A Decentralized Transactive-Based Model for Reactive Power Ancillary Service Provision by Local Energy Communities

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***Abstract*— Local Energy Communities (LECs) have been introduced to facilitate the high penetration of distributed energy resources into distribution systems (DSs), which can also be valuable sources of ancillary services for Distribution System Operators (DSOs). The aim of this paper is to investigate if and how LECs can contribute to the reactive power management of DSs. To this end, a transactive-based model is proposed to manage the reactive power of LECs in a decentralized way. In the proposed model, DSO sends transactive signals to LECs and incentivizes them to inject/absorb reactive power aiming at controlling the voltage profile of DS. Accordingly, the reactive power management and thus voltage control is performed without any direct interferences of the DSO in the resource scheduling of LECs. The proposed model is applied to the DS of Chalmers campus to demonstrate its performance in reactive power management and voltage control.**

Keywords— Ancillary service, decentralized model, reactive power management, transactive signal, voltage control

Indices	
i, j	Index of buses
k	Index of iteration
pv	Index of PVs
t	Index of time
der	Set of DERs
$\mathbb{N}^{DS}$	Set of buses of DS
$\mathbb{N}^{DS_i}$	Set of buses that are connected to bus i
$\mathbb{N}^{LEC}$	Set of buses of LEC
$\mathbb{N}^{PCC}$	Set of PCC buses of LECs
Variables	
$\delta_{t,i}$	Voltage angle of bus
$TS_{t,i}^{Q,k}$	Transactive signal
$\lambda_{t,der}^{Q}$	Opportunity cost for reactive power of DERs
$\rho_{t,i}^{Q,k}$	Penalty factor of voltage control
$E_{t,i}^{DR}/P_{t,i}^{DR}$	Energy/power curtailed at time t with the DR
$\Delta Q_{t,i\in\mathbb{N}^{pcc}}^{LEC}$	Reactive power offered by LECs
$H_{t,i}^{B2DH}$	Heat from boiler to the heating network
$H_{t,i}^{CHP}$	Output heat of CHP
$H_{t,i}^{ch,TES}/H_{t,i}^{dis,TES}$	Charge/discharge heat of TES
$H_{t,i}^{HP}$	Output heat of HP
$H_{t,i}^{idle,TES}$	Idle losses of TES
$H_{t,i\in\mathbb{N}^{pcc}}^{Im,LEC}/H_{t,,i\in\mathbb{N}^{pcc}}^{Ex,LEC}$	Imported/exported heat from/to district heating
$H_{t,i}^{SB}$	Heat input to the smart boiler
$H_{t,i}^{R,Stir}$	Residual heat of Stirling engine
$H_{t,i}^{T}$	Heat of boiler fed to the turbine of CHP
$P_{i,t}^{ch,BES}/P_{i,t}^{dis,BES}$	Charge/discharge power of BES
$P_{t,i}^{CHP}/Q_{t,i}^{CHP}$	Active/reactive power of CHP
$P_{t,der}$	Active power of the distributed energy resource (DER)
$P_{t,i}^{HP}$	Electricity input of HP
$P_{t}^{Im\_init,LEC}/P_{t}^{Ex\_init,LEC}$	Import/export power of LECs to the DS in the initial schedule
$P_{t}^{Im,LEC}/P_{t}^{Ex,LEC}$	Import/export active power to/from the LEC
$P_{i,t}^{LS}/Q_{i,t}^{LS}$	Involuntary active/reactive load shedding
$P_{t,i,j}^{flow}/Q_{t,i,j}^{flow}/S_{i,j}^{flow}$	Active/reactive/apparent power flow
$P_{i=0,t}^{grid}/Q_{i=0,t}^{grid}$	Exchanged active/reactive power with the grid
$P_{t,i}^{SB}/Q_{t,i}^{SB}$	Active/reactive power of SB
$P_{t,i}^{TES-Stir}/P_{t,i}^{in,TES}$	Output/input power of TES
$Q_{t}^{Im,LEC}/Q_{t}^{Ex,LEC}$	Import/export reactive power to/from LEC
$Q_{t,pv}^{PV}$	Reactive power of PV
$Q_{t,i}^{SB}$	Reactive power of SB
S_{pv}^{Nom}	Nominal apparent power of PV inverter
$SOC_{t,i}$	State of charge of BES
$T_{t,i}^{HW}$	Hot water temperature of SB tank
$u_{t,i}^{ch,BES}/u_{t,i}^{d,BES}$	Binary variables for charge/discharge of BES
$u_{t,i}^{ch,TES}/u_{t,i}^{d,TES}$	Binary variables for charge/discharge of TES
$W_{t,i}^{Stir}$	Mechanical work output of the Stirling engine
$V_{t,i}$	Voltage magnitude of bus
Parameters	
$\epsilon^{H,Stir}$	Effectiveness of Stirling engine heat exchanger
η_d/η_{ch}	Charge/discharge efficiency of BES
$\eta^{h,TES}/\eta^{h,SB}$	Efficiency of TES/SB heater
η^{Gen}	Efficiency of TES output generator
η^{T}	Efficiency of CHP turbine
$\eta^{W,Stir}$	Efficiency of Stirling engine
Δt	Timestep
κ_i^{DR}	Power to energy ratio of DR
θ_{ij}	Branch impedance angle
λ_t^{e}	Spot market price
λ_t^{h}	District heating variable heat price
ξ^{DR}	Parameter correlating maximum energy capacity of DR as a percentage of load
ξ^{l}	Active and reactive power correlation of CHP
b_{ij}	Susceptance of branch
c_1, c_2, c_3, c_4	Parameters of transactive signal
c^{CHP}	Generation cost coefficient of boiler and CHP
c^{deg}	Parameter to emulate degradation cost of BES
C^{LS}	Load shedding cost
C^{W}	Specific heat of water
COP_i	Coefficient of performance of HP
k	Thermal convection parameter of SB tank

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A	Area of SB tank
$P_{i,t}^{l}/Q_{i,t}^{l}$	Active/reactive demand
$P_{t,i}^{PV}$	PV power generation
$S_{t,i}^{SB}$	Nominal apparent power of SB
$T_{t,i}^{a}$	Ambient temperature
$T_{t,i}^{CW}$	Temperature of cold water in SB tank
RR^{B}	Ramp rate limit of CHP boiler
$V/V_{t,i}^{HW}$	Tank volume of SB/ Hot water demand
Z_{ij}	Branch impedance magnitude
Symbol	
$\overline{(\bullet)}/\underline{(\bullet)}$	Maximum/minimum bounds of variable $(\bullet)$.

I. INTRODUCTION

Voltage issues affects the efficiency and supply quality and thus the operation of distribution systems (DSs) [1]. Most distribution system operators (DSOs) utilize the tap changer of substation transformer and compensation devices to keep the voltage at various feeder locations in the DS within the allowable operating ranges. Thanks to the rapid integration of DERs into DSs, they can be a source of reactive power for DSOs to handle voltage issues. DERs with supplying reactive power locally can decrease losses and contribute to voltage control of DSs. Many researchers have studied the possibility of DERs in providing reactive power in DSs. In [2], a reactive power market has been proposed for photovoltaics (PVs), while [3] introduces a cost associated to loss of life of PV inverters when they participate in the reactive power management of DSs. In [4], a community energy storage is introduced to manage reactive power compensation and load leveling in DSs. The research of [5] proposes a nodal reactive power pricing mechanism in which customers with low power factor are charged, while DERs receive incentives to provide reactive power support.

To facilitate the operation of DSs with high penetration of DERs, the European Commission has introduced the concept of Local Energy Communities (LECs) in the EU legislation [6]. LECs are aggregated DERs in different energy carriers, i.e., electricity and heat, which operate as a unified entity and can provide ancillary services for DSOs. Although aggregated DERs in the form of LECs can be a more effective source of reactive power for DSOs, many researchers have focused on the active power management of LECs and provision of active power ancillary services by LECs. In [7], a risk-averse energy management system for LECs has been proposed for optimal heat and power scheduling. Authors of [8] have proposed a model to provide flexibility by LECs for DSOs which is utilized for peak shaving and reducing the operating costs. The work in [9] has proposed an optimal dispatching model of LECs to mitigate congestion in DSs. In [10] a framework has been presented for LECs to provide reserve for DSOs. A few research have investigated capability of LECs in providing reactive power support. In [11], an energy trading model is presented in this article to provide reactive power from a LEC for DSOs. Although the role of one LEC in providing reactive power support has been studied in [11], however, contribution of multiple LECs in the reactive power support of DSs still remains a research gap in the literature. To fulfill this gap, a decentralized transactive-based model is proposed in which several LECs can participate in providing reactive power for DSOs to alleviate voltage issues of DSs. The main contributions of the proposed model are as following:

- A decentralized transactive-based model is presented where multiple LECs can provide reactive power without any direct interference of the DSO.
- An opportunity reactive power cost is considered for DERs with reactive power capability. LECs optimize their reactive power bids based on the opportunity cost of DERs and transactive signals they receive from the DSO.
- Reactive power ancillary service prices are determined by a market mechanism that enables LECs to participate in both energy and reactive power ancillary service markets.

The remainder of this study is organized as follow. In Section II the proposed framework is discussed and in Section III the detailed mathematical model is presented. Finally, the performance of the proposed framework is evaluated using the DS located at the Chalmers University of Technology campus in section IV, followed by the conclusion in Section V.

II. REACTIVE POWER MANAGEMENT FRAMEWORK

As shown in Fig. 1, modern DSs consist of multiple LECs, which each of them independently operates its own local resources. While this structure facilitates high penetration of DERs in DSs, developing a practical framework to cope with operational problems such as voltage issues in modern DSs considering the independent operation of LECs is crucial. Hence, in this section, a decentralized framework is presented that enables interaction between the DSO and LECs using transactive signals to manage reactive power of LECs. In this regard, the independent operation of LECs is preserved while the voltage issues in DSs are alleviated by managing the reactive power of LECs.

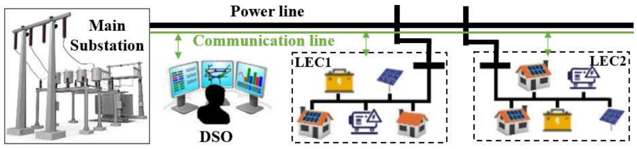

Fig. 1. The structure of DSs with multiple LECs

A. *Interaction between DSO and LECs*

The developed framework for implementing decentralized reactive power management is structured in an iterative way as shown in Fig. 2. As shown, first, the retailer sends purchase/sell price of active power from/to LECs. Then, LECs schedule their resources and optimize their active power exchange with the retailer and inform the DSO. Next, the DSO runs the load flow and checks the voltage criteria. In case of voltage violation, the reactive power management program is conducted. Accordingly, DSO determines and sends the transactive signals to LECs in each iteration. Next, LECs update their reactive power exchange based on prices and their operating costs. Transactive signals are changed in subsequent iterations until all voltage issues in the DS are alleviated.

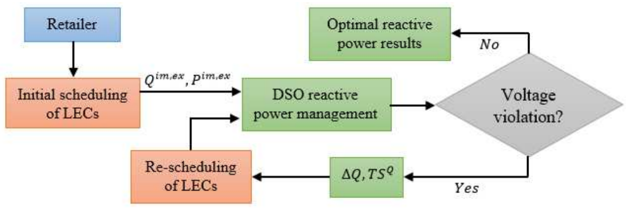

Fig. 2. The interaction between DSO and LECs to manage reactive power

B. *Reactive power pricing of DERs*

Reactive power support by DERs can cause financial losses to LECs and due to their conflicts of interest with the DSO, LECs may be unwilling to participate in reactive power management. Accordingly, for each LEC a cost should be considered for the provided reactive power of DERs. Many research has neglected the cost associated with reactive power support of DERs [12-14]. However, efforts have been made to set a price for reactive power. In [15, 16] compensation mechanisms are introduced for reactive power supply. Some as [3, 16] present nodal pricing strategies based on marginal loss reduction factors to calculate the reactive power prices while others are based on the cost function of the DERs [15, 17, 18]. In this work, a model based on [5] is utilized to represent an opportunity cost for reactive power supply from the DERs. In this model, the DERs cost for reactive power is based on the apparent power increase of the DER. This model can be used for all types of DERs making it applicable for LECs with any kind of resources. Accordingly, the price of the reactive power compensation from a DER is presented by the following:

$$\lambda_{t,der}^{Q} = \lambda_t^e \times P_{t,der}\gamma_{t,der}^{Q} \tag{1}$$

$$\gamma_{t,der}^{Q} = \left(\frac{1}{\cos\varphi_{t,der}} - 1\right) \tag{2}$$

In the above formulation as depicted in Fig. 3, the term $P_{t,der}\gamma_{t,der}^{Q}$ is the value of the increase in apparent power due to the reactive power injection by the DER. If the DER does not inject reactive power, this term will be zero and no cost will be associated to the reactive power. Note that this will be the opportunity cost that DERs in the LEC will bid their reactive power based on.

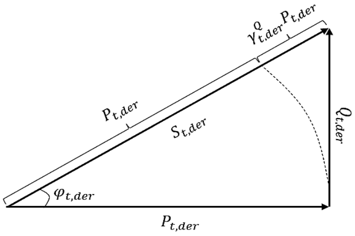

Fig. 3. Apparent power increase of DER due to reactive power injection

To avoid a non-convex problem, equation (2) is linearized by the method in [19] as follows:

$$\textstyle\sum_{l1=1}^{L1}\sum_{l2=1}^{L2}\alpha_{l1,l2,t} = 1 \tag{3}$$

$$P_{t,der} = \textstyle\sum_{l1=1}^{L1}\sum_{l2=1}^{L2}\alpha_{l1,l2,t}\hat{P}_{l1,t,der} \tag{4}$$

$$\cos\varphi_{t,der} = \textstyle\sum_{i=1}^{L1}\sum_{j=1}^{L2}\alpha_{l1,l2,t}\widehat{cos\varphi}_{l2,t,der} \tag{5}$$

$$f_t = \textstyle\sum_{l1=1}^{L1}\sum_{l2=1}^{L2}\alpha_{i,j,t}f\left(\hat{P}_{l1,t,der},\widehat{cos\varphi}_{l2,t,der}\right) \tag{6}$$

Where $\alpha_{l1,l2,t} \in [0,1]$ is a continuous variable, $\hat{P}_{l1,t,der} \in \left[\hat{P}_{1,t,der},\hat{P}_{2,t,der},\dots,\hat{P}_{n,t,der}\right]$ and $\widehat{cos\varphi}_{l2,t,der} \in \left[\widehat{cos\varphi}_{1,t,der},\widehat{cos\varphi}_{2,t,der},\dots,\widehat{cos\varphi}_{m,t,der}\right]$ are parameters. Also, f is defined as following:

$$f\left(\hat{P}_{l1,t,der},\widehat{cos\varphi}_{l2,t,der}\right) = \lambda_t^e\hat{P}_{l1,t,der}\left(\frac{1}{\widehat{cos\varphi}_{l2,t,der}} - 1\right) \tag{7}$$

C. *Transactive signals*

To manage reactive power of LECs, DSO uses transactive signals which are calculated as following:

$$TS_{t,i}^{Q,k+1} = TS_{t,i}^{Q,k} + \rho_{t,i}^{Q,k} \tag{8}$$

$$\rho_{t,i}^{Q,k} = c_1\lambda_t^e(c_2 + c_3e^{c_4k})\left(Q_i^{DN,k} - \Delta Q_{t,i\in\mathbb{N}^{pcc}}^{k}\right) \tag{9}$$

where $\rho_{t,i}^{Q,k}$ is the penalty factor to update transactive signals proportional to the required reactive power for alleviating the voltage violation at bus i of DS. AS mentioned, the transactive signals are updated in each iteration to incentive LECs for providing reactive power and alleviate voltage issues.

III. Mathematical model

In the following sections, the mathematical model of all participants i.e., LECs and the DSO is presented.

A. *LECs Scheduling*

The aim of the LEC operator is to optimally schedule its available DERs, while satisfying electricity and heat balance within and the technical constraints of the resources.

1) Objective Function: In the initial scheduling problem LECs tend to minimize their operation cost as presented in Fig. 2 and submit their baseline power exchange to the DSO. Equation (10)-(46) are valid for the buses located in each of the LECs ($\forall i \in \mathbb{N}^{\boldsymbol{LEC}}$):

$$\begin{aligned} min\textstyle\sum_t\lambda_t^e\left(P_t^{Im,LEC} - P_t^{Ex,LEC}\right) + c^{CHP}\left(H_t^{B2DH} + \right.\\ \left.H_t^T\right) + \left(\lambda_t^h\left(H_t^{Im,LEC} - H_t^{Ex,LEC}\right) + c^{H,var}H_t^{Im,LEC} + \right.\\ \left.c^{H,fix}\right) + \textstyle\sum_{t,pv}\lambda_{t,pv}^{Q}Q_t^{PV} + \sum_t\lambda_{t,CHP}^{Q}Q_t^{CHP} + \sum_t\lambda_{t,sb}^{Q}Q_{t,sb}^{SB} + \\ \textstyle\sum_t c^Q\left(Q_t^{Im,LEC} - Q_t^{Ex,LEC}\right) \end{aligned} \tag{10}$$

The first three terms of (10) are related to the cost of active power exchange, cost of generating active power by the CHP, and cost of heat exchange with the grid. λ_t^e is the spot price while c^e is the network tariff (Fixed fee for utilizing the network) when the LEC imports energy. The district heat retailer charges the district heating consumers by $c^{H,var}$ for the peak power input and $c^{H,fix}$ which is a fixed annual cost (scaled to hourly value). The fourth to sixth terms represent the cost associated with the reactive power opportunity cost by the PV, CHP, and SB, respectively. The last term is the cost of imported reactive power from the grid. Currently, there is no market-based price for reactive power in Sweden and the customers only pay for a monthly reactive fee which is indicated by c^Q [20]

2) Electricity energy balance: The active and reactive balances of the LECs are considered by:

$$\begin{aligned} P_{t,i\in\mathbb{N}^{pcc}}^{Im,LEC} - P_{t,i\in\mathbb{N}^{pcc}}^{Ex,LEC} = P_{t,i}^{CHP} + P_{t,i}^{PV} + P_{t,i}^{LS} + P_{t,i}^{DR} \\ + P_{t,i}^{dis,BES} + P_{t,i}^{TES-Stir} \\ - P_{t,i}^{ch,BES} - P_{t,i}^{in,TES} - P_{t,i}^{L} - P_{t,i}^{HP} \end{aligned} \tag{11}$$

$$Q_{t,i\in\mathbb{N}^{pcc}}^{Im,LEC} - Q_{t,i\in\mathbb{N}^{pcc}}^{Ex,LEC} = \textstyle\sum_i\left(Q_{t,i}^{CHP} + Q_{t,i}^{PV} + Q_{t,i}^{SB} - Q_{t,i}^{L}\right) \tag{12}$$

3) Heat energy balance: The heat balance of the LECs is presented as:

$$\begin{aligned} H_{t,i\in\mathbb{N}^{pcc}}^{Im,LEC} - H_{t,i\in\mathbb{N}^{pcc}}^{Ex,LEC} = \textstyle\sum_i\left(H_{t,i}^{CHP} + H_{t,i}^{R,TES} + H_{t,i}^{HP} - \right.\\ \left.H_{t,i}^{SB} - H_{t,i}^{L}\right) \end{aligned} \tag{13}$$

4) Biomass boiler and CHP: The biomass boiler and turbine can provide electricity and heating simultaneously to the electricity and district heating networks. The heat of the boiler can be dispatched directly to the heating network and to the turbine of the CHP unit presented by (14). The output electricity of the turbine is reflected as (17) and coupled with the CHP output heat with (18). The ramp rates of the boiler are shown with (15) while its output heat is limited by its operational limit (16). The active and reactive power of the CHP can be dispatched within their operational limits. The reactive capability of the turbine is coupled to its active power.

$$H_{t,i}^{B} = H_{t,i}^{B2DH} + H_{t,i}^{T} \tag{14}$$

$$-RR^B \le H_{t,i}^{B} - H_{t-1,i}^{B} \le RR^B \tag{15}$$

$$\underline{H_{t,i}^{B}} \le H_{t,i}^{B} \le \overline{H_{t,i}^{B}} \tag{16}$$

$$P_{t,i}^{CHP} = \eta^T H_{t,i}^{T} \tag{17}$$

$$H_{t,i}^{CHP} = (1-\eta^T)P_{t,i}^{CHP} \tag{18}$$

$$\underline{P_{t,i}^{CHP}} \le P_{t,i}^{CHP} \le \overline{P_{t,i}^{CHP}} \tag{19}$$

$$\xi^l\overline{P_{t,i}^{CHP}} \le Q_{t,i}^{CHP} \le \xi^h P_{t,i}^{CHP} \tag{20}$$

5) PV: Several PVs located at Chalmers network have reactive power control capability. The reactive power output of the PVs is limited by a percent of their converter capacity

(21). The maximum capability of reactive power of the current installed PVs is also constrained by their active power as (22). The operational limit of PVs converter is shown in (23). Equation (23) is linearized by the method in [23]

$$-\xi^{PV} S_{pv}^{Nom} \leq Q_{pv,t}^{PV} \leq \xi^{PV} S_{pv}^{Nom} \quad (21)$$

$$Q_{pv,t}^{PV} \leq P_{pv,t}^{PV} \quad (22)$$

$$\sqrt{\left(P_{t,i}^{PV}\right)^2 + \left(Q_{t,i}^{PV}\right)^2} \leq S_{t,i}^{PV} \quad (23)$$

6) BES: The operational constraints of the BES are considered as following:

$$SOC_{t,i} = SOC_{t-1,i} - P_{t,i}^{d,BES}/\eta_d + P_{t,i}^{ch,BES}.\eta_{ch} \quad (24)$$

$$0 \leq P_{t,i}^{ch,BES} \leq u_{t,i}^{ch,BES}.\overline{P_{t,i}^{ch,BES}} \quad (25)$$

$$0 \leq P_{t,i}^{d,BES} \leq u_{t,i}^{d,BES}.\overline{P_{t,i}^{d,BES}} \quad (26)$$

$$u_{t,i}^{ch,BES} + u_{t,i}^{d,BES} \leq 1 \quad (27)$$

$$\underline{SOC_{t,i}} \leq SOC_{t,i} \leq \overline{SOC_{t,i}} \quad (28)$$

7) Demand response: The model of demand response in LECs is described by (29)-(31) and similar to an energy storage model [21]. The maximum energy capacity of the DR source is a percentage of the load at the LEC bus and power-to-energy ratio parameter which depends on the technology of the DR resource [22].

$$E_{t,i}^{DR} = E_{t-1,i}^{DR} + P_{t,i}^{DR} \quad (29)$$

$$0 \leq E_{t,i}^{DR} \leq \xi^{DR} P_{t,i}^{L} \quad (30)$$

$$-\kappa_i^{DR} \xi^{DR} P_{t,i}^{L} \leq P_{t,i}^{DR} \leq \kappa_i^{DR} \xi^{DR} P_{t,i}^{L} \quad (31)$$

8) TES: A latent phase TES which is coupled with a stirling engine can be dispatched by the LECs. The energy balance of the TES and its constraints are expressed by (32)-(33). The TES is charged through an electrical heater as (34). The charge and discharge power of the TES are constrained by its operational limit represented in (35)-(36). (37) prevents simultaneously charge and discharge of the TES.

$$\varphi_{t+1,i}^{TES} = \varphi_{t,i}^{TES} + \left(H_{t,i}^{ch,TES} - H_{t,i}^{dis,TES} - H_{t,i}^{idle,TES}\right)\Delta t \quad (32)$$

$$\underline{\varphi_{t,i}^{TES}} \leq \varphi_{t,i}^{TES} \leq \overline{\varphi_{t,i}^{TES}} \quad (33)$$

$$H_{t,i}^{ch,TES} = \eta^{h,TES} P_{t,i}^{in,TES} \quad (34)$$

$$P_{t,i}^{in,TES} \leq u_{t,i}^{ch,TES} \overline{P_{t,i}^{in,TES}} \quad (35)$$

$$0 \leq H_{t,i}^{dis,TES} \leq u_{t,i}^{d,TES} \overline{H_{t,i}^{dis,TES}} \quad (36)$$

$$u_{t,i}^{ch} + u_{t,i}^{dis} \leq 1 \quad (37)$$

The discharged heat of the TES is directed through a Stirling engine. The Stirling Engine mechanical work drives a DC generator which produces electricity while the low temperature residual heat of the Stirling Engine is transferred to the heat network through a heat exchanger which are presented by (38)-(40).

$$W_{t,i}^{Stir} = \eta^{W,Stir} H_{t,i}^{dis,TES} \quad (38)$$

$$H_{t,i}^{R,Stir} = \epsilon^{H,Stir} H_{t,i}^{dis,TES} \quad (39)$$

$$P_{t,i}^{TES-Stir} = \eta^{Gen} W_{t,i}^{M,Stir} \quad (40)$$

9) Smart boiler: The SB is a controllable electrical boiler tank which it's active and reactive input power are controllable. The active power of SB is fed by a controllable heater as presented in (41). The reactive power of the SB is constrained by its operational limits and the converter capability (42)-(43). Equation (43) is linearized by the method in [23]. The limit of reactive power is 10%. It is assumed the water storage is assumed to be always full and the consumed hot water is replaced with the same volume of cold water in each time interval [24]. The temperature of water storage can be calculated according to (44).

$$H_{t,i}^{SB} = \eta^{h,SB}.P_{t,i}^{SB} \quad (41)$$

$$Q_{t,i}^{SB} \leq 0.1.P_{t,i}^{SB} \quad (42)$$

$$\sqrt{\left(P_{t,i}^{SB}\right)^2 + \left(Q_{t,i}^{SB}\right)^2} \leq S_{t,i}^{SB} \quad (43)$$

$$T_{t+1,i}^{HW} = H_{t,i}^{SB}/VC^W - \left[V_{t,i}^{HW}.\left(T_{t,i}^{HW} - T_t^{CW}\right) + V.T_{t,i}^{HW}\right]/V - kA\left(T_{t,i}^{HW} - T_{t,i}^{a}\right)/VC^W \quad (44)$$

B. *LECs re-dispatch*

If the DSO detects a voltage violation and requires reactive power it will send transactive signals to the LECs to request them to change their reactive power. Based on the transactive signals the LECs re-dispatch their DERs.

1) Objective Function: In LEC re-dispatch problem based on the transactive signal that the DSO sends, the LECs tend to minimize their operation cost while offering reactive power to the DSO as follow:

$$\begin{aligned} min \textstyle\sum_t \lambda_t^e\left(P_t^{Im,LEC} - P_t^{Ex,LEC}\right) + \sum_t c^{CHP}(H_t^{B2DH} + H_t^{T}) + \left(\sum_t \lambda_t^h\left(H_t^{Im,LEC} - H_t^{Ex,LEC}\right) + c^{H,var} H_t^{Im,LEC} + c^{H,fix}\right) + \sum_{t,pv} \lambda_{t,pv}^{Q} Q_{t,pv}^{PV} + \sum_t \lambda_{t,CHP}^{Q} Q_t^{CHP} + \\ \textstyle\sum_t \lambda_{t,sb}^{Q} Q_{t,sb}^{SB} + \sum_{t \notin t^Q} c^Q\left(Q_t^{Im,LEC} - Q_t^{Ex,LEC}\right) + \sum_{t \in t^Q} c^Q\left(Q_t^{Im,LEC} - Q_t^{Ex_{base},LEC}\right) + \sum_{t \in t^Q} TS_{t,i}^{Q}\, \Delta Q_{t,i \in \mathbb{N}^{pcc}} \end{aligned} \quad (45)$$

$$\Delta Q_{t \in t^Q, i \in \mathbb{N}^{pcc}} = Q_{t,i \in \mathbb{N}^{pcc}}^{Ex,LEC} - Q_{t,i \in \mathbb{N}^{pcc}}^{Ex_{base},LEC} + Q_{t,i \in \mathbb{N}^{pcc}}^{Im_{base},LEC} - Q_{t,i \in \mathbb{N}^{pcc}}^{Im,LEC} \quad (46)$$

In this problem t^Q is the set of hours that the DSO requires reactive power from the LECs. The objective function is the same as (10) except than the last three terms. The revenue the LECs gain from changing their reactive power is reflected in the last term. The two other terms reflect the cost of reactive power which is exchanged in the initial schedules. Note that the LECs will be compensated with the transactive signal $TS_{t,i}^{Q}$ for the amount they changed in their exchanged reactive power and the rest will be charged with the normal reactive price (c^Q). The operational constraints of the DERs of the LEC are the same as the initial scheduling problem (11)-(44).

C. *DSO*

The DSO is the responsible for the secure operation of the DS and resilient supply to the energy consumers. In the proposed framework the DSO runs the power flow analysis and determines the amount of reactive power it requires to keep the voltage of the system in secure limits. The DS is connected to the upstream network at the substation network denoted as node 0 and can insert reactive power from it as well. The equations of this section are valid for $\forall i \in \mathbb{N}^{\boldsymbol{DS}}$.

1) *Objective function*: The DSO's objective is to minimize its costs of procuring reactive power from the LECs and the cost of reactive load shedding:

$$Min \textstyle\sum_{t,i \in \mathbb{N}^{pcc}} TS_{t,i}^{Q} \Delta Q_{t,i \in \mathbb{N}^{pcc}} + C^{LS} Q_{i,t}^{Shed} \quad (47)$$

2) *Power flow constraints:* The power flow equation of the DS are modelled as an AC power flow as (48)-(52). The term $\Delta Q_{t,i \in \mathbb{N}^{pcc}}$ is the amount of reactive power required from each of the LECs to maintain the voltage of the busses in the secure limits.

$$\textstyle\sum_{j \in \mathbb{N}^{DN^i}} P_{t,i,j}^{flow} = P_{t,i}^{CHP} + P_{t,i}^{PV} + P_{i,t}^{LS} + P_{i=0,t}^{grid} - P_{i,t}^{l} - P_{t,i}^{LEC} \quad (48)$$

$$\textstyle\sum_{j \in \mathbb{N}^{DN^i}} Q_{t,i,j}^{flow} = Q_{i=0,t}^{grid} + Q_{i,t}^{Shed} - Q_{i,t}^{l} - Q_{t,i \in \mathbb{N}^{pcc}}^{LEC} + \Delta Q_{t,i \in \mathbb{N}^{pcc}}^{Q} \quad (49)$$

$$P^{flow}_{t,i,j} = \frac{V_{t,i}^2}{Z_{i,j}}\cos(\theta_{ij}) - \frac{V_{t,i}V_{t,j}}{Z_{i,j}}\cos(\delta_{t,i}-\delta_{t,j}+\theta_{ij}) \quad (50)$$

$$Q^{flow}_{t,i,j} = \frac{V_{t,i}^2}{Z_{i,j}}\sin(\theta_{ij}) - \frac{V_{t,i}V_{t,j}}{Z_{i,j}}\sin(\delta_{t,i}-\delta_{t,j}+\theta_{ij}) - \frac{b_{i,j}V_{t,i}^2}{2} \quad (51)$$

$$\underline{V_{t,i}} \le V_{t,i} \le \overline{V_{t,\iota}} \quad (52)$$

IV. CASE STUDIES

The 10.5 kV distribution system located at Chalmers campus is used to evaluate the performance of the proposed model. The single-line diagram of the system is shown in Fig. 4. The line parameter and load demand of the system can be found in [25]. It should be mentioned that the power factor of loads in LECs is assumed 0.9 lag. Likewise, the whole system is connected to a district heating network which is not shown. Two network areas indicated by dotted lines in Fig. 4, are considered LECs that are capable of exchanging electricity and heat with upstream networks. The DERs of LEC1 are PVs, heat pump, battery, and a CHP. DERs of LEC2 are PVs, battery, flexible loads, smart boiler, and a thermal energy storage. The details data of DERs operated by LECs are given in Table I [7, 26]. It is assumed the allowable voltage range of the system is between 95% and 105% of nominal voltage. The simulations are carried out on a day in April 2021 over 24 hours with 1 hour time interval. The heat price for April is 0.359 SEK/kWh and the tariffs $c^{H,var}$ and $c^{H,var}$ are 76.33 and 2.35 SEK/day, respectively. Likewise, LECs trade active power with the retailer at the Nord Pool spot market price [27].

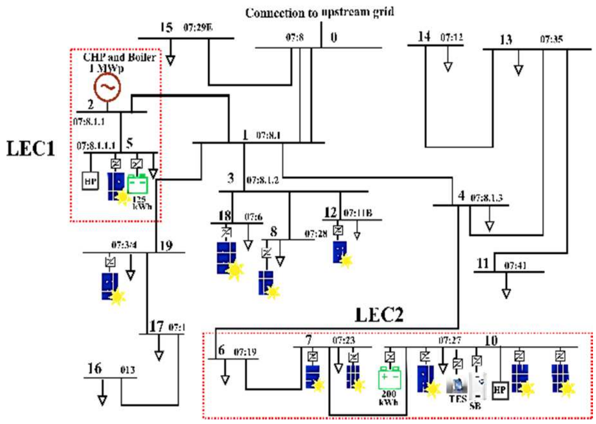

Fig. 4. Single-line diagram of distribution system at the Chalmers campus

A. *Voltage reduction control*

In this case the length of lines between busses 1-4, 4-6, and 6-7 are increased and an inductive load is added to buses 3 and 7 to emulate a voltage reduction in the system. The voltage profile of the buses during scheduling horizon are depicted in Fig. 5. As can be seen the voltage at buses 2 and 7 violate the limits (0.95-1.05 p.u) at hour 14:00 and 17:00, respectively. Therefore, the DSO runs the proposed model to manage the reactive power of LECs and keep voltage within the determined range. Fig. 6 shows transactive signals in each iteration of the model. As can be seen, the DSO increases the prices after each iteration to incentive LECs for providing more reactive power. The voltage reduction violation is alleviated at iteration 6 and optimal results are obtained as presented in Table I. Although LEC2 sells more reactive power to the DSO, however, the transactive signal for LEC1 is higher than LEC2. The reason is that DERs of LEC1 have a higher cost to provide reactive power. The reactive power scheduling of LECs is shown in Fig. 7. As can be seen, in both LECs, PVs are the main resource to provide reactive power.

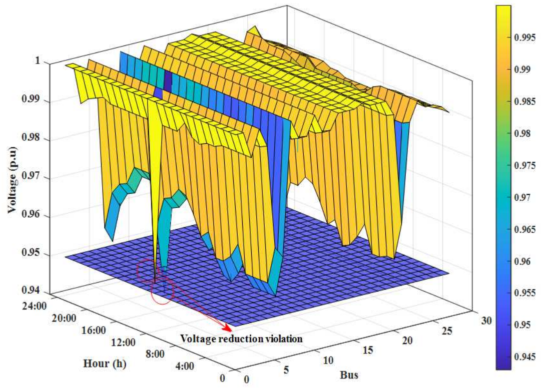

Fig. 5. Voltage profile at all buses during scheduling horizon

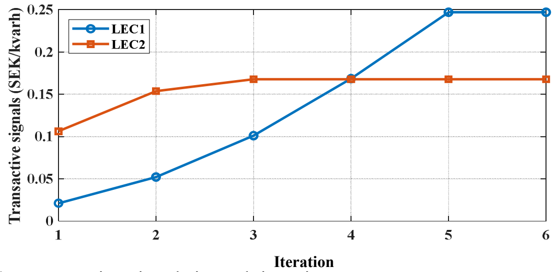

Fig. 6. Transactive signals in each iteration

TABLE I. OPTIMAL TRANSACTIVE PRICES AND PROVIDED REACTIVE POWER IN VOLTAGE REDUCTION CONTROL

Provision of reactive power by LECs (kVarh)		Transactive price (SEK/kVarh)	
LEC1	**LEC2**	**LEC1**	**LEC2**
10.096	50.812	0.2471	0.1678

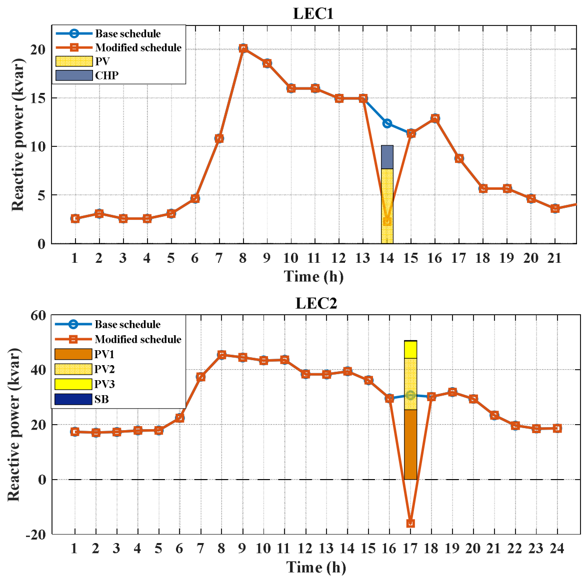

Fig. 7. Reactive power scheduling of LECs to alliviate voltage reduction

In LEC1 at hour 14:00 the PV and CHP generates 7.698 kVarh and 2.398, respectively, resulting in an 10.0096 kVarh total flexibility. In LEC2 at hour 17:00 the PVs provide a total amount of 50.47 kVarh while the SB provides 0.275 kVarh.

B. *Voltage rise control*

This is the same as the previous case, but some capacitive load is added to bus 3 to simulate the voltage rise in the system. The optimal results are presented in Table II. The reactive power scheduling of LECs is shown in Fig. 8. The voltage rise issue occurs near to LEC1 i.e., bus 2 at hour 14:00, however, DSO incentives LEC2 to absorb some part of reactive power as well. This strategy manages the reactive power in the DS at a lower cost.

TABLE II. OPTIMAL TRANSACTIVE PRICES AND PROVIDED REACTIVE POWER IN VOLATAGE RISE CONTROL

Provision of reactive power by LECs (kVarh)		Transactive price (SEK/kVarh)	
LEC1	LEC2	LEC1	LEC2
33.38	27.89	0.2763	0.0714

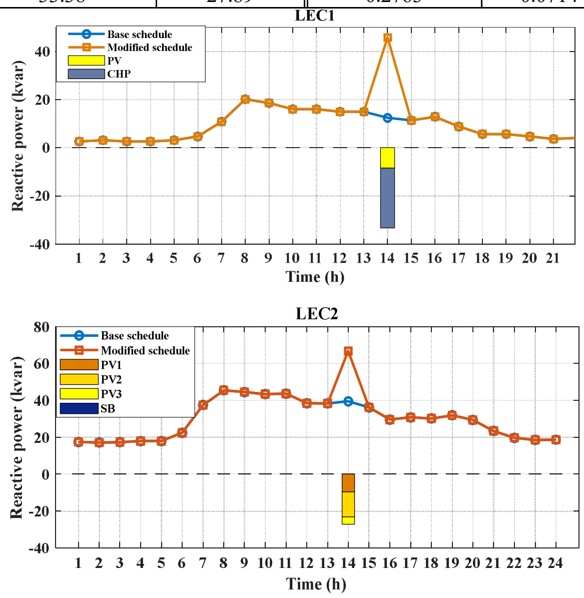

Fig. 8. Reactive power scheduling of LECs to aleiviate voltage rise

V. CONCLUSION

This paper proposed a novel decentralized transactive-based framework to manage reactive power of multiple LECs in DSs. The proposed model was applied in real case studies at the Chalmers university of technology campus. Numerical results shown that voltage issues in DSs can be effectively alleviated by incorporation of the provided reactive power of LECs. In addition, it was indicated that using the proposed market mechanism, LECs can optimally participate in both energy and reactive power ancillary service markets without any direct interference from the DSO. Future work will be allocation of the profit between reactive power resources of the LEC which provide reactive power ancillary service.

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