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White Paper

Functional Description Of

Core Market Management System (MMS) Applications For

"Look-Ahead SCED"

**Version 0.1.2**

Revision History

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| --- | --- | --- | --- |
| Date | Version | Description | Author |
| 10/31/2011 | 0.1.0 | Initial Working Draft | ERCOT Team |
| 11/1/2011 | 0.1.1 | Second Working Draft | ERCOT Team |
| 11/17/2011 | 0.1.2 | Third Working Draft | ERCOT Team |
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# Executive Summary

## Scope and Purpose

This White Paper provides a high level functional description of the core Market Management System (MMS) applications for the proposed “Look-Ahead SCED”. Settlement details are out of scope in this White Paper. The Settlement component will be addressed separately.

The purpose of this White Paper is to provide a starting reference point for discussions with stakeholders. This White Paper is a living document that will be refined with inputs from stakeholder discussions as the scope of “Look-Ahead SCED” is finalized.

## Goals of “Look-Ahead SCED”

The goal of “Look-Ahead SCED” in its final version is to address the following limitations of the current single interval SCED optimization:

1. Improve ERCOT Real-Time operations for both economic efficiency and system reliability by taking into account a look-ahead perspective of system operations and providing Market Participants and ERCOT Operators with a short-term look-ahead projection of system conditions (short-term future prices, expected congestion etc.)
2. More efficient commitment and dispatch of QSGRs, Load Resources and Storage Resources with temporal constraints via intra-hour commitment having a study horizon of two hours.
3. Add capability to enable participation of Load and Storage Resources in the Real-Time Market for Energy and Ancillary Services.
4. Add capability of Real-Time Co-Optimization of Energy and Ancillary Services to efficiently utilize available Resource capacity.
5. Add capability to consider future topology changes. e.g. Outages.

These goals will be achieved in several stages. This White Paper establishes the framework to implement these goals.

## Overview of Core Applications for “Look-Ahead SCED”

In its final version, “Look-Ahead SCED” will output binding dispatch instructions (Base Points) and pricing (LMP) for the first 5-minute time interval and advisory dispatch instructions (Base Points) and pricing (LMP) for the subsequent eleven 5-minute time intervals within a one hour study period. “Look-Ahead SCED” will also output Commitment Instructions and Ancillary Service awards for Generation, Load and Storage Resources for multiple 15-minute intervals with study period up to two hours. The Ancillary Service awards and Ancillary Service prices (i.e. MCPCs) will be binding for the first 15-minute time interval lasting over the multi interval block. Additionally, all issued Resource Commitment Instructions will be binding.

This requires a new suit of Real-Time Market applications that will optimize Resource dispatches and commitments and co-optimize Energy and Ancillary Services for each time interval during the study period for efficient and reliable system operation taking into account ramping capabilities of Resources, responding to changes in system topology (due to planned and forced outages) and honoring temporal constraints (e.g. minimum up and down times of generators, minimum deployment time for loads, storage capacities of batteries etc).

The core Real-Time Market look-ahead applications are:

* Real-Time Commitment (RTC) application to optimize intra-hour commitments and co-optimize Energy and Ancillary Service procurements every wall clock 15 minutes over a rolling window of up to two hours study period with 15-minute time intervals while respecting 15-minute system Load Forecast, Ancillary Service plans, transmission constraints, hourly Resource commitments and Resource physical characteristics. A 15-minute Load Forecast of system load over the study period will be derived from 5-minute Load Forecast.
* Real-Time Dispatch (RTD) application to dispatch energy every wall clock 5 minutes over a rolling window of one hour study period with 5-minute time intervals while respecting system 5-minute Load Forecast, transmission constraints, 15-minute Ancillary Service awards, 15-minute Resource commitments and Resource physical characteristics. The system demand for each 5-minute time interval over study period is predicted by a 5-minute Load Forecasting application.

## Real-Time Commitment (RTC) Application

The Real-Time Commitment (RTC) represents an optimal unit commitment application executed every wall clock 15 minutes with a study period up to two hours (configurable) divided into 15-minute time intervals. The 15-minute time intervals included in the study period shall coincide with the Real-Time Settlement Intervals.

The outputs of the Real-Time Commitment application include the 15-minute Commitment Instructions for Generation, Load and Storage Resources and the 15‑minute Ancillary Service awards along with the associated Market Capacity Clearing Prices (MCPCs). The Resource commitments are consistent with ramping capabilities and temporal constraints (e.g. startup time for Generation Resources, minimum deployment time for Load Resources, storage capacities for Storage Resources, etc). Only those Generation, Load and Storage Resources with two hour or less notification times and intra-hour inter-temporal constraints are considered by the Real-Time Commitment application.

The Real-Time Commitment application will determine optimal commitment statuses and co-optimize Energy and Ancillary Services from Generation, Load and Storage Resources for each 15-minute time interval across the study period based on their Three-Part Offers and Ancillary Service Offers taking into account the system 15-minute Load Forecast, Ancillary Service plan and transmission constraints. The existing RUC make whole provisions will continue to apply but may require revision to address issues unique to short notice Generation Resources, the temporal nature of Load Resources and the operation specifics of Storage Resources.

The 15-minute Load Forecast model will be derived from 5-minute Load Forecast and could be automatically and manually adjusted to be consistent with hourly system Load Forecast.

The Ancillary Service requirements in the 15-minute Real-Time Market application suite will be the same as the Ancillary Service plan in DAM. The deployed Ancillary Services will not be compensated, i.e. the Ancillary Services will be procured to be available for deployment.

To better address Ancillary Service deliverability, 15-minute Real-Time Market will accommodate the use of one or more Ancillary Service regions. The Ancillary Service regions are determined in advance by Ancillary Service deliverability studies and can be re-configured to address changes in load pattern and transmission topology. The Ancillary Service procurement from Resource fixed, variable and multi-interval block offers will be optimized for every Ancillary Service region in every 15-minute time interval.

Also, the Ancillary Service substitution will be accommodated to procure higher quality of Ancillary Service type in excess of the Ancillary Service plan to substitute for lower quality Ancillary Service if it is economically beneficial. The Ancillary Service shortage in respect to Ancillary Service requirements can be penalized by Ancillary Service scarcity prices.

The online Ancillary Service awards for the first 15-minute time interval are binding, while online Ancillary Service awards for subsequent 15-minute time intervals are advisory. A multi-interval block Ancillary Service awards are binding for the whole interval block starting with the first 15-minute time interval. The offline Non-Spin awards could be binding for several subsequent 15-minute time intervals to reflect Resource inter-temporal constraints (minimum up and down times). All Ancillary Service awards are settled at 15-minute Ancillary Service region MCPCs.

The energy awards are considered by Real-Time Commitment application only to co-optimize Ancillary Services, i.e. the 15-minute energy awards will not be settled.

The 15-minute Commitment Instructions are binding for time intervals that cannot be re-optimized in subsequent Real-Time Commitment application runs. The advisory Resource Commitment Instructions will not be issued. The Generation, Load and Storage Resources committed by the Real-Time Commitment application are eligible for make-whole payments.

The Real-Time Commitment application can be executed in open loop control mode. In this case all Base points and LMPs determined by the Real-Time Commitment are advisory/indicative.

## Real-Time Dispatch (RTD) Application

The Real-Time Dispatch (RTD) application is a multi-interval dispatch program that is executed every 5 minute clock interval with a study period extending 60 minutes (configurable) into the future. The Real-Time Dispatch application must complete execution to allow sufficient time before the start of the study period to issue and communicate timely Dispatch Instructions and LMPs to Resources. Only already committed Resources will be dispatched. This application will optimize energy to satisfy 5-minute Load Forecast respecting the 15-minute Ancillary Service awards.

A projection of the future 5-minute values of the system load over two-hour time horizon will be calculated by 5-minute Load Forecast application. The two-hour forecasting time horizon is necessary to derive 15-minute system load forecast over two-hour study period for 15-minute Real-Time Market application suite.

The Real-Time Dispatch application will optimally dispatch and price Generation, Load and Storage Resources. The outputs are the energy dispatches and energy prices for each 5-minute time interval in the study period. Both Resource Base Points and Locational Marginal Prices (LMP) are binding for the first 5-minute time interval and advisory for the remaining eleven 5-minute time intervals in the study period. The Real-Time Settlement Interval will continue to be 15 minutes for both Energy and Ancillary Services.

RTD can be executed in open loop control mode as well. In this case, the system operation is controlled by Base Points and LMPs determined by current SCED, while Base Points and LMPs from RTD are advisory/indicative.

The Real-Time Dispatch application will include several salient features including simultaneous energy optimization across all time intervals in the study period with the ability to model ramping capabilities of Resources symmetrically across the 5-minute time intervals. The application will also have the capability to run on demand subject to specific settings managed by the Market Operator.

RTD will utilize the current Real-Time SCED input data set expanded over the study period to include submitted hourly energy offers, data for demand response, Resource data from COP, individual WGR production forecast, system 5-minute Load Forecast, Resource ramping characteristics and settings for ramp sharing between LFC and RTD. The input data set will also take into account 15-minute Commitment Instructions (binding and advisory) for Generation, Demand and Storage Resources from the most recent run of Real-Time Commitment application.

## Wind Forecast processing for Real-Time Commitment and Real-Time Dispatch

For Wind resources, the HSL for future intervals under consideration by RTC/RTD will be a function of the Short-Term Wind Power Forecast (STWPF). STWPF is a forecast for the next 48 hours by hour of the expected wind power produced by each Wind Resource.

The 5-minute HSL value for Wind Resources input to RTD will be a function of the STWPF hourly value and the last six 5-minute average Telemetered HSL from each Wind Resource. The first 5–minute interval will use the most current Wind Resource telemetered HSL (persistence), and on a graduated decreasing scale, the future 5-minute intervals will have less weights on the past 5-minute average telemetered HSL in determining the HSL for future intervals. The intent of using the last six 5-minute average telemetered HSL is to capture short term trends.

A similar approach will be taken for the 15-minute intervals in RTC.

For Wind Resources that do not submit an Energy-Offer Curve (EOC), the proxy offers for each 5-minute interval (RTD) or 15-minute interval (RTC) will be created around the HSL determined by the above method.

## Ramp Rate processing for Real-Time Commitment and Real-Time Dispatch

For the first interval (5-minute interval for RTD and 15-minute interval for RTC), the telemetered ramp rates will be used. For future time intervals (5-minute or 15-minute), if the QSE in its RARF or MMSUI submission has provided ramp rates as a function of MW output, then these submitted ramp rates will be used. Note: based on observed results during testing, modifications based on a combination of telemetered ramp rates and the RARF/MMSUI-submitted ramp rate functions will be used. Validation (reasonability limit checks) on telemetered ramp rates will be performed. If the validation fails then the ramp rate will default to the RARF/MMSUI submitted ramp rates.

## State Estimator/EMS output processing for Real-Time Commitment and Real-Time Dispatch

Initially, State Estimator input usage by RTC/RTD will remain the same with some exceptions listed below.

1. SE Load MW will be transformed into distribution factors. These distribution factors will remain the same for all intervals under consideration in RTC/RTD. The Load MW will be recomputed using these distribution factors and the 5-minute Short Term Load Forecast (similar to RUC). The future 5 or 15 minute Load MW will be used to update (for future 5 or 15 minute intervals), transmission constraint equations – flows, Load Zone LMP calculation, etc.
2. Telemetered DSR telemetered output schedule and telemetered DSR load will be kept persistent for all the 5-minute intervals under consideration by RTC/RTD. If the DSR resources submit future 5-minute output Schedules then these values will be used.
3. HDL, LDL will not be used as explicit ramp rate modeling is implemented in RTC/RTD.
4. Short Term Load Forecast (adjusted by latest GTBD) will be used.

# Load and Storage Resource Modeling and QSE Data Submission

## Load Resource

1. *Operational Characteristics*

A Load Resource can operate within Real-Time Market framework in variety of ways, as follows:

* Load Resource with Energy Offer or Demand Resource (DR) that acts as a generation resource is allowed submitting offers to inject energy that reflects the curtailment and reduction of consumption. The Demand Resource can represent a behind the meter generator, individual industrial consumer or aggregated loads. The focus of remaining chapters of this White Paper is participation of this type of Load Resources in the Real-Time Market.

The Demand Resources with notification times and inter-temporal parameters less than one hour will be considered by the 15-minute Real-Time Commitment application and optimized by the 5-minute Real-Time Dispatch application considering all operational characteristics of Demand Resources.

* Load Resource with Energy Bid (LR) that acts as a price sensitive Controllable Load Resources (CLR) or interruptible Load Resources (NCLR) could be allowed submitting bids to buy energy in the Real-Time Market. These Load Resources can represent individual consumption entities or aggregated loads consuming energy. The direct participation through submitted bids to buy energy at a specific network location may require changes in PUCT rules.
* Load Resource representing Aggregated Retail Resource (ARR) that is responsive to wholesale market prices as a price taker. The response to the wholesale energy prices will be represented through a price responsive demand curve that is used to determine impacts of retail load responses to the dispatch of remaining system. This price responsive demand curve will be an adjustment to the load forecast. This approach is based on what PJM is proposing.
* Emergency Interruptible Load Resource (EILR) that can be interrupted in emergency based on contractual arrangement, but not participating in the Real-Time Market.

**For ability to participate in the Real-Time Market, a Settlement Point needs to be identified for every Load Resource. The philosophy of determining the location and any associated metering will need to be worked out. This has possible implications on hedging and settlements from CRR to DAM to Real-Time Market.**

A hypothetical station with variety of Resource types is illustrated on the following figure (this is not metering and telemetry specification):

*Telemetry Points*

*WGR*

*EPS*

*SR*

*Gen*

*DR*

*LR*

*Aux*

*ARR*

*LZ Loads*

*EPS*

Figure 1**: Load, Demand, Storage and Aggregated Retail Resources**

1. *Resource Registration*

All Load Resources will be registered with their characteristics specified to participate in the Real-Time Market. At this point of time, a RARF form shall be developed to accommodate submission of all relevant parameters for the various flavors of Load Resources - Demand, Load and Aggregated Retail Resources.

For Demand Resources, a fully symmetrical treatment to generation entities will be established for registration of Demand Resource physical parameters including commitment, dispatching and ramping parameters. The registered parameters are subject to appropriate validation rules.

The Aggregated Retail Resources should be registered with reduced set of operating parameters.

1. *Market Submission*

The registered Load Resources are not obligatory to participate in the Real-Time Market. The interruptible Demand Resources can be self-committed, DAM/RUC committed, available for Real-Time Commitment application, or unavailable. The self-committed or DAM/RUC committed Demand Resources can submit hourly Energy Offer Curves or 5-minute Output Schedules with or without Inc/Dec Offer Curves. The average 5-minute Output Schedule is used as a proxy for the 15-minute Output Schedule.

The available Demand Resources can submit hourly Three-Part Offers to be committed by the Real-Time Commitment application and, if committed be dispatched by Real-Time Dispatch application, as it is illustrated on the following diagram:

*$/MWh*

*0 MW*

*MWload*

*0 MW*

*MWDR*

*Metered Load*

*Base Load*

*Startup*

*Cost Offer*

*LDL*

*Energy Offer Curve*

*HDL*

*Base Point*

*Min Energy Offer*

*Demand Response*

Figure 2: Three-Part Offer for Demand Resource

Instead of utilizing Verifiable Costs for the Three Part Offer from Load Resources, floors for all the three parts can be made. The Three-Part Offer of Demand Resource represents consumption interruption and reduction in respect to the Base Load point. Taking Base Load point as a reference, the demand response is seen from system prospective as energy injection. An alternative approach would be the requirement to submit future 5-minute Scheduled Power Consumption (like Output Schedules) to be used as a reference. Therefore, the Three-Part Offers (i.e. Startup Cost Offer, Minimum Energy Offer and Energy Offer Curve) for Demand Resources can be interpreted as Three-Part Offers for Generation Resources.

All parameters (i.e. HRL, MPC, LPC, LRL, …) for the Demand Resource should be specified in respect to the Base Load point. The Base Load is the reference for Demand Resource settlement and billing as well.

A fixed or variable Energy Offer Curve, Inc/Dec price curves or Three-Part Offer price curves for Demand Resources are submitted in Adjustment Period to be used by both Real-Time Commitment and Real-Time Dispatch application. The price offer floor should be established to prevent unintentional damages of Real-Time Market efficiency and stability. The submitted price curves are subject to Market Power Mitigation in 15-minute and 5-minute time domains. Here the mitigation will ensure that after mitigation the mitigated offer does not fall below a certain level.

Qualified Demand Resources can submit hourly fixed or variable Ancillary Service offers in the existing format in Adjustment Period. The Demand Resource participation in Real-Time Ancillary Service Market is voluntary.

The Aggregated Retail Resources can submit the price responsive demand curves to be accounted to determine Aggregated Retail Resources responses to wholesale energy prices over study period. The price responsive demand curves must be non-increasing piecewise linear functions with up to ten break points. If the price responsive demand curves are not submitted then the ERCOT will estimate the curves from historical data. In any case, the Aggregated Retail Resources will be treated as price takers. This has been adopted from PJMs approach to handling Price Responsive Demand.

## Storage Resource Participation

1. *Operational Characteristics*

The Storage Resources (SR) can be organized in plant facilities in variety of configurations and operate as bidirectional storage devices. The dynamics of Storage Resources charging and discharging processes can vary from seconds, minutes, hours and days to even seasons and years, i.e. the Storage Resources can be used for wide range of system applications. The disturbances of system stability, voltage levels, and harmonics can be compensated by duration limited Storage Resources on second basis. The frequency control, power balancing and transmission congestion can be efficiently supported by Storage Resources to improve system reliability. The firming of renewable Resources and smoothing load profiles are essential application of Storage Resources. The electric energy time-shift and system load peak shaving improve system efficiency and reduce needed resource capacity.

The Storage Resources with notification times and inter-temporal parameters less than one hour will be considered by the Real-Time Commitment and Dispatch applications considering Storage Resource operational characteristics. These are mostly flywheel and chemical battery type of Storage Resource. The focus will be on areas of Storage Resource applications that fall within the Real-Time Market framework:

* System regulation to support system frequency control backed with operating reserves, and
* Look-ahead dispatch to utilize Storage Resource capabilities for load following, energy time shift, transmission congestion and intermittent Resource firming.

A Storage Resource can operate in multiple modes, for example:

* Charging Mode, i.e. electric energy conversion to be stored
* Discharging Mode, i.e. stored energy conversion into electric energy, and
* Offline Mode, i.e. not operating, but available.

For example, the flywheel batteries operate only in one state (i.e. they are always in online operating mode performing charging and discharging, if they are available), while storage hydro units operate in three operating modes (pumping, generating and offline), or even in four modes if condenser mode is considered.

The transitions between operating modes can take some time and can cause some costs as it is illustrated on the following diagram:









*Charging Mode*

*Offline Mode*

*Discharging Mode*

*Transitions*

Figure 3: Three-State Storage Resource Operating Modes

For duration limited Storage Resources, the transition times are below 5 minutes, i.e. these transition times, as well as transition costs, can be ignored. Also, the minimal charging and discharging power is very low, practically equal to zero. In this case, there is no need to differentiate between charging and discharging operating modes for duration limited Storage Resources. The duration limited Storage Resources can be treated by Real-Time Commitment application as single-state Storage Resources being always online (if available), as it is illustrated on the following diagram:







*Charging Mode*

*Discharging Mode*

Figure 4: Single-State Duration Limited Storage Resource Operating Modes

The charging, discharging and storing processes of Storage Resource cycling cause energy losses. In general, the efficiencies of Storage Resource operating modes can be measured separately and considered by Real-Time Commitment and Dispatch applications.

The charging and discharging rates are limited as well as storage capacity. Additionally, the Storage Resources should be dispatched in the way that there is sufficient amount of stored energy to be charged and discharged properly and to be able to deliver Ancillary Services.

**For ability to participate in the Real-Time Market, a Settlement Point needs to be identified for every Storage Resource. The philosophy of determining the location and any associated metering will need to be worked out. This has possible implications on hedging and settlements from CRR to DAM to Real-Time Market.**

1. *Resource Registration*

All Storage Resources will be registered as a separate Resource type to participate in the Real-Time Market. An appropriate RARF form should be developed to accommodate registration of Storage Resource operating modes and parameters. Storage Resources parameters should be specified for each operating mode including ramp rate functions for both upward and downward directions. The Storage Resource operating modes and parameters are subject to appropriate validation rules.

1. *Market Submission*

All available (online) Storage Resource are obligatory to participate in Real-Time Market in both 15-minute and 5-minute time domains; otherwise a Proxy Offer with zero transition costs and zero charging and discharging prices will be considered. A Storage Resource can be self-committed, DAM/RUC committed, available for Real-Time Commitment application, or unavailable. Available duration limited Storage Resources are always assumed to be in online operating mode capable to perform both charging and discharging in continuous manner.

The multi-state Storage Resources can submit Three-Part Offers for both charging and discharging transitions. The duration limited Storage Resources can submit Energy Offer Curves for charging and discharging operating modes. If offers are not submitted then operating costs are assumed to be equal to zero. A process for Verifiable Costs for the Three Part Offer from Storage Resources needs to be setup.

The Storage Resources do not generate energy (i.e. they do not have fuel costs) and the Storage Resources do not consume energy (i.e. there is no consumption benefits). The Storage Resource operating costs are related to investment, maintenance and replacement costs. These costs can be associated with all three aspects of Storage Resource operation: charging, discharging and storing. Following the standard formats of market submissions, the Storage Resources operating costs can be specified as Three-Part Offers for charging and discharging operating modes, as it is illustrated on the following figure:

*MW*

*MPC*

*LPC*

*HSL*

*LSL*

*$/MWh*

*Discharging Mode*

*Charging*

*Mode*

*Charging*

*3PO*

*Discharging*

*3PO*

Figure 5: Three-Part Offers for Storage Resource

Note that discharging power and discharging offer prices are positive, while charging power and charging offer prices are negative. Therefore, the Storage Resource energy cost curves are positive and convex for both charging and discharging modes.

The Transition Cost, Minimum Energy Cost and Energy Offer Curves can be submitted for both charging and discharging operating modes to specify transition, charging and discharging operating costs without internal energy losses. The internal energy losses for Storage Resources are represented by efficiency coefficient and accounted in energy accumulation during study period.

The Ancillary Service offers for Storage Resources can be submitted using the existing formats. The participation of Storage Resources in the Real-Time Ancillary Service Market is voluntary.

## COP Data

The COP data should not be updated for binding Commitment Instructions and binding Ancillary Service awards determined by the Real-Time Commitment application. A separate mechanism will be provided for QSEs to confirm their acceptance to follow the binding 15-minute Commitment Instructions and 15-minute Ancillary Service awards. The outputs from Real-Time Commitment application will be saved to be used by its subsequent runs, and automatically transferred to Real-Time Dispatch application without Market Participant involvement.

The LPC and MPC for Aggregated Retail Resources can be submitted into COP as hourly consumption power limits.

## Virtual Bids and Offers

Virtual bids and virtual offers are not considered by the Real-Time Market.

# 15-Minute Real-Time Market Operation

## 15-Minute Real-Time Market Timeline

The market data submitted for Real-Time Market is hourly and the submission window closes at the top of the hour for the next Operating Hour. The offers and bids are available at least for one Operating Hour and the most for two Operating Hours in advance. The market data availability determines the length of Real-Time Market 15-minute study period.

The Real-Time Market clearing and pricing is executed every o’clock 15-minute considering study period up to two hours with 15-minute time intervals. The length of study period depends on availability of submitted market data as it is illustrated in the following diagram:

*00:45* ***01:00*** *01:15 01:30 01:45* ***02:00***  *02;15 02:30 02:45* ***03:00*** *03:15 03:30 03:45* ***04:00***  *04:15*

*Submission*

*Closing*

*RTC Executions*

*Study Periods*

*Submission*

*Closing*

Figure 6: Figure 1: Real-Time Market 15-Minute Timeline

At market submission closing time, the market data is available for the next two Operating Hours. The first Real-Time Commitment execution at the top of the hour will have seven 15-minute time intervals in the study period lasting till the end of the second Operating Hour. Subsequent Real-Time Commitment executions at clock 15, 30 and 45 minutes will have study periods lasting six, five and four 15-minute time intervals. There is no additional market data submission within the first Operating Hour, consequently the study period will not be extended at the end. At the next top of our new set of market data will be available for the next Operating hours and study period can be extended to seven 15-minute time intervals for the top of the next hour execution.

## 15-Minute Load Forecasting

The 15-minute system Load Forecast is provided for the next eight 15-minute time intervals and updated every 15 minutes. The 15-minute Load Forecast is derived from 5-minute Load Forecast by averaging 5-minute Load Forecasts for each three 5-minute time intervals correspondent to o’clock 15-minute time intervals.

The 15-minute Load Forecast can be adjusted to be consistent with hourly Mid-Term Load Forecast (MTLF). It is assumed that hourly Mid-Term Load Forecast is “ramping” symmetrically from the middle to the middle of hourly time intervals. The 15-minute load trajectory is derived from this hourly MTLF load profile as it is illustrated on the following diagram:

*00:45* ***01:00*** *01:15 01:30 01:45* ***02:00***  *02;15 02:30 02:45* ***03:00*** *03:15 03:30 03:45* ***04:00***  *04:15*

*Symmetrical Load Profile*

*15-minute Load Trajectory*

*Hourly MTLF*

Figure 7: 15-Minute Load Forecast Adjustment

The adjusted 15-minute Load Forecast is determined as weighted average of 15-minute load profile derived from MTLF and 15-minute Load Forecast derived from 5-minute Load Forecast. The weighting factor is enterable and determined by the Market Operator. The same weighting factor is used for all 15-minute time intervals.

The 15-minute system Load Forecast is adjusted for price sensitive responses of Demand Resources and Aggregated Retail Resources. The dispatches of Demand Resources and Aggregated Retail Resources from the last run of Real-Time Commitment application are used as expected projections of load responses over the study period. The last 15-minute time interval in the study period is replicated.

The 15-minute system Load Forecast is main requirement for Real-Time Commitment application, i.e. the Resources are committed and dispatched to satisfy the adjusted 15-minute Load Forecast. Any over or under generation is penalized higher than Ancillary Service plan shortages.

## Real-Time Commitment

### Optimization Framework

The Real-Time Commitment (RTC) application consists of two phases:

1. The MIP Phase that solves the Mixed Integer Programming (MIP) problem with piecewise linear objective function subject to system power balance, Ancillary Service requirements, transmission constraints, multi-interval block constraints, Resource inter-temporal constraints, and Resource capacity, ramping and operating limits. The outcome of the MIP Phase is the optimal solution for binary variables, i.e. the optimal discrete decisions over the study period. MIP hot start feature is utilized in every MIP Phase execution. And,
2. The QP Phase that solves Quadratic Programming (QP) problem with piecewise quadratic objective function subject to system power balance, Ancillary Service requirements, transmission constraints, Resource inter-temporal constraints, and Resource capacities, ramping capabilities and operating limits. The values of binary variables are fixed at the optimal solution of the MIP Phase. The outcomes of the QP Phase are optimal values of Energy and Ancillary Service awards as well as shadow prices for binding constraints.

In each run of Real-Time Commitment application, both MIP and QP Phases are executed two times to perform market power mitigation. The transmission constraints are determined in studies outside of the Real-Time Market and considered by the Real-Time Commitment application without iterations.

The penalties for system power balance violations, Ancillary Service plan shortages and transmission constraint violations are 10 times higher (configurable) in the MIP Phase than in QP phase to enforce commitments of all available Resources before constraint violation. In the QP Phase the values for constraint violation penalties are determined in the way that energy and Ancillary Service prices represent signals for efficient short-term system operation and long-term system capabilities.

### Ancillary Service Procurement

1. DAM/SASM Ancillary Service Awards

All Ancillary Services awarded in DAM and SASM market runs will be bought back at 15-minute Real Time MCPCs and procured again by Real-Time Commitment application to satisfy Ancillary Service plan. The procured Ancillary Services are settled at 15-minute MCPCs and available to deployment according to deployment procedures.

The Ancillary Service self-arrangements should be allocated to individual Resources and reported in the COP in the existing formats. The Ancillary Service self-arrangements are respected by Real-Time Commitment application.

1. Ancillary Service Types

A Generation, Load and Storage Resource can provide any Ancillary Service type, if it is qualified. In Real-Time Market framework, the Ancillary Service Types are::

* 1. Regulation Up
  2. Regulation Down
  3. Responsive Reserve
  4. Non-Spin

1. Ancillary Service Plan

The Ancillary Service plan in 15-minute Real Time Market is the same as (or more than) the Ancillary Service plan in DAM. In the Real-Time Market, the Ancillary Service plan is specified on hourly bases for each Ancillary Service region and for each Ancillary Service type. Both maximal and minimal Ancillary Service requirements can be specified for each Ancillary Service region and each Ancillary Service type. For ERCOT system wide Ancillary Service region only the minimal Ancillary Service requirement can be enforced. The 15-minute Ancillary Service prices (i.e. MCPCs) will be determined for each Ancillary Service type and each Ancillary Service region over the study period.

Currently, this White Paper does not consider Ancillary Self-Arranged for Real-Time. If this is to be considered, further discussions are necessary on how AS self arrangement for Real-Time AS and Energy Co-optimization.

The RRS and Non-Spin are procured by Real-Time Commitment application and deployed by Real-Time Dispatch application according to deployment procedures, i.e. the Ancillary Service plans will be fully respected by Real-Time Commitment application without reduction for deployed amounts. The deployment of Regulation Service by LFC will be ignored by Real-time Commitment application as well, i.e. the Regulation Up and Regulation Down will be always procured to satisfy Regulation Service plan.

The Market Operator can modify Ancillary Service plan to cover outages and address current operating conditions.

1. Ancillary Service Regions

The determination and re-configuration of Ancillary Service regions is based on studies of Ancillary Service deliverability. The Deliverability Evaluation Function (DEF) will be updated to support these studies.

The number of Ancillary Service regions is determined by grouping Resources of similar impact on binding transmission constraints. In this sense, the Ancillary Service regions represent transmission congestion areas. The methodology for determination and re-configuration of Ancillary Service regions is subject to approval.

The minimal and maximal Ancillary Service requirement for an Ancillary Service region is determined by analysis of Resource outages within Ancillary Service region and import capacities for the Ancillary Service region. This analysis should determine the amount of Ancillary Services that must be procured within each Ancillary Service region.

The business process for Ancillary Service deployment is subject to approval.

1. Ancillary Service Substitution

The higher quality Ancillary Service can be procured above its Ancillary Service plan and be a substitute for lower quality Ancillary Services, if it is economical. The Regulation Up can substitute for RRS and Non-Spin, and RRS can substitute for Non-Spin. As Non-Spin requires a 30 minute lead time, the substitution rules in procuring Non-Spin will need further discussions.

Criteria to be developed on how substituted Ancillary Services awards are identified and communicated to QSEs.

The Ancillary Service substitution guaranties cascading of Ancillary Service prices, i.e. higher quality Ancillary Service will always have higher MCPC than lower quality Ancillary Service.

1. Ancillary Service Scarcity

The shortage in Ancillary Service procurement in respect to Ancillary Service plan will be penalized by scarcity price curve. The scarcity price curve will be developed for each Ancillary Service type and each Ancillary Service region to reflect relative priorities of Ancillary Service types. The Ancillary Service scarcity price curves are step-wise with up to ten segments, The methodology for Ancillary Service scarcity curve specification is subject to approval.

### Transmission Constraints

The transmission constraints are developed by network operation studies outside of the Real-Time Market framework. The current network topology and State Estimator solution is used for the current 15-minute time interval. The transmission and generation outages are considered for subsequent 15-minute time intervals until the end of the study period.

The main objective of network operation studies is selection of potentially binding constraints for base case, contingencies and generic constraints to be considered by Real-Time Commitment. The shadow prices for all binding transmission constraints will be reflected in LMPs.

The maximal shadow prices will be applied to penalize transmission constraint violations.

### Market Power Mitigation

The Generation Resource offers are mitigated using the existing market power mitigation measures. The Load Resource offers are mitigated in opposite direction setting offer prices at higher of reference LMPs or price floor for Load Resources to guaranty non-negative net profit. The Storage Resource offers and demand response price curves for Aggregated Retail Resources are not mitigated.

The MIP and QP Phases are executed two times in each run of the Real-Time Commitment application. In the first run, the Real-Time Commitment application considers Competitive Constraints only and determines the reference LMPs for all 15-minute time intervals. The offers are mitigated for every 15-minute time interval using the existing methodology for market power mitigation. In the second run, the Real-Time Commitment application considers mitigated offers and all transmission constraints. The calculated Base Points and constraint shadow prices represent the final 15-minute outcomes of the Real-Time Commitment application.

### Resource Multi-Interval Constraints

Any Generation, Load and Storage Resource can submit multi-interval block offers for both Energy and Ancillary Services. The fixed offers will be awarded in all block time intervals, or in none. The variable offers will be awarded at the same MW level in all block time intervals.

The multi-interval block awards are binding if they cannot be re-optimized in subsequent runs of the Real-Time Commitment application.

### Resource Inter-Temporal Constraints

The inter-temporal constraints for Generation, Load and Storage Resources are enforced as firm constraints. The Commitment Instructions are binding if they cannot be re-optimized due to inter-temporal constraints in subsequent runs of Real-Time Commitment.

The following inter-temporal constraints are considered:

1. Generation Resources

The inter-temporal parameters for Generation Resources are submitted in the existing formats:

1. Notification time
2. Minimum/maximum online time
3. Minimum offline time
4. Maximum number of starts within study period
5. SGR commitment constraints
6. CC transition constraints.

The maximal number of starts depends on the length of study period. It will be assumed that a Resource cannot start more than once within one o’clock hour time period. The other inter-temporal constraints will determine the optimal Resource cycling.

The inter-temporal dependencies for a Generation Resource are illustrated on the following diagram:

*00:30 00:45* ***01:00*** *01:15 01:30 01:45* ***02:00***  *02;15 02:30 02:45* ***03:00*** *03:15 03:30 03:45* ***04:00***  *04:15*

*Released for Dispatch*

*Min/Max Online Time*

*Shutdown Time*

*Commitment Instruction*

*Notification Time*

*Min Offline Time*

*Released for Dispatch*

Figure 8: Generation Resource Inter-Temporal Constraints

1. Load Resources

The inter-temporal parameters for Demand Resources are submitted symmetrically to the Generation Resources:

1. Notification time
2. Minimum/maximum interruption time, i.e. time when Load Resource is “online”
3. Minimum not-interruption time, i.e. time when Load Resource is “offline”
4. Maximum number of interruptions within study period, i.e. number of Load Resource “starts”

The inter-temporal characteristics of a Load Resource are illustrated on the following diagram:

*00:30 00:45* ***01:00*** *01:15 01:30 01:45* ***02:00***  *02;15 02:30 02:45* ***03:00*** *03:15 03:30 03:45* ***04:00***  *04:15*

*Released for Dispatch*

*Min/Max Interruption Time*

*Restoration Time*

*Curtailment Instruction*

*Notification Time*

*Min*

*Non-Interruption Time*

*Released for Dispatch*

*Shutdown Time*

Figure 9: Load Resource Inter-Temporal Constraints

1. Storage Resources

The following inter-temporal parameters for multi-state Storage Resources should be submitted to represent operational characteristics of multi-state Storage Resources:

1. Notification time
2. Transition time to/from charging/discharging operating mode
3. Minimum/maximum charging/discharging time
4. Minimum offline time
5. Maximum number of transitions within study period.

The inter-temporal characteristics for a three-state Storage Resource are illustrated on the following diagram:

*00:45* ***01:00*** *01:15 01:30 01:45* ***02:00***  *02;15 02:30 02:45* ***03:00*** *03:15 03:30 03:45* ***04:00***

*Released for Discharging*

*Min/Max Discharging Time*

*Transition Time*

*Transition Instruction*

*Notification Time*

*Min*

*Down Time*

*Transition Time*

*Released for Charging*

*Min/Max Charging Time*

Figure 10: Three-State Storage Resource Inter-Temporal Constraints

Additionally, the Storage Resources must maintain appropriate stored energy level to be able to perform charging and discharging over the study period. The inefficiencies of energy storing, charging and discharging should be accounted in that process. Also, the sufficient amount of stored energy must be maintained to be able to perform awarded Ancillary Services. These operating characteristics are unique to the Storage Resources.

### Resource Ramping Limits

1. Symmetrical Ramping

The symmetrical ramping across 15-minute time intervals is deployed for Generation, Demand and Storage Resources. The ramping time is configurable with default value of 10 minutes (i.e. 5 minute before and 5 minute after 15-minute interval boundaries). The 10-minute ramping time (shorter than 15-minute time interval) is selected to commit and schedule Resources to meet 15-minute Load Forecast considering reduced ramping capabilities. The remaining Resource ramping capabilities will be available to Real-Time Dispatch to cover volatility of 5-minute Load Forecast, startup and shut down disturbances, contingency events, WGR variability, etc. Otherwise, the Real-Time Commitment application will optimize Resources so efficiently that there is no any ramping flexibility for Real-Time Dispatch application to address any variation of system load and Resource behavior. The 15-minute symmetrical ramping for Real-Time Commitment is illustrated on the following diagram:

*MW*

*BP0*

*BP1*

*BP2*

*BP3*

*BP4*

*BP5*

*BP6*

*BP7*

*00:45* ***01:00*** *01:15 01:30 01:45* ***02:00***  *02;15 02:30 02:45* ***03:00*** *03:15*

*RTC Execution*

*Telemetry MW*

*Study Period*

Figure 11: Resource Symmetrical 10-Minute Ramping

1. Ramp Rate Functions

The Resource ramping capabilities are specified in the form of step-wise ramp rate functions that are illustrated on the following diagram:

**

*0*

*MW12*

*HSL*

*MW*

**

**

**

**

**

**

**

**

**

*LSL*

*MW2*

Figure 12: Upward and Downward Ramp Rate Functions

Each segment of ramp rate function represents the maximal ramp rate value in MW/min if Resource power output is in that MW range. The dashed segments between 0 MW and LSL represent ramping rates during startup and shutdown processes. Both upward and downward ramp rate functions are specified at the same MW break points.

1. Dynamic Ramping Limits

The maximal ramp rate is changing whenever Resource is passing from one segment to another. Therefore, the ramping limits are determined by ramping time and the change of Resource power output. For example, for Resource ramp rate function presented on the following diagram:

*0*

*130*

*HSL=220*

*MW*

*5*

*10*

*4*

**

**

*6*

*10*

*5*

*LSL=100*

*180*

The Resource 10-minute ramping limits will be as follows:

*80*

*LSL=100*

*105*

*205*

*0*

*130*

*HSL=220*

*MW*

**

**

*60*

*180*

*70*

*75*

*70*

*40*

*75*

If the Resource starts to ramp upward from LSL then it will ramp 6 minutes with speed of 5 MW/min to get into MW break point 130. The remaining 4 minutes the Resource will ramp up 40 MW with speed of 10 MW/min. Within 10 minutes, the total ramping from LSL is 70 MW. Note if the Resource starts ramping from 105 MW then it may increase its power output up to 180 MW, i.e. the total ramping is 75 MW. This MW point of 105 MW is becoming a new break point for ramping upward limit function. At the end, the Resource may get at the HSL in 10 minutes if it starts ramping up from 180 MW power output. The last segment keeps Resource power output at HSL.

In the other direction, if Resource starts to ramp downward from HSL then it will ramp 40 MW in 8 minutes with speed of 5 MW/min. The remaining 2 minutes the Resource will ramp 20 MW with speed of 10 MW/min. The total ramping from HSL is 60 MW. If the Resource starts ramping down from 205 MW then it may decrease its power output to 130 MW, i.e. the total ramping is 75 MW. This MW point of 205 MW is becoming a new break point for downward ramping limit function. At the end, the Resource may get at the LSL in 10 minutes if it starts ramping down from 180 MW power output. The last segment keeps Resource power output at LSL.

If ramp rate functions are step-wise then the dynamic ramping limits are general form piece-wise linear functions of Resource power output. Note that upward and downward ramping limits can have different MW break points even if the ramp rate functions have the same MW break points.

### Resource Initial Conditions

For the first 15-minute time interval the Resource Commitment Instructions and Base Points and Ancillary Service awards are already determined by the last run of Real-Time Commitment application. Also, the telemetry of Resource operating status and power output is available and assumed that telemetered Resource status will not be changed during the first 15-minute time interval.

The Resource Base Point for the first 15-minute time interval is validated against telemetry of Resource power output and telemetered ramp rates, and used as the initial condition to optimize Resource commitments and Energy and Ancillary Service awards over the study period. Using notation illustrated on the following figure, the Resource initial Base Point is determined as follows:

*BPinit = Max{TelemetryMW- TelemetryRampRateDn \* ½ \* RampingTime;*

*Min{BP0; TelemetryMW + TelemetryRampRateUp \* ½ \* RampingTime}}.*

If Resource Base Point for the first 15-minute time interval (*BP0),* calculated in the last run of Real-Time Commitment application, is within ramping range in respect to the telemetry of the Resource power output than that Base Point is used as the initial Resource power output to optimize Base Points for subsequent 15-minute time intervals. If Resource binding Base Point *BP0* is outside ramping range than the closest boundary point of ramping range is used as the initial Resource power output.

The initial Resource 15-minute Base Point setting is illustrated on the following figure where ramping time is 10 minutes:

*MW*

***Initial Base Point***

*BP0*

*Telemetry MW*

*BP1*

*BP2*

*15-Minute Time Interval*

*Ramping Range*

*RTC Execution*

*00:55* ***01:00*** *01:05 01:10* ***01:15*** *01:20 01:25* ***01:30*** *01:35 01:40* ***01:45***

Figure 13: Resource Initial 15-Minute Base Point

If a Resource is in startup mode then its power output telemetry will be between zero MW and LSL. It will be assumed that Resource will ramp full time (i.e.15 minutes) at telemetered upward ramp rate (or segment of upward ramp rate function between zero MW and LSL) at maximal speed from telemetry power output to LSL. It may take several time intervals to achieve the LSL. When the LSL is achieved it is becoming the initial Base Point for the rest part of the study period.

On the other way, if a Resource is in shutdown mode then its power output telemetry will be between LSL and zero MW. It will be assumed that Resource will ramp full time (i.e.15 minutes) at telemetered downward ramp rate (or segment of downward ramp rate function between zero MW and LSL) at maximal speed from telemetry power output to zero MW. It may take several time intervals to achieve the zero MW (i.e. breaker open). When the breaker is open the Base Point is equal to zero MW for the rest part of the study period (until next startup).

The initial Resource commitment status is determined by historical commitment data and Resource minimum run and down times. At the end of study period, the final Resource commitment status is equal to the COP Resource status.

### Ancillary Service Ramping Limits

The Ancillary Service awards are constrained by Resource ramping limits. For Regulation and Non-Spin reserves the normal ramp rates are used while for RRS the emergency ramp rates are used. Within 15-minute Real-Time Market the Energy and all Ancillary Services fully share Resource ramping capabilities.

### Resource Capacity Limits

The Generation and Demand Resource capacity between LSL and HSL can be used for Energy or any type of Ancillary Service (if qualified). The same applies for both charging (LPC; MPC) and discharging (LSL; HSL) ranges of Storage Resources.

Only inclusive Energy and Ancillary Service offers are considered in the Real-Time Market. The total Energy and Ancillary Service awards cannot exceed available Resource capacity.

For Aggregated Retail Resources, the first and the last point of responsive demand price curve are treated as Resource capacity limits.

## 15-Minute Real-Time Pricing

### 15-Minute Pricing Setting

The QP Phase of Real-Time Commitment that performs multi-interval optimization of mitigated energy offers represents the pricing run for 15-minute Real-Time Market. If Ancillary Service requirements are not feasible for any region and scarcity price curves are not considered then the Ancillary Service requirements are relaxed and the QP phase of Real-Time Commitment re-executed to calculate 15-minute Real-Time Market prices.

### 15-Minute Energy Prices

The 15-minute LMPs are calculated in standard way. The power balance penalties as well as transmission constraint maximal shadow prices are incorporated into LMPs**. These LMPs are for advisory purposes only.**

### Ancillary Service Prices

The MCPCs are calculated for every region and every Ancillary Service type for every 15-minute time interval of the study period. The Ancillary Service substitution as well as the Ancillary Service scarcity prices is reflected in MCPCs. **The MCPCs for binding Ancillary Service awards are used for settlement purposes, while MCPCs for remaining Ancillary Service awards are advisory.**

### Make Whole Payments

The issued 15-minute Commitment Instructions are binding. The committed Resources are eligible for Make-Whole Payments. The Make-Whole Payment is calculated for the Operating Day using the existing methodology and considering all Resource benefits based on Real-Time 5-minute LMPs and 15-minute MCPCs.

## 15-Minute Real-Time Outputs

### Commitment Instructions

The 15-minute Commitment Instructions are issued as binding decisions if they cannot be re-optimized in subsequent runs of Real-Time Commitment application. The Resource notification, startup and transition times, inter-temporal constraints and offer availability are considered. The issued Commitment Instructions are eligible for Make-Whole Payments.

Any issued Commitment Instruction and binding Ancillary Service awards that are going beyond the first 15-minute time interval are respected by subsequent runs of the Real-Time Commitment application.

### Awards and Prices

**All 15-minute energy awards and correspondent LMPs are for advisory purposes only.** The energy offers are considered to co-optimize Energy and Ancillary Service.

**The Ancillary Service awards are binding if they cannot be re-optimized in subsequent runs of Real-Time Commitment. The 15-minute MCPCs for binding Ancillary Service awards are used for Settlement and Billing purposes. The remaining Ancillary Service awards and MCPCs are advisory. Note that the binding interval time frame for Non-Spin would be different from binding RegUp, RegDown and RRS.**

### Results Publishing

Both binding and advisory, i.e. all results of 15-minute Real-Time Market are published after every run of Real-Time Commitment application. This includes binding and advisory Commitment Instructions, advisory energy 15-minute awards and LMPs and Ancillary Service 15-minute awards and MCPCs.

# 5-Minute Real-Time Market Operation

## 5-Minute Real-Time Market Timeline

Hourly market data submitted to the Real-Time Market are used for both 15-minute and 5-minute Real-Time Market clearing and pricing. The 5-minute Real-Time Market clearing and pricing is performed every five minutes considering one hour study period with o’clock 5-minute time intervals. The length of the study period depends on availability of submitted market data as it is illustrated on the following diagram:

*00:55* ***01:00*** *01:05 01:10 01:15 01:20 01;25 01:30 01:35 01:40 01:45 01:50 01:55* ***02:00*** *02:05*

*Submission*

*Closing*

*Study Period*

*RTD Executions*

Figure 14: Real-Time Market 5-Minute Timeline

The Real-Time Dispatch application is executed periodically at the middle of o’clock 5-minute intervals, i.e. at 52.5”, 57.5”, 2.5”, 7.5”, etc. and must be completed within five minutes. For the first next 5-minute time interval after execution starts, the Resource Base Points are already issued in previous run of the Real-Time Dispatch application. The Base Points for subsequent twelve 5-minute time intervals will be optimized.

## 5-Minute Load Forecasting

The 5-minute system Load Forecast is provided for the next two hours, i.e. for the next twenty four 5-minute time intervals. Two-hour forecasting time period is needed to provide 15-minute system Load Forecast.

The 5-minute Load Forecast is updated every five minutes to adjust to the current operating conditions. The Market Operator can bias the 5-minute Load Forecast manually to account for unpredictable upcoming events.

The 5-minute system Load Forecast for the first hour that is considered by the Real-Time Dispatch adjusted is adjusted for price sensitive responses of Load Resources (Demand and Aggregated Retail Resources). The dispatches of Load Resources (Demand Resources and Aggregated Retail Resources) from the last run of the Real-Time Dispatch application are used as expected projections of 5-minute load responses over the study period. The last 5-minute time interval is replicated.

## Real-Time Dispatch

### Optimization Framework

The Real-Time Dispatch (RTD) application solves energy dispatch problem over twelve 5-minute intervals respecting COP statuses and Resource Commitment Instructions from Real-Time Commitment (RTC) application. The Real-Time Dispatch application considers both discrete decisions and continuous variables. The Real-Time Dispatch, like Real-Time Commitment, consists of MIP phase and QP phase followed with pricing run as the third phase, as follows:

1. The MIP Phase that solves the Mixed Integer Programming (MIP) problem with piecewise linear objective function subject to system power balance, transmission constraints and multi-interval constraints respecting Resource capacities, ramping capabilities and operating limits. The outcome of the MIP Phase is the optimal solution for binary variables, i.e. the optimal discrete decisions over the study period. The MIP hot start feature is utilized in every MIP Phase execution.
2. The QP Phase that solves Quadratic Programming (QP) problem with piecewise quadratic objective function subject to system power balance, transmission constraints and multi-interval constraints respecting Resource capacities, ramping capabilities and operating limits. The values of binary variables are fixed at the optimal solution of the MIP Phase. The outcome of QP Phase is the optimal values of energy awards, i.e. optimal Resource Base Points.
3. The Pricing Phase is proposed to better handle inconsistencies between Resource LMPs and Resource Base Points from the QP Phase.

All three phases are executed two times in every run of the Real-Time Dispatch application to perform Step1 and Step2 of market power mitigation process.

**The published (binding and advisory) Base Points are from the multi-interval QP Phase and the published (binding and advisory) LMPs are from the Pricing Phase.**

In the Real-Time Dispatch application the awarded Ancillary Services are not available for energy dispatch unless they are deployed. The deployed ancillary Services can be protected by Price Adders or Price Floors applied to Ancillary Service segments within Energy Offer Curves. These penalties reflect policy and priority order of Ancillary Service deployment.

The penalty functions for system over and under generation and maximal shadow prices for transmission constraint violations are represented explicitly in the optimization objective.

### Transmission Constraints

The transmission constraints are determined in network operation studies outside the Real-Time Market framework. The constraints used by 15-minute Real-Time Unit Commitment application are considered by Real-Time Dispatch application as well in addition to constraints that are eventually developed to address current network operating conditions. The Market Operator can add or deselect constraints to be considered by Real-Time Dispatch application.

The current network topology and State Estimator solution are used for the first 5-minute time interval. The transmission and generation outages are considered for subsequent 5-minute time intervals till the end of the study period. The Real-Time Dispatch application considers potentially binding or overloaded constraints for base case, contingencies and generic constraints. Shadow prices of all binding transmission constraints are reflected in LMPs. The maximal shadow prices are applied to penalize transmission constraint violations.

### Market Power Mitigation

The Generation Resource offers are mitigated using the existing market power mitigation measures. The Load Resource offers are mitigated in opposite direction setting offer prices at higher of reference LMPs or price floor for Demand Resources that guaranties non-negative net profit. The Storage Resource offers are not mitigated.

The MIP and QP Phases are executed two times in each run of the Real-Time Dispatch application. The first run of Real-Time Dispatch application represents the Step1 of market power mitigation procedure that considers only Competitive Constraints and determines the reference LMPs for all 5-minute time intervals within the study period.

The Energy Offer Curves are mitigated for every 5-minute time interval using the existing methodology for market power mitigation.

The second run of Real-Time Dispatch application represents the Step2 of market power mitigation procedure that considers the mitigated Energy Offer Curves, and all transmission constraints. The calculated Resource Base Points and constraint shadow prices represent the final 5-minute outcomes of the Real-Time Dispatch application.

### Resource Ramping Limits

1. Symmetrical Ramping

The symmetrical ramping across 5-minute time intervals is deployed. The ramping time is configurable with default value of 5 minutes (i.e. 2.5 minutes before and 2.5 minutes after 5-minute interval boundaries). The full 5-minute ramping time allows Real-Time Dispatch application to fully utilize Resource ramping capabilities. The 5-minute symmetrical ramping for Real-Time Dispatch is illustrated on the following diagram for the Real-Time Dispatch execution at 57.5”:

*MW*

*BP11*

*BP12*

*BP10*

*BP8*

*BP0*

*BP1*

*BP2*

*BP3*

*BP4*

*BP5*

*BP6*

*BP7*

*Telemetry MW*

*BP9*

*Study Period*

*RTD Execution*

*00:55* ***01:00***  *01:05 01:10 01:15 01:20 01;25 01:30 01:35 01:40 01:45 01:50 01:55* ***02:00*** *02:05*

Figure 15**: Resource Symmetrical 5-Minute Ramping**

1. Ramp Rate Functions

The Resource ramping capabilities are specified in the form of step-wise ramp rate functions as it is illustrated on the following diagram:

**

*0*

*MW12*

*HSL*

*MW*

**

**

**

**

**

**

**

**

**

*LSL*

*MW2*

Figure 16: Upward and Downward Ramp Rate Functions

Each segment of ramp rate function represents the maximal ramp rate value in MW/min if Resource power output is within that MW range. The dashed segments between 0 MW and LSL represent Resource ramping rates during startup and shutdown processes. Upward and downward ramp rate functions are specified at the same MW break points.

1. Dynamic Ramping Limits

The maximal ramp rate is changing whenever Resource is passing from one segment to another. Therefore, the ramping limits are determined by ramping time and the change of Resource power output. For example, for Resource ramp rate function presented on the following diagram:

*0*

*130*

*HSL=220*

*MW*

*5*

*10*

*4*

**

**

*6*

*10*

*5*

*LSL=100*

*180*

The Resource 5-minute ramping limits will be as follows:

*180 200 205*

*50*

*LSL=100*

*105*

*0*

*130*

*HSL=220*

*MW*

**

**

*25*

*50*

*20*

*25*

*30*

If the Resource starts to ramp upward from LSL then it will ramp 5 minutes with speed of 5 MW/min to get at power output 125 MW, i.e. the Resource can ramp up 25 MW. This ramping limit will stay until Resource gets into break point 130 MW, i.e. between 100 and 105 MW power output. From 130 MW the Resource will ramp 5 minutes with speed of 10 MW/min, i.e. the ramping limit is 50 MW. At the end, the Resource may get at the HSL in 5 minutes if it starts ramping up from 200 MW power output. The last segment keeps Resource power output at HSL.

In the other direction, if the Resource starts to ramp downward from HSL then it will ramp 25 MW in 5 minutes with speed of 5 MW/min. The same ramping limit will stay until Resource power output gets at 180 MW, i.e. if the Resource starts ramping down from 205 MW. If Resource starts ramping from 180 MW then it may decrease its power output down to 130 MW, i.e. the total ramping down is 50 MW. At the end, the Resource may get at the LSL in 5 minutes if it starts ramping down from 130 MW power output. The last segment keeps Resource power output at LSL.

If ramp rate functions are step-wise then the dynamic ramping limits are general form piece-wise linear functions of Resource power output. Note that upward and downward ramping limits have different MW break points.

### Resource Ramp Sharing

For Resources performing the Regulation Ancillary Service a flexible ramp sharing between Real-Time Dispatch and LFC is used, i.e. a portion of Resource ramping capability reserved for Regulation capacity will be available for Real-Time Dispatch application to change Resource Base Points. The changes of Base Points of regulating Resource will be limited by this fraction of its ramping rate. The form of ramp rate function will remain the same just a fraction of ramp rate values will be used. The sharing parameter is configurable and it has the same value for all Resources.

### Resource Initial Conditions

The Resource power output telemetry is used as initial power output at the moment of execution of the Real-Time Dispatch application. Already issued Resource Base Point for the first next 5-minute time interval is validated against Resource power output telemetry and telemetered ramping rates. Eventual inconsistency of this Base Point is corrected as follows:

*BPinit = Max{TelemetryMW- TelemetryRampRateDn \* RampingTime;*

*Min{BP0; TelemetryMW + TelemetryRampRateUp \*RampingTime}}.*

If Resource Base Point *BP0* for the first 5-minute time interval*,* calculated in the last run of the Real-Time Dispatch application, is within ramping range in respect to the Resource telemetry power output than that Base Point is used as Resource initial power output to optimize Base Points for subsequent 5-minute time intervals. If Resource binding Base Point *BP0* is outside ramping range than the closets boundary point of the ramping range is used as Resource initial power output. This setting of Resource initial Base Point is based on assumption that Resources has incentive to follow binding Base Point as close as possible.

The Resource initial 5-minute Base Point setting is illustrated on the following figure where ramping time is 5 minutes:

*MW*

***Initial Base Point***

*BP0*

*BP2*

*BP1*

*Telemetry MW*

*5-Minute Time Interval*

*Ramping Range*

*RTD Execution*

*00:57.5* ***01:00*** *01:02.5* ***01:05***  *01:07.5* ***01:10*** *01:12.5* ***01:15***

Figure 17: Resource Initial 5-Minute Base Point

If a Resource is in startup mode then its power output telemetry will be between zero MW and LSL. It will be assumed that Resource will ramp full time (i.e. 5 minutes) at telemetered upward ramp rate (or segment of upward ramp rate function between zero MW and LSL) at maximal speed from telemetry power output to LSL. It may take several time intervals to achieve the LSL. When the LSL is achieved it is becoming the initial Base Point for the rest part of the study period.

On the other way, if a Resource is in shutdown mode then its power output telemetry will be between LSL and zero MW. It will be assumed that Resource will ramp full time (i.e.5 minutes) at telemetered downward ramp rate (or segment of downward ramp rate function between zero MW and LSL) at maximal speed from telemetry power output to zero MW. It may take several time intervals to achieve the zero MW (i.e. breaker open). When the breaker is open the Base Point is equal to zero MW for the rest part of the study period (until next startup).

### Resource Multi-Interval Constraints

Any Generation, Load and Storage Resource can submit multi-interval block energy offers. The Real-Time dispatch application considers only variable multi-interval block offers. These offers will be awarded at the same MW level at all block time intervals.

The multi-interval block awards are binding if they cannot be re-optimized in subsequent runs of Real-Time Dispatch application.

### Resource Dispatch Limits

For Generation and Load Resources the operating limits LSL and HSL (or LPC and MPC) will be considered. The same applies for both charging (LPC; MPC) and discharging (LSL; HSL) ranges of Storage Resources.

The Ancillary Service awarded capacities will not be available for dispatch until they are deployed, i.e. they will be protected by Low and High Ancillary Service Limits (LASL and HASL). The ramping limits are modeled explicitly, i.e. they will not be incorporated into dispatch limits LDL and HDL.

For Aggregated Retail Resources, the LPC and MPC are treated as Resource dispatch limits.

## 5-Minute Real-Time Pricing

### 5-Minute Pricing Setting

The Real-Time Dispatch considers system operating conditions in future time intervals (load forecast, expected WGR generation, unit trips, transmission outages, etc.). The LMPs and Base Points from the multi-interval QP Phase that optimizes dispatch can sometimes lead to inconsistencies between Resource LMPs and Resource Base Points. The objective of pricing Phase component of RTD is to better handle these inconsistencies by running a single interval SCED for each of the intervals converting Resource ramping constraints into Resource dispatch limits thus eliminating impacts from previous and future intervals on a given interval shadow prices (power balance constraint and transmission constraint).

The Base Points and LMPs calculated by the QP phase of the multi-interval dispatch optimization can lead to the following conditions:

1. Resource Ramp Up constraint binding.
   1. Resource LMP for a given Base Point is **sometimes** less than the corresponding point on the Resource Energy Offer Curve (EOC). This condition happens when forecasted conditions in future intervals require changes in dispatch in prior intervals (e.g. need to dispatch Resources higher to catch a sharp increase in load in the future).
   2. In this case, the Resource is being instructed to a Base Point above the economic level.
   3. Note in current SCED if the Ramp Up constraint is binding i.e. dispatched at HDL, the LMP is always greater than or equal to the corresponding point on the EOC.
2. Resource Ramp Down constraint binding.
   1. Resource LMP for a given Base Point is **sometimes** greater than the corresponding point on the Resource Energy Offer Curve (EOC). This condition happens when forecasted conditions in future intervals require changes in dispatch in prior intervals (e.g. need to dispatch Resources down to catch a sharp decrease in load in the future).
   2. In this case, the Resource is being instructed to a Base Point below the economic level.
   3. Note in current SCED if the Ramp Down constraint is binding i.e. dispatched at LDL, the LMP is always less than or equal to the corresponding point on the EOC.
3. Advisory/Indicative LMPs calculated by the QP phase of the multi-interval dispatch optimization for future intervals **may be different** for a give time interval with respect to subsequent runs of RTD. This is because different RTD runs will be optimizing across a different set of intervals (rolling window).

In the Pricing Phase, LMPs will be calculated for all Resource Nodes, Load Zones and Hubs using the same current methodology. The LMPs from the first binding 5-minute interval are used to calculate Real-Time 15-minute Settlement Point Prices for all Settlement Points.

Further discussions of the 5-minute Pricing Phase will be required before finalization.

Given below are two possible options. **Please note that ramping make-whole payment will be required in all options.**

**Also note that Published (binding and advisory) Base Points will be from the QP phase whereas the Published LMP (binding and advisory) will be from the Pricing Phase.**

#### Option 1: 5-Minute Pricing Setting

The Resource ramping constraints are converted into Resource Low and High Dispatch limits (LDL and HDL) for each 5-minute interval (binding and advisory intervals) using Resource ramping limits for its optimal Base Point at previous 5-minute time interval, i.e.:

*LDLt+1 = RampingLimitdown(BasePoint t )*

*HDLt+1 = RampingLimit up(BasePoint t ).*

For the first time interval the telemetered Resource power output and telemetered ramp rates are used. i.e. for the binding first 5-minute interval the Resource LMPs will be the same as LMPs calculated by the current single interval SCED (both will use telemetered Resource MW). However, the issued Base Points **may** be different.

#### Option 2: 5-Minute Pricing Setting

The Resource ramping constraints are converted into Resource Low and High Dispatch limits (LDL and HDL) for each 5-minute interval (binding and advisory intervals) using the following rules:

1. If LMP < Offer Price at Base Point then set LDL= Base Point and HDL = Ramping Up Limit at Base Point
2. If LMP = Offer Price at Base Point then set LDL = Ramping Down Limit at Base Point and HDL = Ramping Up Limit at Base Point
3. If LMP > Offer Price at Base Point then set LDL = Ramping Down Limit at Base Point and HDL = Base Point.

For the first time interval the telemetered Resource power output and telemetered ramp rates are used

### Power Balance Penalty Functions

The system power balance, i.e. system over or under generation in respect to 5-minute system Load Forecast are penalized according to established policy. The penalties have a form of step-wise function up to ten segments.

### Maximum Shadow Prices

The maximum shadow prices are applied to penalize transmission constraint violations in the existing way. The maximum shadow prices are reflected in LMPs.

## 5-Minute Real-Time Market Outputs

### 5-Minute Binding/Advisory Dispatch Instructions

The Base Points for the first 5-minute time interval are binding. Also, multi-interval block dispatches are binding if they cannot be re-dispatched by subsequent runs of the Real-Time Dispatch application. All other Dispatch Instructions are advisory.

### 5-Minute Binding/Advisory LMPs

The LMPs for the first 5-minute time interval are binding. All other LMPs are advisory.

The Real-Time Settlement Point Prices, calculated by using binding LMPs, are binding and the anticipated Real-Time Settlement Point Prices, calculated by using only advisory LMPs, are advisory.

### 5-Minute Results Publishing

The binding Base Points and LMPs are delivered to Market Participant as control actions through ICCP communication channels.

The advisory Base Points, LMPs and Real-Time SPPs are published through MIS system.

# Appendix A: Real-Time Commitment Mathematical Optimization Model

*Note: The following mathematical formulations are for functional specification purposes only, i.e. the formulations do not represent software design, development and implementation.*

1. **Optimization Objective**

The objective of the Real-Time Commitment is the minimization of the total energy and Ancillary Service offer costs for Generation Resources (GR), Demand Resources (DR) and Storage Resources (SR) minus the demand response bid costs for Aggregate Retail Resources (ARR) over the study period:



Where:

 is Base Point for Resource *t* at time interval *t*

 is startup variable for Resource *r* at time interval *t*

 is commitment status for Resource *r* at time interval *t*

 is Ancillary Service, i.e. Reg Up/Down, RRS and Non-Spin award for Resource *r* at time *t*

 is system over generation at time interval *t*

 is system under generation at time interval *t*

 is violation of transmission constraint *l* at time interval *t*

 is Ancillary Service under procurement at time interval *t*

 is Energy Offer Cost for Resource *r* at time interval *t*

 is Price Responsive Cost for Aggregated Retail Resource *r* at time interval *t*

 is Start Up Cost for hot, intermediate and cold state of Resource *r* at time *t*

 is Minimum Energy Cost for Resource *r* at time interval *t*

 is Ancillary Service Cost for Resource *r* at time interval *t*

 is penalty function for over generation

 is penalty function for under generation

 is maximal shadow price for transmission constraint *l*

 is scarcity penalty for Ancillary Service shortage

 is set of Generation, Demand and Storage Resources

 is set of Aggregate Retail Resources

 is set of transmission constraints

 is study period.

The penalty functions for system over/under generation and maximal shadow prices for transmission constraints are represented explicitly in the optimization objective. The scarcity prices for Ancillary Services are considered as penalties for Ancillary Service shortages.

1. **System Power Balance**

The main requirement for Real-Time Commitment is the system power balance, i.e. the sum of Resource Base Points must be equal to system load at each time interval:



Where:

 is Base Point for Resource *r* at time interval *t*

 is response projection of Resource *r* at time interval *t*

 is system over generation at time interval *t*

 is system under generation at time interval *t*

 is system 15-minute Load Forecast at time interval *t*

 is set of Generation, Demand and Storage Resources

 is set of Demand Resources

 is set of Aggregate Retail Resources

 is study period.

For Storage Resources the Base Points in discharging operating mode are positive and in charging operating mode negative.

The system 15-minute Load Forecast is adjusted to reflect price sensitive responses of Demand and Aggregate Retail Resources. The system over and under generation is considered as well.

1. **Ancillary Service Requirements**

The Ancillary Service plan for each Ancillary Service type and each Ancillary Service region is considered by the Real-Time Commitment application.

The Ancillary Service substitutes are expressed as separate variables:





Where:

 is awarded Regulation Up for Resource *r* at time interval *t*

 is part of awarded Regulation Up used as Regulation Up for Resource *r* at time *t*

 is part of awarded Regulation Up used as RRS for Resource *r* at time interval *t*

 is part of awarded Regulation Up used as Non-Spin for Resource *r* at time *t*

 is awarded RRS for Resource *r* at time interval *t*

 is part of awarded RRS used as RRS for Resource *r* at time interval *t*

 is part of awarded RRS used as Non-Spin for Resource *r* at time interval *t*

 is set of generation, Demand and Storage Resources

 is study period.

The awarded Regulation Up is used as Regulation Up, or as a substitute for RRS or Non-Spin. All these three portions of the Regulation Up Service will be awarded at Regulation Up offer price. Similarly, the awarded RRS will be used to meet the RRS plan or to substitute for Non-Spin at RRS offer price. The Regulation Down and Non-Spin are not used as substitutes, i.e. there is no need to break down awards.

Using above notation, the minimal and maximal Ancillary Service requirements with accommodated Ancillary Service substitution can be specified for each Ancillary Service region in the following form:







Where:

 is Regulation Down shortage for Ancillary Service region *reg* at time interval *t*

 is Regulation Up shortage for Ancillary Service region *reg* at time interval *t*

 is RRS shortage for Ancillary Service region *reg* at time interval *t*

 is Non-Spin shortage for Ancillary Service region *reg* at time interval *t*

 is minimal Regulation Down requirement for Ancillary Service region *reg* at time *t*

 is minimal Regulation Up requirement for Ancillary Service region *reg* at time interval *t*

 is minimal RRS requirement for Ancillary Service region *reg* at time interval *t*

 is minimal Non-Spin requirement for Ancillary Service region *reg* at time interval *t*

 is maximal Regulation Down requirement for Ancillary Service region *reg* at time *t*

 is maximal Regulation Up requirement for Ancillary Service region *reg* at time *t*

 is maximal RRS requirement for Ancillary Service region *reg* at time interval *t*

 is maximal Non-Spin requirement for Ancillary Service region *reg* at time interval *t*

 is set of Resources within Ancillary Service region *reg*

 is study period.

Since Non-Spin requires a 30 –minute lead time, the AS substitution for Non-Spin will require special consideration. In addition to Ancillary Service awards, the Ancillary Service shortages are considered as well. The Ancillary Service shortages are penalized by Ancillary Service scarcity prices in the optimization objective. The shadow prices for above Ancillary Service requirements represent Ancillary Service prices (i.e. MCPCs) for each Ancillary Service region and each 15-minute time interval.

1. **Transmission Constraints**

The Real-Time Commitment application considers a set of base case, contingency and generic transmission constraints. The transmission constraints are expressed in linearized form of line power flows for each time interval:



Where:

 is Base Point for Resource *r* at time interval *t*

 is violation of transmission constraint *l* at time interval *t*

 is Shift Factor for Resource *r* and transmission constraint *l*

 is maximal limit for transmission constraint *l*

 is set of Generation, Demand and Storage Resources

 is set of Aggregate Retail Resources

 is set of transmission constraints

 is study period.

1. **Resource Inter-Temporal Constraints**

The Resource minimum and maximum run time, the minimum down time and the maximal number of starts are enforced. Additionally, the initial Resource conditions and the final Resource state at the end of the study period are respected as well.

1. *Minimum Run Time*

The Resource minimum run time is enforced for each Resource as follows:



Where:

 is shutdown variable for Resource *r* at time interval *t*

 is startup variable for Resource *r* at time interval *t*

 is minimum run time for Resource *r.*

If a Resource *r* starts at time interval *t* then it cannot be shutdown in following  time intervals, i.e. it must stay online at least  time intervals.

1. *Maximum Run Time*

The Resource maximum run time constraint is enforced for each Resource as well:



Where:

 is shutdown variable for Resource *r* at time interval *t*

 is startup variable for Resource *r* at time interval *t*

 is maximum run time for Resource *r*

 is set of Generation, Demand and Storage Resources

 is study period.

If Resource *r* starts at time interval *t* then it must be shutdown at least once in following  time intervals, i.e. it cannot stay online longer than  time intervals.

1. *Minimum Down Time*

The minimum down time constraint can be specified as follows:



Where:

 is shutdown variable for Resource *r* at time interval *t*

 is startup variable for Resource *r* at time interval *t*

 is minimum down time for Resource *r*

 is set of Generation, Demand and Storage Resources

 is study period.

This constraint does not allow Resource to startup earlier than time intervals after its shut down.

1. *Maximum Number of Starts*

The Resource minimum number of starts within the study period is enforced for each Resource:



Where:

 is startup variable for Resource *r* at time interval *t*

 is maximum number of starts for Resource *r* within study period *T*

 is set of Generation, Demand and Storage Resources

 is study period.

The maximal number of starts depends on the length of the study period. It will be assumed that each Resource can start only once within one clock hour time period. Therefore, the maximal number of starts is equal to one for the end-hour run of Real-Time Unit Commitment application and equal to one or two in other runs. The other inter-temporal constraints will determine the actual Resource cycling.

1. **Multi-Interval Block Constraints**

The Energy and Ancillary Service offers can be submitted as multi interval blocks. The awards across whole block are the same, i.e.:



And:



Where:

 is Base Point for Resource *r* at time interval *t*

 is Ancillary Service, i.e. Reg Up/Down, RRS and Non-Spin award for Resource *r* at time *t*

 is multi interval block for Resource *r*

 is set of Generation, Demand and Storage Resources

 is study period.

1. **Storage Resource Constraints**
   * *Storage Capacity Limits*

The efficiency of charging, discharging and energy storing should be considered as well. The energy accumulation over the study period with 15-minute time intervals can be represented by the following constraint:



And the capacities of Storage Resources are limited:



Where:

 is charging power for Storage Resource *r* at time interval *t*

 is discharging power for Storage Resource *r* at time interval *t*

 is stored energy level for Storage Resource *r* at time *t*

 is maximal stored energy level for Storage Resource *r* at time *t*

 is length of time interval, i.e. 15 minutes

 is charging efficiency

is discharging efficiency

is storing efficiency

 is set of Storage Resources

 is study period.

The initial storage level is telemetered and the final storage level is within a pre-specified range around the initial level.

* + *Resource Power Limits*

The Base Point for the Storage Resource is equal to the difference between discharging and charging powers, i.e.:



Where:

 is Base Point for Storage Resource *r* at time interval *t*

 is charging power for Storage Resource *r* at time interval *t*

 is discharging power for Storage Resource *r* at time interval *t.*

The duration limited Storage Resource can use its full charging (LPC=0; MPC) and discharging (LSL=0;HSL) operating range for Energy and Ancillary Services, i.e.:



And:

.

* + *Resource Storage and Ancillary Service Limits*

The Storage Resource must have sufficient amount of stored energy to be dispatched properly and to be able to deliver Ancillary Services. For example, if a Storage Resource needs to deliver 0.5 MW of Regulation Up Service in a 15 minute time interval then the Storage Resource should be dispatched in the way that it always have reserved at least (0.5/4) MWh of stored energy. In general, the effective Base Points should be limited by stored energy level to be able to deliver Ancillary Services over certain period of time as it is expressed by the following relations:



And:

.

Where:

 is Base Point for Storage Resource *r* at time interval *t*

 is stored energy level for Storage Resource *r* at time interval *t*

 is maximal stored energy level for Storage Resource *r* at time interval *t*

 is length of time interval, i.e. ¼ hour

 is Regulation Service time domain

 is RRS time domain

 is Non-Spin time domain.

1. **Resource** **Ramping Limits**

The Resource ramp rates are step-wise functions of Resource power output. In general, a Resource can ramp over several segments within ramping time, i.e. the Resource ramping limits are piecewise linear functions of power output for given ramping time. In this case, the upward and downward Resource ramping limits can be specified as the following constraints:



Where:

 is downward ramping limit for Resource *r*

 is upward ramping limit for Resource *r*

 is Base Point for Resource *r* at time interval *t*

 is ramping time

 is set of Generation, Demand and Storage Resources

 is study period.

The Resource ramping limits represent general form of piecewise linear function. The segment selections represent discrete decisions that must be modeled by binary variables.

1. **Resource Operating Limits**

Each Resource is dispatched within its operating limits, i.e.:



Where:

 is Base Point for Resource *r* at time interval *t*

 is Low Sustainable Limit for Resource *r* at time interval *t*

 is High Sustainable Limit for Resource *r* at time interval *t*

 is set of Generation, Demand and Storage Resources

 is study period.

Note for Load Resources LSL and HSL are replaced with LPC and MPC.

# Appendix B: Real-Time Dispatch Mathematical Optimization Model

*Note: The following mathematical formulations are for functional specification purposes only, i.e. the formulations do not represent software design, development and implementation.*

1. **Optimization Objective**

The objective of the Real-Time Dispatch application is the minimization of the total energy offer costs over study period for online Generation Resources (GR), Demand Resources (DR) and Storage Resources (SR), minus the response costs for Aggregate Retail Resources (ARR):



Where:

 is Base Point for Resource *t* at time interval *t*

 is system over generation at time interval *t*

 is system under generation at time interval *t*

 is violation of transmission constraint *l* at time interval *t*

 is Energy Offer Cost for Resource *r* at time interval *t*

 is Price Responsive Costs for Aggregate Retail Resource *r* at time interval *t*

 is penalty function for over generation

 is penalty function for under generation

 is maximal shadow price for transmission constraint *l*

 is set of Generation, Demand and Storage Resources

 is set of Aggregate Retail Resources

 is set of transmission constraints

 is study period.

The penalty functions for system over/under generation and the maximal shadow prices for transmission constraints are represented explicitly in the optimization objective.

1. **System Power Balance**

For Storage Resources the Base Points in discharging operating mode are positive and in charging operating mode negative.

In addition to Resource Base points the system over and under generation is considered as well.

The main requirement for Real-Time Dispatch application is the system power balance, i.e. the sum of Resource Base Points must be equal to system load at each time interval:



Where:

 is Base Point for Resource *r* at time interval *t*

 is response projection of Resource *r* at time interval *t*

 is system over generation at time interval *t*

 is system under generation at time interval *t*

 is system 5-minute Load Forecast at time interval *t*

 is set of Generation, Demand and Storage Resources

 is set of Demand Resources

 is set of Aggregate Retail Resources

 is study period.

For Storage Resources the Base Points in discharging operating mode are positive and in charging operating mode negative.

The system 5-minute Load Forecast is adjusted to reflect price sensitive responses of Demand and Aggregate Retail Resources. The system over and under generation is considered as well.

1. **Transmission Constraints**

The Real-Time Dispatch application considers a set of base case, contingency and generic constraints. The transmission constraints are expressed in linearized form of line power flows for each time interval:



Where:

 is Base Point for Resource *r* at time interval *t*

 is violation of transmission constraint *l* at time interval *t*

 is Shift Factor for Resource *r* and transmission constraint *l*

 is maximal power flow for transmission constraint *l*

 is set of Generation, Demand and Storage Resources

 is set of Aggregate Retail Resources

 is set of transmission constraints

 is study period.

1. **Storage Resource Constraints**
   * *Storage Capacity Limits*

The efficiency of charging, discharging and energy storing should be considered as well. The energy accumulation over the study period with 5-minute time intervals can be represented by the following constraint:



And the capacities of Storage Resources are limited:



Where:

 is charging power for Storage Resource *r* at time interval *t*

 is discharging power for Storage Resource *r* at time interval *t*

 is stored energy level for Storage Resource *r* at time *t*

 is maximal stored energy level for Storage Resource *r* at time *t*

 is length of time interval, i.e. 5 minutes

 is charging efficiency

is discharging efficiency

is storing efficiency

 is set of Storage Resources

 is study period.

The initial storage level is telemetered and the final storage level is within a pre-specified range around the initial level.

* + *Resource Operating Limits*

The Base Point for the Storage Resource is equal to the difference between discharging and charging powers, i.e.:



Where:

 is Base Point for Storage Resource *r* at time interval *t*

 is charging power for Storage Resource *r* at time interval *t*

 is discharging power for Storage Resource *r* at time interval *t.*

For a Storage Resource the operating limits can be specified as follows:

 - for charging mode

 - for discharging mode.

The duration limited Storage Resource can be dispatched over its full charging (LPC=0; MPC) and discharging (LSL=0;HSL) operating ranges, i.e. the Resource operating limits are:



1. **Resource** **Ramping Limits**

The Resource ramp rates are step-wise functions of Resource power output. In general, a Resource can ramp over several segments within ramping time, i.e. the Resource ramping limits are piecewise linear functions of power output for given ramping time. In this case, the upward and downward Resource ramping limits can be specified as the following constraints:



Where:

 is downward ramping limit for Resource *r*

 is upward ramping limit for Resource *r*

 is Base Point for Resource *r* at time interval *t*

 is ramping time

 is set of Generation, Demand and Storage Resources

 is study period.

The Resource ramping limits represent general form of piecewise linear functions. The segment selections represent discrete decisions that must be modeled by binary variables.

1. **Multi-Interval Block Constraints**

The energy offers can be submitted as multi interval blocks. Only variable multi-interval block offers are considered by the Real-Time Dispatch application. In this case, the Base Points are the same across all block time intervals, i.e.:



Where:

 is Base Point for Resource *r* at time interval *t*

 is multi interval block for Resource *r*

 is set of Generation, Demand and Storage Resources

 is study period.

1. **Resource Dispatch Limits**

Each Resource is dispatched within its operating limits with excluded Ancillary Service awards, i.e.:



Where:

 is Base Point for Resource *r* at time interval *t*

 is Low Ancillary Service Limit for Resource *r* at time interval *t*

 is High Ancillary Service Limit for Resource *r* at time interval *t*

 is set of Generation, Demand and Storage Resources

 is study period.