Transmission Constraint Control Logic and Penalty Factors

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Constrained Optimization

- PJM's Market Clearing Engines (MCEs) which perform unit commitment, dispatch and pricing software are all constrained optimization problems
- Minimize system cost subject to limitations (objective function)
  - Resource limitations
    - Eco min/max emergency min/max, ramp rate, startup time, notification time, etc.
  - Transmission system limitations
    - MW flow limits on lines
  - System balance
    - Generation = Load + Losses

Optimization Limitations (Constraints)

- Limitations are expressed in mathematical terms as inequalities, equalities and integer constraints
  - x < 500
  - a + b + c = 10
  - Line Flow <= Line Limit
  - DispatchMW + Tier2MW <= EcoMax
  - Reserve MW >= Reserve Requirement

- These limitations/constraints confine the solution

Penalty Factors

- "Soft constraints" are those that can be violated in the optimization (if needed) in order to reach a solution

- Because it is desirable to find a solution that adheres to all constraints, **penalty factors** are assigned to discourage the optimization from violating a constraint

- The current **penalty factor** for not meeting a reserve requirement in PJM is $850/MWh

Penalty Factor Hierarchy

- Constraints that are the most desirable to adhere to typically have the highest penalty factors associated with them
  - Power Balance
  - Transmission facility limits

- Each time a constraint is violated, the objective function is penalized
  - Penalty Factor * MWh of violation

- Penalizing the objective function increases the cost of the solution and acts as a deterrent

- **Penalty Factors** and **Marginal Value Limits (MVL)** are the same
  - Marginal Value Limit is the term used to describe a penalty factor associated with the violation of a transmission constraint

- A $2,000/MWh Marginal Value Limit means PJM will not dispatch beyond a cost of $2,000/MWh to control a constraint

Use of Penalty Factors

- Penalty factors are use in every application of constrained optimization
  - Transportation
  - Energy (PJM, MISO, NYISO, ISONE, CAISO)
  - Telecommunications
  - Airline

- They are necessary to produce feasible solutions when all constraints cannot be honored

Penalty Factors and Price-Setting

- Penalty Factors can be used to set market clearing prices or disallowed from setting market clearing prices
  - When we are short reserves and in shortage pricing, the penalty factor is setting the clearing price for reserves and used in the determination of the LMP
- The same concepts apply to penalty factors for transmission constraints (or marginal value limits)

What are Transmission Constraint Penalty Factors?

- Transmission constraint penalty factors are parameters used by the MCE to determine the maximum cost willing to be incurred to control a transmission constraint.

- The transmission constraint penalty factor parameter itself is defined in $/MWh terms

- The ultimate effect of the transmission constraint penalty factor is that it limits the controlling actions the MCE can take to resolve a constraint by limiting the cost that is willing to be incurred to control it.

Unit Effective Cost

- The cost of using a resource to control a constraint, or its effective cost, can be calculated using the equation below.
  - Effective Cost ($/MWh) = |(Energy Price – Incremental Cost) / Dfax|
- Holding the denominator constant, the effective cost will increase as the difference between the energy price and a resource’s marginal cost grows larger.
- Holding the numerator constant, the effective cost will increase as the resource’s dfax on the constraint gets smaller.

Transmission Constraint Penalty Factor Defaults and Exceptions

- PJM internal constraints, regardless of voltage level, are defaulted to a $2,000/MWh transmission constraint penalty factor
  - Selected as the default value because historically most constraints can be effectively controlled at a cost below $2,000/MWh

- The default value can be overridden on an individual constraint basis
  - Dependent on system conditions and the amount of generation able to be re-dispatched to control the constraint

- In the linear constraint optimization, only one of the following three possibilities can occur
  - nonbinding (shadow price = 0)
  - binding (shadow price < marginal value limit)
  - violated (shadow price = marginal value limit)
- If the transmission constraint is binding, the shadow price is a linear function of marginal units' offer prices

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- The transmission constraint penalty factor does not directly impact the shadow price of a constraint as long as the constraint can be solved by resources whose effective costs are lower than the value of the penalty factor.

Transmission Constraint Control Process

- Input Variables to the MCE
  - **Constraint Limit.** The constraint limit is typically the long-term thermal rating of the facility (usually a 4-hour rating). It is passed to the MCE from the EMS for each active constraint.
  - **Limit Control.** The limit control is the percentage of the constraint limit to which the operator controls the constraint.
  - **Target Limit.** The target limit is the product of the constraint limit and the limit control and is ultimately the limit to which the MCE attempts to control the constraint.
    - Target Limit = Constraint Limit * Limit Control
  - Transmission Constraint Penalty factor
  - Resource Dfax
  - Resource specific information (offer curve, economic limits, ramp rate etc.)

Transmission Constraint Control Outcomes

- The objective of the constraint control logic is to dispatch the least cost set of resources to meet the target limit of the constraint at a marginal cost at or below the transmission constraint penalty factor.

Constraint Flow	Violation Degree (MW)	Shadow Price ($/MWh)	Constraint Outcome
< Target Limit	0	0	non-binding
= Target Limit	0	non-zero < penalty factor	binding
> Target Limit	non-zero	= penalty factor	binding & violated; constraint relaxation applied

Violation Degree = amount by which the constraint flow exceed the target limit

Transmission Constraint Relaxation

- PJM does not allow the transmission constraint penalty factor to set the shadow price of a constraint.
  - The longstanding business practice is to have the price set by a resource that is providing constraint control in the dispatch solution

- In the MCE, constraints that are violated must be relaxed to prevent the penalty factor of a violated constraint from setting the clearing price (referred to as Constraint Relaxation).

- For a constraint which initially solves with a non-zero violation degree, the constraint relaxation logic adds the violation degree back to the target limit of the constraint and re-solves.

- **This practice produces congestion prices that can understate the severity of the localized transmission shortage**

Example 1: Binding Constraint, Zero Violation Degree (adequate control)

- Inputs:
  - Penalty Factor = $2,000/MWh
  - Constraint Limit = 100 MW
  - Limit Control = 95%
  - Target Limit = 95 MW

- Final Constraint Solve:
  - MCE calculated flow on the constraint = 95 MW
  - Violation Degree = 0 MW
  - Shadow Price of the constraint = $500/MWh

Example 2 - Constraint Is Violated and Constraint Relaxation Logic Is Applied

- Inputs:
  - Penalty Factor = $2,000/MWh
  - Constraint Limit = 100 MW
  - Limit Control = 90%
  - Target limit = 90 MW

  - Target Limit = ~~90~~ **95** MW

Initial Constraint Solve Results	Constraint Relaxation Solve Results
Calculated Flow = 95 MW	Calculated Flow = 95 MW
Violation Degree = 5 MW	Violation Degree = 0 MW
Shadow Price = $2,000/MWh	Shadow Price = $1,200/MWh
Constraint Violated ➡ Apply Constraint Relaxation!	

Historical Data

	2013			2014			2015		
	Number of Constraints	Percent	Average Shadow	Number of Constraints	Percent	Average Shadow	Number of Constraints	Percent	Average Shadow
PJM Internal Binding Transmission Constraints	61,067	49%	($173.28)	131,929	62%	($172.93)	141,007	66%	($160.37)
PJM Internal Violated Transmission Constraints	18,065	15%	($532.80)	32,888	16%	($642.99)	21,179	10%	($985.62)
Market to Market Transmission Constraints	44,564	36%	($299.26)	47,347	22%	($444.04)	50,294	24%	($255.70)
Total	123,696	100%	($271.17)	212,164	100%	($306.30)	212,480	100%	($265.19)

	2016			2017		
	Number of Constraints	Percent	Average Shadow price	Number of Constraints	Percent	Average Shadow price
PJM Internal Binding Transmission Constraints	131,088	64%	($120.33)	102,639	63%	($123.40)
PJM Internal Violated Transmission Constraints	19,907	10%	($660.56)	12,480	8%	($729.49)
Market to Market Transmission Constraints	54,244	26%	($255.45)	47,408	29%	($328.99)
Total	205,239	100%	($208.44)	162,527	100%	($208.44)

- On average, 21,000 or 11 percent of PJM internal transmission constraints were violated, where flow exceeded the facility limit.

- Violated transmission constraints had shadow prices that are on average four times higher than that of binding transmission constraints.

- Market to Market transmission constraints include reciprocally coordinated flowgates between PJM and neighboring RTOs.

PJM/MA Proposed Solution Option

- Phase 1
  - Removal of the constraint relaxation logic for violated constraints in the market clearing engines
  - Allow the transmission constraint penalty factor of the violated constraint to set the shadow price of the constraint
  - Develop a process to notify market participants of changes to the transmission constraint penalty factor for an individual constraint.
- Phase 2

  Revisit the level and shape of the transmission constraint demand curves pending any revisions to the Operating Reserve Demand Curves resulting from the Energy Price Formation Senior Task Force discussions.