VOLTTRON^{TM} Agent Development for Enabling Reactive Power Support of Non-Utility DERs by Integrating Transactive Energy Approach

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Abstract — **To enable better voltage regulation in power systems with high penetration of photovoltaics (PV) and other distributed energy resources (DERs), inverters are now being required to provide reactive power support to the grid in addition to providing real power generated by PV panels. This paper develops a framework that coordinates the support from DER-based inverters, which are grid-connected non-utility assets, by using a transactive energy approach. Results of the implementation demonstrate participation of DER-based inverters can be achieved by using the coordination between distributed controllers and a centralized controller. With the transactive energy approach, both the customer and utility can achieve benefits that meet their individual needs.**

Index Terms—Agents system, distributed control, grid support, transactive energy system, distributed energy resources

I. INTRODUCTION

Currently, distribution systems face many challenges including increased penetration level of distributed energy resources (DERs) in the system that increases the complexity of the grid and can result in voltage issues in a grid that had not been designed considering this type of generation. Also, many major storm events have occurred in the past few years that require an extended period of time for restoration, and reveals that grid resiliency needs to be improved [1]. Adding equipment and systems to improve voltage issues and the resiliency of the grid requires substantial investment and in some cases a lengthy timeframe for planning, acquiring, installing, and maintaining these new assets [2].

Many utilities are trying to overcome issues presented by DERs by searching for solutions that do not require significant investments in new equipment and/or systems. In this paper, the work focuses on improving voltage regulation in the distribution system. Many existing solutions require the installation of equipment to support reactive power to the system, for example: STATCOM, on-load tap changer, capacitor bank, and inverter [2, 3, 4]. Based on the voltage issues in the system and the limited solutions available, a transactive approach has been proposed by Pacific Northwest National Laboratory (PNNL). The idea behind the approach is to engage non-utility assets to support the voltage in the system by injecting or absorbing the reactive power of customer owned inverters based on an incentive signal that will be sent from a transactive energy system (TES) [5, 10]. In case the system requires support from a non-utility inverter, the TES will be responsible for sending the incentive signal, which is based on price per kVar ($/kVar) to engage the support from non-utility assets for voltage support [1, 5]. Based on this approach, the customer can get an economic benefit by providing the reactive power support from available capacity of an inverter, and the utility can get the var support without installing new equipment and/or systems which would require substantial investment.

To be able to engage the support from a customer, distributed controllers are developed to be the connection between the customer devices and the centralized controller. Coordination between these systems are required in order to perform the bidding of reactive power based on the integration of transactive energy approach. This paper provides the framework for a distributed controller and simulation results using the proposed approach.

The paper is organized as follows. Section II gives a background of related systems. Section III presents the agent development for enabling the support from non-utility inverters. Section IV is the simulation results of the framework, and conclusions and future work are described in Section V.

II. BACKGROUND

For a traditional power grid, centralized control typically has one main controller that has to accommodate all of the events in the system. With an increase in the number of devices and systems adding more complexity, a centralized controller faces several new issues for handling situations in the system. On the other hand, a distributed control system has several benefits in terms of performing real time functions, and a lower cost to add more functions later after an initial system has been installed when compared to a centralized control system [1]. With the limited flexibility and cost of adding more functions of the central controller, the idea of integrating distributed control and centralized control is proposed [1].

The coordination between a centralized control system and distributed control system, which is called laminar control architecture, is developed by using the Open Field Message Bus (OpenFMB) framework. The aim is to increase the operational flexibility of the system without the investment of new deployment and also can improve the reliability and resiliency of the power system [1].

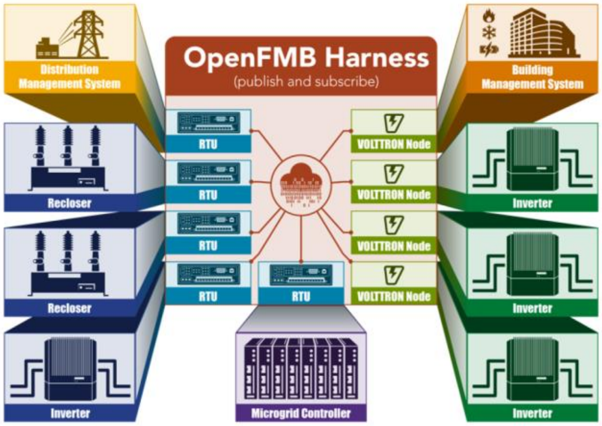


Fig. 1. OpenFMB Harness structural diagram [1].

OpenFMB harness is an implementation of OpenFMB in the control structure which acts as the message bus to which many devices in the system can connect [1]. As can be seen in Fig. 1, all of the grid devices and systems including distribution management system, reclosers, utility inverters, and microgrid controller are connected with an OpenFMB harness by using remote terminal units (RTUs). For the customer side, the inverters and building management system are connected to the harness via VOLTTRON™, the open source distributed platform that has been developed by PNNL [6, 7].

To enable the connection between the OpenFMB harness and the customer assets, an adapter for each platform is required. This paper mainly focuses on controlling and monitoring using non-utility inverters owned by the customers to enable the voltage support from an inverter by integrating a transactive approach. For the control, VOLTTRON™ agents are developed to be the distributed controller for the non-utility inverters. NATS is a publish and subscribe messaging system, and it has been used for the communication between the OpenFMB message bus and the outside platforms which enables peer to peer communication among the devices. Each device can receive data based on the subscription topics. This peer-to-peer idea reduces the latency of direct communication between DMS and devices, which normally includes delay time [1]. VOLTTRON™ agents development for enabling control and monitoring over inverters will be described in more detail in section III.

The transactive energy system framework (TESF) proposed by PNNL [5] is implemented in this paper. The aim of this transactive approach is to engage economics to balance supply and demand over the system dynamically [10]. TESF is used for enabling the support from customers by sending the incentive signal in terms of price per kVar ($/kVar) to the customer for requesting the voltage support from non-utility inverters. When customer DERs have available capacity apart from producing real power, DERs can support the grid by providing reactive power to regulate the grid voltage [8]. The reactive power capacity depends on the rating of the inverter and operated real power, which can be calculated based on the following equation [2, 3]:

$$Q_{capacity} = \sqrt{S_{rated}^2 - P_{inv}^2} \tag{1}$$

where $Q_{capacity}$ is the available reactive power capacity of the inverter, S_{rated} is the rated apparent power of the inverter, and P_{inv} is the current real power operating point of inverter.

The transactive energy algorithm consists of two sections. First is a demand curve that represents the required amount of reactive power from the system. The second part is the DERs' supply curves, which is a cost curve related with the price of inverters to curtail their real power in order to supply more reactive power into the system. In the case where an inverter has available capacity without the need of real power curtailment, that portion will be considered as the non-curtailment zone in which the price of the provided reactive power is low when compared with the cost to provide reactive power while in the curtailment zone. So, for the non-curtailment zone, the cost of providing reactive power is equal to zero [5, 10].

$$C_{curt} = ET \times [\left(\sqrt{S_{INV}^2 - Q_{INV}^2} - P_{INV}\right) - (\sqrt{S_{INV}^2 - (Q_{INV}^2 + Q_{OFR}^2)} - P_{INV})] \tag{2}$$

$$MP_{curt} = \frac{dC_{curt}}{dQ_{OFR}} \tag{3}$$

where C_{curt} represents the cost to DERs for providing reactive power, ET is electricity tariff, S_{INV} is the rated apparent power of the inverter, P_{inv}, Q_{inv} are the real and reactive power operating points of inverter respectively, and Q_{OFR} is the offered reactive power from the DER. MP_{curt} is the marginal curtailment cost to the DER for providing reactive power [10].

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

Based on the transactive energy approach, both the utility and customer can receive tangible benefits. 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.

III. AGENTS DEVELOPMENT

Agents are developed within VOLTTRON™ to enable communication between customer devices and the centralized system. Agents are developed to perform specific tasks [9, 11] as shown in Fig. 2.

In this work, the two main responsibilities of agents are represented. First, the VOLTTRON™ agent should be able to communicate with the customers' devices, which is focused on inverters in order to integrate the support from a customer owned DER inverter to the grid based on the incentive signal from TES. The second is to build the VOLTTRON^{TM}/OpenFMB adapter in order to communicate with the OpenFMB harness for updating operating points of inverters and also scheduling control over the inverter [1]. The developed agents consist of an inverter modbus agent and an inverter control agent. The functions of the agents are described in the following sections.

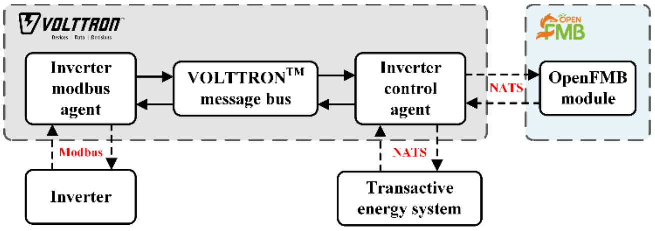


Fig. 2. VOLTTRON^{TM} agents framework.

A. *Inverter Modbus Agent*

An inverter modbus agent is developed to form the connection between the VOLTTRON^{TM} platform and an inverter for monitoring and controlling the inverter, which is using modbus TCP/IP for communication. The inverter parameters such as voltage, current, and power are read from modbus registers of the inverter. These data are published to the VOLTTRON^{TM} message bus for the inverter control agent to subscribe these data and then uses these data to achieve other tasks, such as constructing a DER supply curve and updating the inverter data into the OpenFMB module. The agent can also subscribe to the control signals from the message bus for setting new operating points which are real and reactive power of the inverter.

B. *Inverter Control Agent*

The inverter control agent is designed to be the connection between VOLTTRON^{TM} and OpenFMB harness. The agent can send the inverter data to OpenFMB model via NATS. In part of TES, the inverter control agent is also designed to be the connection between VOLTTRON^{TM} and TES in order to subscribe to the transactive signal and publish data which is required from TES.

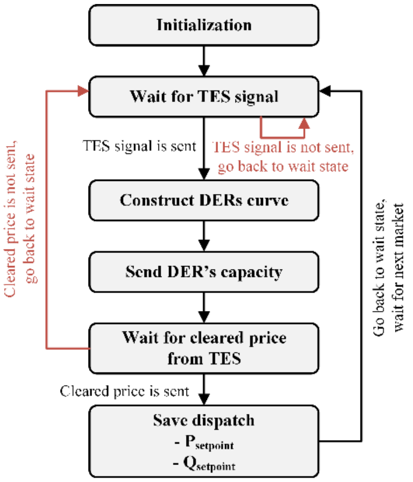


Fig. 3. State machine implementation in VOLTTRON^{TM} agents.

To coordinate with the TES, a state machine is implemented into the inverter control agent. Steps of the coordination between two systems are shown in Fig. 3.

Inverter control agent is in the waiting state until the agent receives a TES signal which is sent from the TES. In the case when the agent waits for an extended period of time, the agent will flag the timeout error and close the connection between VOLTTRON^{TM} and the TES, and will wait for participating in the next market. After the agent receives the TES signal, the agent moves to construct the DER's cost curve and send the required data including the curve back to TES to participate in the market. After the market is cleared, the agent will receive the cleared price from the TES and the price will determine the amount of reactive power the inverter should supply to the system. After the amount of reactive power is determined, the set point of real and reactive power will be calculated in the agent and sent to the message bus to the inverter modbus agent for setting new set points of the inverter as shown in Fig. 4.

Raspberry Pi^{TM} with installed VOLTTRON^{TM} agents is used in the demonstration of this work. The framework is illustrated in Fig. 4 with multiple agents performing with different rated inverters. After the transactive signal is sent by the TES for requesting the support from customers, multiple DERs will submit their own DER's supply curve for bidding. When the market is cleared, each inverter will dispatch the power based on its individual price curve.

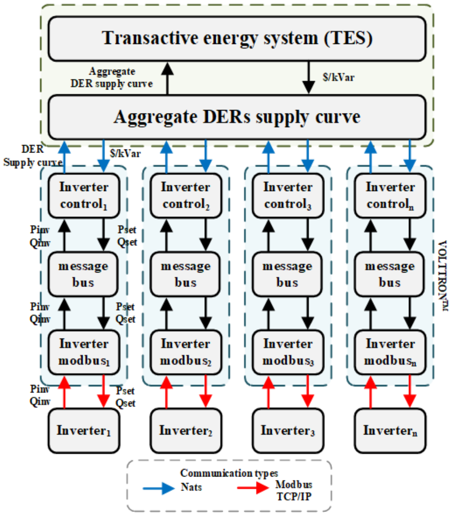


Fig. 4. Framework of VOLTTRON-TES.

IV. RESULTS

This paper demonstrates the implementation of reactive power support from customer owned inverters by using a transactive control approach. DERs' supply curves for different ratings of inverters are illustrated in Fig. 5. When considering these inverters are all operated at the full load condition, the curves for 5 kVA inverters (lowest power) have the highest cost for providing the reactive power followed by 10 kVA and 15 kVA units, respectively.

Fig. 6 shows the aggregated curve of these inverters which can be determined by sequence of price per kVar ($/kVar) based on DERs' supply curves from the lowest to the highest value. The aggregated curve and demand curve are used to determine a cleared price of a market. After the market is cleared, the cleared price is sent to the participating DERs for dispatching real and reactive power to support the system based on their own DER's supply curves.

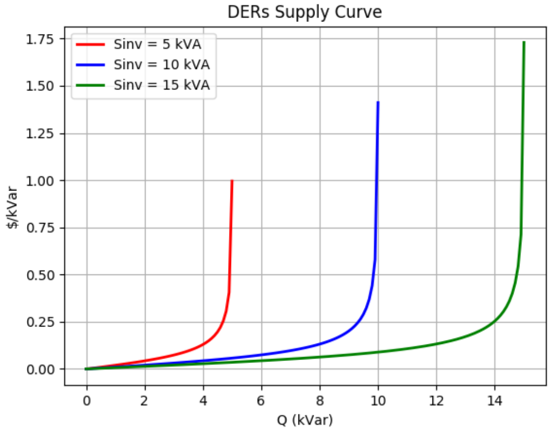


Fig. 5. DERs' supply curves of inverters with $Sinv_1$ = 5 kVA (red curve), $Sinv_2$ = 10 kVA (blue curve), and $Sinv_3$ = 15 kVA (green curve).

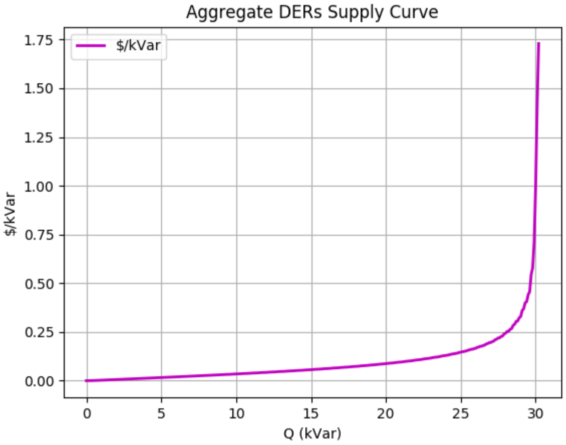
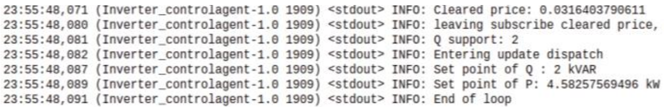


Fig. 6. Aggregated DER's supply curve of all inverters.



```
23:55:48,071 (Inverter_controlagent-1.0 1909) <stdout> INFO: Cleared price: 0.0316403790611
23:55:48,080 (Inverter_controlagent-1.0 1909) <stdout> INFO: leaving subscribe cleared price,
23:55:48,081 (Inverter_controlagent-1.0 1909) <stdout> INFO: Q support: 2
23:55:48,082 (Inverter_controlagent-1.0 1909) <stdout> INFO: Entering update dispatch
23:55:48,087 (Inverter_controlagent-1.0 1909) <stdout> INFO: Set point of Q : 2 kVAR
23:55:48,089 (Inverter_controlagent-1.0 1909) <stdout> INFO: Set point of P: 4.58257569496 kW
23:55:48,091 (Inverter_controlagent-1.0 1909) <stdout> INFO: End of loop
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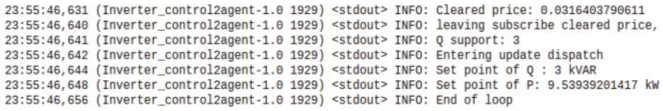
Fig. 7. VOLTTRON^{TM} agent result for DER1 with $Sinv_1$ = 5 kVA



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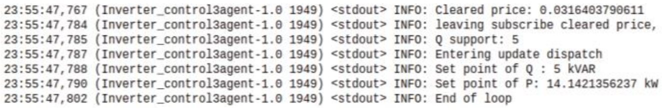
23:55:46,631 (Inverter_control2agent-1.0 1929) <stdout> INFO: Cleared price: 0.0316403790611
23:55:46,640 (Inverter_control2agent-1.0 1929) <stdout> INFO: leaving subscribe cleared price,
23:55:46,641 (Inverter_control2agent-1.0 1929) <stdout> INFO: Q support: 3
23:55:46,642 (Inverter_control2agent-1.0 1929) <stdout> INFO: Entering update dispatch
23:55:46,644 (Inverter_control2agent-1.0 1929) <stdout> INFO: Set point of Q : 3 kVAR
23:55:46,648 (Inverter_control2agent-1.0 1929) <stdout> INFO: Set point of P: 9.53939201417 kW
23:55:46,656 (Inverter_control2agent-1.0 1929) <stdout> INFO: End of loop
```

Fig. 8. VOLTTRON^{TM} agent result for DER2 with $Sinv_2$ = 10 kVA



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23:55:47,767 (Inverter_control3agent-1.0 1949) <stdout> INFO: Cleared price: 0.0316403790611
23:55:47,784 (Inverter_control3agent-1.0 1949) <stdout> INFO: leaving subscribe cleared price,
23:55:47,785 (Inverter_control3agent-1.0 1949) <stdout> INFO: Q support: 5
23:55:47,787 (Inverter_control3agent-1.0 1949) <stdout> INFO: Entering update dispatch
23:55:47,788 (Inverter_control3agent-1.0 1949) <stdout> INFO: Set point of Q : 5 kVAR
23:55:47,790 (Inverter_control3agent-1.0 1949) <stdout> INFO: Set point of P: 14.1421356237 kW
23:55:47,802 (Inverter_control3agent-1.0 1949) <stdout> INFO: End of loop
```

Fig. 9. VOLTTRON^{TM} agent result for DER3 with $Sinv_3$ = 15 kVA

Figures 5-9 show simulation results from agents when TES requires 10 kVar (case 2) and cleared price = 0.03164 $/kVar is sent out to invite non-utility DERs to participate in the market, based on the DERs' supply curve as shown in Fig. 5. Upon receipt of the cleared price, output of reactive power dispatch of each DER = 2 kVar, 3 kVar, and 5 kVar for DER1, DER2, and DER3, respectively.

Table. 1. Real power and reactive power dispatch based on cleared prices from TES.

cases	DER1		DER2		DER3		Total
	P dispatch	Q dispatch	P dispatch	Q dispatch	P dispatch	Q dispatch	Q support
1	4	3	7.14	7	-	-	10
2	4.58	2	9.54	3	14.14	5	10
3	4	3	6	8	7.48	13	25

Case1: Cleared price = 0.0859 $/kVar when Qneed = 10 kVar and only DER1 and DER2 participate in the market.
Case2: Cleared price = 0.03164 $/kVar when Qneed = 10 kVar and all DERs participate in the market.
Case3: Cleared price = 0.1517 $/kVar when Qneed = 25 kVar and all DERs participate in the market.

Table 1 shows the results of cases with the different requirements of reactive power support. The table shows that the DER will support the reactive power based on its own DER curve which depends on DER power rating, and current operating point of DER. For case 1 and case 2 with the same amount of required reactive power, the cleared prices are different. For case 1, only 2 DERs participate in the market and with the required reactive power causes both DERs to operate near their individual power rating, where the price increases sharply. However, compared to case 2, all DERs can participate in the market. So, each DER has more capacity left, and this yields a cleared price that is lower than case 1.

Regarding the idea of reactive power support from non-utility DERs by integrating the transactive algorithm, the developed distributed controller by using VOLTTRON^{TM} demonstrates the capability of DERs to support reactive power to the system by coordinating with the transactive system. With the developed controller, the algorithm within the agent can be improved by including losses of additional operating temperature in order to support reactive power which can improve the cost to DERs for providing ancillary service.

V. CONCLUSIONS

This paper represents the integration framework for a distributed control system and central control system in order to enable voltage support from non-utility DERs from a customer. The transactive approach, which can benefit both a customer and utility is implemented. VOLTTRON^{TM} agents are developed in order to be the distributed controller and enable connection with the central control system (utility). The result of integrating the support from non-utility customer-owned assets is illustrated, and the different inverter power ratings and current operating point for each inverter are two factors that determine the cost of reactive power support of the inverters. With multiple DERs' supply curves bidding, the aggregated curve will be constructed based on the lowest price at the amount of reactive power that the inverter can provide to the system.

Future work will focus on an improvement of the DERs cost equation in order to represent the true cost of DERs when providing the reactive power support in terms of operating cost and reduction in converter lifetime. Integration of loss in the inverter while providing reactive power support and location of reactive power sources will be considered in case multiple locations of DERs have the capability for bidding the DERs' supply curve to participate in the market. Testing with a hardware in the loop which includes a real inverter and communication allows an investigation of the communication delay and overall performance of the platform. Moreover, duration of time for reactive power support from DERs should also be considered based on system events to avoid excessive support that could cause voltage problem after providing the support to the system. In addition, scheduling of reactive power support based on a 24-hour basis in case of normal operation is another interesting topic that can improve the voltage profile in the system with variation of load and generation (solar irradiance profile) during the day.

VI. ACKNOWLEDGEMENTS

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