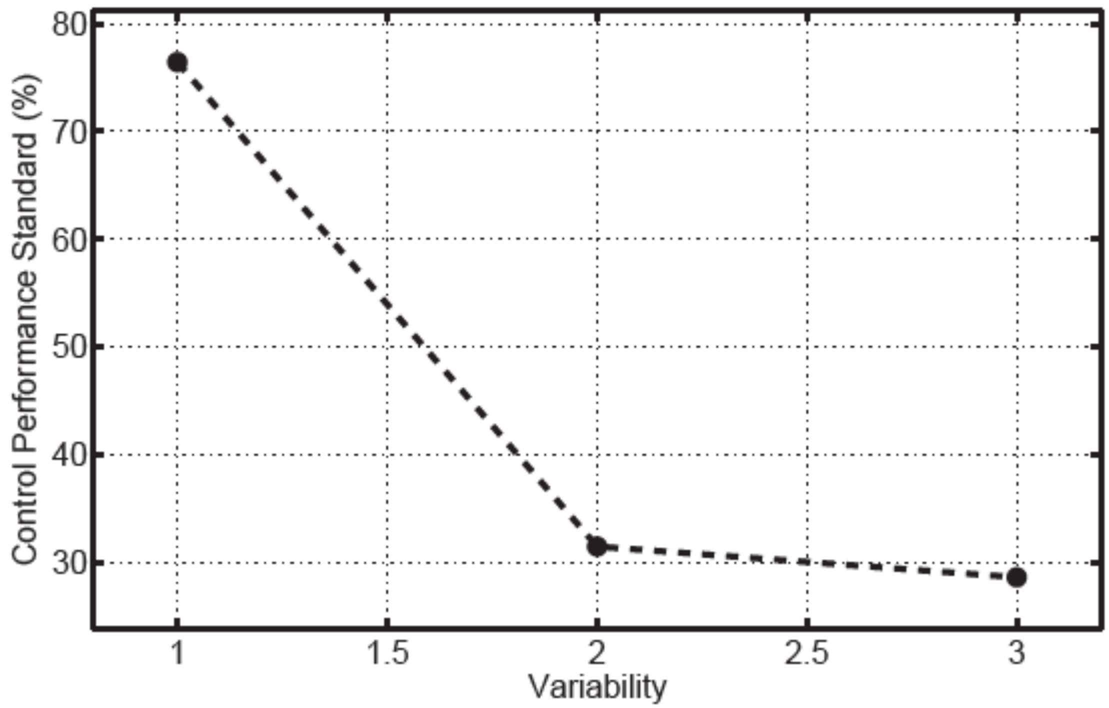

Scenario 3: The impact of wind day-ahead forecast error *ceteris paribus*

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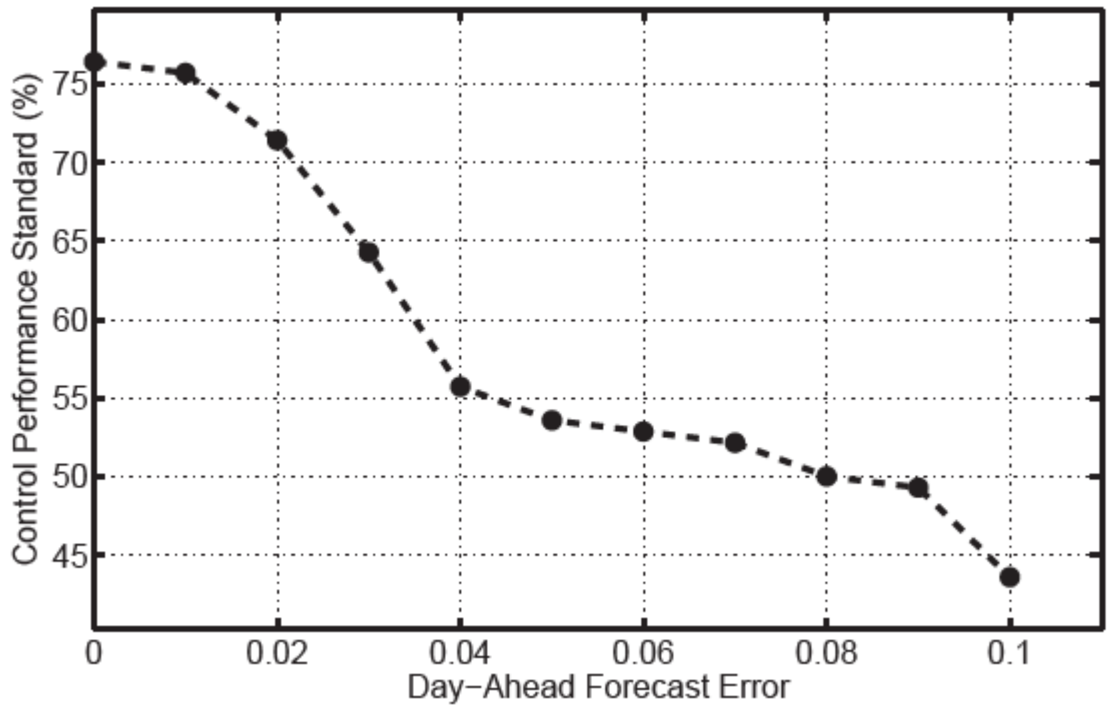

Scenario 4: The impact of wind short-term forecast error *ceteris paribus*

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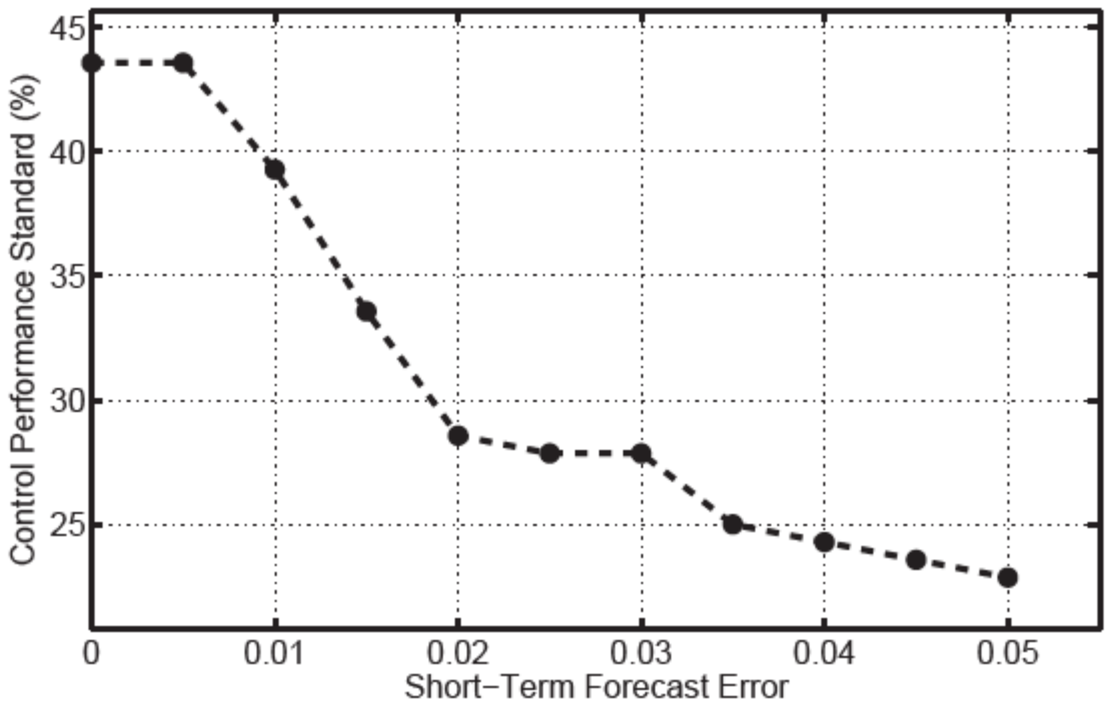

Case Study 2: Imbalance Mitigation by Increased Reserves

Scenario 0: Traditional power system reserve requirement estimation

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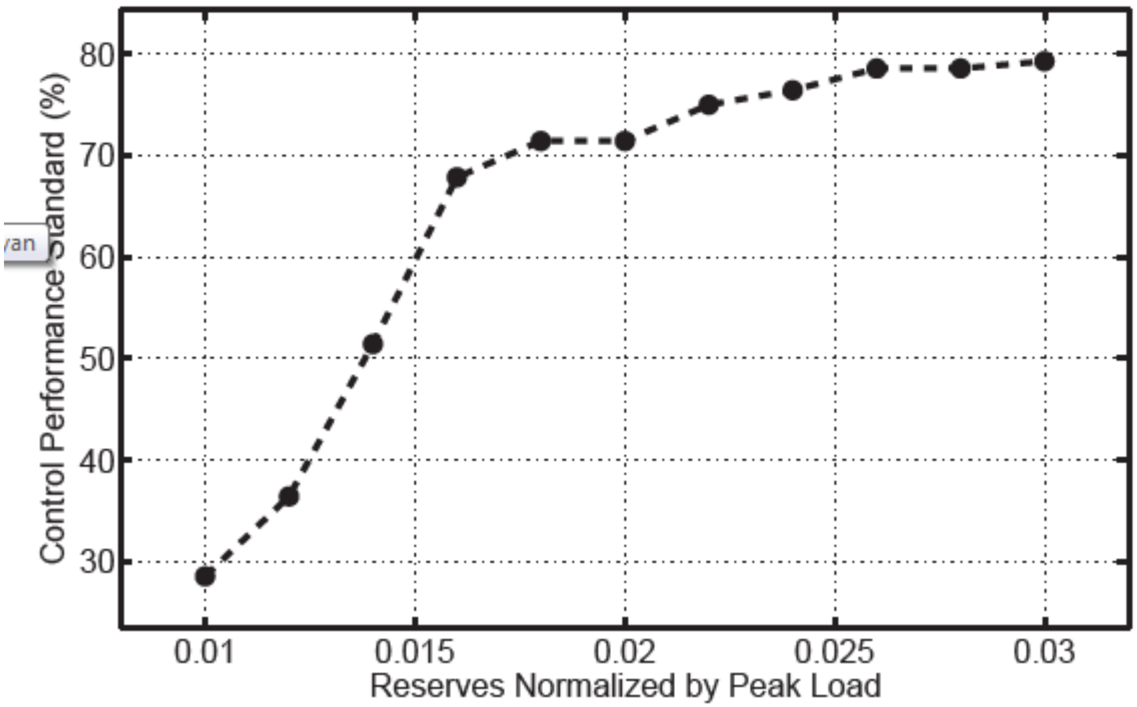

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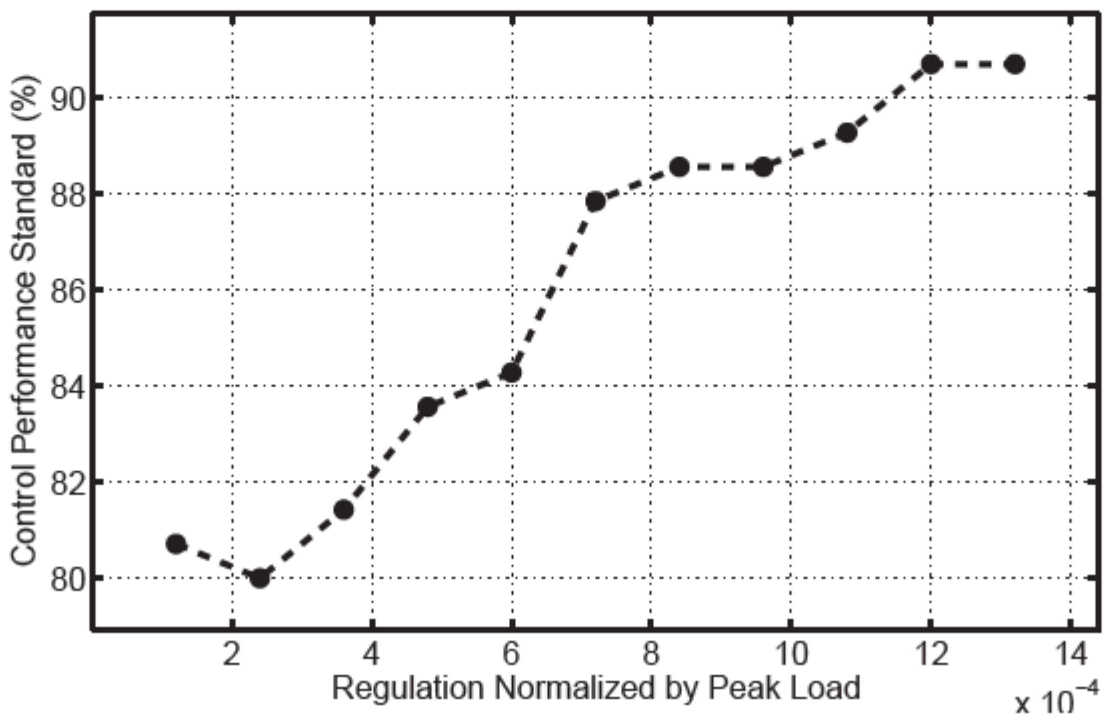

Case Study 2: Imbalance Mitigation by Increased Reserves

Scenario 1: Imbalance mitigation by increased generation reserves *ceteris paribus*

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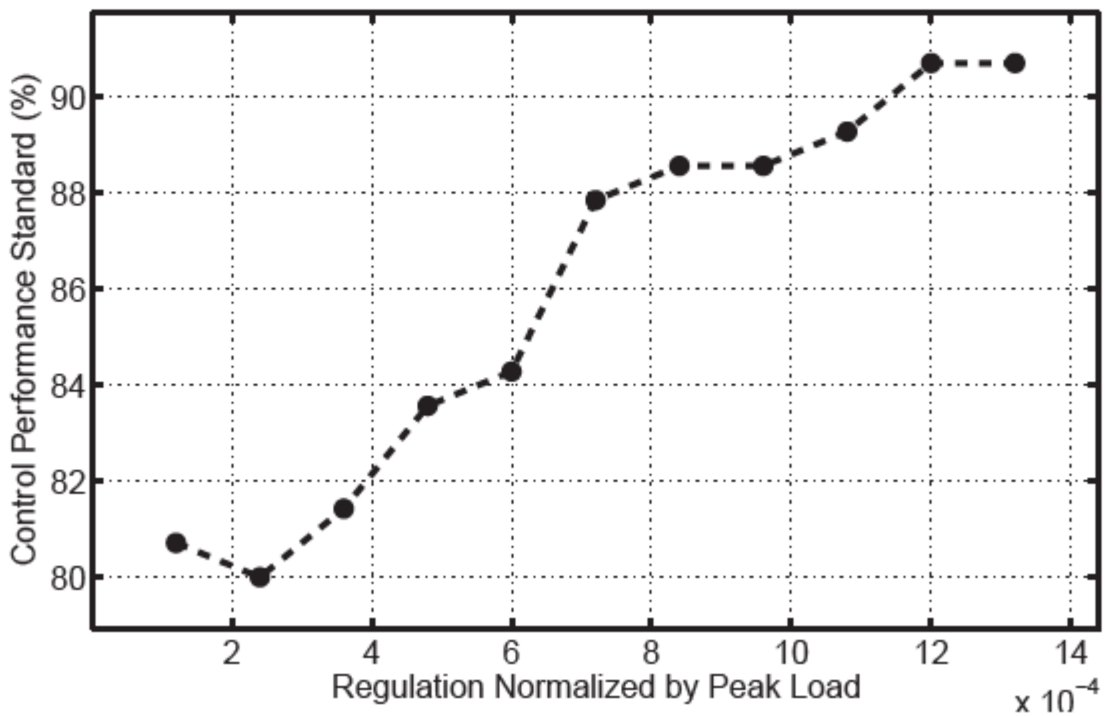

Case Study 2: Imbalance Mitigation by Increased Reserves

Scenario 2: Imbalance mitigation by increased ramping reserves *ceteris paribus*

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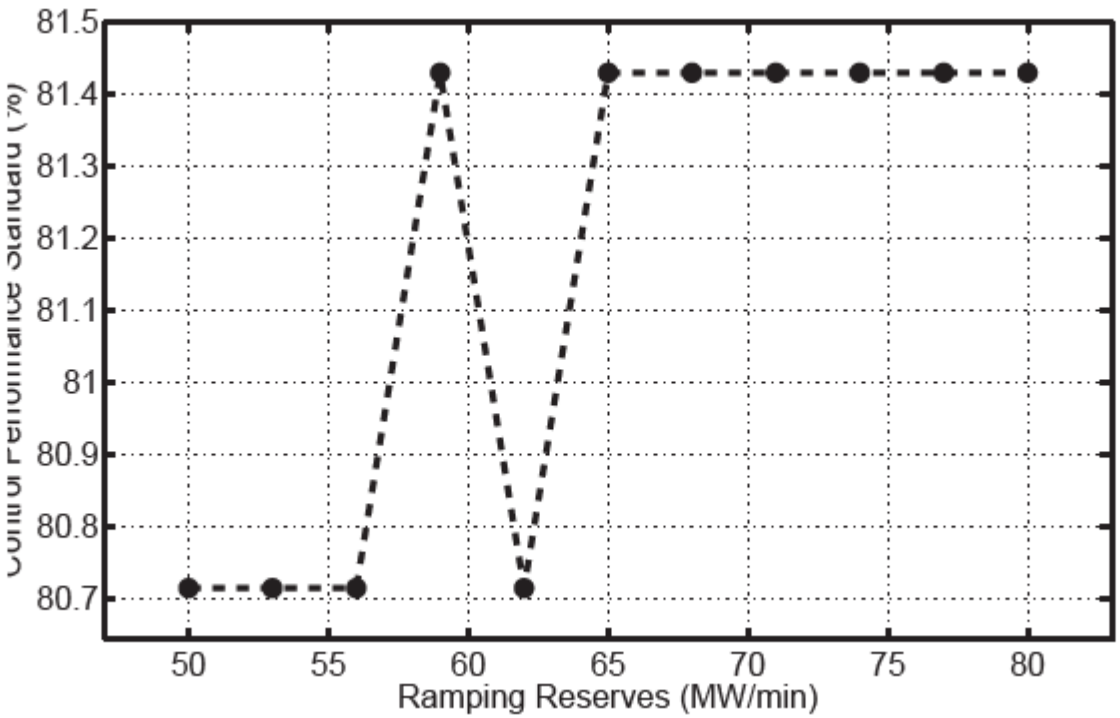

Case Study 2: Imbalance Mitigation by Increased Reserves

Scenario 3: Imbalance mitigation by increased regulation reserves *ceteris paribus*

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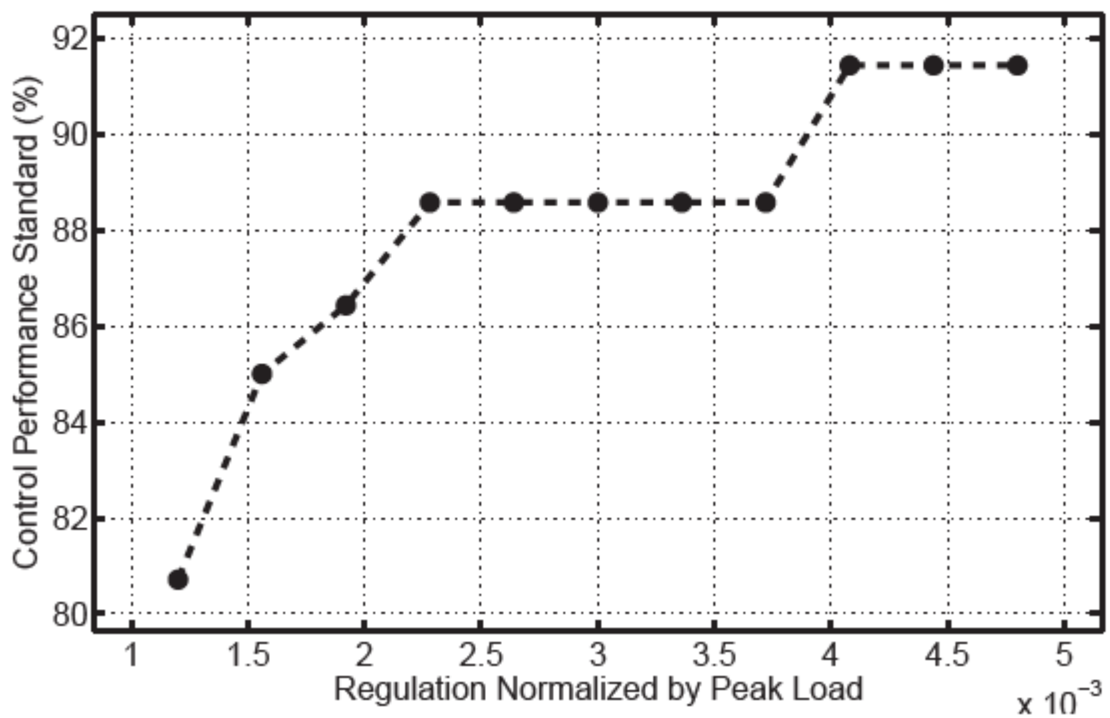

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Conclusion

The power system is modeled as an integrated enterprise consisting of three layers, namely resource scheduling, balancing actions and the physical grid.

The results of the first case study show, that integration VER into the power system increase the imbalances significantly.

The results of the second case study show that VER induced power system imbalances can be effectively mitigated by increased amount of generation, ramping and regulation reserves.

Thank you