~~UG-SD-025_SPD_Model_Formulation_v10~~UG-SD-025_SPD_Model_Formulation_v11

~~Model Formulation Version 10.0~~Model Formulation Version 11.0

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SYSTEM OPERATOR

~~System Operator~~System Operator

~~1/04/2016~~22/08/2016

Keeping the energy flowing

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NOTICE

Version	Date	Change
4.4	24 June 2010	To model new CVP values for 1 May 2010 Rule Changes
5.0	24 November 2011	Major update associated with the decommissioning of pole1 and the commissioning of pole3 and removal of appendix1
6.0	21 May 2012	Update associated with implementing new PRSS, PRSL,NRSS,NRSL schedules
7.0	11 July 2012	Update associated with implementing HVDC Secondary Risk and Frequency Keeping Band into Risk
8.0	18 April 2013	Update associated with implementing the Electricity Industry Participation (Scarcity Pricing) Code Amendment 2011.
9.0	10 April 2014	Update associated with implementing Dispatchable Demand project.
10.0	1 April 2016	Update associated mainly with correction of reserve price definition and generation ramp model.
11.0	22 August 2016	Update associated with implementing National Market for Instantaneous Reserves and risk groups.

	Position	Date
Prepared By:	System OperatorSystem Operator	
Reviewed By:		

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1 Introduction

This document is a mathematical description of Transpower's "Scheduling, Pricing, and Dispatch" (SPD) software to be used by the New Zealand Electricity Market. It has been presented using a mathematical notation designed to be rigorous but (relatively) easy to follow. There are many alternative expressions which are mathematically equivalent, and will produce the same result in the market. Alternative representations may be more convenient for implementation purposes. Thus the mathematical formulation in this document may not necessarily correspond, in detail, with that implemented by ESCA (the developers of the SPD software). Auditing the software to verify that it is mathematically equivalent will be treated as a separate and subsequent task.

The document is in three parts: the first part provides a glossary to the model components such as sets and variables; in the second part the constraints are defined; and the third part defines pre-processing and post processing.

2 Glossary of Sets, Indices, Variables and Parameters

All variables and parameters are non-negative except where stated. There are no "soft" constraints and associated penalty variables to catch and help identify reasons for infeasible solutions for instances of the model.

The word "scheduled" is used when describing the meaning of some variables. For example, "$Generation_g$ is the MW generation scheduled corresponding to offer $g \in OFFERS$". This is used as a shorthand for "scheduled or dispatched". It includes the concept of generation notionally scheduled to meet metered loads in pricing runs.

2.1 Fundamental Sets and Indices

Item	Definition
Islands	An island is represented by an element of the set *ISLANDS* and is indexed by *i*.
Generation Offers	A generation offer is represented by an element of the set *OFFERS* and is indexed by *g*. Only one offer is assumed for each station or unit. Each offer has associated with it an island and a node. For reserve purposes a subset of *OFFERS* called $ISLANDRISKGENERATORS_i$ is defined. This subset is used to determine the potential risk due to generators in each island. A subset is used because not all offers represent a potential risk. For example, the total generation of a hydro station which is represented by one offer is not a potential risk because it is generally made up of many small units that are not themselves at risk generators. *For the generation ramp model a subset of OFFERS called UNITGENERATORS is defined. This subset is used because the total generation from some stations cannot be presented as one unit for ramping purpose; jointly owned units use the ramp rate of the primary unit.*
Demand and Load Forecast	Load consists of a Load Forecast component and Demand Bids. The Load Forecast represents the unscheduled part of the Load which is fixed. Demand Bids represent the scheduled part of the Load.

Item	Definition
	Demand bid is represented by an element of the set *BIDS* and is indexed by *p*. BIDS consist of Nominated bids and Difference bids. *BIDS = NOMINATEDBIDS* U *DIFFERENCEBIDS.* *NOMINATEDBIDS* is the set of ~~N~~nominated bids which can be dispatchable or non-dispatchable. *DIFFERENCEBIDS* is the set of ~~D~~difference bids which can be both positive and negative. Each bid has associated with it an island and a node.
Reserve Offers	A reserve offer from a generator, interruptible load provider or, in the Final Pricing schedule only, a virtual reserve provider, is represented by an element of the set *RESERVEOFFERS* and is indexed by *r*. Like generation offers and demand bids a generator and interruptible load reserve offer is associated with an island and a node. A virtual reserve offer is associated with an island only.
AC Nodes	An AC node is represented by an element of the set *ACNODES* and is indexed by *n*. Associated with a node is an island. There is a subset of *ACNODES* called *REFERENCENODES*. This set contains one and only one node from each island.
AC Lines	An undirected AC line is represented by an element of the set *ACLINES* and is indexed by *k*. There is a "conventional" direction for these lines but this does not imply a direction of flow because the "undirected flow" can be positive or negative. However for the purposes of determining losses direction is important. Therefore for each line *k* there are associated forward and backward lines, referred to as directed lines. A directed line is represented by an element of the set *DIRECTEDACLINES* and is indexed by *q*. The directional nature of lines means it is possible to identify the sending and receiving ends of the line. Functions defined on the set are described below.
HVDC Poles	HVDC Poles are the DC transmission lines from Benmore to Haywards including the submarine cables across the Cook Strait. It is assumed that poles are in pairs.
HVDC Links	An HVDC link is represented by an element of the set *HVDCLINKS* and is indexed by element *l*. The links are always directional. For each pole and direction there is a unique element in *HVDCLINKS*. It is assumed that links connect different islands.
Reserve Types	A reserve type is represented by an element of the set *RESERVETYPES* and is indexed by element *s* *RESERVETYPES* = {*PLSR,TWD,IL,VR*} *PLSR* is partly loaded spinning reserve which can be provided by any generator. *TWD* is tail water depressed reserve which can only be provided by hydro generators. *IL* is interruptible load which is provided by ancillary services agents. *VR* is island based virtual reserve that is used, in the Final Pricing schedule only, to cap reserve prices following the resolution of an infeasibility situation that was caused by a shortage of instantaneous reserve.
Reserve Classes	A reserve class is represented by an element of the set *RESERVECLASSES* and is indexed by *c*. *RESERVECLASSES* = {*Fast,Sustained*}
Risk	Set representing a collection of generation and reserve offers treated

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Item	Definition
Groups	as a group risk. A risk group is represented by an element of the set *RISKGROUPS* and is indexed by element *rg*.
Risk Classes	A risk class is represented by an element of the set $RISKCLASSES_i$ and indexed by *rc*. $RISKCLASSES_i = \{DCCE_i, DCECE_i, ManualCE_i, ManualECE_i\} \cup ACCERISKS_i \cup ACECERISKS_i \cup HVDCSECRISKSAC_i \cup HVDCSECRISKSMANUAL_i \cup ACCERISKGROUPS_i \cup ACECERISKGROUPS_i$,, where $HVDCSECRISKSAC_{i,} = \{HVDCSECRISKSACCE_i \cup HVDCSECRISKSACECE_i\}$ and $HVDCSECRISKSMANUAL_i = \{HVDCSECRISKSMANUALCE_i \cup HVDCSECRISKSMANUALECE_i\}$. $DCCE_i$ indicates the loss of a single HVDC pole. $DCECE_i$ indicates the loss of all HVDC poles. $ManualCE_i$ indicates an island's minimum CE risk. $ManualECE_i$ indicates an island's minimum ECE risk. $ACCERISKS_i, and\ ACECERISKS_i$ indicate the set of ACCE and ACECE risks associated with $g \in ISLANDRISKGENERATORS_i$ as identified in the policy statement. $HVDCSECRISKSACCE_i\ and\ HVDCSECRISKSACECE_i$ indicate the set of HVDC secondary risks associated with ACCE and ACECE risk classes, which in turn associated with $g \in ISLANDRISKGENERATORS_i$. $HVDCSECRISKSMANUALCE_i\ and\ HVDCSECRISKSMANUALECE_i$ indicate the set of HVDC secondary risks associated with islands's manual CE and ECE risks classes. $ACCERISKGROUPS_i, and\ ACECERISKGROUPS_i$ indicate the set of ACCE and ACECE risks associated with $rg \in RISKGROUPS_i$.
Security Measures	A security measure is represented by an element of the set *SECURITY* and is indexed by *v*. The System Operator is able to adjust parameters to meet the Electricity Industry Participation Code Part 8.
Reserve Directions	Set indicating the direction of reserve sharing. This set is indexed by element *rd*. $RESERVEDIRECTIONS = \{Forward, Reverse\}$

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2.2 Derived Sets

Numerous subsets of the fundamental sets are of interest. A subscripted fundamental set represents all elements of the fundamental set having the attribute represented by the subscript.

Examples of derived sets are:

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Item	Definition
$OFFERS_i$	is the set of all generation offers belonging to island *i*.
$BIDS_n$	is the set of all demand bids belonging to node *n*.
$ACLINES_n$	is the set of all AC lines connected to node *n*.

$RESERVEOFFERS_{TWD,Fast,i}$	is the set of all *Fast TWD* reserve offers in island *i*.
$HVDCLINKS$	is the set of *directional HVDC* links.
$OFFERS_{rg,i}$	is the set of all generation offers in island *i* belonging to risk group *rg*.
$RISKGROUPS_i$	is the set of all risk groups belonging to island *i*.

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Some combinations of sets and subscripts may not have any useful purpose, or for that matter any meaning whatsoever.

2.3 Functions Defined on Sets

For ease of description a number of functions are defined that operate on elements of sets and return either another set or a single element. The following functions are defined:

Item	Definition
$k(\cdot)$	where the argument could be a security offer *v* or directed AC line *q* gives the undirected AC line associated with the argument.
$q(v)$	gives the directed AC line *q* of interest in security measure *v*.
$n(v)$	gives the AC node *n* of interest in security measure *v*.
$n(i)$	gives the set of AC nodes *n* located in island *i*.
$g(\cdot)$	where the argument could be a reserve offer *r* or security measure *v* gives the generation offer associated with the argument.
$p(\cdot)$	where the argument could be a reserve offer *r* or security measure *v* gives the demand bid associated with the argument.
$b(\cdot)$ and $e(\cdot)$	give the beginning and ending AC nodes respectively of a line or link where the argument could be an undirected AC line *k* or a HVDC link *l*. For the undirected AC line the conventional direction of the line is used to determine the beginning and end.
$F(k)$ and $B(k)$	give the forward and backward directed AC lines respectively associated with AC undirected line *k*.
$l(v)$	gives the HVDC link of interest in security measure *v*.
$S_{AC}(n)$ and $R_{AC}(n)$	give the sets of AC directed lines for which *n* is the sending AC node or receiving AC node respectively.
$S_{HVDC}(n)$ and $R_{HVDC}(n)$	give the sets of HVDC links for which *n* is the sending AC node or receiving AC node respectively.

2.4 Generation, Demand and Load Forecast

2.4.1 *Parameters*

Item	Definition
$GenerationOfferBlocks_g$	The number of blocks in generation offer $g \in OFFERS$.
$GenerationOfferMW_{g,j}$	The MW element of the j^{th} block of the offer.
$GenerationOfferPrice_{g,j}$	The price element of the j^{th} block of the offer. *The parameter is unbounded.*
$DemandBidBlocks_p$	The number of blocks in demand bid $p \in BIDS$
$DemandBidMW_{p,j}$	The MW element of the j^{th} block of the bid. It can be negative.
$DemandBidPrice_{p,j}$	The price element of the j^{th} block of the bid. *The parameter is unbounded.*
$LoadForecast_n$	A fixed part of MW Load at node *n*.

2.4.2 *Variables*

Item	Definition
$Generation_g$	The scheduled part of MW generation corresponding to offer $g \in OFFERS$.
$GenerationBlock_{g,j}$	The scheduled part of MW generation corresponding to the j^{th} block of the offer.
$Demand_p$	The scheduled part of MW load corresponding to bid $p \in BIDS$. It can be negative
$DemandBlock_{p,j}$	The scheduled part of MW load corresponding to the j^{th} block of the bid. It can be negative

2.5 HVDC Transmission System

2.5.1 *Parameters*

Item	Definition
$HVDCLinkCapacity_l$	The MW capacity of HVDC link $l \in HVDCLINKS$.
$HVDCLinkFixedLosses_l$	The fixed losses of the link. The losses attributed to each *link* are half the fixed losses of the *pole*.

HVDCBreakpoint MWFlow$_{l, bp}$	Value of power flow at the break point *bp* of HVDC Link *l*.
HVDCBreakpoint MWLoss$_{l, bp}$	Value of variable (non-fixed) loss at the breakpoint *bp* in the loss curve of HVDC Link *l.*
HVDCBreakpoints$_l$	The number of breakpoints in the loss curve of HVDC Link *l.*

2.5.2 *Index*

Item	Definition
bp	Index of the break points from 1 to *HVDCBreakpoints*$_l$

2.5.3 *Variables*

Item	Definition
HVDCLinkFlow$_l$	The MW flow at the sending end scheduled for HVDC link $l \in HVDCLINKS$.
HVDCLinkLosses$_l$	The MW losses for the link.
Lambda$_{l, bp}$	Non-negative weight applied to breakpoint *bp* of *HVDC Link*$_l$.

2.6 AC Transmission System

2.6.1 *Parameters*

Item	Description
ACLineCapacity$_k$	The MW capacity of AC line $k \in ACLINES$.
ACLineAdmittance$_k$	The admittance of the line. It is really the susceptance but the use of “admittance” seems to be widespread. The admittance of a line is a complex number *G* – *iB* where *G* is the conductance and *B* is the susceptance. It is the susceptance which is used in the DC power flow calculations.
ACLineLossBlocks$_k$	The number of blocks in the loss curve of the line.
ACLineLossMW$_{k, j}$	The MW element of the j^{th} block of the loss curve.
ACLineLossFactor$_{k, j}$	The loss factor element of the j^{th} block of the loss curve.
ACLineFixedLosses$_k$	The fixed losses of the line.

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2.6.2 Variables

Item	Description
$ACNodeNetInjection_n$	The MW injection at node $n \in ACNODES$. *The variable is unbounded.*
$ACNodeAngle_n$	The voltage angle at the node. *The variable is unbounded*
$ACLineFlow_k$	The MW flow scheduled for line $k \in ACLINES$. *The variable is unbounded*
$ACLineFlow_q^{Directed}$	The MW flow scheduled for directed line $q \in DIRECTEDACLINES$.
$ACLineFlowBlock_{q,j}^{Directed}$	The MW flow corresponding to the j^{th} block of the loss curve.
$ACLineLosses_q^{Directed}$	The MW losses for the directed line.
$ACLineLossesBlock_{q,j}^{Directed}$	The MW losses corresponding to the j^{th} block of the loss curve.

2.7 Risk and Reserve

A generic reserve offer structure is used. Differentiation between types of reserve is achieved by using the fundamental set *RESERVETYPES* to create subsets of *RESERVEOFFERS*. Reserve is assumed to be available while ramping.

2.7.1 *Parameters*

Item	Description
$ReserveOfferBlocks_r$	The number of blocks in reserve offer $r \in RESERVEOFFERS$.
$ReserveOfferProportion_{r,j}$	The incremental MW percentage of the j^{th} block of offer $r \in RESERVEOFFERS_{PLSR}$.
$ReserveOfferPrice_{r,j}$	The price element of the j^{th} block of the offer. *The parameter is unbounded*
$ReserveOfferMaximum_{r,j}$	The maximum MW reserve available from the j^{th} block of the offer.
$ReserveGenerationMaximum_g$	The maximum MW generation and reserve capability associated with generation offer $g \in OFFERS$.[1]
$ReserveMaximumFactor_{g,c}$	The factor to adjust the maximum reserve of class $c \in RESERVECLASSES$ associated with generation offer $g \in OFFERS$.
$IslandRiskAdjustmentFactor_{i,c,rc}$	The risk adjustment factor for island $i \in ISLANDS$, reserve class $c \in RESERVECLASSES$ and risk class $rc \in RISKCLASSES_i$.
$IslandMinimumRisk_{i,rc}$	The minimum MW risk level for island $i \in ISLANDS$ and risk classes $rc \in ACCERISKS_i \cup ACECERISKS_i \cup HVDCSECRISKSAC_i \cup HVDCSECRISKSMANUAL_i$
$RiskOffsetParameter_{i,c,rc}$	Input from RMT, which accounts for HVDC frequency sharing, net free reserve, AUFLS, non-compliant generation, secondary generators risk , for island $i \in ISLANDS$, reserve class $c \in RESERVECLASSES$ *and risk class* $rc \in RISKCLASSESS_i \,/\, \{DCCE_i, DCECE_i\}$
$RampupMax_i$	Input from RMT, which accounts for maximum remaining HVDC capacity following an HVDC contingency event (DCCE) for island

[1] The reference is made to a generation offer because the maximum capability is advised in a generation offer.

Item	Description
	$i \in ISLANDS$
$NetFreeReserve_{i,c,rc}$	Input from RMT, which accounts for AUFLS and non-compliant generation, for island $i \in ISLANDS$ reserve class $c \in RESERVECLASSES$ and risk class $rc \in \{DCCE_i, DCECE_i\}$
$HVDCSecondaryRiskSubtractor_i$	Available capacity on the HVDC pole that is not the secondary risk, for island $i \in ISLANDS$ and is available from RMT
$FKBand_g$	Frequency keeping band, set at risk generators $g \in ISLANDRISKGENERATORS_i$
$ResShareReceivedEffectiveness_{i,c,rc}$	Effectiveness factor applied to the shared reserve received in the risk island $i \in ISLANDS$ for reserve class $c \in RESERVECLASSES$ and for $rc \in \{ACCERISKS_i, ACECERISKS_i, ManualCE_i, ManualECE_i, ACCERISKGROUPS_i, ACECERISKGROUPS_i\}$
$SharedNFRMaxLimit_{i,c}$	Limit on the SharedNFRMax$_{i,c}$ parameter for non-risk island *i* for reserve class *c*. A non-zero value is only applicable for reserve class $c \in \{FIR\}$.
$SharedNFRFactor$	Proportion of load in the non-risk island that provides damping which can be considered for reserve sharing.
$SharedNFRLoadOffset_i$	Load in non-risk island $i \in ISLANDS$ that does not provide load damiping for shared reserves.
$ResShareControlBand_{rd}$	Reserve sharing limit on the HVDC due to HVDC modulation limit or HVDC monopole limit during reduced voltage operation mode.
$ModulationRisk_{i,rc}$	HVDC modulation risk due to frequency keeping for $i \in ISLANDS$ and $rc \in \{DCCE_i, DCECE_i, HVDCSECRISKSAC_i, HVDCSECRISKSMANUAL_i\}$
$HVDCMax_i$	HVDC transfer capability from island $i \in ISLANDS$.
$RoundPowerZoneExit_c$	MW value above which cannot guarantee the HVDC ability to reduce below the monopole minimum fast enough to provide reserve sharing in the reverse direction for reserve class $c \in RESERVECLASSES$.
$MonopoleMin$	HVDC minimum monopole transfer.
$HVDCSentFlowBreakPoint_{bp}$	Value of power flow at the breakpoint *bp* of the HVDC sent flow.
$HVDCSentLossBreakPoint_{bp}$	Value of the variable loss at the breakpoint *bp* of the HVDC sent flow.

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Item	Description
$HVDCAfterResShareFlowBreakPoint_{rsbp}$	Value of power flow at the breakpoint *rsbp* of the HVDC flow after reserve sharing.
$HVDCAfterResShareLossBreakPoint_{rsbp}$	Value of the variable loss at the breakpoint *rsbp* of the HVDC flow after reserve sharing.
M	Large positive number.
$ExcessSharedNFRPenaltyPrice$	Small non-zero penalty price to prevent excess net free reserve sharing
$ExcessSharedIslandResPenaltyPrice$	Small non-zero penalty price to prevent excess island reserve sharing
$ExcessResShareEffectivePenaltyPrice$	Small non-zero penalty price to prevent excess sharing of the effective reserves

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2.7.2 Index

Item	Definition
rrz	Index indicating the operational range of the HVDC for providing shared reserves in the reverse direction. $rrz \in \{RoundPowerZone, NoReverseZone, ReverseZone\}$
$rsbp$	Index of the reserve sharing break points from 1 to $ReserveShareBreakpoints$ which are used to model the HVDC flow and losses after reserve sharing.

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~~2.7.2~~2.7.3 Variables

Item	Description
$Reserve_r$	The reserve scheduled corresponding to reserve offer $r \in RESERVEOFFERS$.
$ReserveBlock_{r,j}$	The reserve scheduled corresponding to j^{th} block of the offer.
$IslandRisk_{i,c,rc}$	The MW risk for island $i \in ISLANDS$, reserve class $c \in RESERVECLASSES$ and risk class $rc \in RISKCLASSES_i$. The variable is unrestricted.
$HVDCRec_i$	The total net pre-contingent HVDC flow received at island *i*. The variable is unrestricted (i.e. negative for export).
$RiskOffset_{i,c,rc}$	The risk offset applies for island $i \in ISLANDS$, reserve class $c \in RESERVECLASSES$ and *risk class*

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	$rc \in \{DCCE_i, DCECE_i\}$
$Rampup_i$	HVDC pole rampup, applies only for the DCCE risk.
$IslandReserve_{i,c}$	The reserve of class $c \in RESERVECLASSES$ scheduled at island $i \in ISLANDS$
$HVDCSent_i$	HVDC energy sent from island *i*. Calculated as the sum of flow at the sending nodes.
$SharedNFR_{i,c}$	Component of shared reserves that is provided by load damping in the non-risk island *i* for reserve class *c*.
$SharedIslandReserve_{i,c}$	Reserve cleared in the non-risk island *i* that could be shared for reserve class *c*.
$ResShareEffective_{i,c,rc}$	Reserve sharing received after adjustment for effectiveness in island *i*, reserve class *c* and risk class *rc*.
$ResShareSent_{i,c,rd}$	Reserve sharing provided by the non-risk island *i* for reserve class *c* in reserve sharing direction *rd*.
$ResShareReceived_{i,c,rd}$	Reserve sharing received by the risk island *i* for reserve class *c* in reserve sharing direction *rd*.
$IsSendingHVDC_i$	Binary variable indicating if island *i* is the sending end of the HVDC flow. 1 = Yes.
$InZone_{i,c,rrz}$	Binary variable (1 = Yes) indicating if the HVDC flow is in a zone (*rrz*) that facilitates the appropriate quantity of shared reserves in the reverse direction to the HVDC sending island *i* for reserve class *c*.
$HVDCSentLoss_i$	For the purposes of reserve sharing the HVDC variable losses for island *i* associated with the $HVDCSent_i$ flow.
$LambdaHVDCSent_{i,bp}$	Non-negative weight applied to breakpoint *bp* for island *i* sent flow and loss.
$HVDCSentAfterResShare_{i,c,rd}$	HVDC sent flow after the activation of reserves provided by reserve sharing for island *i*, reserve class *c* and reserve sharing direction *rd*. This variable is unrestricted.
$HVDCLossAfterResShare_{i,c,rd}$	HVDC sent losses associated with sent flow after the activation of reserves provided by reserve sharing for island *i*, reserve class *c* and reserve sharing direction *rd*.
$LambdaResShare_{i,c,rd,rsbp}$	Non-negative weight applied to breakpoint *rsbp* for island *i* sent flow and loss after activation of reserves provided by reserve sharing for reserve class *c* and reserve sharing direction *rd*.
$ExcessResSharePenalty$	Small non-zero penalty cost to prevent

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	sharing of reserves in excess of benefit ("over-sharing"). This "over-sharing" occurs when the incremental cost of sharing reserves is zero.

2.7.32.7.4 *Parameters for pre-processing*

Item	Description
$ReserveGenerationMaximum_{g,c}$	The MW combined maximum capability for generation and reserve of class $c \in RESERVECLASSES$ associated with generation offer $g \in OFFERS$.
$SharedNFRMax_{i,c}$	The maximum net free reserve provided by load damping in the non-risk island *i* that could be shared across the HVDC for reserve class *c*. A non-zero value is only applicable for reserve class $c \in \{FIR\}$.
$ResShareMaxLessMR_{i,rd}$	Maximum reserve sharing at island *i* in reserve direction *rd* due to the HVDC modulation limit less the modulation risk.
$HVDCMaxLessMR_{i}$	HVDC transfer capability from island *i* less the modulation risk.
$MonopoleMinPlusMR$	HVDC minimum monopole transfer increased by the modulation risk.

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2.8 Security

The System Operator may impose generation, reserve and purchase limits and flow limits on AC and DC transmission equipment for security reasons, using the constraint forms defined in Section 3.5 to meet the requirements of the Grid Operating Security Policy.

2.8.1 *Sets*

Item	Description
$SECURITY_{GenerationMaximum}$	The set of maximum generation offer security constraints.
$SECURITY_{GenerationMinimum}$	The set of minimum generation offer security constraints.
$SECURITY_{ACLineCapacity}$	The set of all directed AC transmission line flow security constraints.
$SECURITY_{HVDCLinkCapacity}$	The set of HVDC link flow security

Item	Description
	constraints.
$SECURITY_{GroupACLinesFlow}$	The set of group AC transmission line flow security constraints.
$SECURITY_{GroupACNodesNetInjection}$	The set of all group AC node net injection security constraints.
$SECURITY_{GroupMarketNodes}$	The set of group market node security constraints on generation, demand and reserve.
$SECURITYACLINESGROUP_v$	The set of AC directed transmission lines used in a group flow security constraint for security measure *v*.
$SECURITYACNODESGROUP_v$	The set of AC node net injections used in market node group constraint for security measure *v*.
$SECURITYMARKETDEMNODESGROUP_v$	The set of demand bids used in market node group constraint for security measure *v*
$SECURITYMARKETGENNODESGROUP_v$	The set of generation offers used in market group constraint for security measure *v*
$SECURITYMARKETRESNODESGROUP_v$	The set of reserve offers used in market node group constraint for security measure *v*

2.8.2 *Parameters*

Item	Description
$SecurityGenerationMaximum_v$	The MW generation maximum associated with security measure $v \in SECURITY_{GenerationMaximum}$ imposed on a generation offer by the System Operator for security reasons.
$SecurityGenerationMinimum_v$	The MW generation minimum associated with $v \in SECURITY_{GenerationMinimum}$.
$SecurityACLineCapacity_v$	The MW directed AC line capacity associated with $v \in SECURITY_{ACLineCapacity}$.
$SecurityHVDCLinkCapacity_v$	The MW HVDC link capacity associated with $v \in SECURITY_{HVDCLinkCapacity}$.

Item	Description
$SecurityGroupACLineFlow_v$	The MW maximum total flow of a group of directed AC lines, associated with security measure $v \in SECURITY_{GroupACLinesFlow}$. *The parameter is unbounded.*
$SecurityGroupACLineWeight_q$	The weight associated with directed line $q \in SECURITYACLINESGROUP_v$. *The parameter is unbounded.*
$SecurityGroupACNodesNetInjection_v$	The MW maximum total AC node net injection of a group of AC nodes, associated with security measure $v \in SECURITY_{GroupACNodesNetInjection}$. *The parameter is unbounded.*
$SecurityGroupACNodeWeight_n$	The weight associated with AC node $n \in SECURITYACNODESGROUP_v$. *The parameter is unbounded.*
$MarketNodeDemWeight_p$	The weight associated with demand bid $p \in SECURITYMARKETDEMNODEGROUP_v$. *The parameter is unbounded.*
$MarketNodeGenWeight_g$	The weight associated with generation offer $g \in SECURITYMARKETGENNODEGROUP_v$. *The parameter is unbounded.*
$MarketNodeResWeight_r$	The weight associated with reserve offer $r \in SECURITYMARKETRESNODEGROUP_v$. *The parameter is unbounded.*
$MarketNodeSecurityLimit_v$	The limit associated with security measure $v \in SECURITY_{GroupMarketNodes}$. *The parameter is unbounded.*

2.9 Mixed Constraints

This facility allows the System Operator to impose mixed constraints on any existing variables. It also provides a powerful facility for the creation of new models. Approval for the creation of new mixed constraints is required to go through the consultation process used for Code amendments under section 39 of the Electricity Act 2010. Such consultation (and subsequent approval) relates to the form of the mixed constraints, and may include specification of permanent conditions with respect to the level of, or relationships between, parameters in the constraint. Other parameters may be adjusted by specified processes. Any formulation constraint involving mixed constraint variables may also be implicitly involved.

2.9.1 *Sets*

Item	Description

$MIXEDCONSTRAINTS_{Type1}$	The set of all Type 1 mixed constraints. Each constraint, *m*, will normally define one new variable, $MixedConstraintVariable_m$, and can link it to any combination of existing model variables.
$MIXEDCONSTRAINTS_{Type2}$	The set of all Type 2 mixed constraints. Each Type 2 constraint is a group constraint creating links between the new variables created by Type 1 constraints.
$MIXEDVARGROUP_b$	The set of Type 1 mixed constraints whose new variables are linked by Type 2 mixed constraint *b.*
$MIXEDDEMNODEGROUP_m$	The set of demand bids used in Type1 mixed constraint *m*.
$MIXEDGENNODEGROUP_m$	The set of generation offers used in Type1 mixed constraint *m*.
$MIXEDRESNODEGROUP_m$	The set of reserve offers used in Type1 mixed constraint *m*.
$MIXEDDIRACLINEGROUP_m$	The set of AC lines whose flow used in Type1 mixed constraint *m*.
$MIXEDDIRACLINELOSSGROUP_m$	The set of AC line whose losses are used in Type1 mixed constraint *m*.
$MIXEDACFIXLOSSGROUP_m$	The set of AC lines whose fixed losses used in Type1 mixed constraint *m*.
$MIXEDDCLINEGROUP_m$	The set of DC lines whose flow is used in Type1 mixed constraint *m*.
$MIXEDDCLNLOSSGROUP_m$	The set of DC lines whose losses are used in Type1 mixed constraint *m*.
$MIXEDDCFIXLOSSGROUP_m$	The set of DC lines whose fixed are losses used in Type1 mixed constraint *m*.

2.9.2 *Parameters*

Item	Description
$MixedConstVarWeight1_m$	The weight associated with mixed security constraint variable $m \in MIXEDCONSTRAINTS_{Type1}$ *The parameter is unbounded.*
$MixedConstDemWeight_{p,m}$	The weight associated with demand bid $p \in MIXEDDEMNODEGROUP_m$.

Item	Description
	The parameter is unbounded.
$MixedConstGenWeight_{g,\,m}$	The weight associated with generation offer $g \in MIXEDGENNODEGROUP_m$. *The parameter is unbounded.*
$MixedConstResWeight_{r,\,m}$	The weight associated with reserve offer $r \in MIXEDRESNODEGROUP_m$. *The parameter is unbounded.*
$MixedConstACLineWeight_{q,\,m}$	The weight associated with the flow in directed AC line $q \in MIXEDDIRACLINEGROUP_m$. *The parameter is unbounded.*
$MixedConstACLineLossWeight_{q,\,m}$	The weight associated with the variable loss in directed AC line $q \in MIXEDDIRACLINEGROUP_m$. *The parameter is unbounded.*
$MixedConstACLineFixedLossWeight_{k,\,m}$	The weight associated with the fixed loss in undirected AC line *k* $l \in MIXEDACLINEGROUP_m$. *The parameter is unbounded.*
$MixedConstDCLinkWeight_{l,\,m}$	The weight associated with the flow in HVDC link $l \in MIXEDDCLINEGROUP_m$. *The parameter is unbounded.*
$MixedConstDCLinkLossWeight_{l,\,m}$	The weight associated with the variable loss in HVDC link $l \in MIXEDDCLINEGROUP_m$. *The parameter is unbounded.*
$MixedConstDCLinkFixedLossWeight_{l,\,m}$	The weight associated with the fixed loss in HVDC link $l \in MIXEDDCLINEGROUP_m$. *The parameter is unbounded.*
$MixedConstraintLimit1_m$	The limit associated with mixed security constraint $m \in MIXEDCONSTRAINTS_{Type1}$. *The parameter is unbounded.*
$MixedConstVarWeight2_{m.b}$	The weight associated with mixed security constraint variable $m \in MIXEDVARGROUP_b$ in constraint $b \in MIXEDCONSTRAINTS_{Type2}$. *The parameter is unbounded.*
$MixedConstraintLimit2_b$	The limit associated with mixed security constraint $b \in MIXEDCONSTRAINTS_{Type2}$. *The parameter is unbounded.*

2.9.3 *Variables*

Item	Description
$MixedConstraintVariable_m$	Mixed security constraint variable defined by constraint $m \in MIXEDCONSTRAINTS_{Type1}$. *The variable is unrestricted.*

2.10 Ramping

A generator has limits on its ability to move from one level of generation to another. Ramping constraints are enforced by constraining the generation level based on available power applied over a trading period. SPD uses generation unit MW- based ramp rate and duration of interval.

2.10.1 *Parameters for pre-processing*

Item	Description
$RampRate_g^{Up}$	The *ramping up* rate in MW per minute associated with generation offer $g \in UNITGENERATORS$.
$RampRate_g^{Down}$	The *ramping down* rate in MW per minute associated with the offer $g \in UNITGENERATORS$.
$Generation_g^{Start}$	The MW generation level associated with the offer $g \in UNITGENERATORS$ at the start of a trading period.
$TradingPeriodLength$	The length of a trading period in minutes.

2.10.2 *Parameters used in the pre-processing*

Item	Description
$Generation_g^{End,Up}$	The MW generation level associated with the offer at the end of a trading period assuming ramping up at rate $RampRate_g^{Up}$
$Generation_g^{End,Down}$	The MW generation level associated with the offer at the end of a trading period assuming ramping down at rate $RampRate_g^{Down}$.

3 Constraints

3.1 Generation, Demand and Load Forecast

3.1.1.1. $GenerationBlock_{g,j} \leq GeneratorOfferMW_{g,j}$

$j = 1, \dots GenerationOfferBlocks_g \quad \forall\, g \in OFFERS$

3.1.1.2 $Generation_g = \sum_{j=1}^{GenerationOfferBlock_g} GenerationBlock_{g,j}$

$\forall\ g \in OFFERS$

3.1.1.3 $0 \leq DemandBlock_{p,j} \leq DemandBidMW_{p,j}$

if $DemandBidMW_{p,j} \geq 0, \quad j = 1, \ldots DemandBidBlocks_p\ \forall p \in BIDS$

3.1.1.4 $0 \geq DemandBlock_{p,j} \geq DemandBidMW_{p,j}$

if $DemandBidMW_{p,j} \leq 0, \quad j = 1, \ldots DemandBidBlocks_p\ \forall p \in BIDS$

3.1.1.5 $Demand_p = \sum_{j=1}^{DemandBidBlocks_p} DemandBlock_{p,j}\ \ \forall\ p \in BIDS$

3.2 HVDC Transmission

3.2.1.1. $HVDCLinkFlow_l \leq HVDCLinkCapacity_l\ \ \forall l \in HVDCLINKS$

3.2.1.2. $HVDCLinkLosses_l = \sum_{bp=1}^{HVDCBreakpoints_l} HVDCBreakpointMWLosses_{l,bp} \times Lambda_{l,bp}$

3.2.1.3. $HVDCLinkFlow_l = \sum_{bp=1}^{HVDCBreakpoints_l} HVDCBreakpointMWFlow_{l,bp} \times Lambda_{l,bp}$

3.2.1.4 $\sum_{bp=1}^{HVDCBreakpoints_l} Lambda_{l,bp} = 1$

3.3 AC Transmission

3.3.1.1. $ACNodeNetInjection_n = \sum_{q \in S_{AC}(n)} ACLineFlow_q^{Directed} - \sum_{q \in R_{AC}(n)} ACLineFlow_q^{Directed}$

$\forall n \in ACNODES$

3.3.1.2. $ACNodeNetInjection_n = \sum_{g \in OFFERS_n} Generation_g - \sum_{p \in BIDS_n} Demand_p - LoadForecast_n - \sum_{l \in S_{HVDC}(n)} HVDCLinkFlow_l + \sum_{l \in R_{HVDC}(n)} (HVDCLinkFlow_l - HVDCLinkLosses_l) - \sum_{l \in HVDCLINKS_n} \frac{1}{2} \times HVDCLinkFixedLosses_l - \sum_{q \in R_{AC}(n)} ACLineLosses_q^{Directed} - \sum_{k \in ACLINES_n} \frac{1}{2} \times ACLineFixedLosses_k$

$\forall n \in ACNODES$

3.3.1.3. $ACLineFlow_q^{Directed} \leq ACLineCapacity_{k(q)}$

$\forall\, q \in DIRECTEDACLINES$

3.3.1.4 $ACLineFlow_k = ACLineFlow_{F(k)}^{Directed} - ACLineFlow_{B(k)}^{Directed}$

$\forall\, k \in ACLINES$

3.3.1.5. $ACLineFlow_k = ACLineAdmittance_k \times \left(ACNodeAngle_{b(k)} - ACNodeAngle_{e(k)}\right)\ \forall\, k \in ACLINES$

3.3.1.6. $ACLineFlowBlock_{q.j}^{Directed} \leq ACLineLossMW_{k(q)}$

$j = 1, \ldots, ACLineLossBlocks_{k(q)}\ \ \forall q \in DIRECTEDACLINES$

3.3.1.7. $ACLineFlow_q^{Directed} = \sum_{j=1}^{ACLineLossBlocks_{k(q)}} ACLineFlowBlock_{q,j}^{Directed}$

$\forall q \in DIRECTEDACLINES$

3.3.1.8. $ACLineLossesBlock_{q,j}^{Directed} = ACLineFlowBlock_{q,j}^{Directed} \times ACLineLossFactor_{k(q),j}$

$j = 1, \ldots, ACLineLossBlocks_{k(q)}\ \ \forall q \in DIRECTEDACLINES$

3.3.1.9. $ACLineLosses_q^{Directed} = \sum_{j=1}^{ACLineLossBlocks_{k(q)}} ACLineLossesBlock_{q,j}^{Directed}$

$j = 1, \ldots, ACLineLineLossBlocks_{k(q)}\ \ \forall q \in DIRECTEDACLINES$

3.3.1.10. $ACNodeAngle_n = 0\ \ \forall n \in REFERENCENODES$

3.4 Risk and Reserve

3.4.1 *Risk*

3.4.1.1. $IslandRisk_{i,c,rc} = IslandRiskAdjustmentFactor_{i,c,rc} \times \left(HVDCRec_i - RiskOffset_{i,c,rc} + ModulationRisk_{i,rc}\right)$

$\forall c \in RESERVECLASSES\ \ \forall i \in ISLANDS\ \ \forall rc \in \{DCCE_i, DCECE_i\}$

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3.4.1.2. $RiskOffset_{i,c,rc} - Rampup_i = NetFreeReserve_{i,c,rc}$

$\forall c \in RESERVECLASSES\ \ \forall i \in ISLANDS\ \ \forall rc \in \{DCCE_i\}$

3.4.1.3. $Rampup_i = RampupMax_i \quad \forall i \in ISLANDS$

3.4.1.4. $RiskOffset_{i,c,rc} = NetFreeReserve_{i,c,rc}$

$$\forall c \in RESERVECLASSES \;\; \forall i \in ISLANDS \;\; \forall rc \in \{DCECE_i\}$$

3.4.1.5. $$HVDCRec_i = \sum_{n(i)} \begin{pmatrix} -\sum_{l \in S_{HVDC}(n)} HVDCLinkFlow_l \\ +\sum_{l \in R_{HVDC}(n)} (HVDCLinkFlow_l - HVDCLinkLoss_l) \end{pmatrix}$$

$$\forall i \in ISLANDS$$

3.4.1.6. $$IslandRisk_{i,c,rc} = IslandRiskAdjustmentFactor_{i,c,rc} \times \left(Generation_g - RiskOffsetParameter_{i,c,rc} + FKBand_g + \sum_{r \in RESERVEOFFERS_{g,c}} Reserve_r\right) \cancel{+ \sum_{r \in RESERVEOFFERS_{g,c}} Reserve_r} - ResShareEffective_{i,c,rc}$$

$$\forall g \in ISLANDRISKGENERATORS_i \;\; \forall c \in RESERVECLASS$$

$$\forall i \in ISLANDS \;\; \forall rc \in \{ACCERISKS_i, ACECERISKS_i\}$$

3.4.1.7. $$IslandRisk_{i,c,rc} = IslandRiskAdjustmentFactor_{i,c,rc} \times \left(IslandMinimumRisk_{i,rc} - RiskOffsetParameter_{i,c,rc}\right) - ResShareEffective_{i,c,rc}$$

$$\forall c \in RESERVECLASS \;\; \forall i \in ISLANDS \; for \; rc \in \{ManualCE_i, ManualECE_i\}$$

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3.4.1.8. $$IslandRisk_{i,c,rc} = IslandRiskAdjustmentFactor_{i,c,rc} \times \left(Generation_g - RiskOffsetParameter_{i,c,rc} + HVDCRec_i + ModulationRisk_{i,rc} - HVDCSecondaryRiskSubtractor_i + FKBand_g + \sum_{r \in RESERVEOFFERS_{g,c}} Reserve_r\right) \cancel{+ \sum_{r \in RESERVEOFFERS_{g,c}} Reserve_r}$$

$$\forall g \in ISLANDRISKGENERATORS_i \;\; \forall c \in RESERVECLASS$$

$$\forall i \in ISLANDS \;\; \forall rc \in \{HVDCSECRISKSAC_i\}$$

3.4.1.9. $$IslandRisk_{i,c,rc} = IslandRiskAdjustmentFactor_{i,c,rc} \times \left(IslandMinimumRisk_{i,rc} - RiskOffsetParameter_{i,c,rc} + HVDCRec_i + ModulationRisk_{i,rc} - HVDCSecondaryRiskSubtractor_i\right)$$

$$\forall c \in RESERVECLASS \;\; \forall i \in ISLANDS \; for \; rc \in \{HVDCSECRISKSMANUAL_i\}$$

3.4.1.10. $$IslandRisk_{i,c,rc} = IslandRiskAdjustmentFactor_{i,c,rc} \times \left(\sum_{g \in OFFERS_{rg,i}} \left(Generation_g + FKBand_g + \sum_{r \in RESERVEOFFERS_{g,c}} Reserve_r\right) - RiskOffsetParameter_{i,c,rc}\right) - ResShareEffective_{i,c,rc}$$

$$\forall rg \in RISKGROUPS_i \;\; \forall c \in RESERVECLASS$$

$$\forall i \in ISLANDS \;\; \forall rc \in \{ACCERISKGROUPS_i, ACECERISKGROUPS_i\}$$

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3.4.2 *Reserve sharing*

3.4.2.1. $ResShareEffective_{i,c,rc} \leq \sum_{rd} ResShareReceivedEffectiveness_{i,c,rc} \times ResShareReceived_{i,c,rd}$

$$\forall i \in ISLANDS, \quad \forall c \in RESERVECLASS$$

$$\forall rc \in \left\{ \begin{matrix} ACCERISKS_i, ACECERISKS_i, ManualCE_i, ManualECE_i \\ ACCERISKGROUPS_i, ACECERISKGROUPS_i \end{matrix} \right\}$$

3.4.2.2. $SharedIslandReserve_{i,c} \leq IslandReserve_{i,c}$

$$\forall i \in ISLANDS, \quad \forall c \in RESERVECLASS$$

3.4.2.3. $SharedNFR_{i,c} \leq SharedNFRMax_{i,c}$

$$\forall i \in ISLANDS, \quad \forall c \in RESERVECLASS$$

3.4.2.4. $ResShareSent_{i,c,rd} \leq SharedIslandReserve_{i,c} + SharedNFR_{i,c}$

$$\forall i \in ISLANDS, \quad \forall c \in RESERVECLASS, \quad \forall rd \in RESERVEDIRECTIONS$$

3.4.2.5. $ResShareSent_{i,c,rd} \leq ResShareMaxLessMR_{i,rd}$

$$\forall i \in ISLANDS, \quad \forall c \in RESERVECLASS, \quad \forall rd \in RESERVEDIRECTIONS$$

3.4.2.6. $HVDCSent_i + ResShareSent_{i,c,rd} \leq HVDCMaxLessMR_i$

$$\forall i \in ISLANDS, \quad \forall c \in RESERVECLASS, \quad \forall rd \in \{FORWARD\}$$

3.4.2.7. $ResShareSent_{i,c,rd} \leq M \times (1 - IsSendingHVDC_i)$

$$\forall i \in ISLANDS, \quad \forall c \in RESERVECLASS, \quad \forall rd \in \{REVERSE\}$$

3.4.2.8. $ResShareReceived_{i,c,rd} \leq ResShareMaxLessMR_{i,rd} \times IsSendingHVDC_i$

$$\forall i \in ISLANDS, \quad \forall c \in RESERVECLASS, \quad \forall rd \in \{REVERSE\}$$

3.4.2.9. $ResShareReceived_{i,c,rd} \leq M \times (1 - IsSendingHVDC_i)$

$$\forall i \in ISLANDS, \quad \forall c \in RESERVECLASS, \quad \forall rd \in \{FORWARD\}$$

3.4.2.10. $HVDCSent_i - ResShareReceived_{i,c,rd} \geq MonopoleMinPlusMR - M \times (1 - InZone_{i,c,rrz})$

$$\forall i \in ISLANDS, \quad \forall c \in RESERVECLASS, \quad \forall rd \in \{REVERSE\}$$

$$\forall rrz \in \{REVERSEZONE\}$$

3.4.2.11. $ResShareReceived_{i,c,rd} \leq M \times (1 - InZone_{i,c,rrz})$

$$\forall i \in ISLANDS, \quad \forall c \in RESERVECLASS, \quad \forall rd \in \{REVERSE\}$$
$$\forall rrz \in \{NOREVERSEZONE\}$$

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3.4.2.12. $\sum_{i \in ISLANDS} \sum_{rrz} InZone_{i,c,rrz} = 1$

$$\forall c \in RESERVECLASS$$

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3.4.2.13. $HVDCSent_i \le M \times \sum_{rrz} InZone_{i,c,rrz}$

$$\forall i \in ISLANDS, \quad \forall c \in RESERVECLASS$$

3.4.2.14. $HVDCSent_i \le RoundPowerZoneExit_c + M \times (1 - InZone_{i,c,rrz})$

$$\forall i \in ISLANDS, \quad \forall c \in RESERVECLASS, \quad \forall rrz \in \{ROUNDPOWERZONE\}$$

3.4.2.15. $IsSendingHVDC_i = \sum_{rrz} InZone_{i,c,rrz}$

$$\forall i \in ISLANDS, \quad \forall c \in RESERVECLASS$$

3.4.2.16. $\sum_{i \in ISLANDS} IsSendingHVDC_i = 1$

3.4.2.17. $HVDCSent_i = \sum_{n(i)} \sum_{l \in S_{HVDC}(n)} HVDCLinkFlow_l$

$$\forall i \in ISLANDS$$

3.4.2.18. $ResShareSent_{i,c,rd} = HVDCSentAfterResShare_{i,c,rd} - HVDCSent_i$

$$\forall i \in ISLANDS, \quad \forall c \in RESERVECLASS, \quad \forall rd \in \{FORWARD\}$$

3.4.2.19. $ResShareReceived_{i,c,rd} = ResShareSent_{j,c,rd} - HVDCLossAfterResShare_{j,c,rd} + HVDCSentLoss_j$

$$\forall i,j \in ISLANDS \text{ and } i \ne j, \quad \forall c \in RESERVECLASS, \quad \forall rd \in \{FORWARD\}$$

3.4.2.20. $ResShareReceived_{i,c,rd} = HVDCSent_i - HVDCSentAfterResShare_{i,c,rd}$

$$\forall i,j \in ISLANDS, \quad \forall c \in RESERVECLASS, \quad \forall rd \in \{REVERSE\}$$

3.4.2.21. $ResShareReceived_{i,c,rd} = ResShareSent_{j,c,rd} - HVDCLossAfterResShare_{i,c,rd} + HVDCSentLoss_i$

$$\forall i,j \in ISLANDS \text{ and } i \ne j, \quad \forall c \in RESERVECLASS, \quad \forall rd \in \{REVERSE\}$$

3.4.2.22. $\sum_{bp} LambdaHVDCSent_{i,bp} = 1$

$$\forall i \in ISLANDS$$

3.4.2.23. $HVDCSent_i = \sum_{bp} HVDCSentFlowBreakPoint_{i,bp} \times LambdaHVDCSent_{i,bp}$

$$\forall i \in ISLANDS$$

3.4.2.24. $HVDCSentLoss_i = \sum_{bp} HVDCSentLossBreakPoint_{i,bp} \times LambdaHVDCSent_{i,bp}$

$$\forall i \in ISLANDS$$

3.4.2.25. $\sum_{rsbp} LambdaResShare_{i,c,rd,rsbp} = 1$

$$\forall i \in ISLANDS, \quad \forall c \in RESERVECLASS, \quad \forall rd \in RESERVEDIRECTIONS$$

3.4.2.26. $HVDCSentAfterResShare_{i,c,rd} = \sum_{rsbp} HVDCAfterResShareBreakPoint_{i,rsbp} \times LambdaResShare_{i,c,rd,rsbp}$

$$\forall i \in ISLANDS, \quad \forall c \in RESERVECLASS, \quad \forall rd \in RESERVEDIRECTIONS$$

3.4.2.27. $HVDCLossAfterResShare_{i,c,rd} = \sum_{rsbp} HVDCAfterResShareLossBreakPoint_{i,rsbp} \times LambdaResShare_{i,c,rd,rsbp}$

$$\forall i \in ISLANDS, \quad \forall c \in RESERVECLASS, \quad \forall rd \in RESERVEDIRECTIONS$$

3.4.2.28. $ExcessResSharePenalty = \sum_{i,c,rc} ExcessResShareEffectivePenaltyPrice \times ResShareEffective_{i,c,rc} + \sum_{i,c} ExcessSharedNFRPenaltyPrice \times SharedNFR_{i,c} + \sum_{i,c} ExcessSharedIslandResPenaltyPrice \times SharedIslandReserve_{i,c}$

3.4.23.4.3 ***Reserve***

3.4.2.1.3.4.3.1. $ReserveBlock_{r,j} \leq ReserverOfferProportion_{r,j} \times Generation_{g(r)}$

$$j = 1, \ldots, ReserveOfferBlocks_r \quad \forall r = RESERVEOFFERS_{PLSR}$$

3.4.2.2.3.4.3.2. $ReserveBlock_{r,j} \leq ReserveOfferMaximum_{r,j}$

$$j = 1, \ldots, ReserveOfferBlocks_r \quad \forall r = RESERVEOFFERS$$

3.4.2.3.3.4.3.3. $Reserve_r = \sum_{j=1}^{ReserveOfferBlocks_r} ReserveBlock_{r,j}$

$$\forall r = RESERVEOFFERS$$

3.4.2.4.3.4.3.4. $Generation_g + ReserveMaximumFactor_{g,c} \times \sum_{r \in RESERVEOFFERS_{g,c}} Reserve_r \leq ReserveGenerationMaximum_g$

$$\forall g \in OFFERS \quad \forall c \in RESERVECLASSES$$

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3.4.33.4.4 Matching of requirements and availability

3.4.3.1.3.4.4.1. $IslandRisk_{i,c,rc} \leq IslandReserve_{i,c}$

$$\forall rc \in RISKCLASSES \ \forall c \in RESERVECLASSES \quad \forall i \in ISLANDS$$

3.4.3.2.3.4.4.2. $IslandReserve_{i,c} = \sum_{r \in RESERVEOFFERS_{i,c}} Reserve_r$

$$\forall c \in RESERVECLASSES \quad \forall i \in ISLANDS$$

3.5 Security

3.5.1.1. $Generation_{g(v)} \leq SecurityGenerationMaximum_v$

$$\forall v \in SECURITY_{GenerationMaximum}$$

3.5.1.2. $Generation_{g(v)} \geq SecurityGenerationMinimum_v$

$$\forall v \in SECURITY_{GenerationMinimum}$$

3.5.1.3. $ACLineFlow_{q(v)}^{Directed} \leq SecurityACLineCapacity_v$

$$\forall v \in SECURITY_{ACLineCapacity}$$

3.5.1.4. $HVDCLinkFlow_{l(v)} \leq SecurityHVDCLinkCapacity_v$

$$\forall v \in SECURITY_{HVDCLinkCapacity}$$

3.5.1.5. $\sum_{q \in SECURITYACLINESGROUP_v} ACLineFlow_q^{Directed} \times SecurityGroupACLineWeight_q \leq SecurityGroupACLinesFlow_v$

$$\forall v \in SECURITY_{GroupACLinesFlow}$$

3.5.1.6. $\sum_{n \in SECURITYACNODESGROUP_v} ACNodeNetInjection_n \times SecurityGroupACNodeWeight_n \leq SecurityGroupACNodesNetInjection_v$

$$\forall v \in SECURITY_{GroupACNodesNetInjection}$$

3.5.1.7. $\sum_{p \in SECURITYMARKETDEMNODEGROUP_v} Demand_p \times MarketNodeDemWeight_p + \sum_{g \in SECURITYMARKETGENNODEGROUP_v} Generation_g \times MarketNodeGenWeight_g + \sum_{r \in SECURITYMARKETRESNODEGROUP_v} Reserve_r \times MarketNodeResWeight_r = \leq \geq MarketNodeSecurityLimit_v$

$$\forall v \in SECURITY_{GroupMarketNodes}$$

Note that the sign =≤≥ in Constraint 3.5.1.7, and in subsequent constraints, is taken as meaning three constraint types set in one formula, these being =, ≤ and ≥.

3.6 Mixed Constraints

3.6.1.1. $MixedConstraintVariable_m \times MixedConstVarWeight1_m + \sum_{p \in MIXEDDEMNODEGROUP_m} Demand_p \times MixedConstDemWeight_{p,m} + \sum_{g \in MIXEDGENNODEGROUP_m} Generation_g \times MixedConstGenWeight_{g,m} + \sum_{r \in MIXEDRESNODEGROUP_m} Reserve_r \times MixedConstResWeight_{r,m} + \sum_{q \in MIXEDDIRACLINEGROUP_m} ACLineFlow_p^{Directed} \times MixedConstACLineWeight_{q,m} + \sum_{q \in MIXEDDIRACLINEGROUP_m} ACLineLosses_q^{Directed} \times MixedConstACLineLossWeight_{q,m} + \sum_{k \in MIXEDACLINEGROUP_m} ACLineFixedLosses_k \times MixedConstACLineFixedLossWeight_{k,m} + \sum_{l \in MIXEDDCLINKGROUP_m} HVDCLinkFlow_l \times MixedConstDCLinkWeight_{l,m} + \sum_{l \in MIXEDDCLINKGROUP_m} HVDCLinkLosses_l \times MixedConstDCLinkLossWeight_{l,m} + \sum_{l \in MIXEDDCLINKGROUP_m} HVDCLinkFixedLosses_l \times MixedConstDCLinkFixedLossWeight_{l,m} =\leq\geq MixedConstraintLimit1_m$

$$\forall m \in MIXEDCONSTRAINTS_{Type1}$$

3.6.1.2. $\sum_{m \in MIXEDVARGROUP_b} MixedConstraintVariable_m \times MixedConstVarWeight2_{m,b} =\leq\geq MixedConstraintLimit2_b$

$$\forall b \in MIXEDCONSTRAINTS_{Type2}$$

3.7 Ramping

3.7.1.1. $Generation_g \leq Generation_g^{End,Up} \quad \forall g \in UNITGENERATORS$

3.7.1.2. $Generation_g \geq Generation_g^{End,Down} \quad \forall g \in UNITGENERATORS$

Notes: RHS is from pre-processing section 5.3.1.1 and 5.3.2.1.

3.8 Integer Constraints

The Mathematical model presented in this document has a linear objective function with integer variables used in some constraints thus resulting in a mixed integer linear programming (MILP) formulation. Section 2.7.3. list the integer variables used in the initial model solve in constraints (3.4.2.7)-(3.4.2.16) and (3.4.2.22)-(3.4.2.27).

Most of the constraints discussed are also linear and create a convex feasibility region. However the cConstraints (3.3.1.6.)-(3.3.1.9.) in section 3.3 are used to linearise a non-linear equality constraint, a technique which is really only applicable for convex optimisation problems. However when the effective cost of losses is negative, the solution must be forced to lie in a non-convex feasible region, and this approximation will not produce the correct result.

Apart from that, tThe $ACLineFlow_k$ constraint (3.3.1.4.) in section 3.3 defines the unrestricted power flow by two positive variables, each representing a directed power flow. Then the transmission loss is modelled as a function of these directed power flow variables in (3.3.1.8.)-(3.3.1.9.) equation in section 3.3. This approach is used to satisfy the market rule requirement to have line losses modelled at the receiving end of the line. When the objective becomes non-convex (globally or locally) this formulation can give circulating branch flows. Similarly, two parallel DC poles can have circulating branch flows in non-convex situations.

A two-stage process will be used to prevent the above-mentioned circulating branch flows and non-physical losses. An initial MILP pure LP formulation is used first and, when circulating branch flows or non-physical losses are identified in the solution, the problem will be re-solved with additional "integer constraints" which force the model to choose between the physically feasible alternative solutions.

There are instances where a continuousthe initial linear program (MILP) formulation can produce solutions that could not be physically implemented. This applies to commitment of HVDC poles in particular directions. In these instances a method must be used to reflect the integer nature of the constraints and allow the optimisation to use the least cost solution.

3.8.1 *AC branch integer constraints.*

In order to prevent physically infeasible "circulation" on AC lines in the SPD formulation, an integer constraint can be activated to ensure that one of two variables $ACLineFlow_{F(k)}^{Directed}$ or $ACLineFlow_{B(k)}^{Directed}$ $\forall k \in ACLINES$ must be zero, the other can be non-zero. This integer constraint only operates when the existence of non-physical losses is detected in the initial MILP solution. AC branch integer constraints are not applied to lossless AC branches.

3.8.2 *Integer constraints to prevent HVDC circulating flows*

There can be situations when the SPD solution could schedule circulating power flow between directed lines within the HVDC poles. This is not a practical outcome and must be prevented to produce a real solution. To prevent these circulating flows it is necessary to introduce integer constraints that allow only one line within each HVDC pole to have a non-zero flow. The same situation can occur with circulating power flow between HVDC poles and there are similar integer constraints to prevent this. In some circumstances there may be a requirement to intentionally schedule circulating power flow between HVDC poles. When this is required the integer constraints that prevent the circulating power flow between HVDC poles will be disabled. This feature will only be used during commissioning.

3.8.3 *Piece-wise linear approximation of HVDC losses (Lambda formulation).*

The lambda formulation for the HVDC given in the equations in section 3.2 will not, of itself, remove non-physical losses completely. When non-physical losses are detected in the initial MILP solution, integer constraints will be applied to the lambda formulation so as to ensure that at most two adjacent $Lambda_{l,bp}$, $Lambda_{l,bp+1}$ are greater then zero in the model. The others must be zero. This approach forces the model to interpolate between adjacent breakpoints on the curve, rather than between non-adjacent points which would produce non-physical flow/loss pairs above it.

3.8.4 *Integer Constraints for non-continuous limits*

When the limits on a set of circuits, transformers, and/or market nodes is dependent on the sign of another variable (indicating a direction of flow, for example), then a decision must be made as to what sign that variable will have, and hence which limits shall apply. Where appropriate an integer optimisation may be used to determine the most appropriate sign, and set limits accordingly. These integer constraints existed only in mixed constrains section 3.6, and will be subject to approval in accordance with the procedures established for constraints in each of those sections. Such integer constraints will effectively force the model to examine an LP solution for each possible constraint limit condition, and then select the lowest cost solution from those options.

3.8.5 *Reserve sharing*

Integer constraints have been introduced to the model formulation to represent the non-convex operating region of the HVDC when sharing reserves in the reverse direction. The integer variables (described in 2.7.3) are used to identify the HVDC sending island and also identify the zone within which the HVDC is operating, which in turn affects the constraints that limit the quantity of reserves that can be shared across the HVDC in the reverse direction, as shown by constraints (3.4.2.7)-(3.4.2.16).

The lambda formulation is used to model the losses for the sent HVDC flow and the HVDC flow after accounting for shared reserves, as shown by constraints (3.4.2.22)-(3.4.2.27). These losses are used to adjust the shared reserves received in an island. Integer constraints are applied to the lambda formulation so as to ensure that at most two adjacent lambda variables are greater than zero in the model.

4 Objective Function

The *NetBenefit* is maximised.

4.1.1.1.

$$NetBenefit = \sum_{p \in BIDS} \sum_{j=1}^{DemandBidBlocks_p} DemandBlock_{p,j} \times DemandBidPrice_{p,j} - \sum_{g \in OFFERS} \sum_{j=1}^{GenerationOfferBlocks_g} GenerationBlock_{g,j} \times GenerationOfferPrice_{g,j} - \sum_{r \in RESERVEOFFERS} \sum_{j=1}^{ReserveOfferBlocks_r} ReserveBlock_{r,j} \times ReserveOfferPrice_{r,j} - ExcessResSharePenalty$$

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5 Pre-processing

5.1 HVDC Transmission

The importance and nature of the HVDC link together with its peculiarities requires some pre-processing to better model the HVDC link. This relates to the poles being in and out of service.

5.1.1 *Both poles operating*

This is considered the normal situation.

5.1.2 *One or more poles not operating*

5.1.2.1. $HVDCLinkCapacity_l = 0$

$\forall l \in HVDCLinks_{POLEOUT}$ where $POLESOUT$ is the set of poles not operating.

5.1.2.2. $HVDCLinkFixedLosses_l = 0 \quad \forall l \in HVDCLinks_{POLEOUT}$

5.2 Reserve

5.2.1.1. $$ReserveMaximumFactor_{g,c} = \frac{ReserverGenerationMaximum_g}{ReserveGenerationMaximum_{g,c}}$$

$$\forall g \in OFFERS \quad \forall c \in RESERVECLASSES$$

5.2.1.2. $$SharedNFRMax_{i,c} = min\left(SharedNFRMaxLimit_{i,c}, SharedNFRFactor \times \left(\sum_{n(i)} LoadForecast_n + \sum_{p \in NOMINATEDBIDS_{n(i)}} \sum_{j=1}^{DemandBidBlocks_p} DemandBidMW_{p,j} - SharedNFRLoadOffset_i\right)\right)$$

$$\forall i \in ISLANDS \quad \forall c \in \{FIR\}$$

5.2.1.3. $SharedNFRMax_{i,c} = 0$

$$\forall i \in ISLANDS \quad \forall c \in \{SIR\}$$

5.2.1.4. $$RiskOffsetParameter_{i,c,rc} = RiskOffsetParameter_{i,c,rc} - SharedNFRMax_{j,c}$$

$$\forall i,j \in ISLANDS \text{ and } i \neq j, \qquad \forall c \in \{FIR\}$$

$$\forall rc \in \left\{\begin{matrix} ACCERISKS_i, ACECERISKS_i, ManualCE_i, ManualECE_i \\ ACCERISKGROUPS_i, ACECERISKGROUPS_i \end{matrix}\right\}$$

5.2.1.5. $$HVDCMaxLessMR_i = max\left(0, HVDCMax_i - max\left(ModulationRisk_{i,DCCE_i}, ModulationRisk_{i,DCECE_i}\right)\right)$$

$$\forall i \in ISLANDS$$

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5.2.1.6. $ResShareMaxLessMR_{i,rd} = max\left(0, ResShareControlBand_{rd} - max\left(ModulationRisk_{i,DCCE_i}, ModulationRisk_{i,DCECE_i}\right)\right)$

$$\forall i \in ISLANDS, \quad \forall rd \in RESERVEDIRECTIONS$$

5.2.1.7. $MonopoleMinPlusMR = MonopoleMin + max_i\left(ModulationRisk_{i,DCCE_i}, ModulationRisk_{i,DCECE_i}\right)$

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5.3 Ramping

SPD uses a MW-based ramping model, assuming that generators ramp instantaneously. In the case of jointly owned units the ramp rate of the primary market node unit is applied to the total generation output of the primary and secondary node units.
The following pre-processing is performed for all generation offers
$g \in UNITGENERATORS$

5.3.1 *Ramping up*

5.3.1.1. $Generation_g^{End,Up} = Generation_g^{Start} + \left(RampRate_g^{Up} \times TradingPeriodLength\right)$

5.3.2 *Ramping down*

5.3.2.1. $Generation_g^{End,Down} = Generation_g^{Start} - \left(RampRate_g^{Down} \times TradingPeriodLength\right)$

5.4 Loss Approximations

For each AC line and HVDC link, the variable loss part of the loss curve is approximated by a piecewise linear curve with a pre-determined number of segments. The approximation does not include the fixed losses, which are handled separately (see Constraint 3.3).

For an AC line or HVDC link the variable MW losses are approximated by $R \times F^2$ where *R* is the resistance per unit for an AC line, or the HVDC link resistance scaled to allow for using MW instead of current (assuming a constant voltage). *F* is the MW flow in the line.

A sequence of "breakpoints", MW and loss pairs, define the beginning and end points of the segments making up the approximation. The beginning of the first segment is the (0,0) point and the end of the last segment is at the point defined by the capacity of the line and the loss incurred when the flow is equal to the capacity of the line. The breakpoints are determined by minimising the difference between the approximation and the quadratic curve.

For AC lines, loss factors are derived to define losses for points within the "block" between each pair of breakpoints. The same effect is achieved automatically by the "lambda formulation" used for HVDC links.

A piecewise linear curve approximation of total inter-island HVDC variable losses is used for reserve sharing. The inter-island HVDC variable losses use the combined capacity of in-service HVDC links and the resistance of in-service parallel HVDC links to determine the sequence of "breakpoints" of MW and loss pairs that define the beginning and end points of the segments making up the approximation.

6 Post Processing

6.1 Energy Prices

Item	Description
$ACNodePrice_n$	The energy price for an AC node *n* is the dual variable value (shadow price) of the constraint (3.3.1.2), the energy balance constraint, for that node.

Under scarcity pricing the energy price may be subject to scaling in the Final Pricing schedule, such that:

$$ACNodePrice_n = ACNodePrice_n \times ScarcityPricingFactor_s$$

$$\forall n \in \{ACNODES_n \; in \; Scarcity \; Area \; s \; \in SCARCITYAREAS\}$$

6.2 Reserve Prices

Item	Description
$ReservePrice_{i,c}$	The reserve price for reserve class *c* and island *i* is the dual variable value (shadow price) of the reserve balance constraint (3.4.43.2) for reserve class *c* and island *i.*

Under scarcity pricing the reserve price may be subject to scaling in the Final Pricing schedule, such that:

$$ReservePrice_{i,c} = ReservePrice_{i,c} \times ScarcityPricingFactor_s$$

$$\forall c \in \{RESERVECLASSES\}$$

$$\forall i \in \{ISLANDS_i \; in \; Scarcity \; Area \; s \; \in SCARCITYAREAS\}$$

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6.3 Scarcity Pricing

In the event that the system operator requires the disconnection of demand for a trading period then when preparing the Final Pricing schedule the pricing manager may determine that a scarcity pricing situation exists for the scarcity area in which the disconnection(s) occurred, where a scarcity area is defined as either one island or both islands together. Provided that the average of the Generation Weighted Average Prices (GWAP) from prior periods falls below a defined threshold, scarcity pricing will be applied, resulting in energy and reserve prices in the scarcity area being scaled such that, after scaling, the resulting GWAP falls between defined floor and ceiling values. Note that although GWAP is based on generation node energy prices, any scaling factor that is determined will be applied to all energy and reserve prices in the scarcity area.

6.3.1 *Set*

Item	Definition
$SCARCITYAREAS_s$	The set of all scarcity areas, indexed by *s*, to which a scarcity situation may apply. The scarcity area may be either one island or both islands together i.e. $s \in \{NI, SI, NI \cup SI\}$

6.3.2 *Parameters*

Item	Description
$GWAP_s$	Generation Weighted Average Price (GWAP) for scarcity area *s*. Used to determine $ScarcityPricingFactor_s$.
$GWAP_i$	Generation Weighted Average Price (GWAP) for island *i*. Used in the calculation of $AveragePriorGWAP_i$, which is used by the threshold check.
$ScarcitySituationExists_s$	Flag to indicate that the pricing manager has determined that a scarcity situation exists for the scarcity area *s.*
$AveragePriorGWAP_i$	Average of $GWAP_i$ for island *i* for the 336 trading periods prior to the trading period being solved. Used by the threshold check.
$GWAPThreshold_i$	GWAP price threshold for island *i*. If a scarcity situation exists where the scarcity area *s* is an individual island *i*, then if $AveragePriorGWAP_i$ is above the threshold $GWAPThreshold_i$ then scarcity pricing will not apply. If a scarcity situation exists where the scarcity area *s* consists of both islands *i*, then if $AveragePriorGWAP_i$ is above the threshold $GWAPThreshold_i$ for <u>either</u> island *i* then scarcity pricing will not apply.
$GWAPFloor_s$ $GWAPCeiling_s$	To apply scarcity pricing, a $ScarcityPricingFactor_s$ is determined such that, when this factor is applied to the prices in scarcity area *s*, the resulting $GWAP_s$ for scarcity area *s* will be at or above $GWAPFloor_s$ and at or below g_s .
$ScarcityPricingFactor_s$	Scaling factor calculated such that when applied to all energy and reserve prices in the scarcity area *s* then $GWAP_s$ will fall between $GWAPFloor_s$ and $GWAPCeiling_s$

6.3.3 *GWAP calculations*

$$GWAP_s = \frac{\sum_{n(s)} \sum_{g \in OFFERS_n} (Generation_g \times ACNodePrice_n)}{\sum_{n(s)} \sum_{g \in OFFERS_n} Generation_g}$$

$$\forall n \in \{ACNODES_n \text{ in Scarcity Area } s \in SCARCITYAREAS\}$$

$$GWAP_i = \frac{\sum_{n(s)} \sum_{g \in OFFERS_n} (Generation_g \times ACNodePrice_n)}{\sum_{n(s)} \sum_{g \in OFFERS_n} Generation_g}$$

$$\forall n \in \{ACNODES_n \text{ in Island } i \in ISLANDS\}$$

6.3.4 *Scaling factor calculation*

$$if\ GWAP_s \geq GWAPFloor_s\ \ AND\ \ GWAP_s \leq GWAPCeiling_s$$

$$then\ ScarcityPricingFactor_s = 1$$

$$else\ if\ GWAP_s < GWAPFloor_s$$

$$then\ ScarcityPricingFactor_s = \frac{GWAPFloor_s}{GWAP_s}$$

$$else\ if\ GWAP_s > GWAPCeiling_s$$

$$then\ ScarcityPricingFactor_s = \frac{GWAPCeiling_s}{GWAP_s}$$