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Forecasting of Dynamic Line Ratings for Market Systems

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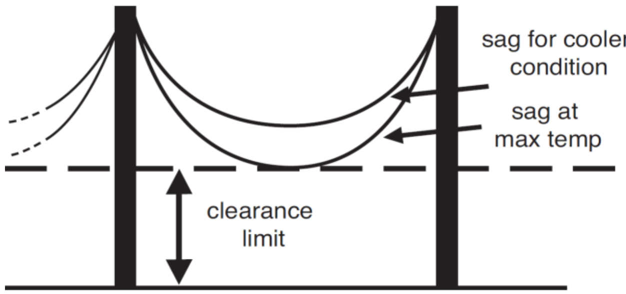
Outline

- Introduction – Dynamic Line Rating (DLR)
- ISO/RTO – Dynamic Line Rating utilization - interaction?
- Dynamic Line Rating – Real-time & Forecasting
  - Example in Belgium Transmission Grid
- Integration of DLR Forecast into ISO/RTO Market Management Systems (Day-ahead, Intra-day & Real-time)
- Conclusions

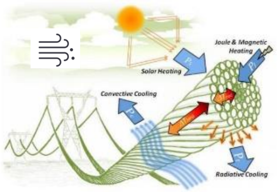
Introduction – Dynamic Line Rating (DLR)

Dynamic Line Rating – is highly variable

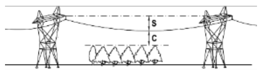


Key Question: "What is the **maximum current (thermal rating)** that can transfer through a line, and still keep the **conductor temperature** below its limit, and therefore keep the conductor below its **maximum sag?**

- Weather conditions – eg: wind speed, air temperature, sunlight, etc
- Location – latitude, elevation, line direction
- Current through the conductor
- Conductor characteristics



→ Conductor temperature → Maximum sag / minimum clearance



→ maximum current (thermal rating)

Example: Drake Conductor 795 AWG 26/7

- Air temperature **40°C**
- Wind speed is **2 ft/sec** perpendicular to conductor
- Emissivity & absorptivity is 0.5 each
- Elevation – sea level
- Clear sky, 12pm July 4

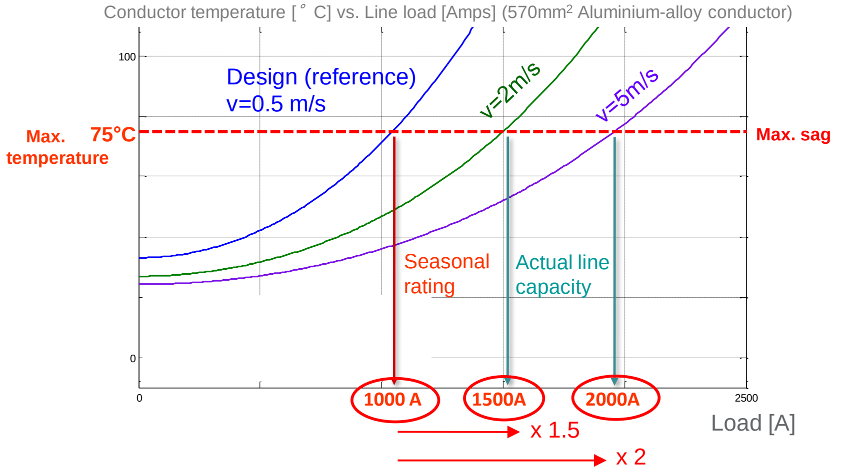
→ Max current @ Max conductor temperature without sagging beyond its limits
903A @ 90°C - Thermal Rating

Thermal Rating @ 90 °C

↓ 10°C to **30°C**	**+10%** to 999A
↑ to **5 ft/sec**	**+35%** to 1250A
↑ to **15 ft/sec**	**+90%** to 1715A

Another Example: Wind speed – most influencing facto

… Wind is the most critical factor (and varies a lot with time and location)



Reference: Finding Hidden Capacity In Transmission Lines, BY DAN LAWRY & BERNIE FITZGERALD, North American Wind Power Online, reprinted from April 2007 Edition

Dynamic Line Rating applications – adds value to all players

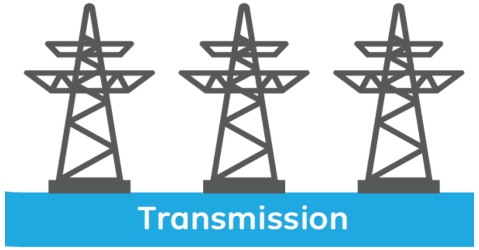
Regulators

- Short-term solution to existing transmission constraints
- avoid or defer significant rate-regulated investments,
- reduce cost to rate-payers

ISO/RTO

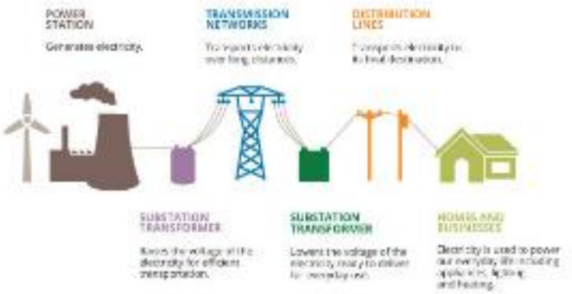
- Improve market efficiency by –LMPs, congestion.
- enhancing grid operational safety,
- accelerate generator interconnection process;
- reduce the impact caused by planned/unplanned transmission outages

Transmission Utilities/Owners/Operators



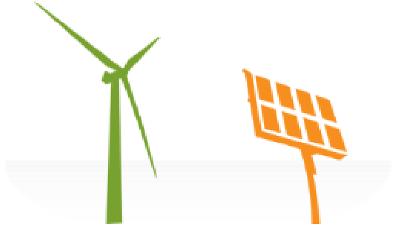
- increase in power transfer capacity,
- Enhance operational safety and reliability, and strict adherence to industry standards

Vertically Integrated Utility



- Optimize cost of transmission in the IRP process,
- avoid or defer capital investment for upgrades,
- improve bilateral market efficiency,
- reduce the impact caused by planned/unplanned transmission outage,
- reduce curtailment of utility-owned generation

Independent Power Producers



- Create economic value by enabling to dispatch more power
- reduce curtailment

ISO/RTO – Dynamic Line Rating utilization - interaction?

DLR in today's ISO/RTO Market operations – interaction with ISO/RTOs

DLR - has the potential to increase line rating → reduce transmission congestion → enhance market efficiency

DLR integration in Markets – Are ISO/RTO using DLR (from transmission owners) in market operations, if so what technology?

DLR data – Are ISO/RTO concerned with Reliability & Accuracy of DLR data?

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Dynamic Line Rating – Real-time & Forecasting
Example in Belgium Transmission Grid

DLR Determination Methods

Weather-based methods *(inaccurate)*

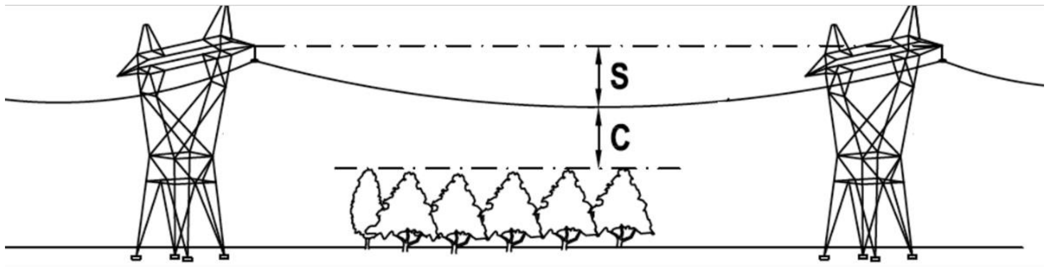
- Rely on monitoring e.g. ambient weather
- Line temperature and sag are determined by theoretical models and calculation

Temperature-based methods *(inaccurate)*

- Based on direct conductor temperature measurements in combination with other measurements.

Sag monitoring methods w/ Measurement of Perpendicular Wind Speed at Conductor

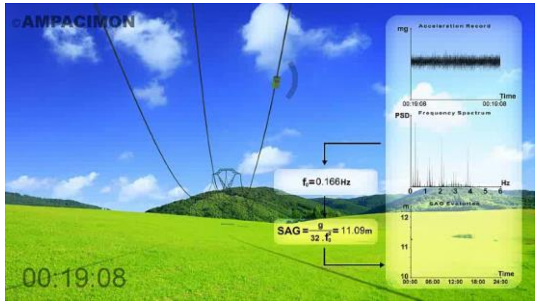
- **Measuring some characteristic of the line (e.g. vibration) to determine the sag**

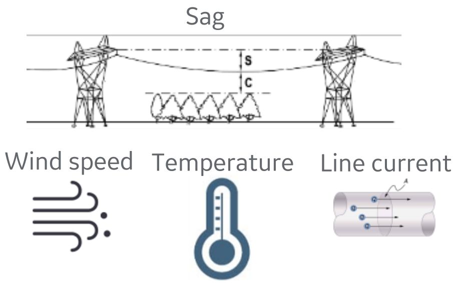


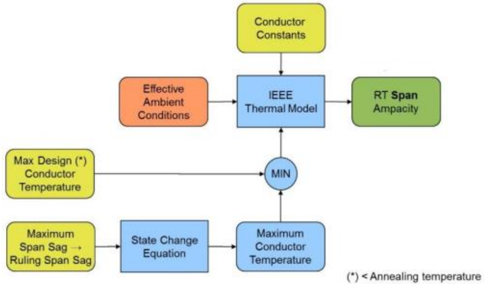
- **Real-time** and **direct** measurement of Sag
- **Sag** (Clearance) is the ultimate limit to operation of an overhead line
- Besides line current, many external factors can be measured / estimated / compounded: Sag is the **ultimate consequence** of line load

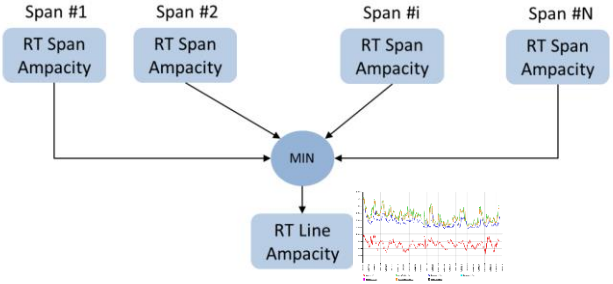
- Wind Speed measurement at the conductor is key
- It is pointless to measure conductor **temperature** (**fluctuating** along the line)

Proposed Real-time and Forecast Dynamic Rating - determination









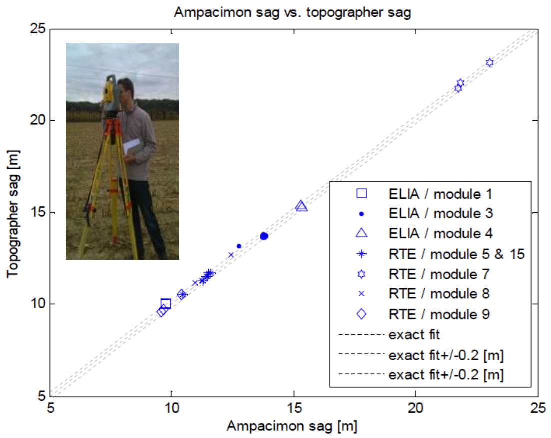
Sensor's 3D Vibration measurements yield - two key parameters

- **sag (patented)**
- real wind speed as seen by the conductor **(patented)**

Why does ADR sense measure wind speed at the conductor? Wind speed is the most influencing factor of dynamic rating. Wind speed and direction will vary significantly over the distance of a span and section.

Why are weather station-based wind speed values inaccurate? High-wind speeds macro-effects
Low Wind Speed local effects

How is the accuracy of the solution validated? sag validated vs. topographer sag measurements in several instances



Real-time dynamic rating:
Calculate real-time rating using the IEEE or CIGRE thermal model with adjusted effective ambient parameters, utilizing the intrinsic accuracy of the ADR sensors

Intra-day dynamic rating Forecasts:
Computes dynamic rating forecast over a 1-4 hour period.

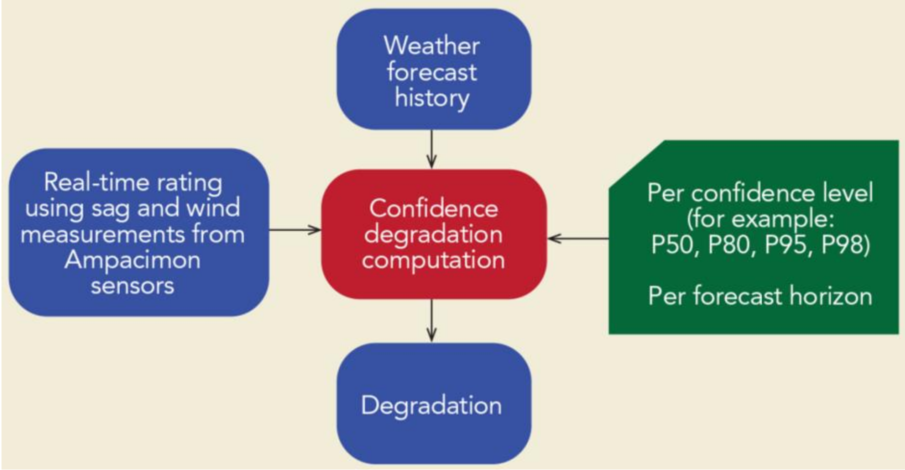
Day(s)-Ahead dynamic-rating Forecast:
Weather-based models, correlated with historical Real-Time measurements 98% confidence interval.

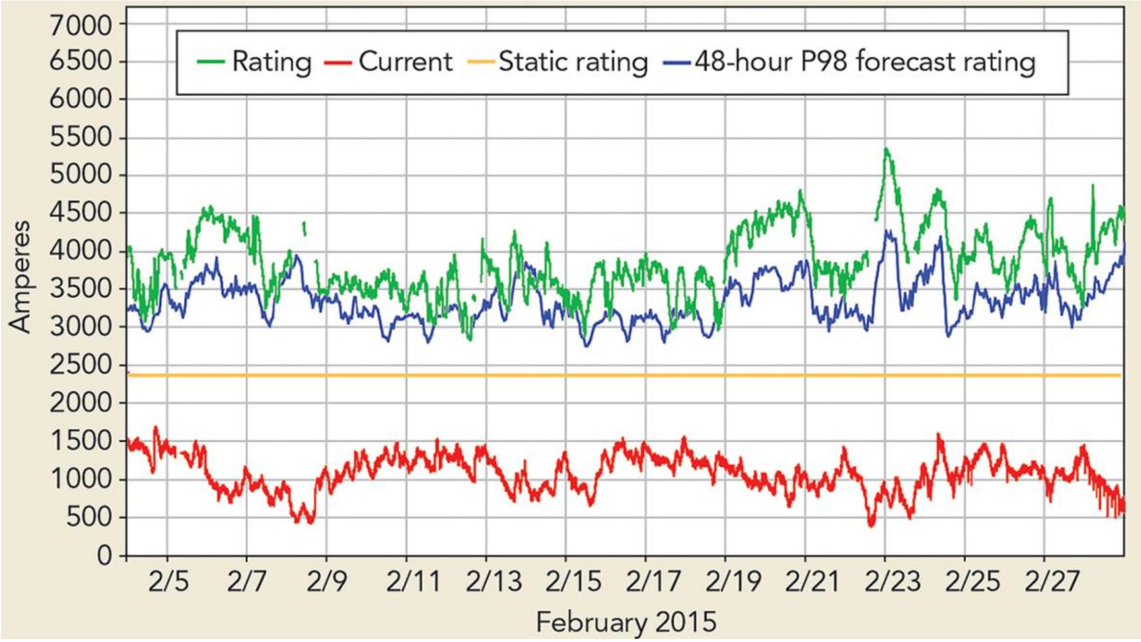
Day(s)-ahead Dynamic rating forecast

Why is weather-based DLR forecast inaccurate? fails to give reliable rating forecasts due to wind speed forecast uncertainties

Improving accuracy of DLR forecast?

- **Machine learning and predictive algorithms** use measured real-time historical data measured by sensors, we statistically adapt the weather forecast to locally observed conditions (as viewed by the line/conductor)
- **Degradation algorithm - >98% Confidence Interval** Degradation of the weather forecast is computed so that the forecast is below actual for >98% of the time.





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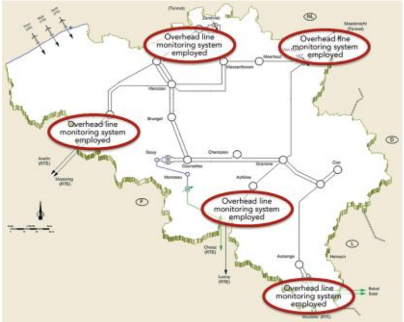
Belgium Transmission Grid (Elia) – uses 48-hour forecast dynamic rating forecast to increase import capacity by 5-10% (for D-2)



Belgium Peak Load: 13 GW

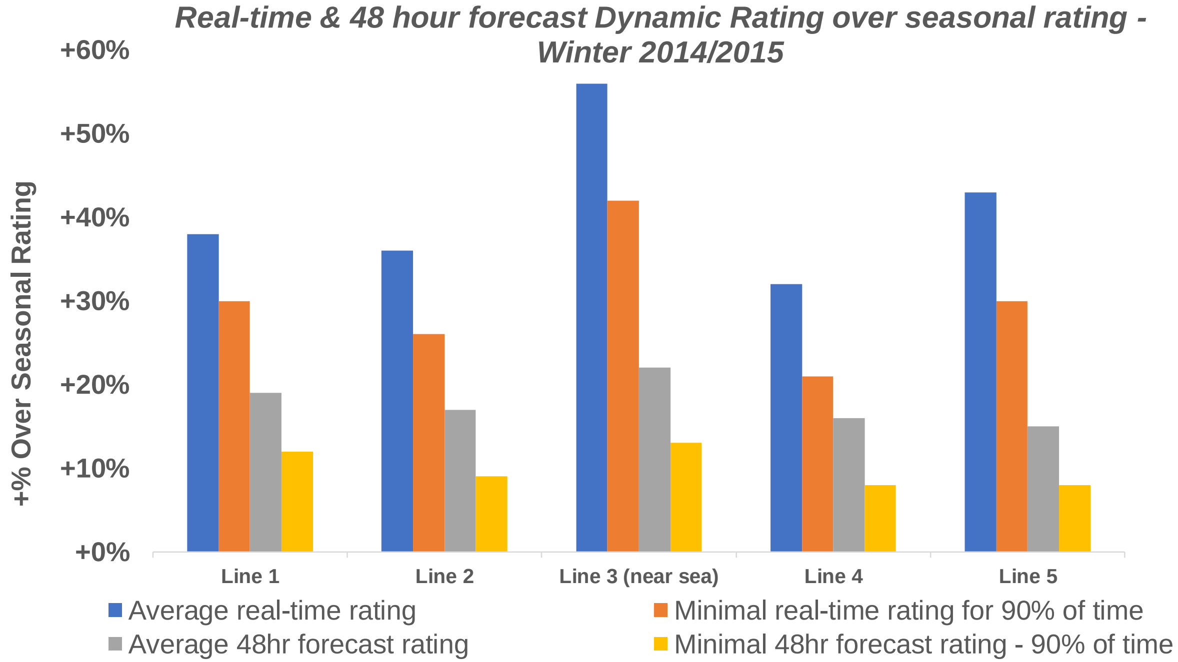
Summer 2014: Loss 3x Nuclear Power Plants of 1GW each

Problem: Belgium required to import power from France & Netherlands, however, maximum import capacity was insufficient during specific winter weather events

Solution: Belgium Transmission Grid Operator (Elia) deployed Ampacimon's Dynamic Rating solution on 8 of its 380 kV T-lines including intra-day and days-ahead forecast

elia

- Elia **integrated real-time, intra-day and 48-hour forecast** dynamic ratings into their **SCADA/EMS/MMS**
- The average real-time dynamic rating **+32 to 56%** over seasonal rating
- The Integrated 48 hour **forecast** into their **market & system operations** yielded a **+5% to 10% for D-2**



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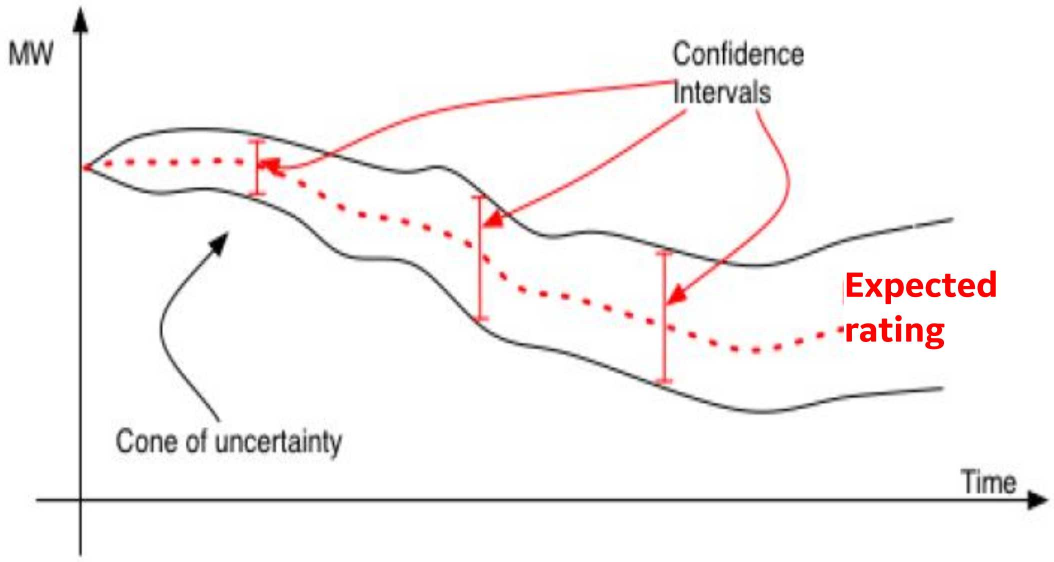
Integration of DLR Forecast into ISO/RTO Market Management Systems (Day-ahead, Intra-day & Real-time)

DLR Approach for System Operations



Network design

Operation Planning

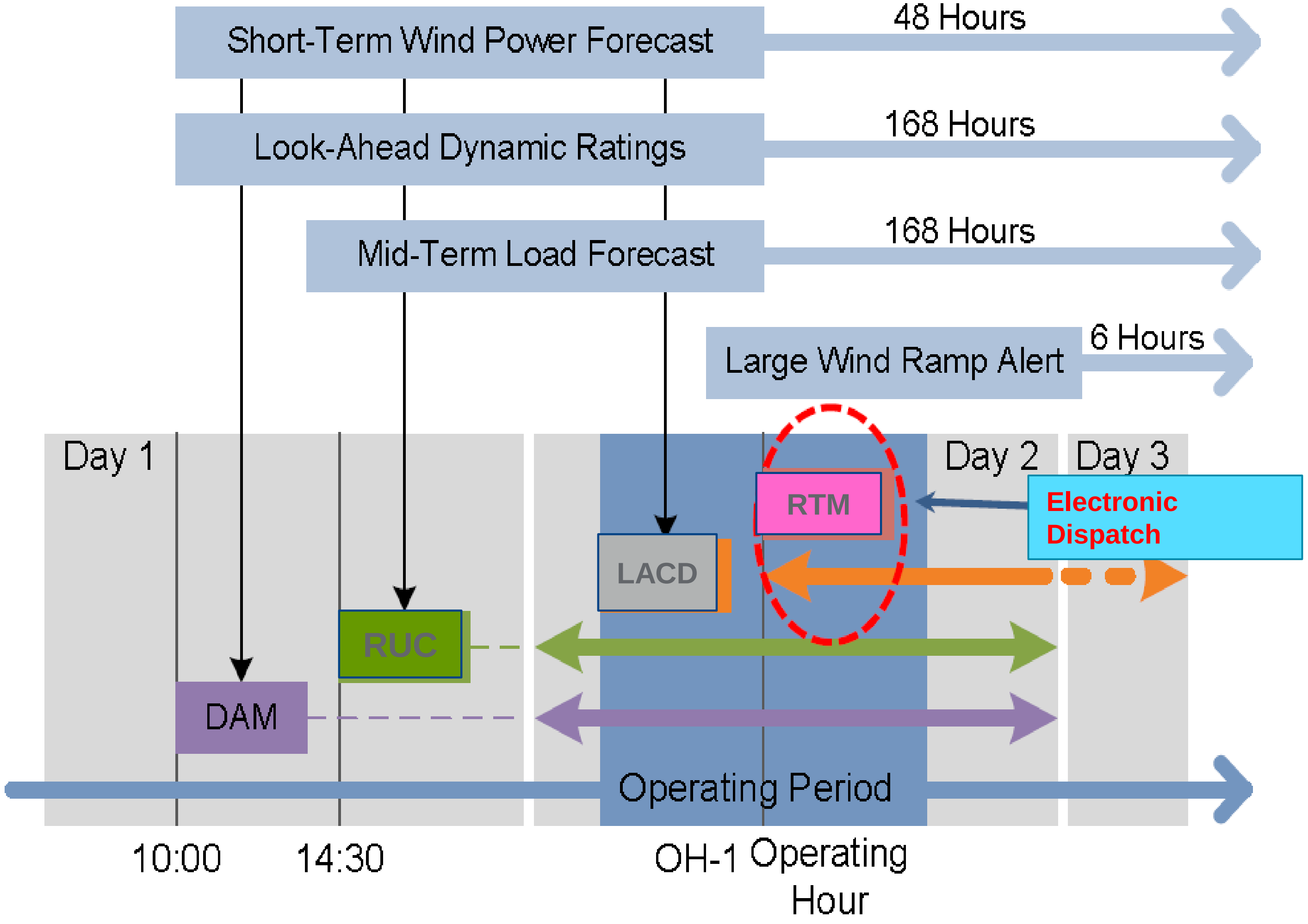
Day-ahead Operation

Real-time Operation

Probabilistic

Deterministic

Typical Business Process Timeline



Application of Real-time, Intra-day and Day-ahead dynamic rating in Real-time and Day-ahead market operations

- Integration of 24 hour dynamic rating forecast into the network model for SCUC and SCED day-ahead
- Data (with 98% confidence interval) can be provided hourly to calculate hourly SCED
- Our experience suggest: Dynamic ratings are at least +5% to +10%. This improves day-ahead market efficiency significantly and reduces congestion costs

- Integration of real-time dynamic rating 1 hour forecast into the state estimator model for SCED real-time
- Data can be provided every 5 minute to calculate SCED
- Our experience suggest: Dynamic ratings are at least +20% to +35%. This improves real-time market efficiency significantly and reduces congestion costs further

Day-ahead dynamic-rating Forecast

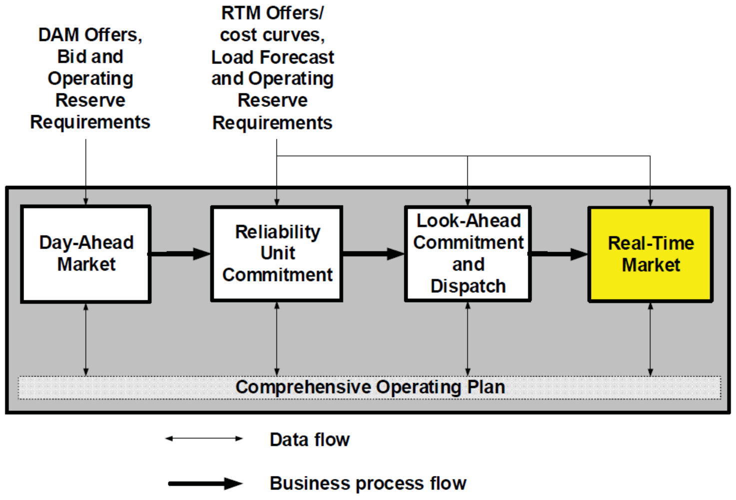
Intra-day dynamic rating Forecast

Real-time dynamic rating

Day-ahead SCUC/SCED System

Network Model Management

SCUC / SCED

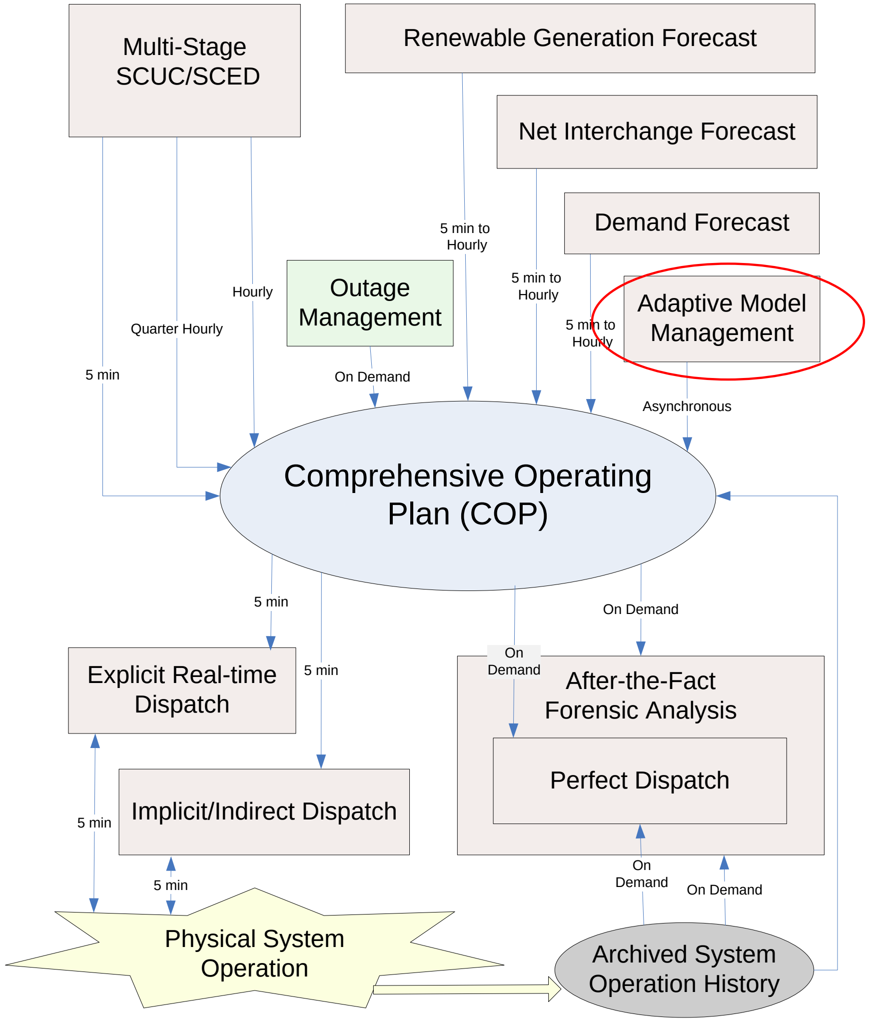


Real-Time SCED System

State Estimation & Contingency Analysis

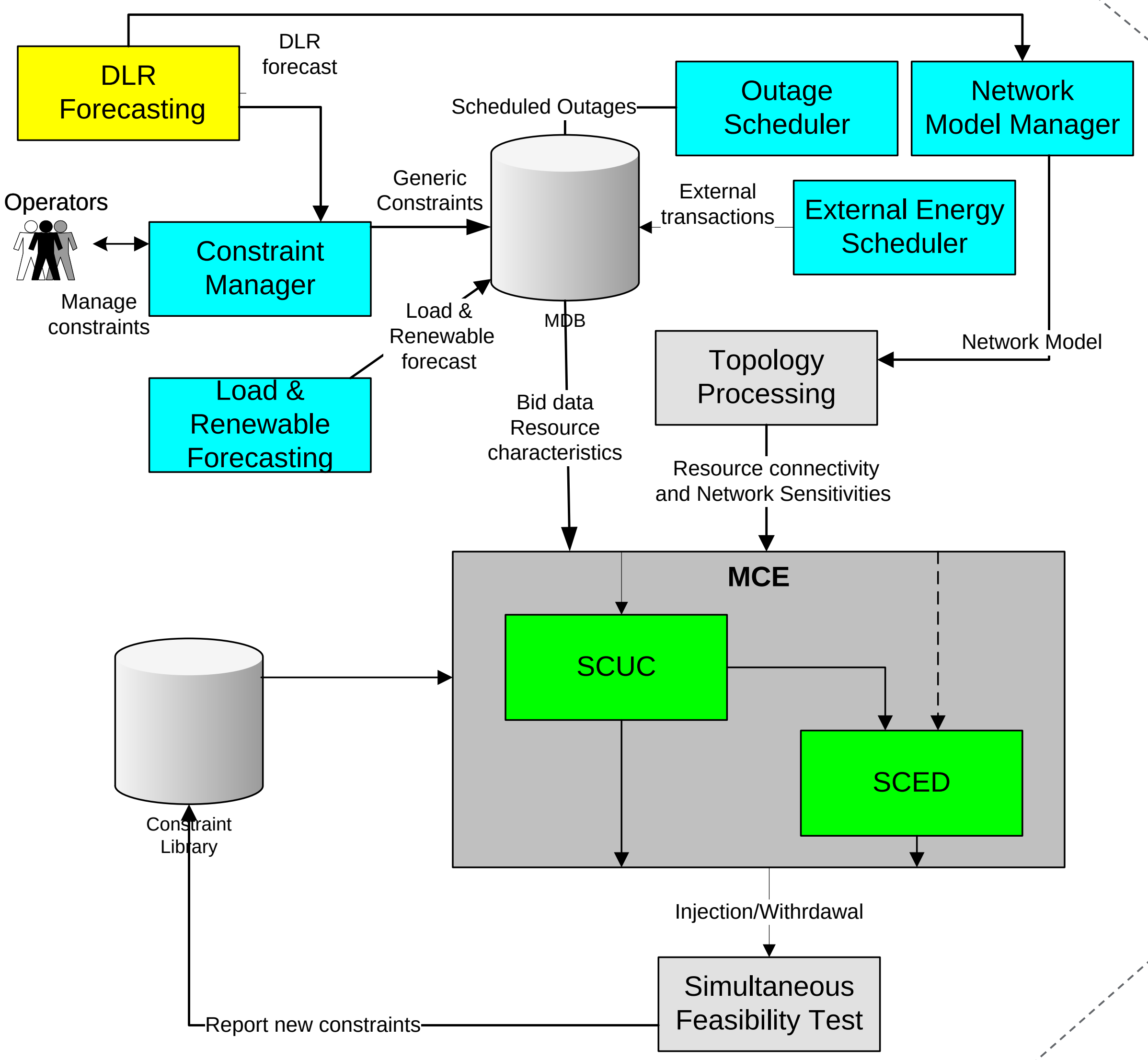
SCED

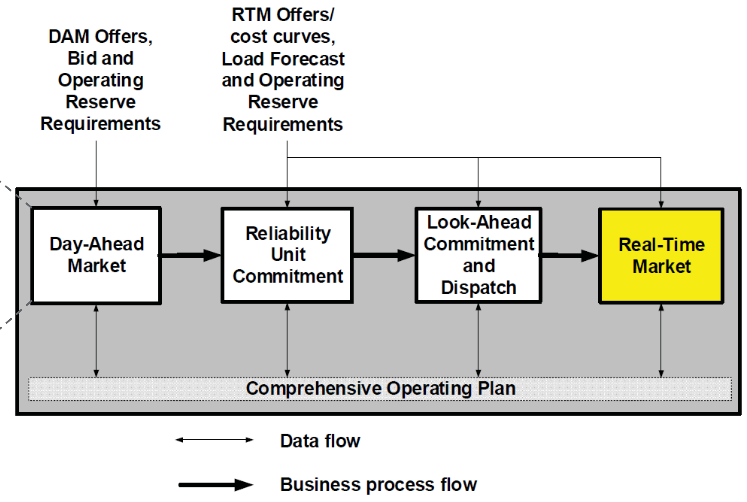
GE's Smart Dispatch Solution Overview



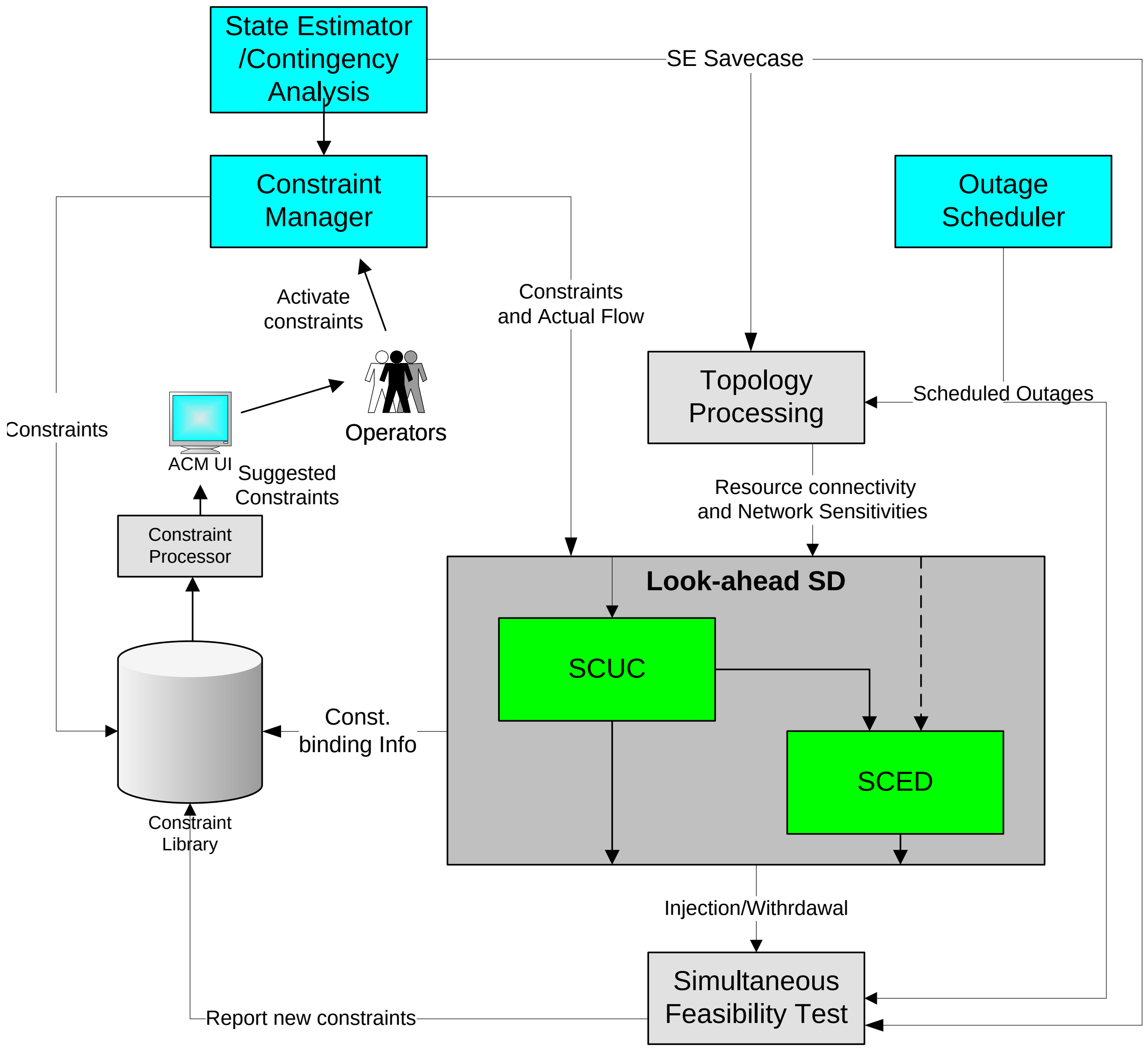
- Multi-stage SCUC/SCED
- Outage management
- After-the-fact forensic analysis (perfect dispatch)
- Renewable generation forecasting
- Net interchange forecasting
- Demand forecasting
- Adaptive Model Management
  - Adaptive generator modeling
  - **Adaptive constraint modeling**

Day-ahead Market SCUC/SCED System with Incorporation of DLR

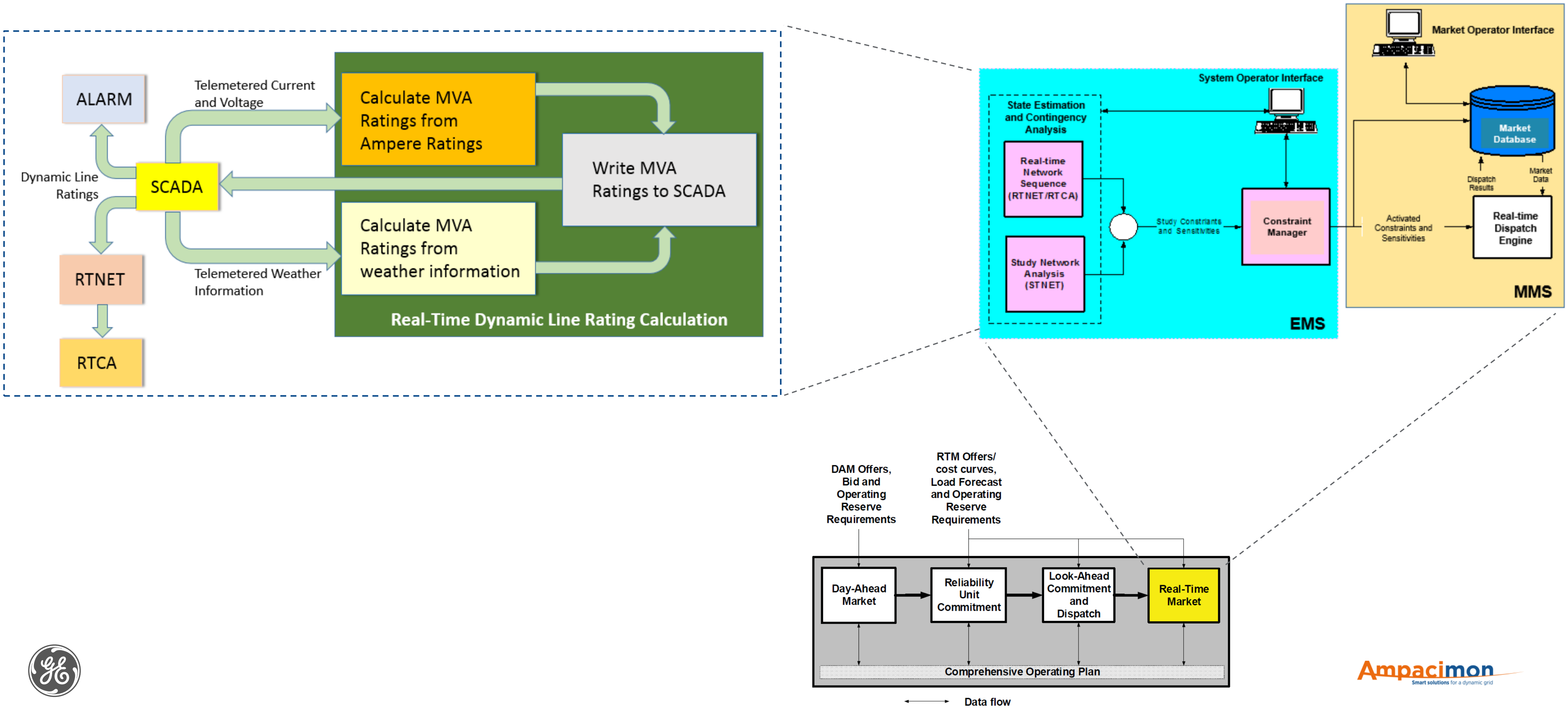




Near Real Time Transmission Constraint Management



Real-time Market - Functional Modules of DLR in EMS



SCED Formulation

$$\min c(P) + co(O) - cd(D)$$

subject to the following constraints:

- System power balance

  $$(\lambda) \quad \sum_i (P_i - D_i) - FD - P_L = 0$$

- Reserve requirement

  $$(\gamma_O) \quad \sum_i O_i \geq O^{\max}$$

- Generator minimum generation limit

  $$(\tau_i^{\min}) \quad P_i \geq P_i^{\min}$$

- Generator joint maximum generation limit

  $$(\tau_i^{\max}) \quad P_i + O_i \leq P_i^{\max}$$

- Price-responsive load dispatch range

  $$(\eta_i^{\max}) \quad 0 \leq D_i \leq D_i^{\max}$$

- Generator ramp-rate limit

  $$(\phi_i) \quad | P_i - P_i^0 | \leq RR_i^{\max}$$

- Grid base-case and contingency

  $$(\mu_l) \quad \sum_i a_{l,i}(P_i - D_i - d_i \times FD) \leq L_i^{\max}$$

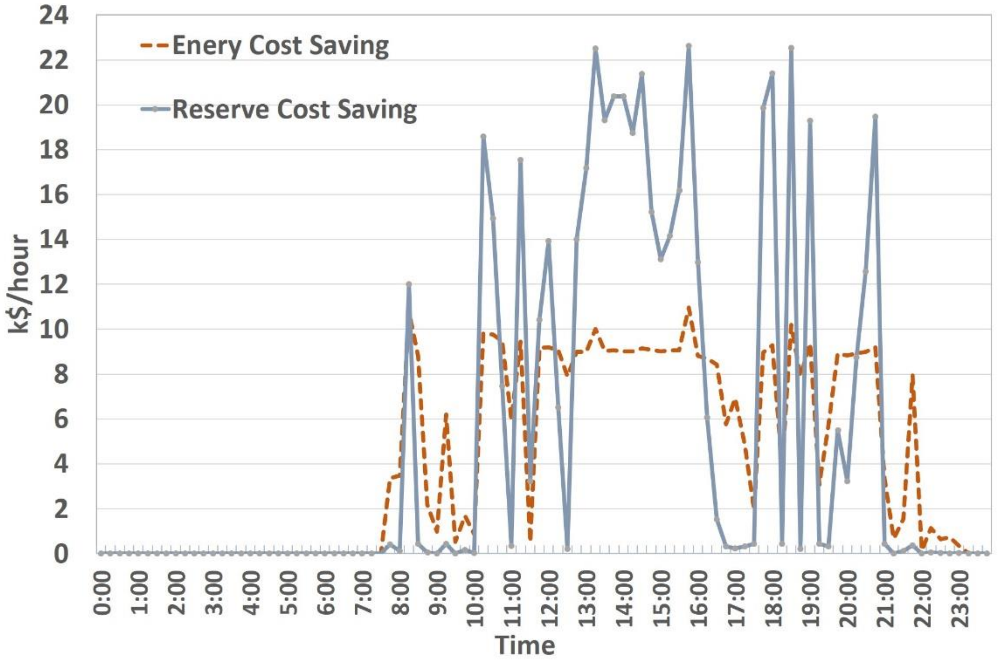
Impacted by DLR determination

Locational Marginal Price

$$LMP_i = \lambda - \lambda \frac{\partial P_L}{\partial P_i} - \sum_l a_{l,i}\mu_l$$

Potential Energy and Reserve Cost Savings

- Applied DLR to the RT-SCED process for a very large power system with more than 37,000 buses and 48,000 transmission lines.



Time	Solutions using Static Line Rating			Solutions using Dynamic Line Rating		
	Energy Cost ($)	Reserve Cost ($)	Reserve Scarcity Cost ($)	Energy Cost ($)	Reserve Cost ($)	Reserve Scarcity Cost($)
0:00	553179	2031	0	553179	2031	0
1:00	480005	2078	0	480005	2078	0
2:00	446669	2136	0	446669	2136	0
3:00	404903	2210	0	404903	2210	0
4:00	381255	2252	0	381255	2252	0
5:00	406548	2220	0	406548	2220	0
6:00	461884	2117	0	461884	2117	0
7:00	609011	2073	0	608168	1968	0
8:00	832161	2036	3254	825842	1739	390
9:00	706032	1817	1727	703686	1654	1727
10:00	656503	1924	11805	649022	1745	1727
11:00	630146	2028	9449	623873	1863	1727
12:00	616593	1997	10273	607815	1874	1727
13:00	610286	1918	21583	601012	1934	1727
14:00	612961	1929	20654	603901	1924	1727
15:00	618795	1935	18218	609263	1905	1727
16:00	609657	2042	6780	601730	1869	1727
17:00	607506	2122	6692	601831	1874	1727
18:00	616534	2043	12731	608737	1899	1727
19:00	620616	2101	7889	613849	1881	1727
20:00	615093	1971	12635	606109	1881	1727
21:00	615558	1993	1727	612174	1759	1727
22:00	721318	1682	1584	720653	1665	1584
23:00	776200	1825	0	776116	1818	0

Conclusions

Final Remarks

- DLR and DLR forecasting can be used to tackle congestion problems.
- Sag monitoring-based along with of wind-speed measurements at the conductor proposed to determine, real-time and forecast DLR
- DLR forecast can be effectively incorporated into the real-time and day-ahead processes of market system operations.

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