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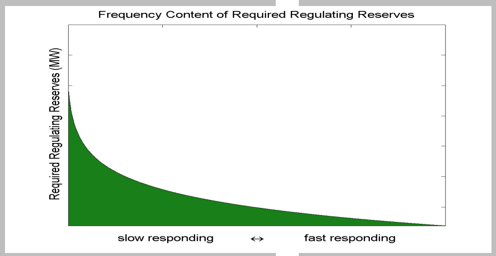

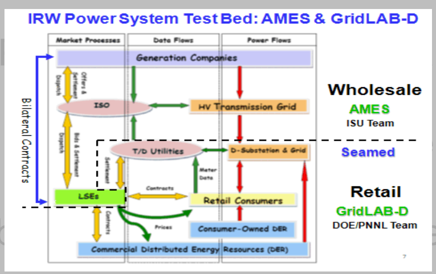

Introduction to the Draft Wholesale Electricity Market Design

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Sandia National Laboratories

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U.S. DEPARTMENT OF ENERGY

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Today's Presentation

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- Introduction (Ross Guttromson)
- Operating Reserve Market Survey (Jim Ellison)
- Overall Market Design Concepts (Leigh Tesfatsion)
- Market Entities, Benefits and Energy Market Design (Verne Loose)
- Reserve Market Design (Ryan Elliott)
- Frequency Domain View of Reserve Markets (Ray Byrne)
- Optimization and Co-Optimization of Markets (Cesar Silva-Monroy)

Please ask us questions and provide comments as we go

Introduction- Project Phases

- Year 1
  - Basic Market Structures and Design Principles
- Year 2
  - Mathematical formulations and optimizations
- Year 3
  - Market modeling in AMES – Performance testing of formulations and optimizations, including tests for possible market power manipulation

Introduction - Motivation for a New Market Design

- Need to eliminate market bias of resource classes such as Energy Storage
- Need to accommodate new technologies, without the need to change market rules

- Move away from resource centric markets toward service centric markets
- Provide a greater incentive of capital funding for resources that provide needed services

Introduction - High Level Functions

We are designing a market that:

- Ensures open access for any resource that can provide services
- Does not require a resource to provide services it can not optimally deliver
- Compensates based on services provided to the grid without the need to partition the market
- Achieves resource adequacy, and meets engineering requirements for a reliable grid
- Achieves economic efficiency
- Supports market reform efforts
- Is implementable in stages; in part or in whole

Old

1. System needs are identified
2. Markets are partitioned to meet system needs
3. Market asks "how much to deliver *this*"?
4. Resources make offers
5. Market optimizes a solution

New

1. System needs are identified
2. Resources state what needs they can offer and at what cost (without regards to market partitions)
3. Market optimizes a solution

Introduction-What We Want From You

We need your guidance and help to make this project successful

- Help us understand the line between 'difficult' and 'impossible'
- Calibrate us regarding what's important and what is not
- Help us understand the implications (e.g. policy implications, computational implications) of what we are trying to do
- Challenge and/or encourage our approach as necessary

Reserve Market Terminology

ISO/RTO	Primary Frequency Control Reserve	Secondary Frequency Control Reserve	Tertiary Frequency Control Reserve			
CAISO	no market	*Regulation Reserve* Regulation Up Regulation Down	Spinning reserve	Non-spinning Reserve		
ERCOT	no market	*Regulation Services* Reg Service - Up Reg Service - Down	Responsive Reserve Service	Non-Spinning Reserve Service	Replacement Reserve Service	
ISO-NE	no market	Regulation	Ten-Minute Spinning	Ten-Minute Non-Spinning	Thirty-Minute Operating	
MISO	no market	Regulating Reserve	*Contingency Reserve* Spinning Reserve	Supplemental Reserve		
NYISO	no market	Regulation	10-Minute Spinning Reserve	10-Minute Non-Synchronized Reserve	30-Minute Spinning Reserve	30-Minute Non-Synchronized Reserve
PJM	no market	Regulation	*Contingency Reserve* Synchronous Reserve	Quick Start Reserve	Supplemental Reserve	
SPP*	no market	*Regulation* Regulation Up Regulation Down	*Contingency Reserve* Spinning Reserve	Supplemental Reserve		

Reserve Market Characteristics

Function	Product	Characteristics	CAISO	ERCOT	ISO-NE	MISO	NYISO	PJM	SPP*
Primary Frequency Control Response	none								
Secondary Frequency Control Response	Regulation Reserve	Governor control necessary for participation?	no	yes	no	yes	no	no	no
		Separate markets for up/down regulation?	yes	yes	no	no	no	no	yes
		AGC signal required?	yes	yes	yes	yes	yes	yes	yes
		Max time to deliver nominated capacity?	10-30**	10	5	5	5	5	
		Min duration to maintain nominated output?			60	60			60
		Min ramp rate? (MW/min)			1				
		Min capacity offered?		1 MW				0.1 MW	
Tertiary Frequency Control Response	Spinning Reserve	Governor control necessary for participation?	no	yes	no	no	no	no	no
		Max delay to deliver nominated capacity?	10	10	10	10	10	10	10
		Min duration to maintain nominated output?	30		60	60			60
		Min capacity offered?		1MW					
		Two-tiered market structure?	no	no	no	no	no	yes	no
	Non-Spinning Reserve	Max delay to be synchronized and at nominated capacity?	10	30	10	10	10	10	10
		Min duration to maintain nominated output?	30		60	60			60
		Min capacity offered?		1 MW					
	Supplemental Reserve	Separated into synchronized and non-synchronized reserve markets?	N/A	no	no	N/A	yes	no	N/A
		Max delay to be synchronized and at nominated capacity?	N/A	agreed upon	30	N/A	30	30	N/A
		Min duration to maintain nominated output?	N/A	agreed upon		N/A			N/A

Market Design Problems

- Reserve market rules assume ramp-rate constrained generators
  - Payment for regulation based on capacity
    - 10MW from coal plant and from flywheel resource compensated the same
    - Ability to follow fast signal, or accuracy of following signal, not considered
  - Payment for spinning reserve based on capacity
- Reserve market products are defined in ways that are biased against some newer resources
  - 60-minute regulation reserve duration requirement
  - Carve-outs are being implemented for storage that partially addresses problem
- No compensation for inertia, primary frequency response capability, or reactive power supply capability
  - Could pose a problem as fraction of variable generation grows
- No direct specification of amount or speed of primary frequency response required

Overall Market Design Concept

- Energy Forward Contract (EFC) representation of energy and reserve products
  - Physically-covered obligations (energy) and options (reserve)
  - **EFC Obligation**: Contract holder ***obligated*** to procure power (or power curtailment) from contract issuer
  - **EFC Option**: Contract holder has ***right (not obligation)*** to procure power (or power curtailment) from contract issuer
  - Contractual terms permit market pricing and procurement
  - Contractual terms permit real-time energy/reserve deployment

Overall Market Design Concept …

- EFC trades take place in a sequence of forward markets
  - Each forward market an ISO-managed exchange based on
    - private-trader supply offers/demand bids for EFC obligations (energy)
    - private trader supply offers for EFC options (reserve)
    - ISO demand bids for EFC options (reserve)
  - Performance periods can range from multiple-year to intra-hour
  - Each market solved via a bid/offer-based optimal power flow (OPF) optimization
  - ***Linkage:*** OPF outcomes in each forward market depend on previously acquired EFCs and possible future EFC procurement
  - Forward markets can include self-scheduled bilateral EFC trades

Linked Forward Markets for EFC Trades

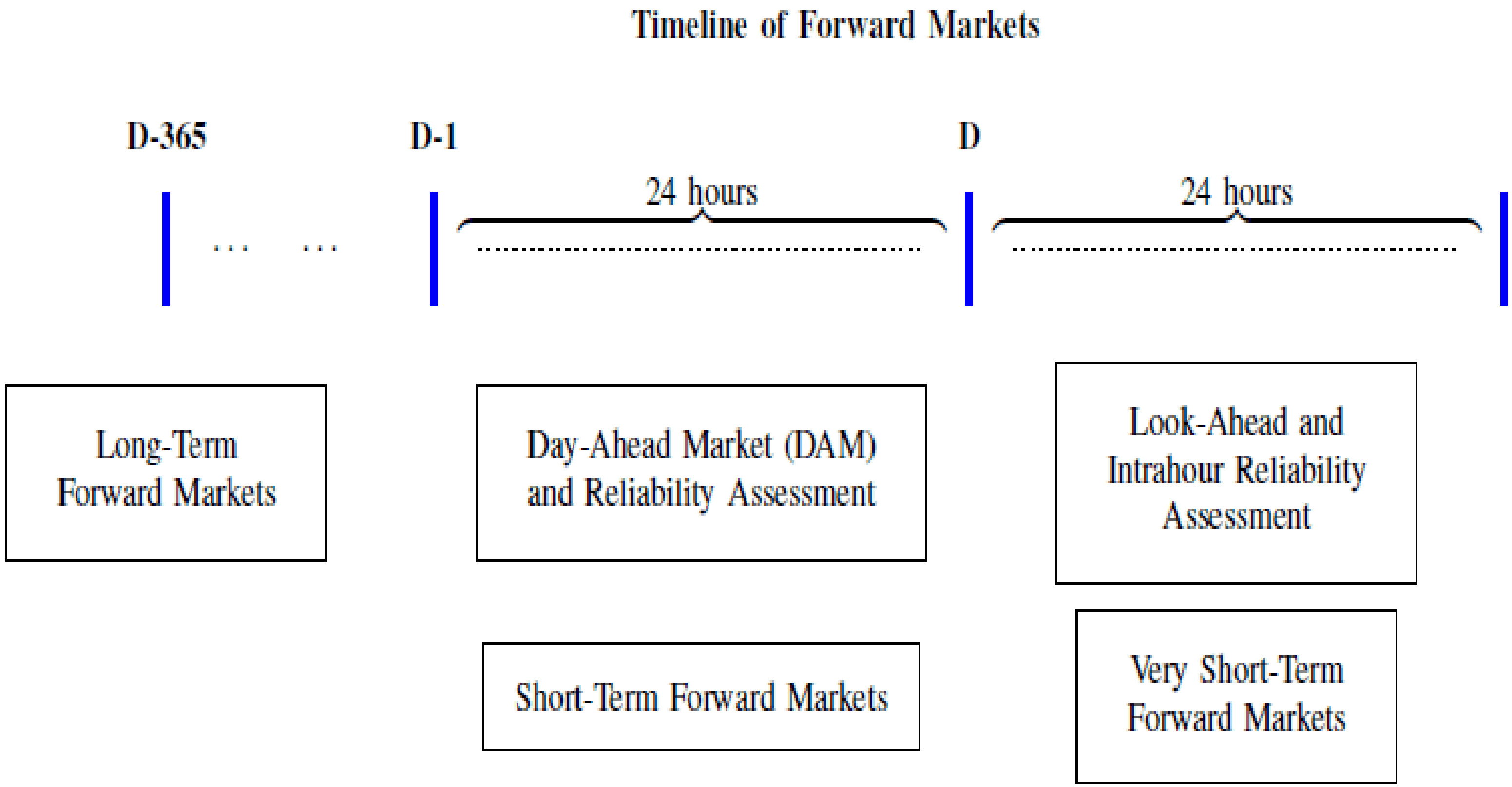


Fig. 1: Linked Forward Markets Permitting the Advanced Procurement of Energy and Reserve for Operating Day D.

Overall Market Design Concept

- Anticipated advantages of market design
  - **Fairness:** Markets equally open to all resources capable of fulfilling EFC contractual terms for service provision
  - **Efficiency Gains:** Reduced transactions costs arising from standardized contracts and standardized market forms
  - **Resolution of "Missing Money" Problem:**
    - Long-term forward markets can use EFC option premiums to attract new capacity by covering capital costs
    - Could reduce/eliminate need for separate capacity markets

Overall Market Design Concept

- Anticipated advantages of market design, continued
  - **Primary Frequency response:** Reserve formulation allows for specification of amount of frequency response reserves required
    - Can be compensated
  - **Market Access:** EES developers and other new GenCo technologies have market access without changing rules, protocols, or definitions
  - **Reduced Market Power:** Inducements to new generation increase may increase competition and lessen tendency for market power

Who are the market entities?

Independent System Operator

Supply	**Demand**

Supply

- Generation owners (GenCos)
  - Regulated utilities
  - Independent Power Producer
  - Merchant Plants
  - Co-generators
  - Co-ops
- Private traders (speculators)

Demand

- Load Serving Entities (LSEs)
  - Regulated utilities
  - Load aggregators
  - Large consumers
  - Co-ops
- Private traders (speculators)

Credentialing process involves formal application, credit substantiation, posting performance bond, and, for GenCos, equipment testing

Energy Product Specification

Forward Obligation Contract Specification

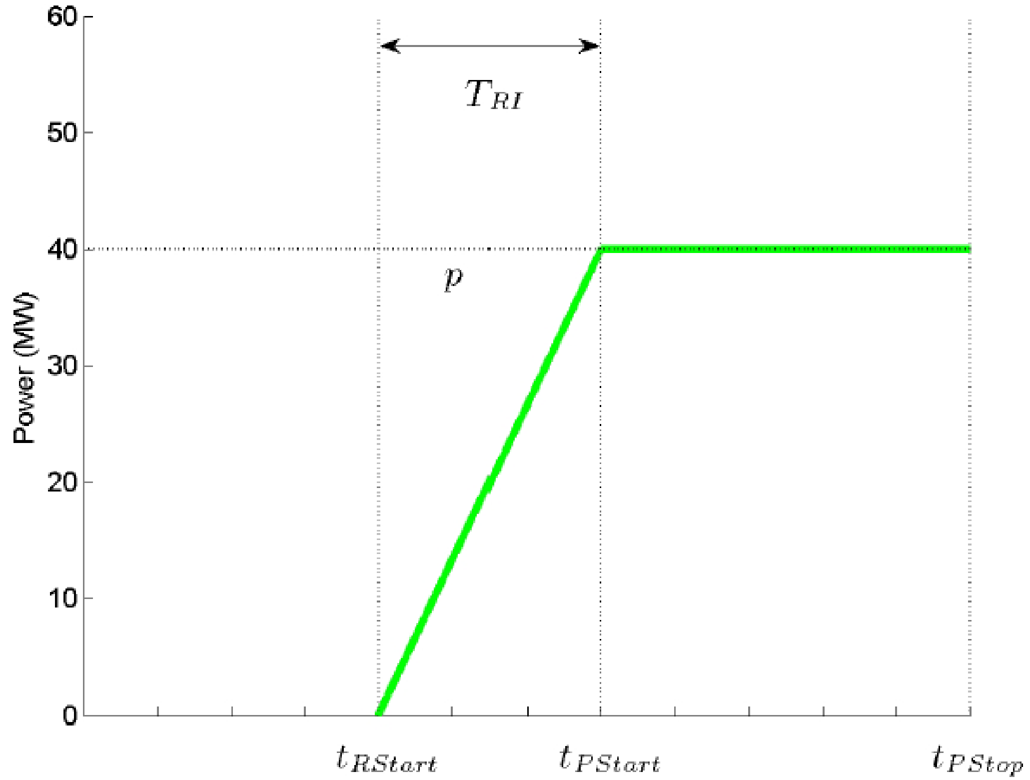
The general quantitative representation proposed for an energy product in EFC obligation form is as follows:

$$\text{Energy Product} = (\text{obligation}, k, \text{direction}, t_{PStart}, p, t_{PStop})$$

where:

$$\begin{aligned} \text{obligation} &= \text{Contract type} \\ k &= \text{Location (bus, zone, ...) where power delivery is to occur} \\ \text{direction} &= \text{Up or down} \\ t_{PStart} &= \text{Power start time} \\ p &= \text{Power increment (MW)} \\ t_{PStop} &= \text{Power stop time} \end{aligned}$$

EFC Obligation (up direction)



T_{RI} = Ramping Interval

Energy Product Design

- The energy obligation is a firm, non-contingent contract
  - Could cover an interval of time
  - Market for commoditized bi-lateral contracts may promote efficiency
  - But their existence doesn't eliminate bi-lateral contracts if market participants see a need
- Long-term EFC obligations could enhance energy supply over a multi-year period
  - If more capacity is procured on a longer-term basis, undesirable spot price volatility should decrease
  - More long-term energy supply might improve future resource adequacy
- As the operating day approaches, short-term EFC obligations can be acquired and/or options exercised to supplement long-term EFC obligations to meet energy demand

Reserve Product Definition

- An EFC call option is a contingent contract that gives the option holder the right to purchase energy, or energy curtailment.
- The option holder may choose not to exercise the option.
  - The forecasted need for energy or energy curtailment may not arise.
  - The option holder may find a cheaper alternative.
- Comparison of obligations and options:

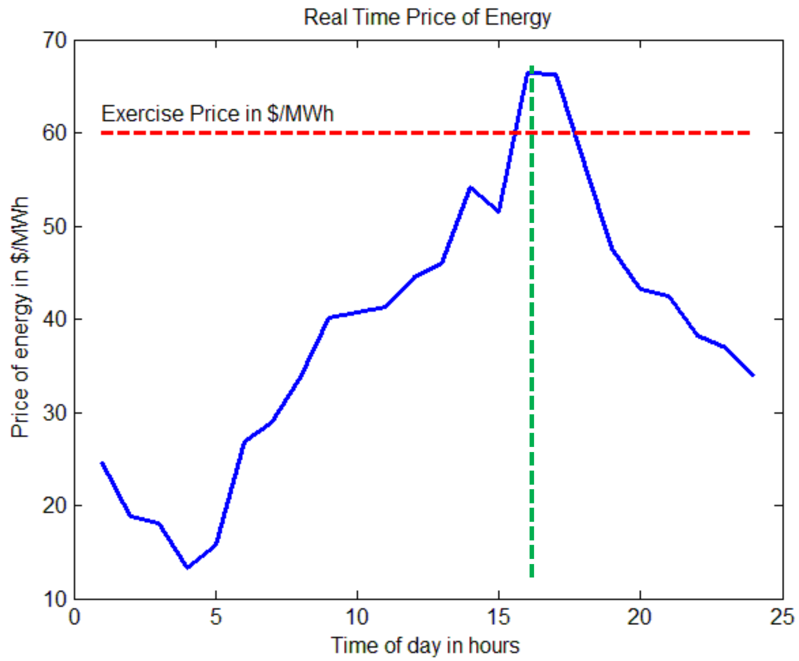
EFC Obligation	EFC Option
Non-contingent contract	Contingent contract
Energy product	Reserve product

Reserve Product Properties

- Contract takes the form of a physically covered EFC option
- Physical coverage: Upon exercise, the issuing resource must provide the specified amount of energy, or curtailment
- Requires the issuing resource to hold a contractually specified amount of capacity in reserve
- Must be physically covered to function as a reserve product, because financial coverage doesn’t hold capacity in reserve
- Provides protection against inadequate capacity and price volatility

EFC Options as Price Insurance

- An EFC call option allows the holder to purchase energy at the exercise price.



- For an ISO, the decision to exercise would be based more on need than price.

EFC Option Contract Terms

- The terms currently specified in an EFC option contract are:
  - Direction (up or down)
  - Bus location of delivery (or curtailment)
  - Energy capacity (for limited energy resources)
  - Start-up ramp rate (while synchronizing)
  - Exercise price (or price calculation method)

  ← May not swing

  - Exercise time
  - Controlled ramp rate
  - Controlled power increment
  - Controlled power start time
  - Controlled power stop time

  ← May swing

EFC Option Types

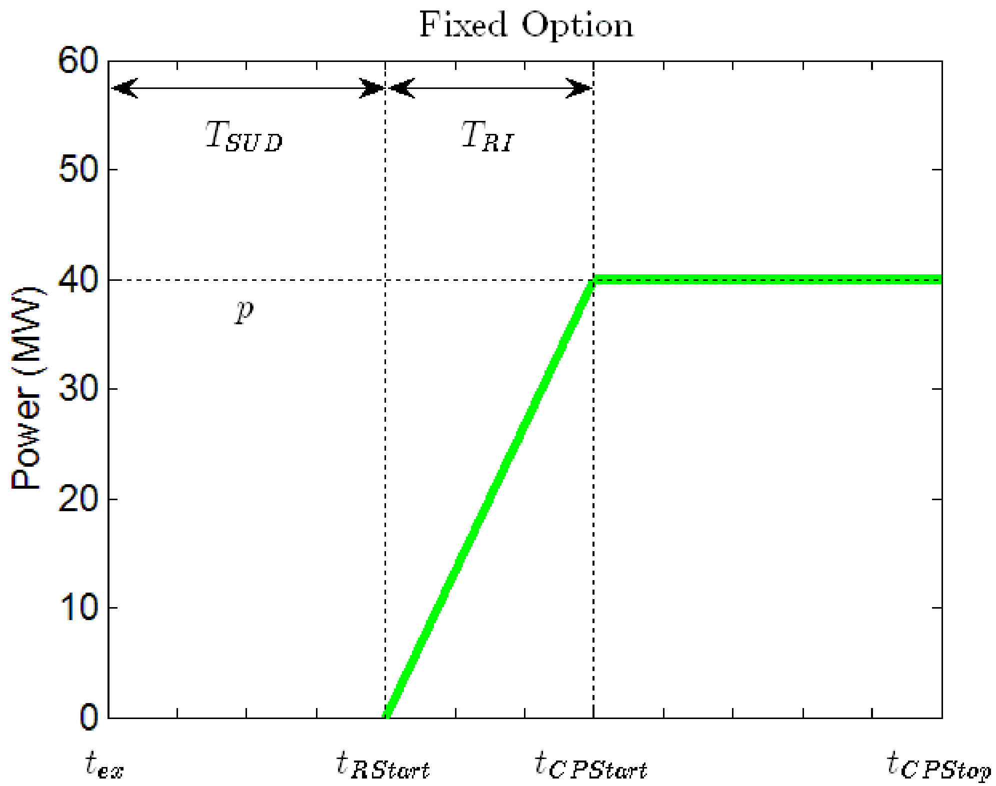
Fixed options

- All contract terms are specified as point values
- Provides block energy reserve
- Single power output level and exercise time

Swing options

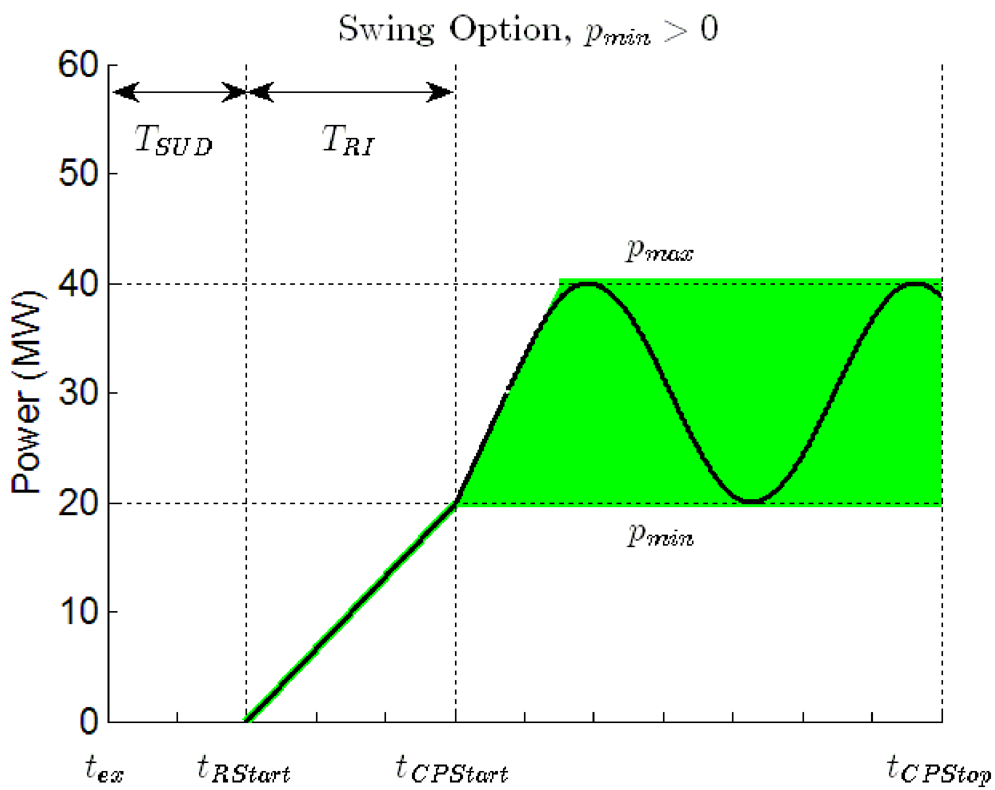
- Some contract terms are specified as intervals (or ranges)
- Capable of providing regulation reserve
- Examples of swing:
  - Power output level, or consumption level
  - Ramping rate (rate of change of power output)
  - Exercise time

EFC Fixed Option (up direction)



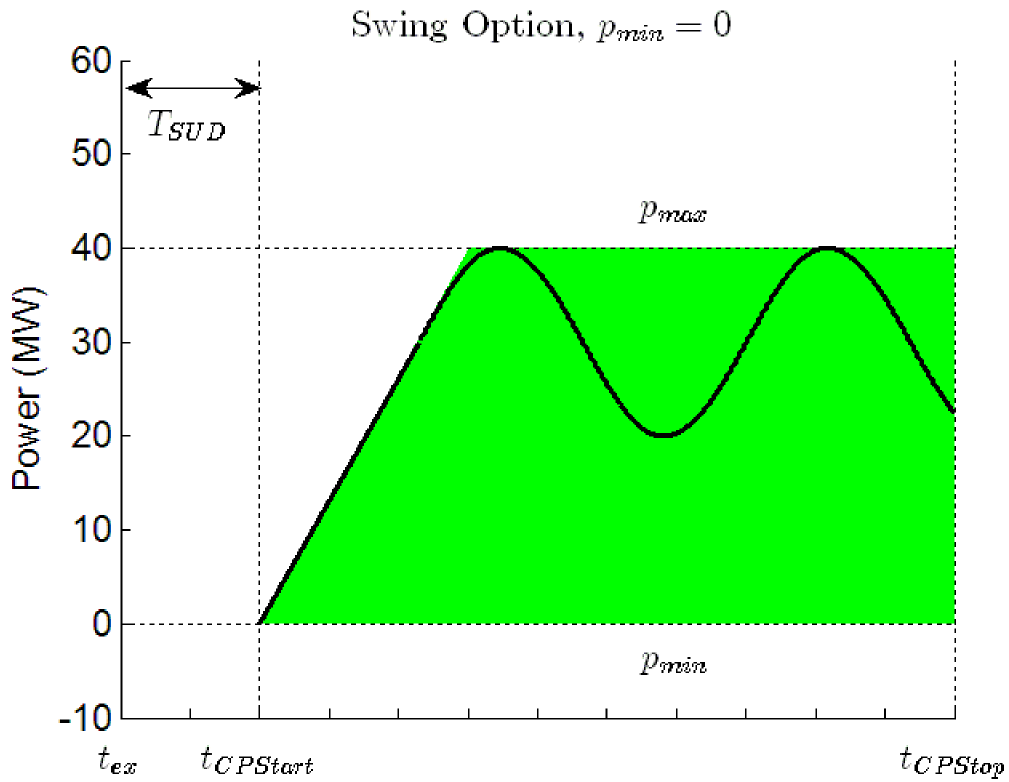
T_{SUD} = Start up delay; T_{RI} = Ramping Interval

EFC Swing Option (up, $p_{min} > 0$)



EFC swing options are capable of providing regulation reserve

EFC Swing Option (up, p_{min} = 0)



The resource's initial power level corresponds to p_{min} = 0

Open Questions on Market Design

- Does the role of EFC options as reserve products preclude LSEs or large industrial consumers from purchasing them?
  - If LSEs were to purchase EFC options, how would the ISO quantify reserve needs?
  - If LSEs were to purchase EFC options, how would the ISO ensure appropriate option exercise?
- If LSEs cannot purchase EFC options in ISO-managed markets, should they be permitted to buy options through bilateral trading?
- Should the power to exercise EFC options reside solely with the ISO?

EFC Option Optimization

- ISO will receive reserve offers that contain different terms, since they will be based on the technical characteristics of the resource
  - How can ISOs select the EFC options that allow them to meet reserve requirements at least cost?
- Any method used should take into account that resources with different responses offer different value
  - A faster resource is worth more than a slower one if an ISO needs that speed to follow load + variable generation variations
    - Or, if there is inadequate fast response to a contingency
- One possibility is to use an optimization algorithm that directly takes delay period, ramp rate, duration, etc. into account
- Another possibility is to convert resource offers, and ISO requirements, into the frequency domain in order to perform the optimization

Electricity Market Design Optimization Concepts -- Introduction

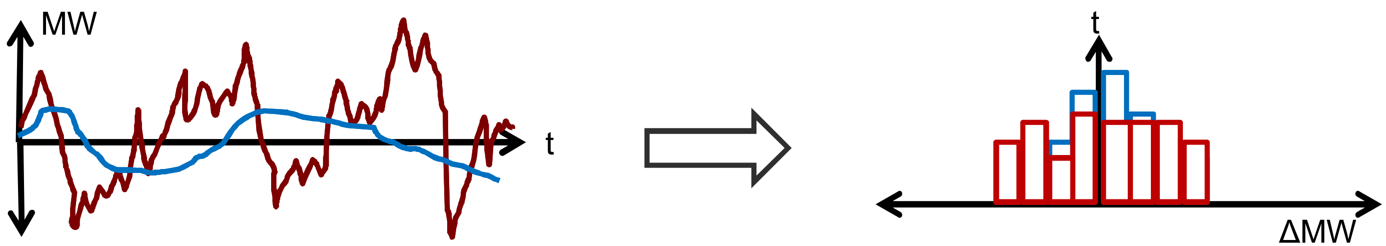
- Provide a glimpse of how a new market design could help addressing specific system needs.
- Based on current (but being refined) market description.
- The purpose of this presentation is to stimulate discussion on this topic.

Current Market Issues

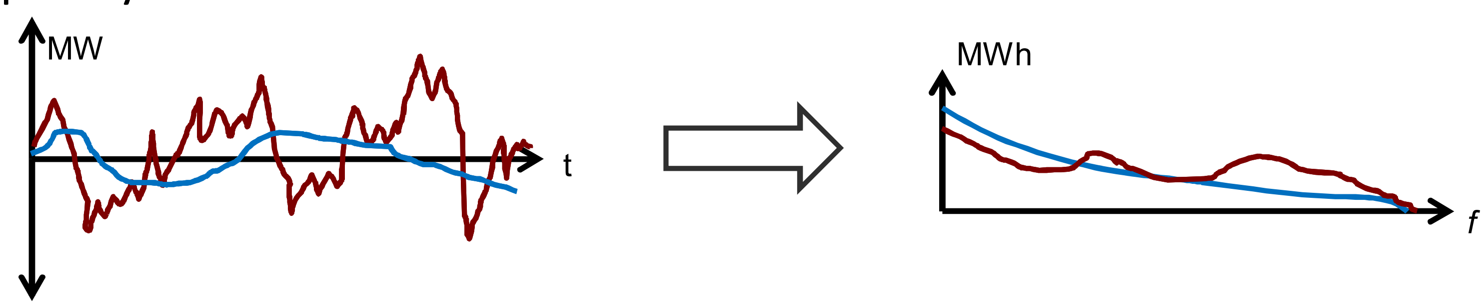
- FERC Order 755
- Today's market practices result in:
  - Inefficient markets that schedule fast and slow resources with no regard to service needs:
    - There is no assessment of fast- vs. slow-responding resources needed
    - Scheduling of faster resources can reduce the amount of frequency reserve procured
  - Unfair compensation to fast-responding resources that provide more frequency regulation:
    - No incentive to accurately follow dispatch signals
    - Faster movement results in more wear and tear of a resource

System Needs

- As renewable energy penetration increases, products that address needs created by their variability are needed
  - CAISO – Flexible Ramping Product
- System need can be described as a function of:
  - Time

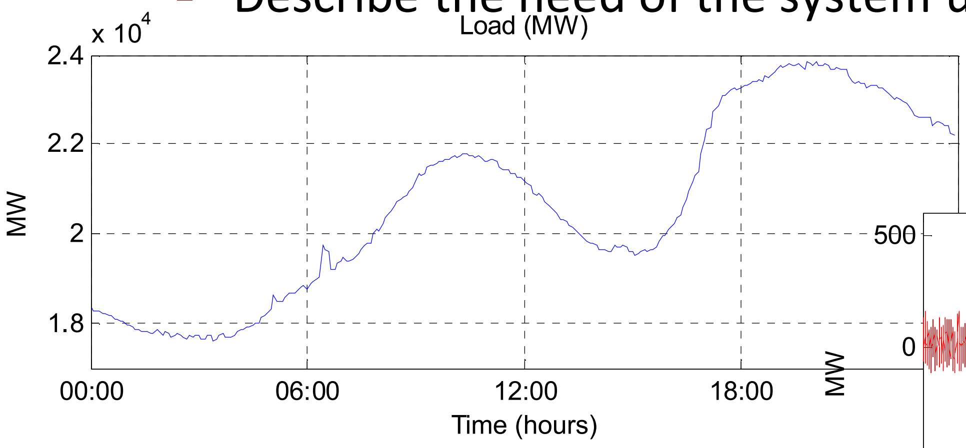


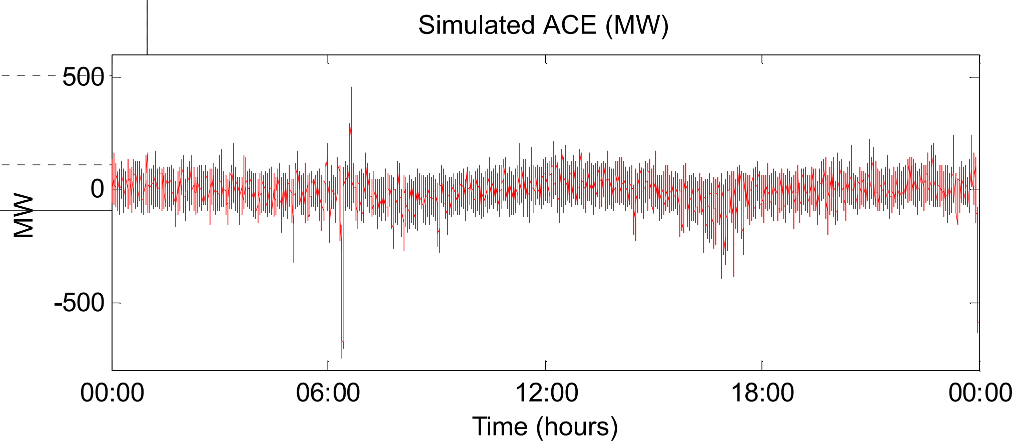
  - Frequency



Market Design Goal

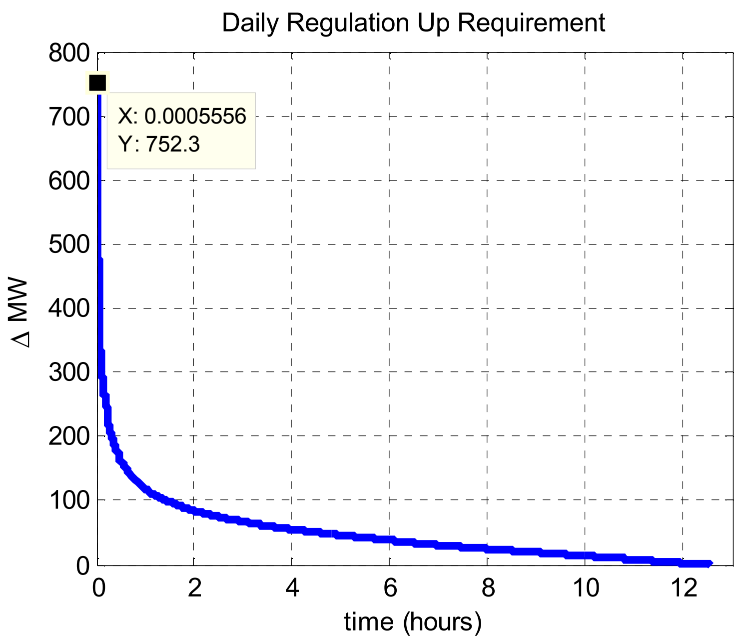
- Perform a better match between system needs with resources procured.
- Give the market participants and the ISO more flexibility to address system needs.
- Time domain approach:
  - Describe the need of the system using balancing duration curves

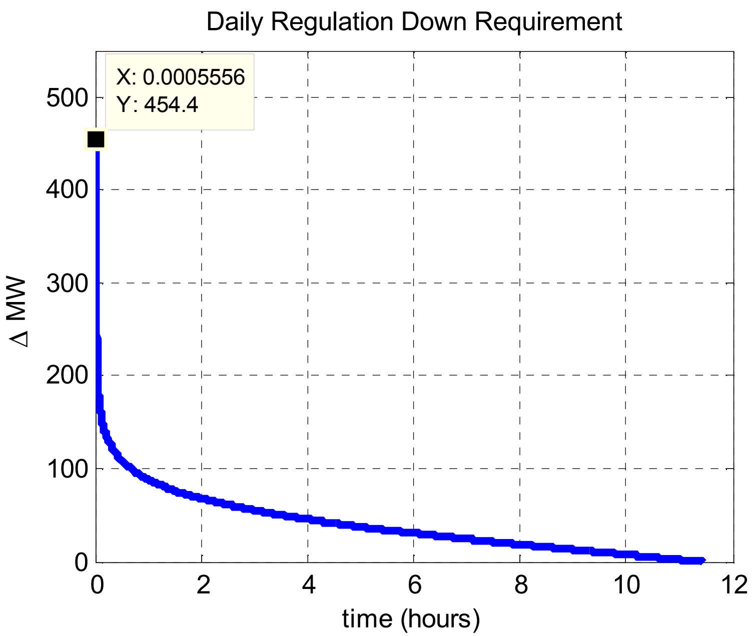




Time Domain Need

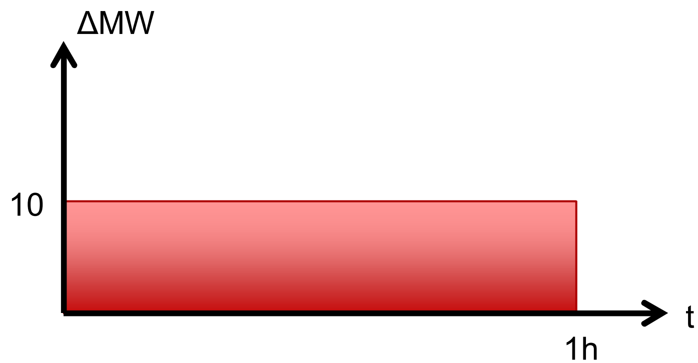
- Regulation up/down requirements can be estimated in the form of balancing duration curves
  - Ramping capability (max. ΔMW up/down)
  - Energy employed at different ΔMW



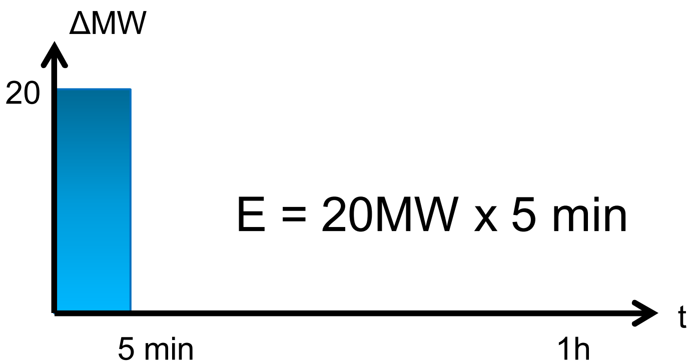


Balancing Energy

- EFC Swing Options provide information on:
  - Power limits
  - Operational ramp rates
  - Energy capacity
  - Energy Price
  - Direction



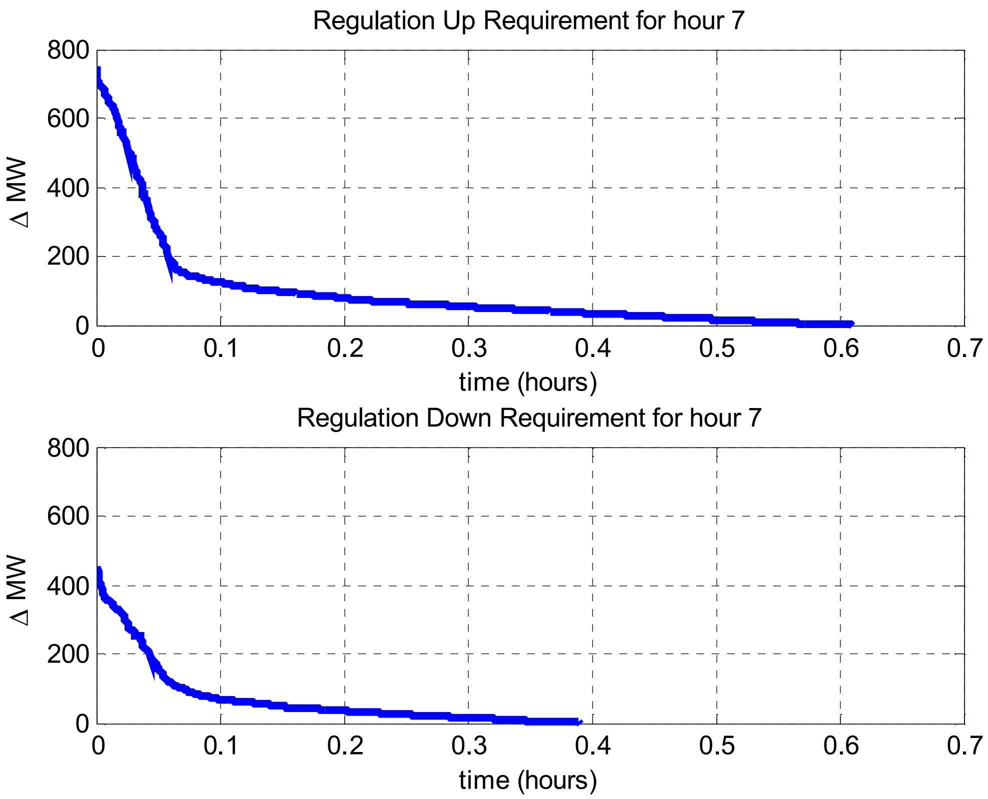
Unlimited energy

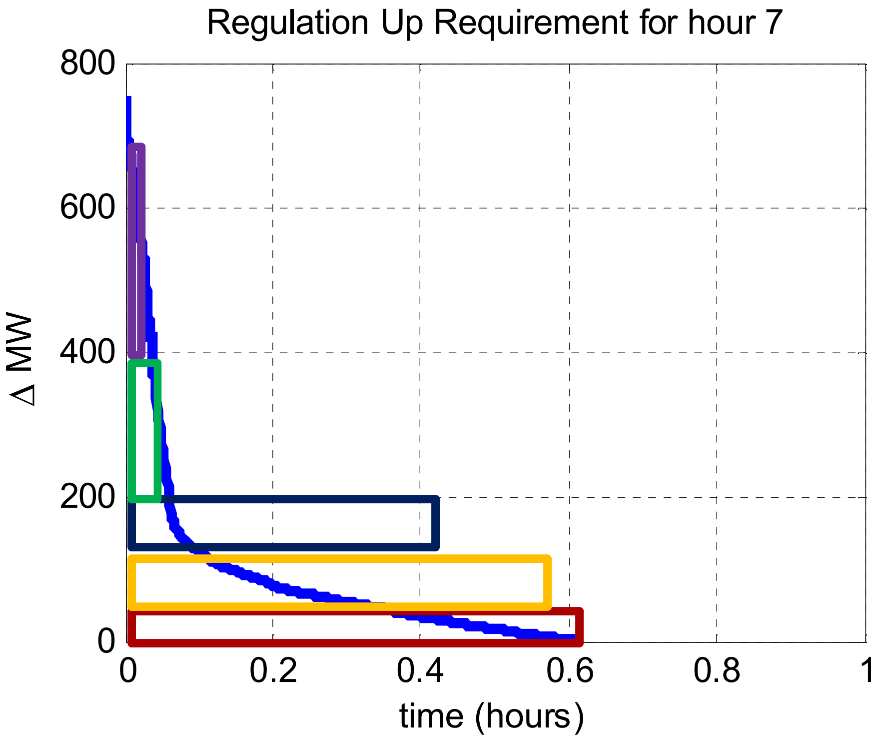


Limited energy

Portfolio selection

- Use optimization (e.g., MIP) to determine best portfolio of options and obligations that meets system needs (hourly):





Market Timeline

- Year-ahead forward market:
  - Private traders submit supply offers and demand bids for EFC obligations
  - Private traders submit supply offers for EFC options
  - ISO submits demand bids for EFC options and virtual supply offers for EFC ob's/op's
  - ISO acts as clearing house
- Day-ahead market:
  - Same participation rules as year-ahead
- Real-time market (5-minute ahead):
  - Private traders submit supply offers for EFC obligations and EFC options
  - ISO submits demand bids for EFC options
  - ISO submits load forecasts
  - Private traders not permitted to submit demand bids for EFCs
- Real-time operations
  - ISO deploys EFC obligations (energy products) and exercised EFC options (reserve products)

ISO roles in forward market

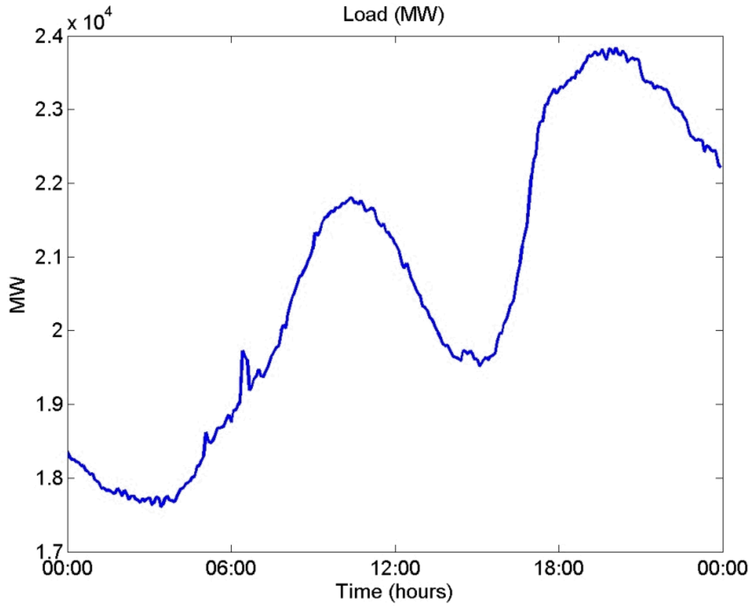
- Year-ahead: Market clear house, purchase of options if necessary (hedge price and quantity risk).
- Day-ahead: Market clearing house, purchase/exercise of additional options.
- Real-time market (5-minute dispatch): Two types of decisions occur
  - Clear real-time offers
  - Exercise options

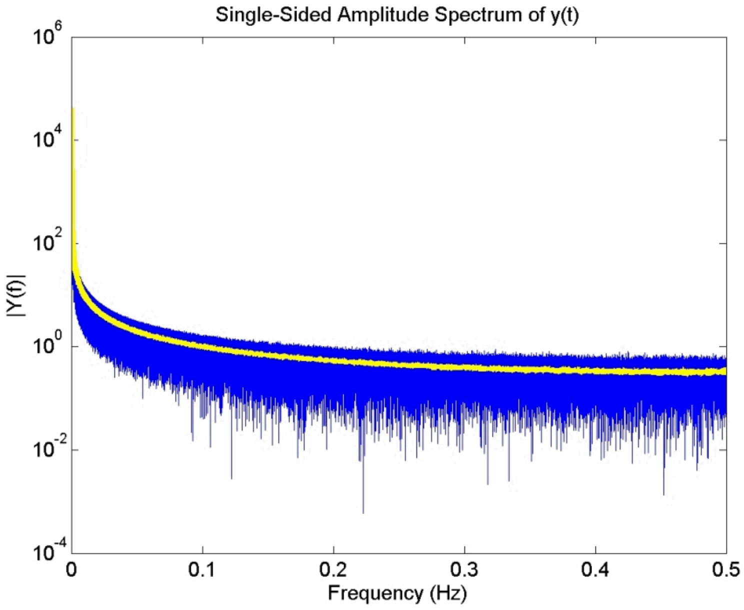
Points for Discussion

- OPF optimization (shadow pricing for energy/reserve) vs. exchange market matching (distinct price set for each matched bid-offer pair)
- Determination of EFC option purchase costs (premiums) (particularly for EFC swing options)
- Should private traders be permitted to purchase EFC options?
- Should private traders be permitted to exercise EFC options, assuming purchase is permitted?
- Should there be additional reliability products for locally controlled processes such as inertia, droop control and voltage support?

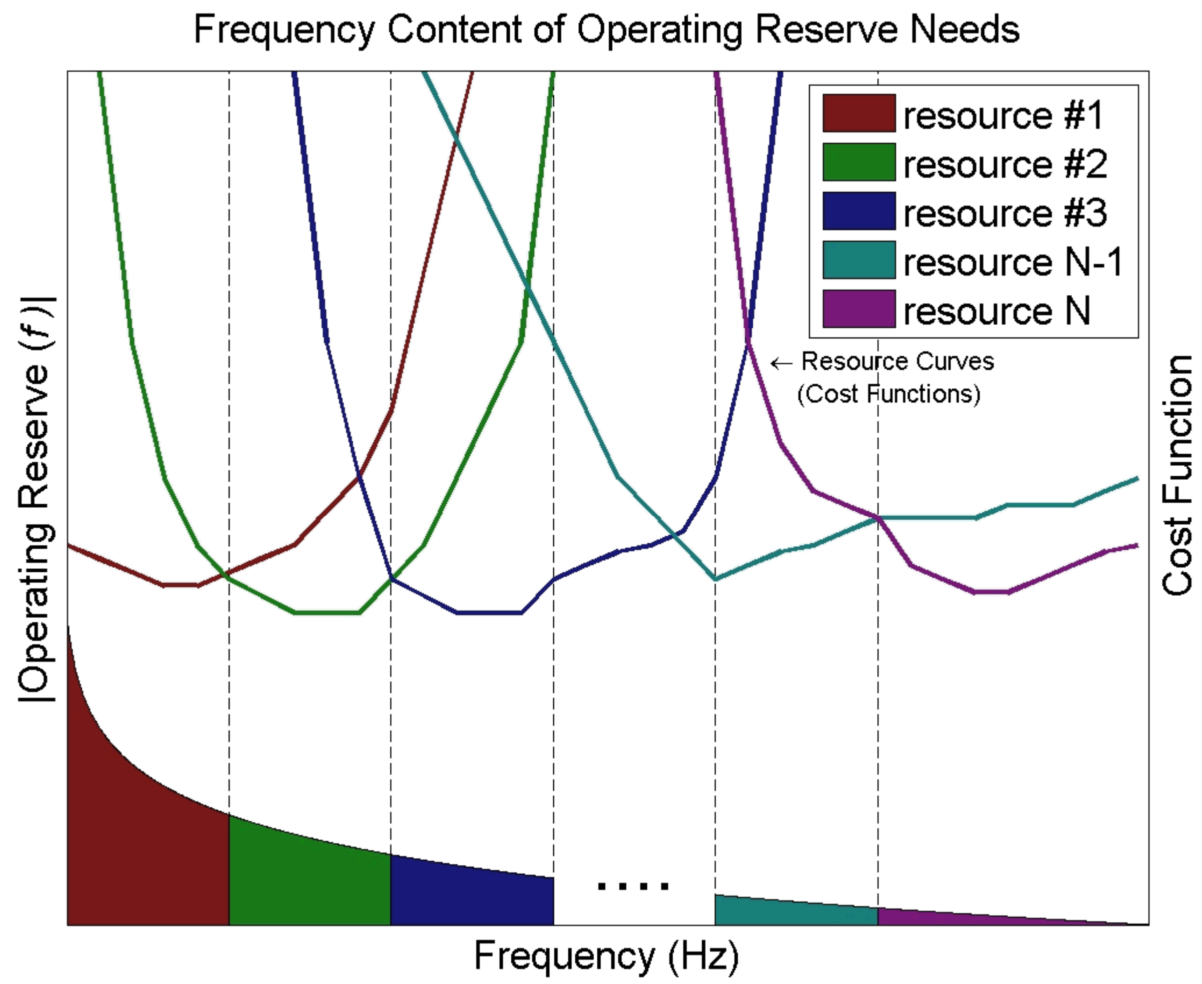
Frequency domain market optimization

- System needs are expressed in the frequency domain
- Market products contain enough information to establish frequency domain characterization
- The minimum cost resources are selected that meet system needs



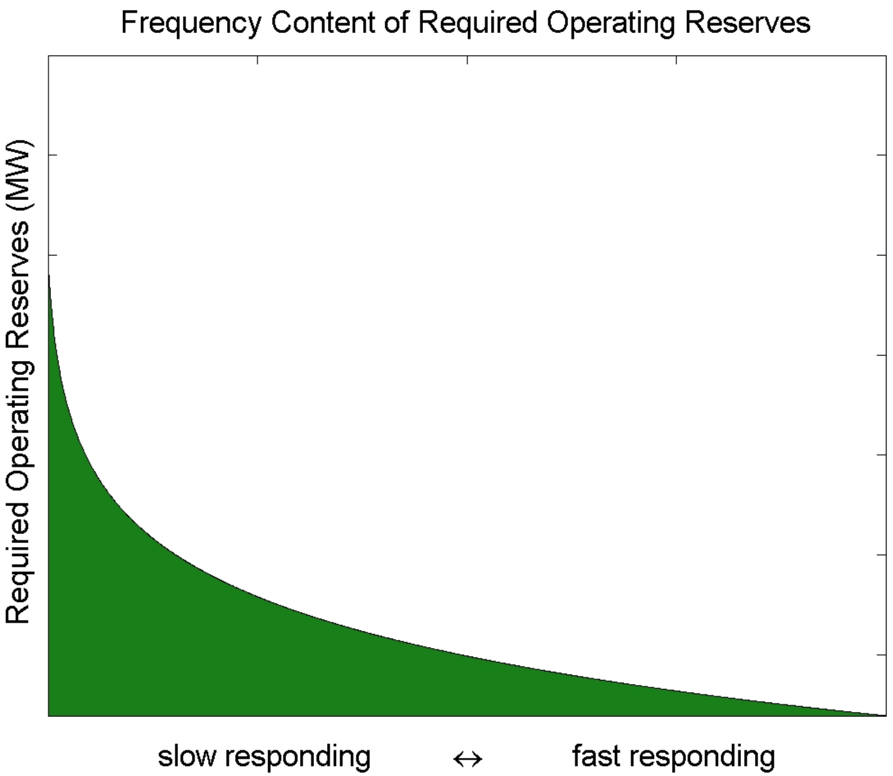


Frequency domain market optimization



Advantages of a frequency domain optimization

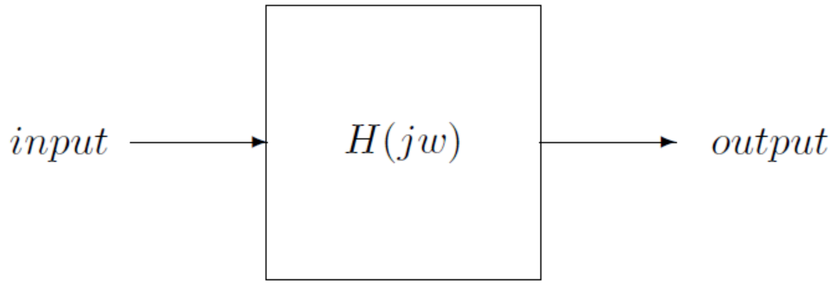
- Resources are selected and compensated for the services provided
- As new resources are developed, no changes are required to the market structure
- Potentially lower cost than current practices
- Based on linear systems theory

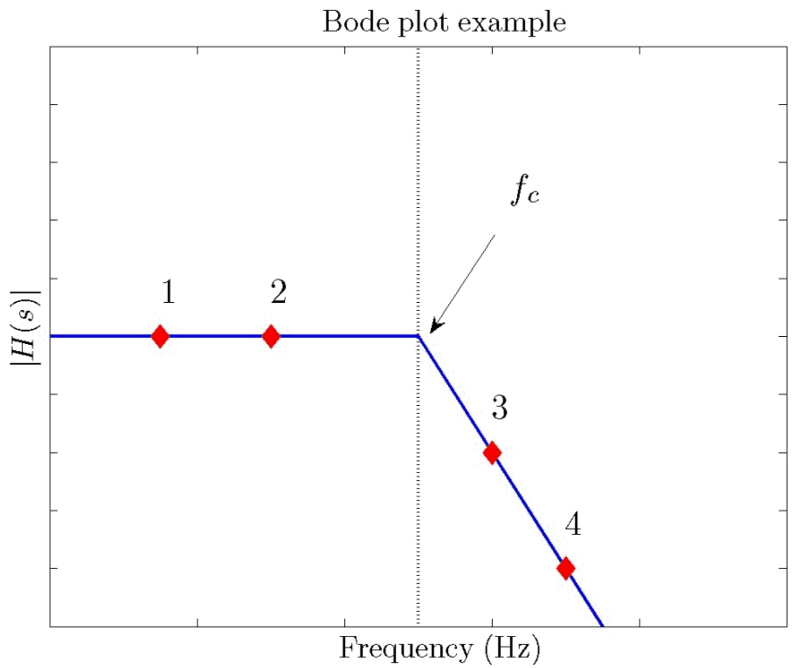


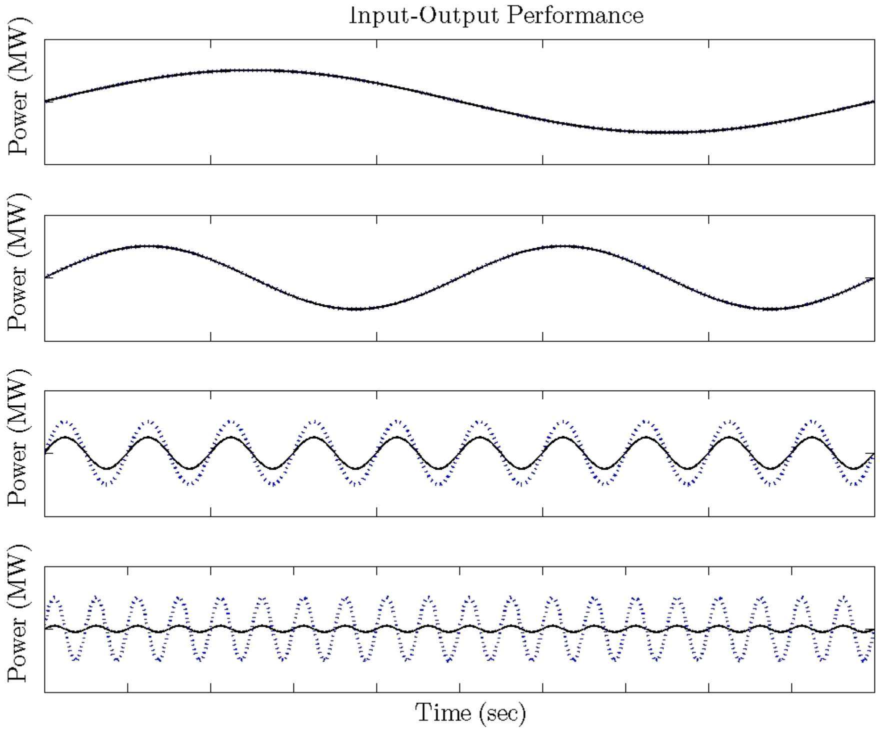
What information do you need for the optimization?

- Frequency domain performance characterization of market participants
- Frequency domain system needs

Frequency domain characterization

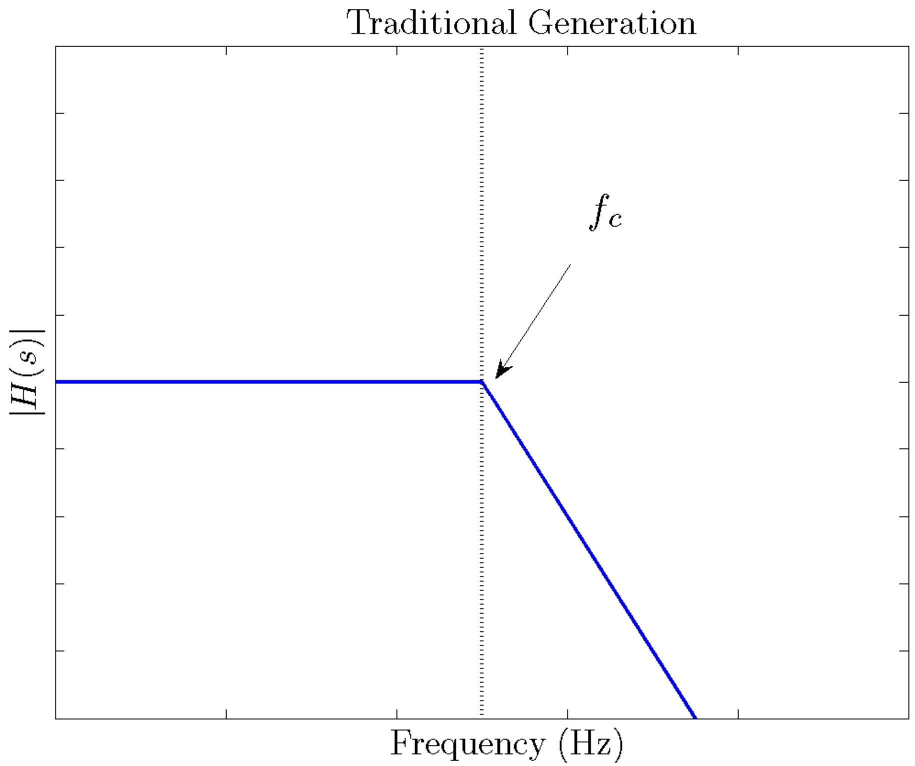






Traditional generation: frequency domain characterization

- Traditional generation
  - Generally not energy constrained (over the period of interest)
  - Ramp rate dependent on technology
- Performance characterized by a low-pass filter



$$f_c = \frac{RR_{max}}{(P_{max} - P_{min})\pi}$$

Traditional generation: frequency domain characterization

- Traditional generation frequency response defined by
  - Ramp rate
  - Maximum power level
  - Minimum power level

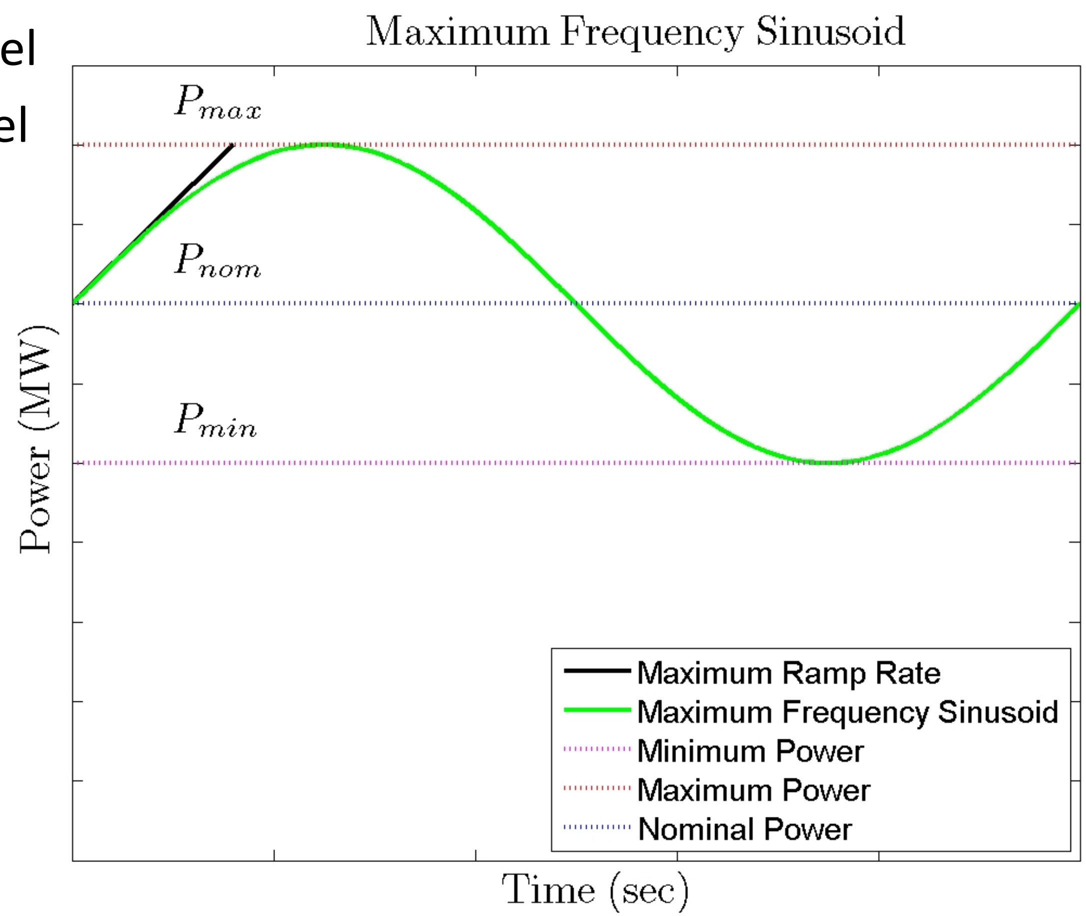
$$g(t) = A\sin(wt), \quad \text{where} \quad w = 2\pi f$$

$$A = \frac{P_{max} - P_{min}}{2}$$

$$\text{ramp rate} = \left|\frac{\partial g(t)}{\partial t}\right|_{max} = Aw$$

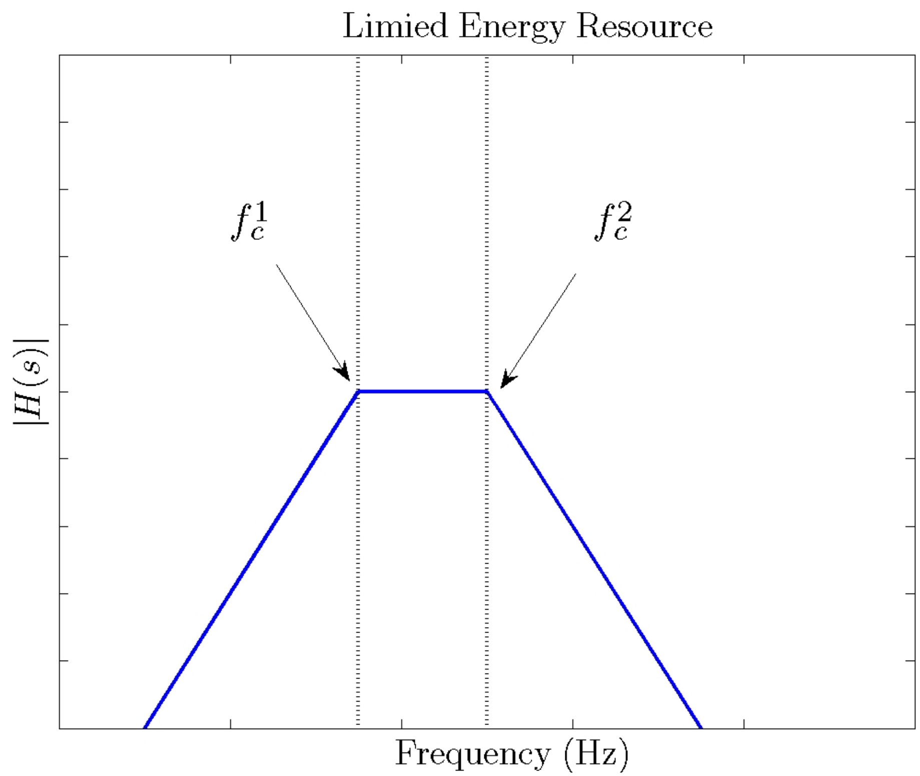
$$w_c = \frac{RR_{max}}{A}$$

$$f_c = \frac{RR_{max}}{(P_{max} - P_{min})\pi}$$



Limited energy resource: frequency domain characterization

- Limited energy resources
  - Energy is limited (e.g. energy storage)
  - Ramp rates are often significantly faster than traditional generation
- Performance characterized by a band-pass filter



$$f_c^2 = \frac{RR_{max}}{(P_{max} - P_{min})\pi}$$

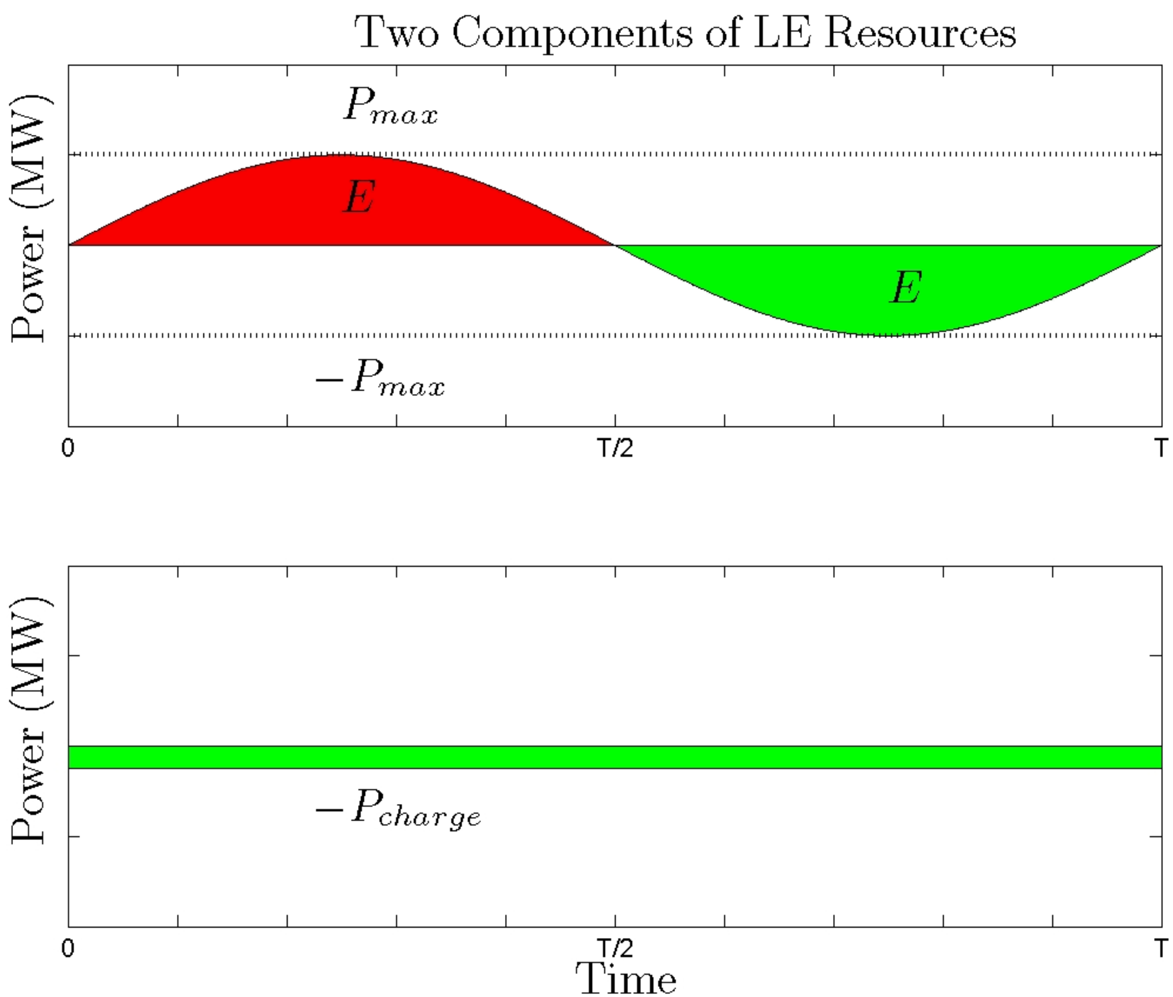
$$f_c^1 = \frac{A}{E\pi}$$

$$A = \frac{P_{max} - P_{min}}{2}$$

Limited energy resource: frequency domain characterization

- Limited energy resource frequency response defined by:
  - Ramp rate
  - Maximum power level
  - Minimum power level
  - Available energy
  - Efficiency (applies only to storage)
- High frequency response limited by ramp rate (same analysis as for traditional generation)
- Low frequency response is limited by available energy
- Available power is limited by efficiency (some power level is dedicated to maintaining state of charge)

Limited energy resource: frequency domain characterization



$$E = \frac{P_{max} T}{\pi}$$

$$f_c^1 = \frac{P_{max}}{E \pi}$$

$$P_{max} = \frac{P_{nameplate}}{1 + \frac{1}{\pi}\left(\frac{1-\gamma}{\gamma}\right)}$$

γ	$\frac{P_{max}}{P_{nameplate}}$
0.7	0.87996
0.8	0.9263
0.9	0.9658

Frequency domain characterization

Sandia National Laboratories

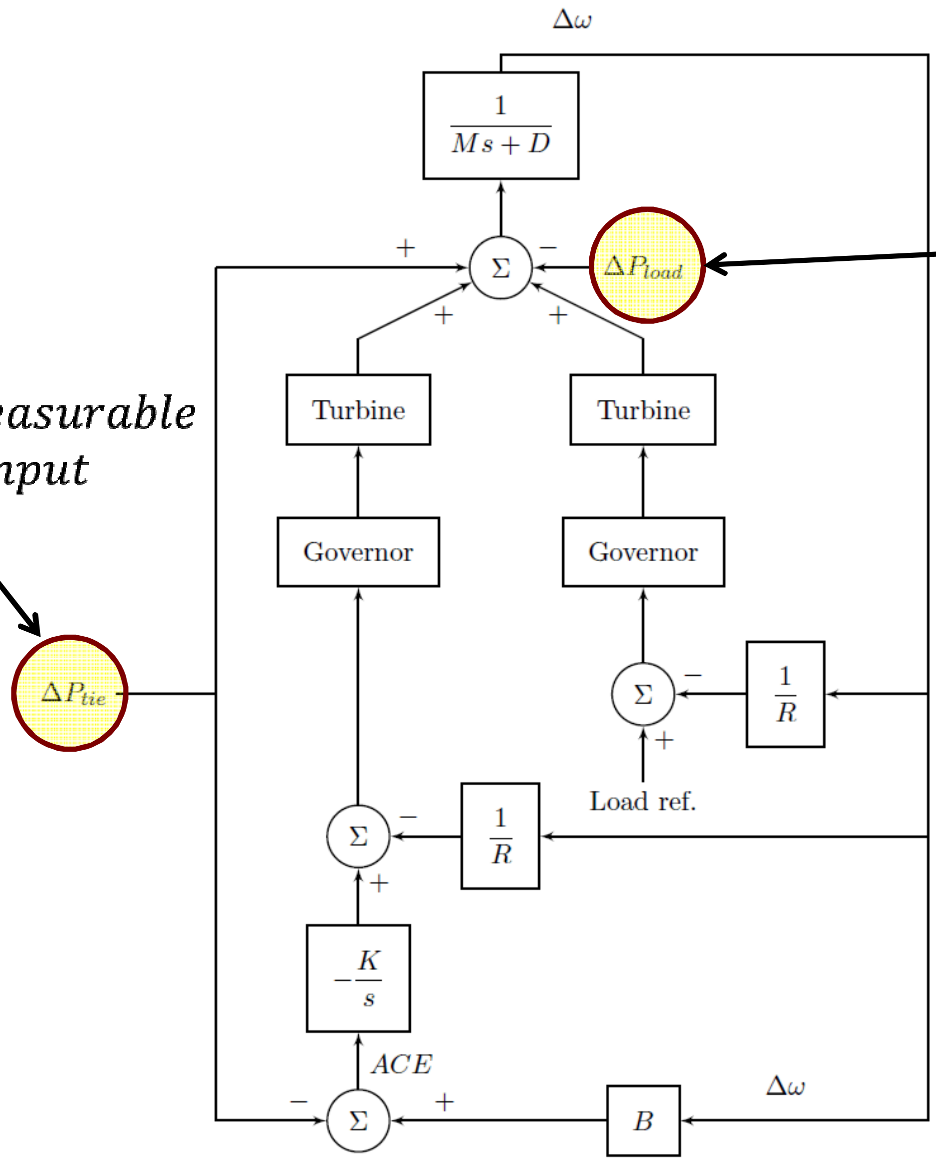
- Frequency domain characterization of resource performance can be estimated using the following parameters:
  - Ramp rate
  - Maximum power
  - Minimum power
  - Available energy (limited energy devices)
  - Efficiency (storage resources)
- These parameters must be included in the market product definition to enable a frequency domain optimization

Defining system needs

- For the purposes of this study, we have assumed that frequency domain needs will be available
- We performed a quick analysis to make sure this assumption is feasible
- What is the need for operating reserves?
  - Performance dictated by NERC
    - CPS1 (Control Performance Standard 1, correlation of frequency error and ACE signals)
    - CPS2 (Control Performance Standard 2, magnitude of ACE signal)
    - DCS (Disturbance Control Standard, return ACE to 0 within 10 minutes of a large disturbance)
  - According to NERC, “Each control area can meet the CPS1 standard by any means they wish”

Area Model with Stochastic Inputs

ΔP_{tie} *is a measurable stochastic input*



ΔP_{load} *is a nonmeasurable stochastic input*

Area Equivalent Model

P1(s): generators selected for AGC

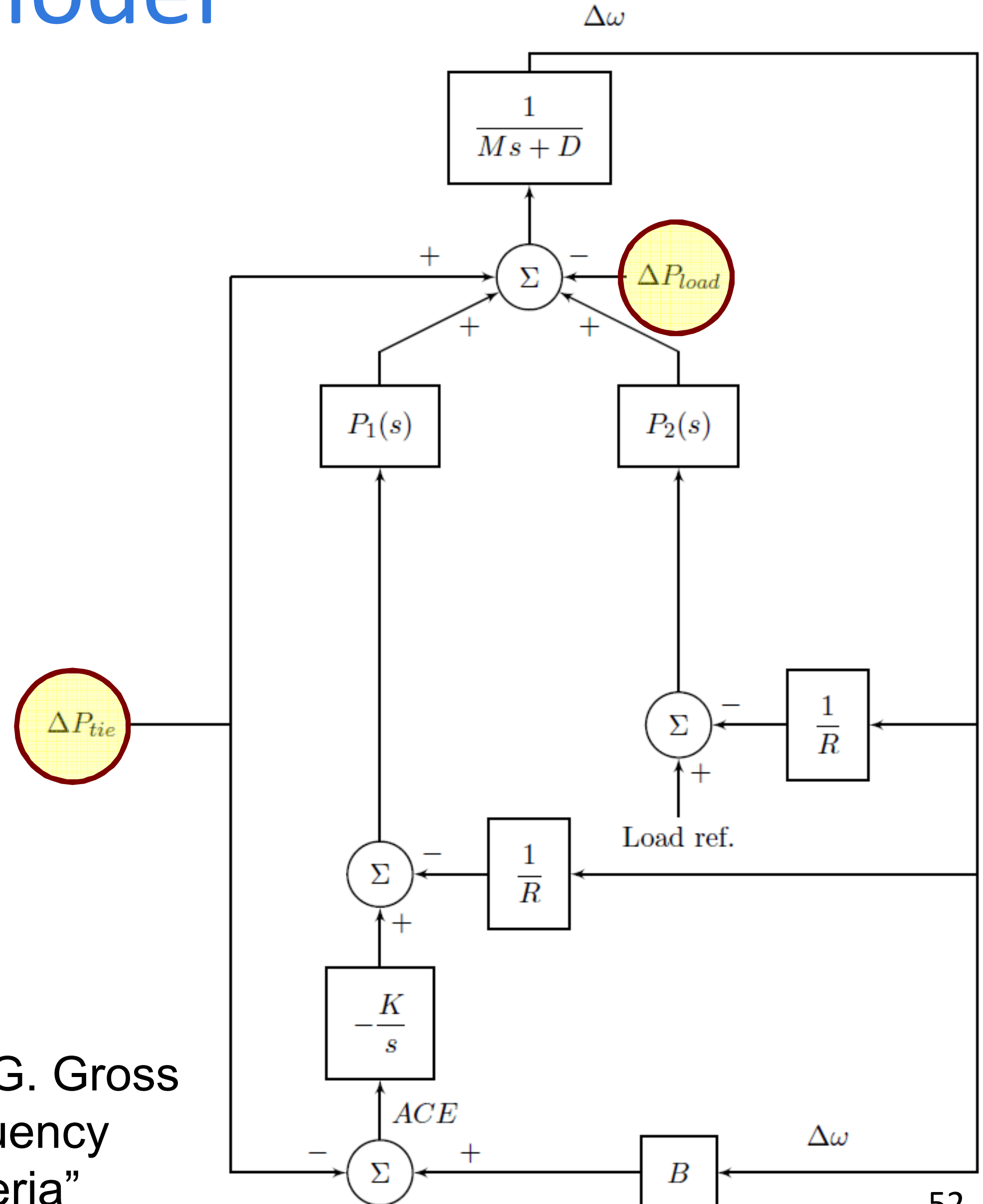
P2(s): generators selected, no AGC

Time – Domain Spec (CPS2): $\mathrm{P}\{|\overline{ACE}| \leq \gamma_i\} \geq 0.9$[1] given the characteristics of ΔP_{tie} and ΔP_{load}

- Regulation

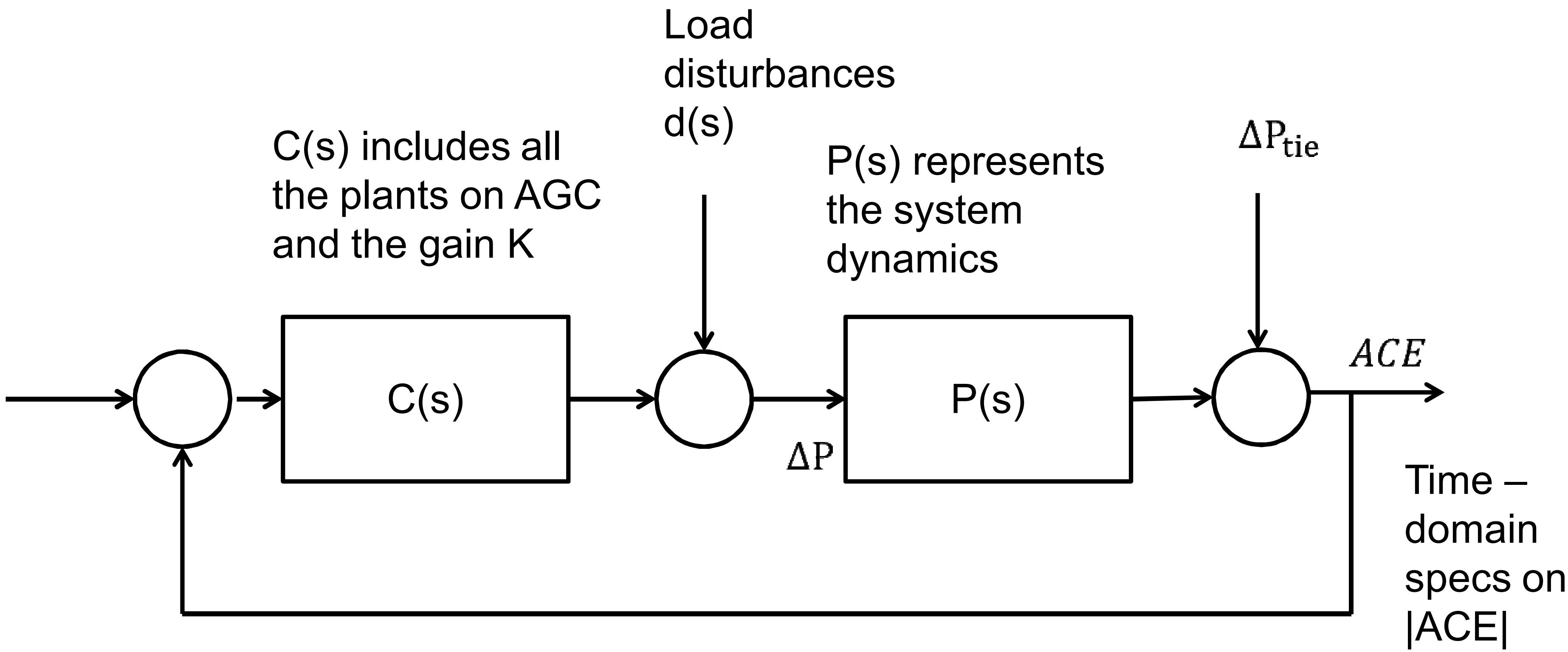
Must also meet the DCS spec

- Regulation
- Spinning reserve
- Non-spinning reserve



[1] CPS1 and CPS2 are equivalent, see G. Gross and J. W. Lee, “Analysis of Load Frequency Control Performance Assessment Criteria”

Equivalent Problem



How do you solve the problem?

- A simplifying assumption would be to assume that P2(s), non-AGC generators, is a known quantity
- Based on the characteristics of the potential generators and their cost curves, select the “optimal” generation mix that meets the CPS2 standard given the characteristics of the stochastic inputs (load and tie flows)

How do you solve the problem?

- Combined cost and performance optimization:
  - Brute force: exhaustive search and Monte Carlo simulations
  - Heuristic or genetic algorithm based optimization
  - Stochastic optimization
- Two step approach:
  - Apply control theory techniques to determine the shape of P1(s) to meet CPS2,
  - then procure those resources via an optimization

Summary

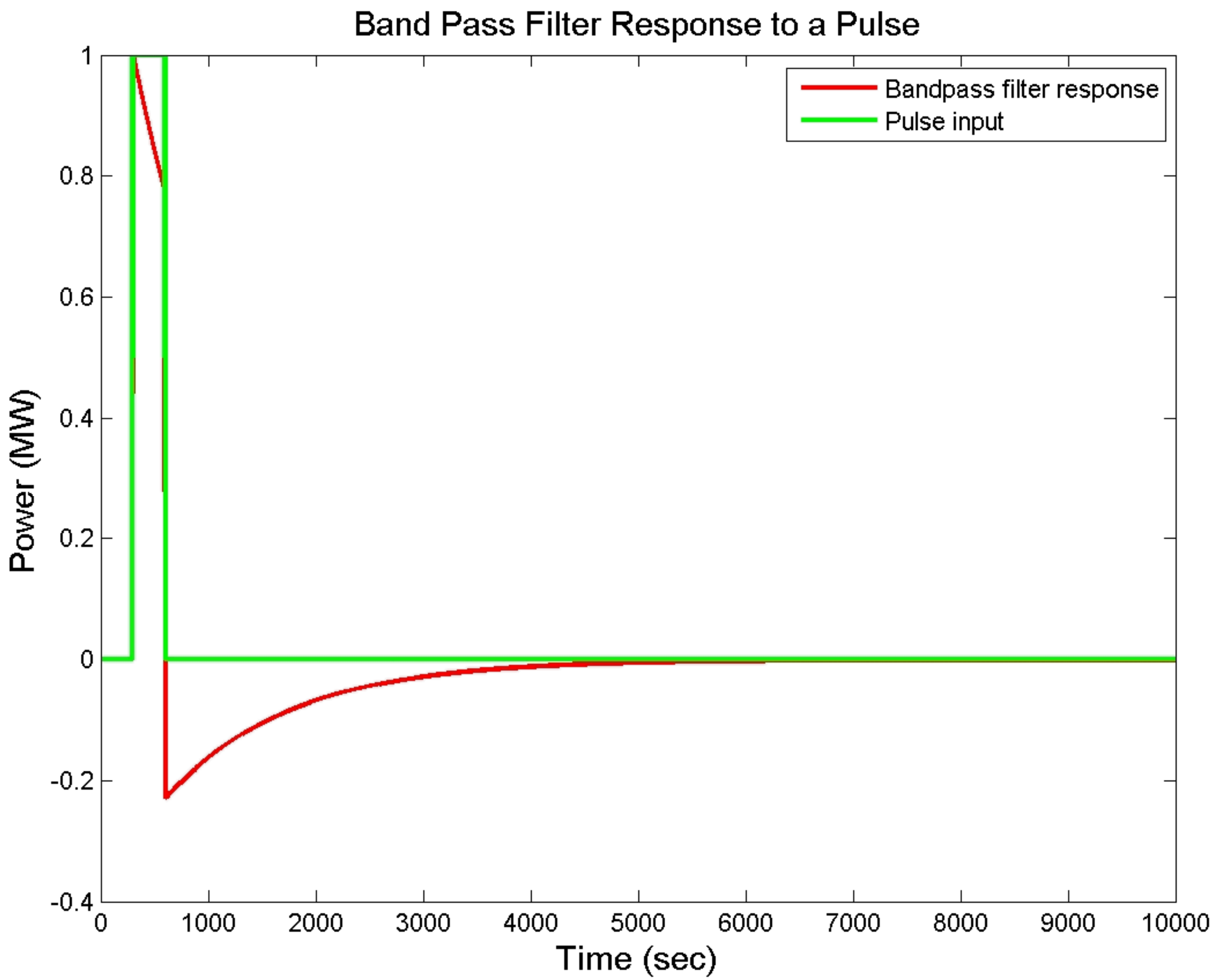
- We have identified the market product parameters necessary for a frequency domain optimization
  - Ramp rate
  - Maximum power level
  - Minimum power level
  - Available energy
  - Efficiency (applies only to storage)
- We have taken a quick look at going from NERC standards to frequency domain requirements and believe that a solution exists via one of the following methods:
  - Brute force: exhaustive search and Monte Carlo simulations
  - Heuristic or genetic algorithm based optimization
  - Stochastic optimization
  - Two step solution: control theory analysis and optimization

Next Steps

THANK YOU FOR YOUR TIME AND INPUT

- Feedback and Discussion
- Next Meeting(s)
  - Teleconferences? Frequency?
  - Face to face meeting?

Frequency domain – Backup slides



Frequency domain – Backup slides