Reactive Power Allocation of PV Inverters for Voltage Support in Power Systems Based on Transactive Energy Approach

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Abstract—**Reactive power support is a part of ancillary services that is becoming more important due to an increase of distributed energy resources (DERs) in today's power systems. The intermittent nature of the DERs also increases the challenges of voltage management in power systems, and limitations of power system reinforcement are becoming a bottleneck to improving reliability of power systems. Thus, cooperation of existing equipment, including utility-owned and nonutility-owned assets, can be utilized to achieve higher reliability of the system. A transactive energy approach is proposed to coordinate the non-utility DERs to participate in reactive power support. Voltage sensitivity is used to determine the impact of DERs at different locations that will simultaneously participate in a reactive power market. The modified DERs' supply curve is constructed to evaluate the impact of DERs' locations based on the transactive energy approach. The performance of the proposed method is validated by comparing to other location-based and non-location-based reactive power dispatch methods. An implementation of the modified DER's supply curve can successfully improve the voltage at the target location by an amount that is specified by the system.**

Keywords— Reactive power support, Transactive energy approach, DER's supply curve, Voltage sensitivity, PV inverters.

I. INTRODUCTION

Reactive power control is one of the main methods used to regulate voltage and increase efficiency in power systems. Reactive power should not be supplied over long distances because it yields high losses in the power lines and increases transmission congestion [1], [2]. Thus, reactive power support is more effectively accomplished by supplying or absorbing reactive power near the needed location. This location issue is a main characteristic of reactive power that limits the number of potential reactive power suppliers at any location and time [2]. To ensure the reliability of the electric system, the grid should have enough reactive power sources available to provide sufficient voltage regulation such that voltages are maintained close to nominal ratings.

To increase the number of providers, other types of generators or equipment should be allowed to participate in the reactive power market. Local loads and distributed energy resources (DERs), such as inverter-based equipment (photovoltaic (PV), wind systems, and energy storage) that also have the capability to generate reactive power, can be considered as potential providers for the reactive power market [3]. When there is an appropriate number of local providers participating in reactive power support, that could provide benefits in terms of reasonable clearing price for system operators, both as customer and supplier. Moreover, voltage issues in the system can be solved efficiently because the local support will generate lower losses when compared to the support from generators located at longer distances from where the voltage support is needed. The challenging part is that it requires a coordinated interaction between the DERs and system operator to assure the DERs can be appropriately controlled.

One method to increase the engagement of non-utility DERs participating in the reactive power market is the transactive energy approach. A DER's supply curve, which represents the cost per kvarh, is used to represent the cost of providing reactive power from DERs based on the transactive energy approach. The customer can earn money based on the available capacity of an inverter for providing reactive power to the system, and the utility receives system operational benefit from voltage support, which can be done without the need of expensive capital investment.

With regards to the voltage management in the system, there are several studies related to reactive power management among resources. Most literature commonly uses voltage sensitivity to help with determining the order of dispatching reactive power resources [4]–[6] by optimizing cost and/or the amount of reactive power to maintain voltage in the system. However, none of them mention applying the transactive energy approach by integrating voltage sensitivity. Therefore, this paper aims to study the impact of different locations of DERs while implementing the transactive energy approach by using a coordination between a VOLTTRON instance [7], which represents a DER's agent, Transactive energy controller (TEC), and GridLAB-D as a power simulator [8]. Parts of the work, including DER's agent and TEC have been previously presented in [9], but the parts of the modified DER's supply curve and using GridLAB-D to verify the effectiveness of the method will be presented in this paper.

This paper is organized as follows. In Section II, the cost of providing reactive power support and market mechanism of the transactive energy approach are described. A voltage sensitivity analysis used in this work is provided in Section III. Section IV presents the integration of the sensitivity analysis with the transactive energy approach. Section V provides the results of the case studies from the simulation. Section VI provides a comparison of the location-based simulation results with non-location-based techniques and the conclusion is provided in Section VII.

II. TRANSACTIVE ENERGY APPROACH

The transactive energy system framework (TESF) proposed by PNNL [10] is implemented in this paper. The aim of this transactive approach is to engage economics to balance supply and demand over the system dynamically [11]. TESF is used for enabling the support from customers by sending the incentive signal, in terms of cost per kvarh ($/kvarh), to the customer for requesting the voltage support from non-utility inverters.

The transactive energy algorithm consists of two sections. The first section is a demand curve that represents the required amount of reactive power from the system. The second section is a DERs' supply curve, which is a cost curve related to the cost of inverters in order to provide reactive power support to the system. In this paper, the focus will be on determining the DER's supply curve.

The DER's supply curve can be categorized into two zones, which are the curtailment and non-curtailment zones [10]. The curtailment zone is related to the cost to provide reactive power when the inverter needs to curtail (reduce) its active power in order to supply more reactive power into the system. The curtailment cost and marginal cost of DERs for providing reactive power support can be calculated as follows [10], [11]:

$$C_{curt} = ET \times \left(\sqrt{S_{inv}^2 - Q_{inv}^2} - \sqrt{S_{inv}^2 - (Q_{inv} + Q_{ofr})^2} \right) \tag{1}$$

$$MC_{curt} = \frac{dC_{curt}}{dQ_{ofr}} \tag{2}$$

where C_{curt} represents the cost of DERs for providing reactive power in the curtailment zone, ET is the electricity tariff (0.1$/kWh), S_{inv} is the rated apparent power of the inverter, P_{inv}, Q_{inv} are the active and reactive power operating points of the inverter, respectively, and Q_{ofr} is the offered reactive power from the DER. MC_{curt} is the marginal curtailment cost to the DER for providing reactive power.

For the non-curtailment zone, the cost of providing reactive power support comes from the power losses in the inverter while providing reactive power in addition to providing active power. The power losses mainly consist of 1) semiconductor switching loss, 2) semiconductor conduction loss, and 3) auxiliary circuit energy consumption [12]. Below are the equations for calculating the cost of power losses while providing reactive power support which is provided by [10].

$$C_{loss} = ET \times \left[\left(\frac{S_2}{\eta_2} - S_2 \right) - \left(\frac{S_1}{\eta_1} - S_1 \right) \right] \tag{3}$$

$$MC_{loss} = \frac{dC_{loss}}{dQ_{ofr}} \tag{4}$$

where C_{loss} represents the cost due to power losses of DERs while providing reactive power, S_2 is an inverter's apparent power while providing reactive power support, and S_1 is an inverter's apparent power before providing reactive power. η_1 and η_2 are the inverter's efficiency related to the operating point of the inverter at S_1 and S_2, respectively. In this paper, test data of the inverters are used to determine inverter efficiency [13] by using the curve fitting method to fit the inverter's test data to the inverter efficiency curve.

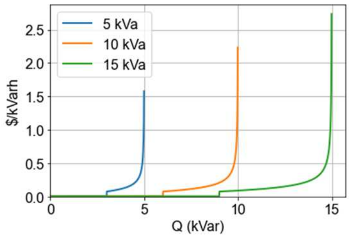


Fig. 1. DER's supply curves of 5, 10, and 15 kVA in partial load condition.

Fig. 1 represents the DERs' supply curves of three different DERs with ratings of 5, 10, and 15 kVA in partial load condition when curtailment starts at 3, 6, and 9 kvar, respectively. As expected, the cost of non-curtailment zone of all inverters is significantly less expensive when compared to the cost of the curtailment zone.

To determine the cleared price for the amount of required reactive power, a double auction market is performed. Based on the market mechanism, the market is cleared when demand and supply curves intersect, and at that point the cost per kvarh ($/kvarh) of the amount of reactive power that the system needs is considered as the cleared price for the DERs [11].

III. VOLTAGE SENSITIVITY OF DERS IN DIFFERENT LOCATIONS

To provide voltage support efficiently, most voltage support devices are installed close to the target location [1]. This can be realized because a voltage issue is considered as a local problem. In the same manner of providing voltage support from DERs, location of the DER should be one factor considered when the voltage in the system needs to improve.

Voltage sensitivity analysis has been used to determine the sensitivity of the voltage based on the change of active and reactive power at different locations in the system. The analysis can determine the most effective locations and amount of the reactive power of DERs to support for the system [14]. There are different ways to obtain voltage sensitivity such as Jacobian matrix, impedance-based method, and perturbation method [5], [15], [16]. For this study, the perturbation method is implemented since it is suitable for adoption with the distributed control system as described in [9], where the sensitivity calculation can be done by using measurement data from the system [17].

The voltage sensitivity by perturbation method should be obtained before constructing the modified DER's supply curve. So that the sensitivities of DERs can represent the relationship between voltage at the target location and amount of reactive power provided by DERs based on the current state of the system [18].

The change of voltage at the target location (node *i*) with respect to the small perturbation of active or reactive power at the DERs' locations (node *j*) can be formulated as follows [19]:

$$\Delta V_i = \sum_{j=1}^{j=n} \left(S_{vp,ij} \Delta P_j + S_{vq,ij} \Delta Q_j \right) \tag{5}$$

where ΔV_i represents the change of voltage at node i, n is total number of DERs in the system. S_{vp} (V/kW) and S_{vq} (V/kvar) are voltage sensitivity matrices due to the change of active power (ΔP_j) and reactive power (ΔQ_j) at node j, respectively.

A larger value of voltage sensitivity will result in larger impact of changing voltage at the target location. For this study, it is assumed that the load in the system remains stable while applying a reactive power perturbation to calculate the voltage sensitivity.

IV. INTEGRATING VOLTAGE SENSITIVITY INTO TRANSACTIVE ENERGY APPROACH

The transactive energy approach is implemented in order to engage the DERs to participate in the reactive power support when the system needs it. The cost curve from the system will be sent to participant DERs, and then each DER will provide reactive power support to the system based on their own cost curves.

The location of each DER is an important factor to determine the impact of voltage support that the DER can contribute to the location that needs voltage support. In this work, the sensitivity factors are implemented in the transactive energy approach to evaluate the impact of voltage support based on different locations of DERs in the system. The proposed method is based on the idea of the cost of providing reactive power support by changing a similar amount of voltage at the target location, and the performance of the approach is evaluated.

Each DER's supply curve will be reconstructed in order to integrate the voltage sensitivity factor based on the DER's location. Since, this paper is mainly focused on the change of voltage based on the reactive power output from the DERs, a relationship between the voltage change at the target location by reactive power contribution of DERs at different locations can be represented by (6).

$$\Delta V_i = S_{vq,ij} \times \Delta Q_j \tag{6}$$

where S_{vq} represents the reactive power sensitivity of the target location and the DER's location. The DERs at the different locations can impact the same amount of voltage at the specific location by providing the amount of reactive power based on their voltage sensitivities. By using this relationship, the modified DER's supply curve based on curtailment cost and cost of power loss in terms of \$/V can be derived as follows.

$$MC_{curt} = \frac{ET \times \dfrac{1}{S_{vq}} \left(Q_{inv} + \dfrac{\Delta V}{S_{vq}} \right)}{\sqrt{S_{inv}^2 - \left(Q_{inv} + \dfrac{\Delta V}{S_{vq}} \right)^2}} \tag{7}$$

$$MC_{loss} = \frac{ET \times \dfrac{1}{S_{vq}} \times \left(\dfrac{1-\eta_2}{\eta_2} \right) \left(Q_{inv} + \dfrac{\Delta V}{S_{vq}} \right)}{\sqrt{P_{inv}^2 + \left(Q_{inv} + \dfrac{\Delta V}{S_{vq}} \right)^2}} \tag{8}$$

Normally, the DER's supply curve, which represents the cost of reactive power support of the DER, will depend on the rating of the inverter and the current operating point of inverter in terms of active and reactive power. When considering the location of DERs, the DER's supply curve will also be impacted by the different values of voltage sensitivity. In the section below, the modified DER's supply curve will be presented based on each impacting factor.

A. *Location*

Voltage sensitivity values of the DERs are affected by the location of DERs. The DER with shorter electrical distance to a target location that needs to improve its voltage will have the larger value of voltage sensitivity, which means that the change of reactive power will cause more change of voltage at the needed location than the one with lower voltage sensitivity. In this case, the modified DER's supply curves of DER1 and DER2 are shown in Fig. 2 with the voltage sensitivities of 0.3835 and 0.3491, respectively for a case where both DERs have similar reactive power capacity of 5 kvar.

From Fig. 2, DER1 is the closest DER to the needed location. With higher voltage sensitivity, it will require less reactive power to change the same amount of voltage. Thus, the cost of DER1 to provide reactive power support to the target location is cheaper than DER2 in all range of voltage.

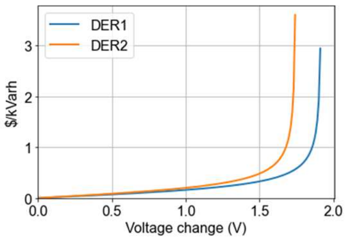


Fig. 2. Modified DER's supply curves of DERs with similar reactive power capacities in different location.

B. *Reactive power capacity*

Based on the transactive energy approach, the cost of providing reactive power will be higher when the DER operates close to its rating. In this case, the modified DER's supply curves of two DERs in the same location but with different reactive power capacities are constructed. The reactive power capacities of DER1 and DER2 are 5 kvar and 10 kvar while they have similar voltage sensitivity at 0.3835. As the modified DER's supply curves of two DERs shown in Fig. 3, DER1 has a smaller rating resulting in a higher cost of providing reactive power than DER2 in this case.

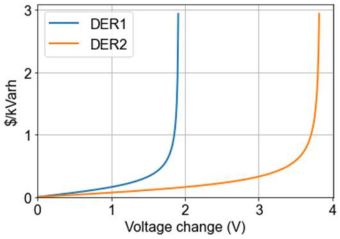


Fig. 3. Modified DER's supply curves of DERs with different reactive power capacities in the same location.

In a real market, there will be multiple DERs that participate in the market at the same time. The aggregate DER's supply curve of participating DERs will be used to determine the cleared price of the market. The aggregate curve is calculated by sequence of the cost of providing reactive power of the DERs from the lowest to highest values. An example of aggregate DER's supply curve of part B is shown in Fig. 4.

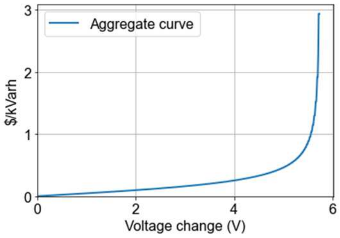


Fig. 4. Aggregate DER's supply curve.

V. SIMULATION

Due to the multiple locations of DERs participating in the market, the system will have many solutions to select the DERs to support the voltage. Since these inverters have different available capacities based on their operations and locations resulting in different cost of providing the reactive power support to the system, the idea of integrating the voltage sensitivity to the transactive energy approach is investigated. The analysis is performed using two different test feeders, including 15-node test feeder, as a proof of concept, and the IEEE 123-node test feeder to represent scalability.

A. 15-node test feeder

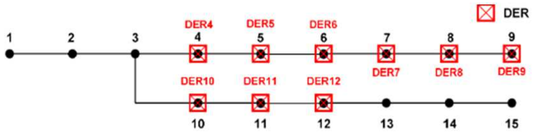


Fig. 5. 15-Node test feeder with line parameters from the 8500 node test feeder.

A simple 15 nodes test feeder with 9 DERs, as shown in Fig. 5, is used to evaluate the result of a modified DER's supply curve. Line parameters of the test feeder are taken from IEEE 8500 node test feeder and parameters of connected DERs are provided in Table I.

TABLE I. PARAMETERS OF 15-NODE TEST FEEDER.

Parameters	Values
Rated apparent power of DERs (kVA)	5[a], 10[b]
Operated active power of DERs (kW)	4[a], 8[b]
Operated reactive power of DERs (kvar)	0
Distance between each section (km)	0.5

[a] For DER7, DER8 and DER9.

[b] For DER4, DER5, DER6, DER10, DER11, and DER12.

Assuming all DERs operate based on the parameters provided in Table I, the aggregate modified DER's supply curve when all DERs participate in the reactive power market is shown in Fig. 6.

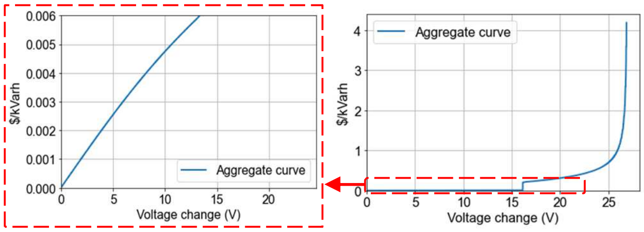


Fig. 6. Aggregate DER's supply curve of participant DERs on the test feeder.

Assume the system requests to change voltage at node 9 by 10 V, the cleared price of changing the voltage would be 0.00475 $/kvarh. Based on the cleared price, reactive power dispatch of the DERs and their respective voltage sensitivity values are shown in Table II.

TABLE II. REACTIVE POWER DISPATCH ON 15-NODE TEST FEEDER.

	DER 4	DER 5	DER 6	DER 7	DER 8	DER 9	DER 10	DER 11	DER 12
S_{vq}	0.355	0.361	0.366	0.372	0.378	0.384	0.349	0.349	0.349
Q (kvar)	4.20	4.30	4.37	2.23	2.28	2.32	4.12	4.12	4.12
% Q dispatch	70	72	73	74.3	76	77.3	68.7	68.7	68.7

Results of reactive power dispatch of DERs show that the DERs that are closer to the target location (Node 9) will provide more reactive power than the farther DERs (as a percentage of their available capacity). When considering DER7, DER8, and DER9, which have similar reactive power capacity at a nearby location, DER9, connected at the target location, will provide more reactive power than DER7 and DER8 because DER9 has the highest voltage sensitivity. If compared to the DERs that are farther from the target location but that have higher capacity, these higher capacity DERs will provide more reactive power because they have lower cost of providing reactive power than the DERs that are closer to the target location.

The feeder model in GridLAB-D with the dispatch of DERs based on the approach is simulated. Voltage profiles of the feeder before and after the reactive power dispatch are shown in Fig. 7. The voltage at node 9 is changed by 10 V corresponding to the set value. Because of the small test feeder, the reactive power support at the target node affects other nodes' voltages in the system which can be explained by the voltage sensitivity of all nodes that are very close to each other. The effectiveness of the proposed method will be investigated on a larger test feeder in the next subsection.

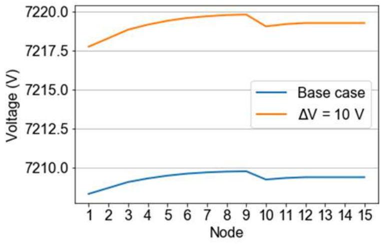


Fig. 7. Voltage profile of the 15-node test feeder before and after reactive power dispatch.

B. *IEEE 123-node test feeder*

To examine the approach with a larger test feeder, a modified version of the IEEE 123-node test feeder [20] by including DERs is used. There are 53 DERs connected to the nodes as shown in Fig. 8 on the test feeder. Loads are modeled as constant power loads. The system is three-phase unbalanced, but only one phase (phase A) will be focused to verify the performance of the approach in this paper.

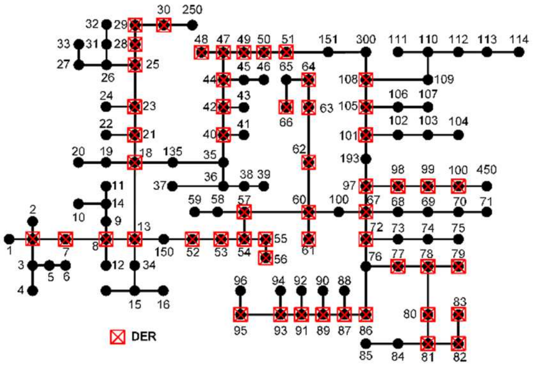


Fig. 8. Modified IEEE-123 node test feeder with connected DERs.

Voltage sensitivity analysis is applied on the test feeder to determine sensitivity factors based on the change of reactive power at different locations. In this case, the voltage sensitivity analysis will be based on the node 114 as the target location, due to this node having the lowest voltage of all the locations. The sensitivities of all nodes associated to the target location are calculated for phase A as shown in Fig. 9.

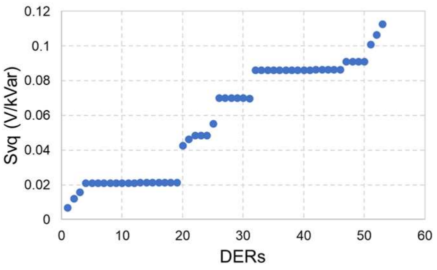


Fig. 9. Voltage sensitivity of all nodes with respect to node 114 in the IEEE-123 node test feeder.

To evaluate the proposed method, case scenarios listed in Table III will be studied. Result of reactive power dispatch based on each scenario will be provided along with the voltage profile after the reactive power support from the DERs.

TABLE III. PARAMETERS OF DERS BASED ON SCENARIOS.

Parameter	**Cases**	
	Scenario 1	***Scenario 2***
Rating (kVA)	10	5[a], 10[b]
Operated active power (kW)	6	3[a], 6[b]
Operated reactive power (kvar)	0	0

[a] For DER25 – DER53.

[b] For DER1 – DER24.

For Scenario 1, the DERs in the test feeder are assumed to operate by producing active power at 6 kW. Hence, the reactive power capacity of the DERs is at 8 kvar without curtailment of the active power. The modified DERs' supply curves of all DERs are shown in Fig. 10.

The modified DER's supply curves show that the DERs that are nearer to the target location have lower cost of providing reactive power than the DERs that are farther away from the target location, when considering the same amount of voltage change at the same location. The aggregate curve of DERs as shown in Fig. 11 is used to determine the cleared price of the market.

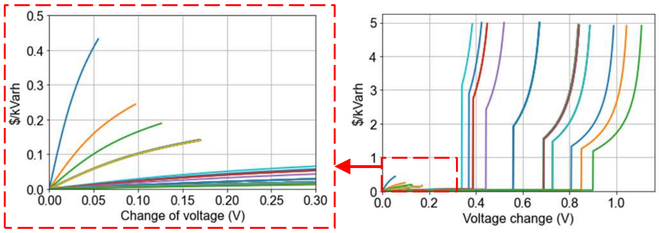


Fig. 10. Modified DERs' supply curves of all participating DERs based on Scenario 1.

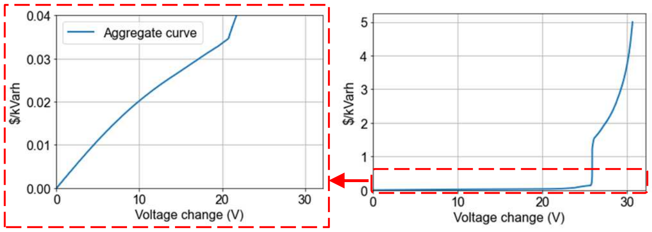


Fig. 11. Aggregate Modified DER's supply curve based on Scenario 1.

Maximum voltage at the target location can be changed based on the contribution of all DERs is at 30.6 V. Assuming the system requires to change the voltage at the target location by 20 V, the cleared price will be 0.034 $/kvarh. After the market is cleared, the reactive power dispatch of each DER is presented in Fig. 12.

Based on the reactive power dispatch result, the DERs that are closer to the target location provide higher amount of the reactive power than the other DERs that are farther away. Since the reactive power capacity of DER are similar at 8 kvar without active power curtailment, the DERs that have more capabilities to change voltage at the target location with lower price to provide reactive power support will provide more reactive power than the DERs that have less capabilities to change voltage i.e. require more reactive power to change the same amount of voltage, which results in higher price of providing reactive power.

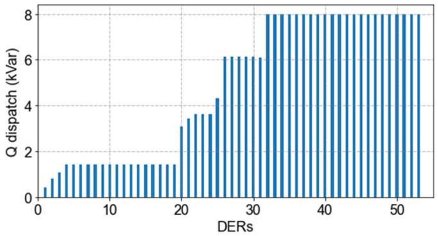


Fig. 12. Reactive power dispatch of all DERs with similar reactive power capacities based on Scenario 1.

Voltage profile after the DERs provide reactive power support to the system is presented in Fig. 13. After the reactive power support from the DERs, the voltage at the target location is changed by 20V based on the system's requirement.

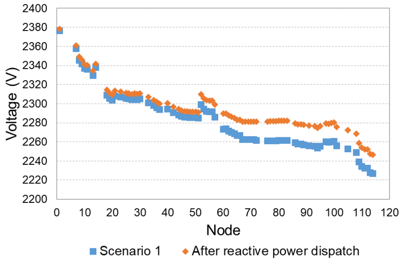


Fig. 13. Voltage profile after the DERs provide reactive power support based on Scenario 1.

For Scenario 2, assume the DERs that are near to the target location (DER25 – DER53) have less capacities of reactive power with DER rating of 5 kVA than the DERs that are farther away (DER1 – DER24) with DER rating of 10 kVA. So that the price of providing reactive power support of the nearer DERs to the target location will be higher than the farther away DERs.

When the system requires to change 10 V at the target location, the cleared price is 0.032$/kvarh. Reactive power dispatch of the DERs is presented in Fig. 14.

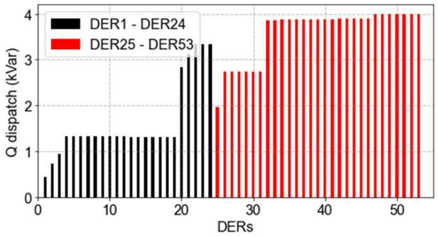


Fig. 14. Reactive power dispatch of DERs with reactive power capacities at 8 kvar (black bar) and 4 kvar (red bar) based on the scenario 2.

In this scenario, the reactive power dispatch based on the proposed method is different to the result of dispatch based on the 1st scenario. For the 2nd scenario, the dispatch of some DERs that are closer to the target location (DER 25 – DER 31) are lower than the farther away DERs (DER 20 – DER 24). Even though the DER 20 – DER 24 have to provide more reactive power than the DER 25 – DER 31 to change the similar amount of voltage, the cost of providing reactive power support of them are lower than the closer DERs due to them having higher reactive power capacities.

Based on the reactive power dispatch of all DERs, the voltage profile of Scenario 2 is presented in Fig. 15. The voltage at the target location increases by 10V after the DERs provide reactive power support.

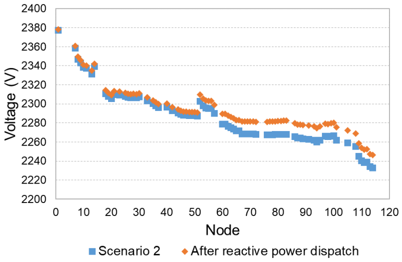


Fig. 15. Voltage profile after the DERs provide reactive power support based on the scenario 2.

VI. COMPARISON OF REACTIVE POWER DISPATCH METHODS

This section aims to investigate the reactive power dispatch of the proposed method when compared to non-locational-based reactive power dispatch and locational-based reactive power dispatch when using an order of voltage sensitivity of the DERs to evaluate cost of providing reactive power support and losses in the system. Each method will have similar DER parameters based on Scenario 2.

For a comparison with non-location-based reactive power dispatch, the reactive power dispatch will be determined by using the amount of total reactive power from the proposed method. While a comparison with location-based reactive power dispatch approach in this case will be based on an optimization method by minimizing the voltage deviation at the target location when considering an order of voltage sensitivity of the DERs. The effectiveness of changing the voltage at the target location among the approaches will be evaluated.

A. Location-based reactive power dispatch : optimization method by minimizing the voltage deviation at the target location

In this section, reactive power dispatch of the DERs will be based on the optimization approach when the objective function is to minimize the voltage deviation at the target location. The formulation of the optimization method is presented in (9).

$$Minimize\left(\Delta V_i = \sum_{j=1}^{j=n} S_{vq,ij} \times \Delta Q_j\right) \tag{9}$$

subject to,

$$P^{min}_{gen,j} \le P_{gen,i} \le P^{max}_{gen,j}, \qquad j = 1,2,\ldots,n$$

$$Q^{min}_{gen,j} \le Q_{gen,i} \le Q^{max}_{gen,j}, \qquad j = 1,2,\ldots,n$$

where n is total number of DERs in the system, j is a DER's connected node, and i is a target node for voltage change.

When the system requires the participating DERs to change the voltage at the target location by 10 V, the total reactive power support needed based on the optimization approach is 137 kvar. The reactive power provided by each DERs is shown in Fig. 16. The voltage profile before and after reactive power dispatch based on the optimization approach by minimizing the voltage deviation at the target location is shown in Fig. 19.

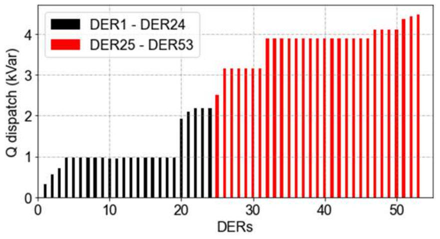
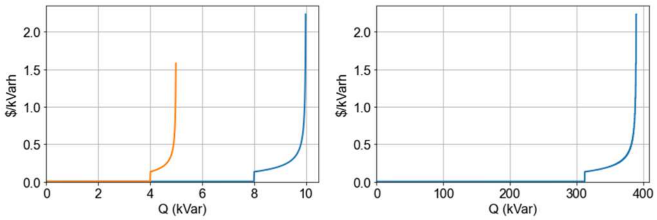


Fig. 16. Reactive power dispatch of DERs with reactive power capacities at 8 kvar (black bar) and 4 kvar (red bar) based on the optimization approach.

B. *Non-location-based reactive power dispatch*

This section aims to investigate the transactive energy approach when not considering the locations of the DERs. The rating of the inverter will be the main factor to determine the cost of DER to provide the reactive power support to the system.

Based on the different rating of DERs, the DER's supply curve of the DERs at 5 kVA and 10 kVA rating are as shown in Fig. 17 (a)., and the aggregate curve is presented in Fig. 17 (b). When the DERs expect to support the voltage at the target location by 10 V, the results of reactive power dispatch of the DERs based on the transactive energy approach when not considering the location of DERs is presented in Fig. 18.



(a) (b)

Fig. 17. Modified DER's supply curves (a) DERs at 5 kVA (orage curve) and 10 kVA rating (blue curve) (b) aggregate curve.

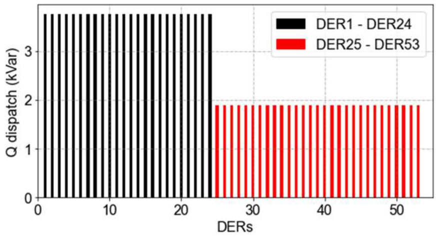


Fig. 18. Reactive power dispatch of DERs with reactive power capacities at 8 kvar (black bar) and 4 kvar (red bar) based on the transactive energy appraoch when not considering the location of the DERs.

Based on the total amount of reactive power at 144 kvar, the reactive power dispatch from DERs are at 3.76 kvar and 1.88 kvar based on the different rating of the DERs at 10 kVA and 5 kVA, respectively. The farther away DERs with higher reactive power capacities at lower cost provide more reactive power support than the closer DERs with higher cost due to the lower capacities. The voltage profiles based on reactive power dispatch of three methods can be presented in Fig. 19.

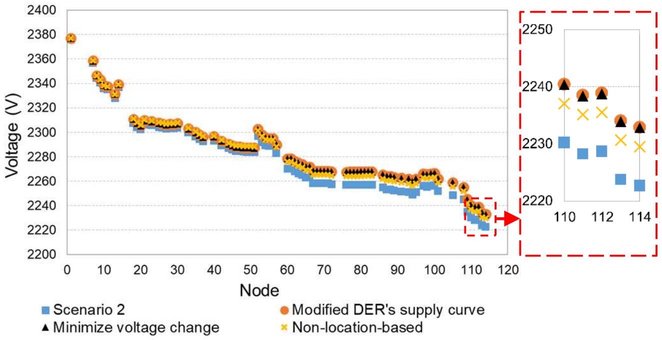


Fig. 19. Voltage profile before (■) and after reactive power dispatch of the DERs based on the modified DERs' supply curves approach (●), optimization approach by minimizing the voltage deviation at the target location (▲), and non-location-based reactive power dispatch (×).

The voltage change at the target location based on three different methods can be done successfully by using the proposed method and the optimization method. The non-location-based reactive power dispatch could only increase the voltage at the target location by 6.9 V while having the same amount of reactive power support based on the proposed method. The reactive power dispatch of the non-location method is determined based on the cost of providing reactive power support which only depended on the capacities of the DERs. Hence, the lower cost DERs with lower impact on the voltage change at the target location provide more reactive power in this case.

For the optimization method, it improves the voltage at the target location with less reactive power provided. Due to the cost of providing reactive power not being considered into the objective function, some closer DERs that have higher impact on voltage change at the target location are required to curtail their active power for providing more reactive power support. So that the cost of providing reactive power support of the DERs will be increased.

Power losses from the power lines in the system after reactive power dispatches of location-based dispatches and non-location-based dispatch are investigated. The power losses including active and reactive power losses of the system based on test cases are shown in Table IV.

TABLE IV. POWER LOSSES IN THE SYSTEM.

Method	Active power loss (kW)	Reactive power loss (kvar)
Before reactive power dispatch from the DERs	27.745	61.238
Proposed	26.850 (3.23 % ↓)	58.469 (4.52 % ↓)
Optimization by minimizing voltage deviation	26.884 (3.10 % ↓)	58.569 (4.36% ↓)
Non-location reactive power dispatch	26.952 (2.86 % ↓)	58.844 (3.91% ↓)

Based on the test feeder without the regulator, the voltage profile of the test feeder has already been lower than the acceptable range at 0.95 pu. Table IV shows that the losses in the system after the reactive power dispatch of all methods can reduce both active and reactive power losses in the system. The system losses are reduced by 3.2% for active power loss and 4.5% for reactive power loss from the base case for both the proposed method and the optimization method. On the other hand, the losses reduced by non-location dispatch method are less than the other two methods.

VII. CONCLUSION

Based on the limitation of location and cost of providing reactive power support, the allocation of reactive power support based on transactive energy approach is studied. To determine which DER provides reactive power more efficiently, the voltage sensitivity is implemented with the DER's supply curve. The results of the test feeder simulation show that the modified DER's supply curves can be used to determine the cleared price of the market, and once the DERs dispatch their reactive power based on the cleared price, the voltage at the target location can be changed accordingly.

The effectiveness of the proposed method is investigated by using two different the test feeders. The results of the reactive power dispatch based on the proposed method can be effective on both feeders. Some test scenarios are provided to illustrate the characteristics of the method. The results show that the DERs with more impact on the voltage with the lower cost of providing reactive power will be considered first based on the approach. The closer DERs might provide less reactive power support if they have lower reactive power capacities than the further away DERs that result in a higher cost to provide voltage support. Voltage profiles of the IEEE 123-node test feeder are compared between different reactive power dispatch approaches. The voltage at the target location can be successfully changed by the implementation of the proposed method and the optimization method. However, the non-location-based reactive power dispatch could not adequately change the voltage at the target location and will required more reactive power than the location-based dispatches. The power loss analysis for the system is performed, and the result shows that the proposed method does not represent a significant change in the system's losses.

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