SECTION C: LINEAR PROGRAM

D.14 OBJECTIVE FUNCTION

14.1 The NetBenefit is maximised, where:

D.14.1.1

$$
\begin{aligned}
\text{NetBenefit} = & \sum_{\{j,p \mid j \in \text{PURCHASEBIDBLOCKS}_p,\ \text{where } p \in \text{BIDS}\}} \text{PurchaseBidPrice}_{p,j} \times \text{PurchaseBlock}_{p,j} \\
& - \sum_{\{j,g \mid j \in \text{GENERATIONOFFERBLOCKS}_g,\ \text{where } g \in \text{ENERGYOFFERS}\}} \text{GenerationOfferPrice}_{g,j} \times \text{GenerationBlock}_{g,j} \\
& - \sum_{\{j,r \mid j \in \text{RAWRESERVEBLOCKS}_r,\ \text{where } r \in \text{RAWRESERVEOFFERS}\}} \text{ReserveOfferPrice}_{r,j} \times \text{RawReserveBlock}_{r,j} \\
& - \sum_{\{j,l \mid j \in \text{REGULATIONOFFERBLOCKS}_l,\ \text{where } l \in \text{REGULATIONOFFERS}\}} \text{RegulationOfferPrice}_{l,j} \times \text{RegulationBlock}_{l,j} \\
& - \sum_{\{j,n \mid j \in \text{EXCESSGENERATIONBLOCKS}_n,\ \text{where } n \in \text{NODES}\}} \text{ExcessGenerationPenalty}_{n,j} \times \text{ExcessGenerationBlock}_{n,j} \\
& - \sum_{\{j,n \mid j \in \text{DEFICITGENERATIONBLOCKS}_n,\ \text{where } n \in \text{NODES}\}} \text{DeficitGenerationPenalty}_{n,j} \times \text{DeficitGenerationBlock}_{n,j} \\
& - \text{ViolationPenalties}
\end{aligned}
$$

Explanatory Note: NetBenefit is the sum of producer surplus and consumer surplus. The objective of the MCE's optimization process is to maximize the value of economic welfare, as measured by the sum of producer surplus and consumer surplus, which is equivalent to minimizing the cost.

D.15 CONSTRAINTS ON ENERGY GENERATION AND PURCHASES

D.15.1.1 Generation Block Constraint:

$$\text{GenerationBlock}_{g,j} \leq \text{GenerationBlockMax}_{g,j}$$

$$\{j,g \mid j \in \text{GENERATIONOFFERBLOCKS}_g, \text{where } g \in \text{ENERGYOFFERS}\}$$

D.15.1.2 Generation Summation Constraint:

$$\text{Generation}_g = \sum_{j \in \text{GENERATIONOFFERBLOCKS}_g} \text{GenerationBlock}_{g,j}$$

$$\{g \in \text{ENERGYOFFERS}\}$$

D.15.1.3 Purchase Block Constraint:

$$\text{PurchaseBlock}_{p,j} \leq \mathit{PurchaseBlockMax}_{p,j}$$

$$\{j,p \mid j \in \text{PURCHASEBIDBLOCKS}_p, \text{where } p \in \text{ENERGYBIDS}\}$$

D.15.1.4 Purchase Summation Constraint:

$$\text{Purchase}_p = \sum_{j \in \text{PURCHASEBIDBLOCKS}_p} \text{PurchaseBlock}_{p,j}$$

$$\{p \in \text{ENERGYBIDS}\}$$

D.15.1.5 $\text{TotalPurchase} = \sum_{\substack{p \in \text{ENERGYBIDS} \\ p \notin \text{INTERTIEENERGYBIDS}}} \text{Purchase}_p$

D.16 TRANSMISSION

D.16.1 Node Balance

D.16.1.1 Node Balance Flow Constraint:

$$\text{NodeNetInjection}_n = \sum_{\{k \in \text{LINES} \mid NodeAtStartOf(k)=n\}} \text{LineFlow}_k - \sum_{\{k \in \text{LINES} \mid NodeAtEndOf(k)=n\}} \text{LineFlow}_k + \tfrac{1}{2} \times \sum_{\substack{k \in \text{LINES}_n, \\ k \notin \text{ARTIFICIALLINES1} \\ k \notin \text{ARTIFICIALLINES3}}} \text{LineLoss}_k$$

$$\{n \in \text{NODES}\}$$

D.16.1.2 Node Balance Generation Constraint:

$$\text{NodeNetInjection}_n = \sum_{g \in \text{OFFERS}_n} \text{Generation}_g - \sum_{p \in \text{BIDS}_n} \text{Purchase}_p + \sum_{j \in \text{DEFICITGENERATIONBLOCKS}_n} \text{DeficitGenerationBlock}_{n,j} - \sum_{j \in \text{EXCESSGENERATIONBLOCKS}_n} \text{ExcessGenerationBlock}_{n,j}$$

$$\{n \in \text{NODES}\}$$

D.16.1.3 Deficit Generation Block Constraint:

$$\text{DeficitGenerationBlock}_{n,j} \leq \text{DeficitGenerationBlockMax}_{n,j}$$

$$\{j,n \mid j \in \text{DEFICITGENERATIONBLOCKS}_n, \text{where } n \in \text{NODES}\}$$

D.16.1.4 Excess Generation Block Constraint:

$$\text{ExcessGenerationBlock}_{n,j} \leq \text{ExcessGenerationBlockMax}_{n,j}$$

$$\{j,n \mid j \in \text{EXCESSGENERATIONBLOCKS}_n, \text{where } n \in \text{NODES}\}$$

D.16.2 Line Flow

D.16.2.1 Flow Reverse Constraint:

$$\text{LineMaxReverse}_k \le \text{LineFlow}_k + \text{ExcessLineFlowReverse}_k$$

$$\{k \in \text{LINES}, k \notin \text{ARTIFICIALLINES1} \cup \text{ARTIFICIALLINES3}\}$$

D.16.2.2 Flow Forward Constraint:

$$\text{LineMaxForward}_k \ge \text{LineFlow}_k - \text{ExcessLineFlowForward}_k$$

$$\{k \in \text{LINES}, k \notin \text{ARTIFICIALLINES3}\}$$

D.16.2.3 Node Angle Constraint:

$$\text{LineFlow}_k = \text{LineAdmittance}_k \times \left(\text{NodeAngle}_{NodeAtStartOf(k)} - \text{NodeAngle}_{NodeAtEndOf(k)} + \text{PhaseAngleShift}_k\right)$$

$$\{k \in \text{LINES}, k \notin \text{ARTIFICIALLINES1} \cup \text{ARTIFIALLNES3}\}$$

However, in the case where the constraint in this section D.16.2.3 corresponds to a notional line connecting two electrically equivalent buses introduced to the dispatch network in accordance with section D.6.3.4, then the following constraint shall be substituted:

$$0 = \left(\text{NodeAngle}_{NodeAtStartOf(k)} - \text{NodeAngle}_{NodeAtEndOf(k)}\right)$$

$$\{k \in \text{ARTIFICIALLINES3}\}$$

D.16.2.4 Reference Node Angle Constraint:

$$\text{NodeAngle}_{\text{REFERENCENODE}} = 0$$

D.16.3 Line Losses

D.16.3.1 Line Flow Constraint:

$$\text{LineFlow}_k = \sum_{j \in \text{DISCRSUB}_k} \text{LineFlowConst}_{k,j} \times \text{Weight}_{k,j} + \text{DeficitWLineFlow}_k - \text{ExcessWLineFlow}_k$$

$$\{k \in \text{LINES}, k \notin \text{ARTIFICIALLINES1} \cup \text{ARTIFICIALLINES3}\}$$

D.16.3.2 Line Loss Constraint:

$$\text{LineLoss}_k = \sum_{j \in \text{DISCRSUB}_k} \text{LineLossConst}_{k,j} \times \text{Weight}_{k,j}$$

$$\{k \in \text{LINES}, k \notin \text{ARTIFICIALLINES1} \cup \text{ARTIFICIALLINES3}\}$$

D.16.3.3 Weight Summation Constraint:

$$\sum_{j \in \text{DISCRSUB}_k} \text{Weight}_{k,j} = 1$$

$$\{k \in \text{LINES}, k \notin \text{ARTIFICIALLINES1} \cup \text{ARTIFICIALLINES3}\}$$

D.16.4 Relaxation of Line Constraints

The provisions of this section shall only apply to a re-run of the *market clearing engine* under Section 10.2.3A.2 and section 10.2.5B of Chapter 6.

D.16.4.1 Revised Flow Reverse Constraint

$$\text{LineMaxReverse}_k \leq \text{LineFlow}_k + \text{ExcessLineFlowReverse}_k$$

$$\{k \in \text{ARTIFICIALLINES2}\}$$

This constraint will replace constraint in D.16.2.1

D.16.4.2 Revised Flow Forward Constraint

$$\text{LineMaxForward}_k \geq \text{LineFlow}_k - \text{ExcessLineFlowForward}_k$$

$$\{k \in \text{ARTIFICIALLINES1} \cup \text{ARTIFICIALLINES2}\}$$

This constraint will replace constraint in D.16.2.2

D.16.4.3 The constraint in section D.21.2 shall apply in place of the constraint in section D.21.1.

D.16.4.4 Revised MaxLineRating

$$\text{MaxLineRating}_k = \text{maximum}(\text{LineRatingForward}_k, \text{LineRatingReverse}_k)$$

$$\text{RevisedMaxLineRating}_k = \frac{\text{AdditionalNumPoints}_k}{2} \times \frac{\text{MaxLineRating}_k}{(\text{NumPoints}_k - 1)/2} + \text{MaxLineRating}_k$$

$$\text{LineFlowConst}_{k,j} = -\text{RevisedMaxLineRating}_k + \frac{j-1}{\text{NumPoints}_k - 1} \times \text{RevisedMaxLineRating}_k \times 2$$

$$\{k,j \mid j \in \{1,\ldots,\text{NumPoints}_k\}, \text{where } k \in \text{LINES},\ k \notin \text{ARTIFICIALLINES}\}$$

This section will replace section D.9.3 for the purposes of constraint relaxation.

Explanatory Note: Additional line flow/line loss points are required in order to accommodate the increased flow that may occur when line flow constraints are relaxed.

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D.17 RISK AND OPERATING RESERVE

D.17.1 Risk

D.17.1.1 Generator Risk Constraint:

$$\text{Risk}_c \geq \text{RiskAdjustmentFactor}_c \times \text{RawCalculatedRisk}_c$$

where:

$$\begin{aligned}\text{RawCalculatedRisk}_c &= \text{Generation}_g - \text{PowerSystemResponse}_{g,c} \\ &+ \text{EstReserveEffectiveness}_{r(g,c)} \times \text{RawReserve}_{r(g,c)} \\ &+ \sum_{h \in \text{SECONDARYRISKGENERATORS}, h \neq g} (\text{Generation}_h + \text{EstReserveEffectiveness}_{r(h,c)} \times \text{RawReserve}_{r(h,c)})\end{aligned}$$

and

$$\begin{aligned}&\text{PowerSystemResponse}_{g,c} = \\ &\text{EstIntertieContribution} \times \text{AcceptableFreqDeviation}_c \times \text{EstLoadDamping}_c \times \text{TotalPurchase} \\ &- \text{EstGTOutputDamping}_c \times \sum_{i \in \text{DAMPINGGENERATORS}, i \neq g} \text{Generation}_i\end{aligned}$$

$$\{g, c \mid g \in \text{RISKGENERATORS},\ c \in \text{RESERVECLASSES}\}$$

D.17.1.2 Minimum Risk Constraint:

$$\text{Risk}_c \geq \text{MinimumRisk}_c$$

$$\{c \mid c \in \text{RESERVECLASSES}\}$$

D.17.2 Supply of Contingency Reserve

D.17.2.1 Raw Reserve Block Constraint:

$$\text{RawReserveBlock}_{r,j} \leq \text{RawReserveBlockMax}_{r,j}$$

$$\{j, r \mid j \in \text{RAWRESERVEBLOCKS}_r, \text{where } r \in \text{RAWRESERVEOFFERS}\}$$

D.17.2.2 Raw Reserve Summation Constraint:

$$\text{RawReserve}_r = \sum_{j \in \text{RAWRESERVEBLOCKS}_r} \text{RawReserveBlock}_{r,j}$$

$$\{ r \in \text{RAWRESERVEOFFERS} \}$$

D.17.2.3 Reserve Proportion Constraint:

$$\text{RawReserve}_r - \text{ExcessRawReserve}_r \le \text{ReserveProportion}_r \times \text{Generation}_{g(r)}$$

$$\{ r \in \text{GENRESERVEOFFERS} \}$$

D.17.2.4 Reserve Generation Max Constraint:

$$\text{Generation}_{g(r)} + \text{RawReserve}_r + \text{Regulation}_{l(r)} - \text{ExcessResGen}_r \le \text{ReserveGenerationMax}_r$$

$$\{ r \in \text{GENRESERVEOFFERS} \}$$

D.17.2.5 Reserve Generation Segment 1

$$\text{RawReserve}_r - \text{ExcessResGenSegment1}_r \le \text{HighLoadReserve}_r + \text{Slope}$$
$$\text{x } (\text{Generation}_{g(r)} - \text{HighLoad x StandingReserveGenerationMax}_{g(r)})$$
$$\{ r \in \text{GENRESERVEOFFERS} \}$$

where :

$$\text{Slope} = -\text{HighLoadReserve}_r \; / \; (\text{StandingReserveGenerationMax}_{g(r)}$$
$$- \text{HighLoad x StandingReserveGenerationMax}_{g(r)})$$

D.17.2.6 Reserve Generation Segment 2

$$\text{RawReserve}_r - \text{ExcessResGenSegment2}_r \le \text{MediumLoadReserve}_r + \text{Slope}$$
$$\text{x } (\mathit{Generation}_{g(r)} - \text{MediumLoad x StandingReserveGenerationMax}_{g(r)})$$
$$\{ r \in \text{GENRESERVEOFFERS} \}$$

where:

$$\text{Slope} = (\text{HighLoadReserve}_r - \text{MediumLoadReserve}_r) \; / \; (\text{HighLoad}$$
$$\text{x StandingReserveGenerationMax}_{g(r)} - \text{MediumLoad x StandingReserveGenerationMax}_{g(r)})$$

D.17.2.7 Reserve Generation Segment 3

$$\text{RawReserve}_r - \text{ExcessResGenSegment3}_r \leq \text{LowLoadReserve}_r + \text{Slope} \times (\text{Generation}_{g(r)} - \text{LowLoad}_{g(r)})$$

$$\{ r \in \text{GENRESERVEOFFERS}\}$$

where :

$$\text{Slope} = (\text{MediumLoadReserve}_r - \text{LowLoadReserve}_r) / (\text{MediumLoad} \times \text{StandingReserveGenerationMax}_{g(r)} - \text{LowLoad}_{g(r)})$$

D.17.3 Matching of requirements and availability

D.17.3.1 Group Response Constraint:

$$\sum_{j \in \text{RESERVEGROUPBLOCKS}_x} \text{GroupResponse}_{x,j} \leq \sum_{r \in \text{RAWRESERVEOFFERS}_x} \text{RawReserve}_r$$

$$\{x \in \text{RESERVEGROUPS}\}$$

D.17.3.2 Group Response Block Constraint:

$$\text{GroupResponse}_{x,j} \leq \text{GroupResponseMax}_{x,j}$$

$$\{ j \in \text{RESERVEGROUPBLOCKS}_x \text{ where } x \in \text{RESERVEGROUPS}\}$$

D.17.3.3 Effective Reserve Constraint:

$$\text{EffectiveReserve}_x = \sum_{j \in \text{RESERVEGROUPBLOCKS}_x} \text{Effectiveness}_{x,j} \times \text{GroupResponse}_{x,j}$$

$$\{x \in \text{RESERVEGROUPS}\}$$

D.17.3.4 Reserve Balance Constraint:

$$\sum_{x \in \text{RESERVEGROUPS}_c} \text{EffectiveReserve}_x + \text{DeficitReserve}_c \geq \text{Risk}_c$$

$$\{c \in \text{RESERVECLASSES}\}$$

D.17.3.5 Reserve Zone Summation Constraint

$$\text{ZoneResponse}_{z,c} = \sum_{r \in \text{RAWRESERVEOFFERS}_{z,c}} \text{RawReserve}_r$$

$$\{z, c \mid z \in \text{RESERVEZONES}_c, c \in \text{RESERVECLASSES}\}$$

D.17.3.6 Reserve Zone Response Constraint

$$\text{ZoneResponse}_{z,c} \le \text{ZoneResponseMax}_z$$

$$\{z, c \mid z \in \text{RESERVEZONES}_c, c \in \text{RESERVECLASSES}\}$$

D.17.3.7 Interruptible Load Max Constraint

$$\sum_{z \in \text{RESERVEZONES}_c} \text{ZoneResponse}_z \le \text{ILProportionMax}_c \times \text{Risk}_c$$

$$\{z, c \mid z \in \text{RESERVEZONES}_c, c \in \text{RESERVECLASSES}\}$$

Note that Constraints D.17.3.6 and D.17.3.7 will limit the raw *reserve*.

D.18 REGULATION

D.18.1 Supply of Regulation

D.18.1.1 Regulation Block Constraint:

$$\text{RegulationBlock}_{l,j} \leq \text{RegulationBlockMax}_{l,j}$$

$$\{ j,l \mid j \in \text{REGULATIONOFFERBLOCKS}_l, \text{where } l \in \text{REGULATIONOFFERS}\}$$

D.18.1.2 Regulation Summation Constraint:

$$\text{Regulation}_l = \sum_{j \in \text{REGULATIONOFFERBLOCKS}_l} \text{RegulationBlock}_{l,j}$$

$$\{ l \in \text{REGULATIONOFFERS}\}$$

D.18.1.3 Regulation Max Constraint:

$$\text{Generation}_{g(l)} + \text{Regulation}_l - \text{ExcessRegGen}_l \leq \text{RegulationMax}_{g(l)}$$

$$\{ l \in \text{REGULATIONOFFERS}\}$$

D.18.1.4 Regulation Min Constraint:

$$\text{Generation}_{g(l)} - \text{Regulation}_l + \text{DeficitRegGen}_l \geq \text{RegulationMin}_{g(l)}$$

$$\{ l \in \text{REGULATIONOFFERS}\}$$

D.18.2 Matching of requirements and availability

D.18.2.1 Regulation Balance Constraint:

$$\sum_{l \in \text{REGULATIONOFFERS}} \text{Regulation}_l + \text{DeficitRegulation} \geq \text{RegulationRequirement}$$

D.18.3 Mixed Integer Program Based Regulation Constraints

The provisions of this section shall apply only to a re-solve of the linear program under section D.21A.2 or section D.22.7 where applicable. In such a re-solve, sections D.18.3.1 to D.18.3.7 shall replace sections D.18.1.3 and D.18.1.4.

D.18.3.1 Mixed Integer Program Based Regulation Max Constraint

$$\text{Generation}_{g(l)} + \text{Regulation}_l - \text{ExcessRegGen}_l - \text{InfinitePositiveValue} \times \text{RegulationSegmentSelector2}_l \le \text{RegulationMax}_{g(l)}$$

$$\{l \in \text{REGULATIONOFFERS}\}$$

D.18.3.2 Mixed Integer Program Based Regulation Min Constraint

$$\text{Generation}_{g(l)} - \text{Regulation}_l + \text{DeficitRegGen}_l + \text{InfinitePositiveValue} \times \text{RegulationSegmentSelector2}_l \ge \text{RegulationMin}_{g(l)}$$

$$\{l \in \text{REGULATIONOFFERS}\}$$

D.18.3.3 Regulation Availability Determination at Regulation Max

$$\text{Regulation}_l - \text{InfinitePositiveValue} \times \text{RegulationSegmentSelector3}_l \le 0$$

$$\{l \in \text{REGULATION OFFERS}\}$$

D.18.3.4 Regulation Availability Determination at Regulation Min

$$\text{Regulation}_l - \text{InfinitePositiveValue} \times \text{RegulationSegmentSelector1}_l \le 0$$

$$\{l \in \text{REGULATIONOFFERS}\}$$

D.18.3.5 Generation Switch at Regulation Max

$$\text{Generation}_{g(l)} + \text{InfinitePositiveValue} \times \text{RegulationSegmentSelector3}_l \ge \text{RegulationMax}_{g(l)}$$

$$\{l \in \text{REGULATIONOFFERS}\}$$

D.18.3.6 Generation Switch at Regulation Min

$$\text{Generation}_{g(l)} - \text{InfinitePositiveValue} \times \text{RegulationSegmentSelector1}_l \le \text{RegulationMin}_{g(l)}$$

$$\{l \in \text{REGULATIONOFFERS}\}$$

D.18.3.7 Regulation Segment Selectors Restrictions

$$\text{RegulationSegmentSelector1}_l + \text{RegulationSegmentSelector2}_l + \text{RegulationSegmentSelector3}_l = 2$$

$$\{l \in \text{REGULATIONOFFERS}\}$$

D.19 RAMPING

D.19.1 Energy Ramping Constraints

D.19.1.1 Up Ramp Constraint:

$$\text{Generation}_g - \text{ExcessUpRampRate}_g \le \text{GenerationEndMax}_g$$

$$\{ g \in \text{ENERGYOFFERS}, g \notin \text{INTERTIEENERGYOFFERS}\}$$

D.19.1.2 Down Ramp Constraint:

$$\text{Generation}_g + \text{ExcessDownRampRate}_g \ge \text{GenerationEndMin}_g$$

$$\{ g \in \text{ENERGYOFFERS}, g \notin \text{INTERTIEENERGYOFFERS}\}$$

D.19.2 Combined ramping, *reserve* and *regulation* constraints

D.19.2.1 Reserve Ramp Constraint:

$$\text{RawReserve}_r + \text{ReserveResponseRatio}_r \times (\text{Generation}_{g(r)} - \text{StartGeneration}_{g(r)}) - \text{ExcessResRamp}_r \le \text{MaxResponse}_r$$

$$\{r \in \text{GENRESERVEOFFERS, where ReserveResponsePeriod}_{c(r)} > \text{CombinedRampThreshold}\}$$

D.19.2.2 Reserve Proportion Ramp Constraint:

$$\text{RawReserve}_r + \text{ReserveResponseRatio}_r \times (\text{Generation}_{g(r)} - \text{StartGeneration}_{g(r)}) - \text{ExcessResPropRamp}_r \le \text{ReserveProportionCombined}_r \times \text{Generation}_{g(r)}$$

$$\{r \in \text{GENRESERVEOFFERS, where ReserveResponsePeriod}_{c(r)} > \text{CombinedRampThreshold}\}$$

D.19.2.3 Regulation Ramp Constraint:

$$\text{Regulation}_l + \text{RegulationResponseRatio} \times (\text{Generation}_{g(l)} - \text{StartGeneration}_{g(l)}) - \text{ExcessRegRamp}_l \leq \text{MaxResponse}_l$$

$$\{l \in \text{REGULATION OFFERS}, \text{ where RegulationResponsePeriod} > \text{CombinedRampThreshold}\}$$

D.20 GENERIC AND MULTI-UNIT CONSTRAINTS

D.20.1 Generic constraint

D.20.1.1 Generic Security Constraint:

$$\sum_{k \in \mathrm{SECURITYLINESGROUP}_s} \mathrm{SecurityGroupLineWeight}_{s,k} \times \mathrm{LineFlow}_k$$
$$+ \sum_{n \in \mathrm{SECURITYNODESGROUP}_s} \mathrm{SecurityGroupNodeWeight}_{s,n} \times \mathrm{NodeNetInjection}_n$$
$$+ \sum_{g \in \mathrm{SECURITYGENERATIONGROUP}_s} \mathrm{SecurityGroupGenerationWeight}_{s,g} \times \mathrm{Generation}_g$$
$$+ \mathrm{DeficitSecurity}_s \geq \mathrm{GenericSecurityLimit}_s$$

$$\{s \in \mathrm{SECURITYCONSTRAINTS}\}$$

D.20.2 Multi-unit Constraint

D.20.2.1 Multi-unit Constraint:

$$\sum_{k \in \mathrm{MULTICONSTRAINTSLINESGROUP}_s} \mathrm{MultiGroup\ LineWeight}_{s,k} \times \mathrm{LineFlow}_k$$
$$+ \mathrm{DeficitMulti}_s - \mathrm{ExcessMulti}_s = 0$$

$$\{s \in \mathrm{MULTIUNITCONSTRAINTS}\}$$

D.21 VIOLATION GROUP CONSTRAINTS

D.21.1 Line Flow Constraint:

$$\sum_{j \in \text{VIOLATIONGROUPBLOCKSLIN}_{y(k)}} \text{ViolationGroupBlock}_{y,j} \geq \text{ExcessLineFlowForward}_k + \text{ExcessLineFlowReverse}_k + \text{DeficitWLineFlow}_k + \text{ExcessWLineFlow}_k$$

$$\{k \in \text{LINES}, k \notin \text{ARTIFICIALLINES}\}$$

D.21.2 Line Flow Constraint (applies only to a re-run of the *market clearing engine* under section 10.2.3A.2 and section 10.2.5B of Chapter 6):

$$\sum_{j \in \text{VIOLATIONGROUPBLOCKSLIN}_{y(k)}} \text{ViolationGroupBlock}_{y,j} \geq \text{DeficitWLineFlow}_k + \text{ExcessWLineFlow}_k$$

$$\{k \in \text{LINES}, k \notin \text{ARTIFICIALLINES}\}$$

D.21.3 Deficit Reserve Constraint:

$$\sum_{j \in \text{VIOLATIONGROUPBLOCKSRES}_{y(c)}} \text{ViolationGroupBlock}_{y,j} \geq \text{DeficitReserve}_c$$

$$\{c \in \text{RESERVECLASSES}\}$$

D.21.4 Deficit Regulation Constraint:

$$\sum_{j \in \text{VIOLATIONGROUPBLOCKSREG}_{y(regulation)}} \text{ViolationGroupBlock}_{y,j} \geq \text{DeficitRegulation}$$

D.21.5 Facility Constraint:

$$\sum_{j \in \text{VIOLATIONGROUPBLOCKSFAC}_{y(g)}} \text{ViolationGroupBlock}_{y,j} \geq \text{FacilityReserveViolation}_g + \text{FacilityRegulationViolation}_g + \text{FacilityRampViolation}_g + \text{FacilityMultiUnitViolation}_g + \text{FacilityLineFlowViolation}_g$$

$$\{g \in \text{ENERGYOFFERS}\}$$

D.21.5.1 Facility Reserve Constraint:

$$\text{FacilityReserveViolation}_{g} = \sum_{c \in \text{RESERVECLASSES}} \text{ExcessRawReserve}_{r(g,c)}$$
$$+ \sum_{c \in \text{RESERVECLASSES}} \text{ExcessResGen}_{r(g,c)}$$
$$+ \sum_{c \in \text{RESERVECLASSES}} \text{ExcessResGenSegment1}_{r(g,c)}$$
$$+ \sum_{c \in \text{RESERVECLASSES}} \text{ExcessResGenSegment2}_{r(g,c)}$$
$$+ \sum_{c \in \text{RESERVECLASSES}} \text{ExcessResGenSegment3}_{r(g,c)}$$
$$+ \sum_{c \in \text{RESERVECLASSES}} \text{ExcessResRamp}_{r(g,c)} + \sum_{c \in \text{RESERVECLASSES}} \text{ExcessResPropRamp}_{r(g,c)}$$

$$\{g \in \text{ENERGYOFFERS}\}$$

D.21.5.2 Facility Regulation Constraint:

$$\text{FacilityRegulationViolation}_{g} = \text{ExcessRegGen}_{l(g)}$$
$$+ \text{DeficitRegGen}_{l(g)} + \text{ExcessRegRamp}_{l(g)}$$

$$\{g \in \text{ENERGYOFFERS}\}$$

D.21.5.3 Facility Ramp Rate Constraint:

$$\text{FacilityRampViolation}_{g} = \text{ExcessUpRampRate}_{g}$$
$$+ \text{ExcessDownRampRate}_{g}$$

$$\{g \in \text{ENERGYOFFERS}, g \notin \text{INTERTIENERGYOFFERS}\}$$

D.21.5.4 Facility Multi-unit Constraint:

$$\text{FacilityMultiUnitViolation}_{g} = \sum_{s \in \text{MULTIUNITCONSTRAINTS}} \text{DeficitMulti}_{s(g)}$$
$$+ \sum_{s \in \text{MULTIUNITCONSTRAINTS}} \text{ExcessMulti}_{s(g)}$$

$$\{g \in \text{ENERGYOFFERS}\}$$

D.21.5.5 Facility Connection Line Flow Constraint:

$$\text{FacilityLineFlowViolation}_g = \sum_{k_1 \in \text{ARTIFICIALLINES1}} \text{ExcessLineFlowForward}_{k_1(g)}$$
$$+ \sum_{k_2 \in \text{ARTIFICIALLINES2}} \text{ExcessLineFlowForward}_{k_2(g)}$$
$$+ \sum_{k_2 \in \text{ARTIFICIALLINES2}} \text{ExcessLineFlowReverse}_{k_2(g)}$$
$$+ \sum_{k_2 \in \text{ARTIFICIALLINES2}} \text{DeficitWLineFlow}_{k_2(g)}$$
$$+ \sum_{k_2 \in \text{ARTIFICIALLINES2}} \text{ExcessWLineFlow}_{k_2(g)}$$

$$\{g \in \text{ENERGYOFFERS}\}$$

D.21.6 Deficit Security Constraint:

$$\sum_{j \in \text{VIOLATIONGROUPBLOCKSSEC}_{y(s)}} \text{ViolationGroupBlock}_{y,j} \geq \text{DeficitSecurity}_s$$

$$\{s \in \text{SECURITYCONSTRAINTS}\}$$

D.21.7 Violation Group Block Constraint:

$$\text{ViolationGroupBlock}_{y,j} \leq \text{ViolationGroupBlockMax}_{y,j}$$

$$\{j,y \mid j \in \text{VIOLATIONGROUPBLOCKS}_y, \text{where } y \in \text{VIOLATIONGROUPS}\}$$

D.21.8 Violation Penalties Constraint:

$$\text{ViolationPenalties} \geq \sum_{j \in \text{VIOLATIONGROUPBLOCKS}} \left(\text{ViolationGroupPenalty}_{y,j} \times \text{ViolationGroupBlock}_{y,j}\right)$$

SECTION D: POST-PROCESSING

D.21A REGULATION ANOMALY CORRECTION

D.21A.1 After each solution of the linear program which did not involve the use of the constraints set out in sections D.18.3.1 to D.18.3.7, the *EMC* shall carry out the procedures in section D.21A.2 to the extent provided in this section D.21A.

D.21A.2 If the following condition:

$$\text{Generation}_{g(l)} = \text{RegulationMin}_{g(1)} \text{ or } \text{Generation}_{g(l)} = \text{RegulationMax}_{g(l)}$$

$$\{ l \in \text{REGULATIONOFFERS} \}$$

is true for any *generation registered facility*, then the linear program shall be re-solved with the constraints set out in sections D.18.3.1 to D.18.3.7 in lieu of the constraints set out in sections D.18.1.3 and D.18.1.4.

D.22 LOSS CALCULATION CORRECTION

D.22.1 The *EMC* shall set and *publish* the following values:

D.22.1.1 the system loss error tolerance; and

D.22.1.2 the maximum number of times the equations in section C ("the linear program") may be solved for the purpose of loss calculation correction under section D.22 for any given *dispatch period* in any given run of the *market clearing engine*.

The *EMC* may update and re-*publish* these values as required.

D.22.2 After complying with the procedures in section D.21A, the *EMC* shall carry out the procedures in sections D.22.3 to D.22.7 to the extent provided in those sections. However, the *EMC* shall not do so if any of the line violation variables, $\text{ExcessLineFlowForward}_k$, $\text{ExcessLineFlowReverse}_k$, $\text{DeficitWLineFlow}_k$ or ExcessWLineFlow_k, for any *dispatch network line k* is greater than zero.

D.22.3 Subject to section D.22.2, if the following condition:

$$\text{Weight}_{k,j} = 0 \text{ or } \text{Weight}_{k,i} = 0$$

$$\{k, j,i \mid j,i \in \text{DISCRSUB}_k, \text{where } k \in \text{LINES}, i > j+1\} \quad ,$$

is false for any pair of non-adjacent line flow/line loss points *i* and *j* on any *dispatch network line k*, section D.22.4 shall apply. Otherwise, the *EMC* may accept the current solution of the linear program.

D.22.4 Subject to section D.22.3, the total erroneous losses in the solution of the linear program, SysError, shall be calculated and checked as follows:

$$\text{SysError} = \sum_k \text{CircuitError}_k$$

where:

$$\text{CircuitError}_k = \text{LineLoss}_k - \text{ActualLoss}_k$$

$$\text{ActualLoss}_k = \text{LineLossConst}_{k,i} + \frac{\text{LineFlow}_k - \text{LineFlowConst}_{k,i}}{\text{LineFlowConst}_{k,i+1} - \text{LineFlowConst}_{k,i}} \times (\text{LineLossConst}_{k,i+1} - \text{LineLossConst}_{k,i})$$

$$\left\{ \begin{array}{l} i,k | i \in \text{DISCRSUB}_k, \text{where } k \in \text{LINES}, \\ i = \text{Max}\left(\begin{array}{l} j | j < N(DISCRSUB_k), \\ \text{LineFlowConst}_{k,j} \leq \text{LineFlow}_k \end{array} \right) \end{array} \right\}$$

If SysError is less than the system loss error tolerance established by the *EMC* under section D.22.1.1, the *EMC* may accept the current solution of the linear program. Otherwise, section D.22.5 shall apply.

D.22.5 Subject to section D.22.4, if the number of times the linear program has been solved for the purpose of loss calculation correction for a given *dispatch period* in a given run of the *market clearing engine*:

D.22.5.1 is equal to the maximum number established by the *EMC* under section D.22.1.2, and that run of the *market clearing engine* is to produce:

a. a *real-time dispatch schedule,* the *EMC* may halt the process of loss calculation correction and the provisions of section 9.1.2.2 of Chapter 5 and section 9.3.2B of Chapter 6 shall apply; or

b. a *short-term schedule*, *pre-dispatch schedule* or *market outlook scenario*, the *EMC* may accept the current solution of the linear program; or

D.22.5.2 is less than the maximum number established by the *EMC* under section D.22.1.2, sections D.22.6 and D.22.7 shall apply.

D.22.6 Subject to section D22.5, for each *dispatch network line k*, the ordered set of line flow/line loss points in set DISCRSUB_k shall be adjusted according to sections D.22.6.1 and D.22.6.2.

D.22.6.1 Line flow/line loss point *i* shall be identified such that:

$$\{i \mid i \in \text{DISCRSUB}_k, \text{ where } k \in \text{LINES}, i = \text{Max}(j \mid \text{LineFlowConst}_{k,j} < \text{LineFlow}_k + \text{SysError})\}.$$

If there is no line flow/line loss point $j \in \text{DISCRSUB}_k$ where $j > i$, no adjustment shall be made. Otherwise, all line flow/line loss points $j \in \text{DISCRSUB}_k$ where $j > i$ shall be discarded and a new line flow/line loss point with line loss and line flow given by $\text{LineLossConst}'_{k,i+1}$ and $\text{LineFlowConst}'_{k,i+1}$ shall be defined:

$$\text{LineFlowConst}'_{k,i+1} = \text{LineFlow}_k + \text{SysError}$$

$$\text{LineLossConst}'_{k,i+1} = \text{LineLossConst}_{k,i} + \frac{(\text{LineFlow}_k + \text{SysError}) - \text{LineFlowConst}_{k,i}}{(\text{LineFlowConst}_{k,i+1} - \text{LineFlowConst}_{k,i})} \times \left(\text{LineLossConst}_{k,i+1} - \text{LineLossConst}_{k,i}\right)$$

D.22.6.2 Line flow/line loss point *i* shall be identified such that:

$$\{i \mid i \in \text{DISCRSUB}_k, \text{ where } k \in \text{LINES}, i = \text{Min}(j \mid \text{LineFlowConst}_{k,j} > \text{LineFlow}_k - \text{SysError})\}.$$

If there is no line flow/line loss point $j \in \text{DISCRSUB}_k$ where $j < i$, no adjustment shall be made. Otherwise, all line flow/line loss points $j \in \text{DISCRSUB}_k$ where $j < i$ shall be discarded and a new line flow/line loss point with line loss and line flow given by $\text{LineLossConst}'_{k,i-1}$ and $\text{LineFlowConst}'_{k,i-1}$ shall be defined:

$$\text{LineFlowConst}'_{k,i-1} = \text{LineFlow}_k - \text{SysError}$$

$$\text{LineLossConst}'_{k,i-1} = \text{LineLossConst}_{k,i} + \frac{(\text{LineFlow}_k - \text{SysError}) - \text{LineFlowConst}_{k,i}}{(\text{LineFlowConst}_{k,i-1} - \text{LineFlowConst}_{k,i})} \times \left(\text{LineLossConst}_{k,i-1} - \text{LineLossConst}_{k,i}\right)$$

D.22.7 The re-defined set of line flow/line loss points determined in section D.22.6 for each *dispatch network line* shall be used to re-solve the linear program for the given *dispatch period* in the given run of the *market clearing engine*. In so re-solving the linear program under this section D.22.7, if the constraints set out in sections D.18.3.1 to D.18.3.7 had earlier been used in re-solving the linear program for that given *dispatch period* in the given run of the *market clearing engine*, then the constraints set out in sections D.18.3.1 to D.18.3.7 shall be used again in re-solving the linear program (in lieu of the constraints set out in sections D.18.1.3 and D.18.1.4).

D.23 QUANTITY FORMATION

D.23.1 *Energy* quantities scheduled from each *generation registered facility* are given by the values of the Generation_g variables.

D.23.2 *Reserve* quantities in each *reserve class* scheduled from each *reserve* provider are given by the values of the RawReserve_r variables.

D.23.3 *Regulation* quantities scheduled from each *regulation* provider are given by the values of the Regulation_l variables.

D.23.4 *Energy* quantities scheduled for import to Singapore across the *interties* are given by the values of the Generation_g for the *intertie dispatch network nodes*. *Energy* quantities scheduled for export from Singapore across the *interties* are given by the values of the Purchase_p variables for the *intertie dispatch network nodes*.

D.24 PRICE FORMATION

D.24.1 The *market energy price* or *MEP* for each *market network node* shall be calculated as follows:

D.24.1.1 For *generation registered facilities* that are not multi-unit facilities, for *generation settlement facilities* represented as *synchronised* or connected to the dispatch network in accordance with section D.6.5 in the *dispatch period*, the *market energy price* shall be calculated as follows:

$$\text{MEP}^{m(g)} = \text{EnergyPrice}_{n(m)}$$

where:

$\text{EnergyPrice}_{n(m)}$ is the dual variable corresponding to constraint D.16.1.2 for the *dispatch network node* *n* corresponding to the *market network node m*

The price MEP^{m} shall then be further modified in accordance with section D.24.5.

D.24.1.2 For *generation registered facilities* that are *multi-unit facilities* represented as being *synchronised* or connected to the dispatch network in accordance with section D.6.5 in the *dispatch period*, the *market energy* prices shall be calculated as follows:

$$\text{MEP}^{m(g)} = \frac{\sum_{u \in \text{UNITS}_g} \left(\text{Proportion}_u \times \text{EnergyPrice}_{n(u)} \right)}{\sum_{u \in \text{UNITS}_g} \text{Proportion}_u}$$

where:

UNITS_g is the set of all constituent generation units that form part of the *generation registered facility* associated with *energy offer g* $\in$ MULTIOFFERS;

Proportion_u is the relevant proportion specified by the *EMC* in accordance with section D.7.3;

$\text{EnergyPrice}_{n(u)}$ is the dual variable corresponding to constraint D.16.1.2 for the *dispatch network node n*; and

The price MEP^{m} shall then be further modified in accordance with section D.24.5.

D.24.2 Nodal spot prices for *dispatch network nodes* or NSP_n shall be calculated from the values of $EnergyPrice_n$, the dual variables corresponding to constraint D.16.1.2 for the relevant *dispatch network node*, and then further modified in accordance with section D.24.5.

D.24.3 *Reserve* prices for each *reserve* class shall be calculated from the values of $ReservePrice_c$, the dual variables corresponding to constraint D.17.3.4, and then further modified in accordance with section D.24.5.

D.24.4 The *market regulation price* or *MFP* shall be calculated from the values of RegulationPrice, the dual variable corresponding to constraint D.18.2.1, and then further modified in accordance with section D.24.5.

D.24.5 The *market clearing engine* shall produce the following modified prices corresponding to the prices referred to in sections D.24.1 to D.24.4 for each *dispatch period*:

D.24.5.1 if the price referred to any of sections D.24.1 to D.24.4 is between the applicable upper and lower limits specified in Appendix 6J section J.1, then the modified price shall equal that price;

D.24.5.2 if the price referred to any of sections D.24.1 to D.24.4 exceeds the applicable upper limit specified in Appendix 6J section J.1, then the modified price shall be set to that upper limit; and

D.24.5.3 if the price referred to any of sections D.24.1 to D.24.4 is below the applicable lower limit specified in Appendix 6J section J.1, then the modified price shall be set to that lower limit.

D.24.6 The *market clearing engine* shall, for each *dispatch period*, determine the *uniform Singapore energy price* for the *settlement interval* corresponding to that *dispatch period* in accordance with the following formula:

USEP = *uniform Singapore energy price*

= $\Sigma_n (W^n \times NSP^n) / \Sigma_n W^n$

where:

$\{n|n \in \text{NODES}\}$

$$W^n = \sum_{\substack{p \in \text{ENERGYBIDS}_n, \\ p \notin \text{INTERTIEENERGYBIDS}}} \text{Purchase}_p - \sum_{j \in \text{DEFICITGENERATIONBLOCKS}_n} \text{DeficitGenerationBlock}_{n,j}$$

NSP^n = the nodal spot price for *DNN* n referred to in section D.24.2 after it has been modified in accordance with section D.24.5.

D.24.7 The *market clearing engine* shall, for each *dispatch period*, determine the *market reserve price* or MRP_x for each *reserve provider group x*, in accordance with the following formula:

$MRP_x = \text{ReservePrice}_c \times \text{Effectiveness}_{x,j}$

where:

$\{x|x \in \text{RESERVEGROUPS}_c\}$

ReservePrice_c = the *reserve class* price referred to in section D.24.3 after it has been modified in accordance with section D.24.5.

$\text{Effectiveness}_{x,j}$ = the effectiveness multiplier of raw *reserve* in block *j* of *reserve provider group x*, where:

j is the last effectiveness block in

$\text{RESERVEGROUPBLOCKS}_x$ for which

$\text{GroupResponse}_{x,j} > 0$

or $j = 1$ if $\text{GroupResponse}_{x,j} = 0$ for all effectiveness blocks in $\text{RESERVEGROUPBLOCKS}_x$.

Explanatory Note: Reserve effectiveness describes the contribution that reserve scheduled for each reserve provider group makes to the reserve requirement for the relevant reserve class, and could include reliability of response as well as the profile of reserve response. There are several tranches of effectiveness specified by the PSO (see Section G.5.3 of Appendix 6G) with the effectiveness declining with increasing reserve supplied from a reserve provider group. The price for each reserve provider group is the reserve class price modified by the marginal effectiveness from the reserve provider group – i.e. the effectiveness corresponding to the last piece-wise linear tranche from which reserve has been scheduled from that reserve provider group, or by the effectiveness corresponding to the first piece-wise linear tranche for that reserve provider group if no reserve is scheduled from that reserve provider group.

D.25 ADDITIONAL OUTPUTS

D.25.1 The *market clearing engine* shall, at a minimum, produce the following information for each *dispatch period*:

D.25.1.1 the total *load* scheduled to be supplied at each *dispatch network node*:

$$\text{Purchase}_p$$

$$\{p \in \text{ENERGYBIDS}\}$$

and in aggregate:

$$\sum_{\substack{p \in \text{ENERGYBIDS} \\ p \notin \text{INTERTIENERGYBIDS}}} \text{Purchase}_p$$

expressed in MW;

D.25.1.2 the total generation scheduled at each *generation registered facility*:

$$\text{Generation}_g$$

$$\{g \in \text{ENERGYOFFERS}\}$$

and in aggregate,

$$\sum_{\substack{g \in \text{ENERGYOFFERS} \\ g \notin \text{INTERTIEENERGYOFFERS}}} \text{Generation}_g$$

expressed in MW;

D.25.1.2A the total transmission losses in the system:

$$\sum_{k \in \text{LINES}} \text{LineLoss}_k$$

expressed in MW;

D.25.1.3 the extent of any shortfall in *energy*, by *dispatch network node*:

$$\sum_{\{j \mid j \in \text{DEFICITGENERATIONBLOCKS}_n\}} \text{DeficitGenerationBlock}_{n,j}$$

$$\{n \in \text{NODES}\}$$

and in aggregate,

$$\sum_{\{j,n \mid j \in \text{DEFICITGENERATIONBLOCKS}_n,\text{ where } n \in \text{NODES}\}} \text{DeficitGenerationBlock}_{n,j}$$

expressed in MW;

D.25.1.4 the extent of any surplus in *energy*, by *dispatch network node*:

$$\sum_{\{j \mid j \in \text{EXCESSGENERATIONBLOCKS}_n\}} \text{ExcessGenerationBlock}_{n,j}$$

$$\{n \in \text{NODES}\}$$

and in aggregate,

$$\sum_{\{j \mid j \in \text{EXCESSGENERATIONBLOCKS}_n,\text{ where } n \in \text{NODES}\}} \text{ExcessGenerationBlock}_{n,j}$$

expressed in MW;

D.25.1.4A total *reserve* requirement by *reserve class*:

$$\text{Risk}_c$$

$$\{c \in \text{RESERVECLASSES}\}$$

expressed in MW;

D.25.1.5 total *reserve* scheduled to supply each *reserve class*, from each *reserve provider group*:

$$\text{EffectiveReserve}_x$$

$$\{x \in \text{RESERVEGROUPS}_c,\text{where } c \in \text{RESERVECLASSES}\}$$

and in aggregate,

$$\sum_{x \in \text{RESERVEGROUPS}_c} \text{EffectiveReserve}_x$$

$$\{c \in \text{RESERVECLASSES}\}$$

expressed in MW;

D.25.1.6 the extent of any shortfall in *reserve*, by *reserve class*:

$$\text{DeficitReserve}_c$$

$$\{c \in \text{RESERVECLASSES}\}$$

expressed in MW;

D.25.1.6A total *regulation* requirement:

RegulationRequirement

expressed in MW;

D.25.1.7 total *regulation* scheduled:

$$\sum_{l \in \text{REGULATIONOFFERS}} \text{Regulation}_l$$

expressed in MW;

D.25.1.8 the extent of any shortfall in *regulation*:

DeficitRegulation

expressed in MW;

D.25.1.9 predicted power flows on *dispatch network lines*

$$\text{LineFlow}_k$$

$$\{k \in \text{LINES}\}$$

and *energy* losses on *dispatch network lines*

$$\text{LineLoss}_k$$

$$\{k \in \text{LINES}\}$$

expressed in MW;

D.25.1.10 a list of *security constraints* and *generation fixing constraints* applied, which is the set SECURITYCONSTRAINTS;

D.25.1.11 details of the extent of any constraint violations

$$\sum_{j \in \text{VIOLATIONGROUPBLOCKSSEC}_y} \text{ViolationGroupBlock}_{y,j}$$

$$\{y \in \text{VIOLATIONGROUPS}\}$$

; and

D.25.1.12 the value, in dollars, of the objective function value NetBenefit specified in section D.14.