Formation of Locational Marginal Pricing and its System Energy Component During Reserve Shortage Events

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Summary

As directed by FERC Order 825 issued on June 16, 2016, shortage pricing(s) should be applied to real-time pricing intervals whenever insufficient reserves are available to meet the reserve requirement(s). The primary purpose of this paper is to provide participants increased understanding of Locational Marginal Price formation under reserve shortage conditions as outlined below:

- Provide greater transparency into the formation of Locational Marginal Prices during shortage pricing by providing a generalized example with reserve shortage conditions.
- Explain how the energy Locational Marginal Price is capped to reflect the capping of reserve prices at two times the operating reserve penalty factor on the first step of the demand curve.

This paper will provide a detailed explanation of how Locational Marginal Prices (LMPs) are formulated during an actual reserve shortage period using the shortage events experienced on March 17, 2021, as a guide. While the events on March 17 are used as a guide, the calculated values and overall shortage prices derived are based on random values to maintain offer confidentiality.

Using the same March 17 event as a guide, the paper has been updated to explain how LMPs are formulated based on reserve price formation changes, which were implemented on Oct. 1, 2022.

Shortage Events of March 17, 2021

On March 17, 2021, system factors contributed to multiple reserve shortages, detected across reserve products in both the PJM RTO and Mid-Atlantic/Dominion (MAD) reserve sub-zone by the real-time Security Constrained Economic Dispatch (RTSCED) engine and reflected in the Locational Pricing Calculator (LPC) pricing for that interval. Reserve shortages were declared by the real-time market clearing engine (MCE) for LPC pricing interval (10:10–10:15) resulting in a system energy component of LMP equal to $3,664.51/MWh.

The system factors that contributed to the reserve shortages were as follows:

- Loss of approximately 560 MW of internal generation
- Limited ramping capability of generation
- Loss of approximately 1,200 MW of external generation that affected frequency and tie line components of PJM's Area Control Error (ACE)

The system energy component of LMP, defined as the total cost increase resulting from increasing the output of the marginal resource while considering the impact of marginal losses to meet the next megawatt of load, for this interval was $3,664.51/MWh. The system energy component of LMP was a result of applying the system energy LMP price cap logic, which exists in the MCE logic. A detailed description of this logic is described in the Final System Energy LMP Formation section of this document.

The total LMP of a given pricing node (Pnode) is the sum of the system energy component of LMP, the congestion component of LMP due to binding transmission constraint(s), and the marginal loss component of LMP due to the effect of marginal losses. Therefore, the total LMP of a given Pnode, for the events on March 17, 2021, may be greater than or less than the system energy component LMP of $3,664.51/MWh when the congestion component of

LMP and loss component of LMP (either of which can be a positive or negative value) is added to formulate the total LMP.

LMP Price Formation – Pre-Reserve Price Formation

The total LMP for a given Pnode is the sum of the following components:

- System energy LMP
- Transmission congestion cost
- Cost of marginal losses

This section provides an explanation of the calculation of the system energy LMP. Generic numeric values are used in the calculations below to demonstrate the formation of the system energy LMP. The system energy component of LMP is set by the resource that can serve the next increment of load at the least cost. However, the cost of serving the next megawatt of load is not based solely on the resource's incremental energy offer. In some instances, the effect of marginal losses may require a resource to provide slightly more than one megawatt to satisfy the next one megawatt of load. Additionally, consideration is given to the impact the delivery of the additional megawatt from the marginal resource on binding constraints when calculating the cost of the marginal megawatt. Finally, if the resource was meeting a reserve assignment in the solution, the impact on reserves is taken into account as the resource converts a megawatt of reserves to provide the next megawatt of energy. In effect, this reflects that the conversion of reserves to energy necessary for power balance is included in the calculation of the system energy LMP. The impacts on the system energy LMP associated with marginal losses, constraints and reserves is described below.

Impact on System Energy LMP From Marginal Losses

The generation resource identified as marginal for energy is modeled at a Pnode, and therefore the MCE will calculate the impact of increasing the output of this resource at the Pnode in relation to one additional megawatt of load at the distributed load reference bus. This impact is measured by the loss sensitivity factor, which is calculated using the formula below:

The Pnode Loss Sensitivity Factor = 1 – (1 / Loss Penalty Factor)

The loss penalty factor is calculated by the PJM Energy Management System (EMS) for each Pnode in the network model and passed to the MCE for use in dispatching and pricing the system. For this example, the loss sensitivity factor for the energy marginal resource is 0.04525.

The power balance equation for the energy marginal resource to serve additional load is as follows:

Additional Load MW = Additional energy needed from marginal resource – Additional Loss MW

Additional Loss MW = Additional energy needed from marginal resource * loss sensitivity factor

Algebraically: 1 = X – (X * 0. 04525), where X is the additional energy needed from marginal resource

Therefore, X = 1/ (1-0.04525) = 1.0474 MW

Due to losses, the marginal resource would need to generate 1.0474 MW in order to serve an additional megawatt of load. For purposes of this example, the marginal resource's incremental cost is $30/MWh.

Impact on System Energy LMP From Congestion

When the output of the marginal resource is increased to meet the next megawatt of load, the congestion impact the delivery of that additional output has on any binding constraints is also considered when calculating the cost of that output. This congestion impact is calculated as the summation of congestion LMPs derived from all binding constraints with respect to the marginal resource.

In the March 17 example, there were two active transmission constraints binding during the real-time pricing interval, which were solved with a shadow price of $2,000/MWh. The $2,000/MWh shadow price is the transmission constraint penalty factor for each constraint. For this example, the distribution factors (Dfax), or impact, of the marginal resource was 0.73254 and 0.00623, respectively, for the two binding constraints.

Therefore, the cost of impact on constraint control is calculated as follows:

> Cost of impact on constraint control = Additional energy needed from marginal resource * sum (ABS (∑ Dfax * constraint shadow price))
>
> = 1.0474 MWs * (($2,000/MWh * 0.73254) + ($2,000/MWh * 0.00623)) = $1547.57 /MWh

Impact on System Energy LMP From Reserves

Finally, the impact of converting a megawatt of assigned reserves on the marginal resource to energy to serve the next megawatt of load is reflected in the system energy LMP. This is referred to as the lost opportunity cost.

On March 17, 2021, the real-time pricing interval solved with reserve shortages for Synchronized Reserves (SR) and Primary Reserves (PR) in both the PJM RTO and MAD reserve sub-zone. In the MCE solution for the impacted pricing interval, the reserve violation for SR was priced at $850/MWh, which is the penalty factor from the first step of the Operational Reserve Demand Curve (ORDC), and PR was priced at $300/MWh, which is the penalty factor from the second step of the ORDC.

Therefore, the cost to convert reserves on the marginal resource to energy to meet an additional megawatt of demand is calculated as follows:

> Lost Opportunity cost = Additional energy needed from marginal resource * (∑ Reserve Penalty Factor – Reserve Offer)
>
> = 1.0474 MW * (($850/MWh *2) + ($300/MWh *2)) – $7.5/MWh) = $2401.16/MWh
>
> Where $7.5/MWh is the ancillary service offer of the marginal unit

Final System Energy LMP Formation

The **original** system energy LMP resulting from increasing the output of the marginal resource is calculated as follows:

> Energy LMP = Incremental Cost + Congestion Cost + Lost Opportunity cost Energy LMP = $30 + $1547.57 + $2401.16 = $3978.73/MWh

In the MCE, the system energy LMP is capped at $3750/MWh**,** as calculated from the summation below:

Generation energy offer cap of $2,000/MWh +

Synchronized Reserve Penalty Factor from the first step on the demand curve of $850/MWh + Primary Reserve Penalty Factor from the first step on the demand curve of $850/MWh +

An adder of $50/MWh (a buffer to account for congestion and losses contribution)

If the **original** system energy LMP exceeds the cap of $3,750, the logic in the MCE resolves the model by iteratively disabling the sub-zone PR requirement and if necessary the sub-zone SR requirement until the system energy LMP is less than the cap. In this example, there were four shortages reported from MCE solution: two @$850 and two @$300. The MAD PR requirement was consequently disabled, and the system energy LMP was then less than the system energy LMP cap.

The re-calculated system energy LMP with MAD PR requirement disabled equals the *Reported* Energy LMP as follows:

Re-calculated Energy LMP = Marginal Cost + Congestion Cost + Re-calculated Lost Opportunity cost.

Re-calculated Lost Opportunity cost = 1.0474 MWs * (($850/MWh *2) + ($300/MWh)) – $7.5/MWh)

= $2,086.94/MWh

Re-calculated Energy LMP = $30 + $1547.57 + $2,086.94 = $3,664.51/MWh

The final recalculated system energy LMP in this exercise was calculated consistent with the method used to formulate reported LMPs.

In addition, as discussed previously, the total LMP of a given Pnode may be greater than or less than the system energy LMP when the congestion component of LMP and loss component of LMP (each of which can be positive or negative) is added to formulate the total LMP.

LMP Price Formation – Post Reserve Price Formation Changes

To reflect reserve price formation changes in the March 17 example, we will include clearing of 30-minute reserves in the RTO and being short on the second step of the Operating Reserve Demand Curve at a penalty value of $300/MWh. This will simulate the impact of the additional reserve service added as part of the reserve price formation changes. The other change to the example was to change the ancillary service offer price from $7.5/MWh to $0.02/MWh to reflect the maximum ancillary service offer under reserve price formation. The final change was the removal of the $50/MWh adder to the system energy LMP. Under reserve price formation, the cap on the system energy LMP was changed from $3,750/MWh to $3,700/MWh. All other data, from this example, used previously are held constant.

The total LMP for a given pricing node (Pnode) is the sum of the following components:

- System energy LMP
- Transmission congestion cost
- Cost of marginal losses

This section provides an explanation of the calculation of the system energy LMP. Generic numeric values are used in the calculations below to demonstrate the formation of the system energy LMP. The system energy component of

LMP is set by the resource that can serve the next increment of load at the least cost. However, the cost of serving the next megawatt of load is not based solely on the resource's Incremental Energy Offer. In some instances, the effect of marginal losses may require a resource to provide slightly more than one megawatt to satisfy the next one megawatt of load. Additionally, consideration is given to the impact the delivery of the additional megawatt from the marginal resource on binding constraints when calculating the cost of the marginal megawatt. Finally, if the resource was meeting a reserve assignment in the solution, the impact on reserves is taken into account as the resource converts a megawatt of reserves to provide the next megawatt of energy. In effect, this reflects that the conversion of reserves to energy necessary for power balance is included in the calculation of the system energy LMP. The impacts on the system energy LMP associated with marginal losses, constraints and reserves is described below.

Impact on System Energy LMP From Marginal Losses

The generation resource identified as marginal for energy is modeled at a Pnode, and therefore the MCE) will calculate the impact of increasing the output of this resource at the Pnode in relation to one additional megawatt of load at the distributed load reference bus. This impact is measured by the loss sensitivity factor, which is calculated using the formula below:

The Pnode Loss Sensitivity Factor = 1 – (1 / Loss Penalty Factor)

The loss penalty factor is calculated by the PJM EMS for each Pnode in the network model and passed to the MCE for use in dispatching and pricing the system. For this example, the loss sensitivity factor for the energy marginal resource is 0.04525.

The power balance equation for the energy marginal resource to serve additional load is as follows:

Additional Load MW = Additional energy needed from marginal resource – Additional Loss MW

Additional Loss MW = Additional energy needed from marginal resource * loss sensitivity factor

Algebraically: 1 = X – (X * 0. 04525), where X is the additional energy needed from marginal resource

Therefore, X = 1/ (1-0.04525) = 1.0474 MW

Due to losses, the marginal resource would need to generate 1.0474 MW in order to serve an additional megawatt of load. For purposes of this example, the marginal resource's incremental cost is $30/MWh.

Please note there is no change to this calculation based on Reserve Price Formation changes.

Impact on System Energy LMP From Congestion

When the output of the marginal resource is increased to meet the next megawatt of load, the congestion impact the delivery of that additional output has on any binding constraints is also considered when calculating the cost of that output. This congestion impact is calculated as the summation of congestion LMPs derived from all binding constraints with respect to the marginal resource.

In the March 17 example, there were two active transmission constraints binding during the real-time pricing interval, which were solved with a shadow price of $2,000/MWh. The $2,000/MWh shadow price is the transmission constraint penalty factor for each constraint. For this example, the distribution factors (Dfax), or impact, of the marginal resource was 0.73254 and 0.00623, respectively, for the two binding constraints.

Therefore, the cost of impact on constraint control is calculated as follows:

Cost of impact on constraint control = Additional energy needed from marginal resource * sum (ABS (∑ Dfax * constraint shadow price))

= 1.0474 MW * (($2,000/MWh * 0.73254) + ($2,000/MWh * 0.00623)) = $1547.57 /MWh

Please note there is no change to this calculation based on Reserve Price Formation changes.

Impact on System Energy LMP From Reserves

Finally, the impact of converting a megawatt of assigned reserves on the marginal resource to energy to serve the next megawatt of load is reflected in the system energy LMP. This is referred to as the lost opportunity cost.

On March 17, 2021, the real-time pricing interval solved with reserve shortages for Synchronized Reserves (SR) and Primary Reserves (PR) in both the PJM RTO and MAD reserve sub-zone. In the MCE solution for the impacted pricing interval, the reserve violation for SR was priced at $850/MWh, which is the penalty factor from the first step of the Operational Reserve Demand Curve (ORDC), and PR was priced at $300/MWh, which is the penalty factor from the second step of the ORDC. As described above, a shortage of the 30-minute reserve service is included in the calculation below. The shortage is modeled on the second step of the ORDC, which is prices at $300/MWh.

Therefore, the cost to convert reserves on the marginal resource to energy to meet an additional megawatt of demand is calculated as follows:

Lost Opportunity cost = Additional energy needed from marginal resource * (∑ Reserve Penalty Factor – Reserve Offer)

= 1.0474 MW * (($850/MWh *2) + ($300/MWh *2) + (300/MWh*1)) – ($0.02/MWh) = $2,723.22/MWh

Where $0.02/MWh is the ancillary service offer of the marginal unit.

Final System Energy LMP Formation

The **original** system energy LMP resulting from increasing the output of the marginal resource is calculated as follows:

Energy LMP = Incremental Cost + Congestion Cost + Lost Opportunity Cost Energy LMP = $30 + $1,547.57 + $2,723.22 = $4,300.79/MWh

Post Reserve Price Formation in the MCE, the system energy LMP is administratively capped at $3,700/MWh. The iterative process described above in the Pre-Reserve Price Formation section is no longer utilized. Furthermore, prior to and effective with Reserve Price Formation, any level of incremental energy offer from the marginal resource(s), cost impact of constraint control, and lost opportunity cost as described above are included up to the capped energy LMP.

The final reported system energy LMP in for this example is $3,700/MWh.

In addition, as discussed previously, the total LMP of a given Pnode may be greater than or less than the system energy LMP when the congestion component of LMP and loss component of LMP (each of which can be positive or negative) is added to formulate the total LMP.