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Case Studies of Distribution Locational Marginal Pricing Methodology Based on Bronzeville Community Microgrid

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SUMMARY

As distribution energy resources (DERs) are increasingly integrated into the distribution grid, utilities are already facing multiple operational and management challenges. To prevent issues presented by DER integration such as network congestion and thermal violations, creating a distribution-level transactive energy market is becoming a promising option. This paper presents the Distribution Locational Marginal Pricing methodology, test scenarios, and simulation results based on the Bronzeville Community Microgrid (BCM) network model to assist utilities in participating in such a market. The market simulator tool called GridOS™ provides optimal dispatch schedule and price signals for each dispatchable DER for day-ahead and real-time markets. The case study consists of two stages: offline simulation for validating the platform functionalities and calculations, and real-time simulation for demonstrating the performance of the tool in a real-time environment and its potential field readiness using a Real-time Digital Simulator. In this paper we mainly concentrate on offline simulation results and findings. Finally, we present a number of case studies to illustrate the effectiveness of the GridOS™ DER participation simulator.

KEYWORDS

DLMP (Distribution Locational Marginal Pricing), DER (Distributed Energy Resources), energy price, congestion prices, residual price

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I. Introduction

Today's electric power distribution systems are undergoing transformative change due to increasing amounts of dynamic electric loads and distributed energy resources (DERs) such as rooftop photovoltaic (PV) solar systems, Electric Vehicles (EV) with Vehicle to Grid (V2G) capability and energy storage [1-2], being integrated on the grid. DERs offer benefits such as reduction of transmission and distribution network congestion, deferral of capacity upgrades, and enhancement of reliability by enabling a local supply of electricity [3]. On the other hand, they pose new challenges for the operation and control of distribution grids.

The continuous growth of installed capacity from DERs is causing the power grid to transition from a traditional unidirectional power flow to a complex bidirectional power flow [4]. With the proliferation of proactive DER providers, modern power systems are on the verge of a paradigm shift which may potentially impact power system markets. To prevent problems like network congestion, voltage issues, or thermal violations that may occur, a market-based approach to energy market transactions is a promising option for efficiently and economically managing new DERs being interconnected [5].

Transactive energy systems are defined by Gridwise AC in [6] as "systems of economic and control mechanisms that allow the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter." This broad definition allows for the application of this methodology to a distribution system. The marketplace created can offer economic opportunities for both prosumers (producer + consumer) and utilities to capture their potential value at the distribution level.

Commonwealth Edison Company (ComEd), an electric utility serving more than 4 million customers in northern Illinois including the city of Chicago, has partnered with Opus One to explore, develop and evaluate an energy transaction platform that is capable of running a Shadow Energy Exchange for DERs (SEEDER). This platform is created by using a network model, running an optimal power flow analysis and calculating optimal dispatch for various DERs and distribution location marginal prices (DLMPs) given various nodes of the network.

As of today, there have been multiple methodologies proposed to calculate the Distribution Locational Marginal Pricing (DLMP). In [7], architects apply a method that calculates the DLMP as the summation of five components: marginal costs for active power, reactive power, congestion, voltage support and losses. ComEd uses this methodology mainly to take into consideration the cost of energy (only real power), cost of congestion and a residual cost that accounts for losses.

The solution focuses on energy trade from dispatchable DERs based on microgrid settings considering both day-ahead (DA) and real-time (RT) markets. It functions similarly to the wholesale markets at the transmission system level. For the day-ahead market, this tool can generate hourly results as well as 5-minute interval results for the same-day market. The main difference between the wholesale market and retail market at the transmission and distribution levels consists in the characteristics of network topology including unbalanced phase loading, islanded/grid-connected for microgrid, as well as flexible operation modes of DERs such as charge and discharge of energy storage systems. ComEd plans on testing the energy exchange platform under two modes:

1. A non-real-time simulation mode focusing on power system and economic analysis to demonstrate different scenarios in which energy exchange is optimized. This testing will allow us to validate the DLMP calculation and results.

2. A real-time mode focusing on integration with a real-time digital simulator (RTDS). The objective of the real-time mode is to demonstrate the performance of the software through commonly used utility protocols (DNP) as well as test its field-readiness.

The real-time mode of testing involves a Hardware in the Loop (HIL) technique which includes the newly developed transactive energy platform and the RTDS system interacting with each other. The execution of tests under different scenarios and use cases is an essential component in ComEd's effort to test and validate its energy exchange platform as well as assess its potential to address some of the challenges arising out of the evolving power system industry.

This paper will primarily concentrate on the learnings and results obtained from the non-real-time solution. It is structured as follows: Section II explains the DLMP methodology, Section III describes the network and different DERs modeled for the simulation study, and Section IV presents the scenarios tested along with the results that demonstrate the effectiveness of market simulation tool. Section V concludes the paper.

II. DLMP METHODOLOGY AND MODELLING FOR A MICROGRID-LEVEL TRANSACTIVE ENERGY MARKET

This section presents a brief explanation of the methodology developed by Opus One for their GridOS™ platform. A more detailed description will be available in future publications.

A. *DLMP Methodology*

Distribution locational marginal price (DLMP) is defined as the price to serve the next unit of energy at a node on a distribution feeder. In this methodology, the DLMP is computed at every resource node. As mentioned before, the DLMP is divided into three components: marginal energy price, marginal congestion price, and residual price representing the remaining marginal components (e.g. loss price and voltage price), as can be seen in equation (1).

$$\lambda_{DLMP}(t,i) = \lambda_{Energy}(t,i) + \lambda_{Congestion}(t,i) + \lambda_{Residual}(t,i) \qquad \forall i \in N_R, \forall t \tag{1}$$

where (i) refers to the specific DER index and (t) represents the time.

The marginal energy price represents the cost of meeting the demand for energy on the feeder, considering available energy resources. It is usually the same across all nodes; the locational variation of DLMP is determined by the congestion and residual price.

The marginal congestion price generally represents the impact of congestion on a line or transformer on the DLMP at a specific node relative to its energy price.

The residual marginal price represents the sum of the marginal loss price and the marginal price of voltage constraints.

The optimal dispatch for all participating resources is obtained by running a time-series constrained AC unbalanced optimization with the objective of minimizing operating cost while respecting thermal and voltage limits in all three phases. Cost optimization takes in bids and offers from DER resources and dispatches them such that the total system operation cost is minimized across all timepoints. In addition to optimal dispatch schedules, the solution to the constrained AC unbalanced optimization includes the voltages at each node as well as current, power, and losses across each line and transformer. From these, we can compute the total cost to operate the network, total power drawn from the substation (if any), and total network losses.

B. Day-ahead and real-time electricity market at a microgrid level

Similar to wholesale markets, this tool can provide numerical results for Day-Ahead and Real-Time markets. The diagram in Fig. 1 summarizes the inputs and outputs of the tool for both real-time and day-ahead markets.

To run an AC unbalanced power flow, a network model is required, which is imported from CYME into GridOS™ using the Common Information Model (CIM). This model includes lines and transformers' limits and characteristics per phase. In addition, the user can select the voltage constraints of the system, e.g. 0.95 to 1.05 p.u. The DLMP methodology requires the substation locational marginal price (LMP) as an input. This price will be compared against the bids and offers submitted by the participants to determine the most cost-effective solution. Finally, the load forecast at the feeder head level will be used to allocate each spot load across the feeder in proportion to its load rating. In case our model includes photovoltaic (PV) solar panels, a generation forecast will also be required.

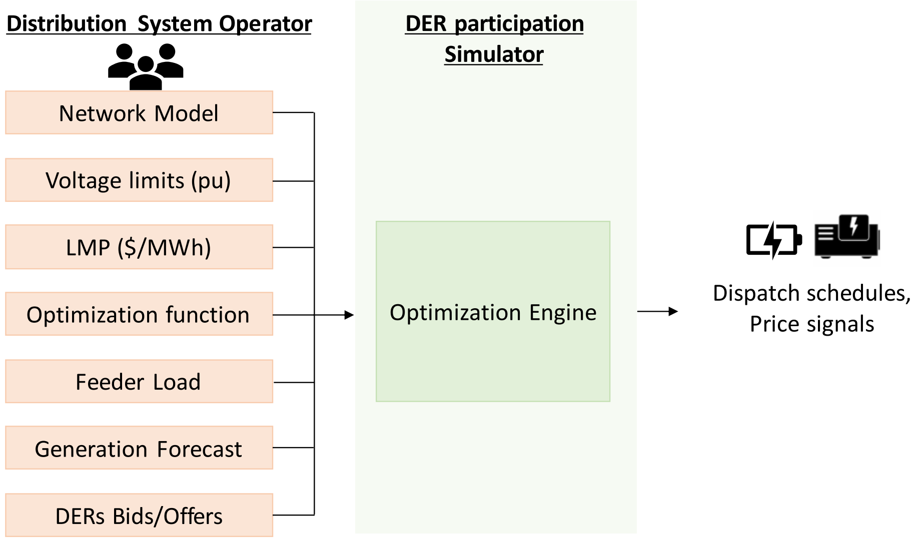

Fig. 1. DLMP Methodology Inputs, Outputs and Key Components

For the market simulator, the main difference between day-ahead and same-day markets is the resolution of the data. For day-ahead, results are on an hourly basis, while for same-day results, the resolution of the data is 5 minutes. This paper will focus on day-ahead results, which will be similar to same-day results. As for testing in real-time mode using the market simulator in the hardware loop with RTDS, we will be able to evaluate the dynamic variations between day-ahead and real-time conditions in terms of DER outputs and loads.

III. Network Topology

One of the inputs needed for running the simulation is a power network model. For this project, the network selected is the Bronzeville Community Microgrid (BCM), which is part of the first utility-operated microgrid cluster located in Chicago, Illinois. The BCM is formed by two 12 kV lines that are fed by two different substations, allowing for enhanced system resilience. In a normal configuration (grid-connected mode), these two feeders are disconnected; however, in the event of grid fault or disturbance, they are mutually connected through multiple tie-switches in the manner that BCM is isolated from the rest of the grid which is islanded operation mode.

The BCM hosts a 750-kW solar installation and 500kW/2000kWh battery energy storage system. To provide sufficient power and inertia during islanding mode, the microgrid also integrates a 4.8 MW natural gas generator. In order to simulate a future scenario with an increased DER penetration, more DERs have been added to the existing network topology, which can create more diverse study cases. Fig. 2 shows the single line diagram of the BCM consisting of the existing and new DERs.

The newly added DERs include a diesel generator, a geothermal unit, a natural gas generator, distributed PV panels, and a flywheel storage system. The DERs are all modeled as balanced three-phase devices.

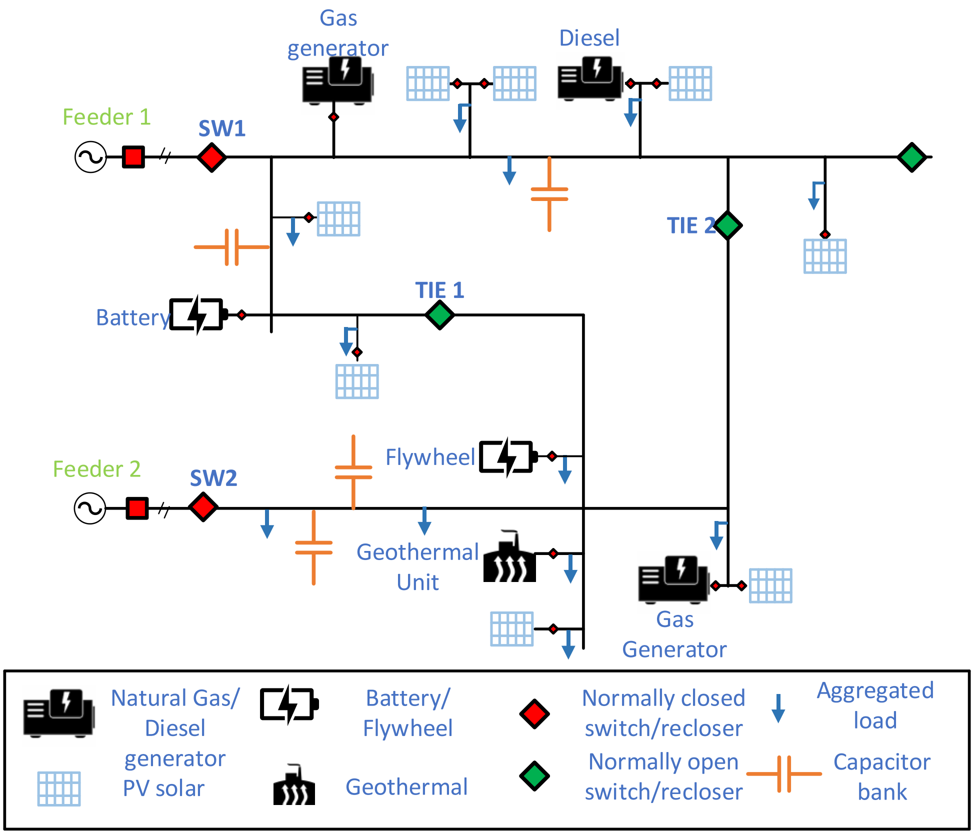

Fig. 2. One-line diagram of the BCM network

IV. Scenario Descriptions and Results

One of the main objectives of the non-real-time testing is to verify that the tool is properly calculating the DLMP components. For that purpose, an extensive list of cases was pre-defined. Due to length constraints, this paper will only present some of the selected scenarios along with explanations of the results, mainly focusing on day-ahead results. As described above, in normal operation, the microgrid operates in grid connected mode with both feeders disconnected from each other. The same topology has been used in the most of cases.

A. *Case I-Feeder I blue-sky day*

In case I, loading represents a blue-sky day, and there are no expected violations on the system. There are enough DERs available for supplying the entire feeder load. However, depending on the offers and the LMP at the substation, there will be instances in which power from the substation is required as it is more cost-effective than buying power from the DER. On the other hand, when the LMP is high, the expected result is that the less costly DERs will be the ones providing power. Fig. 3 shows the optimal result from the tool for the day-ahead market when running the simulation for *Feeder 2* with no solar generation. Note that the real-time conditions for this case are similar to the results for the same-day market, which are close to what is observed below.

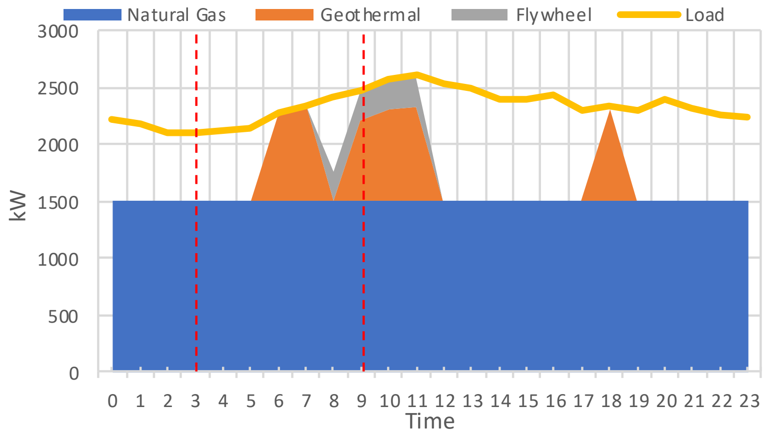

Fig. 3. Case I optimal solution

Fig. 3 shows the load curve compared with the power provided from DERs that have been cleared in the market. The gap area between total DER output and load represents the net energy supplied by the substation.

The data generated at 3:00 AM shows that power is needed from the substation. Therefore, the expected energy price is the LMP. The total loading at the feeder head is 2.1 MW and the LMP is $16.72/MWh. The result from the tool is summarized in Table I below:

TABLE I. CASE I OFFERS AND 3-PHASE DLMP SOLUTION AT 3:00 AM

Asset	Offer ($/MWh)	Capacity Offered (MWh)	Optimal dispatch (MWh)
Natural Gas	13	1.5	1.5
Geothermal	20	2	0
Flywheel	0	0	0

Asset	DLMP ($/MWh)		
	Energy	*Congestion*	*Residual*
Natural Gas	16.72	0	-0.017
Geothermal	16.72	0	-0.006
Flywheel	16.72	0	0.003

It is observed that the energy price is equal to the LMP. Congestion price is zero as there are no thermal violations. The negative residual prices of the Natural Gas and Geothermal unit indicate that one more increment of generation at those locations tends to increase overall system losses. On the other hand, an increment of generation at the flywheel location will reduce total system losses.

One of the constraints of cost optimization is that the DERs will only supply real power to the load at the distribution level. In other words, no power will be sold to the sub-transmission as the DERs are modeled as 3-phase balanced generators, so they will generate the same amount of power across each phase. This point is illustrated by the 3-phase results generated at 9:00 AM. At this time, the LMP is $22.02/MWh, the offer from natural gas is $13/MWh for 1.5 MW, the offer from the geothermal unit is $20/MWh for 2 MW, and the offer from the flywheel is $19/MWh for 0.25 MW. As seen in Fig. 3, all three DERs dispatch power that is cheaper than the substation power. Table II shows the DLMP decomposition of the geothermal unit, which is the most expensive DER cleared in the market.

TABLE II. DLMP RESULT PER PHASE AT 9:00 AT THE GEOTHERMAL LOCATION

Phase	**DLMP ($/MWh)**		
	Energy	***Congestion***	***Residual***
ABC	20.025	0	-0.025
A	22.02	0	-0.021
B	22.02	0	-0.032
C	16.035	0	-0.022

It is noted that the energy price in phases A and B exactly equate with the LMP value. When these two phases demand more loads than phase C, power is supplied from the substation. Looking at phase C, the energy price is below the LMP. This means that if we increase the generation in that phase, it will violate the “no back-feed real power” constraint. For phase C, it is not economical to provide power. However, as it is for phases A and B, the average DLMP is equal to the geothermal offer, and it is economical for the DER to provide power in all three phases.

Another way to interpret this result is that generators that output unique amounts of power per phase might have more value than 3-phase generators with equal output per phase in an unbalanced distribution system.

B. Case II-Feeder I blue sky day with PV generation

In this scenario, the loading conditions, bids and offers are identical with case I. In addition, the same topology for case I is utilized but includes PV generation. Considering that the offer of each PV is $0/MWh, it is expected that all the generation produced will be cleared in the market. The result is observed in Fig. 4.

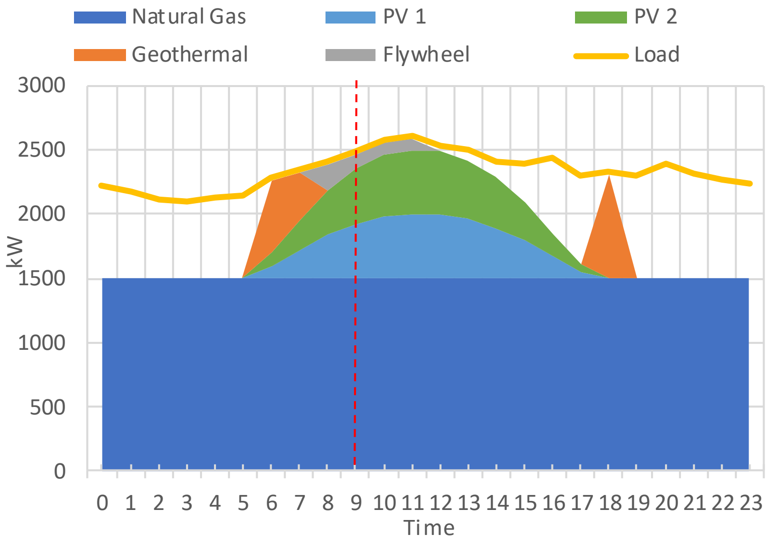

Fig. 4. Case II optimal solution

In case I at 9:00 am, the power was mostly dispatched by the natural gas generator while the geothermal unit and flywheel serve as the two most expensive resources. Due to the availability of solar power at that moment, it is possible to avoid purchasing power from the geothermal owner, reducing the price of the electricity.

TABLE III. MARKET RESULTS AT 9:00 AM FOR CASE II

Asset	**Capacity cleared (MW)**	**DLMP ($/MWh)**		
		Energy	***Congestion***	***Residual***
Natural Gas	1.5	19.004	0	-0.036
Geothermal	0	19.004	0	-0.018
Flywheel	0.1114	19.004	0	-0.004
PV 1	0.4235	19.004	0	-0.003
PV 2	0.4235	19.004	0	-0.036

In this case, the DLMP is close to $19/MWh as opposed to the previous scenario in which price was $20/MWh. In this case, the difference is not significant. It is mainly because the offer prices of both the flywheel and geothermal unit were very close. For all these tests, the offer values are not related to any of the costs that the actual DER might have in the field and they were created only for our case study. In a realistic scenario, it is likely that the price difference between the two most expensive resources can exceed one dollar, allowing solar to further reduce the electricity cost.

However, even though in some time instances solar can reduce the DLMP value based on the availability of resources, it can also increase total system costs. Depending on how the settlement mechanism is designed, curtailing solar power when there is a surplus can lead to an increment of the electricity cost. In addition, a high penetration of intermittent renewable resources brings other challenges such as reduced inertia and increases the need for other markets such as spinning reserves.

C. *Case III-Negative congestion*

This scenario aims to demonstrate negative congestion prices. For that purpose, it is needed to ensure significant loading on the network model so that a cheap generator will be dispatched. In this case, the network selected is Feeder 1 with no PVs connected. In the diagram of *Fig. 5* additional loading was added downstream of the gas generator. To generate negative congestion prices, the load was increased by 3MW to require additional dispatch from the next cheapest generator and the diesel generator is placed closed to the end of the feeder. The limit of the line upstream of the diesel generator (the target congested line) is 100A per phase, which amounts to 2.1 MW. The expected result is that the diesel generator will not be able to fully dispatch despite being the cheapest resource available since further generation from this unit results in system congestion.

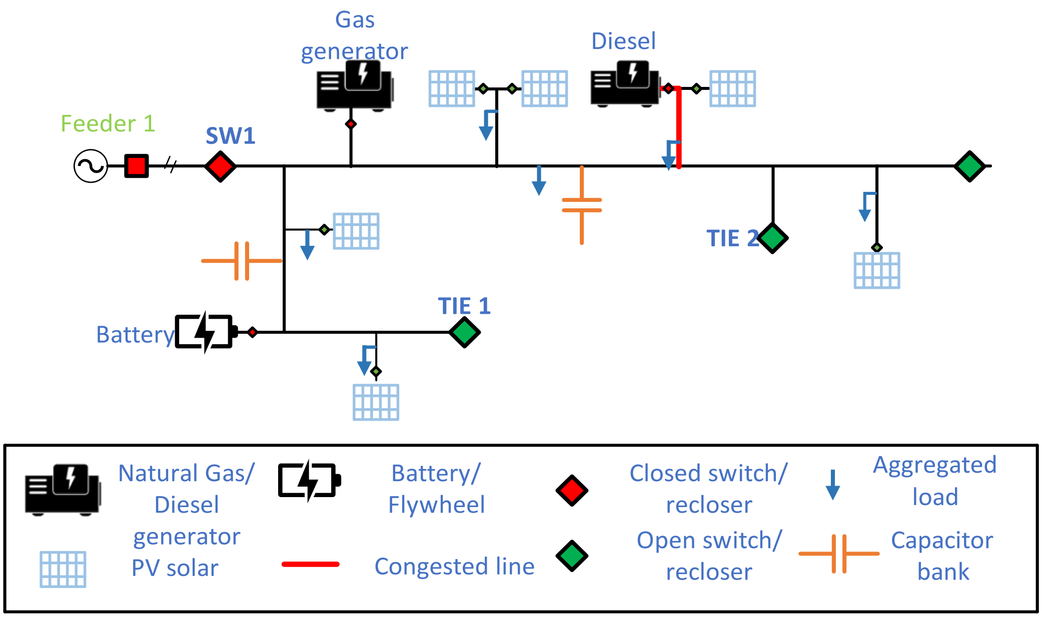

Fig. 5. Network topology for case III showing congested line

In this scenario, as the main objective was to demonstrate negative congestion prices, we will only look at the timestamp which shows congestion. At 12:00 PM, the load is 5.27 MW and the LMP price is 23.33 $/MWh. The offers from the DERs can be found in TABLE IV.

TABLE IV. OFFERS SUBMITTED AT 12:00 PM FOR CASE III

Asset	Offer ($/MWh)	Capacity offered (MW)
Diesel	10	3
BESS	20	0.78
Natural Gas	0	0

The result from the market clearing can be found in Table V.

TABLE V. MARKET RESULTS AT 12:00 PM FOR CASE III

Asset	Capacity cleared (MW)	DLMP ($/MWh)		
		Energy	*Congestion*	*Residual*
Diesel	2.49	23.33	-13.601	0.271
BESS	0.78	23.33	0	0.304
Natural Gas	0	23.33	0	0.313

As seen in TABLE V, the diesel generator has a negative congestion price. Adding these three components of the DLMP, its DLMP is $10/MWh, which is the same as the diesel offer. This result makes sense as the diesel generator cannot be fully dispatched because it would create a thermal violation. The negative congestion price discourages the diesel generator from producing additional power. The congestion price is zero for the natural gas generator and the BESS, as an increment of power from those units at particular nodes will not affect the system congestion.

In TABLE V it is noticed that the total diesel output is higher than the line power limit. This is because additional loads between the diesel generator and that line also need to be served.

D. *Case IV-Positive congestion*

Similarly, we want to demonstrate positive congestion prices. A congestion is created in the line between the natural gas and the diesel generator. This line has a limit of 270 A per phase, which equals a total of 5.8 MW by taking into account the unity power factor.

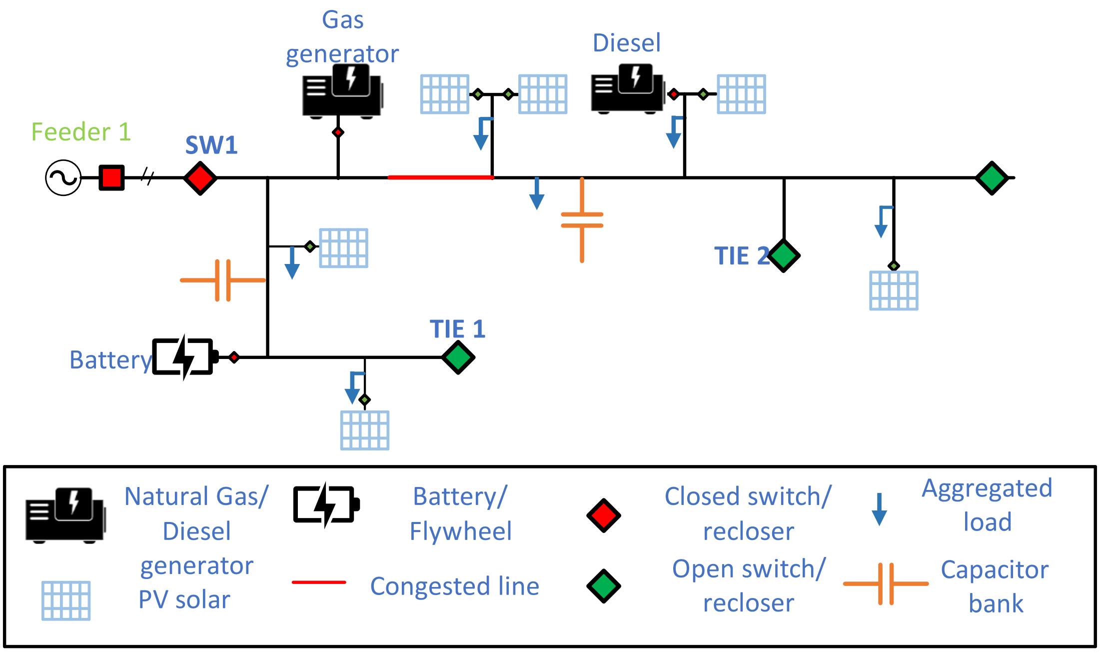

Fig. 6. Network topology for case IV showing congested line

For this scenario, we also only look at the timestamp in which there is congestion. At 12:00 pm, the load is 8.27 MW and the LMP price is 17.08 $/MWh. The offers from the DERs are listed in TABLE VI.

TABLE VI. OFFERS SUBMITTED AT 12:00 PM FOR CASE IV

Asset	Offer ($/MWh)	Capacity offered (MW)
Diesel	25	2
BESS	0	0
Natural Gas	13	8.4

The market clearing results are shown in Table VII.

TABLE VII. MARKET RESULTS AT 12:00 PM FOR CASE IV

Asset	Capacity cleared (MW)	DLMP ($/MWh)		
		Energy	*Congestion*	*Residual*
Diesel	1.51	12.824	12.103	0.073

BESS	0	12.824	0	0.177
Natural Gas	6.64	12.824	0	0.176

TABLE VIII. DLMP SUMMARY AT 12:00 PM FOR CASE IV

Asset	DLMP ($/MWh)
Diesel	25
BESS	13.001
Natural Gas	13

If all the cleared capacities are added in the market, there is roughly 8.15 MW provided by the DER. As seen in case I, the DER in our model are 3-phase generators. The phase with less loading will be the one limiting the power output of the DER. The other two phases will need power from the substation that will make up for the rest of the power needed in the whole system.

Based on the three phase price for the natural gas in TABLE IX, it is worth noting that the natural gas generator is the one establishing the energy price. Again, for phases A and B, their energy price is equal to the LMP and, for phase C, the energy price is calculated so that the result is an average 3-phase DLMP being equal to the offer:

TABLE IX. DLMP DECOMPOSITION FOR NATURAL GAS

Phase	DLMP ($/MWh)		
	Energy	***Congestion***	***Residual***
ABC	12.824	0	0.176
A	17.08	0	0.983
B	17.08	0	0.517
C	4.313	0	-0.973

As illustrated above, the natural gas generator cannot be fully dispatched without incurring a thermal violation. *Fig. 6Fig. 6. Network topology for case IV showing congested line* shows that the diesel generator is downstream of the congested line. That is why the diesel generator, even though it is more expensive with an offer of $25/MWh, needs to produce additional power to serve the load and reduce system congestion. Owing to the positive congestion price, the final DLMP is $25/MWh as its offer value, which is the minimum price a resource is willing to accept.

V. CONCLUSIONS

This paper presented the DLMP methodology and results obtained from evaluating the simulator market tool through various testing scenarios. The results demonstrate that the tool can function as expected. The DLMP is calculated per phase. For a distribution system featuring unbalanced loading, generators capable of dispatching unique power on single-phase will potentially have more value than three-phase generators. Also, if properly managed, an increased penetration of solar can also lead to smaller DLMP values, especially during the central hours of the day. However, depending on the settlements, solar power curtailment can lead to an increase in system costs.

After validating the functionality of this tool in a non-real-time mode, the next step is to test it in real-time. Using a standard communication protocol (DNP) adopted by most utilities, we will be sending real-time measurements, such as the generation output of each DER and the load value, to the market simulator tool. Those measurements will be used as the inputs to calculate the new setpoint of each DER for the next 5-minute interval, allowing us to assess the tool under real-time conditions. With all the testing scenarios in place, we will further study how the tool calculates the DLMP and the setpoints of each DER in case one of the DERs cleared on the day-ahead market is unavailable in real-time, solar output is different from the forecast, and loading conditions vary.

Using RTDS, we leverage the same network model as the one implemented in the market simulator tool. Prior to the testing, the power flow results associated with network model are carefully compared with the original results obtained in CYME to ensure the accuracy of system modeling in RTDS.

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