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ORIGINAL RESEARCH PAPER

Comprehensive platform for distribution transactive energy markets

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Abstract

Reducing the cost of distributed energy resources (DERs) such as renewables, storage, electric vehicles and smart loads is driving their increased connection to distribution systems. Extracting maximum benefits from DERs require liberalising distribution systems by allowing: (1) a distribution transactive energy market (DTEM) operated by a local distribution operator (LDO) and (2) peer-to-peer (P2P), peer-to-LDO (P2LDO) and Transmission-to-LDO (T2LDO) type transactions. A DTEM will bring several benefits such as: (1) enhanced economic opportunity for DERs, making them more profitable and (2) increased social welfare benefiting both buyers and sellers. To achieve this objective, we develop a comprehensive three-phase DTEM platform that provides maximum economic opportunities for DERs and maximises social welfare that benefits all market participants, while considering P2P, P2LDO and T2LDO transactions, for both energy and ancillary services. Interaction between bulk electricity market independent system operator (ISO) and LDO controlled DTEM is presented. The DTEM model is implemented as a practical mixed-integer linear programming formulation that includes a network reconfiguration feature. The DTEM model is studied on three-phase 5-bus and 34-bus systems, demonstrating its effectiveness to settle energy and ancillary service transactions, while obtaining distribution locational marginal prices. Results show that P2P transactions, when allowed, increase social welfare and increases profitability of DERs.

1 | INTRODUCTION

Distributed energy resources (DERs) such as renewables, electric vehicles, energy storage (ES) and smart loads are becoming available at lower costs and are being connected in large numbers to distribution systems (DS). DERs hold immense potential through energy transactions that maximise their revenues and social welfare for all stakeholders in the distribution sector, buyers and sellers.

However, the current regulated environment of local distribution companies (LDCs) impedes this progress as they are designed to procure energy from transmission systems to distribute to all their connected loads. Further, they reactively connect DERs instead of connecting proactively, to leverage their potential.

Therefore, there is a need for development of energy trading solutions to interface between DERs, the distribution system, loads and the transmission bulk power system. In this context, transactive energy systems (TESs) are proposed as a solution to enable commerce between participants while maintaining the distribution system reliability and security [1].

1.1 | What is transactive energy systems (TESs)?

A TES is defined as an electrical grid that enables a dynamic balance between supply and demand, using value (bids) as a key operational parameter. Proper functioning of a TES at a distribution level hinges upon a system of economic and control mechanisms (energy market) that allows the dynamic power balance across the entire electrical infrastructure, that is, an LDC. In this context, a distribution transactive energy market (DTEM) should provide means for DERs to strike peer-to-peer (P2P) and peer-to-local distribution operator (P2LDO) contracts with the other DERs and LDO respectively [2–4].

1.2 | Literature survey

In recent years, the application of TES approaches to power systems has been widely studied and demonstration projects have been implemented around the world. In [5], a TES approach was used in a real-time pricing demonstration project, engaging households to adapt their electricity use in response to a fluctuating 5 minute price signal. In [6] as part of a "Living Smart" demonstration project, 40 households were controlled, aiming to find a balance between energy conservation and home comfort.

A significant number of works that represent contributions to TES have been published, focusing on the optimised control of a large number of devices following economic value signals [7–12]. However, limited studies can be found regarding the implementation of TES markets at a distribution level to enable the participation of DERs while enhancing the grid's operation. In [13] for example, an analytical model for the optimal scheduling of a market-based microgrid is developed. Here, the microgrid is assumed as a player in the electricity market, highlighting the importance of an energy market at the distribution level. In [14], a TES trading framework designed to accommodate high penetrations of PV units in the DS is developed, while integrating trading mechanisms with an optimal power flow (OPF) technique. From the perspective of TES participants, [15] introduced an operational framework to enable the optimal participation of prosumer balancing power services, adopting the concept of network-constrained TES. Recently, a transactive combinatorial auction for a community of prosumers based on game theory is proposed in [16].

In addition, works have been presented tackling the proliferation of TES trading schemes. In [17], an optimal centralised and decentralised scheduling of DERs, together with a distributed, massively parallel architecture that enables tractable transmission and distribution locational marginal price is presented. Here, while in the decentralised operation P2P transactions are introduced, in a centralised manner both transmission and distribution markets are simultaneously settled in a single-ended auction. In addition, [18] proposes a decentralised methodology for P2P transaction authorisation to guarantee an exchange of energy that does not violate network constraints. Here, not only the impact of P2P transactions on the overall social welfare is disregarded, but also P2P transactions for ancillary services are not taken into account. In [19], a framework that harmonises the physical attributes of the DS with the underlying financial transactions of TES is developed. This work reinforces the need fortaking into account the three-phase characteristics of DS when settling the market. Recently, some transactive control frameworks are developed counting for the transactive paradigm from the grid operator perspective [20–22]. A transactive control framework that coordinates the multitude of geographically diverse DERs is developed in [20]. The co-simulation framework of [20] is implemented on a large-scale while wholesale-retail transactive mechanism and the results are presented in [21]. The framework in [20] and [21] considers control model with less focus on the market attributes. Furthermore, a transactive co-simulation framework to evaluate and compare different distribution-level market designs is described in [22].

1.3 | Research gap

To the best of the authors' knowledge, there are no works that present a complete market model tailored for DS that: (1) captures P2P, P2LDO and T2LDO transactions for energy and ancillary services, (2) consider a three-phase DS model and (3) possesses an LDO structure that maximises social welfare such that it will be larger than the case of only LDC operation. This paper presents the DTEM model that address all these aspects.

1.4 | Main contributions and TES attributes proposed in this work

The main contribution of this work is a DTEM model. Departing from the past, where DS were designed to procure energy only from the transmission system, the proposed transactive platform enables:

1. Transactions between DERs and the LDO (P2LDO): While considering technical constraints imposed by participating DERs and DS network, the LDO would settle DTEM to source the least costing energy and ancillary services to satisfy demand within the DS.
2. Peer-to-peer (P2P) transactions: In addition to energy, the proposed DTEM entertains P2P transactions for services such as voltage support and demand response (DR), which will result in increased social welfare where possible.
3. Transmission to LDO (T2LDO) transactions: The LDO, as an aggregation of assets at a distribution level, can participate in the independent system operator (ISO) wholesale market. Here, the LDO is capable of buying or selling energy based on the resources available after the DTEM has been settled.

Using bids as key operational parameter, this paper proposes a DTEM that presents a fully developed double-ended market auction model. The proposed DTEM model takes into account three-phase nodal active and reactive power balance equations, voltage and power flow limits, intertemporal constraints and reconfiguration. This model is implemented as a Mixed-Integer Linear Programming (MILP) formulation.

To the best of the authors' knowledge, this is the first three-phase distribution transactive energy platform which settles both regular energy transactions and ancillary services in a single market settlement. Table 1 compares the features of the proposed DTEM model with the existing models in the literature.

TABLE 1 Comparison between the features of the distribution transactive energy market (DTEM) model and the other existing models

Reference	P2Ptransactions	Three-phase modelling	Settle energy market	Settle ancillary service	Wholesale energy market
[7]–[12]	✓	✗	✗	✗	✗
[13]–[16]	✓	✗	✓	✗	✗
[17] and [18]	✓	✗	✗	✗	✗
[19]	✓	✓	✓	✗	✗
[20]–[22]	✓	✗	✓	✗	✓
ProposedDTEM model	✓	✓	✓	✓	✓

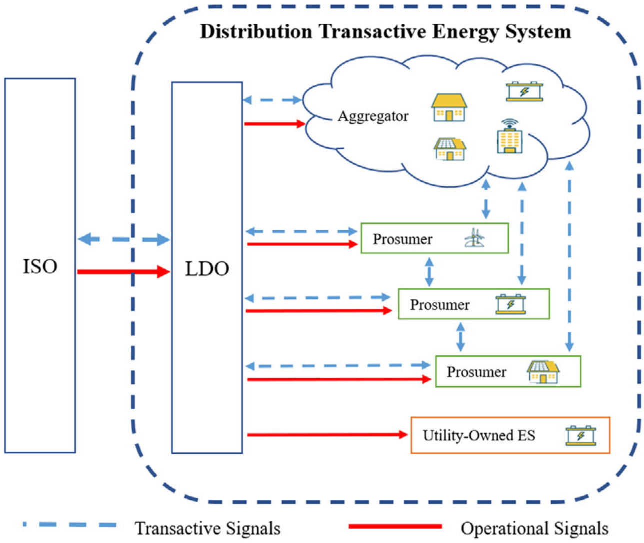

FIGURE 1 Architecture of proposed distribution transactive energy market (DTEM)

2 | DISTRIBUTION TRANSACTIVE ENERGY MARKET

This section presents a DTEM model at distribution level.

2.1 | DTEM architecture

Figure 1 shows the interactions between all the participants of the proposed DTEM trading in energy and services. Participants of the DTEM can be classified into four types. (1) ISO of the connected bulk transmission system (TS). The TS provides for enough capacity to serve total load of a DS less the total local DER capacity. (2) The newly proposed independent entity called the LDO, which coordinates and manages all the interactions that occur within the DTEM. (3) Active market participants such as DERs. (4) Utility-owned assets such as energy storage units.

As illustrated in Figure 1, there are two types of interactions between participants through transactive and operational signals. The transactive signal establishes a two-way channel for economic interaction between participants. For instance, two prosumers will reach a P2P agreement to transact through transactive signals. The operational signals convey dispatch instructions from LDO and ensure that the DS is operated within limits. Further, the LDO will present bids (transactive signals) to the ISO wholesale market to transact in energy and services, and the ISO will dispatch (operational signals) the LDO to deliver on settled amounts of energy and services. This is valid for both a real-time and a day-ahead market. Further explanations are included later in this section.

2.2 | DTEM – Local distribution operator (LDO)

Technical and economic duties within the DS have been attributed to several entities, none of which exist with market responsibilities; as reported in existing literature, and their roles, scopes and limitations are ambiguous. These entities include the distribution system operator (DSO), the distribution market operator (DMO), the distribution network operator (DNO) and the load serving entity (LSE). Although the term DSO is viewed as the evolution of the LDCs, there is no consistent definition for the DSO's responsibilities and limitations in the literature. Given this ambiguity, this work proposes an LDO to be responsible for operating DTEM. The LDO is conceived as an independent entity that overlays on LDCs, overseeing economic activity. Table 2 shows the responsibilities of the LDO, in contrast to the duties of a DMO [23] and the grid operator functions of a DSOs [1].

Although the LDO is not responsible for the operation of the DS, the network physical constraints should be assessed within the settlement process to avoid breaching technical limits.

2.3 | DTEM participants – Prosumers and aggregators

For the purpose of analysis, besides the LDO, all the privately-owned entities participating in the market are classified as aggregators or prosumers. DERs in the form of aggregators and prosumers are considered as active market agents and will be able to transact energy and services with the market and other participants via P2LDO and P2P agreements respectively.

TABLE 2 Responsibilities of the local distribution operator (LDO)

Responsibility	DSO	DMO	LDO
Conducting operational security studies	✓	–	–
Respond to outages	✓	–	–
Direct restoration efforts.	✓	–	–
Forecasting demand along the distribution feeders	✓	–	✓
Forecasting prices of energy at the transmission nodes	✓	–	✓
Collecting bids from the participants	–	✓	✓
Settling the day-ahead distribution energy market	–	✓	✓
Placing bids to the wholesale market for energy	–	–	✓
Optimising any further real-time market settlements	–	✓	✓
Approving P2P operations within the active participants	–	–	✓
Settling the service markets	–	✓	✓

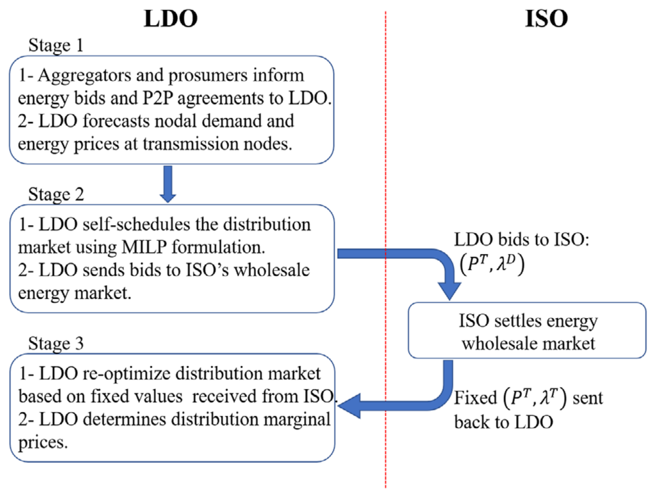

FIGURE 2 Settlement procedure for energy market in distribution transactive energy systems (TES)

A prosumer is defined to be a DER connected behind a single metre, capable of selling/buying energy at this single node. The integration of two or more prosumers will lead to an aggregator. Hence, an aggregator is defined to be an entity in charge of aggregating several DERs behind respective metres, selling/buying energy at respective connection points.

Policy regulations for different jurisdictions may define a certain threshold over which a DER can participate as a prosumer. DERs below this threshold will need to aggregate with other DERS, such that aggregate meets the threshold, to participate in the DTEM. While defining this threshold is outside the scope of this work, the proposed DTEM can be operated with any policy-enforced threshold.

2.4 | DTEM settlement procedure

The LDO is responsible for settling of the DTEM day-ahead for a 24-hour period and in real-time in regular intervals. The settlement procedure is divided into 3 stages as shown in Figure 2.

Stage 1: Aggregators and prosumers should present their bids to the LDO and inform about any out-of-market agreement, through the two-way transactive signal interaction. At this stage, the LDO forecasts bus-wise demand in the DS and the energy price at the connected transmission nodes.

Stage 2: The LDO settles the DTEM, as a double-ended auction that maximises social welfare, using the proposed MILP formulation presented in Section III. Once the DTEM is settled, the LDO sends a buy/sell offer/bid to the ISO to exchange energy with the TS. The ISO then settles the wholesale market that determines the interchange power and nodal price, which is made available to the LDO.

Stage 3: Based on the received operational signal from the ISO, the LDO re-optimises the DTEM to obtain the new distribution locational marginal prices (DLMPs). Finally, using a centralised one-way downstream interaction, the LDO dispatches each participant with the settlement outcomes in the form of operational signals.

2.5 | DTEM: P2LDO and P2P energy transactions

The proposed platform is capable of handling out-of-market energy transactions. For instance, P2P agreements can be added into the DTEM by fixing the seller and the buyer at the lowest generating price and highest demand price. This will ensure that the agreement will only be dishonoured if it causes breaches in the operational limits. Hence, although the final distribution marginal price is not affected, the effects of these transactions on the network congestion are considered.

2.6 | DTEM: P2LDO and P2P service transactions

The proposed DTEM considers P2P, P2LDO and T2LDO type ancillary services alongside energy in a single settlement, maximizing social welfare and economic opportunity for DERs. The DTEM formulation considers two ancillary services and can be expanded to accommodate more.

1. Demand response (DR): The DTEM is designed to entertain P2P contracts between DERs and P2LDO bids with DERs. These P2P DR contracts have the potential of enabling increased participation of DERs and relieving network constraints, leading to increased social welfare.
2. Voltage regulation and reactive power support: DERs can present bids for voltage regulation and reactive power service via P2P, P2LDO and T2LDO contracts. With voltage regulation being an important limitation in DS, reactive power contracts have a significant potential in improving social welfare.

While the energy P2P transactions typically reduce social welfare as a whole [24], the P2P transaction for ancillary services can lead to increased social welfare as will be demonstrated later in the result section.

2.7 | Reconfiguration

In many instances, DS is fed from multiple points of TS where LMPs are different. DS loads would benefit from switching from one TS connection to another. To realise this market benefit within a DTEM construct, the formulation considers network reconfiguration to maximise social welfare while ensuring that the network constraints are satisfied.

3 | MARKET SETTLEMENT – MATHEMATICAL FORMULATION

The DTEM model presented in Section II defines participants and their coordination in the system. In this section, a MILP formulation of three-phase DTEM model is presented that entertains P2P, P2LDO and T2LDO transactions for energy and ancillary services where the three-phase power balance representation is based on [25, 26]. The control variables for DTEM model are generation and loads of prosumers, aggregators, the TS and the state of the switches.

3.1 | Objective function

The objective function (OF) shown in Equation (1) aims to: maximise social welfare that equals demand offers (SWD) less the bids from generation (SWG), demand response (DR) and voltage regulation services (VR).

$$\text{Max (OF)} = \text{SWD} - \text{SWG} - \text{DR} - \text{VR} \tag{1}$$

The first and second terms in the OF are modelled in Equations (2) and (3), respectively. Equation (2) represents the demand bids in the social welfare, which captures:

- A fix bid (K_L) for all conventional loads (P_L) – included to properly calculate social welfare, although $P_L \cdot K_L$ is a constant, as P_L cannot be disconnected.
- Demand bids for P2LDO energy transactions from aggregators and prosumers (K_{A-}, K_{P-}).
- Demand-side P2P energy transactions, where the corresponding K_{A-} or K_{P-} is input as a very high value.

Further, Equation (3) represents the generation terms of the social welfare, capturing:

- T2LDO transactions, input as forecasted LMPs at transmission interconnection nodes (λ_T).
- Generation bids for P2LDO energy transactions from aggregators and prosumers (K_{A+}, K_{P+}).
- Generation-side P2P energy transactions, where the corresponding K_{A+} or K_{P+} is input as a very low value.

$$\text{SWD} = \sum_{\Omega_{\{N,F,T\}}} P^{L}_{i,f,t} \cdot K_L + \sum_{\Omega_{\{N,F,T,S,A\}}} P^{A-}_{i,f,t,s,a} \cdot K^{A-}_{t,s,a} + \sum_{\Omega_{\{F,T,S,P\}}} P^{P-}_{f,t,s,p} \cdot K^{P-}_{t,s,p}. \tag{2}$$

$$\text{SWG} = \sum_{\Omega_{\{N,F,T,S\}}} P^{T}_{i,f,t,s} \cdot \lambda^{T}_{i,t,s} + \sum_{\Omega_{\{N,F,T,S,A\}}} P^{A+}_{i,f,t,s,a} \cdot K^{A+}_{t,s,a} + \sum_{\Omega_{\{F,T,S,P\}}} P^{P+}_{f,t,s,p} \cdot K^{P+}_{t,s,p}. \tag{3}$$

The services DR and VR are modelled in Equations (4) and (5), respectively. The DR and VR terms in Equations (4) and (5) include bids from aggregators and prosumers who are willing to offer these services to the LDO, enhancing its flexibility. Constraints in Equations (4) and (5) capture service bids for P2LDO transactions, as well as P2P service transactions.

$$\text{DR} = \sum_{\Omega_{\{N,F,T,S,A\}}} P^{Adr}_{i,f,t,s,a} \cdot K^{Adr}_{t,s,a} + \sum_{\Omega_{\{F,T,S,P\}}} P^{Pdr}_{f,t,s,p} \cdot K^{Pdr}_{t,s,p}. \tag{4}$$

$$\text{VR} = \sum_{\Omega_{\{N,F,T,S,A\}}} Q^{A+}_{i,f,t,s,a} \cdot K^{AQ}_{t,s,a} + \sum_{\Omega_{\{F,T,S,P\}}} Q^{P+}_{f,t,s,p} \cdot K^{PQ}_{t,s,p}. \tag{5}$$

This OF is subjected to the set Equations (6)–(20) as follows.

Steady state operation constraints

The steady state operation of a three-phase unbalanced distribution network is represented based on the formulation presented in [25, 26]. In this particular formulation, the active power balance in a node is given by Equation (6) based on [26]. Here, the demanded and generated power are expressed as single variables P^{load} and P^{inj}, respectively. Constraints in Equations (7) and (8) associate these variables with the active power injected and demanded by the active agents due to T2LDO, P2LDO and P2P transactions.

$$\sum_{\substack{\Omega_{SW} \\ n=i}} P^{sw}_{(m,n),f,t} - \sum_{\substack{\Omega_{SW} \\ m=i}} P^{sw}_{(m,n),f,t} + P^{inj}_{i,f,t} - P^{load}_{i,f,t} = -\sum_{\Omega_L} P_{(k,i),f,t} + \sum_{\Omega_L} \left(P_{(i,j),f,t} + P^{loss}_{(i,j),f,t} \right) \quad \forall_i \in \Omega_N; \forall_f \in \Omega_F; \forall_t \in \Omega_T. \tag{6}$$

$$P^{inj}_{i,f,t} = P^{T}_{i,f,t} + \sum_{\Omega_A} P^{A+}_{i,f,t,a}\cdot + \sum_{\Omega_P} P^{P+}_{f,t,p}.f\left(i,p\right) + \sum_{\Omega_{ES}} P^{E+}_{f,t,e}.f\left(i,e\right) \forall_i \in \Omega_N; \forall_f \in \Omega_F; \forall_t \in \Omega_T \quad (7)$$

$$P^{load}_{i,f,t} = P^{L}_{i,f,t} + \sum_{\Omega_A}\left(P^{A-}_{i,f,t,a} - P^{Adr}_{i,f,t,a}\right) + \sum_{p\in\Omega_P}\left(P^{P-}_{f,t,p} - P^{Pd}_{f,t,p}\right).f\left(i,p\right) + \sum_{e\in\Omega_{ES}} P^{E-}_{f,t,e}.f\left(i,e\right)\cdot \quad \forall_i \in \Omega_N; \forall_f \in \Omega_F \forall_t \in \Omega_T \quad (8)$$

By the same token, Equations (9)–(11) represent the reactive power balance for each node. Equation (9) for the reactive power balance is based on [26]:

$$\sum_{\substack{\Omega_{SW}\\ n\,=\,i}} Q^{sw}_{(m,n),f,t} - \sum_{\substack{\Omega_{SW}\\ m\,=\,i}} Q^{sw}_{(m,n),f,t} + Q^{inj}_{i,f,t} - Q^{load}_{i,f,t} = -\sum_{\Omega_L} Q_{(k,i),f,t} + \sum_{\Omega_L}\left(Q_{(i,j),f,t} + Q^{loss}_{(i,j),f,t}\right) \cdot \quad \forall_i \in \Omega_N; \forall_f \in \Omega_F; \forall_t \in \Omega_T \quad (9)$$

$$Q^{inj}_{i,f,t} = Q^{T}_{i,f,t} + \sum_{\Omega_A} Q^{A+}_{i,f,t,a}\cdot \sum_{\Omega_P} Q^{P+}_{f,t,p}.f\left(i,p\right); \quad \forall_i \in \Omega_N; \forall_f \in \Omega_F; \forall_t \in \Omega_T \quad (10)$$

$$Q^{load}_{i,f,t} = Q^{L}_{i,f,t} + \sum_{\Omega_A} Q^{A-}_{i,f,t,a} + \sum_{\Omega_P} Q^{P-}_{f,t,p}.f\left(i,p\right); \quad \forall_i \in \Omega_N; \forall_f \in \Omega_F \forall_t \in \Omega_T \quad (11)$$

Voltage drop in lines is modelled in Equation (12). Equation (13) provides a relationship between voltage, current and power flow in a line based on [26], where the squared terms in the right side are linearised as in [27]. In addition, Equations (14) and (15) represent the active and reactive power losses through each branch. Note that in Equations (13)-(15) some approximated values, denoted by (∧), for voltage and power flow are used to enable linear formulation based on [26] and [27]. To obtain these, a two-stage approach is recommended. In the first stage, the problem is solved disregarding power losses and assuming voltage magnitudes equal to 1 p.u. Later, the solution of stage one is used to initialise stage two and the MILP model is once again solved.

$$V^{sqr}_{i,f,t} - V^{sqr}_{j,f,t} = \sum_{h\in F}\left\{2 * \left(\tilde{R}_{(i,j),f,h}P_{(i,j),f,t} + \tilde{X}_{(i,j),f,h}Q_{(i,j),f,t}\right)\right\} + \sum_{h\in F}\left\{\tilde{Z}^2_{(i,j),f,h} I^{sqr}_{(i,j),f,t}\right\} \forall_{(i,j)} \in \Omega_L; \forall_f \in \Omega_F; \forall_t \in \Omega_T \quad (12)$$

$$\hat{V}^{sqr}_{j,f,t}\, I^{sqr}_{i,j,f,t} = P^2_{(i,j),f,t} + Q^2_{(i,j),f,t} \quad \forall_i \in \Omega_N; \forall_f \in \Omega_F; \forall_t \in \Omega_T \quad (13)$$

$$P^{loss}_{(i,j),f,t} = \sum_{h\in\Omega_F} \tilde{R}_{(i,j),f,h}\frac{\left(P_{(i,j),f,t}\hat{P}_{(i,j),h,t} + Q_{(i,j),f,t}\hat{Q}_{(i,j),h,t}\right)}{\hat{V}_{j,f,t}\hat{V}_{j,h,t}} + \sum_{h\in\Omega_F}\tilde{X}_{i,j,f,h}\frac{\left(-Q_{(i,j),f,t}\hat{P}_{(i,j),h,t} + P_{(i,j),f,t}\hat{Q}_{(i,j),h,t}\right)}{\hat{V}_{j,f,t}\hat{V}_{j,h,t}}\cdot \quad \forall_{(i,j)} \in \Omega_L; \forall_f \in \Omega_F; \forall_t \in \Omega_T \quad (14)$$

$$Q^{loss}_{(i,j),f,t} = \sum_{h\in\Omega_F} \tilde{X}_{(i,j),f,h}\frac{\left(P_{(i,j),f,t}\hat{P}_{(i,j),h,t} + Q_{(i,j),f,t}\hat{Q}_{(i,j),h,t}\right)}{\hat{V}_{j,f,t}\hat{V}_{j,h,t}} + \sum_{h\in\Omega_F}\tilde{R}_{i,j,f,h}\frac{\left(Q_{(i,j),f,t}\hat{P}_{(i,j),h,t} - P_{(i,j),f,t}\hat{Q}_{(i,j),h,t}\right)}{\hat{V}_{j,f,t}\hat{V}_{j,h,t}}\cdot \quad \forall_{(i,j)} \in \Omega_L; \forall_f \in \Omega_F; \forall_t \in \Omega_T \quad (15)$$

3.2 | Operational limits

Operational limits are represented by Equations (16) and (17). Here, Equation (16) represents the voltage magnitude limit, while the thermal limits for the current through each branch are given by Equation (17).

$$\underline{V}^2 \le V^{sqr}_{i,f,t} \le \bar{V}^2\% \forall_i \in \Omega_N; \forall_f \in \Omega_F; \forall_t \in \Omega_T \quad (16)$$

$$0 \le I^{sqr}_{(i,j),f,t} \le \bar{I}^2_{(i,j)} \;\; \forall_i \in \Omega_N; \forall_f \in \Omega_F; \forall_t \in \Omega_T \quad (17)$$

3.3 | Network reconfiguration

The set Equations (18)–(20) optimises the network topology. Equations (18) and (19) enable the active and reactive power flow through each switch using the binary variable ω, while Equation (20) links the voltages from the initial and final bus for each switch. Besides in Equations (18)–(20), radiality constraints presented in [28] are included:

$$-\overline{S^{sw}_{(m,n)}}.\omega_{(m,n)} \le P^{sw}_{(m,n),f,t} \le \overline{S^{sw}_{(m,n)}}.\omega_{(m,n)} \quad \forall_{(m,n)} \in \Omega_{SW}; \forall_f \in \Omega_F; \forall_t \in \Omega_T \quad (18)$$

$$-\overline{S^{sw}_{(m,n)}}.\omega_{m,n} \le Q^{sw}_{(m,n),f,t} \le \overline{S^{sw}_{(m,n)}}.\omega_{(m,n)} \quad \forall_{(m,n)} \in \Omega_{SW}; \forall_f \in \Omega_F; \forall_t \in \Omega_T \quad (19)$$

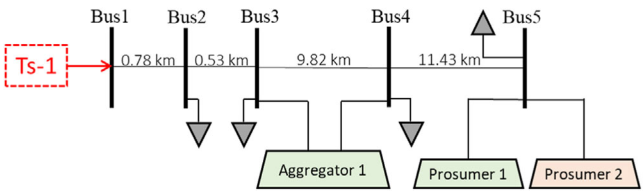

FIGURE 3 Illustrative 5-bus test system

TABLE 3 Summary of 3-phase loading of the 5-bus test system

	A		B		C	
PhaseBus	**kW**	**Kvar**	**kW**	**kvar**	**kW**	**kvar**
1	0	0	kW	0	0	0
2	150	30	0	120	240	114
3	0	0	270	45	75	42
4	120	30	90	30	120	30
5	360	150	120	112.5	315	127.5

$$\left|V_j^{sqr} - V_i^{sqr}\right| = \left(\overline{V}^2 - \underline{V}^2\right) \% \left(1-\omega_{m,n}\right) \% \forall_{(m,n)} \in \Omega_{SW}. \tag{20}$$

The reconfiguration feature in DTEM is only used for day-ahead settlements considering practicality. Therefore, the variable ω (representing the state of the switches) is not time dependent as it remains the same for the whole day.

4 | RESULTS OF CASE STUDIES

In order to assess the performance of the proposed platform, an illustrative 5-bus test system and an adapted IEEE 34-bus test system are used. The mathematical formulation presented in Section III has been coded in *AMPL* and solved using the commercial solver *CPLEX*. In addition, once the DTEM has determined all control variables, a conventional power flow was run to obtain the state of the network.

4.1 | Illustrative 5-bus test system

The 5-bus test system shown in Figure 3 is used to assess the performance of the proposed platform. Here, the IEEE #300 branch configuration was used for all lines. The voltage magnitude at Bus 1 (interconnection bus TS-1) was fixed at 1.0 p.u. (24.9 kV). The maximum and minimum voltage magnitude limits were set at 1.05 p.u. and 0.95 p.u. Phases A, B and C were assigned 29%, 35% and 36% of the total node-wise demand, respectively shown in Table 3. In addition, three active participants are connected in the system, one aggregator (A1) and two prosumers (P1 and P2). Under the DTEM platform, DERs can bid as both generation and demand, while energy prices for final customers are determined via DLMPs. Table 4 summarised the energy bids for all participants, including forecasted LMP at TS-1.

TABLE 4 Summary of energy bidding of all participants

	Case #0		Case #1		Case #2	
Transactions	**MW**	**¢/kWh**	**MW**	**¢/kWh**	**MW**	**¢/kWh**
T2LDOTs-1, segment 1	1	100	1	100	1	100
T2LDOTs-1, segment 2	2	120	2	120	2	120
P2LDO,aggregator 1	–	–	1.8	90	1.8	90
P2LDO,prosumer 1 Gen	–	–	0.9	120	0.9	120
P2LDO,prosumer 2 Dem	–	–	0.6	110	0.6	110

Abbreviations: T2LDO, Transmission-to-local distribution operator; P2LDO, peer-to-local distribution operator.

To illustrate the benefits brought by the DTEM, four cases are presented in the following subsection enabling different features of the DTEM platform in a single time interval market settlement. Initially, in Case #0 the existing energy procurement for LDCs is presented. Later, Cases 1, 2 and 3 show P2LDO and P2P energy and services transactions and reconfiguration features in a double-ended auction market.

4.1.1 | Case #0 – Existing DS energy procurement for LDCs

Under the existing procedure, the TS is considered as the only source for all loads. Customers pay a flat rate at all buses (LDC_RATE), calculated based on the total amount of energy procured from the TS, as shown in Equation (21) [29]. In other words, the LDC runs a simple power flow with conventional loads and both demand power and losses are procured from the TS. The cost of losses is split among all customers:

$$\mathrm{LDC}_{\mathrm{RATE}} = \frac{\sum_{\Omega_{\{N,F\}}} P^{L}_{i,f} + \sum_{\Omega_{\{L,F\}}} P^{loss}_{(i,j),f}}{\sum_{\Omega_{\{N,F\}}} P^{L}_{i,f}} * \lambda^{T}. \tag{21}$$

For the illustrative 5-bus test system 2.2 MW are procured from the TS, while the $\mathrm{LDC}_{\mathrm{RATE}} = 122.5$¢/kWh following Equation (21). In this case, there is no opportunity for DERs to participate in the energy procurement process, that is, there is 0% of P2P and P2LDO transactions. In addition, although in the existing DS energy procurement there is no competitive process, for comparative purposes the social welfare can be calculated as expressed in Equation (1). Hence, fixing the bid of conventional demand at 200 ¢/kWh (above all generation bids), the resulting social welfare for this case is equal to $1,662.36.

4.1.2 | Case #1 – DTEM with P2P, P2LDO and T2LDO energy transactions

The DTEM model is solved using the bids presented in Table 3 for Case #1. Figure 4 reports the DLMPs and the voltage profile for each bus while Table 5 shows the transaction dispatch

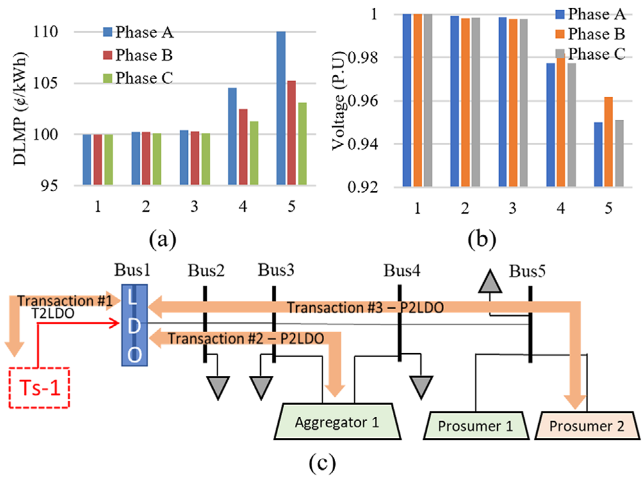

FIGURE 4 Case #1 (a) Distribution locational marginal prices (DLMPs), (b) voltage magnitudes and (c) dispatched transactions

TABLE 5 Transactions dispatched for Case #1

Transaction		Phase A	Phase B	Phase C
1	T2LDO – Ts-1 (kW)	215.48	379.96	371.47
2	P2LDO – Aggregator 1 (kW)	600	600	600
3	P2LDO – Prosumer 2 Dem (kW)	162.871	200	200

Abbreviations: T2LDO, Transmission-to-local distribution operator; P2LDO, peer-to-local distribution operator.

summary for Case #1, illustrating the selection of T2LDO and P2LDO transactions that maximise social welfare.

Comparing with the existing DS energy procurement reported in Case #0, the Case #1 demonstrates that energy procurement via P2LDO leads to 18% reduction in DLMPs. Further, Figure 4 shows the highest DLMP results at Bus 5 (phase A) as Prosumer 1 can draw energy only from Prosumer 2 at Bus 5 and not from the cheaper source TS due to lower voltage limit constraint. It is important to note that DLMPs for phase A are set by Prosumer 2, while DLMPs for phases B and C are set by Ts-1. This evidences that different price setters can coexist within the same DS, highlighting the need for the three-phase representation.

Finally, Table 5 shows a summary of the percentage of transactions per type and the social welfare for all cases. For Case #1 more than 70% of the transactions are made via P2LDO. It is important to highlight that the utilisation of DTEM contributes to the full extraction of DER commercial opportunities, as the flexible demand from P2 (initially unable to participate) is now dispatched with 563 kW, increasing the total system load by 17%; that is, increasing social welfare.

4.1.3 | Case #2 – DTEM with P2P transactions – Ancillary service

This case illustrates the DTEM model via P2P service transactions for reactive power between Prosumer 1 and Prosumer 2. To alleviate high DLMP at Bus 5 in Case #1, Prosumer 2 reaches out to Prosumer 1 via P2P agreement to buy 50 kvar in phases A and C at 50¢/kvar, aiming to improve the voltage profile and secure cheaper energy from connected TS.

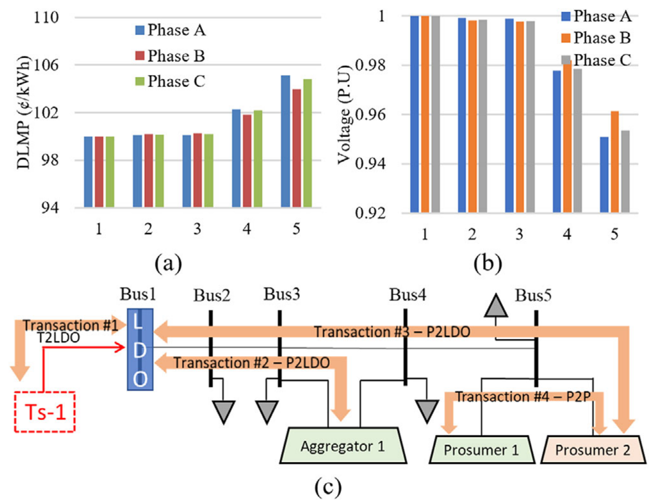

FIGURE 5 Case #2 (a) Distribution locational marginal prices (DLMPs), (b) voltage magnitudes and (c) dispatched transactions

TABLE 6 Transactions dispatched for Case #2

Transaction		Phase A	Phase B	Phase C
1	T2LDO – Ts-1 (kW)	254.11	380.59	370.81
2	P2LDO – Aggregator 1 (kW)	600	600	600
3	P2LDO – Prosumer 2 Dem (kW)	200	200	200
4	P2P – Prosumer 1 Gen (kVAr)	50	0	50

Abbreviations: T2LDO, Transmission-to-local distribution operator; P2LDO, peer-to-local distribution operator; P2P, peer-to-peer.

Using the bids presented in Table 4 for Case #2 and the P2P transaction of Prosumer 1 and 2, Figure 5 presents the DLMPs and the voltage profile for each bus; while Table 6 shows the transaction dispatch summary for Case #2, illustrating the T2LDO, P2LDO and P2P transactions selected after the DTEM settlement.

Finally, Table 7 shows that the P2P transaction represents only a 1.5% of the total transactions in the system. It can be seen, that by striking a P2P contract for reactive power, Prosumer 2 increased social welfare and reduced the DLMP value at Bus 5 (phase A) from 110 ¢/kWh to 105.12 ¢/kWh. Enabling P2P transactions for ancillary services via DTEM

TABLE 7 Percentage of total transactions & social welfare

	ISO-LDO	P2LDO	P2P	Social welfare
Case #0	100 %	–	–	$1,662.36
Case #1	28.6 %	71.4 %	–	$2,322.2
Case #2	28.7 %	69.8 %	1.5 %	$2,324.5
Case #3	29.0 %	69.4 %	1.6 %	$2,426.9

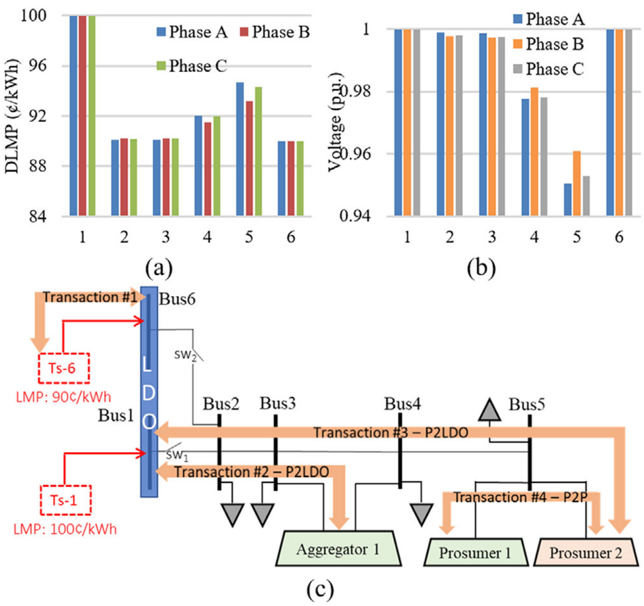

FIGURE 6 Case #3 (a) Distribution locational marginal prices (DLMPs), (b) voltage magnitudes and (c) dispatched transactions

TABLE 8 Transactions dispatched for Case #3

Transaction		Phase A	Phase B	Phase C
1	T2LDO – Ts-6 (kW)	254.34	378.30	370.84
2	P2LDO – Aggregator 1 (kW)	600	600	600
3	P2LDO – Prosumer 2 Dem (kW)	200	200	200
4	P2P – Prosumer 1 Gen (kVAr)	50	0	50

Abbreviations: T2LDO, Transmission-to-local distribution operator; P2LDO, peer-to-local distribution operator; P2P, peer-to-peer.

model increases the system social welfare. This DLMP reduction impacts not only Prosumer 2, but also those end-user customers that are a part of the conventional demand at Bus 5.

4.1.4 | Case #3 – DTEM with reconfiguration

Case #3 demonstrates the reconfiguration feature of DTEM model. One extra transmission interconnection bus at Bus 6 (Ts-6) and one extra 1 km distribution line from Bus 6 to Bus 2 were added to the test system, as shown in Figure 6c. In addition, two switches (SW_1 between Bus 1 – Bus 2 and SW_2 between Bus 6 – Bus 2) were also introduced. In addition to the bids shown in Table 4 and the P2P transaction from Case 2, different LMPs are considered at the interconnection buses from Ts-1 and Ts-6.

Results shown in Table 8 (Case #3) demonstrate that via reconfiguration, the DTEM model increases social welfare by 5% compared with Case 2. Further, Figure 6a demonstrates reduction in DLMPs in comparison with Case #1 where the highest DLMP value drops down to 94.67¢/kWh. Due to a lower LMP at Ts-6, switch SW_1 remains open, while SW_2 is closed. Results demonstrate the benefits of reconfiguring the network within a DTEM model to maximise social welfare and reduce DLMPs.

TABLE 9 Percentage of total transactions & social welfare

Hours	1	2	3	4	5	6	7	8
T2LDO (%)	40.5	34.4	31.7	31.3	35.1	46.8	63.2	71.8
P2LDO (%)	59.5	65.6	68.3	68.7	64.9	53.2	36.8	28.2
Social welfare ($)	260	257	255	255	257	264	269	273
Hours	9	10	11	12	13	14	15	16
T2LDO (%)	74	77.1	78.3	78.6	78.6	78.1	78.3	81.5
P2LDO (%)	26	22.9	21.7	21.4	21.4	21.9	21.7	18.5
Social welfare ($)	275	275	275	276	276	275	275	276
Hours	17	18	19	20	21	22	23	24
T2LDO (%)	83.5	84.8	85.4	85.3	84.2	78.3	66	50
P2LDO (%)	16.5	15.2	14.6	14.7	15.8	21.7	34	50
Social welfare ($)	278	279	279	279	278	276	270	266

Abbreviations: T2LDO, Transmission-to-local distribution operator; P2LDO, peer-to-local distribution operator.

4.2 | IEEE 34-bus test system

An adapted IEEE 34 bus test system is used to show the performance of the presented approach in larger systems. Information for the 34-bus test system can be found in [30], while a summary of the results is shown in Table 9. In this case, 2 aggregators (providing energy bids at 9 different buses) and 2 prosumers were connected to the system. Simulations were conducted for a 24-hour day-ahead market settlement. Table 9 shows the percentage of transactions dispatched for each hour within the settlement.

When compared to existing energy procurement for an LDC, the DTEM for this case improved the social welfare during the 24-hour market settlement by 9.5%. In addition, it was able to reduce DLMPs throughout the system by procuring cheaper energy from existing DERs.

The hourly total three-phase injected power by the transmission system, aggregators and prosumers for the 34-bus case study are illustrated in Figure 7 for each hour of the day-ahead settlement. Furthermore, the total three-phase demand power of the undispatchable loads of the 34-bus system, aggregator demand and prosumer demand are reported in Figure 8.

Figure 9 reports the three-phase DLMPs and the voltage profile for each bus of the 34-bus at hour #19 at the maximum load factor (100%) for the day-ahead settlement.

5 | CONCLUSIONS

Filling the void existing in transactive energy systems, as its main contribution, a comprehensive DTEM model is proposed in this paper. The DTEM model introduces an LDO in charge of

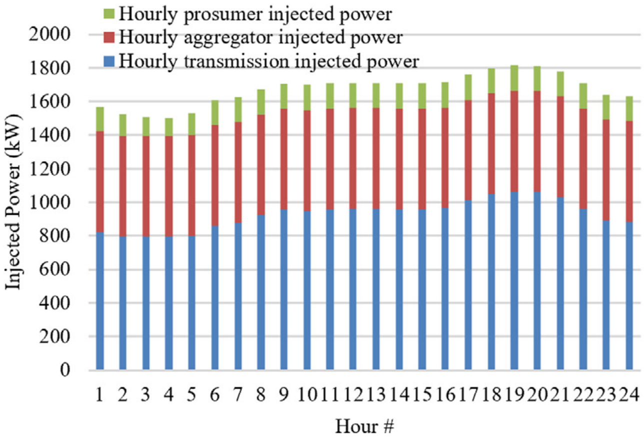

FIGURE 7 Hourly injected power of each considered supply entity of the 34-bus test system

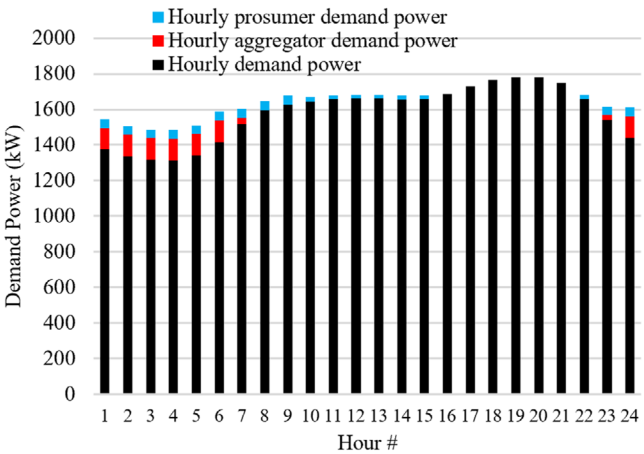

FIGURE 8 Hourly demand power of the distribution system loads and the demand power of considered entities of the 34-bus test system

operating the market. In addition, the general MILP formulation supports unbalanced three-phase DTEM model. The primary purpose of the DTEM model is to:

1. maximise social welfare within a distribution system by competitively procuring energy and services from all sources such as TS and DERs,
2. facilitate P2P, P2LDO and T2LDO transactions that satisfy network constraints,
3. create an improved economic environment for DERs and
4. provide the least costing electricity to customers.

Three cases are studied and they demonstrate improvements over the conventional DS model which is reported as Case #0. Case #1 demonstrates P2P, P2LDO and T2LDO transactions that increases social welfare by 39.6% over Case #0. Case #2 entertains P2P transactions for ancillary services that increases social welfare by 39.8% over Case #0. Case #3 entertains reconfiguration that increases social welfare by 46% over Case #0. These cases also demonstrate increase in P2P participation at lowered DLMPs benefitting prosumers and aggregators.

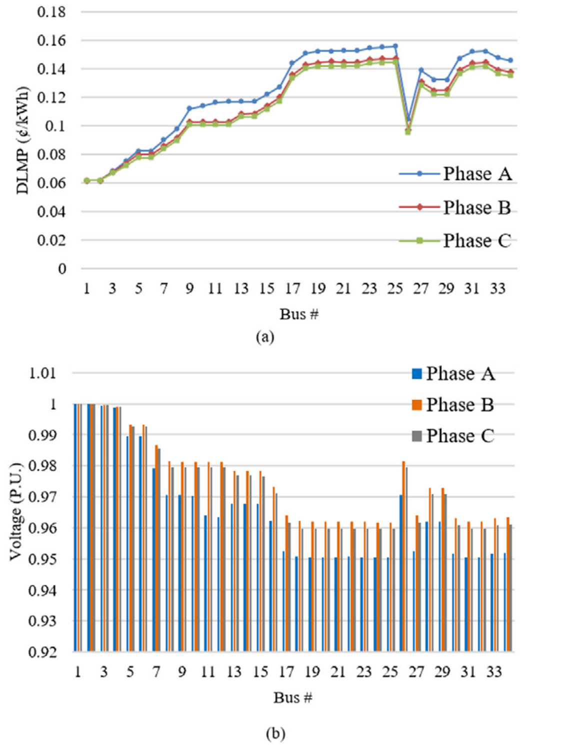

FIGURE 9 Three-phase results of the 34-bus test system. (a) Distribution locational marginal prices (DLMPs) and (b) voltage magnitudes at hour #19 with maximum load factor

6 | LIMITATIONS AND FUTURE WORK

The proposed DTEM model considers a three-phase system and facilitates network reconfiguration. While the results demonstrate the effectiveness of the developed deterministic DTEM model, it does not consider uncertainty of DERs. As a future application, uncertainty of DERs may be considered.

NOMENCLATURE

Indices

t	Hourly time index
i	Bus index
(i, j)	Distribution line index
f/h	Phase indices
a	Aggregator index
p	Prosumer index
s	Bid segment index
(m, n)	Switch index

Sets

Ω_P	Prosumers
Ω_A	Aggregators
Ω_N	Buses
Ω_L	Distribution lines
Ω_F	Phases

Ω_T Time intervals
Ω_S Bid segments
Ω_{SW} Switches

Parameters

λ_T Marginal price in transmission market
K_L Fixed bid for conventional load
K_{A+} Generation bid of aggregator
K_{P+} Generation bid of prosumer
K_{A-} Demand bid of aggregator
K_{P-} Demand bid of prosumer
K_{Adr} Demand response bid of aggregator
K_{Pdr} Demand response bid of prosumer
K_{AQ} Reactive power support bid of aggregator
K^{PQ} Reactive power support bid of prosumer
$\underline{V}^2$, $\overline{V}^2$ Lower and upper nodal square voltage limit
$\bar{I}_2$ Upper Square current limit for each line
$\tilde{R}$, $\tilde{X}$, $\tilde{Z}$ Modified line resistance, reactance and impedance

Variables

P_{A+} Injected active power of aggregator
P_{A-} Demand active power of aggregator
Q_{A+} Injected reactive power of aggregator
Q_{A-} Demand reactive power of aggregator
P_{Adr} Demand response power of aggregator
P_{P+} Injected active power of prosumer
P_{P-} Demand active power of prosumer
Q_{P+} Injected reactive power of prosumer
Q_{P-} Demand reactive power of prosumer
P_{Pdr} Demand response power of prosumer
P_{inj}, Q_{inj} Total nodal power injection
P^{load}, Q^{load} Total nodal power demand
P^{loss}, Q^{loss} Power losses in lines
P, Q Power flowing through lines
P_{sw}, Q_{sw} Power flowing through switches
P_T, Q_T Power exchange between transmission and distribution
P_L, Q_L Non-dispatchable power demand
V^{sqr} Nodal square voltage magnitude
I^{sqr} Square current magnitude for each line

Integer variables

ω Integer variable for switch operation

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