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A Transactive Energy Framework for Real-Time Primary Frequency Support by Active Distribution Networks

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***Abstract*—Modern active distribution networks possess significant potential to deliver ancillary services to transmission networks owing to the rising integration of renewable energy sources. This study explores the provision of primary frequency support from active distribution network to transmission network via price-based transactive control of microgrid inverters. The proposed method aims to achieve efficient coordination among microgrids, optimizing their utility, while also assisting the active distribution network in optimal primary frequency support provision to transmission network. The feasibility of this approach for real-time application is validated using a real-time simulator.**

***Index Terms*—Active Distribution Networks, Transactive Energy, Primary Frequency Support.**

I. INTRODUCTION

Ancillary services (AS) encompass a spectrum of critical functions such as primary, secondary, and tertiary frequency support, voltage regulation, congestion management, and ramp management [1] to ensure secure operation of bulk power system. Historically, ASs have predominantly been provided by conventional generators. However, gradual phasing out of these generators [2] necessitates exploring alternative solutions to maintain a stable and efficient power grid.

The proliferation of renewable energy sources (RESs), energy storage devices, and distributed energy resources (DERs) has transformed conventional distribution networks (DNs) into active distribution networks (ADNs). These modernized ADNs serve as a potential hub for offering AS in a decentralized and cost-effective manner [2]. Despite their immense potential, ADNs have yet to fully realize their capacity for providing AS. Primarily, this is due to the substantial challenge system operators face in effectively coordinating a vast number of DERs towards supplying AS.

To address this problem, transactive energy framework (TEF) has emerged as a promising solution for orchestrating and managing DERs within ADNs [3], thereby enhancing system stability and reliability. GridWise Architecture Council (GWAC), USA described transactive energy as “an economic and controlling mechanism to maintain a real-time balance between demand and generation using price as an operational key parameter [4].”

Early contributions in the field of TEFs, such as those found in references [5]–[7] and [8], adopted centralized and distributed approaches to achieve DER coordination within ADNs. For example, [5] proposed a centralized multi-step bidding strategy for the local energy market that rigorously demonstrated the strategy’s effectiveness. Authors in [6] introduced a centralized bi-level transactive market mechanism, employing a mixed-integer semidefinite programming approach to solve the proposed market framework. Reference [7] delves into an alternating direction method of multipliers based distributed approach to optimize the scheduling of DERs within multi-microgrids (MGs), while authors in [8] discussed a distributed peer-to-peer transaction model for exchange of energy in the context of a reconfigurable DN.

Turning our attention to the provision of ASs, several studies including [9]–[12] have explored the collaborative efforts between transmission system operators (TSOs) and distribution system operators (DSOs) for the delivery of AS from the DN to the transmission network (TN).

Within this context, the research presented in [9], [10] concentrated on voltage support, while [11] and [12] emphasized their contributions in providing frequency support to the TN. However, the works discussed in [9], [11] lacked transactive control, did not safeguard consumer privacy, and adopted a centralized approach for AS provision to TN. In contrast, [12] employed transactive control and distributed methods. They explored residential load control as a means of providing AS but did not include power generation within the DN, omitted the application of inverter control, and utilized a generic system model comprising transfer functions as a testing platform.

Notably, a majority of these studies primarily adopted offline solution methods [5]–[8], [11], with a smaller subset of studies considering online operations [9], [12]. Additionally, it is evident from the aforementioned discussion that the provision of ASs, specifically primary frequency support (PFS) by ADN to the TN, within the TEF has not received extensive attention from researchers thus far and remains largely unexplored. In light of these gaps, this paper focuses on addressing the PFS provided by ADN to the TN within a distributed TEF.

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The main contributions of this paper are stated below.

- A transactive energy formulation is proposed to enable PFS based AS provisioning by ADN to TN. A distributed primal-dual algorithm is developed to solve the centralized problem in a transactive energy framework, where the MGs embedded within the ADN solve their energy scheduling problem locally (Section II and Section III). In contrast with most past works, this work takes into account inverter capabilities and utilizes a smaller number of variables, relying solely on frequency measurements and the corresponding PFS signals by TSO to ensure effective PFS by the ADN. The reduced computational burden enables real-time implementation of the proposed scheme.
- Comprehensive numerical findings are obtained for the IEEE 5-bus transmission system (Section IV). These results are meticulously investigated and discussed to vividly showcase the capabilities of ADN support under TEF in delivering PFS to the TN in real-time.

The paper concludes in Section V with a summary of findings and directions for future research.

II. PRIMARY FREQUENCY SUPPORT BY ACTIVE DISTRIBUTION NETWORKS

A. System Description

Consider a TN with N_t number of buses, N_g number of synchronous generators (SGs) and N_L number of loads. An ADN which has N_b number of buses is connected to this TN. At a subset of buses of ADN, microgrids are connected. ADN is governed by the DSO whereas microgrids are controlled by microgrid operators (MGO). Furthermore, within the ADN, there exist PQ-controlled grid-following inverters, all of which are owned by the MGOs.

B. Problem Formulation

PFS represents the rapid response mechanism triggered within a few seconds upon detecting a mismatch between active power supply and demand within the power system [12]. In the conventional approach, PFS is typically furnished by designated conventional generators through their governor control mechanisms, which operate in accordance with their respective droop characteristics. Diverse countries have established explicit guidelines and regulatory frameworks governing PFS. In the context of this study, we focus on the regulatory standards of the Continental Europe system (ENTSO-E), as documented in [13]. As per the ENTSO-E guidelines, PFS must be initiated within a 15-second timeframe.

Let $P^{\text{pfs}} \in \mathbb{R}$ represent the active power required for PFS in response to a frequency deviation. This quantity can be expressed as a function of the frequency deviation $\Delta f \in \mathbb{R}$ as

$$P^{\text{pfs}}(\Delta f) = \begin{cases} \min(P^{\text{up}}, K.\Delta f), & \text{if} \quad \Delta f > 0, \\ \max(P^{\text{down}}, K.\Delta f), & \text{if} \quad \Delta f < 0, \end{cases} \tag{1}$$

where $P^{\text{up}} \in \mathbb{R}$ and $P^{\text{down}} \in \mathbb{R}$ are the up and down-regulation contract between TSO and responsible units, whereas $K \in \mathbb{R}$ is the droop constant. Here, P^{down} has negative sign as power supplied by ADN to TN is taken as negative. Frequency response deadband is not considered in this work for simplicity.

The primary objective of this study is to provide optimal PFS, specifically by the ADN to the TN. In this context, a cluster of DERs exhibits the capability to replicate the PFS actions that are traditionally carried out by conventional generators [12]. Consequently, in response to a frequency deviation, the TSO requests a specific amount of power to be exchanged, determined by (1), with the ADN.

Furthermore, the DSO and the MGO jointly address their optimization problems, presented below, and based on the solution obtained, the MGO establishes the power reference for the inverters under their control. Thus, the ADN responds by supplying the requested power to the TN, aligning with the prescribed actions dictated by the optimization solution.

C. Centralized Optimization Problem

Let $P_t^{\text{pfs}} \in \mathbb{R}$ denote the active power required by TN from ADN at time t based on (1), while $P_t^{\text{tn}} \in \mathbb{R}$ represents the actual active power exchange with TN at time t where a positive value of P_t^{tn} indicates that power is being supplied from TN to ADN. Let $P_t^{\text{sch}} \in \mathbb{R}$ denote the prescheduled active power exchange between TN and ADN, and $P_t^{\text{MG}} \in \mathbb{R}^{N_b}$ is introduced to denote the net active power (load minus generation) drawn out of the ADN bus at time t. The minimum and maximum limits of P_t^{tn} and P_t^{MG} are specified by $P_{\min}^{\text{tn}}$, $P_{\max}^{\text{tn}}$ and $P_{\min}^{\text{MG}}$, $P_{\max}^{\text{MG}}$ respectively.

Furthermore, the utility function of the MG consumers is chosen to be increasing, concave and quadratic [14], and is defined for MG $i \in [N_b]$ (where $[N_b] := [1, 2, \ldots, N_b]$) as

$$U_i(P_{t,i}^{\text{MG}}) = -\frac{1}{2}a_i(P_{t,i}^{\text{MG}})^2 + b_i P_{t,i}^{\text{MG}}, \tag{2}$$

where $a_i, b_i \in \mathbb{R}_{>0}$ being positive constants.

We define the decision vector at time t to be $x_t = [P_t^{\text{tn}}, P_t^{\text{MG}}]^\top$. The centralized optimization problem is

$$\min_{x_t} \; \left[\alpha(P_t^{\text{pfs}} + P_t^{\text{sch}} - P_t^{\text{tn}})^2 - \sum_{i=1}^{N_b} U_i(P_{t,i}^{\text{MG}})\right], \tag{3a}$$

$$\text{s.t.} \; P_t^{\text{tn}} = \sum_{i=1}^{N_b} P_{t,i}^{\text{MG}}, \tag{3b}$$

$$P_{\min}^{\text{tn}} \leq P_t^{\text{tn}} \leq P_{\max}^{\text{tn}}, \tag{3c}$$

$$P_{i,\min}^{\text{MG}} \leq P_{t,i}^{\text{MG}} \leq P_{i,\max}^{\text{MG}}, \quad \forall i \in [N_b]. \tag{3d}$$

The objective function (3a) consists of two terms: the first term penalizes the difference between desired active power from the TN and actual active power supplied by the ADN, and second term maximizes the total utility of the MGs. The constraint (3b) ensures active power balance in the ADN, while (3c) and (3d) limit the active power exchange P_t^{tn} with TN and net active power consumption $P_{t,i}^{\text{MG}}$ by i^{th} ADN bus respectively.

The weighting factor α in (3a) represents the relative priority given to both the objectives; a larger α prioritizes the actual supplied active power to match the desired active power, while a smaller α prioritizes maximizing the total utility of the MGs. The total utility of the MGs is included in the cost function to ensure that the provisioning of AS support is executed in a way which minimizes the loss of utility of the MGs. In other words, the required modification in the power exchange is achieved keeping in the mind the overall utility of the MGs.

The term $P_{t,i}^{\mathrm{MG}}$ on the right-hand side of equation (3b) represents the net active power drawn at the i^{th} bus of the ADN. To avoid introducing additional notation, we have assumed that every bus of the ADN is connected with a microgrid. Note that when there is no microgrid connected to bus i, then the value of $P_{t,i}^{\mathrm{MG}}$ would be equal to the value of the inelastic load connected to this bus i. It is important to observe that the cost of power exchange between TN and ADN has not been incorporated into the objective function. This is because the primary focus of this study is to tackle the PFS problem. Nonetheless, including a cost term in the objective function to account for this exchange will not significantly alter the structure and complexity of the problem.

The centralized approach has a drawback: the DSO holds extensive information about microgrids, including their utility functions, load profiles, and power exchange constraints, and this information is not available at a single central location. This underscores the need to shift to a distributed approach to protect MG privacy and reduce communication burden.

D. Distributed Transactive Algorithm

In this section, the centralized problem (3) is reformulated to enable transactive control of the MG resources. In view of this, a primal-dual algorithm [3], [14] is adopted to solve the centralized problem (3) in distributed way. For this purpose, let λ_t be the dual variable corresponding to the constraint (3b). Note that the dual variable λ_t acts as a transactive price at the MG nodes. Now, DSO, which functions as coordinator, and MGO, which is the follower agent, solve their own local optimization problems subject to local constraints.

1) MGO Optimization Problem: The optimization problem for each MGO $i \in [N_b]$ can be written as

$$\min_{P_{t,i}^{\mathrm{MG}}} \left[\lambda_t P_{t,i}^{\mathrm{MG}} - U_i(P_{t,i}^{\mathrm{MG}})\right], \tag{4a}$$

$$\text{s.t.} \quad P_{i,\min}^{\mathrm{MG}} \leq P_{t,i}^{\mathrm{MG}} \leq P_{i,\max}^{\mathrm{MG}}, \tag{4b}$$

where $P_{i,\min}^{\mathrm{MG}}$ and $P_{i,\max}^{\mathrm{MG}}$ are determined by inverter capacity and local load of MG $i \in [N_b]$. The solution of the above optimization problem for each MGO $i \in [N_b]$ can be written in closed form as

$$\bar{P}_{t,i}^{\mathrm{MG}} = \frac{b_i - \lambda_t}{a_i}, \tag{5a}$$

$$P_{t,i}^{\mathrm{MG}} = \min(\max(\bar{P}_{t,i}^{\mathrm{MG}}, P_{i,\min}^{\mathrm{MG}}), P_{i,\max}^{\mathrm{MG}}). \tag{5b}$$

2) DSO Optimization Problem: The optimization problem for the DSO is given by

$$\min_{P_t^{\mathrm{tn}}} \left[\alpha(P_t^{\mathrm{pfs}} + P_t^{\mathrm{sch}} - P_t^{\mathrm{tn}})^2 - \lambda_t P_t^{\mathrm{tn}}\right], \tag{6a}$$

$$\text{s.t.} \quad P_{\min}^{\mathrm{tn}} \leq P_t^{\mathrm{tn}} \leq P_{\max}^{\mathrm{tn}}. \tag{6b}$$

The solution of the above optimization problem can be written in closed form as

$$\bar{P}_t^{\mathrm{tn}} = \frac{\lambda_t}{2\alpha} + (P_t^{\mathrm{pfs}} + P_t^{\mathrm{sch}}), \tag{7a}$$

$$P_t^{\mathrm{tn}} = \min(\max(\bar{P}_t^{\mathrm{tn}}, P_{\min}^{\mathrm{tn}}), P_{\max}^{\mathrm{tn}}). \tag{7b}$$

3) Dual Variable Update: DSO solves its optimization problem to obtain the optimal power exchange with the TN and monitors its power exchange with MGOs. Following this, the DSO updates the dual variable λ_t as

$$\lambda_{t+1} = \lambda_t + \gamma(\sum_{i=1}^{N_b} P_{t,i}^{\mathrm{MG}} - P_t^{\mathrm{tn}}), \tag{8}$$

where, γ is the step size.

Note that adding all MGO and DSO costs gives the cost of centralized problem (3) as desired.

Remark 1: Power exchange occurs between the TSO and DSO, as well as between the DSO and MGO. When the TSO buys ancillary services from the DSO, it provides incentives to the DSO, which then passes on incentives to the MGO, through transactive price signal, for their assistance in supplying ancillary services.

III. PRIMAL-DUAL ALGORITHM

The distributed optimization problem described above is tackled in real-time through the utilization of the primal-dual algorithm, as outlined in Algorithm 1. In this paper, the primal-dual steps are executed at each control instant, and the resultant solution from each time step is applied to the subsequent time step. This approach leads to the algorithm converging over a finite number of sample times, during which the dual variable λ_t converges to an optimal value and remains constant unless an external disturbance disrupts the system, leading to changes in system conditions. Value of λ_t obtained at each sample time is sent to the MGs as price signal, following which MGs adjusts their power exchange with the ADN, leading to achievement of the desired power exchange between ADN and TN.

Algorithm 1 Primal-Dual Algorithm

```
Initialization: DSO initializes the dual variable (price signal) $\lambda_t$ with an initial guess at $t = 0$.
MGOs receive the price signal from DSO and solve (5) to determine reference signals for their inverters.
DSO solves (7) to obtain the active power exchange with TN ($P_t^{\mathrm{tn}}$).
DSO monitors the $P_t^{\mathrm{MG}}$ exchange with MGOs and updates the dual variable $\lambda_t$ based on (8), subsequently transmitting the price signal to the MGOs.
Output: $P_t^{\mathrm{MG}}$, $P_t^{\mathrm{tn}}$ and $\lambda_t$.
end
```

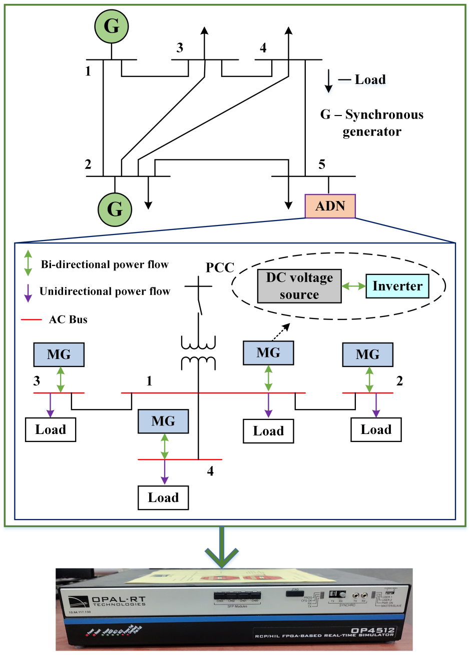


Fig. 1: Modified IEEE 5-bus transmission network simulated on OP4512 (OPAL-RT).

TABLE I: System parameters

Parameter	Value
Nominal frequency	50 Hz
Sampling time	100μsec
N_g, N_t, N_L	2, 5, 4
Each SG capacity	2.5 MVA
SG terminal voltage	6.6 kV (line)
Transmission voltage level	33 kV (line)
TN load	2.3571 MW+j0.5714 MVAR
α, N_b, γ (step size in Eq. (8))	1000, 4, 0.2
ADN line resistance and inductance	0.03 ohm and 0.35 mH
a,b (coefficients in Eq. (2) of MGs)	$[3.6, 2.7, 2.25, 1.5]$, $[7, 6, 5, 6]$
Droop constant of ADN	4.3583 MW/Hz
Each inverter capacity	500 kVA
Total load in ADN	1.2 MW + j0.396 MVAR
DC voltage level	750 V
AC voltage level of ADN	400 V

IV. SIMULATION RESULTS AND DISCUSSION

A. Simulation Setup

Validation of the above formulation is carried out on a modified IEEE 5-bus transmission network [15] as shown in Fig. 1. In the considered system, an ADN is connected at bus 5 and it has 4 buses. At every bus of ADN a MG and an inelastic load are connected. MG consist of DC voltage source and PQ-controlled inverter. Ideal DC voltage source, considered in this study, mimic the behaviour of DC bus, and it can absorb or supply the active power. The system parameters values are shown in Table I. The TN capacity is intentionally set at a low level to clearly illustrate the significant influence of the ADN's ability in providing PFS. Entire setup is simulated on a OP4512 (OPAL-RT) real-time simulator.

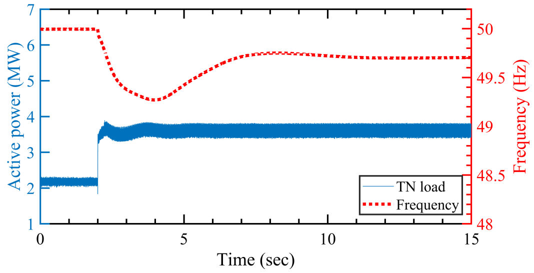


Fig. 2: Step active power load increment followed by system frequency deviation.

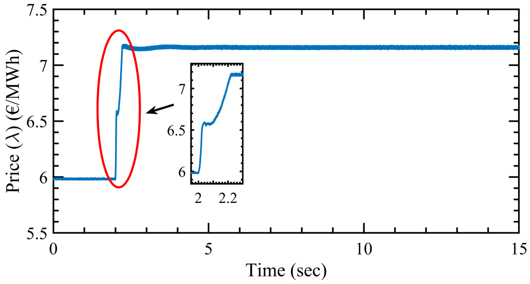


Fig. 3: Convergence of price signal λ to a stationary value in real-time.

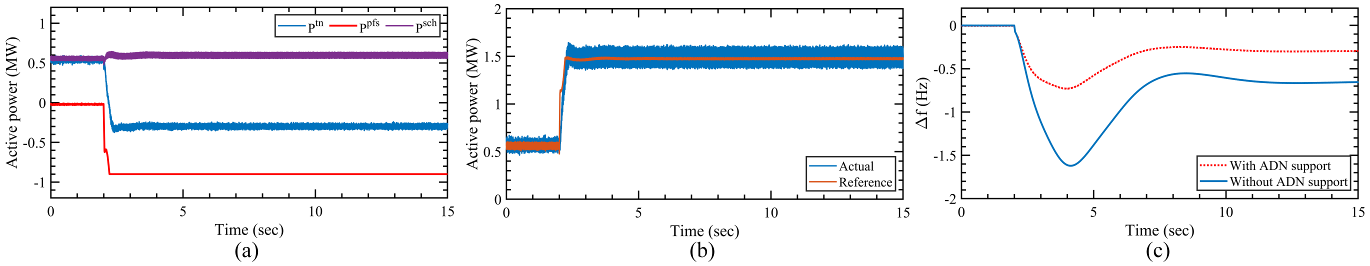
B. Primary Frequency Support by ADN

1) Step load change event: When the system is in steady state, a step load increment of 1.5 MW is introduced at 2 seconds at bus 4 of TN, as depicted in Fig. 2. This results in a shift in the system's frequency from its nominal value of 50 Hz to a minimum of 49.27 Hz, which subsequently stabilizes at 49.7 Hz. This frequency adjustment is achieved through the combined efforts of synchronous generators and the ADN. During the load change event, TSO sends the PFS signal to responsible units including ADN in order to minimize the frequency deviation. Further details on the ADN's role in maintaining system frequency are elaborated below.

2) ADN support: Following the load change event, the TSO dispatches the P^{pfs} signal, determined from (1), to the DSO. The DSO, in response, evaluates the transactive price signal (λ), and conveys it to the MGOs to fulfill the required power. As explained in Section III, λ is calculated at each sampling interval and as system conditions evolve, its value adjusts accordingly and gradually stabilizes after several time steps, as depicted in Fig. 3.

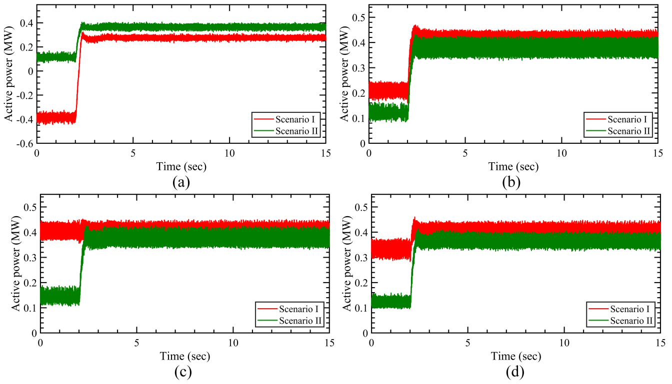
Fig 4(a) portrays the PFS signal (P^{pfs}) transmitted by the TSO, along with the prescheduled (P^{sch}) and real-time (P^{tn}) active power exchange between ADN and TN, respectively. It may be noted here that, prior to the load change event at 2 seconds, the power exchange between ADN and TN adheres to the prescheduled values, and P^{pfs} signal remains at zero. However, after the load change, the power exchange deviates from the prescheduled levels, resulting in ADN supplying additional power to TN in response to the P^{pfs} signal.

Fig. 4(b) illustrates the total sum of reference signals provided to MG inverters and the actual power delivered



(a) (b) (c)

Fig. 4: (a) Active power exchange between ADN and TN (P^{tn}), PFS signal received from TSO (P^{pfs}), prescheduled power exchange (P^{sch}) (power coming from TN to ADN is taken as positive), (b) sum of references to the MG inverters and actual active power supplied by them, (c) deviation in system frequency from its nominal value (Δf) with ADN support to the TN and without ADN support.



(a) (b) (c) (d)

Fig. 5: Active power output of (a) inverter 1, (b) inverter 2, (c) inverter 3 and (d) inverter 4 in Scenario I and Scenario II

by these inverters. MGOs generate reference signals for the inverters based on the price signals received from the DSO. Subsequently, the MG inverters adjust their power output accordingly. At 2 seconds when the load increases, the price also rises (as shown in Fig. 3). Consequently, the MGs are incentivized to augment their local power generation and sell surplus electricity to the ADN for additional profit, thereby effectively regulating power exchange between MGs and ADN. Due to the rapid dynamics of the inverters, this entire process unfolds in milliseconds, enabling the ADN to swiftly assist the TSO in maintaining system frequency.

In Fig. 4(c), a comparison of frequency regulation is conducted between scenarios where the ADN is connected to provide PFS support and when it is not giving support. The data suggests that with ADN support, the maximum frequency deviation is reduced by 0.89 Hz (1.78%). Additionally, the frequency settles at a higher stationary value in less time. This underscores the vital role of ADN support in PFS.

3) Transactive control of MG inverters: The significance of transactive control of MG inverters is validated through a comparative analysis of two scenarios: (I) the incorporation of transactive control, and (II) the provision of only droop control where MGs share the required power in the ratio of their spare capacity.

In Scenario I, the presence of transactive control results in effective coordination among the MGs within ADN as exemplified in Fig. 5. With lower prices, upto 2 seconds, MGs $2, 3$, and 4 generate surplus power beyond their local requirements, selling this excess power to the ADN to generate profit. In contrast, MG 1 consumes power from the ADN, as it is not economical for it to produce its own power. Furthermore, at higher prices, after 2 seconds, (when TSO requires power from DSO), all inverters supply power to gain additional profit, thus enabling DSO to meet TSO's power demand.

Conversely, in Scenario II, where transactive control is absent, all MGs generate power to satisfy their local demand, and provide power for PFS according to the droop control.

Remarkably, the summation of utility of all MGs determined by Eq. (2) using MW values of P^{MG} over entire simulation period (15 seconds) yields a value of -0.0043€in Scenario I and -0.0057€in Scenario II respectively, indicating that the utility of MGs is greater by 0.0014€in Scenario I. Consequently, transactive control maximizes the utility of MGs.

V. CONCLUSION

This paper examines and validates the real-time primary frequency support provision from ADN to TN within a transactive energy framework. Simulation results demonstrate that implementing price-based transactive control facilitates efficient coordination of MG inverters within ADN, leading to decreased frequency deviation during supply and demand mismatches, while maximizing the utility of MGs.

There remain several promising directions for future research. While this work examined the interaction of one DSO with the TN, in practice, there are several DSOs that interact with the TN and need to coordinate to provide AS support. Similarly, more detailed dynamic model of the inverter operation needs to be included in the formulation to obtain more accurate results. Finally, the present work can be generalized to enable additional ancillary service, such as secondary and tertiary frequency support, and voltage support, in a transactive energy framework.

VI. ACKNOWLEDGEMENT

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